Journal of Cleaner Production 482 (2024) 144201

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

The environmental and biodiversity impacts of a new cableway system: A comprehensive life cycle assessment

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ARTICLE INFO

Handling Editor: Mingzhou Jin

Keywords:
Life cycle assessment
Cableway
Ropeway
Urban
Biodiversity
Carbon footprint

ABSTRACT

Cars are still used as the primary mode of transportation for daily commuting, with their emissions significantly affecting urban air quality, contributing to overall greenhouse gas emissions. Efforts to reduce car dependency have led to exploration of alternative transportation options such as cableway systems in urban areas. However, limited information exists regarding the environmental impacts and biodiversity implications of such systems. This study conducted a comparative life cycle assessment between a proposed cableway system for the city of Trieste, Italy and its current car transportation mode. The analysis considered both daily operational profiles and passenger occupancy rates of the cableway system. Drawing from similar cableway systems worldwide, it was calculated that the proposed Trieste cableway would accommodate 2007 daily passengers, on average. Results from the environmental assessment revealed that the cableway's operational phase had by far the greatest impact on all environmental categories, followed by its construction and by land clearance. Additionally, the use phase was found to be the major cause for most biodiversity loss, particularly towards terrestrial ecosystems. Comparisons of life cycle GHG emissions between the cableway and car transportation indicated that the cableway system would be a preferable option if the daily average passengers would reach at least 3,908, which is almost double than the expected ones. Furthermore, the cableway system exhibited larger environmental impacts across most categories compared to current car transportation. Thus, this study challenges the perception that the cableway system is a more sustainable option compared to conventional modes of transport, as additional factors need to be considered for a broader overview of the environmental performances.

1. Introduction

The number of daily commuters is steadily increasing, following the densification trend of European cities. Cars are still considered the predominant mode of transportation in almost all European countries (Armoogum et al., 2022), and their overuse could harm not only air quality, but could also negatively impact the global environment. In fact, transportation is the largest emitter in the European Union (EU), contributing to 22% of total greenhouse gas (GHG) emissions (Hill et al., 2020). The same analysis also concluded that road transport is responsible for 36% of all nitrogen oxide, 19% of carbon oxide and 11% of particulate matter formation-related emissions. Another publication by European Environment Agency (2023) reported that concentrations of nitrogen dioxide and particulate matter in all of the reported countries are well above World Health Organization (WHO) recommendations. Those compounds have been reported to exhibit not only an impact on the environment, but also on human health (Anenberg et al., 2019). Moreover, road traffic contributes to air pollution and has a substantial impact on temperature fluctuations (Teufel et al., 2021) and noise levels in cities (Khomenko et al., 2022). To tackle the problem of air pollution in cities, efforts have been made to reduce the number of internal combustion vehicles travelling every day. The reduction in road vehicles can lead to better air quality of the metropolitan area, which has been proven during the Covid-19 lockdown (Venter et al., 2020). Congestion

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[1] Prof. Maurizio Fermeglia passed away unexpectedly on February 25, 2024. His profound intellect, tireless dedication, and unwavering passion for scientific research will continue to inspire us.

https://doi.org/10.1016/j.jclepro.2024.144201
Received 17 February 2024; Received in revised form 10 October 2024; Accepted 9 November 2024
Available online 12 November 2024

fees, limited traffic zones, parking restrictions, traffic control strategies, and the introduction of mobility services are just a few examples of the policies suggested and implemented to reduce the number of cars in cities (Kuss and Nicholas, 2022). Indeed, some of those restriction policies have resulted in better air quality and lower noise pollution (Lebrusán and Toutouh, 2021). However, a partial or total ban on cars in cities can only be successful if there is already sufficient public transport infrastructure, adequate financial funding for future sustainable projects, public acceptance, and minimal topographical constraints (Doheim et al., 2020).

Among the various modes of transport, including buses, cars and trains, cableways are gaining increasing attention.

Cableway transit is divided into two main technology groups: aerial tramways and detachable gondola systems. The latter category can be further subdivided based on the number of cables employed: as the number of cables increases, so does the operating speed and passenger capacity of the cableway. Most operational cableways worldwide are monocable ropeways, which employed a single cable for both hauling and tracking (Cardona-Urrea et al., 2024), with a typical peak hour capacity of 1200 to 4200 passengers (Hofer et al., 2024). The main components of the cableway systems are ropes supported by steel-framed, usually pylon-shaped towers, and cabins, which are suspended on the ropes and transport the passengers from the drive station to the return one (Alshalalfah et al., 2012). In the past, cableways were mainly used for alpine tourism. For example, the oldest passenger cableway in the world, Funivia del Colle, is still a major tourist attraction in South Tyrol (Brida et al., 2014). Furthermore, they are also used to connect locations that are difficult to access, anything from natural monuments (Phuyal, 2020), to historical and religious sites (Biberos-Bendezú and Vázquez-Rowe, 2020). In addition to tourism, many urban cableways are currently in operation today in various countries globally (Canon Rubiano et al., 2020). For instance, the Emirates Air Line in London was meant as an expansion of the public transportation network, offering a quicker and more direct connection for crossing the River Themes. This system is comprised of a 1.1 km monocable gondola, equipped with 34 cabins, capable of transporting up to 2500 passenger per hour (Fruehwirth and Winter 2014). South America has been in the forefront of incorporating cableway systems into existing transportation network. The Colombian city of Medellin is currently using 3 cableway systems, with lines K and J operating at a maximum hourly capacity of 3000 passengers per hour, while the smaller third line L has a maximum hourly capacity of 1200. These systems have been judged beneficial not only in terms of transportation but also in terms of social factors, as inhabitants' quality of life has enhanced due to improved neighborhood accessibility (Brand and Davila, 2011). In general, using a cableway also shortens the duration of trips. This is demonstrated by the Bolivian 10 km La Paz-El Alto cableway system, which can carry 80,000 passengers per day and cut the daily travel time by 9 min (Garsous et al., 2019). Research is also focused on the potential implementation of such alternative transport systems into current transportation modes. For example, a cableway route plan has been developed for a 2.15 km line across the Doha Bay area in Qatar. The initial capacity of this line is estimated at 300 passengers per hour, with the potential to increase to up to 2400 passengers per hour in the future (Tahmasseby, 2021). An equivalent-size cableway was also proposed for the city of Makassar, in Indonesia, which would connect the city center with the Lae Lae island (Sutopo et al., 2020). Another project also investigated the possibility of incorporating a 3000 passengers per hour cableway system to enhance the connectivity to religious sites in Jerusalem (Feitelson, 2021). A proposal was made for a cableway system in Athens, Greece, with a capacity of 6000 passengers per hour as an alternative to a metro line. This cableway system fulfils all three pillars of sustainable design, but due to the lack of primary data, further research is recommended (Papadopoulou and Tzanetatos, 2022).

Although cableways are considered a sustainable option, most research focused on the social aspects of sustainability, while neglecting any environmental aspect. Flesser and Friedrich (2022) observed this phenomenon, concluding that most of the publications on aerial transportation systems primarily focus on the social dimension. The author highlighted that some studies have analysed the demand for cable cars and the mobility behaviour of passengers through surveys and interviews, while others have examined public perception of cable car systems as alternative public transport. However, they are mainly dealing with the accessibility and integration of disadvantaged communities in South America into urban structures to promote social equity. The geographical concentration of cableways in South America may explain the emphasis on social factors.

Environmental impacts are becoming increasingly important for policymakers, starting from the preliminary evaluation of construction and building projects, as they can provide insights into potential outcomes and inform decision-making processes (Sandanayake, 2022). Many authors describe cableways as an environmentally sustainable option, adding that, unlike other modes of transport, their operation does not contribute directly to CO_2 emissions (Težak et al., 2016). Such claims were investigated through a proposed cableway project, which is set to replace existing traffic junctions in the Manizales–Villamaria metropolitan area in Colombia, with a 21% reduction of CO_2 emissions, as the cableway would replace a significant number of trips by car, motorbike and taxi (Escobar et al., 2022). However, these calculations only took into account the CO_2 emissions during the operational phase and neglected the environmental impact of the other phases in the cableway's life cycle. Moreover, relying only on one impact category while neglecting other potential environmental impacts does not provide a thorough understanding of the system. Thus, a more comprehensive environmental impact assessment must be carried out using the life cycle thinking approach, where environmental impacts are assessed across all life cycle phases.

Life Cycle Assessment (LCA) is a widely used tool for assessing the environmental impacts of the entire life cycle of a product, service, or activity. It involves a comprehensive analysis of all stages of the functional unit's life cycle from the perspective of sustainable development, as the life cycle can affect the environment in many ways. LCA provides information and support in seeking potential solutions to environmental problems and allows the evaluation of the environmental impacts of the life cycle from the first to the last life cycle phase. The methodology includes defining the goal and scope, inventory analysis, impact assessment, and interpretation, as defined in the ISO 14040 (International Standards Organisation, 2006a) and ISO 14044 (International Standards Organisation, 2006b) standards. First, it is necessary to define the goal and scope of the assessment to ensure a consistent LCA implementation. Second, the inputs and outputs of the associated system are quantified in the inventory analysis. In the third step, during the life cycle impact assessment (LCIA), emissions and resource extraction are converted into a number of environmental impact categories using characterisation factors (CF). CFs represent the environmental impact per unit of the stressor. Environmental impacts may be then categorised and evaluated, based on which conclusions are drawn for specific needs. Finally, the conclusions are reviewed, interpreted, and prepared for dissemination.

To the best of the author's knowledge, only two cableway assessments have so far been carried out using the LCA approach. Biberos-Bendezú and Vázquez-Rowe (2020) employed a life cycle approach to compare two transport methods for visiting the Kuelap Archaeological complex in Peru, using personal vehicles or a hybrid cableway-bus transport scenarios. They considered six different impact categories, ranging from global warming potential to terrestrial acidification and fossil resource scarcity. The analysis showed a significant reduction in on-site exhaust and resuspended emissions, with over 80% reduction in all environmental impact categories, except for freshwater eutrophication, which was higher due to the production of the structural parts of the cableway system. Similarly, Franch et al. (2021) utilized a life cycle approach to assess the sustainability of the Trento-Monte Bondone project in Italy. They found that the cableway had significantly smaller environmental impacts than other means of transport, such as cars or buses, with an 80% decrease in emitted CO_2. Additionally, both studies also highlighted that cableway systems have a lower impact, as they both used renewable energy as primary electricity source. Although they conclude that cableways are more environmentally friendly, some of the impact categories show a slightly higher score compared to conventional transportation methods. This is particularly due to the high use of construction materials (steel, concrete), that are part of the main cableway infrastructure. It is worth noting that existing environmental studies on cableway system mainly focus on their construction and operation, while the decommissioning and end-of-life is usually omitted from their scopes. Furthermore, the construction of a cableway also influences the overall appearance of the region, typically seen as changes in land-use, which is not usually included in the analysis.

