SNOWFALL & SUSTAINABILITY: CLIMATE CHANGE ADAPTATION AND MITIGATION STRATEGIES FOR COLORADO'S SKI INDUSTRY

by

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This thesis investigates adaptation and mitigation strategies that Colorado's ski resorts can implement to remain viable in an industry vulnerable to climate change. Home to the highest concentration of ski resorts in the U.S., Colorado's ski industry contributes over $1.4 billion annually to state GDP and plays a critical role in regional tourism and economic development. However, rising temperatures, declining snowfall, and increasingly variable precipitation patterns due to climate change threaten snow reliability and shorten ski seasons, posing significant risks to the industry. The goal of this research is to identify ways for Colorado's ski industry to maintain operations despite the physical and transitional risks that climate change poses. This research analyzes the economic value of the ski industry, historical climate data from 2000–2024, and the sustainability initiatives of Vail Resorts Inc., a leading operator in the sector. Drawing on these findings, the thesis proposes three strategies to enhance climate resilience: expanded snowmaking, adoption of dry slope technology, and emissions reductions through more sustainable transportation. Ultimately, the study underscores the need for proactive adaptation and mitigation to secure the future of ski resort operations in a changing climate.

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Chapter 1: Introduction

Colorado stands as one of the world's premier skiing destinations, attracting thousands of visitors annually to its resorts. Tourists come from across the globe to participate in snow sports and activities creating a profitable industry. However, the enterprise is facing significant challenges. Warmer winter temperatures reduce natural snowfall and cause snow to melt earlier, threatening the viability of Colorado's ski resorts (VandenEinde, 2024). In the 2023-2024 ski season, snowfall fell 10% below the ten-year average, creating significant risks to tourism, revenues, and quality of the ski seasons (Posada, 2025). These resorts rely heavily on snowfall to maintain their operations and, by default, their profitability. With climate change impacting the level of natural snow cover, there is significantly reduced business, limited skiing options as runs and lifts may be closed due to insufficient snow coverage, and increased reliance on artificial snowmaking – all impacting the economic well-being of the resort and their ability to maintain their operations.

The ski industry is a vital component of Colorado's economy, with 31 active ski mountains across the state. As of 2025, the industry is expected to reach $1.4 billion in revenue, reflecting an annualized growth rate of 2% from 2020. Although the number of resorts has remained stable over the past five years, the industry still supports over 15,000 direct jobs and thousands of others in secondary businesses, like lodging and retail, that relies on ski tourism. Meanwhile, total wages have grown up to 3.5% annually to $530.6 million by 2025. Looking ahead, the industry is projected to continue expanding through 2030 (IBIS World, 2025). This economic performance highlights the central role of Colorado's ski industry and its importance for tourism, employment, and regional development. The potential destabilization of this sector due to climate change would have far-reaching implications for communities, businesses, and the

state's overall economic health. This thesis will examine the economic benefits that the ski industry offers Colorado as well as the harms of climate change on this sector to highlight the importance of implementing sustainable business practices and strategies to maintain viability.

As defined by the United Nations, sustainability is "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 2025). Sustainable business practices can help to protect Colorado's ski industry and ensure that they are available in the future. This thesis will culminate by developing recommendations for long-term industry success, focusing on the diversification of revenue streams beyond traditional winter activities, sustainable practices to reduce greenhouse gas emissions, and snowmaking infrastructure to enhance viability. These solutions are informed by what is currently being done to mitigate and adapt to climate change risks, and what additional strategies would be beneficial. This thesis will utilize Vail Resorts, owner of a majority of the ski resorts in Colorado, to highlight the current efforts to curb the negative effects of climate change by examining their most recent sustainability reports.

Ideally, offers valuable insights for the ski industry as a whole. Climate change impacts everyone, and mitigation and adaptation strategies can be adapted by any industry to help enhance resilience. This research also contributes to the body of knowledge surrounding sustainable business practices by examining how tourism-driven, climate-sensitive industries can adapt to environmental challenges. This thesis will provide suggestions to how all ski resorts, not just those in Colorado, can maintain viability in the face of climate threats by implementing climate-conscious business practices.

The Process

The primary research question that guided this thesis is, “what strategies can Colorado's ski industry adopt to mitigate and adapt to the risks of climate change and ensure long-term viability?”. To answer this question, this thesis also poses a secondary question of, “what are the biggest risks climate change poses to the ski industry and how is a major industry player responding?”.

There are a few limitations that impact this thesis. My research focuses primarily on Colorado, which limits the applicability to other ski regions with different climates and tourism patterns. Additionally, measuring the effectiveness of the proposed sustainability strategies can be challenging because of limited long-term data and the need to project far into the future. This thesis focuses on what is currently being done and identifying potential strategies than can be employed now.

This thesis uses a mix-method approach, combining quantitative data analysis with qualitative research and literature reviews to assess the impact of climate change on Colorado’s ski industry and evaluate adaptation and mitigation strategies. First, the research analyzes key economic performance indicators of Colorado’s ski industry to highlight its importance: contributions to the state’s GDP, employment figures, and industry drivers. Next, the thesis analyzes historic temperature data from 2000-2024 in Grand Junction area, Colorado, where a majority of the state’s ski resorts are located to identify long-term warming trends. To further explore the implications of a warming climate, the thesis will include an analysis on the causes, consequences, and Colorado-specific impacts of climate change. Particular attention will be paid to how these warming temperatures affect snow, resort operations, and tourism behavior.

The next part of the research focuses on Vail Resorts Inc. as a case study to evaluate how a major industry player is responding to these risks. By examining the company's sustainability reports, including their *Epic Promise for a Zero Footprint* 2021-2022 Progress Report and their Environmental, Sustainability, and Responsibility Report from the 2022-2023 season, the study will identify and assess the current adaptation and mitigation efforts.

