Master's Degree in Environmental and land Engineering
Specialization in Climate Change

Carbon footprint and climate change in ski resorts: a case study in Piemonte

By

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I would like to dedicate this thesis to my loving parents and sister

Abstract

Climate change poses significant risks to the winter tourism industry, as many ski resorts face shorter, milder winter seasons. Given these challenges and their critical role in both tourism attraction and economic vitality, it is important for ski resorts to consider proactive measures for all winter enthusiasts who want to enjoy snow-based sports and the natural beauty of a mountain environment.

The present study investigates the carbon footprint associated with the Alpe di Mera ski resort, with a specific emphasis on three key elements: ski lifts, snowmaking, and grooming. The Alpe di Mera ski resort intends to replace two existing chair lifts with a single cable car lift as a part of its future renovation plan. In light of this development, a novel methodology was developed to assess the energy consumption of the new ski lift (cable car) using passenger data from existing chair lifts. The carbon footprint of the new ski lift, as well as other ski lifts and elements, was calculated as a result. The findings highlight the various contributions of individual elements to the overall carbon footprint. Furthermore, the study introduces a set of indicators based on the calculated carbon footprint and characterization of the ski resort that allow comparisons between different ski resorts. These indicators offer significant insights into the operational efficiency of the resort and its environmental consequences.

One of the key elements in carbon footprint is snowmaking, which is directly related to meteorological conditions (i.e., wet bulb temperature), and thus exposed to climate change. The Copernicus Mountain Tourism Meteorological and Snow Indicators (MTMSI) dataset was used to illustrate the evolution of these indicators over four distinct time periods, and three different Representative Concentration Pathways (RCPs). The results derived from this examination offer a more profound comprehension of the potential consequences of climate change on mountain tourism across diverse altitudes and under varying future scenarios.

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Chapter 1

Introduction

1.1 Global Warming

Climate change is defined as a modification in the condition of the climate, which can be detected through statistical analysis by observing alterations in the average and/or the variability of its characteristics. This alteration endures for a prolonged duration, usually spanning several decades or more. The phenomenon of climate change can potentially be attributed to either natural internal processes or external forcings, including persistent anthropogenic alterations in atmospheric composition or land use[5]. Global warming is considered to be one of the most concerning manifestations of climate change. The subject quickly became a focal point of discussion within public and political communities. In recent years, there has been an increase in initiatives focused on addressing this phenomenon, which is attributed to the reduction of greenhouse gas emissions into the atmosphere. These emissions are now widely recognized as the primary driver of climate change. According to the data presented in **Figure 1.1**, the increase in global warming observed in 2022 is estimated to be around 0.89 °C greater than the average temperature recorded during the thirty-year timeframe from 1951 to 1980. In order to mitigate the exacerbation of the situation and minimize the potentially more detrimental consequences, it is imperative to restrict the increase in global temperatures to 2 °C [5] In order to achieve this objective, it is imperative to mitigate the emission of these deleterious gases prior to the year 2050.

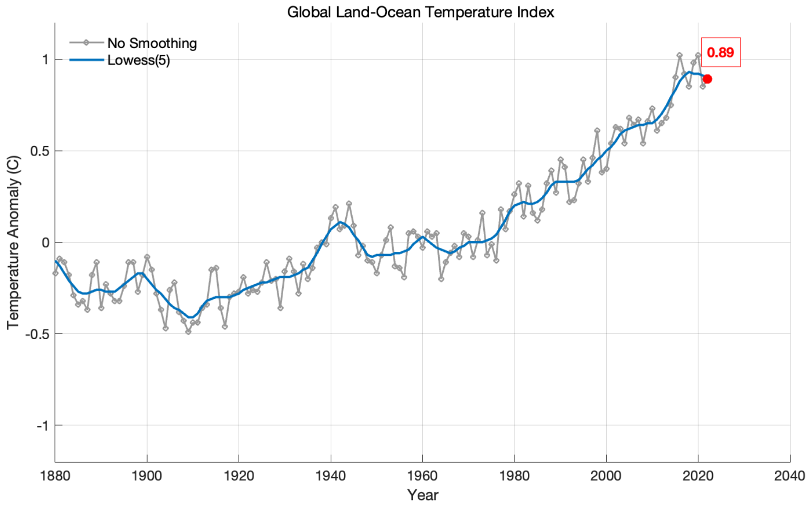

Fig. 1.1 Global Land-Ocean Temperature Index, change in global surface temperature compared to the long-term average from 1951 to 1980 [1]

1.2 Winter Tourism and Ski Industry

Tourism is widely recognized as a highly influential human activity, encompassing the movement of tourists and the range of activities they engage in, as well as the provision of accommodation facilities. Additionally, it is worth noting that tourism has emerged as one of the most rapidly expanding economic sectors globally and is widely acknowledged as an established industry [6] [7].

Skiing holds significant importance within the tourism industry, particularly for European countries situated along the Alpine arc, namely Italy, France, Switzerland, Austria, Germany, and Slovenia, as well as the USA and Canada [8] [7]. Winter tourism, particularly ski tourism, is heavily reliant on the prevailing snow conditions. Natural snow conditions exhibit interannual variability and are profoundly influenced by climate change. The increase of temperatures contributes to diminished snowfall and accelerated snowmelt, thereby compromising the reliability of snow conditions and reducing the duration of the ski season. The presence of snowfall is a crucial requirement for the practice of this particular sport, thus establishing a strong connection between the activity and climate change. As mentioned before the rise in global temperatures has resulted in a progressively diminished occurrence of natural snow on ski slopes. Consequently, ski resorts feel obligated to allocate additional financial resources or explore alternative methods to sustain snow coverage and still attract tourists, who want to enjoy snow sports and experience natural beauty of a mountain environment. Nonetheless, despite ski resorts' efforts to improve their operations, there are tourists whose choices have a significant impact on climate change. Individuals who participate in winter activities must be aware of current issues related to climate change and how their ski adventures may contribute to this phenomenon. Their awareness of the steps they can take to reduce their environmental impact is equally important [9].

The ski industry in Italy holds significant importance as it attracts a considerable number of winter sports enthusiasts. The mentioned industry not only provides avenues for leisure and enjoyment but also assumes an important role in the nation's economic landscape. Despite experiencing fluctuations in attendance and revenue over time, the ski industry continues to maintain its significance [10]. Due to this specific reasoning, the necessity to sustain this industry arises as a result of improvements in the field of technology. To date, the ski industry has witnessed significant advancements. Improvements have been implemented on snow-making machines to maximize their operational efficiency in elevated temperature conditions. In order to mitigate waiting times for skiers, ski lifts have been designed with enhanced dimensions and raised power. Furthermore, ski resorts have increased the number of snow groomers to ensure optimal skiing conditions consistently, regardless of fluctuations in climate. It is necessary to sustain these innovations in order to meet future demand effectively. Since, these improvements result in an increase in the utilization of energy, consequently causing a rise in the release of greenhouse gases.

1.3 Carbon Footprint

Since the beginning of systematic measurements of atmospheric carbon dioxide (CO2) concentration in 1958, there has been a consistent and notable increase in the average concentration of this compound. Specifically, the concentration has risen from 313 parts per million (ppm) to 419 ppm **Figure 1.2**, a level unprecedented in the context of previous geological periods [2]. In addition to carbon dioxide (CO2), there is a notable rise in the concentrations of other gases, including methane (CH4) and nitrous oxide (N2O), which occur naturally in the atmosphere. Furthermore, there are additional gases produced by human activities, such as compounds containing fluorine, chlorine, sulfur, and others. Research on the concentrations of carbon dioxide (CO2) and other gases and their impact on the energy balance of the atmosphere consistently acknowledges a clear association between elevated concentrations and global warming, attributable to the phenomenon known as the "greenhouse effect." Gases possessing the capacity to influence the energy and thermal equilibrium of the atmosphere are commonly referred to as "greenhouse gases" or "climate gases".

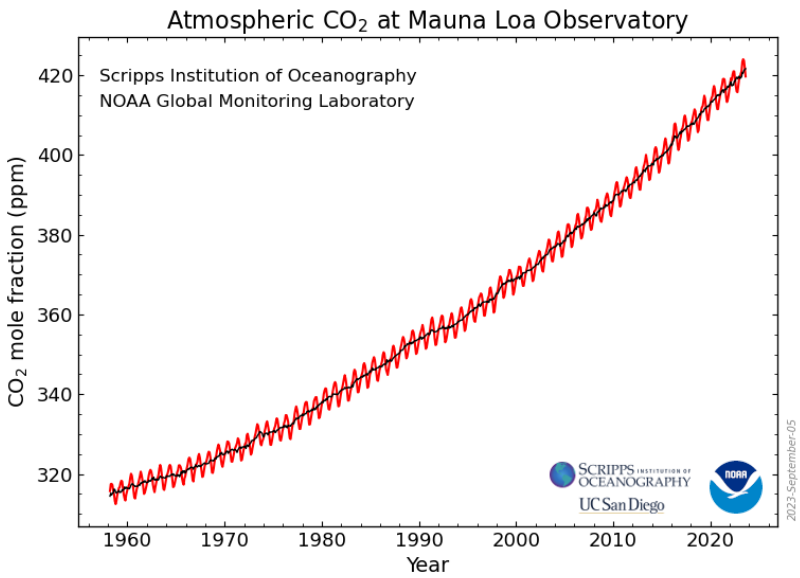

Fig. 1.2 The graph depicts the monthly average levels of carbon dioxide that have been measured at the Mauna Loa Observatory in Hawaii. [2]

In conversations surrounding the impact of gases on the thermal equilibrium of the atmosphere, it is typical to refer to the CO2-equivalent quantity, indicating the amount of carbon dioxide that possesses an equivalent warming potential, also known as Global Warming Potential, as the gas under consideration. The previously stated value is derived by multiplying the mass of the specific greenhouse gas under examination by its corresponding Global Warming Potential (GWP), taking into account the temporal scale over which climate impacts become apparent, in accordance with the average atmospheric residence times of the gas (standardized at 100 years) [11]. The "carbon footprint" indicator (CF) was proposed as a means to quantify greenhouse gas emissions resulting from human processes, activities, and the utilization of products and services. This indicator is part of a group of indicators, which includes the ecological footprint and the water footprint, among others. These indicators have been proposed in the past few decades to measure the

extent of human impact on natural resources and assess the sustainability of various activities and products. There are two primary methods for evaluating the carbon footprint (CF): the CF associated with a specific product and the CF associated with a particular activity or organization. In the broader context of mitigating the impacts of climate change and preventing the most significant consequences of global warming, it is essential to reduce the release of carbon dioxide (CO2) and other greenhouse gases into the Earth's atmosphere. In order to achieve this objective, the computation of carbon footprint (CF) and the assessment of how it changes in relation to new products/services and human activities is an important measure to increase the sustainability of human activities. Similarly, the analysis and comparison of carbon footprint values enable us identify critical phases, plan improvements, and program compensatory activities that can facilitate sustainable development while minimizing any worsening of greenhouse gas concentrations in the atmosphere.
The estimation of a product's carbon footprint necessitates a comprehensive evaluation of all stages in its life cycle, encompassing its creation (including material procurement and resource utilization) to its ultimate disposal (such as scrap and recycling). This evaluation is typically conducted through the application of a methodology known as life cycle assessment, or LCA. **Figure 1.3** illustrates a life cycle diagram of a cable car transport system, where the "cradle to grave" approach and the different phases in which it can be summarized are highlighted. In order to

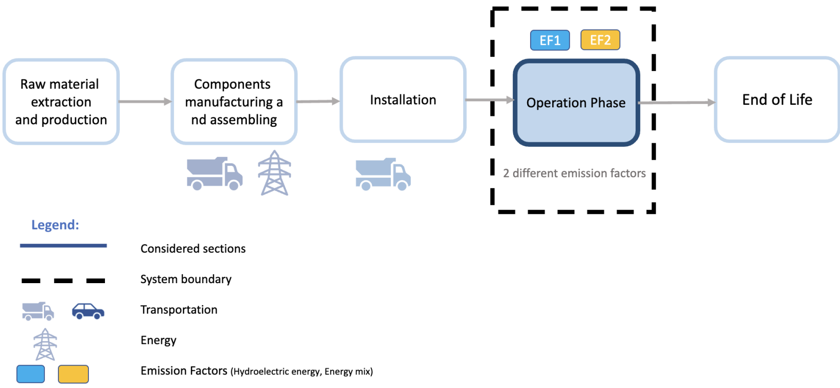

Fig. 1.3 LCA of a ski lift

determine the carbon footprint (CF) of an activity or organization, it is necessary to take into account the direct emissions linked to the production of thermal energy (such as for buildings and vehicles) as well as the indirect emissions associated with electricity consumption. According to The National Ski Areas Association

[3], which used the GHG Protocol Standard in its studies, three types of direct and indirect factors from ski resorts contribute to GHG emissions. **Figure 1.4** represents:

- Direct Scope 1: emissions from vehicles (fuel), emissions from buildings
- Indirect Scope 2: Purchased electricity for snowmaking, buildings and lifts
- Indirect Scope 3: Waste disposal, skier travel, business travel

Therefore, the primary direct contributions come from service vehicles and room heating. The main indirect contributions arise from electricity consumption for transportation, artificial snow production, and facility usage. Additionally, users indirectly contribute through waste generation and emissions resulting from travel.

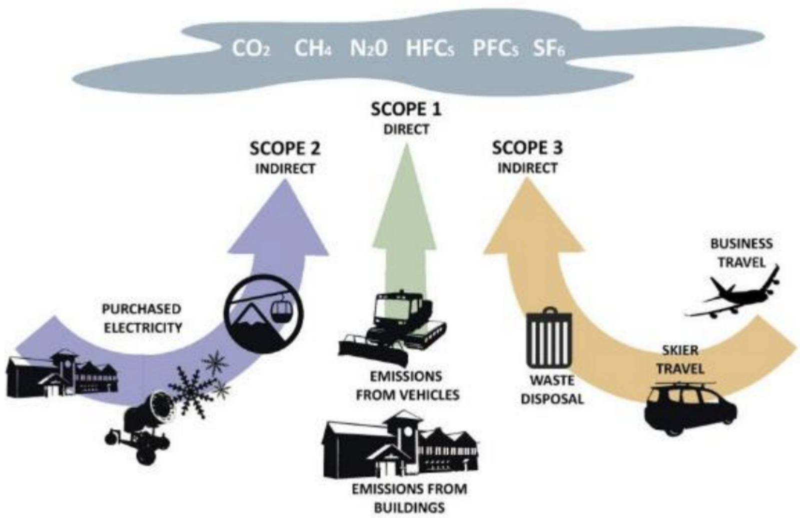

Fig. 1.4 A ski resort's contribution to the emissions scheme [3]

1.4 Goal of study

The goal of this research is to conduct a comprehensive assessment of the carbon footprint associated with a ski resort that is scheduled to undergo a renovation project (2.1.2). The primary goal of this assessment is to quantify the energy consumption and carbon emissions associated with the operation of the new ski lift that will replace two existing lifts. In addition, the study will evaluate the carbon footprint of other existing ski lifts and other important elements within the ski resort.