Indeed, introducing a cableway system into a region's environment, could lead to deforestation of some forestry areas (Palantas, 2015), which is tightly connected to climate change, losses of water and soil resources and is overall shown to decrease biodiversity and habitation (Chakravarty et al., 2012). Biodiversity is indeed pivotal to many ecosystem services that benefit both humans and environment, such as agricultural productivity and natural water purification. Therefore, protecting our planet's biodiversity requires a thorough understanding of the impact of our actions (Coustillas, 2023). A startling 68% decline in the biodiversity of various vertebrates since 1970 World Wildlife Fund WWF (2020) underscores the urgency of studying human-induced impacts on biodiversity, which can range from various activities, such as plastic disposal (Harding, 2016) to land-use changes through agricultural production (Michelsen et al., 2012). Rapid global biodiversity decline, driven by climate change and resource overexploitation factors, demands robust scientific assessment methods, which are essential to assess the biodiversity impacts of products or processes throughout the value chain. These models enable practitioners to discern the causes of biodiversity loss, track the progression of impacts, and develop mitigation strategies (Crenna et al., 2020). Multiple models and methods have been formulated to gauge biodiversity loss within LCA, even though quantifying biodiversity appropriately is challenging, typically due to a lack of data. Numerous advanced models and methods have emerged with the escalating attention towards biodiversity impacts in LCA. Some authors emphasized how poorly the current models can represent the complexity of biodiversity (Crenna et al., 2020), while others reviewed and compared 23 selected methods for biodiversity assessment methods applied in LCA, concluding that none of the methods comprehensively capture all biodiversity dimensions (Damiani et al., 2023). A comparison of strengths and weaknesses of current estimation tools emphasized that the progress of LCA methods should focus on enhancing the coverage of biodiversity loss drivers, ecosystems, and taxonomic groups, incorporate ecosystem service assessments, and establish indicators for analysing essential biodiversity facets. At the time being, just three "ecosystems" assessment methods, i.e., ReCiPe2016 (Huijbregts et al., 2017), LC-Impact (Verones et al., 2020) and IMPACT World+ (Bulle et al., 2019), are suitable for assessing biodiversity issues, as they cover terrestrial, freshwater and marine ecosystems (Damiani et al., 2023). LCIA methodology and its focus on biodiversity have evolved over time, particularly since the ReCiPe method's last release in 2016 (Huijbregts et al., 2017). This is the reason why the work developed throughout this paper evaluates aspects related to the quantitative assessment of biodiversity using the ReCiPe2016 method.

It is essential to highlight that a fair comparison between transportation modes shall consider the passengers demand for cableway to determine whether this alternative mode of transport is superior to conventional car transport. In fact, the implementation of cableways in urban areas is beneficial only if passenger demand is sufficient to justify the investment. For example, a 4000 passengers per hour tricable detachable gondola system was proposed to support the existing public transport infrastructure in Munich, Germany, but, despite the high level of public acceptance, estimated demand remains limited as only around 250 passengers per hour (Tiessler et al., 2019).

There is currently no environmental study on cableways that considers daily passenger flow patterns, with cableways often assumed to be operating at full capacity. However, real-life urban passenger movement show varying patterns, generally described by models that indicate differences in passenger mobility depending on the time of day and week (Liu and Yuan, 2024). Therefore, this study aims to fill this gap by estimating cableway occupancy rates based on the mobility of passengers in the area nearby.

As previously described, no prior study has considered the entirety of a cableway system's life cycle, while in this study a cradle to grave perspective has been adopted. This study employs the project of a cableway system that is proposed for the city of Trieste, Italy to assess not only the impact of a cableway using midpoint indicators, but also the biodiversity, as such analysis has been previously conducted only for buses (Gabriel et al., 2021) and cars (Helmers et al., 2020). Addressing both environmental impacts and biodiversity can provide a holistic overview of the cableway project. For instance, midpoint indicators would have failed to capture the whole impacts of forest clearing, whereas the addition of biodiversity endpoint indicators provided a novel and more complete viewpoint on animal species losses, which is essential for project dealing with loss of natural land.

In this study additional factors such as operating times, energy consumption and cableway occupancy rate have been also considered, generating several usage scenarios based on cableway occupancy, which have been compared with conventional vehicle transport. The aim of this analysis is to determine whether the proposed cableway system in Trieste genuinely yields a lower environmental impact than conventional vehicle transport.

2. Methodology

LCA is the most widely used method for assessing potential environmental impacts over the life cycle of products. Many technological applications, such as chemical industry (Puhar et al., 2022), steel manufacturing (Mio et al., 2022), food and packaging production (Molina-Besch et al., 2019), and transportation logistics (Mio et al., 2023) are among those in which LCA is crucial, just to mention a few. It is an environmental-oriented assessment method that analyses the impact of a product system or a human activity on the various natural compartments. This study follows the structure described by International Organisation for Standardization (ISO) standards 14040 (International Standards Organisation, 2006a) and 14044 (International Standards Organisation, 2006b) where four LCA phases are reported, i.e., goal and scope definition, life cycle inventory (LCI), life cycle impact assessment LCIA, and results interpretation.

2.1. Goal

This study aims to assess the environmental impacts related to the implementation of a cableway system connecting the city centre of Trieste (Italy) with Opicina, which is located north of the city and is surrounded by the Bovedo forest. The cableway is intended to relieve car traffic and reduce congestion at the northern entrance to the city. This cableway system would also include additional parking infrastructure in the proximity of Opicina cableway station. Under this arrangement, commuters would have the opportunity to drive to Opicina, park their vehicles in the designated parking area near the cableway station, and then utilize the cableway system to descend to Trieste city centre. Then, the cableway would facilitate their return to the Opicina area at the end of the working shift, where they originally parked their cars. Moreover, this cableway system would also be accessible to individuals interested in visiting Opicina, such as city visitors, tourists, and local residents. After the estimation of the environmental impacts associated to the implementation of the Trieste-Opicina cableway, the results have been compared with an equivalent transportation by car, considering various occupation scenarios. The intended audience includes the scientific community, as well as stakeholders, policymakers, and urban commuters.

2.2. Scope

The functional unit must be identified and clearly defined, as it is essential for a fair comparison between different product systems. This study adopted the following functional unit: "the daily transportation of passengers between Opicina and Trieste city centre for 30 years". The life cycle of the cableway system incorporates various stages, ranging from land preparation, material acquisition and energy expenditure for the construction phase, the operation of the cableway for 30 years, the final decommissioning and the end-of-life of used materials, resulting in a cradle-to-grave approach, as illustrated in Fig. 1. All the necessary material and energy flows connected to the cableway system's construction, operation, decommissioning and end-of-life have been referred to the defined functional unit.

Given the hilly terrain of the Opicina region, which is surrounded by the Bovedo forest, land preparation is expected to involve deforestation of a section of the forest. This includes the eradication of trees and other vegetation using machinery to remove any obstacles that would interfere with the construction and operation of the cableway system. Additional forestry area needs also to be removed for providing the necessary car infrastructure, such as parking spaces and additional service roads. Furthermore, the removal of trees and other vegetative species would also result, in the long run, in a higher accumulation of CO_2 in the atmosphere. This is primarily due to the absence of such vegetative species, as they use CO_2 for their anabolic processes.

The cableway was designed as a monocable detachable gondola system, which comprises of stations, pylons, ropes, motors and cable carts. Additional storage facilities for the cable carts were also considered, which are used during harsh weather events. Moreover, the construction phase included the layout of additional non-cableway-related elements, such as parking spaces and service roads. The scope of the analysis also included the energy that is needed for the construction and layout of the cableway system, as well as the average transportation of construction materials from the manufacturers to the designated area.

The third life cycle stage focus on the operation of the cableway system. The operation phase included the energy consumption of electric motors required to move the cable carts from one station to another, using the average Italian electricity mix. The maintenance connected to the overall cableway operation as well as the one required to remove the regrown vegetation and landscaping of the cableway path were considered negligible and have been excluded from the scope of the analysis. After a 30-year operation period, the cableway system is expected to be decommissioned. This step included the additional energy required to dismantle the cableway system. The last life cycle stage of the cableway encompassed the end-of-life of used materials. This comprehended various material handling, including different scenarios for the disposal of materials.

The materials and processes employed for modelling the entire life cycle of the cableway system were retrieved within the attributional (Cut-off) version of ecoinvent v3.8 database and the calculations have been implemented using openLCA v2.2.0.

2.2.1. Midpoint indicators

The environmental impacts of cableway have been assessed using both ReCiPe2008 (Goedkoop et al., 2008) and ReCiPe2016 (Huijbregts et al., 2017) methods. The former was employed to compare the environmental performance of the cableway system with the traditional car transportation, as calculated by Bauer, C. et al.(2015), whose outcomes have been assessed using ReCiPe2008 superseded method. The latter, was used to provide the cableway environmental impacts using an up-to-date impact assessment method. Indeed, the state-of-the-art ReCiPe2016 method encompasses numerous impact categories dealing with different environmental impacts, such as Climate Change, Ozone Depletion, Terrestrial Acidification, Human Toxicity, Eutrophication, Land Use and others. These indicators allow to understand and quantify the various environmental impacts associated with different stages of a product's life cycle. Updates in ReCiPe2016 provide environmental impact assessment at the global level rather than the European one, while allowing the option to assess the national and continental levels for many impact categories (Huijbregts et al., 2017). Additionally, using an equivalent time perspective across different impact categories enhances consistency in developing midpoint and endpoint models. The ReCiPe2016 method defines three distinct perspectives to accommodate

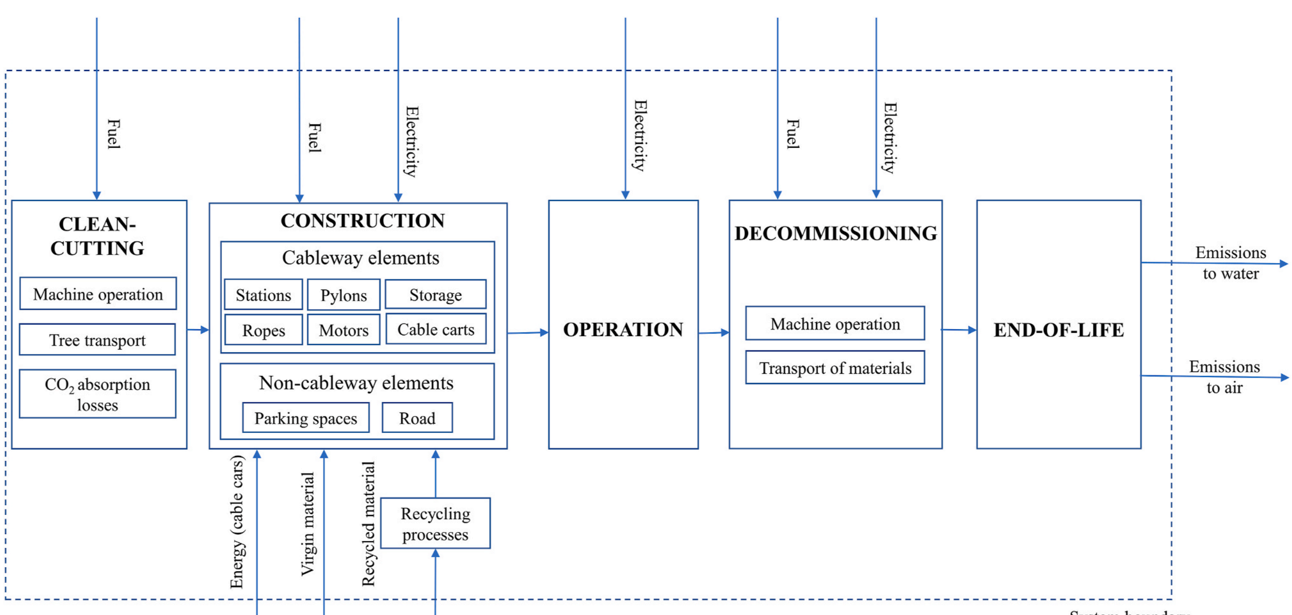

Fig. 1. Schematic representation of the system boundary.

different socio-economic contexts and policy settings: Hierarchist (H), Egalitarian (E) and Individualist (I) perspectives. A Hierarchist Perspective (H), which was used in this work, assumes a balance between economic and environmental aspects and it is often used as a benchmark. The assessment carried out in this study was firstly conducted at the midpoint level, focusing on directly measurable environmental impacts.