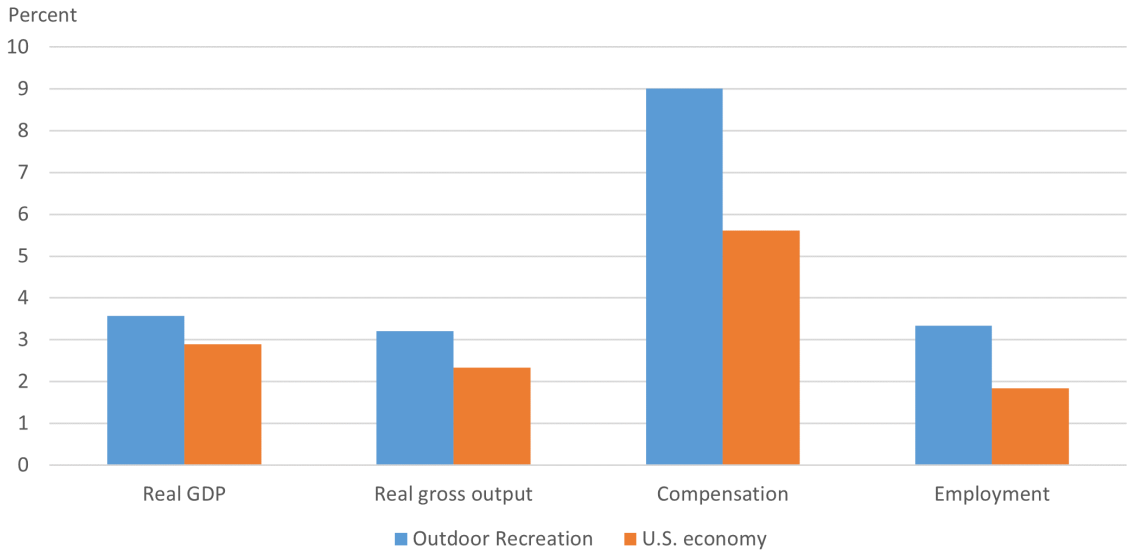
Finally, the thesis will combine the quantitative and qualitative findings to develop recommendations for Colorado's ski industry to enhance climate resilience. These methods allow for a comprehensive understanding of the intersection between economic viability, environmental responsibility, and strategic climate adaptation and mitigation strategies.

Chapter 2: The U.S. Ski Industry

The U.S. ski industry is a subsection of the tourism and recreation industry that is composed of over 486 ski resorts across the nation. These resorts make their money during the winter season through day passes, season tickets, lodging, dining, equipment rentals, and ski lessons along with other experiences. With over 60.5 million visits in the 2023-2024 season, it's clear that this industry has a large economic impact (National Ski Areas Association, 2024).

The U.S. outdoor recreation economy, including the ski industry, generates $639.5 billion in economic output–accounting for 2.3% of the nation's GDP. It grew 3.6% in inflation-adjusted real GDP in 2023, faster than the 2.9% growth of the overall economy (Bureau of Economic Analysis, 2023).

Chart 1. Change in Outdoor Recreation, Compared With U.S. Economy, 2023



U.S. Bureau of Economic Analysis

The ski industry itself operates within a saturated market, with hundreds of companies operating ski resorts nationwide. There are many small resorts that make up 12.8% of the market

share, but the main players are Vail Resorts, Alterra Mountain Company, and Boyne Resorts (Kerwin, 2022).

There are many macro-environmental factors that have an impact on the U.S. ski industry. The industry is influenced by several factors including the rise of disposable income, legislative changes, technology innovations, and climate factors.

In the United States, disposable income is increasing. In February 2025, disposable personal income increased $191.6 billion, 0.9%, from January 2025 (Bureau of Economic Analysis, 2025). This is good for the ski industry as ski trips are non-essential and luxury expenses. When people have more money to spend, they're more likely to spend it on recreation and experiences like skiing. People may visit resorts more often, stay longer, and buy more services like ski lessons. This not only benefits resorts, but local businesses like hotels, restaurants, and gear shops as well. However, it is important to monitor economic fluctuations as financial downturns can lead to a drop in visits and profits.

Legal implications impact the U.S. ski industry as well. State, local, and federal laws impact how resorts have to run. Regulations from the Clean Water Act, U.S. Forest Service, and EPA affect snowmaking, water use, emissions, and waste management. Many resorts operate on public lands, which requires compliance with land-use permits and forest management practices. These legal obligations can increase operation complexity and costs, but they also play a vital role in protecting natural resources and ensuring sustainable resorts.

Tech advancements also impact this sector by improving efficiency and the guest experience. One major advancement that is key for the ski industry is snowmaking. Snowmaking is the use of large machines to create on-slope snow from water and pressurized air. This technology helps ski resorts reduce reliance on natural snowfall, helping them to open earlier,

close later, and ensure there is sufficient coverage for skiers to enjoy the slopes. Technological advancements in snowmaking are beneficial for industry and can help to ensure climate change endurance (Steiger & Mayer, 2008).

One main factor that has a large impact on this industry is the environment. Climate change impacts snowfall levels and disrupts traditional seasons. Because of this, ski resorts face volatility in revenue and profits. Snow shortages cost the industry around $252 million annually in extra expenses and lost income, and ski seasons are expected to continue to shrink by up to 33 days by 2050, creating serious financial repercussions (Posada, 2025).

This industry is situated for a complex future where it needs to balance climate challenges and economic opportunities. Disposable income, technological improvements, and snowmaking systems can help influence the demand of winter sports, however maintaining viability in the face of climate change is a priority for this industry as well.

Colorado's Industry Specifics

In Colorado, the outdoor recreation sector, including the ski industry, is rapidly growing (Berdychowski, 2024). The state has over 30 ski areas and welcomed more than 14 million skier visits during the 2023-2024 season alone, making it one of the most visited ski destinations in the U.S. (Blevins, 2024).

The ski industry provides significant economic benefits to the state of Colorado. In 2023, the state's real GDP was $529.63 billion according to the Federal Reserve Bank of St. Louis (Federal Reserve Economic Data, 2025). Winter outdoor recreation, including skiing, snowboarding, snowmobiling, and snowshoeing, had a significant impact. Snow activities added $1.6 billion in value to Colorado's economy in 2023 (Frank, 2024). While this is a modest share

of the state's GDP, approximately 0.30%, it highlights the impact that snow sports have on the state and mountain communities that rely on tourism and seasonal activity.