Furthermore, this research develops measurable criteria that can be used to forecast future resort conditions, specifically in terms of snowfall (both natural and artificial) and temperature. This study aims to provide valuable insights into the resort's environmental impact following its renovation.

Chapter 2

Energy consumption of a ski lift

2.1 Case Study: Alpe di Mera Ski resort

The ski resort known as Alpe di Mera is located in the northern region of Italy,more specifically in the Piemonte region, situated within the province of Vercelli (**Figure2.1**). Situated within the Valsesia region, the location is elevated in the Italian Alps, providing breathtaking views of the surrounding mountainous landscape. Alpe di Mera is easily accessible from the valley municipality of Scopello, acting as a gateway to the elevated delights of the Italian alpine region.

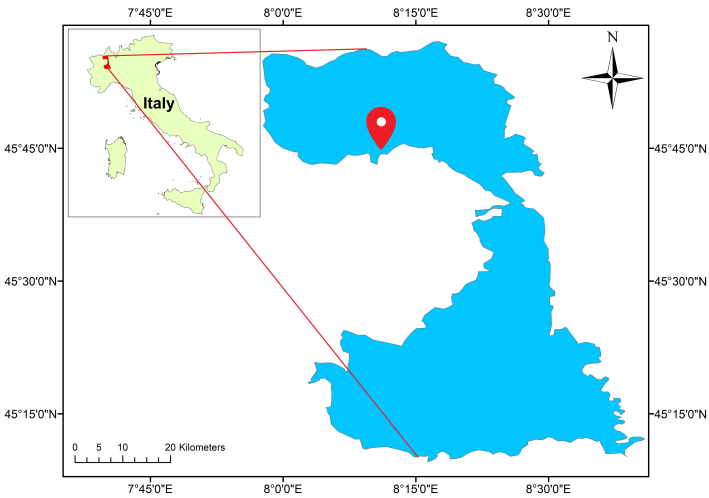

Fig. 2.1 Geographic overview of Alpe di Mera:Locatedin Vercelli province, the heart of Piemonte, Northern Italy.

2.1.1 The existing plant

The facilities of the Alpe di Mera ski resort extends from the base of the valley, starting at an elevation slightly above 700 m, to the peak of the Camparient chairlift at 1739 m (**Figure 2.2**). This chairlift, in conjunction with the Bimella chairlift, allows access to the watershed area shared with Valsessera. The ski lifts facilitate access to a comprehensive network of 19 slopes, with a particular focus on the main slopes that are equipped with snow-making systems (**Table 2.1**). This infrastructure ensures the availability of suitable conditions for engaging in winter sports activities, thereby catering to the diverse needs and preferences of all user groups interested in skiing.

Skilifts:

1. Scopello-Mera two-seater chairlift (702-1540 m), built in 1977;
2. Capricorno four-seater chairlift (1156-1508 m), built in 2006;
3. Camparient four-seater chairlift (1420-1739 m), built in 2006;
4. Bimella two-seater chairlift (1348-1722 m), built in 2006;
5. Nuova Campo II ski lift (1510-1560 m), repositioning year 2010;
6. Campo treadmill;
7. Camparient treadmill.

It is noteworthy to mention that as part of the ski resort renovation project that coincided with the Turin 2006 Olympic Games, the existing ski lifts from the 1970s, were replaced with three detachable newly designed chairlifts, the Camparient chairlift, the Bimella chairlift, and the Capricorno.

Within the ski lift of Alpe di Mera, there are two notable ski lifts that hold particular importance for our analysis: the Capricorno and the Scopello-Mera chairlifts. Here are more details on both: The Capricorno chairlift, which operates from a relatively low altitude (1156 m above sea level) and follows a route roughly parallel to that of the Scopello - Mera chairlift, has a capacity of 1800 p/h and allows skiers to be recovered even from two parking areas, the 4 x 4 car park and the Trogo car park, from which it is possible to directly access the ski slope that leads to the chairlift's valley station. In the current situation, the direct connection between the valley bottom areas and Alpe di Mera is offered by the Scopello – Mera two-seater chairlift. The plant, rebuilt in 1977, has a nominal flow rate of 569 p/h, with an operating speed of 2 m/s and a total travel time of approximately 19 minutes.

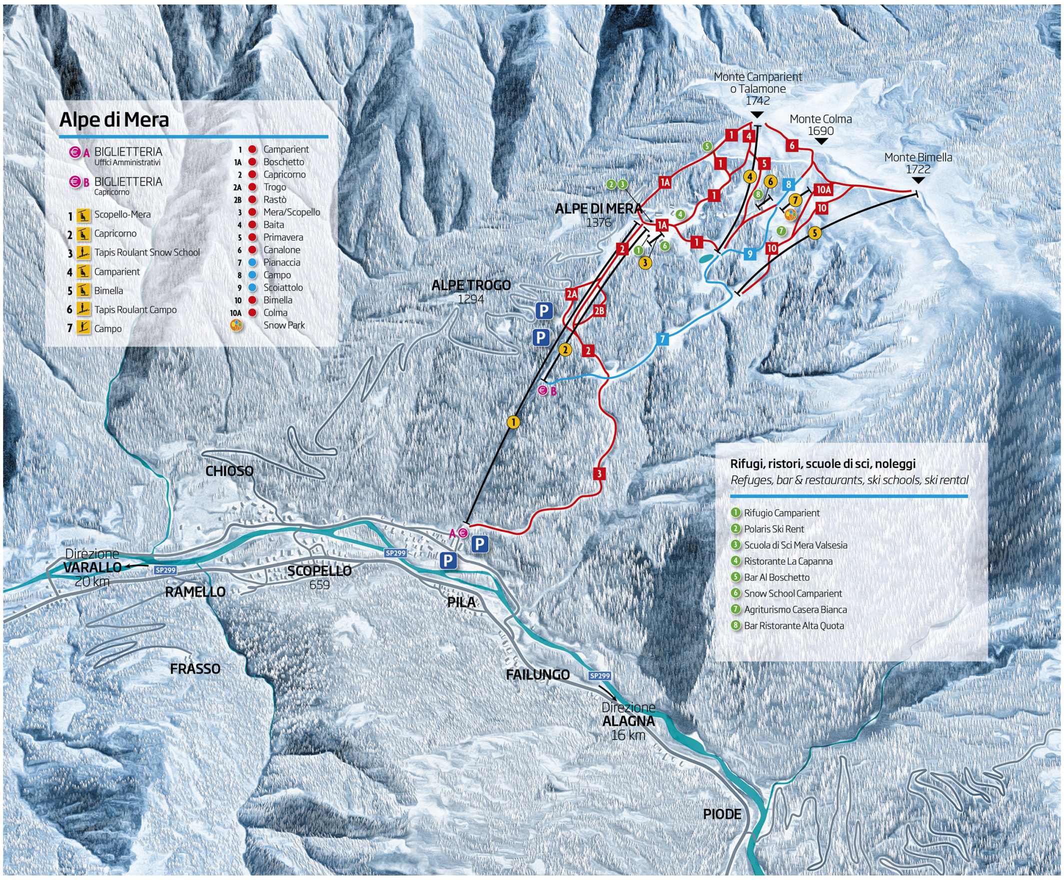

Fig. 2.2 Alpe di Mera – Network of amenities and slopes [4]

2.1.2 Future renovation project

The ski lifts, namely the Capricorno and Scopello-Mera chairlifts, are of most significance in facilitating the accessibility of skiers to Alpe di Mera ski resort. Nevertheless, both of these establishments encounter obstacles that interfere with their maximum utilization. The Capricorno chairlift, despite its initial purpose, is now experiencing a lack of utilization. Skiers generally tend to avoid utilizing the ski lift in question due to its relatively slower operational speed. However, it is important to note that its peak usage is primarily observed during the initial daily ski access.

Table 2.1 Slopes of the Alpe di Mera ski resort [4]

Codice	Nome	Starting altitude m. s.l.m.	Arrival altitude m. s.l.m.	Length (m)	Average slope	Snowmaking	Surface (m^2)
M1a	Camparient alto	1737	1643	438	0.21	YES	14016
M1a	Camparient alto	1520	1420	711	0.14	YES	14931
M1c	Skiweg Camparient	1470	1420	430	0.12	NO	4300
M2a	Canalone alto	1737	1577	674	0.24	YES	21568
M2b	Canalone basso	1533	1434	472	0.21	YES	14632
M3	Primavera	1736	1484	792	0.32	YES	36432
M3a	Raccordo Primavera	1727	1656	187	0.38	YES	9163
M4	Campo	1577	1507	352	0.2	YES	16544
M4a	Fun slope	1591	1507	366	0.23	YES	27450
M5	Azzurri	1735	1577	472	0.33	NO	23128
M6	Scoiattolo	1703	1604	374	0.26	NO	10098
M6a	Variante Scoiattolo	1712	1669	256	0.17	YES	3328
M6b	Skiweg Scoiattolo	1604	1529	349	0.21	NO	3490
M7	Boschetto	1643	1520	697	0.18	YES	13940
M8	Baita	1643	1483	688	0.23	YES	24768
M9	Area bob	1517	1503	160	0.09	NO	3040
M10	Bimella	1719	1343	1538	0.24	YES	78438
M10a	Skiweg Bimella	1507	1480	189	0.14	NO	2268
M11	Colma	1664	1555	463	0.24	NO	24539
M11a	Skiweg Colma	1664	1660	327	0.01	NO	5559
M11b	Skiweg ciclabile	1647	1624	283	0.08	NO	5094
M12	Autostrada	1719	1555	1242	0.13	NO	28566
M13	Roticcia	1635	1419	945	0.23	NO	36855
M14	Chignolo	1578	1360	937	0.23	NO	27173
M15	Capricorno	1520	1155	1577	0.23	YES	42579
M15a	Raccordo Capricorno	1509	1506	78	0.03	NO	2106
M15b	Skiweg Capricorno	1476	1401	578	0.13	NO	5202
M15c	Tapis Camparient	1485	1469	98	0.16	NO	4606
M16	RastÃ²	1374	1302	331	0.22	NO	7282
M17	Trogo	1384	1268	478	0.24	NO	12906
M17a	Skiweg Trogo	1315	1288	247	0.11	NO	2964
M17b	Raccordo 4x4	1291	1209	418	0.2	NO	5016
M18	Pianaccia	1343	1189	1069	0.14	NO	16035
M18a	Raccordo Pianaccia alto	1420	1343	397	0.19	NO	7543
M18a	Raccordo Pianaccia basso	1389	1318	351	0.2	NO	8775
M18c	Variante Pianaccia	1315	1256	268	0.22	NO	3216
M19	Mera Scopello	1194	680	2224	0.23	NO	42256
M19a	Raccordo Mera Scopello	1216	1182	220	0.15	NO	3520

This observation serves to underscore the inherent limitations and shortcomings of the foundational ski lift system. Furthermore, individuals who do not engage in skiing, the population that was also included in the target user group, exhibit minimal interest in the facility primarily because of the necessity to access it by walking. In addition to the previously mentioned operational challenges, there exists the challenging responsibility of managing the maintenance and administration of the road that connects to Scopello. The maintenance of road accessibility, particularly in the face of significant snowfall, necessitates the implementation of thorough snow removal procedures and the enforcement of strict safety protocols. This becomes increasingly crucial as it is imperative to sustain uninterrupted connectivity between

the valley and the parking areas, thereby guaranteeing their operational efficiency and convenient accessibility.
Similarly, the Scopello-Mera chairlift, which serves as the primary link between the valley's base and Alpe di Mera, faces its own set of difficulties. Its northward-facing slope, combined with the lengthy duration of its ascent, makes it less appealing to skiers. This deterrent effect is amplified during precipitation, making it even less appealing.

Given the problems and challenges of current Scopello-Mera and Capricorno chairlifts, there is a clear and pressing need for infrastructure optimization and renovation. To address these concerns, a solution has been proposed by the Monterosa2000 company. The plan involves a single telecabin system to replace the current Scopello-Mera chairlift (**Figure2.3**), on the same route, and the Capricorna chairlift, which run parallel to the upper part of the Scopello-Mera chairlift. This initiative aims to redefine the skiing experience at Alpe di Mera, promising faster, safer, and more delightful access to its exquisite slopes. The planned system at

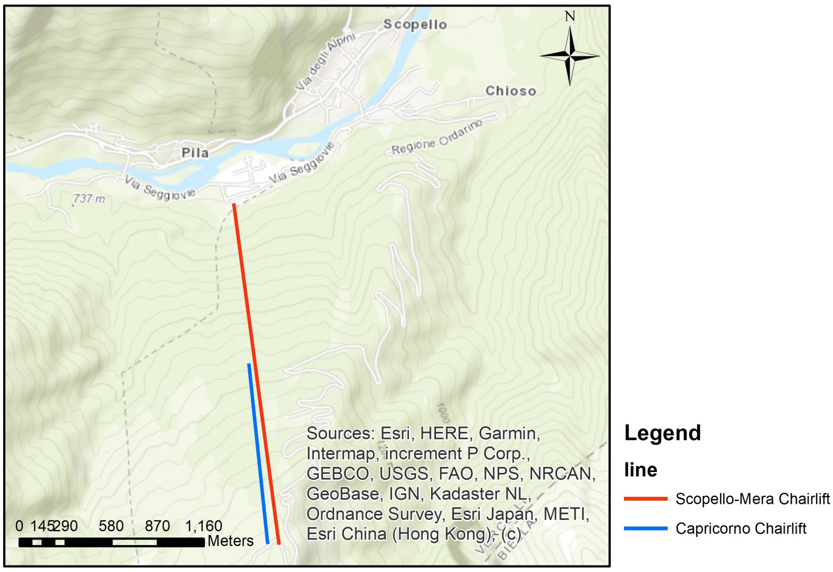

Fig. 2.3 Description of The Scopello-Mera and Capricorno chairlifts will be replaced by a single cable car lift on the same route.

Alpe di Mera is made up of 10-seater vehicle cabins and spans about 2375 m. It is designed to transport up to 2400 people/hour at a speed of 6 m/s. 59 cabins are expected to be in use under these conditions. At this speed, the ride lasts about 6 minutes and 30 seconds. However, during its initial phase, the system will have a capacity of 1600 people/hour. This renovation goes beyond simply correcting inefficiencies. It aims to provide an inclusive future for the ski resort. The following advantages will be achieved by implementing the system:

- Long-term Technical Excellence; Alpe di Mera will benefit from a cable car that is technologically advanced and long-lasting, effectively addressing the challenges posed by the existing, outdated system.
- Improved Ascent Experience; The new system will provide a comfortable lift service for non-skiers or those who find the current setup difficult.
- Prioritizing Safety; Young skiers will be protected from falls caused by open chairlifts. Enclosed cabins designed for children's safety can accommodate nine children and a ski instructor for ascent, eliminating the need for accompanying adults.
- Accessibility for All; The proposal ensures that Alpe di Mera remains accessible to all. Individuals of all ages and abilities can travel to the top without relying on vehicles during the winter and summer seasons.
- Environmentally Friendly Approach; The new system also addresses concerns by reducing traffic to high altitude parking areas, resulting in lower emissions. It is an effort to eliminate motorized vehicles from the Alpe region.