2.2.2. Endpoint indicators

Since this work aims to investigate the influence of the cableway systems on biodiversity loss, an additional endpoint indicator included within ReCiPe2016 was employed (ReCiPe 2016 Endpoint (H)). Therefore, the endpoint level allowed to transpose the midpoint impacts into Areas of Protection (AoP) that include “human health”, “ecosystem quality”, and “resource scarcity”. “Ecosystem quality” represents biodiversity regarding local relative species loss, integrated over space and time, in potential disappeared fraction (PDF) (Woods et al., 2018). The unit of measure for terrestrial ecosystems is [PDF species-m^2-year], while for freshwater and marine ecosystems, it is [PDF species-m^3-year] (Goedkoop et al., 2008), where PDF stands for Potentially Disappeared Fraction. This approach does not quantify total extinctions associated with a functional unit LCA in absolute terms, but indicates the percentage of species at risk of global extinction. For instance, a PDF of 0.01 indicates that 1% of the global species pool is at risk of extinction if the stressor (*e.g.,* land use) persists. Because of the inherent lag between the occurrence of a stressor and its ecological impact, there is usually no immediate global species extinction following a change in the stressor. Therefore, exposure duration is integrated into the ecosystem impact unit (PDF yr).

Seven primary impact categories were investigated within the Areas of Protection (AoP) “Ecosystem quality”. Damage to freshwater species is reflected in four categories (global warming, water consumption, freshwater ecotoxicity and freshwater eutrophication). Damage to terrestrial species is reflected in six categories (global warming, water consumption, ozone formation, terrestrial ecotoxicity, terrestrial acidification and land use). The damage to marine species is depicted in two categories (marine ecotoxicity and marine eutrophication).

The impacts on marine, freshwater and terrestrial ecosystems, quantified as PDF•yr, can be aggregated assuming equal importance of the ecosystems. Nevertheless, the relative importance of these ecosystems should ideally be considered in the weighting phase of the LCIA. As there is no generally accepted weighting scheme for these ecosystem types, the impact values for each ecosystem has been presented separately in this study.

2.2.3. Limitations of the study

The environmental study on the Trieste cableway project is subjected to some limitations, mainly related to the collection of primary data for the Life Cycle Inventory. As the system is not yet operational, assumptions have been made about various elements of the cableway, using information retrieved within the project documents. When no specific data was available for the cableway system, the values were determined through literature research, industry standards or observations of similar cableway structures. In addition, since some peculiar cableway components were not available in the ecoinvent database, proxy data have been occasionally used, choosing the most similar available data sets with analogous characteristics.

Furthermore, it was also assumed that there are no mass losses during the construction and demolition phases and that the fuel consumption for demolition is equivalent to the fuel consumption for construction, as it is mainly related to transportation of materials.

Another limitation was related to the estimation of the number of passengers using the cableway system. This number was based on the average occupancy rate of urban cableways worldwide and not on specific forecasts for Trieste cableway system.

Regarding car transportation, the limitations of the study include the selection of a conservative scenario considering the longest path between stations to avoid providing any benefit to traditional transfer, the estimation of car passages coming from a single on-field tally conducted by Trieste municipality and the usage of a car market with a low share of low-emission vehicles, which are expected to increase in the near future.

2.3. Life cycle inventory (LCI)

As described earlier, the life cycle of the cableway has been divided into five stages: land preparation, construction, operation, decommissioning and end-of-life. The material and energy balances for each life cycle stage has been reported in the Supplementary Material.

2.3.1. Land preparation

The construction phase of the cableway and related infrastructural elements exert an impact on the natural environment. Specifically, land alterations are expected along the path of the cableway connecting Opicina region with Trieste city centre. The cableway system is designed to connect the hilly Opicina region with the Trieste city centre through three different subsections connecting four stations namely Opicina, Bovedo, Porto Vecchio and Trieste (Gobber et al., 2022a) as presented Table 1, with an overall length of the cableway system of 4.904 km.

Given that the Bovedo forest surrounds Opicina municipality, some vegetation must be cleared. The cableway installation includes the deforestation of a vegetation strip under the designed track, the deforestation for construction and maintenance of roads, and the land clearance for upper stations and car parks. The impacts related to deforestation include the machines employed to cut the trees and transport them, the infrastructures necessary for the machinery (access road, shed), the burning of residual biomass and the depletion of CO_2-absorbing vegetation.

The overall construction of the cableway system and its associated components would necessitate deforestation across an area of 5.4 ha. This area can be divided as follows: 3.2 ha for the cableway system, 1.2 ha for the site and safety road, and the remaining 1 ha for the construction of parking areas. The clear-cutting (deforestation) has been modelled based on the “clear-cutting, primary forest to arable land” ecoinvent process. This activity starts with the natural state of the primary forest and ends with providing arable land tenure, measured in [m^2]. Since vegetation removal affects the Bovedo forest’s annual carbon absorption capacity, it is essential to determine the number of trees that would be removed. Owing to the various soil types and compositions in different areas, a forest like Bovedo has varying densities of trees per hectare. A maximum of 5000 vascular plants have been sampled in the area, among which less than 20% may be constituted by trees, given an estimated average number of 900 trees/ha (Zara et al., 2021). The annual CO_2 offsetting can range from 21.77 $kgCO_2$/tree to 31.5 $kgCO_2$/tree (Encon, 2023). An average CO_2 adsorption of 30 $kgCO_2$ per tree was considered for the Bovedo forest, with *Pinus nigra* and *Quercus pubescens* being the most common tree species. After considering the forest area loss of 5.4 ha and the 30-year operative lifetime of the cableway system, the total losses in absorbed CO_2 is around 4374 tCO_2. This calculation does not consider the subsequent absence of tree after the operating lifetime of the cableway, which will result in a loss of sequestration for several years after the decommissioning, too.

Table 1
Individual subsection length of the cableway system(Gobber et al., 2022a).

Subsection	Lenght [km]
Opicina - Bovedo	2.344
Bovedo - Porto Vecchio	1.425
Porto Vecchio - Trieste	1.135
Total	4.904

2.3.2. Manufacturing and installation

The cableway system is designed as a monocable gondola system, comprising of 6 elements: rope, pylons, cabins, motors, stations, and a storage facility.

2.3.2.1. Ropes. Being the cableway a monocable gondola system, it is sustained by one single rope with a diameter of 34.9 mm and a weight of 7.51 kg/m, which is typically employed in such systems (Alshalalfah et al., 2012). The total rope length is equivalent to a round trip of the cableway system (9.808 km). A modified process of wire drawing from ecoinvent v3.8 “wire drawing, steel” was used, where all of the steel material was designed to match the Italian steel production mix, where approximately 84% of the steel alloy is produced by electric arc furnace, with the remaining 16 % being made from iron ore (Mapelli et al., 2022).

2.3.2.2. Pylons. The cableway system is supported by pylons constituted by a steel frame and a concrete base. Each pylon is assumed to be a cylindrical structure with a radius of 1.5 m, a height of 20 m, and a width of 30 mm. All the aforementioned tower dimensions are coherent with the typical tower height (Dopplemayr, 2023) and diameter (Urban Planning Committee, 2018) for nondetachable gondolas. Additionally, each pylon is assumed to set upon an 8 m^3 concrete base, where the “market for concrete” ecoinvent process was used. The last version of the cableway’s construction project is planning 37 pylons over the entire cableway’s pathway.

2.3.2.3. Motors. Two electric motors will serve as primary driving force for the cableway. They have been modelled using the ecoinvent “marine electric motor construction” benchmark and sized to a 5.6 ton motors as reported in the following operation phase paragraph.

2.3.2.4. Cabins. The cableway system features cabins, which are suspended from the ropes and responsible for transporting passengers between stations. For simplicity, cabins have been modelled employing an elevator cabin design as a proxy. In particular, the structure, materials and size reported by Milijögiraff AB (2015) have been used, due to the two products’ great degree of resemblance. These cabins primarily consist of low-alloyed steel with a minor usage of stainless-steel components. The cabins adopt the same Italian steel production mix as for the previous cableway elements. Each cabin is primarily constituted by low-alloyed steel (502.2 kg) with some chromium-plated stainless steel (217 kg). Additionally, the cabins incorporate other materials such as aluminium, plastic, glass, and medium-density fibreboard. The production of these cableway cabins was also investigated in terms of energy consumption during manufacturing. All material and energy flows were scaled to match the complete set of 100 cabins to be installed (Gobber et al., 2022a).

2.3.2.5. Stations and warehouse. The last cableway elements are the 4 stations and the storage facility. The stations were modelled as building halls using the ecoinvent product “building construction, hall” with an area of 725 m^2 for each station, based on the current stations used for the London Emirates line (Rowe and Narey, 2014). Furthermore, the cableway system also employs an additional building meant for the storage of the cable carts during severe weather events. That being said, a storage building, using the ecoinvent product named “market for storage building, chemicals, solid” was used as a proxy, with an initial capacity of 30,000 m^3 and area of 6000 m^2. Such storage facility was adapted to accommodate only the 100 cabins, considering 10 m^2 of area required by each cabin, thus 0.17 of the original ecoinvent process was utilized.

2.3.2.6. Construction energy. The analysis also included an assessment of the energy requirements for assembling the individual components of the cableway system. This dataset encompassed the consumption of diesel fuel during the operation of construction machinery and helicopters rides, which are primarily employed during the transportation and construction phases of the pylons (Bisták et al., 2022). The construction data used for the cableway project in Peru (Biberos-Bendezú and Vázquez-Rowe, 2020) served as benchmark for this information, which was subsequently rescaled for the cableway system under analysis. In the case of helicopters, only the pylons were taken into account, while the diesel consumption was determined based on the combined mass of ropes, pylons, and cabins. Stations and storage buildings were excluded from these calculations, as the energy required for their construction had already been factored into their respective construction processes. The ecoinvent processes named “transport, helicopter” and “diesel, burned in building machine” were used for the helicopter transport and for diesel consumption during the construction phase, respectively.

2.3.2.7. Non-cableway related elements. To meet passengers’ needs, the construction of the cableway system involves additional elements and components that are not related to the cableway itself. These elements include providing extra parking spaces near the Opicina hill station and constructing roads primarily designated for service and maintenance of the cableway system. Both components are integrated into the cableway system’s construction phase. The primary construction materials for these parking spaces and the utility road are concrete, bitumen and gravel, which are all gathered within the ecoinvent process “market for road”, which is based on material needed for construction of a Swiss highway. Using the average European lane width (Teodorović and Janić, 2017), a road width of 12.25 m for a typical 2 lane highway with an added slow lane was determined. As the roads and parking space occupy an area of 2.2 ha, an estimated 53.878 km of road is required, including construction, replacement and maintenance over a time period of 30 years.

2.3.3. Operation

The cableway system is supplied by the Italian national power grid to operate during its lifetime. The total electricity consumption is not only related to the main drives, but it also includes ancillary and station equipment services that must be taken into account during operating hours. Furthermore, a certain amount of energy is needed for lighting and parking facilities during the overnight period, which have been assumed based on the technical report of the cableway system (Gobber et al., 2022b).

In order to calculate the environmental impacts resulting from the operation of the cableway, it is necessary to estimate the daily power profile so that the electrical energy consumed can be computed.

To fulfil this task, the hourly profile of vehicles travelling along the main road section connecting the bottom station with the top one has been retrieved from an on-field detection performed by Trieste’s municipality, as shown in Fig. 2 (Sintagma, 2019). The cableway is set to run for a total of 14 h per day, *i.e.,* from 7:00 to 21:00, as shown by the orange area in Fig. 2. In the blue areas of the same figure, which represent overnight hours, the cableway is not operational, forcing users to use conventional transportation. By carrying out a sensitivity study on the share of commuters who would replace the adoption of private vehicles with the cableway during operating hours, it has been possible to obtain the energy consumed by the cableway system as the number of passengers increase.

