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Developing and testing an "Integrated Energy Management System" in a ski resort: The "Living Lab Madonna di Campiglio"

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ABSTRACT

Nowadays, ski resorts represent an energy-intensive industry in the mountain environment. On the one hand, their energy consumptions (and costs) have greatly increased in the last 40 years, linked to growing: (I) snow production and grooming demands, facing climate change and ski season extension, (II) number of ski lifts, with a share expansion of the energy-intensive ones (e.g. gondola), (III) need of operational buildings (e.g. warehouses, workshops). On the other hand, their energy transition calls for energy efficiency improvement and renewable sources integration, to be part of cleaner energy systems with low emissions and low environmental impacts (e.g. water use). This paper describes the developing and testing of an "Integrated Energy Management System - IEMS" in the "Living Lab Madonna di Campiglio", as part of the Interreg Alpine Space - Smart Altitude project. After a detailed characterization of the case study, this paper describes the development of the new IEMS as an integration of existing and new monitoring systems and platforms. This IEMS aims to facilitate and stimulate ski resort technicians and managers in the continuous analysis of energy, environmental and economic performance, paving the way for greater awareness and targeted interventions.

1. Introduction

According to Vanat (2021), 5716 equipped outdoor ski areas are operational all over the world, in 68 countries, 2084 of these can be qualified as ski resorts considering that can count more than 4 ski lifts. The share of the European Alps countries in the worldwide ski industry is considerable: 37% of all ski resorts, 38% of the ski lifts, 79% of the major ski resorts[1]. Therefore, ski tourism is a key economic sector in the European Alps and many regions depend on the revenue it generates (Bausch & Gartner, 2020). In each major European Alps country it guarantees more than 100,000 jobs. The many ski resorts attract millions of tourists to the slopes each year; winter season 2020/2021 being an exception due to the COVID situation (Schlemmer & Schnitzer, 2021). An estimated 150 million skier-days were counted in the European Alps in winter season 2018/2019, (excluding Germany) (Vanat, 2021).

Ski resorts are also an energy-intensive industry. Their energy consumptions (and costs) have greatly increased in the last 40 years due to several reasons. First, snow production and grooming demands have increased both for climate change effects (Pickering & Buckley, 2010) and tourist demand for ski season extension (Spandre, et al., 2016). The effects of climate change include less reliable snow cover (Steiger, et al., 2019) and shorter snow season (Wobus, et al., 2017). Second, the number of ski lifts have increased (Falk, 2015), with a preference for the energy-intensive ones (e.g. gondola) (Falk, 2011). Third, the number of operational buildings (e.g. warehouses, workshops) have increased (Moreno-Gené, et al., 2018). At the same time, for political, economic and environmental reasons, ski resorts are increasingly being pressured to reduce CO_2 emissions and save energy costs and thus build a more resilient future for winter tourism regions. Among the guiding directives for the mitigation and adaptation to climate change, the following must certainly be mentioned: the 17 goals for the Sustainable Development (United Nations, 2015), the Paris Agreement (United Nations Framework Convention on Climate Change, 2015) and the European Green Deal (European Commission, 2019). A cleaner energy system is the target increasingly shared by many ski resorts worldwide, where attention is paid not only to reducing energy consumption but also to emissions and environmental impacts, in particular the use of water to produce snow. Multiple studies have explored decarbonisation strategies

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[1] Major ski resorts reach over 1 million skier visits per winter season.

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in the regions (such as (Viesi, et al., 2020) in the Province of Trento) and valleys (such as (Mahbub et al., 2016) in the Giudicarie Esteriori and (Mahbub, et al., 2017) in the Val di Non) of the European Alps. However, strategies at these scales often lack a focus on the specific solutions to be implemented in a ski resort, including detailed consideration of sustainability and management guidelines.

In the existing literature the concept of energy sustainability and management in ski resorts has been explored by various authors, from energy, environmental, social, economic and marketing points of view. Among them, in 1996, Hudson (1996) investigated the environmental impact of skiing both in North America and in Europe, and looked at sustainability as an emerging concept that can bring marketing opportunities, considering Verbier in Switzerland as a case study. With a focus on US ski resorts, Farrell (2019) has evaluated what are the issues and barriers to renewable energy development, and what type of technologies are most attractive. Pröbstl et al. (2011) have explored to which extent the integration of renewable energy solutions and the goal of energy self-sufficiency are relevant for the image and the marketing potential of a ski resort. North American hotels and ski resorts have been the target of Smerecnik and Andersen (2011), to characterize the diffusion of environmental sustainability innovations, while French ski resorts have been the target of Goncalves et al. (2016), to measure and compare two environmental strategies: "concerned citizen" and "proactive". An interesting study by Rech et al. (2019) shows how a tourist area can be transformed by various changes, especially climatic, providing a description of the actors, their arguments, and organizational changes. "Distributed generation" (Krarti, 2015) and "smart grid" (Cervi, et al., 2020) approaches are the future of sustainable ski resorts. Some studies have also focused on the concepts of "Environmental Management System" and "Sustainability Management System". Concerning the "Environmental Management System", Todd and Williams (1996) suggest that it can provide a management framework for guiding all the ski resort activities towards sustainability objectives, Duglio and Beltramo (2016) underline the key role in increasing the awareness of ski operators and tourists, while Pröbstl-Haider et al. (2019) suggest that it should carefully consider legal requirements, safety aspects and emergency planning. The development of a "Sustainability Management System" could be a response to the significant levels of environmental degradation and social challenges for local communities posed by ski areas (Eydal, 2004), influencing the management of winter tourism offers (Martini, et al., 2019). On the other hand, studies dedicated to the concept of "Integrated Energy Management System" are missing.

The Smart Altitude project (Smart Altitude, 2022), funded by the Alpine Space Interreg Programme from 2018-2021, aimed to "enable and accelerate the implementation of low-carbon policies in winter tourism regions by demonstrating the efficiency of a step-by-step decision support tool for energy transition" (Smart Altitude Toolkit, 2022). This transdisciplinary approach to sustainable winter tourism (Polderman, et al., 2020) has been tested in four Living Labs in the Alps (Polderman, et al., 2021). These Living Labs were real-life ski resorts that functioned as pilot sites for creating and testing the Smart Altitude approach. In each Living Lab ski operators collaborated with multiple stakeholders, including public authorities, energy experts, researchers, and tourism associations, to develop innovative solutions to achieve a low-carbon economy in response to climate change and to improve the sustainability and resilience of the ski resorts. The adoption of Living Labs as boundary spanners in innovation has already been proven successful by Van Geenhuizen (2018), enhancing user-centric innovation, and Garcia Robles et al. (2016), describing the living lab phenomena and the international living lab network (ENoLL or European Network of Living Labs). One of the Smart Altitude Living Labs was the ski resort Madonna di Campiglio in Italy, where an "Integrated Energy Management System - IEMS" was developed and tested. The main objective of introducing an IEMS in Madonna di Campiglio was to facilitate and support ski area technicians and managers in the continuous analysis of energy, environmental and economic performance in order to pave the way for greater awareness and targeted interventions.

Knowledge gaps emerge from the literature review in detailing the development and testing of "Integrated Energy Management Systems" in the context of ski resorts. The studies relating to the concepts of "Environmental Management System" and "Sustainability Management System" are still rather generic and lack a clear subdivision of a ski resort into its four main sectors: ski lifting, snow production, snow grooming and buildings. The novelty and the relevance of this paper lie in describing in detail the analysis of the monitoring systems of a ski resort and how these can be further enhanced and integrated, placing them within a single platform capable of evaluating Key Performance Indicators (KPIs) useful both for energy efficiency, for the integration of renewable sources, and for environmental sustainability. How an Integrated Energy Management System can drive the evolution of a cleaner energy system in the context of a ski resort is the main target of this paper.

After a comprehensive description of the case study, this paper details the development of the new IEMS during which existing monitoring systems were integrated with new monitoring systems and new platforms. Then, the innovative results with the new IEMS brought by the Smart Altitude project are presented, followed by a conclusion in which the experiences in Madonna di Campiglio with low carbon and cleaner interventions are placed within the broader context of making ski resorts more resilient to climate change.

2. Case study

The case study Madonna di Campiglio is a well-known ski resort in the north-east of Italy (Campiglio Dolomiti, 2022) and one of the four Living Labs of the Interreg Alpine Space "Smart Altitude" project. Moreover, Madonna di Campiglio is included in the most important ski area within the Province of Trento, the Skiarea Campiglio Dolomiti di Brenta (Skiarea Campiglio Dolomiti di Brenta, 2022) together with the ski resorts of Pinzolo and Folgarida-Marilleva (Fig. 1). Since the last half of the 19th century, Madonna di Campiglio is a renowned holiday destination. Indeed, signs of the presence of the Habsburg imperial couple Sissi and Franz Joseph I are part of place names and event titles. World Cup races have been hosted in Madonna di Campiglio since 1967 (3Tre).