2.2 Energy consumption of the new lift

In the context of this study, which focuses on evaluating the carbon emissions linked to the renovation project of the ski resort, the utilization of energy consumption data is of paramount significance. The renovation project is characterized by the implementation of a new cable car lift. The energy consumption of the new cable car lift was predicted by employing a functional dependency approach, utilizing data from existing chairlifts. This prediction took into consideration both the energy consumption and passenger data.

2.2.1 Data processing

Understanding the energy consumption patterns of the ski lifts is crucially dependent on the data quality and timeframe. High-quality data ensures that the calculations are both reliable and accurate. Raw data, on the other hand, frequently contains inconsistencies, inaccuracies, or irrelevant entries. As a result, the energy consumption and passenger data were refined and processed prior to diving into the core analysis. The steps taken to cleanse and prepare the data are detailed below, providing a solid foundation for subsequent analyses.

- Year Selection: While hourly energy consumption and passenger number data for the years 2018 to 2022 were provided by the ski resort, only the year 2021-2022 had comprehensive datasets for both energy consumption and passenger numbers. Consequently, this year was selected as the primary focus for our analysis.

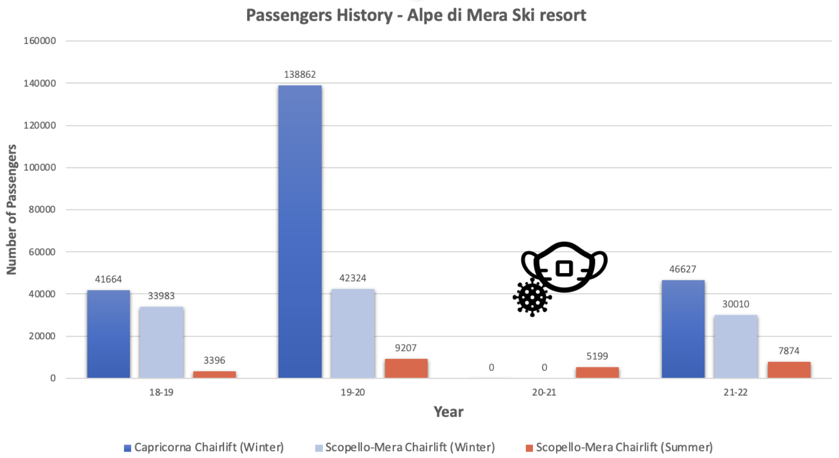

Fig. 2.4 Passengers history for Alpe di Mera ski resort.

As depicted in **Figure2.4**, the 2020-2021 season was significantly impacted by the outbreak of Covid-19 and subsequent implementation of quarantine protocols. The total number of passengers during the selected winter season was 76,231, while during the summer season it was 7,874.

- Seasonal Considerations: the winter season under consideration for our analysis encompasses the time period from December 3rd, 2021, to April 9th, 2022. This corresponds to a cumulative duration of 122 days. The summer season spanned from July 9th, 2022, to September 11th, 2022, encompassing a duration of 50 days.

- Daily Operating Hours: Irrespective of the season, the ski lifts' operating hours were consistently considered from 8:00 AM to 6:00 PM. This translates to 11 operational hours per day. Accordingly:
  - Summer Data Points: A total of 550 hourly data points (50 days x 11 hours/day).
  - Winter Data Points: A total of 1,340 hourly data points (122 days x 11 hours/day).

Following the definition of the data scope and time frame, it was determined that further data refinement was required to align with the objectives of our study.

- Exclusion of Zero-Passenger Data: To develop a functional dependency that accurately captures the correlation between energy consumption and passenger numbers, hours with zero passengers were considered irrelevant and were excluded. This step was crucial because without passengers, deriving a meaningful connection between energy usage and passenger numbers isn't feasible. The exclusions resulted in **Figure 2.5**. The blue data points represent winter

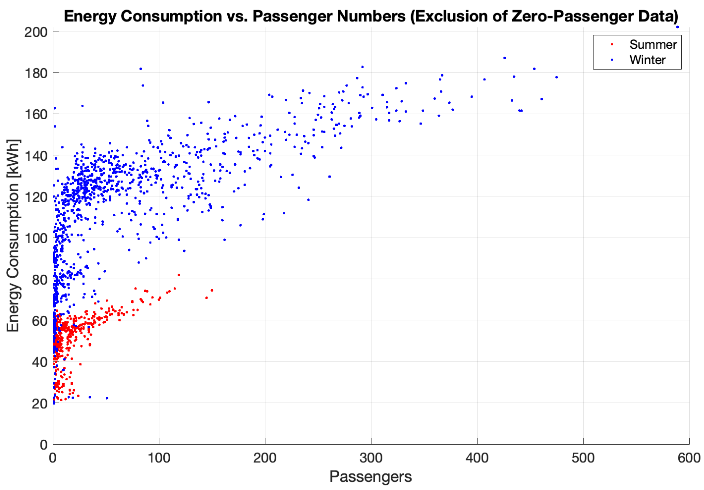

Fig. 2.5 Representation of energy consumption Vs passenger number for winter and summer seasons while data points related to the zero passenger were excluded.

data that encompasses the operational periods of both lifts, indicating the energy consumption linked to the total number of passengers transported by both lifts.

- Summer data: 161 data points were removed, leaving us with 389 valid data points.
- Winter data: 307 data points were removed, resulting in 1035 valid data points.

• Winter Data Refinement: During the winter season, both the Scopello-Mera and Capricorno lifts are operational. As a result, the energy consumption recorded during a given hour would generally refer to the total number of passengers using both lifts. However, a more refined analysis was required for the purposes of our study's objectives and the anticipated renovation project, which aims to replace the two chairlifts with a single cable car.

The winter data was carefully selected to address this. Only the hours when the Scopello-Mera chairlift had a non-zero passenger, and the Capricorno chairlift had zero passengers were considered **Figure 2.6**. The winter data has

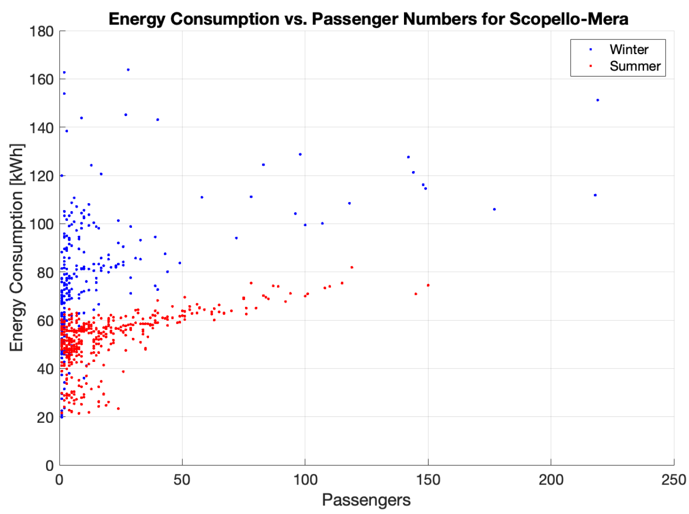

Fig. 2.6 Shows Energy consumption Vs passenger numbers for the Scopello-Mera lift during the winter and summer seasons.

been refined to focus solely on the energy consumption of the Scopello-Mera lift, excluding periods of operation simultaneously with the Capricorno lift. Following this approach narrows the scope of the analysis, capturing only the energy consumption associated with the Scopello-Mera chairlift, providing a clearer representation and understanding of its operational metrics.

- There were 246 instances where only the Scopello-Mera lift was operational, as opposed to Capricorno which had zero passengers in the corresponding hours.
- It's also noteworthy that there were 132 instances in total where only the Capricorno lift was operational.

• Analysis of Hourly Energy Consumption and Passengers Patterns : As the **Figure 2.6** notable observation displayed unusual behavior, particularly for hours with a small number of passengers, both the mean energy consumption and passenger numbers for each unique hour of the day were computed. This was done to observe how energy consumption and passenger patterns evolve throughout the day.**Figure 2.7** & **Figure2.8**

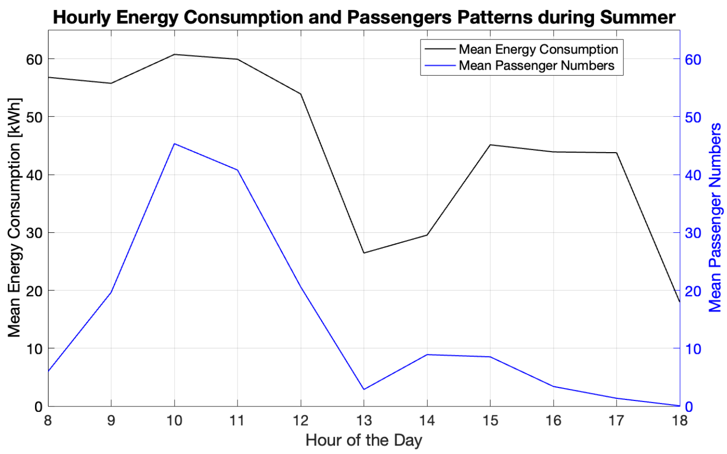

Fig. 2.7 illustration the mean energy consumption and mean number of passenger per hour during the summer season.

It was discovered that the ski lift begins with a significant energy load during its initial operating hours. As the number of passengers increased throughout the day, so did energy consumption, which decreased as the passenger number decreased. Interestingly, during the summer, there was an observed spike in energy consumption between 14:00 and 15:00. This was unexpected, especially since there was a simultaneous drop in the number of passengers during this interval (**Figure 2.7**).

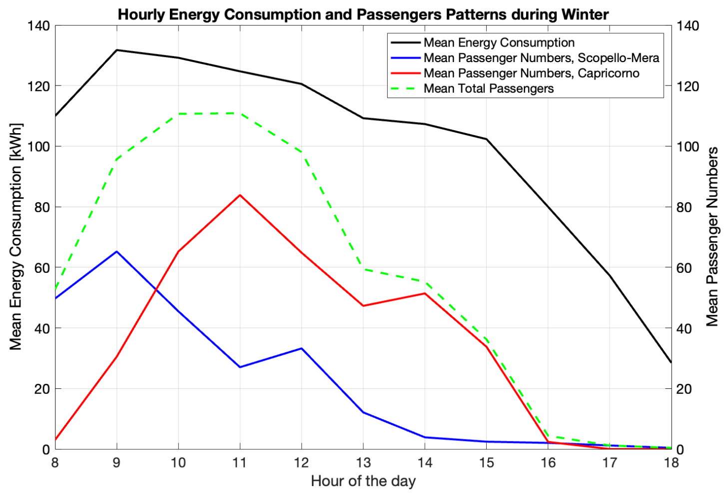

Fig. 2.8 Representation the average hourly energy consumption in winter.

- Hourly Differentiation of Energy Consumption at Low Passenger Numbers: Continuing the investigation into the anomalies observed at lower passenger counts and based on insights from **Figure 2.7** and **Figure2.8** , **Figure2.9** was constructed. This figure presents the hourly energy consumption based on the

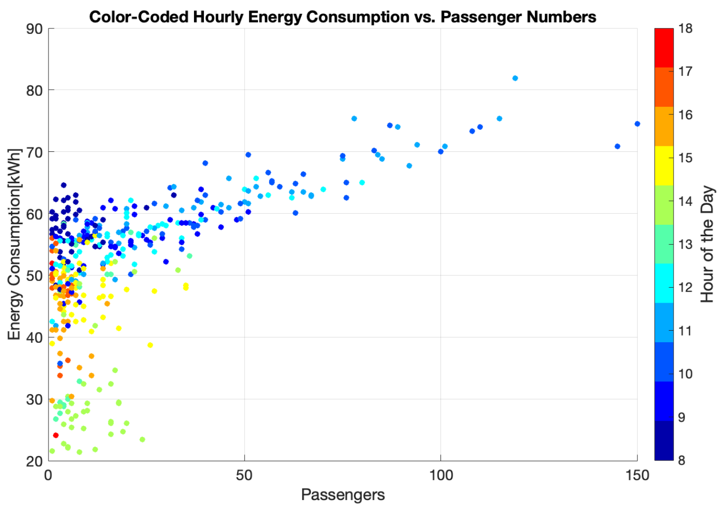

Fig. 2.9 Relationship between hourly energy consumption and passenger numbers, distinguishing each unique hour by color (Summer as an example).

passenger numbers, with each unique hour delineated by a distinct color. The visualization offers insights into the energy consumption patterns at different times of the day, especially during hours with fewer passengers.

Following the insights gained from **Figure2.9** , there's a clear validation of our earlier hypothesis. The noticeable Chaos related to the data points with low energy consumption and low number of passengers, during the post-noon hours, supports the idea that these passengers primarily use the lifts for descent, which naturally requires less energy.

- Focus on Morning Hours Data: In light of the previous analysis' findings, data for the morning hours (from 8 a.m. to 12 p.m.) for both summer and winter were extracted. The purpose of this decision is to ensure that the data points used to develop an energy consumption model based on passenger numbers are both reliable and representative.

2.2.2 Functional dependency between energy consumption and number of passengers:

The basis of reliable and representative information has been established as a result of meticulous data processing and refinement. After obtaining these reliable datasets, the subsequent stage of the study centers on establishing a functional relationship between energy consumption and passenger numbers. The aim is to develop a methodology that not only accurately represents observed patterns, but also enables the prediction of future outcomes and the generation of valuable insights.

- Polynomial Curve Fitting:

  A polynomial curve fitting of degree 1 (linear regression) was used to determine the relationship between energy consumption and passenger numbers. The method was used separately for summer and winter datasets to account for the distinct characteristics of each season. The following are the results of this approach:

  Summer Model:

  Linear model (Poly1):

$$f(x) = p1 \times x + p2$$

Coefficients (with 95% confidence bounds):

$$p1 = 0.1728\,(\text{between } 0.1555 \text{ and } 0.1901)$$
$$p2 = 53.62\,(\text{between } 52.94 \text{ and } 54.3)$$

Goodness of fit:

$$\text{SSE} : 3328$$
$$R^2 : 0.6236$$
$$\text{Adjusted } R^2 : 0.622$$
$$\text{RMSE} : 3.771$$

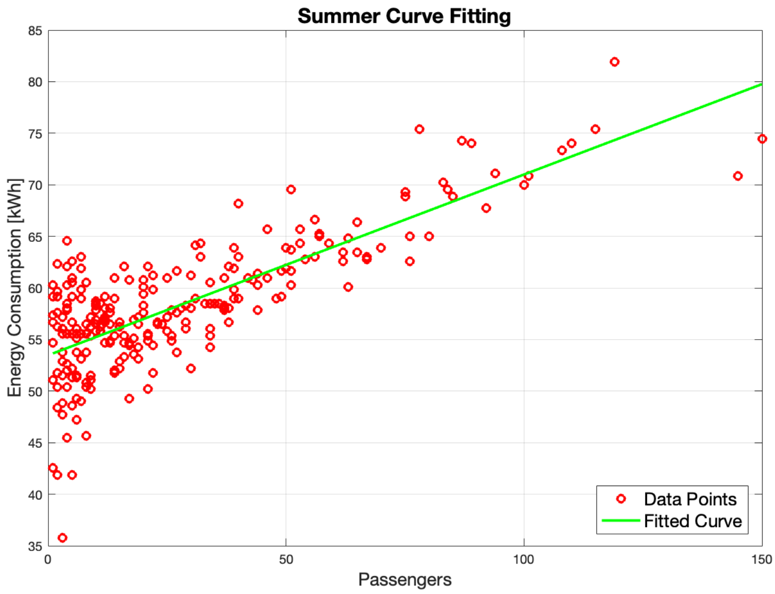

Fig. 2.10 Polynominal curve fitting corresponding to summer only data points before 12 considered.