Considering the hourly profile shown in Fig. 2, the total number of vehicle passages during the operating hours of the cableway is 11,921, while those during the night hours are 1,010, for a total of 12,930 daily vehicles passages. However, in order to obtain a fair comparison between the different transportation modes, the number of passages must be converted into a number of passengers. For this purpose, an occupancy of 1.17 passengers/vehicle was estimated in 2021 according to

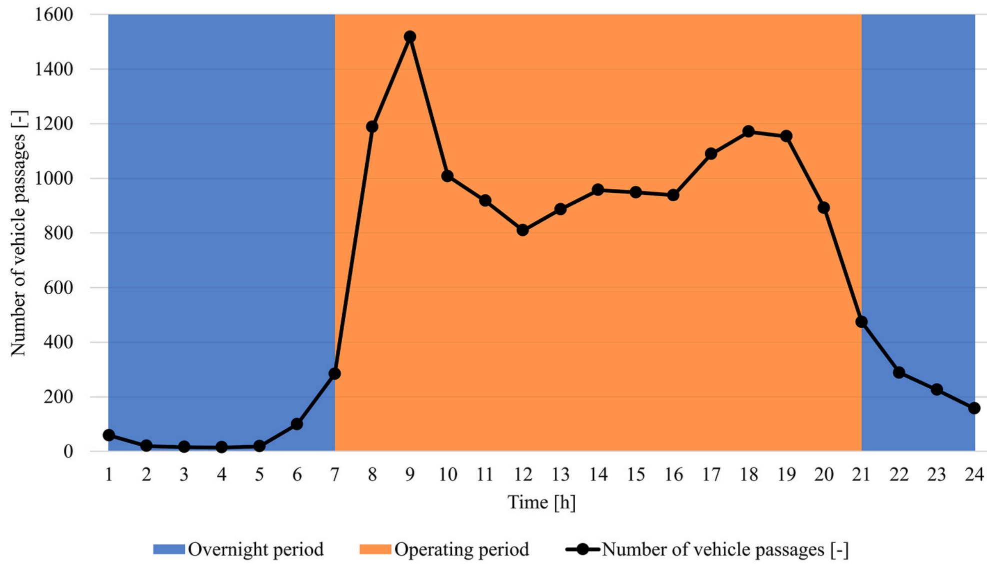

Fig. 2. Hourly profile of vehicles passages on the road section connecting bottom and top station.

Eurostat Statistics (Eurostat Statistics Explained, 2021). Thus, the total number of vehicles passengers is considered equal to 13,947 during the operating period and equal to 1181 during overnight period, for a total of 15,128 passengers. The proposed sensitivity analysis aims to proportionally scale the passengers profile only during the operating hours in order to obtain a total number of cableway passengers ranging from 0 to 13,947, *i.e.,* a share of cableway passengers ranging from 0% to 100%.

The power absorbed by a cableway depends on several parameters including its length, altitude difference, speed and rated capacity. For example, a cableway with a rated capacity of 2000 passengers/h, a length of 1 km and an elevation difference of 400 m has a motor with a maximum power of approximately 415 kW (Blasuttigh et al., 2023). Maintaining a steady speed ensures a constant travel duration such that, with a growing number of users, the necessary power also rises exhibiting significant fluctuations throughout the day.

The amount of work required to move a mass between two different points is calculated using the law of potential energy. In this case, the mechanical work is provided by two electric motors installed in the Opicina and Bovedo stations. The nominal power of the motors is 800 kW and 750 kW for the two sections respectively, both with a rated capacity of 1800 pers/h (Gobber et al., 2022b). Usually, a load test is carried out on cableway systems in order to yearly certify its performances. During this test, the no-load and full-load power are measured by emulating the weight of travelers using sandbags. Using this data, it is possible to estimate the instantaneous electrical power of the two main drives P_{el} depending on the number of passengers, according to Eq. (1) (Blasuttigh et al., 2023):

$$P_{el} = P_0 + \frac{p}{p_{max} \cdot \Delta t} \left(P_f - P_0\right) \tag{1}$$

where p is the number of passengers in the time period Δt [h], p_{max} is the cableway nominal capacity [person/h], P_0 is the measured no-load power [kW] and P_f is the measured full-load power [kW].

Typically, the effective power at which a motor is operated depends on the specific application. Some factors to consider include the efficiency of the motor at different power ratings, equipment requirements and operating conditions. In general, it is beneficial to drive a motor in a load range where the efficiency is optimal, often achieved at a fraction of the rated power. For this reason, we assume that the full-load power absorbed by the cableway, when the maximum user capacity is reached, is 80% of the motors' rated power (De Almeida et al., 2014) Conversely, 30% of the motors' rated power is assumed for the no-load power (Blasuttigh et al., 2023).

As mentioned above, the power related to ancillary services and station equipment was also taken into account during the operating hours. These power values have been estimated to be 100 kW and 150 kW for the Opicina and Bovedo stations, respectively, and are added to the electrical power P_{el} for the same operating period.

The driving stations also provide lighting facilities and services for the parking lots alongside them. However, in contrast to the other power terms, these are assumed to occur during the non-operation timespan of the cableway, *i.e.,* from 21:00 to 7:00. Thus, a power of 100 kW and 50 kW are estimated for the two driving stations, respectively.

The other two stations, *i.e.,* Porto Vecchio and Trieste, merely operate as intermediate terminals for passengers and therefore do not include traction motors. However, power for smooth boarding and alighting, auxiliary services and station equipment must be considered. Thus, an estimated power of 60 kW is assumed for both intermediate stations.

Finally, the overall nominal powers distribution over the cableway stations corresponding to the main operating periods are shown in Table 2.

Based on the above assumptions, an example of an hourly profile of the mentioned electrical powers is shown in Fig. 3, where the cumulative number of daily passengers is considered equal to 50% of the number of potential cableway users during operational timespan, *i.e.,* 6973 daily passengers. In electricity terms, a total daily electrical energy

Table 2
Nominal power distribution over the four cableway stations [kW].

	Operating period	Opicina	Bovedo	Porto Vecchio	Trieste	Total
Main drive P_{el}	7:00–21:00	800	750	–	–	1550
Ancillary services and station equipment P_{aux}	7:00–21:00	100	150	60	60	370
Lighting system and parking lots services P_{night}	21:00–7:00	100	50	–	–	150
Total P_{tot}		1000	950	60	60	2070

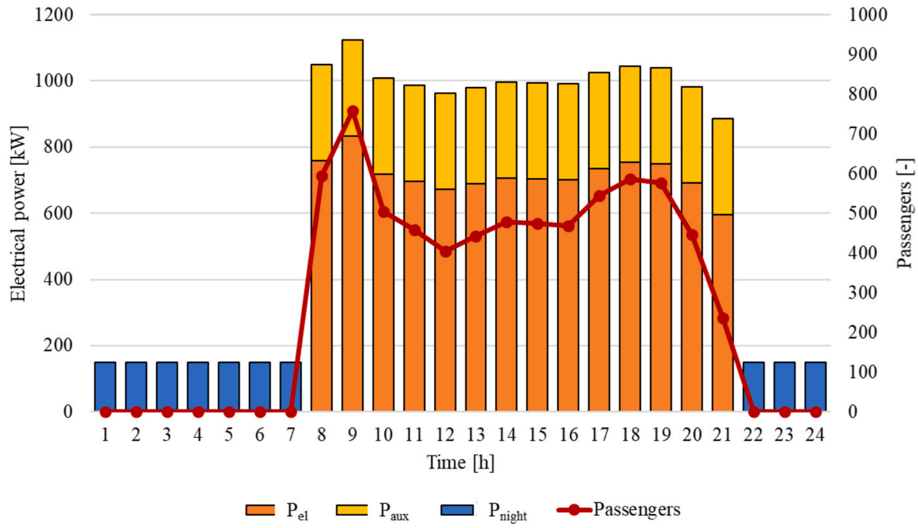

Fig. 3. Hourly electrical power and passengers' profiles for a total daily passengers' value equal to 50% of the potential cableway user.

E_{tot} of 15.56 MWh is computed in this case.

Applying the same procedure, it is possible to determine a global power profile for each percentage (0–100%) of the potential users that actually travel by cableway during operating hours. Using these power profiles, it is possible to obtain a linear function correlating the total daily electrical energy consumed with the percentage of commuters using the cableway rather than their own vehicle, as shown in Fig. 4. Thereby, the total electricity consumption for the entire cableway lifetime can be computed from this curve based on total operating days.

The number of yearly operating days was based on the operating conditions, primarily related to maintenance activities and weather events. Since Trieste is a North-Adriatic coastline city, strong cold winds (Bora) are frequently blowing, particularly during winter. The cableway system is designed to operate at wind speeds up to 75 km/h, which is similar to the typical operating conditions of other detachable monocable gondola system (Tiessler et al., 2019). If the wind speed exceeds the threshold value, the cableway is closed to public and cable carts are stored in a designated facility. Based on the wind trends and cableway maintenance times, the cableway is expected to operate for 285 days annually, based on historical weather patterns and operational conditions specific to the region (Gobber et al., 2022a). The effects of climate change could potentially impact future cableway operations by altering weather patterns, which may either increase or decrease the number of feasible operating days. However, this study's scope is to assess the environmental impacts of the cableway based on the data available at the time of the study. The "market for electricity, medium voltage - IT" has been chosen from ecoinvent database for operating the cableway system.

2.3.4. Decommissioning

After 30 years of operation, the cableway system is supposed to be disassembled and decommissioned. An assumption of the study is that the parking lots and utility roads would be preserved, and only the cableway system would be demolished. Additionally, it was also assumed that the energy required for decommissioning the cableway would mirror the energy spent during the construction activities. Consequently, an equivalent amount of diesel and helicopter transportation hours were used for decomissioning. This assumption applied only to cableway components lacking of dedicated decomissioning activities by ecoinvent, such as pylons, ropes, motors and cabins. The decommissioned components of the cableway were also subsequently removed form the operation site using freight road transportation from ecoinvent, assuming a travelling distance of 100 km.

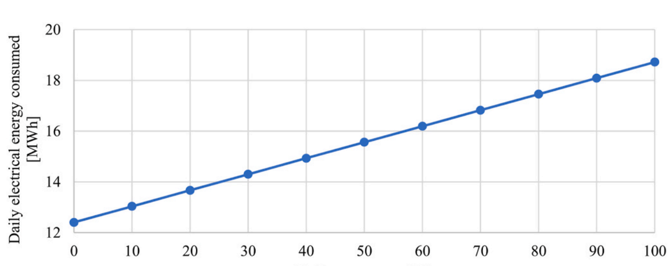

Fig. 4. Daily electrical energy consumed by cableway system as a function of potential share of users using the cableway during operating hours.

2.3.5. End-of-life

The last life cycle phase of the cableway is the end-of-life of the used materials, as a result of the decommissioning stage. In this stage, no losses in materials were assumed, meaning that the mass of input materials equals the amount of materials that is being discarded. The cableway system is constituted primarily by steel and concrete; thus, appropriate treatments of such waste materials were modelled using "market for waste reinforcement steel" and "market for waste concrete" from the ecoinvent database. Furthermore, this stage also includes the waste treatment of additional materials used in the construction phase of the cable carts. Detailed descriptions of such processes can be found in the life cycle inventory reported in Supporting Information.

2.4. Car transportation

The current transportation model based on traditional passenger vehicles needs to be modelled for a comparison with the novel system based on cableway usage. The impacts from vehicle traffic are a result of both car constructions and exhaust emissions during the vehicle's use phase. A weighted average value for the emissions was utilized in the calculations, as the operating phase emissions vary depending on the fuel used (gas, diesel, and methane). The life cycle impact assessment scores based on ReCiPe2008 (H) for the different car categories have been taken from the publication of Bauer, C. et al. (2015) where an assessment of the entire life cycle of different cars has been conducted. In their work, the authors assessed the impacts of 1 km driven using internal combustion engine vehicles (ICEV) running by gasoline, diesel or compressed natural gas (CNG), battery electric vehicles (BEV), and hybrid electric vehicles (HEV) based on gasoline or diesel engines coupled with an electric one. In this work, Bauer's results have been implemented using a weighted average of the running cars in Italy in

2021, as shown in Fig. 5 and reported in the annual report published by the Italian vehicles register (ANFIA, 2021). In our work we gathered gpl-running cars with natural gas-running ones, since both needs to install a pressurized container and the fuel composition is similarly constituted by gaseous light organic compounds. In this work, a conservative scenario has been employed for the car market share, despite it is quite likely that an increase in low-emission vehicles will be seen in the next years.