Funivie Madonna di Campiglio S.p.A. (Funivie MdC) is the company that manages the ski resort, which counts 60 km of ski slopes situated in a range of elevation between 1513 and 2501 m.a.s.l. During the winter season the average operating days are 156, from the start in mid-November until the end in mid-April. Concerning the skier-days, these are on average 1.2 M in the overall winter season, supporting a turnover of 25 M€. Overall, 19 ski lifts are operative, supporting a transport capacity of roughly 39,000 passengers/hour and counting about 10 M entrances per winter season. A modern snow production system guarantees about 1.1 Mm^3 of snow per winter season, using 629 snow lances and 117 snow guns, with a water demand of about 500,000 m^3. Its operation is supported by some water storage basins, with an overall volume of 240,000 m^3. The main water basin is called "Lake Montagnoli", which is an artificial lake realized in 2014 with a volume of 200,000 m^3. Finally, 20 diesel-fueled snow groomers work for a daily regular preparation of the slopes while multiple buildings support the technical and managerial operations.

In Supplementary Materials A and Supplementary Materials B the temporal evolution of the energy and environmental performance in the ski resort of Madonna di Campiglio is characterized; annual data for the last available decade 2010/2011 - 2019/2020 were collected from the ski operator Funivie MdC, focusing on the winter season. From the collected data it is of interest to report the ranges of variability: skier-days (850,000–1,250,000), entrances (7,500,000–11,200,000), snow production (400,000–1,800,000 m^3), snow grooming (9,500–16,000 hours), total electricity consumption (6.8–13.2 GWh), electricity consumption for snow production (1.8–5.9 GWh), electricity consumption for ski

Fig. 1. Location of the Skiarea Campiglio Dolomiti di Brenta.

lifting (3.2–3.7 GWh), electricity consumption for other e.g. operational buildings (1.0–3.6 GWh), oil consumption for snow grooming (250,000–500,000 liters), oil consumption for space heating (0–1.0 GWh), biomass consumption for space heating (0–1.0 GWh), total energy consumption (11.9–19.2 GWh), RES share (22–31 %), CO_2 emissions (3300–5400 tCO_2).

The following paragraphs provide more details on the local characteristics of the four main sectors into which a ski resort can be divided: ski lifting, snow production, snow grooming and buildings.

2.1. Ski lifting

The main features of the 19 ski lifts active in Madonna di Campiglio are shown in Table 1. The producer is the Austrian company Doppelmayr, with only one exception (Miramonti by Nascivera). The ski lifts' typologies enclose 7 high speed chairlifts, 6 gondola lifts, 5 chairlifts and 1 J-bar, with a capacity in the range 1-12 passengers per vehicle and a construction year from 1981 to 2020. The drop varies from 78 to 810 m (total 6519 m) whilst the lengths are in the range 394-3320 m (total 27283 m). A transport capacity from 720 to 3600 passengers/hour is guaranteed, supporting overall 38883 passengers/hour, while the speed range is from 2.2 to 6 m/s. To conclude, concerning the engines, there are 9 ski lifts at 2 CC, 6 ski lifts at 1 AC and 4 ski lifts at 1CC, representing a power range from 20.8 to 1472 kW (total 9137 kW).

2.2. Snow production

Snow production represents a crucial asset in modern ski resorts. Since the late 1980s, in Madonna di Campiglio has been realized and continuously updated a complex snow production system composed by multiple interlinked components: water withdrawal points, water basins, maneuvering stations with pumps and compressors, an extended water and air distribution network, appropriate power supply, a modern data network, several snow lances and snow guns and distributed weather stations, all supervised by the software TechnoAlpin Liberty.

Fig. 2 shows the tailor-made snow making system diagram. It represents a hydraulic scheme in which withdrawal points are indicated in green, the main collector in red, distribution networks in blue and links with the snow generation plants (snow lances and snow guns) in light blue. Key components of the hydraulic scheme in Madonna di Campiglio are: (I) two withdrawal points, the Lake Campiglio and the Nambino River, (II) 5 water basins and (III) 11 maneuvering stations. The 5 water basins are placed in the altitude range 1495 - 2078 m.a.s.l. and

Table 1

Characteristics of the ski lifts in the ski resort Madonna di Campiglio. D = Detachable; F = Fixed; CC = Constant Current; AC = Alternating Current.

Ski lifts	Manufacturer	Type	Vehicle capacity (pass.)	Start (year)	Drop (m)	Length (m)	Transport capacity (pass./hour)	Speed (m/s)	Type of engine	Running power (kW)
5 Laghi	Doppelmayr	Gondola (D)	8	2007	539	2007	2360	6	2 CC	593
Boch	Doppelmayr	High speed chairlift (D)	4	2011	113	665	2400	5	1 AC asynchronous	190
Fevri (spinale 2)	Doppelmayr	Chairlift (F)	3	1988	368	1057	1500	2.2	1 CC	260
Fortini	Doppelmayr	Gondola (D)	10	2020	456	2432	3600	6	1 AC synchronous	714
Genziana	Doppelmayr	High speed chairlift (D)	4	2003	380	1600	2070	5	2 CC	394
Grostè 6posti	Doppelmayr	High speed chairlift (D)	6	2004	260	1379	2800	5	2 CC	387
Grostè I tronco	Doppelmayr	Gondola (D)	6	1987	434	3320	2240	5	2 CC	1472
Grostè II tronco	Doppelmayr	Gondola (D)	6	1987	359	2279	2240	5	2 CC	1472
Larici	Doppelmayr	J-bar (F)	1	2008	78	394	720	2.8	1 AC asynchronous	20.8
Miramonti	Nascivera	Chairlift (F)	2	1981	183	466	1125	2.5	1 CC fixed excitation	110
Nube d'Argento	Doppelmayr	Chairlift (F)	2	1984	150	875	1200	2.5	1 CC	100
Nube d'Oro	Doppelmayr	High speed chairlift (D)	6	2019	303	1174	2800	4.5	1 AC synchronous	429
Pancugolo	Doppelmayr	Chairlift (F)	4	2012	212	447	1600	2.5	1 AC asynchronous	131
Patascoss	Doppelmayr	High speed chairlift (D)	4	1996	810	1772	1800	5	2 CC	517
Pradalago	Doppelmayr	Gondola (D)	12	1995	562	1843	3000	5	2 CC	835
Rododendro	Doppelmayr	High speed chairlift (D)	4	1998	379	2307	1600	5	2 CC	421
Spinale	Doppelmayr	Gondola (D)	12	1992	588	1606	3000	5	2 CC	795
Vagliana	Doppelmayr	Chairlift (F)	2	1981	185	786	1028	2.5	1 CC fixed excitation	100
Zeledria	Doppelmayr	High speed chairlift (D)	4	2005	160	874	1800	4.5	1 AC asynchronous	196

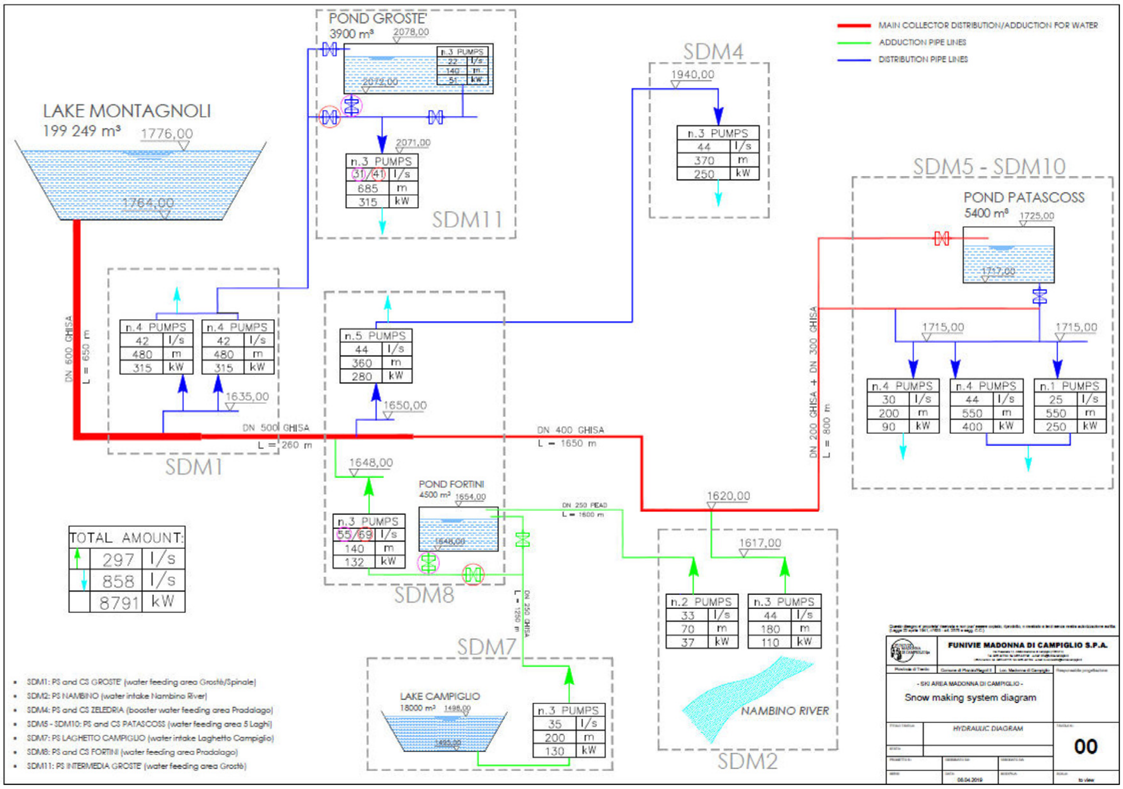


Fig. 2. Snow making system diagram in the ski resort Madonna di Campiglio.