Winter Model:

Linear model (Poly1):

$$f(x) = p1 \times x + p2$$

Coefficients (with 95% confidence bounds):

$$p1 = 0.1902 \, (\text{between } 0.1073 \text{ and } 0.2732)$$
$$p2 = 89.17 \, (\text{between } 84.67 \text{ and } 93.68)$$

Goodness of fit:

$$\text{SSE}: 4.035 \times 10^4$$
$$R^2: 0.1646$$
$$\text{Adjusted } R^2: 0.1566$$
$$\text{RMSE}: 19.6$$

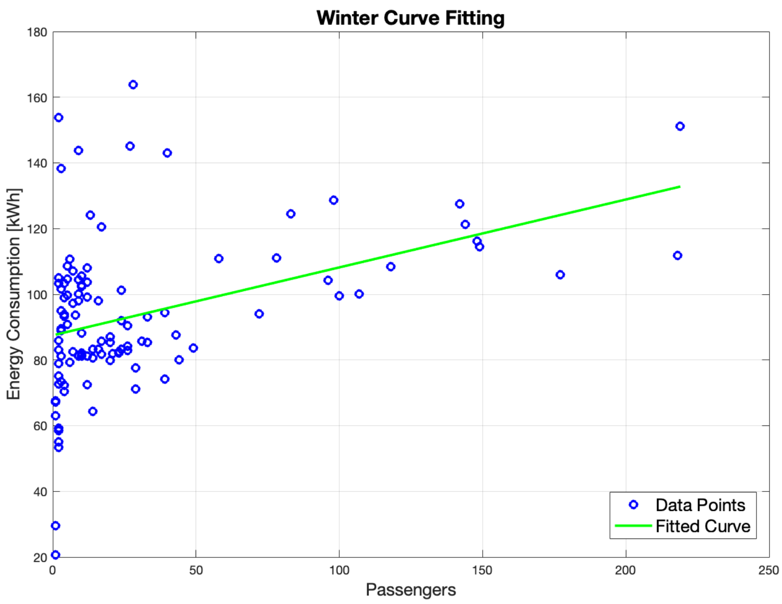

Fig. 2.11 Polynominal curve fitting corresponding to winter only data points before 12 considered.

The provided analysis highlights the differences between summer and winter ski lift operations, focusing on the fixed load or baseline energy consumption (represented by P2). While passenger dependency (P1) appears to be similar across both seasons, the significant difference in the constant term P2 can be attributed to a variety of season-specific factors. The base energy consumption for winter operations is consistently higher. This rise could be caused by:

- Increased Seating Utilization: Because winter is the peak season for skiing, ski lifts are most likely operating at or near capacity. This means that more seats are occupied, and the lift may be transporting ski equipment in addition to passengers, requiring more energy.
- Increased Frictional Forces: Cold temperatures present additional difficulties. Lubrication, which ensures smooth operation, may become less effective in cold conditions, resulting in increased friction and, as a result, higher energy requirements.
- Material Resistance: Cold winter temperatures can cause certain materials to become less flexible, contributing to increased resistance. In contrast, warmer temperatures during the summer may make materials flexible, potentially reducing energy consumption.

Given the observed similarities in passenger dependency between summer and winter, a decision was made to unify the models by standardizing the P1 coefficient. This approach acknowledges the operational consistencies between the seasons while also accounting for the differences in baseline energy consumption.
By setting P1=0.18 for both models, it was inferred that the relationship between energy consumption and the number of passengers remains largely consistent throughout the year. The varying baseline energy consumption, or the fixed load, is encapsulated by the P2 coefficient, distinguishing between the seasons.

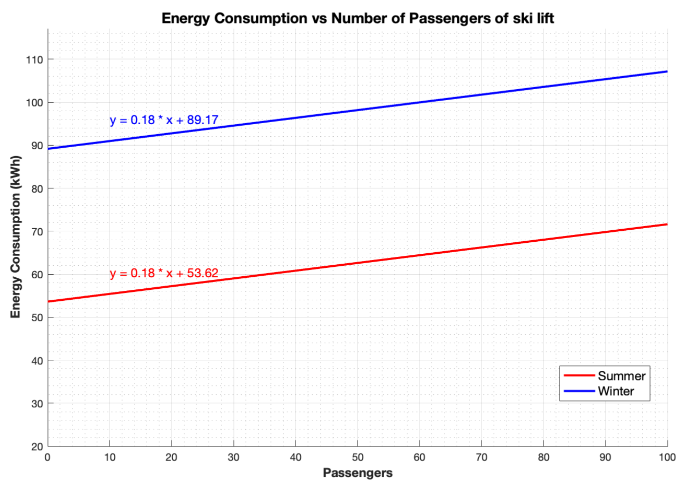

Fig. 2.12 The revised energy consumption vs passenger functional dependency for both the summer and winter seasons.

These revised functional dependency (**Figure2.12**) offer a more concise understanding of the ski lifts' energy consumption patterns.The parallel lines show a consistent passenger dependency across the two seasons, while the different y-intercepts show the distinct baseline energy consumptions of each season. By merging the consistent trends observed across seasons with the distinct characteristics inherent to each season, the functional dependencies' accuracy is likely enhanced, making them more suitable for comparative studies or future decision-making processes.

2.3 Results

Once the energy consumption versus passenger functional dependency for both the summer and winter seasons has been established **Figure2.12**, it is critical to use it in order to estimate the ski lift energy consumption.
Estimations of daily energy consumption were made by employing the derived functional dependency and utilizing the current passenger data for the ski lift. The calculations that were obtained are represented in the **Figure2.13**, which presents

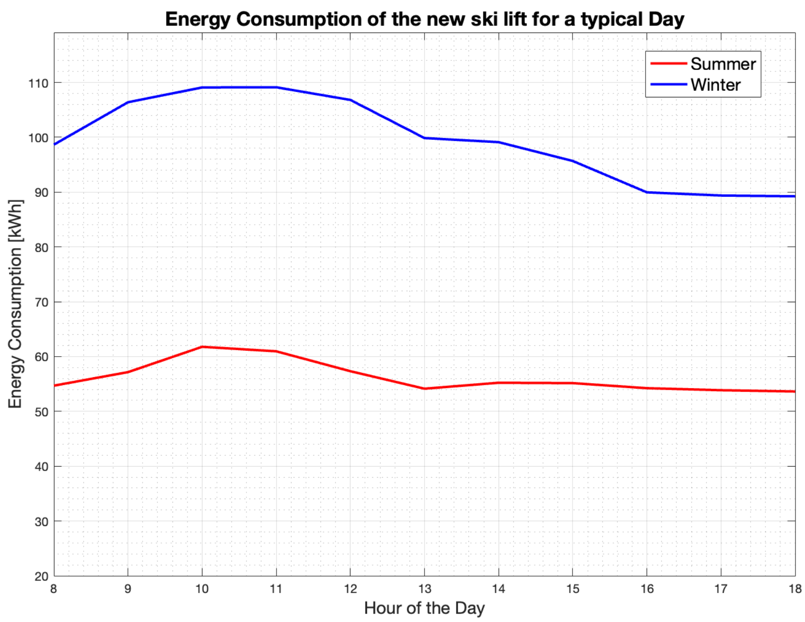

Fig. 2.13 Hourly energy consumption of the ski lift for a representative day in both summer and winter seasons, based on the developed passenger-dependent model.

a comprehensive breakdown of the ski lift's energy usage on an hourly basis for a typical day during both the summer and winter seasons. This day-long perspective offers insights into the patterns and peak consumption periods for the lift. As previously stated, an essential consideration that underlies these calculations is the assumption of the ski lift's passenger count remaining constant in the future. In a realistic scenario, it can be anticipated that the renovation project will lead to enhancements that will likely result in an increase in patronage. This can be attributed to the improved amenities and enhanced accessibility that will be made available.

The precise prediction of energy consumption holds significant importance within the framework of climate change and the pursuit of environmental sustainability. By attaining a comprehensive comprehension of the energy dynamics within the ski resort, there exists a potential avenue for implementing environmentally friendly operational modifications. The knowledge acquired from these predictions could assist the resort in making informed decisions regarding the selection of sustainable energy sources, enhancing energy storage efficiency, and strategically planning operations during periods of reduced carbon emissions in the energy grid. The implementation of a proactive approach to energy management has the potential to substantially mitigate the resort's carbon emissions.

Chapter 3

Energy Consumption of Snow-Making

Snow-making systems are of great importance in ski resorts. The maintenance of dependable skiing conditions, particularly in the face of unpredictable weather patterns, is contingent upon the utilization of these systems. Therefore, it is crucial to understand the energy consumption associated with the process of snow-making. Energy consumption is influenced by various components involved in the snow-making process. The two main components consist of the pumping systems, which facilitate the transportation of water to designated locations, and the snow cannons, which are responsible for the conversion of water into snow. It is imperative to differentiate and discern the energy consumption of each individual component. By conducting a detailed analysis of the various components that contribute to the energy consumption of snow-making, ski resorts can acquire invaluable knowledge and understanding. This knowledge not only facilitates the development of focused operational enhancements but also assists in the identification of potential opportunities for energy conservation. Moreover, by possessing a comprehensive comprehension, ski resorts can make well-informed choices that are in line with both environmental sustainability and cost-efficiency strategies. Snowmaking in ski resorts has evolved significantly. Previously regarded as a supplemental measure to replenish snow-depleted areas, the practice is now considered proactive. Resorts have begun to create a foundational layer of artificial snow prior to the start of the season, taking advantage of early cold temperature windows that frequently appear around November. This proactive strategy ensures that subsequent natural snowfalls

cover a solid layer of artificial snow, enhancing the durability and performance of the skiing surface.
The total energy demand, however, is not solely dependent on snow cannons, whose performance can vary depending on climatic variables. The pumping mechanism accounts for a significant and relatively constant portion of this energy consumption. This mechanism is critical in snowmaking, ensuring that water flows smoothly from its source to the snow cannons.
Exploring the specifics of the future project of the Alpe di Mera ski resort provides insight into the pumping infrastructure. The water comes primarily from the Torrente Boscaiolo. An additional water intake initiative is set to be operational near the bridge on the Fiume Sesia as part of the upcoming expansion. Following extraction, the water is routed to a storage basin. A network of high-pressure pumps transports water from this reservoir to various snow generators scattered across the ski slopes with snow production. The expansion project is expected to improve both storage capacity and overall pumping efficiency. The project calls for new pumps at Scopello, as well as an additional air compressor. Significantly, the use of inverters on existing high-pressure pumps promises more efficient flow regulation, reducing inefficiencies caused by modulating valves. In terms of water consumption, the existing snowmaking system consumes approximately 100,000 m3 per year. When completed, the expanded network is expected to command a water volume of 130,000 m3 per year.

Understanding the energy demand associated with this vertical transfer is critical given the varied elevations ranging from the water extraction point to the highest tracks. We can estimate the energy requirements of pumping by mapping these altitude variations. When combined with other factors, this provides a comprehensive picture of the energy dynamics inherent in snow production. The following analysis will provide a comprehensive overview of the calculation of pumping-related energy demands, shedding light on this critical aspect of snowmaking.
In order to determine the energy requirements for water pumping during the snowmaking process, the methodology took into account the pumping of water from the Boscaiolo river, situated at an approximate elevation of 700 meters above sea level (asl), to the water storage basin positioned at an elevation of 1420 meters asl approximately. The energy required for this pumping process is given by **Equation 3.1**.

$$E = \frac{(V \times \Delta H) \times \rho \times g}{\eta} \tag{3.1}$$

Where:

- E denotes the energy demand in joules.
- V is the volume of water in m^3.
- ΔH represents the elevation difference or head in meters.
- ρ is the water density, taken as 1000 kg/m^3.
- g is the gravitational constant, approximately $9.81\,\text{m/s}^2$.
- η is the pump's efficiency, assumed to be 60%.

Applying this formula, an energy demand of 425100 kWh/year is derived for the pumping of water from the river to the reservoir.
Additionally, the ski resort utilizes a high-pressure pump network to distribute water from the reservoir to snow generators positioned across various ski slopes. To compute the energy demand for this process, the total surface area of tracks with snowmaking capabilities was determined to be 317789 m2, as outlined in **Table 2.1**. With an estimated water volume of 130,000 m3 split across the various ski tracks, the average water requirement per square meter was calculated to be 0.4 m3/m2, which is sensible assumption as the density of artificial snow is normally high, around 350-400 kg per cubic meter, compared to 70-100 kg of natural snow[12]. This estimate aligns with the assumption that 0.4 m3 of water is required for each cubic meter of snow, effectively establishing a 1 m layer of artificial snow across the ski tracks. For each individual ski track, we consider its surface area multiplied by its elevation gain from the reservoir then took the sum of them and Using **Equation 3.1**, the energy demand for this segment of water transport was found to be 76064 kWh/year, resulting in a total energy requirement of 501164 kWh/year for the entire water pumping process.
Furthermore, to determine the energy consumption of the snow cannons, a typical snow cannon's power demand was taken as 22kW, based on data from TechnoAlpin [13]. Given a water flow rate of 3 L/s at a wet bulb temperature (*Twb*) of -8 C (as depicted in **Figure 3.1**), the snow production rate is 27 m3 per hour.The provided

flow rate pertains to a specific ski resort that has a comparable elevation with Alpe di Mera. This assumption has been taken into account for the purpose of conducting the calculation. Consequently, the energy requirement was calculated to be 0.815 kWh/m3 of snow, totaling 264815 kWh/year for snow cannon operations. Thus, the overall energy demand for the snowmaking process is approximately 765978 kWh/year.