2.5. Passenger cars and cableway occupancy

The daily passenger capacity of the Opicina-Trieste cableway was assessed by considering existing worldwide cableway systems. Table 3 provides an overview of the cableway systems included in the analysis, along with their respective locations and daily passenger occupancy (Canon Rubiano et al., 2020). Notably, these cableways exhibit variations in capacity, with those situated in South America generally showing higher ones. This discrepancy can be attributed to the crucial role these cableways play in the local urban public transport infrastructure of South American cities. For each cableway, an occupancy ratio based on the average daily passenger capacity of the cableway over the number of city inhabitants was determined.

Fig. 6a compares the occupancy ratios of all the cableway systems, with an average occupancy ratio of $6.7 \cdot 10^{-3}$. Looking at the graph, it can be seen that some locations, such as Mexico State, Rio de Janeiro, New York, London and Amazonas all have extremely low cableway occupancy ratios, mainly due the vast metropolitan area that they need to serve. Amazonas' cableway, at the opposite, is mainly used for touristic purpose, therefore exhibits a low flux of passengers. To calculate a more realistic average daily passenger capacity for a non-touristic city like Trieste, those locations were not considered for the average occupancy ratio calculation of Fig. 6b, that compares the occupancy ratios of urban cableways, excluding popular touristic sites and locations, giving an average occupancy ratio of 0.01. The latter average occupancy ratio was used to estimate the future occupancy of the Opicina-Trieste cableway system. With the city of Trieste having roughly 200,000 inhabitants, the average daily passenger capacity was determined to be 2,007, considering the average occupancy ratio as calculated without popular touristic locations.

3. Results and discussion

The results of comprehensive analysis of the environmental profiles related to the implementation of the Opicina-Trieste cableway system into the urban transportation services are reported in this paragraph. Here different impact categories, ranging from global warming,

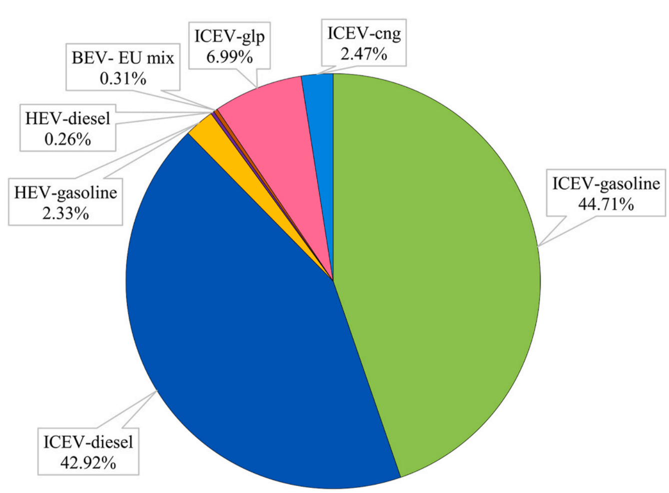

Fig. 5. market share of car categories in Italy in 2021.

Table 3
Urban cableway systems across the world.

Cableway	Location	Daily capacity	City inhabitants	Ratio Capacity/ inhabitants
Mexicable	Mexico State, Mexico	17,000	16,990,000	1.00E-03
Metrocable	Medellín, Colombia	38,689	2,569,007	1.51E-02
TransMiCable	Bogotá, Colombia	21,000	7,968,095	2.64E-03
Cable Aéreo	Manizales, Colombia	8500	552,155	1.54E-02
Aerovía de Guayaquil	Guayaquil, Ecuador	40,000	2,698,077	1.48E-02
Metro Cable	Caracas, Venezuela	23,744	3,242,000	7.32E-03
Line 1 Santo Domingo	Santo Domingo, Dominican Republic	19,495	1,029,110	1.89E-02
Telecabinas de Kuélap	Amazonas, Peru	274	379,384	7.22E-04
Emirates Air Line	London, United Kingdom	3609	9,787,426	3.69E-04
Yenimahalle	Ankara, Turkey	8219	5,187,949	1.58E-03
Roosevelt Island	New York, United States	4110	8,804,190	4.67E-04
Téléphérique des Capucins	Brest, France	1781	139,456	1.28E-02
MioCable	Calí, Colombia	6000	3,400,000	1.76E-03
Teleférico do Complexo do Alemão	Rio de Janeiro, Brazil	10,000	12,280,702	8.14E-04

ecotoxicity, eutrophication, acidification and many more were considered. Table 4 reports the outcomes of the various impact categories for the system boundaries shown in Fig. 1, where the five cableway life cycle stages have been included in the analysis: from clear-cutting and construction, to 30 years operation considering 2007 passengers/day for 285 days/year, concluding with decommissioning and end-of-life. The last column of Table 4 shows the uncertainty range for high-quality results within 95% confidence related to the overall score gained for each impact category. The uncertainty is usually under ±18% of the median value, except for human carcinogenic toxicity, ensuring a good robustness of the outcomes. The uncertainty analysis has been performed through a 1000-iterations Monte Carlo simulation within openLCA software, after assessing the data quality and the relative uncertainty value using the ecoinvent data quality system. In addition, Fig. 7 shows the distribution of impacts among the various life cycle stages for each impact category, which has been normalized to 100%. It can be seen that the construction and operation phases show the highest impacts for almost every impact category, while clear-cutting generates appreciable contributions for land use, fine particulate matter formation and global warming, while end-of-life causes significant impacts for freshwater and marine ecotoxicity. The former is mainly related to the loss of both natural land and potential absorption of emissions by the forest, while the latter correlates to the aqueous emissions generated by usage of dumps. Compared to other studied categories, the construction phase exhibits a greatest influence on the depletion of mineral resources for construction materials, along with the human and ecotoxicity categories. The latter can be attributed to the release of heavy metals during the production and manufacturing of electrical motors and steel. Except for human carcinogenic toxicity, land use and mineral resource scarcity, the cableway's operation phase is the main contributor to the overall impacts for every impact category. For instance, in the global warming potential category, the operation phase represents more than 77% of the total CO_2eq emissions due to electricity consumption, followed by the clear-cutting (14%) and construction phases (8%). Previous studies by Franch et al. (2021) and Biberos-Bendezú and Vázquez-Rowe (2020) did

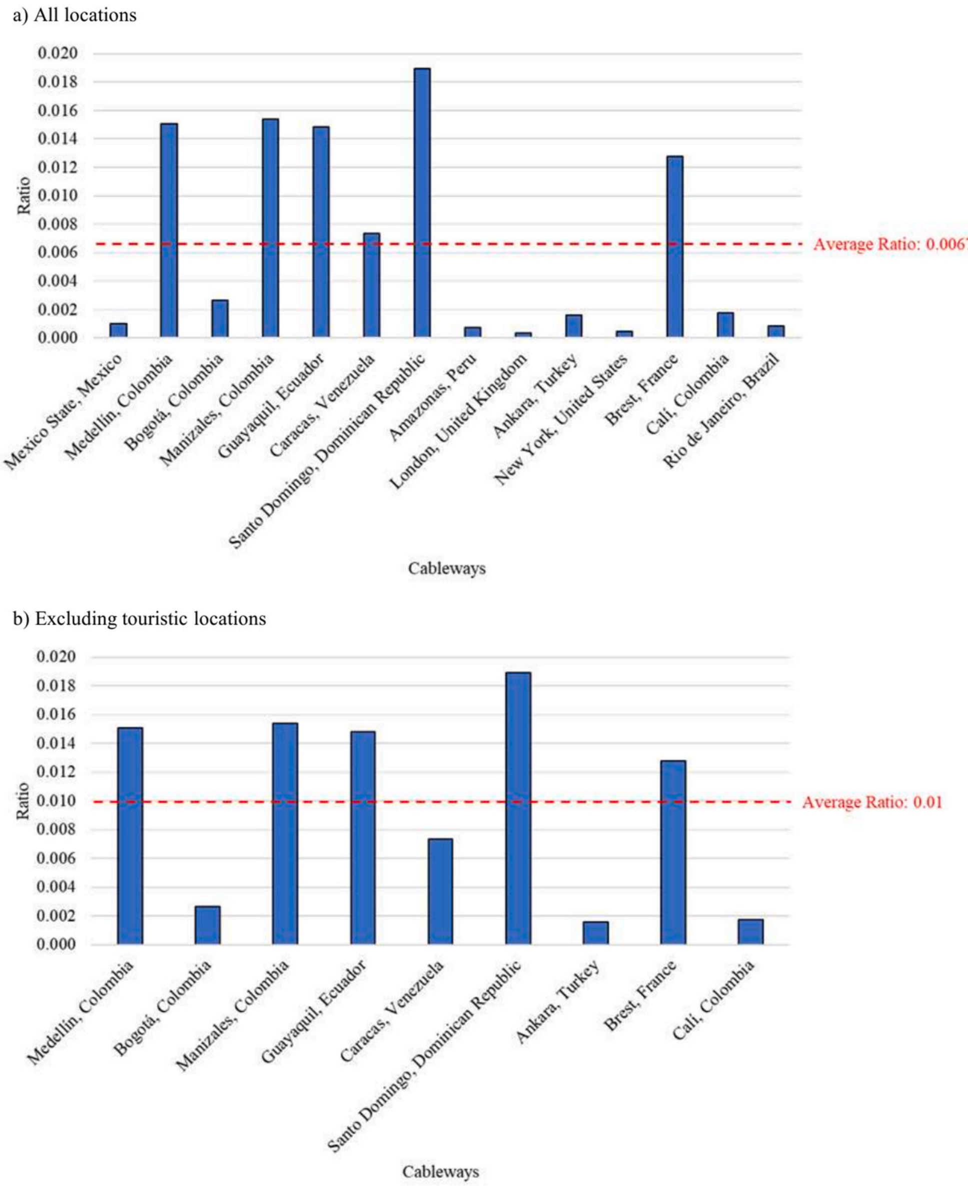

Fig. 6. Occupancy ratio comparison (a) for all cableways and (b) for cableways excluding touristic locations.

Table 4
Results of the LCIA calculation for the cableway system using ReCiPe2016 method.

Impact category	Unit	Clear-cutting	Construction	Operation	Decommis	End-of-life	Total	Uncertainty (5–95%)
Fine particulate matter formation	kg PM2.5 eq	4.94E+03	9.71E+03	4.86E+04	3.96E+02	3.12E+02	6.40E+04	−10.24%,+11.88%
Fossil resource scarcity	kg oil eq	1.07E+04	1.38E+06	1.41E+07	5.79E+04	3.87E+04	1.56E+07	−11.53%,+13.50%
Freshwater ecotoxicity	kg 1,4-DCB	2.29E+02	5.70E+05	1.05E+06	1.20E+03	9.57E+04	1.71E+06	−10.00%,+11.77%
Freshwater eutrophication	kg P eq	1.00E+01	1.48E+03	1.06E+04	6.16E+00	4.98E+00	1.21E+04	−11.44%,+13.47%
Global warming	kg CO2 eq	8.37E+06	4.90E+06	4.63E+07	1.78E+05	1.21E+05	5.98E+07	−9.95%,+12.11%
Human carcinogenic toxicity	kg 1,4-DCB	9.28E+03	1.43E+07	1.26E+06	5.77E+03	8.11E+03	1.55E+07	−22.61%,+31.99%
Human non-carcinogenic toxicity	kg 1,4-DCB	7.13E+03	7.97E+06	2.08E+07	3.57E+04	1.06E+05	2.89E+07	−10.76%,+12.74%
Ionizing radiation	kBq Co-60 eq	4.06E+02	2.21E+05	5.86E+06	2.36E+03	1.91E+03	6.09E+06	−11.96%,+14.34%
Land use	m2a crop eq	1.99E+06	5.71E+05	8.30E+05	2.00E+03	8.81E+02	3.39E+06	−13.22%,+15.55%
Marine ecotoxicity	kg 1,4-DCB	5.29E+02	7.93E+05	1.36E+06	2.08E+03	1.15E+05	2.27E+06	−9.79%,+11.99%
Marine eutrophication	kg N eq	2.14E+00	1.59E+02	9.00E+02	6.43E-01	2.88E+00	1.06E+03	−11.71%,+13.72%
Mineral resource scarcity	kg Cu eq	5.68E+01	9.70E+04	4.24E+04	2.59E+02	2.02E+02	1.40E+05	−13.50%,+17.80%
Ozone formation, Human health	kg NOx eq	2.01E+03	1.83E+04	7.75E+04	1.58E+03	1.34E+03	1.01E+05	−11.00%,+13.06%
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.53E+03	1.92E+04	7.89E+04	1.60E+03	1.36E+03	1.04E+05	−10.94%,+13.15%
Stratospheric ozone depletion	kg CFC11 eq	1.12E+00	1.83E+00	3.02E+01	8.95E-02	7.78E-02	3.33E+01	−11.22%,+13.39%
Terrestrial acidification	kg SO2 eq	2.01E+03	2.38E+04	1.46E+05	8.43E+02	6.24E+02	1.73E+05	−11.20%,+13.01%
Terrestrial ecotoxicity	kg 1,4-DCB	2.38E+05	3.73E+07	5.01E+07	8.00E+05	3.13E+05	8.87E+07	−10.18%,+12.02%
Water consumption	m3	1.43E+02	5.92E+04	8.25E+05	1.62E+02	2.80E+02	8.85E+05	−11.91%,+13.57%