Fig. 3. Lake Montagnoli in Madonna di Campiglio.

guarantee an overall water storage capacity of about 240,000 m^3, of which 200,000 m^3 in the Lake Montagnoli.

Lake Montagnoli (Fig. 3) is the main artificial water basin in Madonna di Campiglio. Requiring an investment of 10 M€, it is operational since 2015 (in this year it was the largest reservoir in the Italian ski resorts). It is placed at an elevation of 1775 m.a.s.l., the depth is 11.7 m and it has an elongated shape along the direction northeast-southwest. The supply/withdrawal is from one point placed at the bottom of the north bank. The water basin includes a boulage for water mixing. The supply is performed by pumping water from three sources: the Nambino River (1647 m.a.s.l.), the Pond Fortini (1654 m.a.s.l.) and the Lake Campiglio (1498 m.a.s.l.). The water supply system is capable to provide a flow rate of 297 l/s while the water delivering to the slopes can reach 858 l/s. Overall, this allows to snow the full ski area in 80-100 hours.

Fig. 4 shows the temporal evolution of the snow production systems, which features both snow lances and snow guns. The first 10 snow lances were installed in 1987 while the first snow guns later in 2007. From the

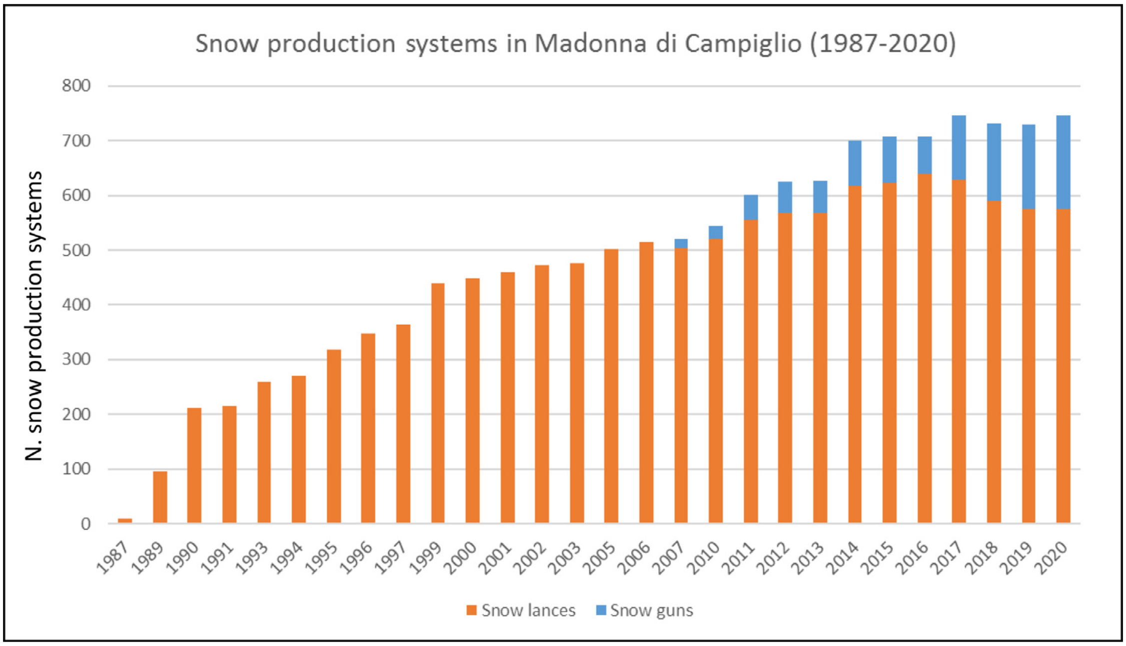


Fig. 4. Snow production systems trend (1987-2020) in the ski resort Madonna di Campiglio.

year 2007 snow lances have been yearly both added and removed whiles than from 2017 have been recorded only snow guns additions and snow lances removals. It is significant to note the large investment in expanding the snow production systems, from the initials 10 snow lances in 1987 to the currents 576 snow lances plus 170 snow guns in 2020. Reasons behind this large investment are both the climate change, with temperature increase and reduction of snowfall, and the desire of customers to have slopes ready early in the winter season (November) and continuously available until the beginning of the spring season (April).

2.3. Snow grooming

Currently, 20 snow groomers are operational in Madonna di Campiglio, of which 14 branded by the German company Kässbohrer and 6 by the South Tyrolean Prinoth. Several digital innovations characterize these snow groomers. Firstly, all integrate a software that saves data about diesel consumption, km traveled and operating hours. Moreover, recently some of these vehicles have adopted snow thickness acquisition systems by SNOWsat and Leica. The 20 active models have been purchased from 2005 to 2019. The data sheets show that the expected diesel consumption is in the range 19-22 l/h.

2.4. Buildings

Funivie MdC operates multiple buildings in the ski resort, including technical and management offices, ticket offices, garages, ski lifts stations, maneuvering stations, water tanks, electrical cabins, ski depots, warehouses and workshops. In the Smart Altitude project these buildings have been categorized as operational buildings while apartments, shelters and one hotel, also owned by Funivie MdC, have been categorized as non-operational.

A complete list of buildings, operational and non-operational, was provided by Funivie MdC, including information such as surface, volume, estimated number of lighting-hours along the winter season (from November to April) and typology of space heating. The so called “operational buildings” occupy a total area of 47,400 m^2, the total volume is 189,000 m^3 while the estimated winter-season lighting-hours are 7700. Concerning the “non-operational buildings”, the total area is 6100 m^2, the total volume is 18,000 m^3, the lighting-hours along the winter-season are not estimated. Three technologies satisfy the overall space heating demand in these buildings: pellet boilers, oil boilers and electric convectors. However, some buildings are not heated.

3. Methods

In this chapter the development of a new “Integrated Energy Management System” in the Smart Altitude Living Lab of Madonna di Campiglio is defined as an integration of existing monitoring systems with new ones and new platforms. It is worth pointing out that the new IEMS considers and quantifies the cleaner aspect of the energy system: CO_2 emissions and environmental impacts related to the water use for snow production.

The method suggested by this paper is based on the concept that only a holistic and integrated view of monitoring data can support an effective and complete analysis of energy and environmental sustainability by a ski manager. The procedure is based on the analysis of the existing monitoring asset, on the identification of the monitoring gaps and on the merging of monitoring data in an organized and hierarchical way.

3.1. Existing monitoring systems

Funivie MdC can leverage on an existing well-structured monitoring asset. Indeed, several monitoring systems, already installed and operational before the start of the Smart Altitude project, include:

- SKIDATA: “ski lifts’ entrances and skier days”.
- EnergyTeam: “electricity consumption at the points of connection with the medium voltage network”.
- TechnoAlpin Liberty: “snowmaking system including data of: (I) slopes: water consumption, estimate of snow production; (II) machine rooms: estimate of total electricity consumption, air performance (flow rate, pressure, temperature, estimate of electricity consumption of compressors, hours of operation of compressors), water performance (flow rate, pressure, temperature, tank level)”.
- AMA: “fuel supplied to the overall vehicles (snow groomers and other types of vehicles)”.
- Prinoth and Kässbohrer: “snow groomers operational data (fuel consumption, km, operating hours)”.
- SNOWsat and Leica: “snow thickness measured by snow groomers”.
- Weather: “snow thickness, fallen snow, temperature”.

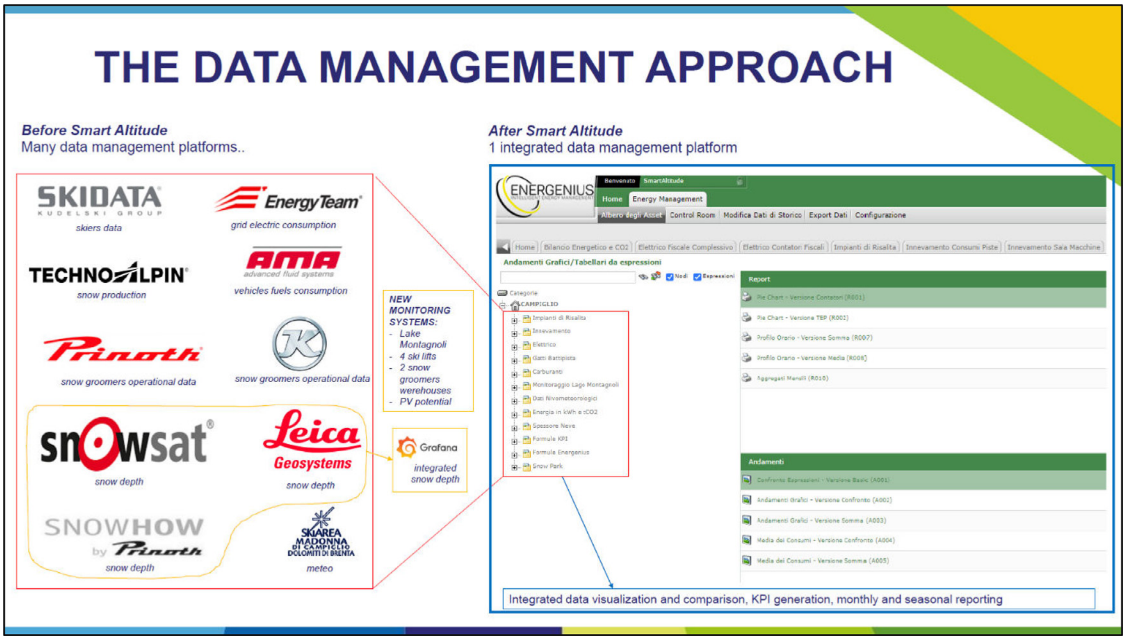


Fig. 5. The innovative IEMS approach of Smart Altitude developed and tested in the Living Lab Madonna di Campiglio.