Colorado's ski industry plays a vital role in job creation and supporting secondary businesses statewide. The industry supports over 46,000 jobs, ranging from seasonal to full-time positions and encompassing both primary employment (e.g. lift operators, ski instructors, ski patrol) to ancillary work (e.g. dining, transportation, retail) (RCC Associates, n.d.). These jobs contribute to the economy, provide opportunities, and reinforce the ski industry's position as a key economic driver for the state.

Vail Resorts Inc. is a front leader in this industry. This company owns and manages 42 mountain resorts across the US, Canada, Australia, and Switzerland. In Colorado alone, Vail Resorts operates five of the state's most profitable and popular resorts: Vail Mountain, Beaver Creek, Breckenridge, Keystone, and Crested Butte (Vail Resorts, 2025). Its namesake, Vail Mountain, located in Eagle County, Colorado, is the largest ski mountain in Colorado with over 5,000 acres of skiable terrain and consistently listed as "the best ski resort in Colorado" (Peiffer, 2024).

Vail Resorts Inc. generates a majority of its revenue in the winter through lift ticket sales, lodging, skiing, retail, and ski gear rentals. These sources of revenue depend on how many visitors frequent their mountains, which depends heavily on season snowfall—without sufficient snow coverage, the company struggles. Although Vail Resorts does not break down their individual resort visitation reports, company-wide data shows that skier visits were down 9.7% in the 2023-2024 season with snowfall 42% lower than the start of the 2022-2023 winter season (Blevins, 2024a). This highlights the reliance of even the largest ski operators on snowfall in order to maintain visitation, which is threatened by climate variability.

These insights into Vail Inc. show this company's contribution to Colorado's economic stability while emphasizing the need for strategic business model adjustments in the face of climate-related uncertainties. With the economic benefit that Colorado's ski industry supplies and the growing threat of climate change, there is a clear need for ski resorts to adapt their business models to be prepared for uncertain snowfall in the future. Colorado's ski industry is a major economic driver that sustains entire mountain communities, supports secondary businesses, and contributes significantly to regional and national economies. Understanding how climate shifts threaten this sector is crucial for protecting not just resort profits but the livelihoods of thousands of workers and the vitality of our mountains.

Chapter 3: Climate Change

Climate change is shifts in temperature and weather patterns over long periods of time. While some of these changes are natural, human activity is heavily responsible for warming temperatures (Bolles & Velev, 2024). Burning fossil fuels, energy use, manufacturing, and transportation create greenhouse gas emissions that raise global temperatures. These rising temperatures go beyond warm days and contribute to extreme weather events like droughts, fires, rising sea levels, intense storms, lower biodiversity, and decreased snowfall.

Not only does this pose a threat to the wellbeing of our planet, but it also impacts business operations worldwide. The environmental threats posed by climate change affect virtually every sector of the global economy, whether directly or indirectly. Tourism and recreation businesses dependent on reliable weather patterns face significant threats—ski resorts struggle with shorter seasons and inconsistent snowfall, beach destinations contend with erosion and extreme weather events, and outdoor recreation industries face disrupted operations and diminished access to natural landscapes.

Natural resource dependent sectors are especially vulnerable. Agricultural sectors experience direct impacts through crop failures from drought, flooding, extreme temperatures, and other events. This can lead to crop failures, livestock loss, and increased costs for food, animal feed, and ethanol that depends on crop yields. As climate change intensifies, these disruptions are expected to become more frequent and severe.

Climate change also disrupts manufacturing and supply chains. Fires, extreme weather, and other climate-related events all impact the ease of obtaining raw materials, delay transportation, and ultimately raise the cost of goods for industries across the board. This threatens the stability of both local livelihoods and global supply chains and economies.

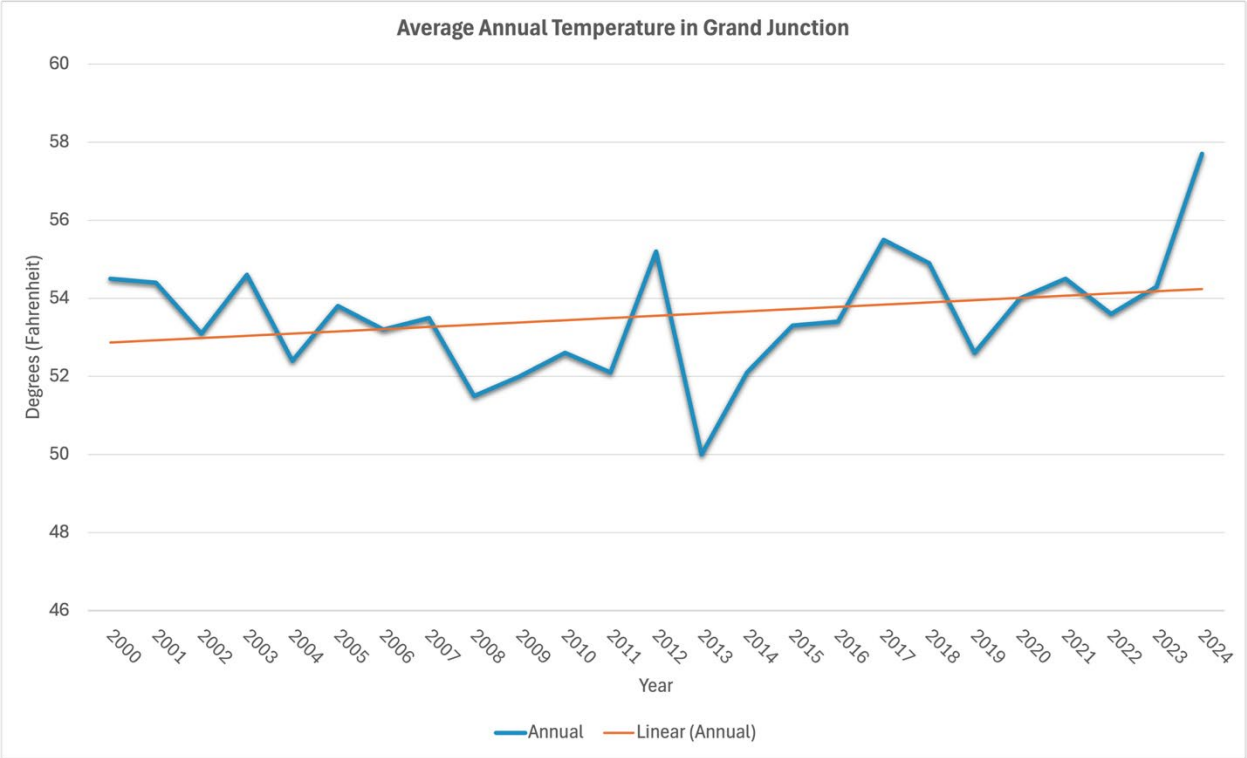
Through the lens of systems thinking, coined by Barry Richmond in 1987, it can be understood that the systems and industries of the world all influence each other. Actions within the system impact the entire structure. The impacts of climate change ripple throughout the global economy as losses in one sector inevitably affect connected industries. As climate events become more extreme, their economic consequences—ranging from direct asset damages and adaptation expenses to productivity losses and supply chain breakdowns—continue to grow. These are not future concerns, but current realities that affect the viability of many sectors.