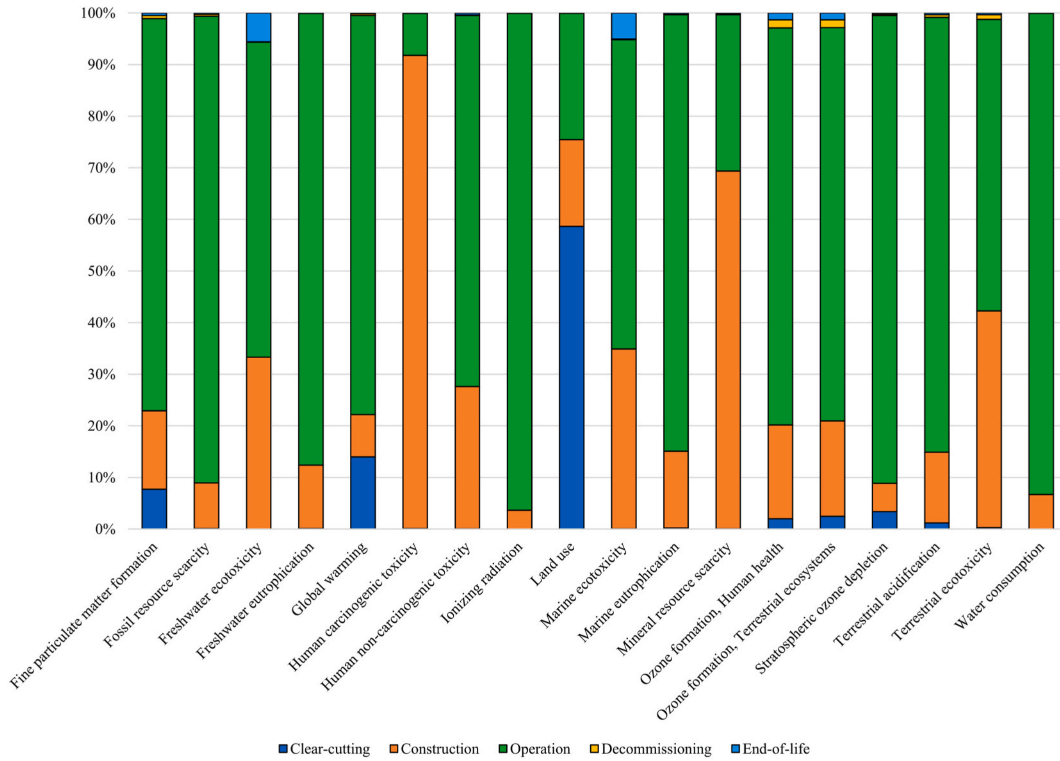

Fig. 7. Impact distribution of cableway life cycle phases for different impact categories of ReCiPe2016 method.

not highlight the great contribution of the operational phase of the cableways investigated in their studies. This might, however, be the result of the significant discrepancies between the energy mix used in their research, which is primarily produced by hydropower, and the Italian one, which is generated from natural gas by almost 50%.

Furthermore, the impact of the cableway system was also investigated through the lens of biodiversity loss. In Fig. 8a, the potential disappeared fraction of species across all three ecosystems is depicted. Notably, terrestrial environments experience predominant losses, which was anticipated by the direct impact of the cableway system on this particular category. In contrast, damages to freshwater and marine environments are considerably lower than those observed for the terrestrial compartment. The primary driver of biodiversity loss in the marine environment is attributed to marine ecotoxicity, while freshwater eutrophication emerges as the predominant factor in the freshwater ecosystem. These two categories contribute for over 85% of the total impacts in their respective compartments. The high impact in the marine ecotoxicity category is linked to the significant accumulation of heavy metals, while the elevated levels of phosphorous content are responsible for freshwater eutrophication, being the predominant impact category for damages to freshwater species. Conversely, the distribution of impacts on terrestrial environments reveals a different pattern. Global warming emerges as the primary contributor (64%), followed by terrestrial acidification (14%) and land use (11%).

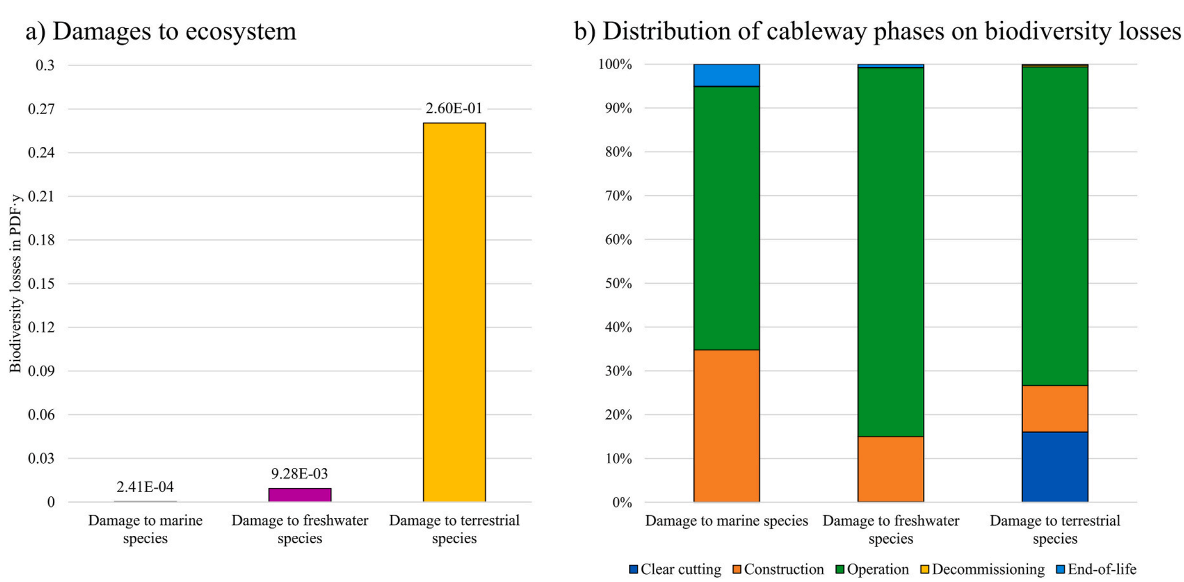

Fig. 8. Endpoint Life Cycle Impact Assessment of damage to ecosystems using ReCiPe2016

Analysing the individual life cycle stages of the cableway system, as depicted in Fig. 8b, the operational phase stands out as the major contributor to ecological damages. Considering the aquatic environment, the construction phase also plays a non-negligible role in biodiversity loss, representing 15% and 35% of the total freshwater and marine species loss, respectively. Furthermore, the end-of-life phase of the cableway system is also reported to generate some of the species' loss in marine environments, due to the release of heavy metals, such as copper, zinc or nickel, during the treatments of cableway's materials. As for terrestrial ecosystems, clear-cutting accounts for 16% of total damages. This can be attributed to changes in land use and the accumulation of CO_2 in the environment, stemming from carbon sequestration losses during the clear-cutting stage and land preparation.

The main reason behind the implementation of new transportation mean is usually related to the reduction of GHG emissions for meeting the goal of decarbonization of the transportation sector by 2050. Therefore, several sensitivity analyses have been carried out in order to assess the comparison between cableway and car transportation from a decarbonization viewpoint based on Global Warming Potential (GWP) impact category only, calculated using ReCiPe2008 method, as in Bauer et al. (2015). Based on the municipality field test as reported in Fig. 2, the average daily one-way vehicles passages have been measured as 12, 931, which are composed by 1010 passages during night-time (21:00–7:00) and 11,921 passages during cableway operational period (7:00–21:00). During the closing-time of the cableway, all the trips from Opicina to Trieste city centre ought to be carried out by car, regardless of the implementation of the cableway system. Therefore, the emissions related to night transportation is not affected by the cableway construction. This is not the case during day-time, when 11,921 passages bring 13,947 passengers between the stations, given the passenger car occupancy in Italy of 1.17 passengers/car (Eurostat Statistics Explained, 2021). Assuming that all the cars follows the same route, the distance travelled by each car is 9.7 km, gaining a total distance travelled by the vehicles of 115,629 km every day, which is covered by different vehicle categories as shown in Fig. 5. To be as cautious as possible and to avoid giving any benefits to car transportation, the longest (but fastest) of the various possible routes from Opicina to the city center of Trieste has been selected as the base case. An additional scenario will take into account a shorter, but typically more crowded, route. The substitution of running cars through cableway usage has been introduced gradually by increasing the percentage of passengers taking the cableway instead of using their own vehicle, using the impact category GWP as a basis for comparison. As the amount of life cycle GHG emissions differ based on fuel type (gasoline, diesel, and methane), a weighted average value of GWP of 0.2196 $kgCO_2eq/km$ was used in the calculations, based on the publication of Bauer et al. (2015). The outcomes of the analysis are shown in Fig. 9, where the total amount of passengers has been kept constant at 13,947 (Fig. 9a) or at 2007 (Fig. 9b). The former takes into