Besides the automated monitoring systems, manual monitoring is also directly performed by the staff of Funivie MdC. For example, overnight an employee visits the slopes to verify that there are no issues, such as an air flow directed on the snow gun. Furthermore, regularly an employee manually measures the snow thickness in selected points of the slopes. Finally, a structured system records energy bills of electricity, diesel and biomass consumptions.

3.2. The Smart Altitude “Integrated Energy Management System”

In the Living Lab Madonna di Campiglio three main improvements have been implemented by the Smart Altitude project:

- integration of 4 new monitoring systems on: Lake Montagnoli (weather data, water levels and water temperatures), four ski lifts (electrical consumption), two snow groomers’ warehouses (electricity consumption) and new Telecabina Fortini (solar irradiance and weather temperature);
- development of a new platform (Grafana) for the integrated management of snow thickness data;
- development of a new platform (ZEnergy) for the integrated management of (I) all the existing monitoring systems, (II) the new ones and (III) the new Grafana platform, including consideration and quantification of the cleaner aspect of the energy system (CO_2 emissions and environmental impacts related to the water use for snow production), this is the core of the new “Integrated Energy Management System - IEMS”.

Fig. 5 shows the innovative approach developed and tested in the Smart Altitude project to reconfigure the management of data in the ski resort Madonna di Campiglio. The main objective of the new IEMS is to unify all data in a single platform and in this way provide support to the ski managers in defining sustainable actions. Together with the technicians and managers of Funivie MdC, the main characteristics of the IEMS have been defined: data folders organization by type of data and by geographical location within the ski resort, possibility to self-generate graphs but also to have pre-set ones, possibility to export graphs in Excel and as images, automatic generation of KPIs, sending monthly reports by e-mail.

4. Results

This paragraph describes the innovative results brought by the Smart Altitude project in the Living Lab Madonna di Campiglio, dividing them by type of new monitoring system and new platform.

4.1. The new monitoring system of Lake Montagnoli

To manage snow production (and water consumption) optimally, advanced technology and also in-depth knowledge of the environmental conditions (altitude, slope exposure, local weather, water characteristics) are required. The “sine qua non” condition is a low environmental temperature. However, at the start of the winter season, this climatic condition occurs for a very restricted time-frame, this means the necessity of maximize the production of snow in a short period. The solution is represented by water basins ensuring significant water flows. If the temperature of water is not optimal, dedicated cooling systems are adopted, with the related energy demand. Basin temperatures are controlled by climatic parameters (temperature, wind, irradiation), the water supply and withdrawal, the plano-altimetric location of the supply/withdrawal points and the boulage operation.

As already described in paragraph 2.2, Lake Montagnoli is the main water basin in Madonna di Campiglio and it is operated in this way:

- filling in August-September after the summer emptying for maintenance;
- first operational use when the external air temperatures allow the snow production (October-November);
- subsequent filling and emptying throughout the winter season considering the needs for snowmaking.

The Smart Altitude monitoring was designed to study the lake thermal trend over time. The monitoring system is composed by two buoys collecting weather data, water levels and water temperatures from the lake bottom to the lake surface (Fig. 6).

The first data acquisition campaign started on 26/9/2019 and ended on 26/11/2019 (autumn season until the first snow production), collecting data provided by the new lake monitoring system (2 buoys). The data acquisition frequency was 10 minutes. The south buoy was equipped with an air thermometric sensor while the north bouy with a

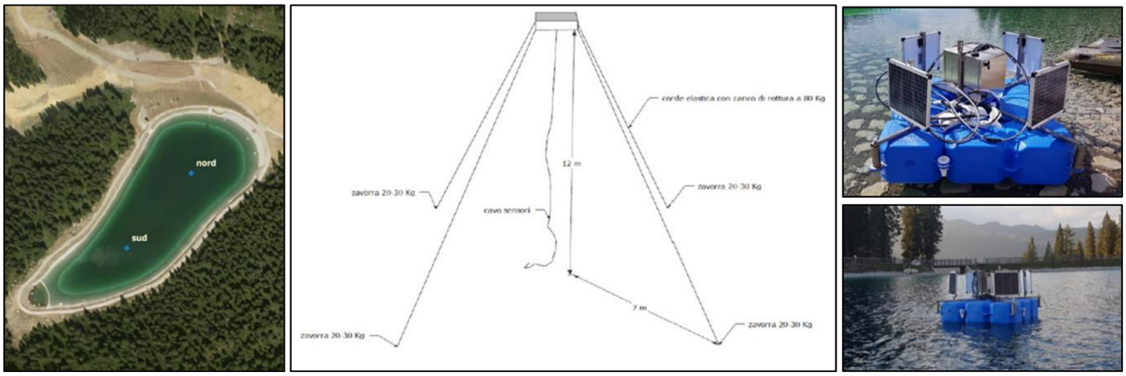


Fig. 6. The Smart Altitude Lake Montagnoli monitoring system.

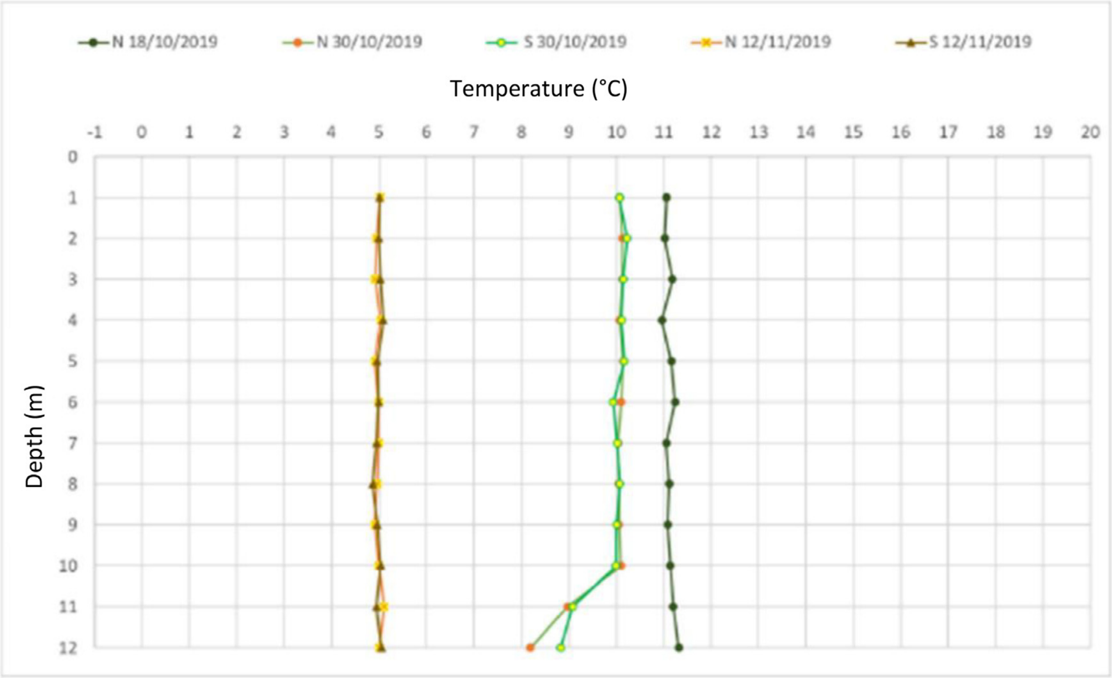


Fig. 7. Lake Montagnoli - first monitoring campaign – vertical thermal profiles. N = North buoy; S = South buoy.

water level sensor (see Supplementary Materials C). The average daily data indicate the control of the lake temperature by the external air temperature. The lake shows no stratification because the operation of the boulage induces the continuous water mixing. An exception is late October when the boulage was stopped for few days during a test that induced stratification related to the introduction of colder water at -11 and -12 m. Fig. 7 shows the water temperature trend in function of water depth. It is clear the natural cooling of the lake starting from 11°C in mid-October until 5°C in mid-November. The mid-October water temperatures are not suitable for the production of snow while instead in mid-November these are good. Moreover, in the vertical profile of 30/10/2019 the supply of cold water into the lake bottom is clearly visible.