Climate Change Risks for the Ski Industry

Colorado's Climate Shifts

The warming climate is a significant threat to the future of Colorado's ski industry. The industry is dependent on the consistent snowfall and low temperatures that will allow for sufficient snow coverage. Rising temperatures have led to reduced snowfall, shorter ski seasons due to lack of coverage, and increased reliance on artificial snowmaking — trends that increase costs and hurt the industry's profitability (Wobus et al., 2017).

Since 2000, there have been noticeable increases in the average annual temperature in the Grand Junction Area in Colorado–where a majority of Vail Inc.'s ski resorts are located (US Department of Commerce, 2024). This time series graph uses the mean monthly temperatures from 2000 to 2024 to illustrate the yearly averages in temperature. A linear regression of this data yields the trend line equation $y = 0.092x + 35.23$, where y is the average temperature in Fahrenheit and x is the year. This shows that the average temperature has increased by approximately 0.092ºF per year, or about 2.3º over the 25-year period.



This upward trend aligns with the broader climate change impacts observed in the U.S. and indicates that this region has experienced warming over the past two decades. Global warming and climate impacts pose risks to the ski industry–both physical and transitional.

Physical Risks

Physical risks of climate change are the consequences that arise from increasing temperatures and extreme weather events. These risks can be divided further to include acute and chronic risks. Chronic physical risks are climate impacts that are drawn out for long periods of time, like the warming temperatures in Grand Junction Area, Colorado. This isn't the only region that's experiencing warming temperatures. Around 95% of the United States' land surface has seen increased temperature of around 1.5 degrees Celsius, and this trend has been steadily increasing (Kerwin, 2022). As the world warms, snowpack decreases, winters are shorter, and

snowfall is less reliable. Snowpack is the amount and thickness of snow that accumulates on the ground (US EPA, 2016). Climate change drives lower snowpack levels because as the average temperatures rise, a greater amount of winter precipitation is rain as opposed to snow, especially at lower elevations and during bookend months of the ski season. Even when the snowfall does occur, warmer temperatures can lead to faster melting and hinder nighttime freeze-thaw cycles that builds snowpack. When snow falls later in the year and melts earlier in the spring, the length and reliability of ski seasons is impacted, which impacts skier turnout and revenue. A 2017 study created a model to simulate natural snowfall in 247 winter recreation locations throughout the United States to determine how winter recreation will be impacted by climate shifts. The results show that, while it varies slightly based on location, elevation, and climate scenarios, almost all locations will see reductions in season lengths in the upcoming decades. By 2050, many ski resorts could face season reductions of up to 50% and by 2090 up to 80% (Wobus et al., 2017). These season length changes could result in foregone visits, unsold tickets, unrented gear, and other revenue losses. Snow quality also suffers when temperatures warm, which makes terrain less suitable for recreation. If skiers feel like they are not getting sufficient value for their money or that they could find better conditions elsewhere, they are less likely to visit Colorado's resorts. This leads to a compounding economic impact: fewer lift tickets sold, lower gear rental revenues, empty hotel rooms, and decreased local spending.

The second part of physical risks are acute risks. These arise from increase weather severity. More extreme weather events not only pose safety risks from high winds, storms, and freezing temperatures, but creates logistical disruptions that cause lift closures, canceled ski lessons, and asset damages that contribute to guest dissatisfaction and profit loss. In February 2025, a series of storms in the Pacific Northwest forced several major resorts to close early.

Mount Hood, Timberline Lodge, and White Pass Ski Area had to suspend their operations due to wind gusts that reached over 80mph. The conditions were deemed unsafe for recreation and led to lift closures and refunded tickets. In Colorado, high winds have also forced shutdowns. On April 1st of this year, Wolf Creek did not run any lifts due to wind speeds that reached up to 60mph (Deck, 2025). On January 29th, 2025, Ski Cooper in Leadville, Colorado closed down their operations due to temperatures below negative 20 degrees Fahrenheit (McKee, 2025). The growing volatility of winter weather patterns shows how climate change can create unsafe conditions, resulting in revenue loss, guest dissatisfaction, and logistical issues.

It's clear that climate change poses significant risks to the ski industry, further emphasizing the importance of implementing strategies to enhance resort resilience and prevent these weather events from becoming even more extreme.

Transition Risks

Beyond physical risks, climate change also creates transition risks for Colorado's ski industry. These refer to the challenges companies face as they shift to more sustainable business practices and lower carbon operations (EPA, 2025). When organizations make operational changes to reduce greenhouse gasses, it comes with costs. These transition risks can be further broken down into four subsections: policy and legal, technology, market, and reputation. For Colorado's ski industry, these risks are significant and stem from a combination of changing consumer preferences and the financial implications of adapting operations to sustainability demands.

As local, state, and federal policies and legislation changes around emission reductions, energy use, and water management, ski resorts are under growing pressure to invest in more

sustainable infrastructure–such as transitioning to renewable energy or reducing emissions. Making transitions to adhere to updating regulations can pose costs.