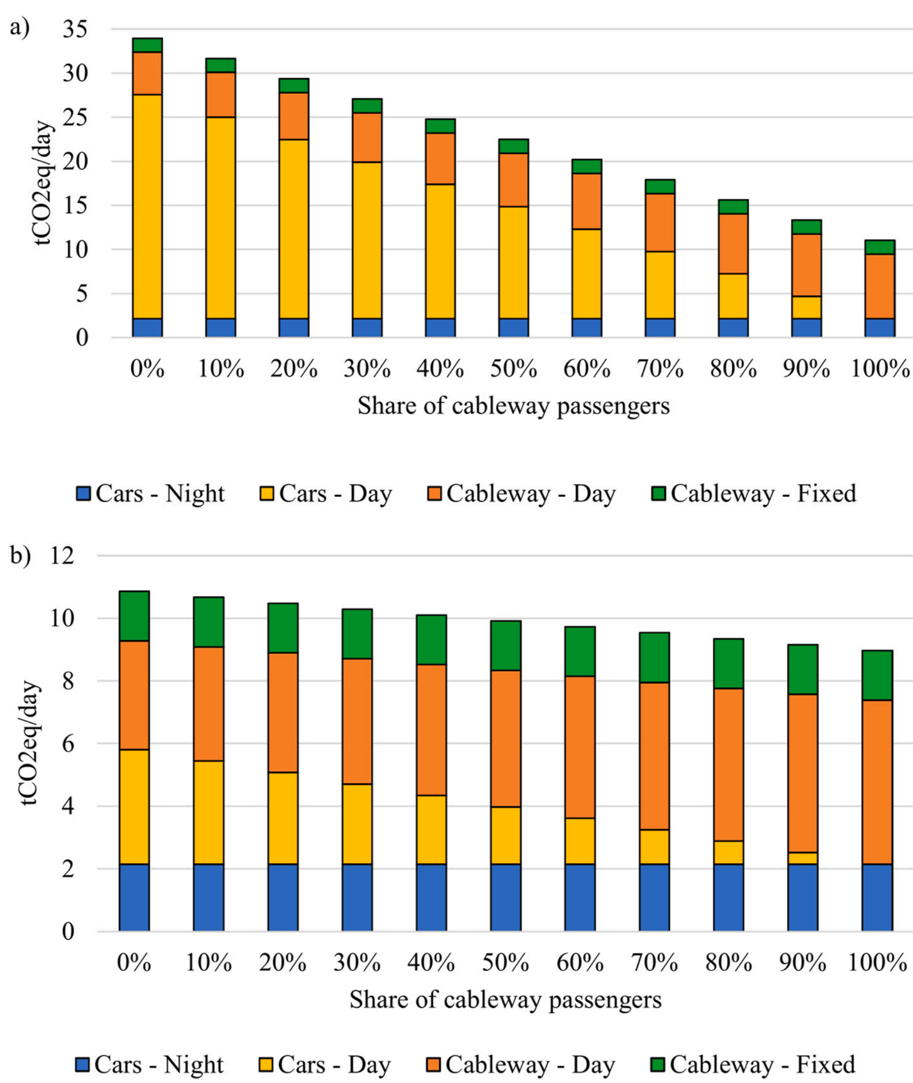

Fig. 9. GWP results (ReCiPe2008) for a combination of cars and cableway daily transportation for a maximum number of a) 13947 passengers or b) 2007 passengers.

consideration the overall number of passengers following the route interested by the cableway service during operating period, while the latter accounts for the maximum number of expected passengers, given the average occupancy ratio of 0.01 and the city population of 200,000 inhabitants. Four contributions have been reported coming from cars or cableway utilization with an increasing share of passengers using the latter. The Cars-Night and Cars-Day contributions account for the lifecycle GHG emissions of running-cars normalized on the functional unit (a daily transportation of passengers for 30 years). The former is constant, since commuters can only travel by car during night-time (1182 from 21:00 to 7:00), while the latter decrease with share of passengers replacing personal vehicles with cableway during operational timespan (7:00–21:00). Cableway's lifecycle emissions are represented by Cableway-Day and Cableway-Fixed contributions, where the former takes into account the increasing operation-related emission as the share of passengers using cableway rises, while the latter accounts for the GHG emissions during the other lifecycle phases, which are independent from the passengers occupancy and have been normalized on the functional unit (285 days for 30 years)

Fig. 9a) makes it evident that there is a progressive decrease in GHG emissions as the share of passengers using cableways increases. When looking at the impacts of the cableway, however, the trend indicates a progressive increase in GHG emissions due to the growing percentage of passengers utilizing the system. This is due to the relatively slow increment of GHG emissions with cableway passengers increase, in comparison with the significant rise of emissions generated by driving-car passengers share growth. Therefore, for a great number of passengers, the cableway GHG emissions are surely lower than the ones generated by running-cars. Nevertheless, as Fig. 9b) illustrates, the opposite occurs when the potential number of passengers using the cableway decreases to 2007. Even though the overall tendency of GHG emissions is still decreasing with the share of passengers using cars, the low number of passengers using the cableway does not justify its construction in the first place. In fact, even if no one is using the cableway (as shown in the 0% share column), the GHG emissions from the running cableway adds up to cars emissions, increasing the overall commuters' emissions in comparison to the equivalent situation in which the cableway was not built. Indeed, without the cableway, the cars' GHG lifecycle emissions are 5.81 tCO_2eq/day, while the GHG lifecycle emissions for an equivalent number of passengers (2,007) using the cableway is 8.45 tCO_2eq/day. This means that the operation of the cableway consistently produces more greenhouse gas emissions than just the running-cars. Given these two quite distinct behaviors, a certain number of passengers should be reached where the lifecycle emissions from cars and the cableway are equal. This represents the threshold value of daily passengers, where the two transportation modes emit an equivalent amount of CO_2eq emissions. If the number of passengers during operational period exceeds this threshold, the cableway system is a better alternative, with lower CO_2eq emissions. Conversely, if the daily passenger count is below the threshold, vehicle traffic produces lower CO_2eq emissions.

Since it is possible to connect the stations using car transportation through alternative ways, a different scenario has been modelled, which consider the shortest, but generally more congested, path of 4.5 km between the stations.

From Fig. 10, it appears clear that the GHG emissions related to the number of passengers for the cableway system increases much slower than the GHG emissions due to running-cars, primarily due to more motorized vehicles on the road. However, the cableway generates GHG emissions during operational period even if there are no passengers, while cars are not subjected to this issue. Fig. 10 also reveals a number of passengers' value where the two transportation modes intersect. These threshold values were estimated as 3908 and 9619 passengers/day throughout the operational period for base case scenario (fastest pathway) and short pathways scenario, respectively. These are the minimal number of passengers that must use the cableway to generate less CO_2eq emissions than traditional vehicles using the two alternative routes. Since the expected number of passengers is 2,007, the usage of the cableway should be almost doubled to emit less GHG than traditional cars for base-case scenario (+95%) or shorter path (+479%), which is quite a challenging task. In fact, in touristic cities with far higher population densities like London or New York, passenger occupancy can reach approximately 4000 passengers every day. This inevitably means that, at current state, implementing the Opicina–Trieste cableway would essentially produce more CO_2 emissions, compared to vehicle traffic.

In order to provide a complete overview on the comparison between the two transportation means, Fig. 11 shows the normalized values of the various impact categories of ReCiPe2008 considering the expected number of 2007 passengers (while numerical values are provided in the Supporting Information) and in Bauer et al. (2015)'s paper focused on car transportation. The normalization has been performed on the maximum value for each impact category, aiming to provide an easy comparison on the various categories. The cableway impacts are generally higher than traditional vehicles ones for the expected number of passengers (15 out of 18). The impact categories that shows lower cableway impacts are "fossil depletion", due to the fuel consumption for travelling by car,

"urban land occupation" mainly due to the road construction, and "terrestrial ecotoxicity", generated by clear-cutting of the Bovedo forest, electricity production and waste treatment processes. Surprisingly, impact categories that are traditionally related to car transportation, such as particulate matter formation or photochemical oxidant formation, appears more affected by cableways system. This can be attributed to the use of fossil fuels to generate energy, the clearing of forests, and

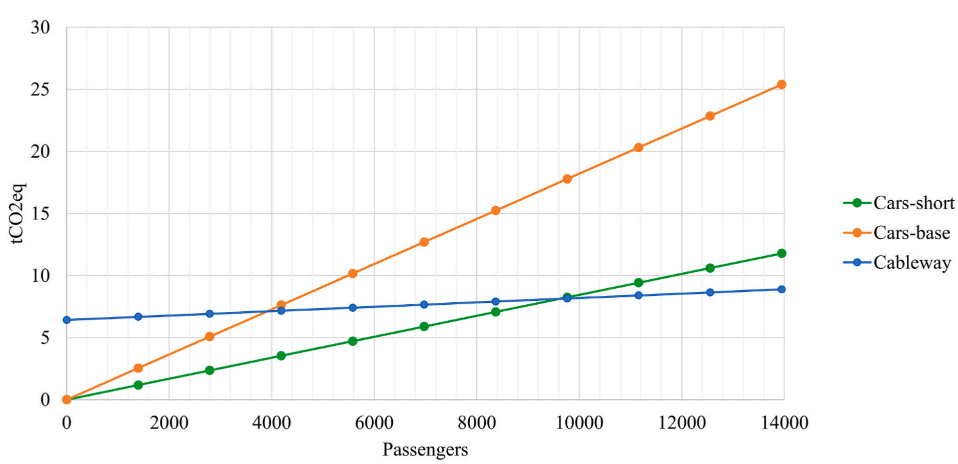

Fig. 10. Carbon footprint of the different transportation means based on the number of passengers during operational timespan.

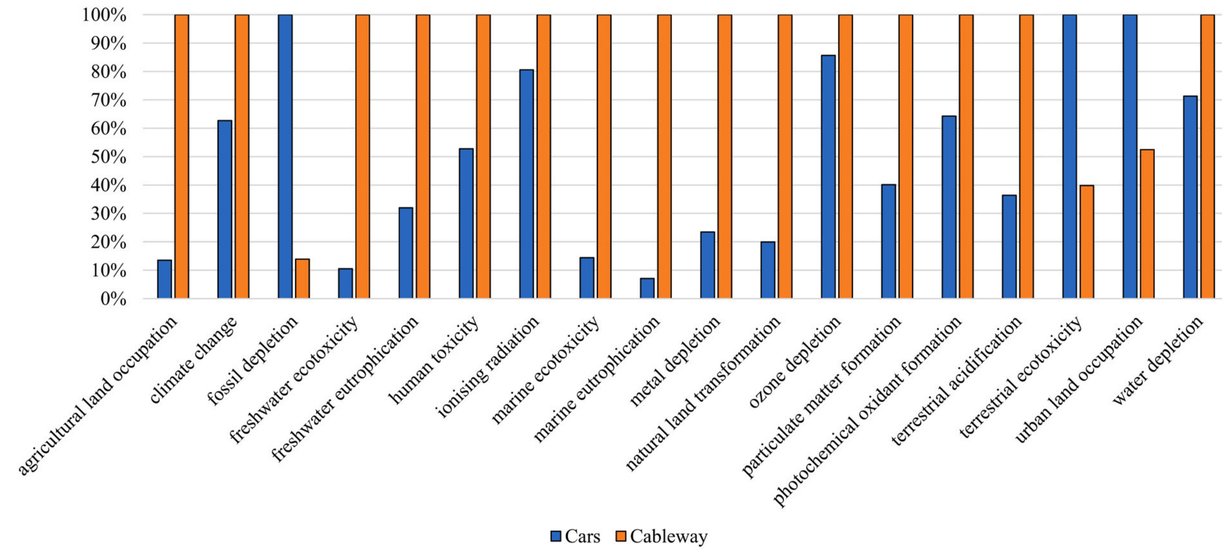

Fig. 11. Comparison of LCA results of the cableway system and cars for 2007 passengers for 30 years using ReCiPe2008

the diesel burnt by construction machines, which has not been offset by a sufficient number of running cars.

4. Conclusions

Cableway systems, which are characterized by their unique topological use features, have traditionally been used as an alternative means of transportation, particularly for connecting remote and challenging-to-access mountainous locations. Recent years have seen a shift in this approach because to the growing popularity of cableway integration into public transit in urban areas. Despite their perceived environmental friendliness, this research challenges such notions and underscores the importance of a broader analysis. Potential ecological issues during the integration of cableway systems into existing landscape can pose a serious threat to different ecosystems. Thus, employing a life cycle thinking approach for a comprehensive environmental assessment of cableway systems becomes essential for a thorough understanding of the multiple repercussions that such transportation means may have both on environmental compartments and biodiversity.

This study adopted the LCA methodology to analyse the potential environmental impacts of a proposed cableway system in Trieste, Italy, carrying on a comparison with the traditional car transportation. The projected cableway aims to enhance the connections between Trieste city centre and the hilly Opicina region, while simultaneously trying to reduce car usage on this route. The analysis of the cableway system encompassed all life stages, considering not only the technical viewpoint, but also topological and landscape characteristics of the Trieste cableway project. The operational phase was deeply examined, with particular attention on the electricity usage based on the system's expected operating hours. Despite its high capacity, Trieste's cableway system revealed an expected average daily occupancy of 2007 passengers, based on population density and other similar cableway systems around the world. The environmental results of the cableway system highlighted that its operational phase is the primary contributor to each environmental impact category used by ReCiPe(H) methodology. The impacts of building the cableway or clearing the land came in second, depending on the particular impact category. In terms of endpoint categories, the terrestrial environment emerged as the main recipient of impacts, showcasing the highest potential species loss. This is primarily attributed to the direct impact that the alternative cableway system exerted on the terrestrial environment and its alterations in land use. Furthermore, it was crucial to analyse the cableway operation in great detail. Compared to conventional vehicle transport, the cableway system showed a fixed operation time schedule, thus the traditional car transportation during non-operational hours was inevitable. Additionally, even if the cableway system was not transferring any passenger, its presence still contributed to the total GHG emissions, due to baseline energy consumption.