The second data acquisition campaign was planned in a following period from September 2020 to February 2021, considering these goals:

- integrate new data at the beginning of the autumn season as they have indicated a clear influence on the behavior of the basin;
- extend the monitoring period also to the months of December and January in order to study the behavior of the lake in the heart of the winter season;
- analyze the phenomena induced on the water thermals right before and after the activation of the boulage.

The second data acquisition campaign planned the reinstallation only of the north buoy, in the deepest area of the lake. The results are shown in Supplementary Materials C and represent the air temperature and the water temperatures at different depths. September 2020 stands for the “initial conditions”. The water thermals show a substantial non-stratification, with temperatures of about 17°C, though the surface is affected by a day/night temperature range. This “hot-phase” ends on day 25th when an air temperature cooling of 6-7°C induces a reduction in water temperatures of 3-4°C. October 2020 stands for the “first use of water”. The non-stratified trend goes on until October 12th when the Lake Montagnoli is subject to three supplying phases. The water cooling in the deepest layers where the introduced water (at 4.4°C) is placed is remarkable. The boulage is operational from October 23th and therefore do not impact the filling phases of mid-October. However, the three filling phases show the aptitude for spontaneous water mixing. November 2020 stands for the “overall thermal drop”. The withdrawal of water in the second half of the month and the lowering of the air temperatures, from average daily values of 7.2°C to 1.5°C, induce a lowering in the overall basin temperature which keeps thermically mixed and moves

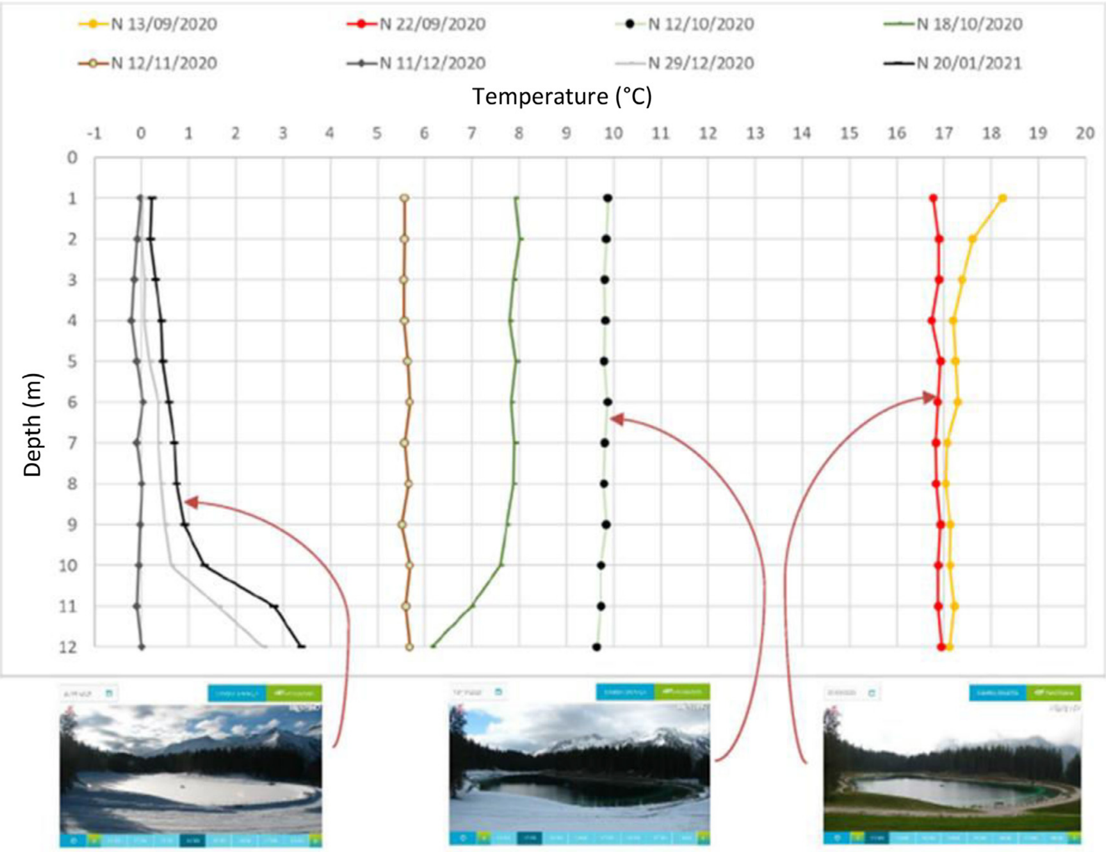


Fig. 8. Lake Montagnoli - first monitoring campaign – vertical thermal profiles. N = North buoy.

from average values of 6.6°C to 1.4°C. The boulage is operational from November 7th. Finally, December 2020 and January 2021 stand for the “confining of the water”. At the beginnig of December the lowering of air temperatures below zero induces the formation of surface ice. This fact substantially split the water and the weather trends. As reported by the staff of Funivie MdC: “the buoy, incorporated into the ice and covered by snow, monitors false air temperature (erroneously shows values above zero)". On December 14th, a process of stratification starts determing the movements of the less cold waters towards the basin bottom, indeed those are closer to the peak of density (about 4°C). Fig. 8 shows the trend of the water temperature vertical profiles during the second monitoring campaign

Overall, the analysis of the two measurement campaigns suggests the following good practices in the management of the Lake Montagnoli, aimed at reducing energy-demanding cooling activities:

- first filling of the lake as late as possible;
- once filled, the autumn suppling, consisting of colder waters, need to be introduced at the bottom of the reservoir and should be the first to be exploited, avoiding the boulage activation;
- during the winter season the lowering of the air temperature gradually cools the superficial water and the boulage should be turned on in a long cold period.

4.2. *The new monitoring systems of four ski lifts*

Ski lifting is another energy-intensive sector within a ski resort. For this reason, during the Smart Altitude project was decided to install new monitoring systems in four ski lifts (Fig. 9): two existing facilities (Seggiovia Grostè and Telecabina 5 Laghi) and two new facilities (Seggiovia Nube d’Oro and Telecabina Fortini). The parameter monitored is the electrical consumption of the ski lift engines, considering as main objective the comparison of different models / technologies (i.e. chairlift / gondola and Uni-G / D-Line), normalizing collected data with entrances (from SKIDATA) and drop performed. In Supplementary Materials D the graphs relating to the Telecabina 5 Laghi - Engine 1.

First of all, the following operating conditions are reported:

- Telecabina 5 Laghi (gondola, Uni-G): both engines have been monitored and show the same behavior; monitoring started on 15/01/2020.
- Seggiovia Grostè (chairlift, Uni-G): both engines have been monitored and show the same behavior; monitoring started on 16/01/2020.
- Seggiovia Nube d’Oro (chairlift, D-Line): the only existing engine has been monitored; monitoring started on 17/01/2020.
- Telecabina Fortini (gondola, D-Line): the only existing engine has been monitored; monitoring started on 18/11/2020.

Considering winter operations, a focus is dedicated to the period 1/2/2020-14/2/2020 for Telecabina 5 Laghi, Seggiovia Grostè and Seggiovia Nube d’Oro and to the period 18/11/2020-29/11/2020 for Telecabina Fortini. Unfortunately, the COVID-19 hasn’t made it possible to analyze the real operation of Telecabina Fortini, the only data available are related to few tests without entrances.

A comparison among the monitored ski lifts is proposed in Fig. 10 which considers energy consumption and entrances. As expected, energy consumption increases with increasing entrances. However, this relationship is non-linear, for low loads the efficiency of the engines is lower. Moreover, Fig. 11 compares the KPI energy consumption/entrances and the load factor, the latter calculated as the ratio between entrances and maximum transport capacity. This graph shows that the most energy-intensive ski lift is the one of Telecabina 5 Laghi, followed by the Seggiovia Nube d’Oro and the Seggiovia Grostè, this latter resulting the most efficient ski lift.

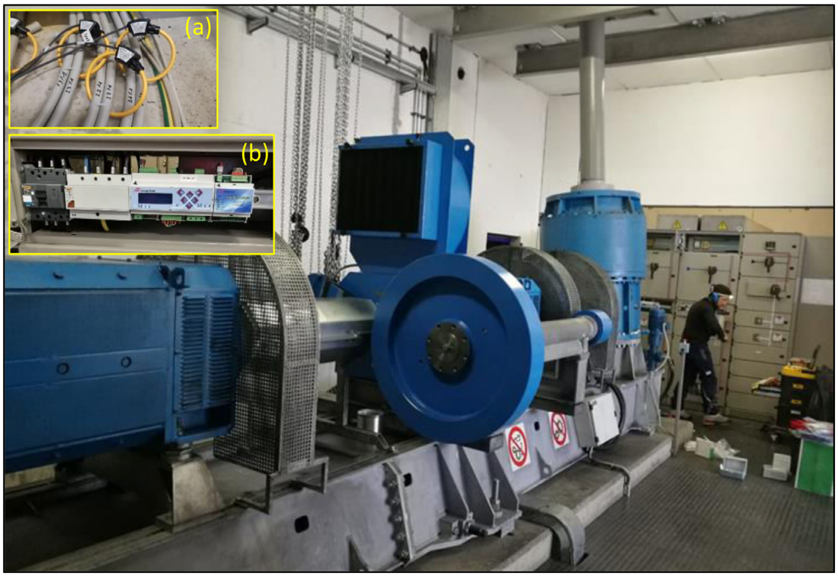


Fig. 9. Madonna di Campiglio - installation of a new monitoring system in a ski lift. (a) Rogowski Amperometric Probes. (b) Electrical network analyzer and datalogger.