Beyond policy and legal risks, shifts in technology can pose transitional risks. Investing in lower-emission expenditures, like energy-efficient snow groomers or solar powered snowmaking machines, require substantial investments. This reliance on sufficient capital can pose a challenge for small or independently owned resorts. Ski Cooper is a smaller resort in Leadville, CO and run by a nonprofit. Because of the high costs of investment and the financial capacity of this small resort, Ski Cooper doesn't invest in snowmaking technology and relies on 100% natural snowfall (Ski Cooper, 2025). Because of Ski Cooper's size and resources, transitioning to more eco-friendly expenditures put their profitability at risk.

In the market, consumer preferences are shifting, particularly among younger generations. Younger generations of skiers are becoming increasingly environmentally conscious and prefer supporting businesses that demonstrate transparent climate responsibility (Reichheld et al., 2023). These visitors are more likely to support businesses that demonstrate genuine climate responsibility, transparency, and sustainability leadership (Reichheld et al., 2023). As a result, ski resorts that fail to align with these values risk reputational harm and potential declines in visitation. To maintain credibility and retain consumer loyalty, resorts must actively communicate their environmental efforts and integrate sustainability into their operations. However, this shift is not without challenges—implementing green initiatives, improving operational transparency, and creating formal sustainability reports all require substantial financial investment.

Similarly to consumer preferences in the market, reputation also poses transition risks. Skiers, mountain enthusiasts, and other stakeholders alike pay attention to weather and snow

conditions. Tourism behavior and the demand in this market are impacted by the snowpack, weather, and temperature conditions at the resorts. A simulation study published in April 2020 highlights how low snowfall reliability and poor snow coverage could cause "market-wide demand losses of 64%" (Steiger et al., 2020). If consumers prefer other resorts with better snowfall or even feel that Colorado's resorts have a reputation for poor quality conditions, this puts the revenue of Colorado's resorts in jeopardy.

This combination of regulatory, tech, consumer, and climate pressures make the transition to more sustainable practices complex, but also urgent. Although it is hard to pinpoint exactly when and how ski resorts will feel the impacts of climate change due to variability in climate and challenges measuring the effects of mitigation and adaptation strategies, it is evident that the ski industry needs to be prepared for both physical and transition risks.

Chapter 4: Current Adaptation and Mitigation Strategies

There are many strategies Colorado's ski resorts are using to lessen the negative impacts of climate change on their business, including focusing on adaptation and mitigation. Adaptation and mitigation strategies are terms coined by the Intergovernmental Panel on Climate Change (IPCC), a body of the United Nations that analyzes the science, impacts, and solutions related to climate change. The IPCC defines these terms as:

> "…complementary strategies for responding to climate change. Adaptation is the process of adjustment to actual or expected climate and its effects in order to either lessen or avoid harm or exploit beneficial opportunities. Mitigation is the process of reducing emissions or enhancing sinks of greenhouse gases (GHGs), so as to limit future climate change" (IPCC, 2010).

In other words, adaptation helps ski resorts cope with the impacts of climate change, such as reduced snowpack and shorter seasons, while mitigation focuses on slowing the root causes, like emissions from energy use. These strategies are important not only for maintaining economic stability, but also for preserving the environment and securing the long-term future of the industry.

Case Study: Vail Resorts

Vail Resorts Inc. utilizes these strategies and is currently striving to shift their business model to be more sustainable. According to internal analysis and their own sustainability reports, mitigating and adapting to climate change is at the forefront of their business model.

Vail Resorts Inc. has an admirable goal of reaching a zero net operating footprint by 2030 (Vail Resorts, 2022). Zero net operating footprint, also called net zero, means that there is a balance between the amount of greenhouse gasses Vail Resorts produces across all their

operations, and the amount that they remove from the atmosphere. This is part of their "Epic Promise for a Zero Footprint", announced in 2017, which also includes zero waste going to the landfill and a zero net operating impact on forests and habitats all by 2030. Vail outlines how they are going to reach their goals in their 2021-2022 Progress Report. To reach net zero emissions by 2030, Vail Inc. plans to reduce electricity and natural gas usage by an additional 15%, building on a 19% reduction already achieved since 2008, adjusted for new acquisitions and operations. This includes a $25 million dollar investment in innovative energy-saving technologies such as low-energy snowmaking systems, green building designs, and more efficient grooming equipment and practices. The company is also working closely with local, state, and federal governments to bring more renewable energy to the grids where they operate. To address greenhouse gas emissions, Vail is investing in carbon offset programs like tree planting to help slow the effects of climate change. Additionally, Vail encourages vendors and suppliers to reduce emissions across its supply chain and provides guests with information and opportunities to reduce or offset their own carbon footprints while visiting its resorts. The company also tracks its progress through an annual sustainability report, aligned with Global Reporting Initiative (GRI) standards. As a benchmark, Vail Resorts aims to achieve a 50% reduction in net emissions by 2025, using 2016 levels as a baseline. As of 2025, Vail Resorts achieved 100% renewable energy at its North American Resorts and 6.1 million pounds of landfill waste reduction (Vail Resorts, 2022).

The strength of these initiatives lies in Vail Inc.'s clear recognition of the climate risks that are facing the industry and its both adaptive and mitigative approach. From a mitigation perspective, the plan includes concrete goals like achieving net zero emissions, eliminating waste, and off setting the carbon footprint that actively combats global warming. Not only are

these mitigation strategies reducing the company's own contribution to climate change, but it's setting a precedent for other firms in the industry to implement their own mitigation strategies and become more sustainable. Since Vail Resorts Inc. is an industry leader, other firms will be encouraged to also take environmental accountability.

On the adaptation side, initiatives like energy-efficient snowmaking and more green, efficient, infrastructure show how Vail is adjusting their operations to maintain viability despite warmer temperatures and more variable ski seasons. These steps enable the company to still maintain visitor expectations even as environmental conditions are changing.

Chapter 5: Recommended Strategies

There are many strategies that can be employed to adapt to and mitigate some of the effects of climate change. The following section outlines recommended adaptation and mitigation strategies for Colorado's resorts, including expanded snowmaking, diversifying revenue beyond winter sports, and reducing greenhouse gas emissions through more sustainable operations.

Adaptation

Snowmaking

Snowmaking is the process of using water and pressurized air to create frozen water droplets that mimic natural snowfall. While often called "artificial snow", this is still snow, just with higher density that allows it to last longer and be more durable.