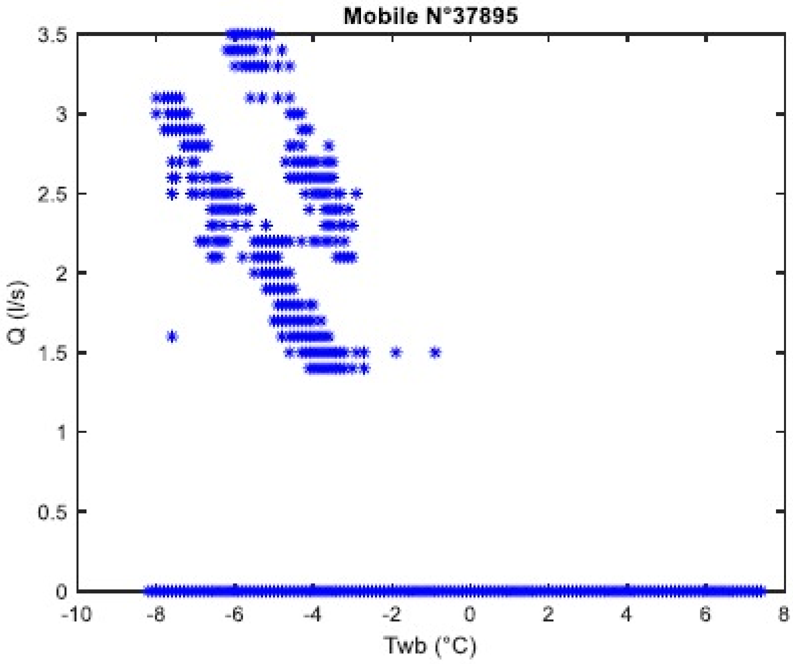

Fig. 3.1 Graph showcasing the relationship between flow rate and wet-bulb temperature for a ski resort's snow cannon. Data processed by Costanza Gamberini (Politecnico di Torino) within the PITER Alpimed INNOV project.

3.1 Discussion

In conclusion, this comprehensive examination of energy consumption related to snow-making procedures sheds light on the complex interaction among different elements within the broader energy system. The analysis highlights the importance of every element, ranging from the pumping systems to the snow cannons, in their contribution to the energy footprint of the resort.

Based on the results, it is noteworthy that the computed total energy demand closely corresponds to the reported gross figure of 800,000 kWh/year provided by the ski resort[4]. This congruence serves as an external validation for the methodology and computations conducted in this chapter.The findings of this chapter give rise to two primary implications. To optimize energy conservation and efficiency measures, stakeholders in ski resorts can enhance their understanding of the snow-making process by identifying the specific elements that consume substantial amounts of energy. It is possible to develop targeted interventions that are customized to address the specific factors that have the greatest impact on energy consumption. By doing so, it is possible to optimize energy utilization as a whole and potentially achieve cost savings in operations. Furthermore, it is crucial to acknowledge that these findings regarding energy consumption serve as a fundamental basis for conducting an accurate assessment of the carbon footprint (CF) linked to the process of snow-making. With the growing global focus on sustainability and environmental accountability, various industries, including ski resorts, encounter the simultaneous task of complying with regulatory requirements and meeting the demands of a progressively environmentally conscious society. The precise quantification of the carbon footprint is essential for effectively addressing these challenges. In the following chapter, the focus of the study will shift from energy metrics to carbon emissions. The objective is to convert the energy consumption data collected in this study into measurable carbon footprint values. This particular stage holds significant importance in comprehending the wider environmental consequences associated with the operations of ski resorts. The primary goal persists: to conduct a thorough assessment of the ecological impact of ski resorts and, consequently, identify potential strategies for mitigating this impact. Through conducting comprehensive analyses, this research makes a valuable contribution to the expanding corpus of knowledge that emphasizes the interconnectedness between recreational activities and their environmental consequences. It advocates for the adoption of sustainable practices that promote the alignment of leisure activities with the principles of environmental stewardship.

Chapter 4

Carbon footprint

4.1 System boundary

Numerous activities are conducted in the contexts of skiing and ski resorts, all of which contribute to the formation of their carbon footprint. However, for the purposes of this research, especially in light of the forthcoming renovation project, the analysis narrows its focus on the most significant contributors. The three primary elements for scope 1 and scope 2 that have the most influence on this parameter encompass ski lifts, snowmaking, and slope grooming [9]. With the impending renovation project in mind, this chapter emphasizes the carbon footprint analysis of the mentioned elements, understanding that they will play a pivotal role in the resort's future carbon dynamics. Less influential elements, such as the energy consumption of the buildings located along the slopes and the operation of mountain rescue vehicles, etc., are not considered in this detailed analysis to maintain clarity and specificity in assessing the resort's major carbon emission sources.

4.2 Emission Factor

In evaluating the carbon footprint, it is imperative to include the concept of emission factor (EF) alongside the knowledge of energy consumption associated with a particular activity.
In a general sense, an emission factor serves to quantify the amount of emissions gen-

erated per unit of activity. The metric in question plays a crucial role in establishing a direct correlation between a given activity and its subsequent environmental impact. In the realm of energy, the conventional representation is gCO2eq/kWh, denoting the quantity of greenhouse gas emissions generated per kilowatt-hour of energy utilized. Alternatively, in the context of evaluating the manufacturing of goods, the metric can be represented as grams of carbon dioxide equivalent per unit (gCO2eq/unit) or grams of carbon dioxide equivalent per kilogram (gCO2eq/kg) of product, which quantifies the emissions associated with the production of each individual unit or kilogram of the product.

In the context of a ski resort and the goal of this study, the focus on emission factors encompasses two distinct domains: the electricity usage of the resort's infrastructure and the fuels utilized for the resort's vehicular operations. Electricity plays a crucial role in powering ski lifts and snow production machines, serving as their primary source of energy. On the other hand, vehicle fuels are essential for facilitating snow grooming tasks. Every form of energy, such as electricity sourced from the grid or fuel used for vehicles, has its own distinct emission factor. The emission factors play a crucial role in establishing a connection between energy consumption and quantifiable carbon footprints. Therefore, it is imperative to thoroughly examine the emission factors related to electricity consumption and vehicular fuels in order to develop a comprehensive carbon footprint analysis for a ski resort. The following parts will offer a detailed analysis of these emission factors, establishing the foundation for a comprehensive evaluation of the resort's carbon footprint.

4.2.1 Electricity

When determining the emission factor, it is imperative to consider the diurnal fluctuations in the energy composition of the electricity grid. During the period of daylight, there is a significant impact of renewable energy, primarily derived from photovoltaic sources. The emission factor of greenhouse gases in the electricity grid is naturally lower during daytime hours in comparison to nighttime hours. During nighttime hours, there is an increased reliance on fossil fuels within the grid, resulting in a corresponding rise in emissions. Moreover, the temporal variation in the availability of renewable energy sources, specifically solar energy, exerts a substantial influence. The utilization of solar energy during the winter season presents a distinct set of challenges compared to the summer period, primarily attributable to reduced daylight duration and diminished solar irradiance. The electricity consumption during the operational period of ski resorts, which usually spans from December to April, is intrinsically associated with an increased carbon footprint. This is primarily due to a reduction in the utilization of renewable energy sources and a greater reliance on energy derived from fossil fuels within the power grid. The aforementioned contextual comprehension underscores the necessity of conducting a thorough assessment of emission factors across various seasons and different times of the day, thereby guaranteeing a more precise depiction of the environmental consequences associated with ski lift operations.

The data related to energy production in Italy for the years 2021 and 2022 were acquired from the Terna website [14]. These data were categorized based on the various sources of origin and further separated by different hours throughout the day. Each energy source has been assigned an emission factor, which is determined based on international scientific literature or specific national reports, as indicated in the **Table 4.1**.

Table 4.1 Emission factor of different enegy source used in Italy.

SOURCE	**EF (gCO2/kWh)**	**SOURCE**
Waste incinerator	1294.30	ISPRA (2020, [15]), Tab. 2.3
Coal	899.90	ISPRA (2020, [15]), Tab. 2.3
Coal-derived gas	1624.80	ISPRA (2020, [15]), Tab. 2.3
Methane	365.00	ISPRA (2020, [15]), Tab. 2.3
Oil	564.60	ISPRA (2020, [15]), Tab. 2.3
Geothermal	30.00	Soltani et al. (2021,[16])
Hydropower (pumped)	651.87	ISPRA (2020, [15], Efficiency 75% [17]
Hydropower (river)	3.62	Gemechu and Kumar (2022, [18])
Hydropower (dams)	10.80	Gemechu and Kumar (2022, [18])
Other	144.00	ISPRA (2020, [15]), Tab. 2.3
Photovoltaic	40.00	Tawalbeh et al. (2021, [19])
Wind onshore	13.65	Ardente et al. (2008, [20])
Wind offshore	13.65	Ardente et al. (2008, [20])

Considering the predominant operational hours of ski lifts during the central part of the day, their peak usage in winter months, and different energy source distribution by hour it was imperative to undertake conduct a comprehensive analysis of the emission factor trends throughout the day separately for summer and winter. Based on the energy source employed and its corresponding emission factor, as detailed in Table 4.1, the hourly emission factor (EF) was determined in hourly scale for each day throughout both 2021 and 2022.

Following that, an average emission factor (EF) was computed for each hour of the day to provide a more precise assessment tailored to the ski resort's operational timeline (8 a.m. to 6 p.m.). This calculation was specifically limited to the times when the ski resort was open: the winter season, which ran from December 2021 to April 2022, and the summer season, which ran from July to September 2022. The results of these computations are delineated in **Figure 4.1** and **Figure 4.2**.

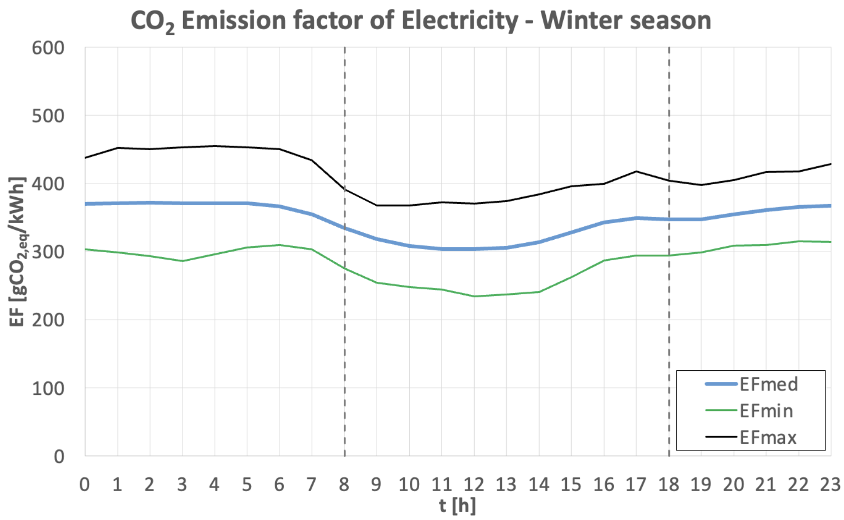

Fig. 4.1 Average Emission Factors (EF) for each hour of the ski resort during the winter season .

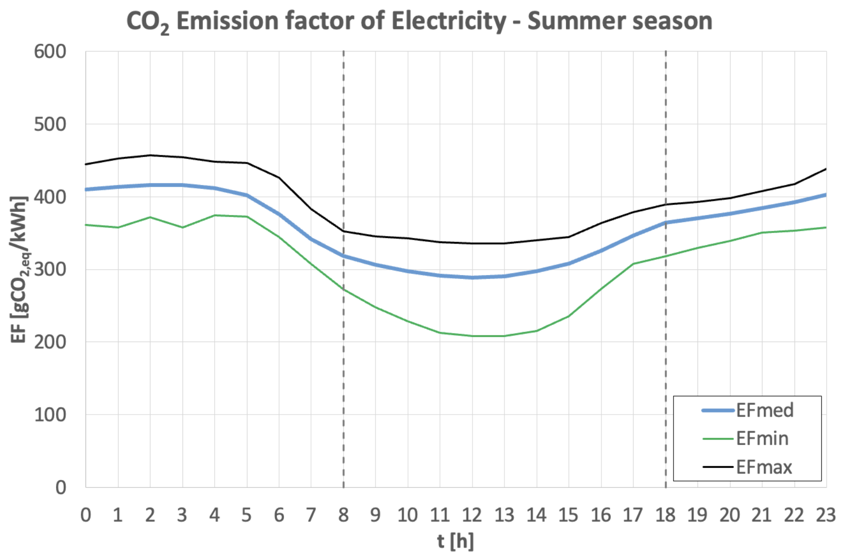

Fig. 4.2 Average Emission Factors (EF) for each hour of the ski resort during the summer season .

From the both figures, it can be observed that the time band considered (8 a.m. to 6 p.m.) consistently displays a lower emission factor in comparison to the night-time hours. This happens in particular during the summer thanks to the contribution of photovoltaic systems. The averaged emission factors of electricity produced in Italy during the 8 a.m. to 6 p.m. time slot stand at 323.30 gCO2/kWh for the winter and 312.33 gCO2/kWh for the summer. If we were to exclude the time window constraint, the averaged emission factors would rise to 345.9 gCO2/kWh for winter and 356.23 gCO2/kWh for summer. These values can be utilized for an in-depth calculation of the carbon footprint.

4.2.2 Vehicles

In assessing the ski resort's carbon footprint, it's essential to evaluate the greenhouse gas emissions attributable to vehicles. The snow groomers play a crucial role in the assessment as they are essential for the preparation of slopes.Their fuel consumption is notably high, being influenced by factors such as slope, the length of the slopes, and the particular grooming techniques employed. For these groomers, which predominantly rely on diesel fuel, the associated emission factor stands at 2.66 kgCO2/L of fuel. This value emerges from an integration of the specific emission factor per unit of mass and the characteristic density of diesel fuel (ISPRA data, [21]. Significantly, this emission factor demonstrates strong consistency with other estimates found in contemporary literature and prominent databases. An important aspect to underline is the low level of uncertainty concerning vehicle CO2 emissions. This is due to our thorough understanding of the carbon content of fuel. However, when it comes to other greenhouse gases, the emissions are dependent on a variety of factors, most notably engine size and efficiency. As a result, there is inherently more uncertainty in CO2-equivalent terms. However, given the minor proportion of these emissions relative to total vehicular emissions, the overall uncertainty remains low [22].

4.3 Carbon Footprin Calculation

The carbon footprint assessment of Alpe di Mera encompasses three key components, namely ski lifts, snow grooming, and snowmaking. The aforementioned individuals are the key contributors to the carbon emissions of the ski resort, which is in line with the main objective of this research.

4.3.1 Ski lifts

Alpe di Mera encompasses four main ski lifts, namely Scopello-Mera, Capricorno, Camparient, and Bimella, alongside several smaller installations. As previously discussed, there exists a forthcoming renovation proposal that involves the replacement of the Scopello-Mera and Capricorno Chairlifts with a singular cable car lift that will traverse the same route. The comprehensive analysis of the energy consumption of the projected cable car lift was thoroughly explained in a previous section.