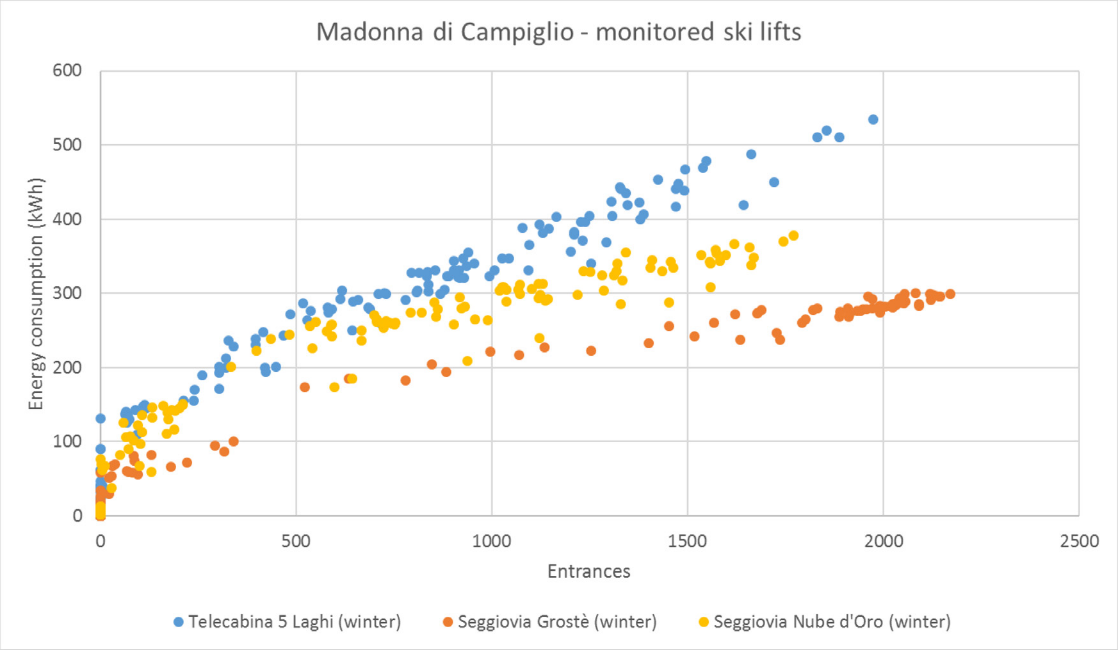


Fig. 10. Madonna di Campiglio - monitored ski lifts: energy consumption vs entrances.

Table 2 confirms and quantifies these considerations, indicating the average values of the KPIs during the periods analyzed. By observing the characteristics of the ski lifts considered, we can explain the results as follows:

- Seggiovia Grostè is the most efficient ski lift due to a high average load factor, a low slope (19%, compared to the 26% of Seggiovia Nube d'Oro and to the 27% of Telecabina 5 Laghi) and a lightness in the chairlift type with respect to the gondola type.
- Comparing Seggiovia Grostè and Seggiovia Nube d'Oro, the Uni-G model appears to be more efficient than the D-Line model, but the confrontation is between two ski lifts characterized by different average slopes; certainly the 19% slope is easier for the Seggiovia Grostè

Table 2
Madonna di Campiglio - monitored ski lifts: average KPIs in the periods analyzed. EelSL = electric consumption ski lift; TD = total distance performed by the ski lift; NE = number of entrances.

	Seggiovia Grostè (winter)	Seggiovia Nube d'Oro (winter)	Telecabina 5 Laghi (winter)
Load factor (%)	32	26	33
EelSL/TD (kWh/km)	43	54	51
EelSL/NE (kWh/E)	0.160	0.308	0.376
EelSL/(TD*NE) (kWh/(1000km*1000E)	375	585	515

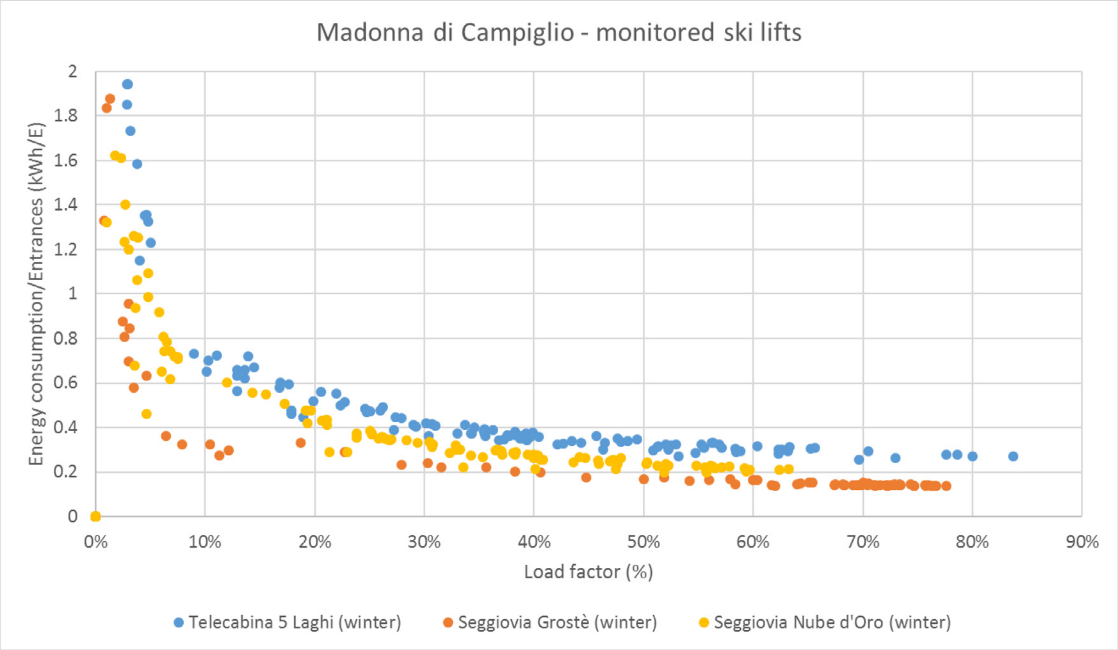


Fig. 11. Madonna di Campiglio - monitored ski lifts: energy consumption/entrances vs load factor.

than the 26% slope for the Seggiovia Nube d'Oro, this is also evident in the power of the two engines i.e. 387 kW against 429 kW.

- Seggiovia Nube d'Oro is characterized by heated seats, which for sure reduce energy efficiency.
- Seggiovia Nube d'Oro and Telecabina Fortini show a constant demand of electricity also in non-operating hours, the reason has been hypothesized in heaters for the anemometers that remain in operation.

4.3. The new monitoring systems for two snow groomers' warehouses

In a ski resort, snow groomers are responsible for energy consumption not only in the demand for traction but also in the demand for heating dedicated warehouses. These warehouses are heated to maintain snow groomers warm during the winter period, thus guaranteeing better protection from the risks of cold / frost and a longer life time, as well as a rapid melting of the snow on the vehicles that facilitate maintenance. In the Living Lab Madonna di Campiglio two snow groomers' warehouses, Intermedia Grostè and Patascoss (see Table 3 and Fig. 12), were monitored. Both are heated with electric convectors (ECs): in the case of the Patascoss it is satisfied a temperature target of 20°C for 24h/day, the same goal is also in the Intermedia Grostè but the system has insufficient power.

The new monitoring systems, based on Rogowski Amperometric Probes, allow to measure the electricity consumption of the ECs and to evaluate alternative, more efficient solutions (i.e. ground source heat pumps – GSHPs as suggested in some studies both on a provincial (Viesi, et al., 2018) and local scale (Viesi, et al., 2022)). The monitoring period starts from 14 February 2021 and ends on 13 June 2021, thus

Fig. 12. Madonna di Campiglio - the snow groomers' warehouse called Patascoss. In the yellow box an electric convector.

Table 3
Characteristics of the two snow groomers' warehouses equipped with the new Smart Altitude monitoring systems.

	Patascoss	Intermedia Grostè
Size (m)	16 × 20 × 4.5	900 × 4.2
Surface (m^2)	320	900
Volume (m^3)	1440	3780
Number of snow groomers	3	6
Type of heating system	electric convectors	electric convectors
Power (kW)	4 × 11	3 × 6 + 4 × 11
Temperature regulation	24h/day at 20°C	24h/day at full power but the system doesn't reach the target temperature (20°C)
Door opening	rare	frequent
Use	garage	workshop and garage
Heat recovery	no	Yes, from the engine room

Table 4
Madonna di Campiglio - monitored snow groomers' warehouses: KPIs in the periods analyzed. EC = electric convector. GSHP = ground source heat pump.