The use of snowmaking is already one of the most visible forms of climate adaptation strategies across the ski industry sector because it helps decrease reliance on natural snowfall, which has become more varied over time (Scott et al., 2022). As noted throughout the thesis, this is a predominant strategy to handle climate change impacts. Since 2023, Winter Park in Colorado has been working to upgrade their 1970's snowmaking system to help extend the length and quality of their ski seasons. Their systems will help the resort to open earlier and stay open longer, minimizing the risk of warming temperatures and melting snow affecting their seasons. Winter Park isn't the only Colorado ski resort that has shown the appeal of snowmaking technology, several others are investing in this adaptation strategy already: Vail Mountain, Keystone, Breckenridge, Aspen, and Eldora have invested as well (The Denver Post, 2025). In 2019, Vail Mountain went through one of the largest snowmaking expansion projects in resort

history. Bill Rock, the president of Vail Resorts Inc., said that this undertaking allowed them to extend their season by 12 days. The goal is to offer more days and more consistent snow conditions for their customers (Scott et al., 2022).

There are various methods for successful snowmaking: lances, snow cannons, and artificial clouds. These machines spray fine droplets of water into cold air, where it freezes and falls (SnowTrex, 2024). Active proteins, like Snowmax, can be added to the water to help ensure that the water droplets freeze and freeze faster, making the process more efficient and able to work at slightly warmer temperatures (Ober Mountain, 2024). The water used for snowmaking is typically sourced from local reservoirs, water storage ponds, and meltwater streams — meaning the process is heavily dependent on regional water.

These guns are typically used in the beginning of the ski season to build a solid base layer before natural snowfall starts. On average, ski areas require between 400 to 500 hours of snowmaking to adequately cover trails and prepare the mountain to open (Wobus et al., 2017). However, this requires a wet bulb temperature of at most 28 degrees Fahrenheit. As climate shifts create warmer and less predictable temperatures, this creates some unreliability to snowmaking operations, which is why other strategies are needed alongside of it to really ensure operational viability in low-snow years.

In addition to this challenge, artificial snowmaking has been discussed as a maladaptation strategy, potentially creating more harm than good, especially in areas facing water and energy insecurity (Scott et al., 2022). To cover an acre with 1-foot of snow, approximately 175,000 gallons of water is needed as well as 4,317-5,304 kWh (Massanutten, 2025). The energy required varies depending on whether lances or snow cannons and weather condition, but as snowmaking production is projected to increase as climate change progresses, the energy and water usage

needed to create adequate snow will also increase (Knowles et al., 2023). By 2050, snowmaking production is projected to increase between 55% and 97%, creating a greater demand for resources. This increased reliance has broad implications: drawing more water from mountain watersheds–areas where rain, snowmelt, and other sources collect in basins, reservoirs, and lakes–can potentially disrupt ecosystems and reduce downstream water availability. Likewise, increased electricity use, if not sourced sustainably, can further contribute to greenhouse gas emissions, creating a self-defeating cycle in which resorts consume more energy to respond to an issue created by fossil fuel dependence in the first place. These risks make it clear that snowmaking cannot be the sole adaptation strategy and needs to be implemented strategically.

There are many ways to ensure snowmaking is utilized efficiently. In 2022, Breckenridge Snowmaking Manager, John Anicito, outlined Vail Resorts' strategy to update snowmaking machines with new technology to reduce the amount of compressed air needed to operate. The new guns allow the resort to "run more guns simultaneously, which means [they] are making more snow without increasing energy consumption" (Vail Resorts, 2022a). They state that they are constantly looking for innovations to upgrade the system to ensure operations are as efficient as possible and are aiming to be "a leader in the snowmaking industry" (Vail Resorts, 2022a).

Beyond more efficient technology, renewable energy sources can help offset unsustainable energy usage. Colorado has almost 300 sunny days per year, making it one of the best states to implement solar energy operations (Colorado.com, 2017). Vail Resorts Inc. already uses 100% renewable electricity in their North America resorts, including for operating their snowmaking machines. They achieved this through investments in renewable electricity sources like large-scale wind farms and other local sources (Vail Resorts, 2022a). A-Basin, a smaller

Colorado resort owned by Vail, is currently operating their 24-machine fleet completely through solar power (OpenSnow, 2024).

Additionally, adhering to water use regulations and being mindful of what watersheds are used can help to avoid these implications. Vail Resorts, for example, already takes several precautions to reduce water usage and protect local watersheds. The company ensures it operates within its state-regulation water usage rights and monitors what watersheds are being used for snowmaking to avoid overuse in sensitive areas. To reduce even further strain, Vail has implemented leak prevention strategies and efficient water use technologies. The company installs low-flow fixtures and leak monitoring systems to track irregulate spikes in usage to ensure there isn't any extreme water withdrawals (Vail Resorts, 2023). Looking for sustainable ways to operate these machines through better technology and renewable resources can ensure it does not become a maladaptation strategy. These practices can be implemented in ski resorts across Colorado and show how careful planning and technology can help resorts operate their snowmaking machines more sustainably to ensure long-term viability.

Snowmaking technology is a critical adaptation strategy for ski resorts. However, implementing these systems require substantial upfront costs, ongoing operational costs, as well as labor, water, and energy inputs. Depending on a resort’s location, size, elevation, natural snowfall, and season length, snowmaking can cost anywhere from $500,000 to over 3.5$ million per season (Flynn, 2013). Despite these costs, snowmaking is an operational tool that must be implemented to adapt to a changing climate. Artificial snow will help Colorado’s resorts to extend their seasons, maintain consistent terrain coverage, and offer their visitors quality conditions. In turn, these benefits sustain guest satisfaction and protect resort revenues by avoiding short seasons, last-minute closures, and limited terrain access–all which impact ticket

sales, visitation, and secondary revenue streams from things like gear rentals and dining. While snowmaking does require significant expenditure, the long-term return on investment is obtained by the ability to operate more predictably despite variable weather. While small resorts might not be able to implement large systems, even limited snowmaking capabilities can serve as a buffer against waning snowfall. This technology can be a vital tool for many Colorado resorts to minimize the operational risks associated with climate change. Snowmaking systems offer Colorado's resorts a way to maintain viability, extend season length, and offer better terrain for their guests. If used strategically with other approaches, snowmaking puts these resorts in a better position to handle variability in snowfall for the foreseeable future and maintain guest expectations.