The carbon footprint associated with the planned installation of the new ski lift was assessed by utilizing the previously calculated data on energy consumption 2.2. The assessment of the remaining ski lifts and minor installations considered the resort's reported annual energy consumption in order to provide a comprehensive evaluation.
Based on the obtained enegy consumption associated to the new lift **Figure2.13** and the emission factor calculated (averaged over the working preiods of the ski lifts but kept the hourly discretisation) on the previous section for winter and summer **Figure4.1** & **Figure4.2**. The carbon footprint of the new ski lift was determined **Figure4.3**

According to the data presented in the **Figure4.3**, a noticeable reduction in the carbon footprint is observed during the midday period. The decrease in energy consumption during peak sunlight hours can be attributed to two main factors. Firstly, there is the effective utilization of solar energy during these hours. Secondly, there is a decrease in energy consumption as a significant number of passengers choose to use the lifts for descending, which inherently requires less energy. Nevertheless, as the conclusion of the workday draws near, there is a noticeable rise in the carbon footprint. The observed increase can primarily be attributed to the utilization of energy sources with higher emission factors (EF) during that time period. In **Figure 4.3**, the areas beneath the curves detail the total daily carbon footprint of the new ski lift across both winter and summer seasons. For the winter, this amounts to 320.22 $KgCO_2$eq/day and for summer, it is 174.19 $KgCO_2$eq/day. Given that the lift operates for 122 days in winter and 50 days in summer, the annual carbon footprints

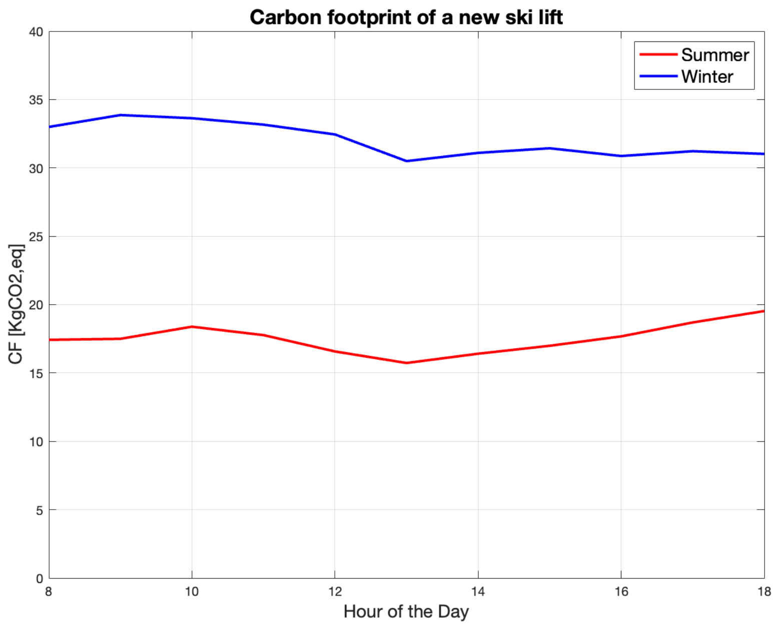

Fig. 4.3 The carbon footprint associated with the daily operation of the new ski lift on an hourly basis.

culminate to $39,066.8\,\mathrm{KgCO_2eq/year}$ and $8,709.5\,\mathrm{KgCO_2eq/year}$ for each season respectively.

A variety of indicators have been established to assess the carbon footprint associated with the new **Table4.2** ski lift . These metrics enable a meaningful comparison of the environmental impact of the lift with other ski lifts, thereby facilitating a comprehensive assessment of its performance. It should be noted that all information regarding the specifications of the new lift has been sourced from the technical report released by Monterosa2000 [4]

Table 4.2 Indicators of the carbon footprint associated with ski lift.

Indicator	Winter	Summer	Total
[kgCO2.eq/day]	320.22	174.19	
[kgCO2.eq/Passenger]	0.51	1.11	
[kgCO2.eq/year]	39066.84	8709.5	47776.34
[kgCO2.eq/ski lift length]	16.45	3.67	20.12
[kgCO2.eq/elevation gained]	45.96	10.25	57.01

Continuing from the previous point, for the other lifts, namely Camparient and Bimella, as well as the minor installations, the ski resort and Monterosa2000 reported an annual energy consumption of 160,000 kWh. In conjunction with this, the average winter emission factor of 323.30 gCO2/kWh, which was detailed in the **Section4.2.1**, was utilized for computations. As a result, the total carbon footprint attributed to these other ski lifts and minor installations is estimated at 51728 KgCO2.eq/year.

Taking into account all the data, the cumulative carbon footprint for all ski lifts and minor installations is determined to be 99504.3 KgCO2.eq/year.

4.3.2 Snow Grooming

The process of snow grooming holds significant importance in the overall functioning of ski resorts, as it plays a crucial role in maintaining the best possible conditions on the slopes for the enjoyment of visitors. This procedure utilizes advanced technology comparable to heavy-duty earth-moving equipment, predominantly propelled by diesel engines. The annual diesel consumption for snow grooming at Alpe di Mera is estimated to be around 60,000 liters. According to the Monterosa2000 technical report [4], snow groomers are commonly equipped with thermal engines that have an average power output of approximately 400 horsepower. The fuel consumption rate of these engines is estimated to be around 30 liters per hour. The machines in use have an average age of about 6,000 hours, except for the newest one, which stands at around 3,500 hours. This recent machine has a diesel engine compliant with the EUROMOT III directive concerning emissions. Hence, it uses the ADBlue additive alongside the fuel. Overall, the machinery fleet is relatively updated in terms of equipment age, reflecting efficiency both in terms of performance and atmospheric emissions.

No significant increases in consumption are anticipated for the future project plan compared to the current average volume, as it pertains to the optimal slope opening condition. Therefore, the rate of consumption is expected to remain consistent in the ski resort's upcoming plan. The annual carbon footprint resulting from snow grooming operations can be calculated by incorporating the previously mentioned emission factor for vehicles **Section4.2.2**, which is measured at 2.66 kgCO2/L. This calculation results in a value of 159,600 KgCO2.eq/year.

However, a lingering question arises when considering carbon emissions: while fuel consumption might remain consistent, does the introduction of ADBlue have a significant effect on the carbon footprint (CF)? To delve into this aspect, the impact of ADBlue on CF was analysed. The details of this assessment are as follows:

The utilization of AdBlue, an additive solution containing urea, has demonstrated a substantial reduction in nitrogen oxide (NOx) emissions within heavy-duty vehicles that are powered by diesel engines. Selective Catalytic Reduction (SCR) systems employ the utilization of AdBlue in order to facilitate the catalytic conversion of NOx emissions into benign nitrogen and water vapor. The process of converting is of extreme significance in enhancing the quality of air. Based on the findings presented in the TNO report [23], it is evident that selective catalytic reduction (SCR) systems have gained significant prevalence in the context of Euro V and VI trucks and buses. The aforementioned statement underscores the capacity of ski resorts to mitigate transportation-related emissions, which are a substantial contributor to carbon emissions, specifically within the context of ski resort operations. In contrast, the TNO report highlights the inclusion of CO2 emissions resulting from the utilization of urea-based additives in catalytic converters as an emerging contributor to greenhouse gas emissions. The methodology employed in this study, as delineated in the IPCC Guidelines of 2006, offers a systematic approach for the quantification of carbon dioxide (CO2) emissions. The CO2 impact is determined by establishing a connection between the emissions produced from the utilization of both the urea additive and diesel fuel. However, it seems that the impact of urea-additive CO2 emissions on the total emissions from diesel fuel combustion is insignificant. In relation to the consumption of diesel fuel, the consumption rates of urea additive for Euro V and Euro VI are 6% and 3% respectively. Consequently, the CO2 emissions resulting from the use of urea additive account for 0.6% and 0.3% of the CO2 emissions from diesel fuel, respectively . Nevertheless, it is imperative to recognize the inherent uncertainties associated with these evaluations, as they may contain potential error margins ranging from 25% at the lower bound to 10-25% at the upper bound [23].

In conclusion, incorporating AdBlue-capable vehicles into ski resort grooming operations can make significant contributions to the resort's overall environmental goals. Even though the direct impact of urea-additive CO2 emissions on the carbon footprint appears to be minor, the broader benefits , such as reduced NOx emissions and improved air quality, are in line with sustainability goals [23].

4.3.3 Snow production

An in-depth examination of the energy consumption in the snowmaking process, as detailed in **Chapter3** serves as a fundamental basis for comprehending the carbon emissions linked to this activity within the ski resort. In order to analyze the environmental consequences, it is necessary to convert the energy requirements of each individual aspect of snowmaking, including water extraction from the river, water distribution to the ski tracks, and the functioning of the snow cannons, into their respective carbon emissions. The calculation of the carbon footprint (CF) for each segment can be accomplished by utilizing the previously derived averaged winter emission factor 345.9 gCO2/kWh. The **Table4.3** provides a summary of the energy consumption attributed to each component, along with its calculated carbon footprint (CF).

Table 4.3 Carbon footprint attributed to each component of snowmaking.

	Energy demand [kWh/year]	Carbon footprint [KgCO2.eq/year]
Water pumping from the river	425100	147042.1
Water distribution to the ski tracks	76064	26310.4
Overall Pumping	501164	173352.5
Snow cannons	264815	91599.4
Overall Snowmaking	765978	264951.9

The data presented in **Table4.3** clearly indicates that the energy utilized for pumping water from the river plays a significant role in the total energy consumption associated with snowmaking. The extent of this dominance is also reflected in carbon emissions, making it a significant aspect that requires careful consideration in any sustainability and efficiency initiatives that the resort may undertake.

4.4 Discussion

Based on the wide carbon footprint calculations conducted in this chapter, it becomes apparent that snow-making, among the essential operational elements of the Alpe di Mera ski resort, stands out as the primary source of the resort's carbon emissions, as can be seen in Figure4.4. This statement emphasizes the ecological impact of producing artificial snow and underscores the significance of investigating alternative, environmentally-friendly snow-making technologies and approaches for resorts in

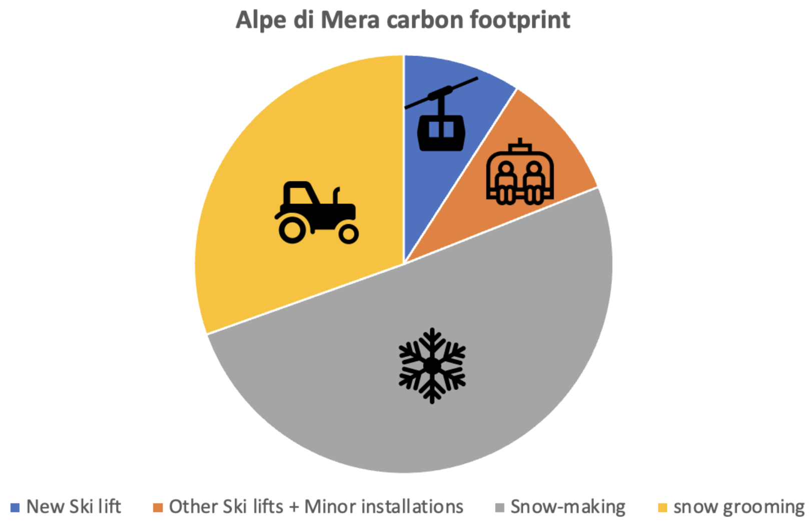

Fig. 4.4 Representation of the Alpe di Mera's carbon emission sources.

response to climate-related difficulties. Given the information previously presented, the optimization of pumping and snow-making operations has the potential to yield a substantial influence on emissions. In addition, the adoption of electricity derived from a greater proportion of renewable resources has the potential to further mitigate the environmental impact of the resort.

In order to complete the carbon footprint assessment of the new system with an approach that considers the entire life cycle, it is recommended to request a carbon footprint assessment from the company that will supply and install the new system. In addition, it is essential to assess the carbon footprint (CF) linked to the decommissioning process of obsolete systems. Nevertheless, as cited in reference [4], it is worth noting that some of the materials derived from these systems could potentially be repurposed, which may result in a minimal carbon footprint.

While the primary focus of this chapter was to calculate the carbon footprint of the Alpe di Mera ski resort, an interesting observation emerged regarding potential mitigation strategies. A significant portion of the resort's carbon footprint could be compensated by streamlining transportation methods to and within the ski resort. Notably, the introduction of new lifts could encourage visitors to reduce their reliance on cars. If the new system effectively discourages car usage for accessing the slopes, even if only to a certain extent, this could result in a meaningful reduction in the resort's overall carbon footprint.

Furthermore, as a result of the comprehensive calculations of carbon footprint, it became evident that there was an apparent requirement to develop precise metrics associated with carbon footprint, energy usage, and unique attributes of the ski resort, such as slope length and overall elevation variances, among others. The purpose of implementing these indicators is to facilitate a comparative evaluation of the Alpe di Mera ski resort with five other distinct ski resorts in Italy, which differ in terms of size and location. For privacy reasons, the identities of these resorts will be anonymous. The comprehensive findings of this comparative examination, with a particular focus on the aforementioned metrics and indicators, are displayed in the **Table4.4**.

Table 4.4 Indicator Comparison of 5 distinct ski resorts in Italy and Alpe di Mera .

	Case 1	Case 2	Case 3	Case 4	Case 5	Alpe di Mera
Km of slopes	80	150	50	50	152	22
n. Skilifts	14	58	13	12	38	4
n. Skiers in one season	199890	1203741	128537	481000	455000	-
n.Skiers/Km of slopes	2499	8025	2571	9620	2993	-
Total height difference of the ski lifts (m)	4491	19017	2825	4534	11075	1631
Fuel consumed (l)	241188	333554	94641	270270	326568	60000
Electricity consumed (MWh)	3426	7024	1542	5878	5045	1077
Liters of fuel/km of slopes	3015	2224	1893	5405	2148	2727
MWh consumed/m of height difference	0.8	0.4	0.5	1.3	0.5	0.7
KgCO2/Skiers	11.6	3.61	7.85	7.5	7.35	-
KgCO2/km of slopes	28988	28970	20182	72150	21999	23821
KgCo2/m of height difference	516	229	357	796	302	321

The **4.4** reveals a notable resemblance between Alpe di Mera and ski resort case 5 in terms of emissions per kilometer of slopes and total meter height difference.

The acquisition of comprehensive and detailed data is of utmost importance when evaluating the energy consumption and carbon footprint of ski resorts, as it ensures a high level of precision and accuracy in the assessment process. The dataset associated with Alpe di Mera exhibited a noteworthy constraint in terms of its availability. Although the documentation included the number of passengers, the specific number of skiers, which is a crucial metric for comparing with other resorts, was not provided. This presented difficulties in making direct comparisons regarding skier numbers with five other ski resorts. Moreover, the study faced additional limitations in terms of data, including the lack of information pertaining to other lifts that remained unchanged, as well as the absence of detailed data on snowmaking procedures. The presence of data gaps imposes constraints on the extent of analysis and the level of detail in the insights that can be extracted from the study. The aforementioned challenges emphasize the significance of possessing comprehensive datasets when conducting an in-depth analysis of the environmental ramifications associated with ski resorts.

Chapter 5

Climate Change and Ski Resorts

Ski resorts, situated within mountainous regions, serve as more than mere recreational areas; rather, they function as dynamic ecosystems intricately interconnected with their immediate surroundings. The equilibrium of these environments is intricately maintained, as even minor alterations in meteorological conditions can significantly impact the functioning of resorts. The preceding chapters provided a comprehensive analysis of energy consumption and carbon footprints within a ski resort, delving into the intricate details of these phenomena. One of the findings highlighted the significant importance of snowmaking, an activity that is greatly impacted by a variety of climate variables such as wet bulb temperature. However, considering the current state of the global climate, it is important to examine the potential impacts on these popular ski destinations. Emerging empirical findings indicate that the phenomenon of climate change is not only a prospective eventuality, but an ongoing and tangible actuality, with mountainous areas exhibiting heightened vulnerability to its effects. This chapter extensively explores the complex relationship between ski resorts and the Climate change, providing an analysis of the potential future scenarios for these destinations renowned for winter recreational activities. By gaining a comprehensive understanding of the potential pathways of climate change, various stakeholders can enhance their preparedness and adaptability measures, thereby guaranteeing the long-term sustainability and allure of these resorts for future generations.