	Patascoss	Intermedia Grosté
February (14/2-28/2) EC el. consumed (kWh)	5947	11847
February (14/2-28/2) EC el. consumed (kWh/m^2)	18.6	13.2
February (14/2-28/2) EC el. consumed (kWh/m^3)	4.1	3.1
March EC el. consumed (kWh)	7975	20490
March EC el. consumed (kWh/m^2)	24.9	22.8
March EC el. consumed (kWh/m^3)	5.5	5.4
April EC el. consumed (kWh)	7805	18489
April EC el. consumed (kWh/m^2)	24.4	20.5
April EC el. consumed (kWh/m^3)	5.4	4.9
May EC el. consumed (kWh)	5227	16715
May EC el. consumed (kWh/m^2)	16.3	18.6
May EC el. consumed (kWh/m^3)	3.6	4.4
June (1/6-13/6) EC el. consumed (kWh)	700	5636
June (1/6-13/6) EC el. consumed (kWh/m^2)	2.2	6.3
June (1/6-13/6) EC el. consumed (kWh/m^3)	0.5	1.5
February 14/2 - June 13/6 EC el. consumed (kWh)	27654	73177
February 14/2 - June 13/6 EC el. consumed (kWh/m^2)	86.4	81.3
February 14/2 - June 13/6 EC el. consumed (kWh/m^3)	19.2	19.4
February 14/2 - June 13/6 EC CO_2 emitted (tCO_2)	8.5	22.5
February 14/2 - June 13/6 EC el. cost (euro)	4701	12440
February 14/2 - June 13/6 EC th. demand (kWh)	26272	69518
February 14/2 - June 13/6 GSHP el. demand (kWh)	6568	17379
February 14/2 - June 13/6 GSHP CO_2 emitted (tCO_2)	2.0	5.3
February 14/2 - June 13/6 GSHP el. cost (euro)	1117	2955

involving the last part of winter, the full spring and the start of the summer.

The energy, environmental and economic performances of the two warehouses are compared in Table 4. By normalizing energy consumption with respect to surface (kWh/m^2) and volume (kWh/m^3), the recorded performances are similar, 86.4 vs 81.3 kWh/m^2 in the first case and 19.2 vs 19.4 kWh/m^3 in the second case. However, a better normalization would require data on indoor temperatures as well. This last parameter has not been monitored but from the information provided by Funivie MdC, as already described above, it is clear that the Intermedia Grostè would be more energy-intensive if reaching the 20°C indoor temperature. In both cases, by converting the heating system from EC to GSHP, assuming a COP = 4 for the latter (Viesi et al., 2018), 76% reductions in electricity consumption, CO_2 emissions and operating costs would be achieved.

4.4. The new monitoring system for the PV potential of the new Telecabina Fortini

Alongside energy efficiency, renewable energy production is a second key challenge for the decarbonisation of ski resorts. In the previous paragraph the potential offered by geothermal energy for space heating has been explored. Another interesting resource is the solar energy, that through photovoltaic (PV) systems can generate renewable electricity.

It is with this motivation that the Smart Altitude project has introduced a monitoring system for the assessment of the PV potential at the top station of the new Telecabina Fortini (Fig. 13). Interesting is the location of the experiment, at high altitude (2100 m.a.s.l.), therefore with solar irradiance and temperature parameters different from conventional ones.

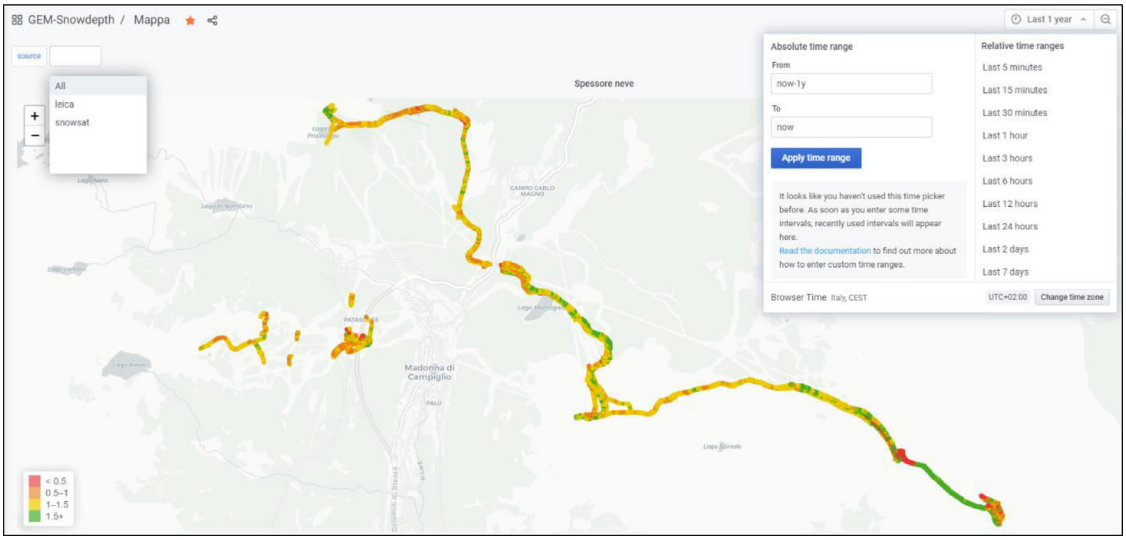
Supplementary Materials E shows the data coming from the measurement campaign, which began on 28/01/2021 for solar irradiance and on 13/02/2021 for weather temperature. First of all, for the potential of the PV integration is beneficial the excellent fitting with the daily operation of the ski lifts (8.00-17.00). Moreover, seasonally, PV production is maximum during summer, this would recommend optimal coupling with ski lifts active also in the summer season.

Table 5 compares, in the same location, the data of the Smart Altitude monitoring with those of the PVGIS TMY (PVGIS, 2022). From this comparison, we can note that in the period February-May 2021 monitored solar irradiance values are 12% higher than those expected by PVGIS. These data confirm multiple studies in which high irradiation

Table 5
Telecabina Fortini - Comparison of solar irradiance and temperature between the Smart Altitude monitoring system and the PVGIS TMY.

		February	March	April	May	Feb-May
Smart Altitude sol. irradiance (W/m2)	Min	1	1	1	0	0
	Max	673	925	1014	1189	1189
	Montlhy average	115	190	207	226	186
	Montlhy sum	77394	141377	148949	167859	535579
PVGIS TMY sol. irradiance (W/m2)	Min	0	0	0	0	0
	Max	649	767	911	1004	1004
	Montlhy average	116	139	180	223	165
	Montlhy sum	77927	102971	129311	166052	476262
Smart Altitude Temp. (°C)	Min	-3.8	-3.6	-3.3	0.4	-3.8
	Max	7.8	8.6	8.6	8.3	8.6
	Montlhy average	2.2	1.6	2.1	3.8	2.5
PVGIS TMY Temp. (°C)	Min	-9.7	-8.9	-5.9	-3.8	-9.7
	Max	5.7	7.8	7.8	12.7	12.7
	Montlhy average	-3.6	-2.3	1.7	4.1	0.1

Fig. 13. Telecabina Fortini - left: under construction in autumn 2020; right: the PV potential monitoring system.



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Read the documentation to find out more about how to enter custom time ranges.

Fig. 14. Grafana: the new Smart Altitude platform for the integration and visualization of snow thickness data.

values in the mountain environment were detected (see for example the Punta Helbronner - Monte Bianco (QUALENERGIA, 2022) and the country of Switzerland (Kahl, et al., 2019) case studies). Indeed, as the altitude increases the filtering action of the atmosphere is reduced, the snow reflection is significant and also low temperatures are beneficial for the operation of PV cells.

4.5. *The Grafana platform*

The Grafana platform was created by the Smart Altitude project to integrate all the snow thickness data measured by the snow groomers and to view them in a single platform. Thus, merging the data from Leica and SNOWsat improved data visualization and historical data analysis to support the operation of the snowmaker. Knowledge of snow thickness data is essential to optimize snow production (and water consumption), in order to achieve a uniform target thickness on all slopes, avoiding on the one hand areas with excess of snow and on the other areas with scarcity of snow. The operation of snow groomers is also guided by these data, moving the snow from thicker areas to thinner ones.

In the Grafana platform (Fig. 14), snow thickness data are represented by cells of 3 m × 3 m. The colors of the cells indicate snow thickness according to a dedicated legend at the bottom left. At the top left of the platform, a first menu allows to filter the type of data source (Leica, SNOWsat, All) and the “+” and “-” buttons allows zooming. At the top right, there is a second menu to select the time period and with respect to this period the displayed data are the last recorded. Finally, selecting a cell of the map opens a dedicated page showing the historical evolution of the snow thickness in that specific cell.

4.6. *The ZEnergy platform*

The key result of the Smart Altitude project at the Living Lab Madonna di Campiglio is represented by the ZEnergy platform: the new “Integrated Energy Management System - IEMS” (Fig. 15). This IEMS includes consideration and quantification of the cleaner aspect of the energy system (CO_2 emissions and environmental impacts related to the water use for snow production).

A “Home” screen contains the main KPIs, these are shown in Table 6.