Diversify Revenue – Dry Slopes

With large swings in snowfall and increased variability in weather patterns, it makes it harder for the ski industry to plan the winter season in advance. A changing climate makes it difficult for firms in the industry to determine what operational strategies will be the most effective for the upcoming season. Rapid changes in season length, opening and closing dates, and snowmaking demands can "leave economies a little bit shaky", says the director of the UC Berkeley Central Sierra Snow Laboratory (Llanes, 2025). With winter revenues at risk, another adaptation strategy that Colorado's ski resorts can employ is focusing on diversifying their revenue beyond winter sports.

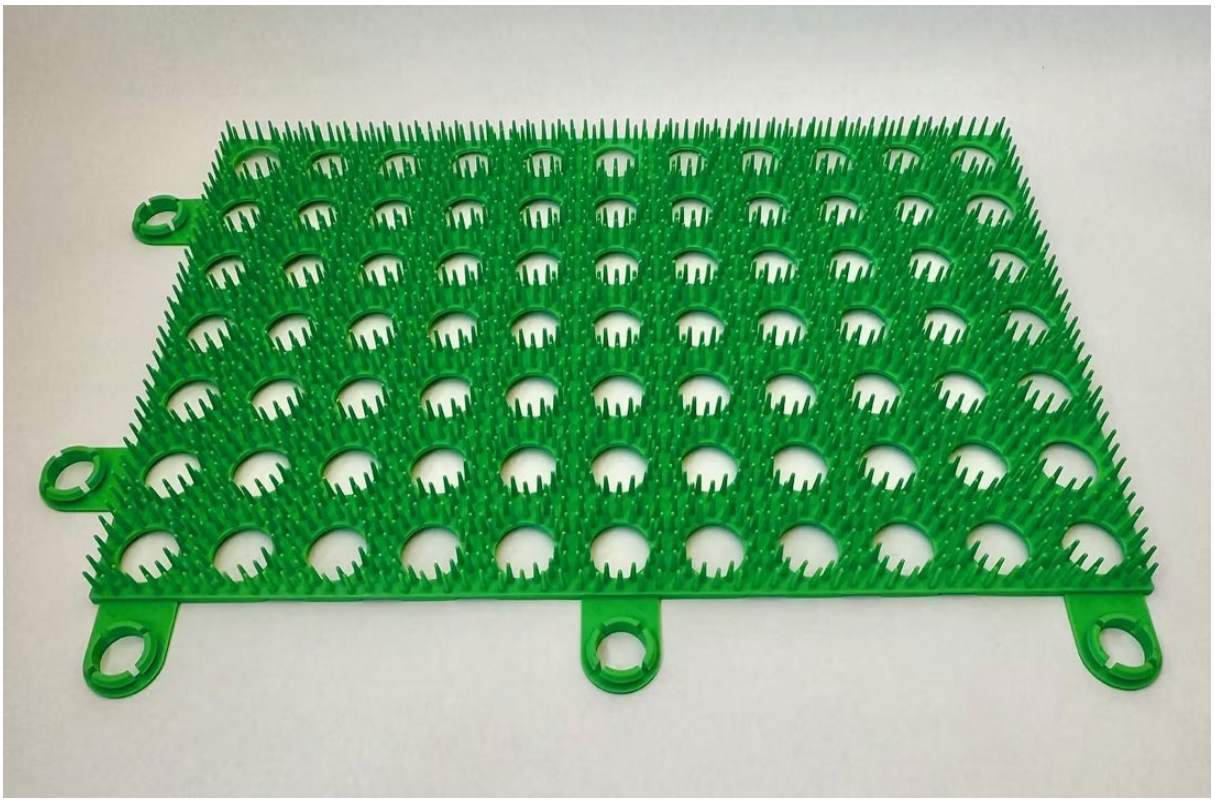
Ski resorts can set their sights on revenue streams outside of lift ticket sales, gear rentals, and typical winter season activities that depend on snowfall. Focusing on de-seasonalization and potential year-round activities can help provide some stability (Rudolf, 2022).

Dry slope skiing is one way that ski resorts in Colorado can step outside of their typical snow-dependent offerings. Dry slope skiing is a form of skiing that can be done inside or outside on artificial surfaces that mimic natural snow. It is a year-round alternative to traditional ski slopes and mitigates the risk of not being able to use ski slopes because of lack of coverage. Rob Stewart, a ski writer for BBC, emphasizes the practicality of artificial ski slopes; “if the dry slope's there and it snows on top, you're never going to know [the synthetic surface] is there. But if the snow doesn't arrive, you've got a surface you can still ski on” (Helfenbaum, 2024). This is an innovative option that can be employed to keep ski resorts open longer and reduce reliance on precipitation. A dry slope can be indoor or outdoor, and the material can be placed over existing ski runs (see Figure 1). These carpet-like pads use polymer fibers to mimic the feeling of real snow. They can be moved, added to, and updated freely and are kept damp with misters to reduce friction and improve user experience.

Currently, the are three dry ski slope options in the US: The Liberty Mountain Snowflex Center in Lynchburg, Virginia, Buck Hill in Montana, and Powder Ridge in Connecticut. They are open all four seasons and offer skiing, boarding tubing, and sledding activities on artificial slopes. Dry slope skiing is significantly more popular in the United Kingdom and countries like Germany, the Netherlands, and France. The UK has over 50 dry slopes for skiers to enjoy, like the one highlighted in the following image in Tallington Lakes, Tallington.

Despite the clear benefits dry slope skiing offers ski resorts, there are important environmental considerations to keep in mind. Most artificial slopes are made from synthetic polymer fibers that are not biodegradable and may contribute to long-term waste, microplastic pollution, and soil degradation. These environmental risks could undermine the sustainability goals of resorts aiming to reduce their environmental footprint.

This concern has been recognized by researchers looking to develop more environmentally responsible dry slopes. Newsnow, an Italian company, recently developed their Ecosnow product–a greener, more environmentally friendly alternative to typical dry slopes.