5.1 Wet Bulb Temperature

The complexities of snow formation, whether arising naturally or through artificial means, are influenced by a fragile equilibrium of climatic factors. The formation of natural snow is reliant upon the convergence of low temperatures, the existence of freezing nuclei, and atmospheric humidity. However, the parameters and possibilities involved in the production of artificial snow exhibit some variation. The temperature within the natural environment exhibits a consistent characteristic, thereby offering restricted opportunities for manipulation. Artificial snowmaking operations primarily rely on two key factors: atmospheric humidity and the introduction of freezing nuclei. Among these factors, the wet bulb temperature (Twb) is a crucial parameter that plays a significant role in determining the viability and effectiveness of snowmaking efforts. The wet-bulb temperature (Twb) is a fundamental parameter that influences the functioning of snow production equipment. It is defined as the minimum temperature achievable by evaporating water into the air under constant pressure. Snow-producing machines operate most effectively when the wet-bulb temperature (Twb) remains below -2°C [24]. One noteworthy characteristic of this temperature threshold is its direct correlation with both the quality and quantity of snow generated. As the temperature of the Twb decreases, there is an increase in the machine's water-to-compressed air ratio within the mixture. This adjustment enhances the production of snow of higher quality and improves the efficiency of energy utilization. On the other hand, higher temperatures require the machinery to utilize larger quantities of compressed air compared to water. The imbalanced ratio discussed not only undermines the quality of the generated snow but also increases energy consumption, consequently reducing the efficiency of producing technical snow.

In order to provide a comprehensive understanding of this complex association, this study will offer a thorough examination, comparing and contrasting temperature and humidity measurements. This analysis aims to provide a comprehensive understanding of the diverse characteristics of snow, ranging from ideal to below-average, that can be attained in different environmental circumstances. The findings of this study will offer valuable insights for the implementation of effective snowmaking strategies in ski resorts.

In order to estimate the total number of hours available for snowmaking at the Alpe di Mera ski resort in a given season, an empirical **Equation5.1** was employed to determine the wet bulb temperature [24]. This information is crucial for assessing the feasibility of producing high-quality snow.

$$\begin{aligned}T_w = T \cdot \arctan\left(0.151977 \times (RH\% + 8.313659)^{\frac{1}{2}}\right) + \arctan(T + RH\%) \\ - \arctan(RH\% - 1.676331) \\ + 0.00391838 \times (RH\%)^{\frac{3}{2}} \times \arctan(0.023101 \times RH\%) - 4.686035 \quad (5.1)\end{aligned}$$

To apply the equation presented in 5.1, which was derived by Roland Stull [24], data on temperature (T) and relative humidity (RH) were needed. This data was sourced from ARPA PIEMONTE. The Camparient Station (1515 m amsl), being the closest to the Alpe di Mera Ski resort, was the initial choice for data collection. However, relative humidity data was not available for this station. To address this, the Rassa station (916 m amsl), another nearby location with available humidity data, was selected. The following paragraph will detail the methodology employed to convert the humidity data from the Rassa station to be representative for the Camparient station.

Starting with a measured temperature, T, one can compute the corresponding saturated vapor pressure, e_s [Pa], using the Clausius-Clapeyron equation:

$$e_s = 611 \times \exp\left(\frac{17.27 \times T}{237.3 + T}\right) \quad (5.2)$$

Relative humidity, RH [%], is defined as the ratio between the partial pressure of vapor, e [Pa], and the saturated vapor pressure, e_s [Pa]:

$$RH = \frac{e}{e_s} \times 100 \quad (5.3)$$

Both temperature and relative humidity are functions of elevation, z [m amsl]. The temperature typically exhibits a linear dependency:

$$T(z) = T_0 - \alpha \times z \quad (5.4)$$

where T_0 [°C] represents the temperature at sea level elevation, and α [°C/m] is the lapse rate. The relationship between relative humidity and elevation is more complex. The non-dimensional specific humidity or mixing ratio is a variable that exhibits minimal dependence on elevation, w, defined as:

$$w = 0.622 \times \frac{e}{P} \tag{5.5}$$

P [Pa] represents the atmospheric pressure, which also linearly depends on elevation:

$$P = P_0 - 9.81 \times \delta \times z \tag{5.6}$$

in **Equation 5.6** P_0 [Pa] denotes the pressure at mean sea level and δ [kg/m^3] is the air density. The absence of specific data, P_0 can be approximated as equivalent to a standard atmosphere ($P_0 = 101300$ Pa), and the air density can be estimated as $\delta = 1.2$ kg/m^3.

By implementing the aforementioned procedure and creating a MATLAB function for it, the relative humidity associated with the Camparient Station (1515 m amsl) derived from the relative humidity measured at the Rassa station (916 m amsl). The wet-bulb temperature for Camparient Station (1515 m amsl) was subsequently calculated for the period of 2021-2022, as depicted in the **Figure5.1**.

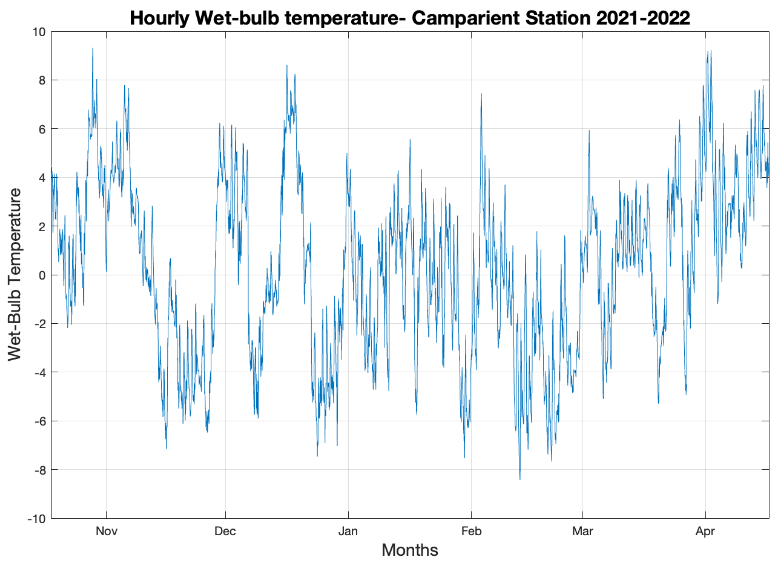

Fig. 5.1 Wet-bulb temperature associated to the Camparient station (1500 amsl) for the year 2021-2022

The potential snowmaking hours for the Alpe di Mera ski resort were determined by analyzing the wet bulb temperature (Twb) data obtained from the Camparient station, which is situated at an elevation of 1500 amsl (**Figure5.1**). The Camparient station functions as a nearby meteorological point of reference for the ski resort, as it is the closest available station. The process of snowmaking can be successfully implemented during periods when the ambient temperature reaches or falls below -2°C [24]. The **Table5.1** provides a comprehensive breakdown of the possible snowmaking hours for each month during the 2021-2022 season. To achieve a more comprehensive comprehension, each month was divided into three distinct periods, commonly referred to as decades.

Table 5.1 Possible snowmaking hours for the Alpe di Mera ski resort for the 2021/2022 season divided into decades

	November			**December**			**January**			**February**			**March**			**April**		
Decade	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
00:00	0	0	2	8	2	3	5	4	3	2	5	6	10	5	0	5	0	0
01:00	0	0	3	8	2	4	5	5	3	2	5	7	9	5	0	5	0	0
02:00	0	0	3	8	2	4	5	4	3	4	5	6	10	5	0	4	0	0
03:00	0	0	3	9	2	4	5	6	5	5	5	6	10	5	0	4	0	0
04:00	0	0	3	9	2	4	5	6	4	5	5	6	10	5	0	4	0	0
05:00	1	0	3	8	1	4	5	6	4	4	5	6	10	5	0	5	0	0
06:00	2	0	3	9	1	4	5	5	4	4	5	6	10	5	0	5	0	0
07:00	0	0	3	9	1	4	5	6	2	3	5	5	9	5	0	4	0	0
08:00	0	0	4	8	1	4	5	6	2	2	5	5	8	5	0	4	0	0
09:00	0	0	3	8	1	4	5	3	2	1	3	4	7	2	0	2	0	0
10:00	0	0	3	6	1	4	5	1	1	1	3	4	7	3	0	2	0	0
11:00	0	0	3	6	0	3	5	1	1	0	3	3	6	1	0	2	0	0
12:00	0	0	3	7	0	3	3	0	0	0	3	2	5	2	0	2	0	0
13:00	0	0	2	6	0	3	3	0	0	0	3	3	5	1	0	2	0	0
14:00	0	0	2	6	0	3	5	0	1	0	3	4	5	1	0	1	0	0
15:00	0	0	2	8	0	3	5	0	1	0	3	3	6	1	0	3	0	0
16:00	0	0	2	8	1	2	6	6	1	2	3	4	6	1	0	3	0	0
17:00	0	0	2	9	1	3	6	3	2	2	3	5	6	2	0	3	0	0
18:00	0	0	2	9	1	3	6	3	2	2	4	6	6	2	0	2	0	0
19:00	0	0	2	9	2	2	6	5	2	2	5	5	7	3	0	3	0	0
20:00	0	0	2	9	2	3	6	4	2	2	5	6	7	3	1	3	0	0
21:00	0	0	2	9	1	3	6	4	2	2	5	7	9	3	1	4	0	0
22:00	0	0	3	9	1	3	6	4	2	2	5	7	8	3	1	4	0	0
23:00	0	0	3	9	1	3	6	5	2	2	5	8	8	4	1	4	0	0

As it can be seen in **Table5.1** The most favorable conditions for snowmaking are typically observed during the initial decades of December and March, particularly in the early hours of the day. These periods present the highest potential for effective snow production. During the winter season, specifically from December to February, there is a notable level of consistency in the ability to produce artificial snow, particularly during the nighttime and early morning hours. On the other hand, transitional seasons such as November and April present restricted opportunities for snowmaking. A discernible decrease in snowmaking capacity is observed universally during the hours of midday, plausibly attributable to elevated temperatures and heightened solar radiation. However, in order to guarantee the most favorable skiing conditions, it is crucial to establish a sufficient snow cover well in advance of the anticipated peak periods. This emphasizes the significance of developing snowmaking equipment that can effectively function at lower temperatures, specifically around Twb=-2 ◦C.

5.2 Mountain Tourism Meteorological and Snow Indicators (MTMSI)

The field of tourism is deeply connected to meteorological conditions, and it is greatly impacted by climate change. The connection between ski tourism and the availability of snowfall can be seen by the mounting concern of diminishing seasonal snow in low elevation mountain areas [25]. The Alps, which are widely recognized as a prominent destination for ski tourism [26], highlight the socio-economic importance of mountainous regions in Europe. The operation of ski resorts is contingent upon meteorological factors, which rely on the presence of natural snowfall as well as favorable conditions for artificial snow production. This makes them vulnerable to the fluctuations in yearly snow conditions and the wider range of long-lasting climate changes. Thorough analyses of historical data, along with projections of meteorological patterns and natural snow conditions, provide valuable insights. The these findings provide a contextual framework for the operations of ski resorts and establish a foundation for predicting forthcoming trends.

Hence, Mountain tourism meteorological and snow indicators application, which is a component of the "European Tourism" Sectoral Information System (SIS) provided by the Copernicus Climate Change Services (C3S), was utilized [27]. This application allows users to compare past and future snow conditions relevant to the tourism industry, as well as explore 39 indicators characterizing meteorological conditions in European mountain regions by elevation and on the scale of NUTS level 3 regions from 1986 to 2100. The application investigates tourism indicators from the recent past using reanalysis data from 1961 to 2015, as well as future indicators based on an ensemble of adjusted climate projections for the near future, mid-century, and end-of-century. These indicators were derived from multiple global climate model (GCM) and regional climate model (RCM) (EURO-CODEX climate projections) pairs for three climate change scenarios: RCP2.6 (2 GCM/RCM pairs) and RCP4.5 and 8.5 (9 GCM/RCM pairs) (**Table5.2**). More details of how this application and indicator were derived and co-designed can be found in the work by Morin et al.(2021,[28]).

Table 5.2 Overview of EURO-CORDEX GCM/RCM pairs used and related RCP.

GCM	RCM	RCP2.6	RCP4.5	RCP8.5
MOHC-Hadgem2-ES	SMHI-RCA4		x	x
CNRM-CERFACS-CNRM-CM5	CNRM-ALADIN53		x	x
IPSL-CM5A-MR	INPSL-INERIS-WRF331F		x	x
MPI-M-MPI-ESM-LR	MPI-CSC-REMO2009	x	x	x
ICHEC-EC-EARTH	SMHI-RCA4	x	x	x
CNRM-CERFACS-CNRM-CM5	SMHI-RCA4		x	x
IPSL-CM5A-MR	SMHI-RCA4		x	x
MPI-M-MPI-ESM-LR	SMHI-RCA4		x	x
MPI-M-MPI-ESM-LR	CCLM4-8-17		x	x

The NetCDF dataset utilized in this study is sourced from the Copernicus website and contains information on the number of days with a minimum snow depth of 30 cm across NUTS3 regions. The dataset consists of 6584 data points, encompassing latitude, longitude, region ID, altitudes, and the count of days with a minimum of 30 cm of natural snow accumulation on the ground. The geographical scope of the data is limited to the Vercelli province in Italy. Additionally, the elevation constraint is set at 1500 m to obtain approximate data specifically related to the ski resort of interest, Alpe di Mera. The **Figure5.2** illustrates the frequency of days with a minimum of 30 cm of natural snow, as indicated in the accompanying table, for various Euro-Codex climate projections. The data is specifically presented for the approximate Vercelli Province at an elevation of 1500 m.Each line corresponds to a GCM/RCM pair.