In the main menu, under “Energy Management”, there is the “Asset Tree” which contains the data divided into folders. Therefore, data of all monitoring systems, both pre-existing and newly introduced ones, are collected and cataloged here:

- Weather: “snowfall and air temperature in some locations of the ski area”;
- PV potential: “at the top station of the new Telecabina Fortini”;
- Snow thickness: “on all the slopes of the ski area”;
- Skier data: “data on the skier days”;

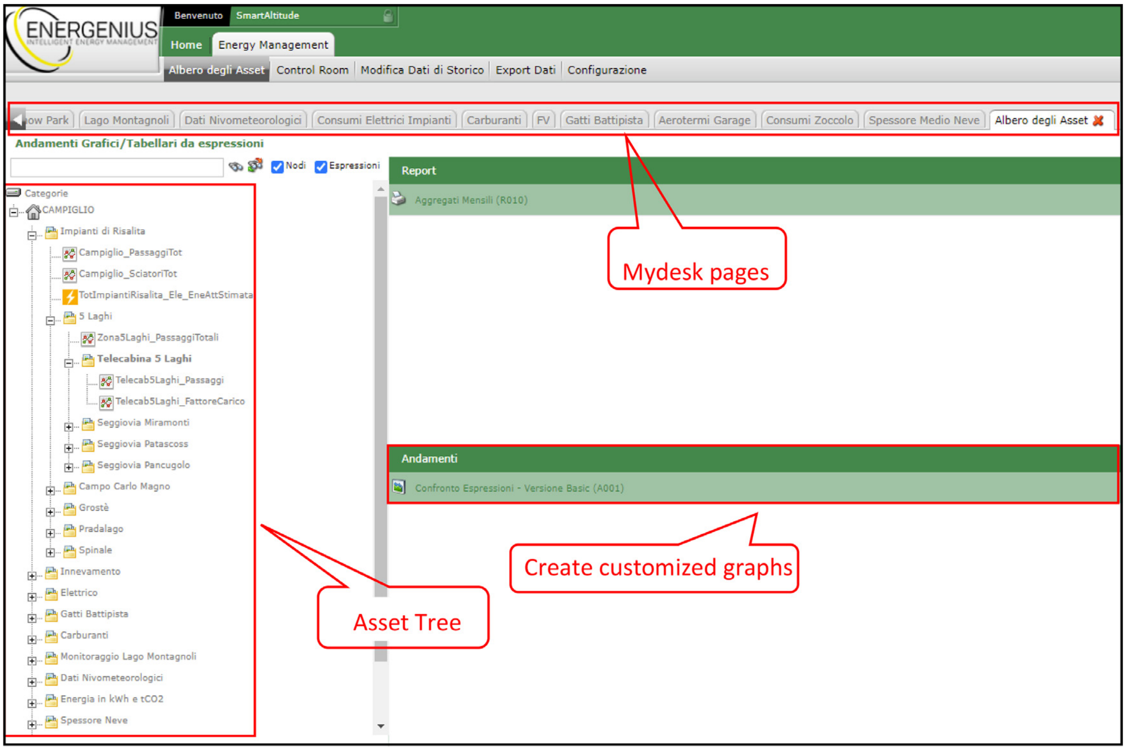

Fig. 15. Smart Altitude IEMS: Energy Management - Asset Tree - data management in the ski lifts folder.

Table 6
Smart Altitude IEMS: Home - KPIs.

Total electric consumption per skier-day	kWh/SD
Ski lifts electric consumption per skier-day	kWh/SD
Snow production electric consumption per skier-day	kWh/SD
Snow production electric consumption per m^3 of produced snow	kWh/m^3
Vehicles fuels consumption per skier-day	kWh/SD
Total energy consumption per skier-day	kWh/SD
CO_2 emission per skier-day	$kgCO_2/SD$
Water consumption per skier-day	m^3/SD
Number of skier-days	SD
Average temperature Lake Montagnoli	°C
Average outdoor temperature (at 2100 m.a.s.l.)	°C
Snow fall (at 2250 m.a.s.l.)	cm

- Ski lifts: “data on electricity consumption and number of entrances”;
- Snow production: “data on water, compressed air and electricity consumption”;
- Snow grooming: “operational data (km, hours) and diesel consumption”;
- Operational buildings: “electricity consumption for heating the Intermedia Grostè and the Patascoss snow groomers’ warehouses”;
- Electric grid: “data on electricity consumption at the withdrawal points of the medium voltage network”;
- Lake Montagnoli: “data on water temperatures at different depths, water surface level and weather conditions”.

Moreover, the Asset Tree allows to manage multiple ski resorts at the same time and each ski resort can be divided into geographical subareas. For example, in Madonna di Campiglio five areas have been distinguished: 5 Laghi, Campo Carlo Magno, Grostè, Pradalago, Spinale. Facilities are divided according to their location, in this way the area 5 Laghi includes the following ski lifts: Telecabina 5 Laghi, Seggiovia Miramonti, Seggiovia Patascoss and Seggiovia Pancugolo (see Fig. 15).

By selecting the item “Expression Comparison - Basic Version (A001)”, in the right part of the Asset Tree screen, it is possible to create customized graphs. It is in fact possible to select the variables to be graphed / compared, choosing various types of graphs (line or bar histogram) and various temporal resolutions (15 minutes, hourly, monthly, daily, etc.). Charts can be zoomed in, exported to Excel and saved as an image (see examples in Supplementary Materials D and Supplementary Materials E). As an alternative, the “Mydesk pages” are gadgets where multiple parameters can be displayed immediately in a user-friendly way.

Finally, another key feature is the automatic generation, by the IEMS, of monthly reports that are sent via e-mail, in the form of an Excel sheet, to the technicians and the management of Funivie MdC. This Excel sheet consists of several pages: electric consumption, water, fuels, environmental data, skier days, KPIs, energy balance. The sending of monthly reports aims to stimulate Funivie MdC in the continuous analysis of the energy consumption and in the continuous evaluation of the environmental and economic performance. The first step towards an efficient and sustainable industry is the acknowledgement of the savings potential that can be performed by the company ownership and management board (Viesi, et al., 2017).

5. Conclusions

With its remarkable reliance on specific climatic and natural conditions, the winter ski industry is considered the tourism market most directly and more rapidly influenced by climate change. The current challenge is therefore to understand how to make ski resorts more resilient to climate change while improving their overall operational efficiency in terms of energy consumption. In fact, ski resorts are characterized by a considerable amount of energy consumption by multiple electrical, thermal and fossil fuels flows, resulting from daily operational activities such as the use of ski lifts, the heating of technical buildings, the snowmaking production and the grooming of slopes. All these activities are energy demanding and costly and operators currently need to find new smart solutions and strategies in order to improve efficiency and at the same time implement renewable energy sources, thus reducing their CO_2 emissions. Targeting a cleaner energy system means facing practical issues related to the reduction of negative impacts on the environment, not only emissions but also the optimal use of a key resource such as water. On this road, the first step is the knowledge of operational and energy data, their orderly management and the possibility of query them effectively and in a comparative manner.

This paper clearly demonstrates the importance of an “Integrated Energy Management System – IEMS” in identifying solutions for energy efficiency, for integration of renewable energy sources and for a broader ecosystem sustainability, by monitoring and displaying the historical and real-time data series of the mountain environment as well as of the overall ski infrastructure. The Smart Altitude Living Lab Madonna di Campiglio greatly benefited from the new platform and from the automatic reports generated, providing the operators with an essential tool to speed up the energy transition - from an environmental and an economic perspective - of the ski resort. In this regard, this research demonstrates that utilising a “living lab” approach helps the set-up of tailor-made solutions able to facilitate the implementation of low-carbon, energy-efficient and sustainable actions at the operational level.

To underline the importance of the results achieved by the Smart Altitude project in Madonna di Campiglio, worth reiterating how ski tourism is a key economic sector in the European Alps and many regions depend on the revenue it generates. In each major European Alps country it guarantees more than 100,000 jobs and an estimated 150 million skier-days were counted in the European Alps in winter season 2018/2019 (excluding Germany). Ski resorts are also an energy-intensive industry and for political, economic and environmental reasons, ski resorts are increasingly being pressured to reduce CO_2 emissions and save energy costs and thus build a more resilient future for winter tourism regions. In this context, with its current skier-days (850,000–1,250,000), snow production (400,000–1,800,000 m^3), total energy consumption (11.9–19.2 GWh) and CO_2 emissions (3300–5400 tCO_2) the Madonna di Campiglio case study is highly significant.

Whilst the adoption of an IEMS helps to accelerate the energy transition to a cleaner ski resort, concrete barriers to the implementation of low-carbon, energy-efficient and sustainable measures can still be found in the overall governance structure of ski resorts as well as in the current lack of specific policies at the national and regional levels which could facilitate the implementation of such tools in a wide variety of ski resorts. Mountain resorts usually encounter a lack in financial and technical support to implement and shape low-carbon energy strategies and to monitor their concrete implementation. The knowledge gained from this project should be utilized for further applied research focusing on the ski industry and the impacts of climate change in order to promote a cleaner and climate resilient winter tourism in mountain regions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cles.2022.100050.

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