This dry slope material is made of recycled plastics and food-grade polymers that do not release harmful chemicals into the soil or air (NEWSNOW, 2016). Ecosnow is also fully recyclable and designed to let water and snowmelt pass through its fibers, reducing water loss and promoting non-consumptive water usage. Newsnow has proven to be a leader in the dry slope industry and will hopefully encourage other dry slope manufacturers to utilize greener materials for their products.

For ski resorts in Colorado where climate change presents a growing threat, integrating these sustainable, eco-friendly dry slope systems could provide both climate resilience and a profitable opportunity. If resorts implement this adaptation strategy, they can diversify their offerings beyond traditional winter seasons and minimize dependence on snowfall.

Mitigation

Reduce GHG

There are three different types of greenhouse gas emissions: Scope 1, Scope 2, and Scope 3. Scope 1 emissions within the ski industry are categorized as emissions that are released directly from resort operations. This could be from on-site fuel usage in snow groomers and company vehicles, or natural gasses used for heating lodges and resort buildings. Scope 2 emissions result from the generation of purchased energy–such as electricity, heating, or cooling supplied by a utility. Scope 2 emissions are indirect from the resort and their impact may vary depending on how the utility generates the electricity–whether they use renewable sources or fossil fuels. Lastly, Scope 3 emissions are emitted throughout a company's value chain, including emissions emitted by consumers and visitors. While these emissions fall outside the direct control of Colorado's ski resorts, they are a large portion of any resort's overall carbon footprint, even exceeding the emissions generated by on-site operations (Scope 1) or purchased electricity (Scope 2). For resorts like the ones owned by Vail Resorts that draw in thousands of visitors per day, the impact of travel GHG emissions from tourists is substantial.

Transportation-related greenhouse gasses are strong drivers of the rising global temperatures that threaten the future of Colorado's ski resorts. Ironically, one of the key contributors to transportation emissions is travel required to access these resorts. To address this contradiction, Colorado ski resorts can encourage more sustainable transportation options such as mountain shuttle services, improved public transit access, and public transportation incentives. By encouraging lower-emission travel, resorts can reduce their environmental footprint and lower the GHG emissions that contribute to global warming.

In order to implement greener transportation, ski resorts can offer shuttle options. Currently, there are dozens of shuttle options in Colorado including Peak 1 Express, Epic Mountain Express, Denver Airport Ski Shuttle, National Park shuttles, and other rideshare organizations. These public buses offer passengers a way to access multiple ski resorts without having to drive their personal vehicles to the mountain. Go Vail 2045 is a community planning initiative implemented by Vail Mountain in Colorado that focuses on transportation opportunities. This program "endeavors to address the challenges and opportunities that lie ahead, weaving together innovative strategies, community input, and sustainable practices" (Town of Vail, 2024).

Vail Mountain's report highlights a few key components of the resort's current and future transportation system, emphasizing a commitment to improving sustainable travel and accessibility. According to Vail, local buses are frequent, free, easy to use, and the community desires more routes and greater frequency for regional buses (Town of Vail, 2024). This reflects the growing need for reliable, accessible, and sustainable public transportation options that can accommodate ski tourism and full-time residents in Colorado's ski towns. To meet this need, Vail's transit plan outlines the need for a layered network approach. The network will operate year-round from 7am to 6pm, and offer frequent buses every 15 minutes, local services every 20-30 minutes, on-demand buses, regional services, and special event services. This plan also includes expanding transportation hubs, developing new rail connections, and implementing public awareness and outreach campaigns to increase usage of the transit system (Town of Vail, 2024). These investments aim to reduce transportation-related greenhouse gas emissions from personal vehicle use and improve access to public transportation. Vail Mountain serves as a prime example of how ski resorts can implement realistic and scalable mitigation strategies

through transit. If other resorts adopt similar plans, the overall carbon impact of ski travel in Colorado can be reduced.

Public transportation is a viable option for visitors in Colorado; however, many skiers arrive by plane. Air travel is a challenging problem in reducing greenhouse gas emissions, as it is one of the most carbon-intensive forms of transportation and ski resorts have minimal control over these Scope 3 emissions. Given the global appeal of Colorado's ski industry, completely eliminating these emissions is unrealistic. To address this, ski resorts should look for alternative ways to reduce their carbon footprint. Investing in carbon offset programs, like reforestation efforts, renewable energy initiatives, and carbon capture technology, can help compensate for these travel emissions (Anderson, 2024). Although carbon offsets are not a perfect solution, they are an immediate step that resorts can take to demonstrate climate responsibility and reduce GHG. In the face of rising temperatures that directly threaten snowfall and ski seasons, it is essential that resorts take every feasible action to mitigate emissions and preserve the future of the industry.

Chapter 6: Conclusion

As climate change accelerates, leading to warmer winters, reduced snowfall, and increased seasonal unpredictability, the long-term viability of ski resort operations is increasingly uncertain. This thesis has shown that while the ski industry contributes significantly to the Colorado's economy, its dependence on consistent snow conditions exposes it to both physical and transitional climate risks, from extreme storms and snow unreliability, to changing regulations and consumer preferences. Through an analysis of historical temperature data in Grand Junction, CO and an examination of the effects of climate change alongside a case study of Vail Resorts Inc.'s sustainability strategies, this research demonstrates the urgent need for adaptation and mitigation strategies to stay operational. Implementing these strategies is also a matter of environmental responsibility. Ski resorts themselves contribute to climate change and even exacerbate the very risks that harm their industry through water use, transportation emissions, and other operational GHGs. As such, Colorado's ski resorts have a social responsibility, and fiduciary responsibility, to address their environmental impact and implement strategies that will help them thrive.

Expanding snowmaking operations, exploring eco-friendly dry slope technologies, and investing in public transportation are viable strategies that can help Colorado's resorts maintain operations more sustainably and protect profits. However, these solutions must be implemented with attention to environmental trade-offs in mind, like water usage for snowmaking machines, to ensure utilization is as efficient and effective as possible. Vail Resorts Inc.'s efforts illustrate progress that has been made and lay groundwork for future efforts.

Ultimately, this thesis argues that building climate resilience in the ski industry requires strategic innovation and sustained investment. The future of skiing in Colorado will depend not only on snow, but on the efforts of its ski resorts to preserve the industry.

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