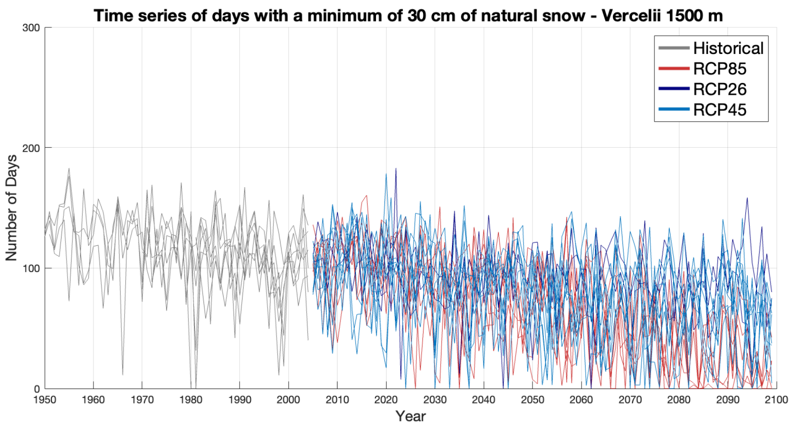

Fig. 5.2 llustratation of the days with a minimum of 30 cm of natural snow timeseries, for historical time period and various Euro-Codex climate projections

The **Figure5.2** clearly illustrates the fluctuation of snow conditions on an annual basis, both in historical and projected scenarios. Additionally, it highlights the significant decline in indicator values anticipated for the 21st century, irrespective of the specific climate scenario. Although the data was geographically limited, which focused solely on the Vercelli province, a region encompassing diverse climatic conditions ranging from pre-alpine to post-alpine, the analysis specifically targeted areas situated at an altitude of 1500 meters. The data can be tentatively associated with the Alpe di Mera ski resort, as the mountainous region in question is situated to the northern part of the province **Figure5.3**, which coincides with the valley where the Alpe di Mera is situated. The utilization of MTMSI indicators enables the

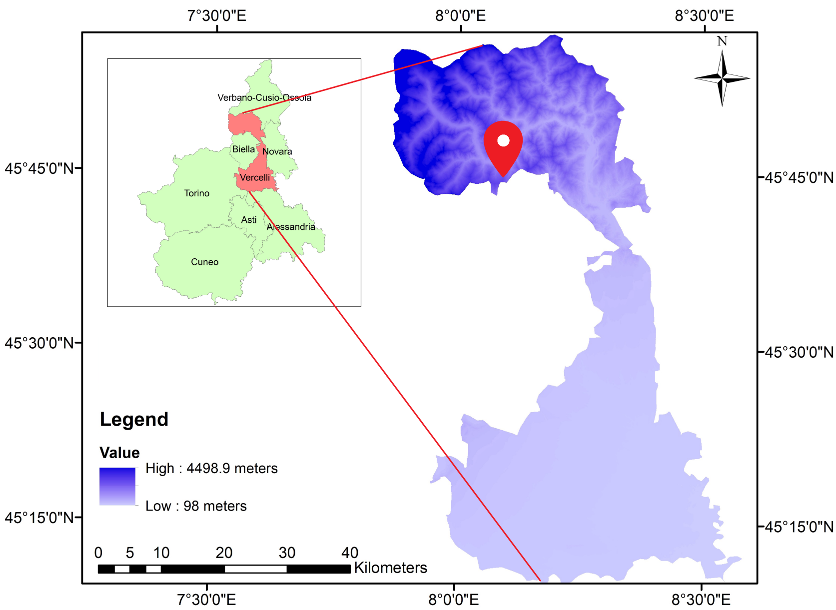

Fig. 5.3 Demonstration of the digital elevation model for the Vercelli province.

direct examination of future developments, under various climate change scenarios, pertaining to automatically generated significant indicators for the ski industry. In this particular case study, relevant indicators for future ski operations were examined. These indicators include the number of days with snow depth (both natural and managed) exceeding the threshold of 30 cm, as well as the annual snow production (in kg/m^2). Additionally, the winter temperature was considered. These indicators were visualized in order to evaluate potential future changes and their implications for ski resort operations. The corresponding data can be found in the provided **Table 5.3**.

Table 5.3 Evolution of key MTMSIs for Alpe di Merea (1500 m) across different RCPs

Indicator	Baseline (1986-2005)	Near future (2021-2040)			Mid future (2041-2060)			End of century (2081-2100)		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Days≥30 cm natural snow	108	92	95	87	97	88	70	94	69	69
Days≥30 cm managed snow	151	140	140	136	139	137	124	139	126	92
Annual snow-making (Kg/m^2)	258	269	269	267	266	278	291	271	293	326
Winter Temperature (°C)	0.07	0.7	1	1.1	2	1.4	2	0.9	2	4.1

The **Table5.3** depicts the evolution of key Mountain Tourism Meteorological Significance Indices (MTMSIs) for the Alpe di Merea ski resort at an elevation of 1500 meters.These indices play a pivotal role in comprehending the feasibility and long-term endurance of ski operations within the framework of evolving climate patterns. The table presents a comprehensive analysis of four discrete temporal intervals, taking into account three Representative Concentration Pathways (RCPs) that represent different trajectories of greenhouse gas concentrations. The presented data offers stakeholders a comprehensive overview, enabling them to evaluate the potential effects on ski operations in light of various climate scenarios. The table comprehensively encompasses various indicators related to snow, including the number of days with adequate snow depth and the annual quantities of snow produced artificially. Additionally, it incorporates a broader climate indicator, specifically the winter temperature. An integrated perspective is essential for the purposes of strategic planning and adaptive management within the ski industry. Moreover, **Figure5.4** depicts the anticipated challenges that the ski area is expected to encounter in terms of snow reliability within the near-term (2021-2040) and mid-term (2041-2060) time intervals. Towards the conclusion of the 21st century (2081-2100), it becomes increasingly apparent that the implementation of snowmaking systems is crucial for the ski area in order to maintain its technical dependability. It is important to acknowledge that although the specific figures for the end-of-century projection may lack precision, the general trend and forecast remain consistent. The time intervals of 2021–2040 and 2041–2060 represent the viewpoint of the business sector that corresponds to investment cycles, while the period of 2081-2100 underscores a regional development strategy with a long-term outlook, prioritizing sustainability objectives within the ski industry. All of these time intervals consistently follow the RCP8.5 trajectory, highlighting the importance of preparing for the most severe climate change scenarios.

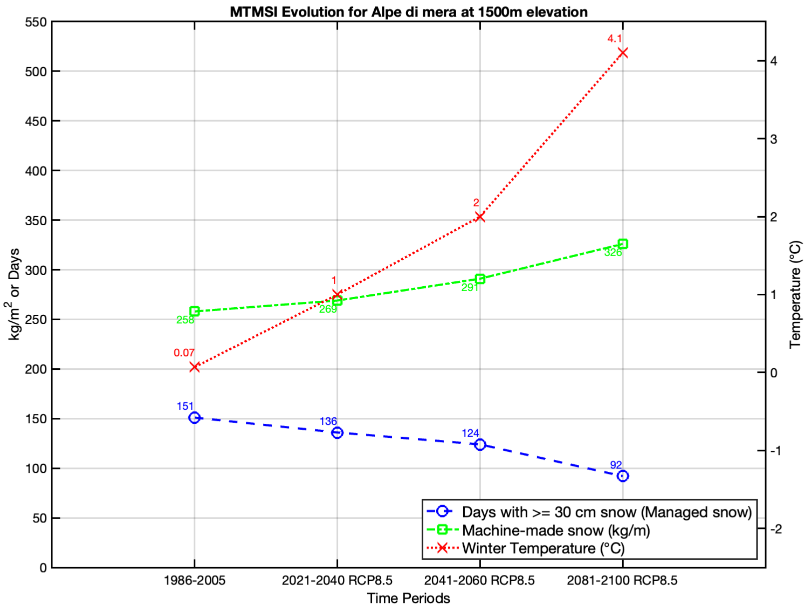

Fig. 5.4 Illustrating the Evolution of some MTMSI Snow-Related Indicators for Alpe di Mera under RCP8.5 Scenario.

5.3 Discussion

The complex role of ski resorts in the ecosystem extends beyond tourism and encompasses their impact on the interconnected balance of natural environments. Upon thorough examination of the complexities surrounding energy usage, carbon emissions, and the significant impact of meteorological conditions on these resorts, it becomes apparent that ski resorts are highly vulnerable to the effects of climate change. The process of snowmaking, which is highly reliant on the wet bulb temperature (Twb), serves as a significant reminder of the susceptibility of these systems to changes in climate factors. The implications of climate change on ski resorts, particularly in mountainous areas, have become increasingly uncertain based on our research findings. The imperative to comprehend and potentially alleviate these effects is motivated not only by recreational considerations but also by the wider environmental and socio-economic ramifications linked to these ecosystems. The data pertaining to wet bulb temperature (Twb) obtained from the Alpe di Mera ski resort serves as a concrete illustration of the difficulties encountered by such establishments. The precise equilibrium necessary for achieving ideal snow production highlights the dependence of these resorts on particular climatic factors and their vulnerability to even slight fluctuations in temperature and humidity. Although advancements in snowmaking technology have been made to address these difficulties, the underlying reliance on weather conditions persists. In addition, the utilization of Mountain Tourism Meteorological and Snow Indicators (MTMSI) has yielded significant insights regarding the future prospects of ski resorts over an extended period of time. Through an analysis of prospective indicators pertaining to snow conditions, a more comprehensive understanding of the forthcoming difficulties can be obtained. The ski tourism industry is confronted with vulnerabilities that are underscored by the projected decline in the number of days with sufficient snow depth and the expected difficulties in maintaining ideal conditions for snowmaking. Furthermore, it is important to acknowledge that although technological advancements and adaptive strategies may alleviate certain challenges in the immediate future, a comprehensive approach is necessary to guarantee the long-term sustainability of these ecosystems. This entails not only the advancement and implementation of more robust snowmaking systems, but also wider endeavors focused on comprehending, and potentially mitigating, the consequences of climate change on these vulnerable ecosystems.

References

[1] NASA. Climate. https://climate.nasa.gov/, 2023.

[2] NOAA Global Monitoring Laboratory. Trends in atmospheric carbon dioxide. https://gml.noaa.gov/ccgg/trends/, 2023. Accessed: 10/08/2023.

[3] National Ski Areas Association (NSSA). Sustainable slopes annual report. https://nsaa.org/webdocs/sustainability/SSAnnualReports/SSAR2015.pdf, 2015.

[4] Monterosa2000. Studio preliminare ambientale, nuova cabinovia ad ammorsamento temporaneo scopello-mera. Technical report, 2022.

[5] IPCC. The fifth assessment report of the ipcc. https://www.ipcc.ch/assessment-report/ar5/, 2014. Accessed: 07/05/2023.

[6] World Tourism Organization UNWTO. *UNWTO Annual Report 2014*. the World Tourism Organization (UNWTO), Madrid, Spain, 2015. Available from: https://www.unwto.org/.

[7] Daniel Scott, Robert Steiger, Natalie Knowles, and Yan Fang. Regional ski tourism risk to climate change: An inter-comparison of eastern canada and us northeast markets. *Journal of Sustainable Tourism*, 28(4):568–586, 2020.

[8] Natalie Knowles, Daniel Scott, and Robert Steiger. Sustainability of snowmaking as climate change (mal) adaptation: an assessment of water, energy, and emissions in canada's ski industry. *Current Issues in Tourism*, pages 1–18, 2023.

[9] Hanna Koloszyc. A case study regarding the carbon footprint for one day trips to different ski destinations in the jamtland region, 2016.

[10] Jacopo De Santis. Carbon footprint of ski resort: Quantification methods and containment hypotheses. Master degree in environmental science, Politecnico di Torino, 2019.

[11] Intergovernmental Panel on Climate Change. Climate change 2013: The physical science basis. contribution of working group i to the fifth assessment report. https://www.ipcc.ch/report/ar5/wg1/, 2013.

[12] Andrea Paganin. Innevamento artificiale, cos''e e come funziona?, 2017. Accessed: 09/05/2020.

[13] TechnoAlpin. TechnoAlpin - The Snow Experts, 2023. Accessed: [10/06/2023].

[14] Terna. Centro statistiche. https://www.terna.it/it/sistema-elettrico/statistiche, 2020.

[15] ISPRA. Fattori di emissione atmosferica di gas a effetto serra nel settore elettrico nazionale e nei principali paesi europei, 2020. Rapporto 317/2020.

[16] M. Soltani, Farshad Moradi Kashkooli, Mohammad Souri, Behnam Rafiei, Mohammad Jabarifar, Kobra Gharali, and Jatin S. Nathwani. Environmental, economic, and social impacts of geothermal energy systems. *Renewable and Sustainable Energy Reviews*, 140:110750, 2021.

[17] Shafiqur Rehman, Luai M. Al-Hadhrami, and Md. Mahbub Alam. Pumped hydro energy storage system: A technological review. *Renewable and Sustainable Energy Reviews*, 44:586–598, 2015.

[18] Eskinder Gemechu and Amit Kumar. A review of how life cycle assessment has been used to assess the environmental impacts of hydropower energy. *Renewable and Sustainable Energy Reviews*, 167:112684, 2022.

[19] Muhammad Tawalbeh, Amani Al-Othman, Feras Kafiah, Emad Abdelsalam, Fares Almomani, and Malek Alkasrawi. Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook. *Science of The Total Environment*, 759:143528, 2021.

[20] Fulvio Ardente, Marco Beccali, Maurizio Cellura, and Valerio Lo Brano. Energy performances and life cycle assessment of an italian wind farm. *Renewable and Sustainable Energy Reviews*, 12(1):200–217, 2008.

[21] APAT. Analisi dei fattori di emissione di co2 dal settore dei trasporti. https://www.isprambiente.gov.it/contentfiles/00003900/3906âĂŘrapportiâĂŘ03âĂŘ28.pdf, 2003.

[22] Ricardo Energy & Environment. Sector, gas, and uncertainty summary factsheets - greenhouse gas emissions. https://naei.beis.gov.uk/resources/Sector_Summary_Factsheet.html#38_transport, 2019. report for Department for Business, Energy & Industrial Strategy of the UK.

[23] U. Stelwagen and N.E. Ligterink. Co2 emission from urea consumption in scr after-treatment systems in heavy-duty vehicles. Technical Report TNO 2014 R11513, TNO, Utrecht, 2014.

[24] Roland Stull. Wet-bulb temperature from relative humidity and air temperature. *Journal of Applied Meteorology and Climatology*, 50(11):2267 – 2269, 2011.

[25] R. Hock, G. Rasul, C. Adler, B. Cáceres, S. Gruber, Y. Hirabayashi, M. Jackson, A. Kääb, S. Kang, S. Kutuzov, A. Milner, U. Molau, S. Morin, B. Orlove, and H. Steltzer. *High Mountain Areas*. 2019. in press.

[26] L. Vanat. 2020 international report on snow and mountain tourism: Overview of the key industry figures for ski resorts. Technical report, Technical Report Laurent Vanat, 2020.

[27] Copernicus Climate Data Store. Mountain tourism meteorological and snow indicators for europe from 1986 to 2100 derived from reanalysis and climate projections. https://cds.climate.copernicus.eu/cdsapp#!/software/app-tourism-mountain-indicators-projections?tab=overview.

[28] Samuel Morin, Raphaëlle Samacoïts, Hugues François, Carlo M. Carmagnola, Bruno Abegg, O. Cenk Demiroglu, Marc Pons, Jean-Michel Soubeyroux, Matthieu Lafaysse, Sam Franklin, Guy Griffiths, Debbie Kite, Anna Amacher Hoppler, Emmanuelle George, Carlo Buontempo, Samuel Almond, Ghislain Dubois, and Adeline Cauchy. Pan-european meteorological and snow indicators of climate change impact on ski tourism. *Climate Services*, 22:100215, 2021.