Based on the GHG life cycle emissions, this study also evaluated a passenger threshold of 3908 passengers per day for a conservative scenario (or 9619 for the short pathway), indicating that the cableway system becomes a superior alternative in terms of GHG life cycle emissions only if daily average passengers overcomes this value. By contrast, the current car transportation scenario generates lower environmental impacts than the expected cableway system, since doubling the passengers is required to reach this threshold. Furthermore, a comparison of midpoint impact categories for the cableway at expected occupancy (2007 passengers/day) with an equivalent number of passengers travelling by car revealed that the cable system generally exerts greater impacts across most categories, except for "fossil depletion", due to the consumption of fossil fuels by cars, "urban land occupation" by road construction, and "terrestrial ecotoxicity," which is a result of waste treatment activities, power generation, and clearing of the Bovedo forest.

This research underscores the importance of understanding the cableway potential users and their mobility patterns. Passengers relying on the cableway to reach the city centre may still require additional transportation to reach their final destination, challenging the viability of exclusive cableway operation without supplementary public transport. Furthermore, the cableway system's limited daily operating period promotes the use of additional transport vehicles for conducting travels outside working hours.

In conclusion, this study challenges the classification of cableways as an environmentally sustainable choice by assessing its potential integration into a small urban setting. To fully grasp the environmental impacts of this alternative transportation system, it is essential to consider various factors, such as the operating phase and presumed daily passenger demand, within a life cycle perspective. Moreover, even though an attributional approach has been chosen to perform an up-to-date lifecycle analysis, future perspectives may be further investigated by a consequential LCA, which will be performed in a future study.

CRediT authorship contribution statement

Annamaria Vujanović: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Andrea Mio:** Writing –

review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Software. **Rok Pučnik:** Writing – original draft, Software, Investigation. **Nicola Blasuttigh:** Writing – original draft, Software, Methodology, Investigation, Data curation. **Damjan Krajnc:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Maurizio Fermeglia:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

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.

5 Abbreviation

AoP	Areas of Protection (AoP)
BEV	Battery Electric Vehicles
CF	Characterisation factors
CNG	Compressed Natural Gas
EU	European Union
GHG	Greenhouse Gases
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicles
ICEV	Internal Combustion Engine Vehicles
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Inventory analysis
LCIA	Life Cycle Impact Assessment
PDF	Potential disappeared fraction
WHO	World Health Organization

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.144201.

Data availability

Life Cycle Inventory is available in Supplementary Material

References

Alshalalfah, B., Shalaby, A., Dale, S., Othman, F.M., 2012. Aerial ropeway transportation systems in the urban environment: state of the art. J. Transport. Eng. 138 (3), 253–262. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000330.

Anenberg, S., Miller, J., Henze, D., Minjares, R., 2019. A global snapshot of the air pollution-related health impacts of transportation sector emissions in 2010 and 2015. International Council on Clean Transportation. Washington, DC, USA.

ANFIA, 2021. Passenger cars in use by fuel and year of first registration in 2021. https://www.anfia.it/it/automobile-in-cifre/statistiche-italia/parco-circolante.

Bauer, C., Hofer, J., Althaus, H.-J., Del Duce, A., Simons, A., 2015. The environmental performance of current and future passenger vehicles: life cycle assessment based on a novel scenario analysis framework. Appl. Energy 157, 871–883.https://doi.org/10.1016/J.APENERGY.2015.01.019.

Biberos-Bendezú, K., Vázquez-Rowe, I., 2020. Environmental impacts of introducing cable cars in the Andean landscape: a case study for Kuelap, Peru. Sci. Total Environ. 718, 137323.

Bisták, A., Hulínová, Z., Vavrík, I., Šťastný, P., 2022. Aerial work with helicopters in the construction of cableways and their impact on the concrete mixture design. IOP Conference Series: Materials Science and Engineering. IOP Publishing, 012005.

Blasuttigh, N., Pastore, S., Scorrano, M., Danielis, R., Pavan, A.M., 2023. Vehicle-to-ski: a V2G optimization-based cost and environmental analysis for a ski resort. Sustain. Energy Technol. Assessments 55, 102916.

Brand, P., Davila, J., 2011. Aerial cable-car systems for public transport in low-income urban areas: lessons from Medellin, Colombia. In: Proceedings of the 3rd WPSC Conference Papers 2011. Perth, Australia.

Brida, J.G., Deidda, M., Pulina, M., 2014. Tourism and transport systems in mountain environments: analysis of the economic efficiency of cableways in South Tyrol. J. Transport Geogr. 36, 1–11.

Bulle, C., Margni, M., Patouillard, L., Boulay, A.-M., Bourgault, G., De Bruille, V., Cao, V., Hauschild, M., Henderson, A., Humbert, S., Kashef-Haghighi, S., Kounina, A., Laurent, A., Levasseur, A., Liard, G., Rosenbaum, R.K., Roy, P.-O., Shaked, S., Fantke, P., Jolliet, O., 2019. IMPACT World+: a globally regionalized life cycle impact assessment method. Int. J. Life Cycle Assess. 24 (9), 1653–1674.

Canon Rubiano, L., Portabales Gonzalez, I., Flor, L., Duarte, D., Sierra Valdivieso, L., 2020. Urban aerial cable cars as mass transit systems : case studies, technical specifications, and business models (English). http://documents.worldbank.org/curated/en/140251611326011996/Urban-Aerial-Cable-Cars-as-Mass-Transit-Systems-Case-Studies-Technical-Specifications-and-Business-Models.

Cardona-Urrea, S., Soza-Parra, J., Ettema, D., 2024. Aerial cable cars as a transit mode: a review of technological advances, service area characteristics, and societal impacts in Latin America and the Caribbean. Transport Rev. 44 (3), 684–708.

Chakravarty, S., Ghosh, S., Suresh, C., Dey, A., Shukla, G., 2012. Deforestation: causes, effects and control strategies. Global perspectives on sustainable forest management 1, 1–26.

Coustillas, J., 2023. Quantifying your activities' impact on biodiversity. https://pre-sustainability.com/articles/quantifying-your-activities-impact-on-biodiversity/.

Crenna, E., Marques, A., La Notte, A., Sala, S., 2020. Biodiversity assessment of value chains: state of the art and emerging challenges. Environ. Sci. Technol. 54 (16), 9715–9728.

Damiani, M., Sinkko, T., Caldeira, C., Tosches, D., Robuchon, M., Sala, S., 2023. Critical review of methods and models for biodiversity impact assessment and their applicability in the LCA context. Environ. Impact Assess. Rev. 101, 107134.

De Almeida, A.T., Ferreira, F.J.T.E., Duarte, A.Q., 2014. Technical and economical considerations on super high-efficiency three-phase motors. IEEE Trans. Ind. Appl. 50. https://doi.org/10.1109/TIA.2013.2272548.

Doheim, R.M., Farag, A.A., Badawi, S., 2020. Success measures for transforming into car-free cities: recommendations for implementation. Humanizing cities through car-free city development and transformation 231–267.

Dopplemayr, 2023. Doppelmayr FAQs. https://www.doppelmayr.com/en/ropeway-faq/.

Encon. Calculation of CO2 offsetting. https://www.encon.eu/en/calculation-co2. (Accessed 14 December 2023).

Escobar, D.A.G., Sarache, W., Jiménez-Riaño, E., 2022. The impact of a new aerial cable-car project on accessibility and CO2 emissions considering socioeconomic stratum. A case study in Colombia. J. Clean. Prod. 340. https://doi.org/10.1016/j.jclepro.2022.130802.

European Commission: Directorate-General for Mobility and Transport, Armoogum, J., Garcia, C., Gopal, Y., Borgato, S., et al., 2022. Study on new mobility patterns in European cities – Final report. Task A, EU wide passenger mobility survey. In: Publications Office of the European Union. https://data.europa.eu/doi/10.2832/728583.

European Commission: Directorate-General for Climate Action, Hill, N., Amaral, S., Morgan-Price, S., Nokes, T., et al., 2020. Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA – Final report. Publications Office of the European Union. https://data.europa.eu/doi/10.2834/91418.

European Environment Agency, 2023. Europe's air quality status 2023. https://www.eea.europa.eu/publications/europes-air-quality-status-2023. (Accessed 7 December 2023).

Eurostat Statistics Explained, 2021. Passenger Mobility Statistics.

Feitelson, E., 2021. Accessing the divine and the past: jerusalem's cable car dilemmas. J. Transport Geogr. 91, 102968.
Flesser, M., Friedrich, B., 2022. Are we taking off? A critical review of urban aerial cable cars as an integrated part of sustainable transport. Sustainability 14 (20), 13560.
Franch, M., Masotti, P., Buffa, F., Meo, F., 2021. The role of the cable car in sustainable mobility: management choices and an assessment of environmental sustainability. The Trento-Monte Bondone projec. Sinergie Italian Journal of Management 39 (1), 37–59.
Fruehwirth, A., Winter, J., 2014. The emirates air line cable car an innovative, urban transportation system. T&DI Congress 2014: Planes, Trains, and Automobiles, pp. 727–736.
Gabriel, N.R., Martin, K.K., Haslam, S.J., Faile, J.C., Kamens, R.M., Gheewala, S.H., 2021. A comparative life cycle assessment of electric, compressed natural gas, and diesel buses in Thailand. J. Clean. Prod. 314, 128013.
Garsous, G., Suárez-Alemán, A., Serebrisky, T., 2019. Cable cars in urban transport: travel time savings from La Paz-El Alto (Bolivia). Transport Pol. 75, 171–182.
Gobber, A., Crepaz, H., Bacher, C., 2022a. Progetto di Fattibilità Tecnica ed Economica - CABINOVIA METROPOLITANA TRIESTE - PORTO VECCHIO - CARSO - RELAZIONE GENERALE TS1, 0110.01.R.1. https://portovecchio.comune.trieste.it/cabinovia-metropolitana/.
Gobber, A., Crepaz, H., Bancher, C., 2022b. Progetto di Fattibilità Tecnica ed Economica CABINOVIA METROPOLITANA TRIESTE - PORTO VECCHIO - CARSO - RELAZIONE SUGLI ALLACCIAMENTI IDRAULICI ED ELETTRICI ALLE STAZIONI TS1.0400.01, R.1. https://portovecchio.comune.trieste.it/cabinovia-metropolitana/.
Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A., Struijs, J., Zelm, R., 2008. ReCiPE 2008: A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level.
Harding, S., 2016. Marine Debris: Understanding, Preventing and Mitigating the Significant Adverse Impacts on Marine and Coastal Biodiversity. In: Technical Series No.83. Secretariat of the Convention on Biological Diversity. CBD Technical Series.
Helmers, E., Dietz, J., Weiss, M., 2020. Sensitivity analysis in the life-cycle assessment of electric vs. combustion engine cars under approximate real-world conditions. Sustainability 12 (3), 1241.
Hofer, K., Haberl, M., Fellendorf, M., 2024. Modeling of an urban ropeway integrated into a crowded transit system. Transport. Res. Rec. 2678 (2), 654–665.
Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22 (2), 138–147.
International Organization for Standardization, 2006a. Environmental Management: Life Cycle Assessment: Requirements and Regulations. ISO, Geneva, Switzerland.
International Organization for Standardization, 2006b. Environmental Management: Life Cycle Assessment; Principles and Framework. ISO, Geneva, Switzerland.
Khomenko, S., Cirach, M., Barrera-Gómez, J., Pereira-Barboza, E., Iungman, T., Mueller, N., Foraster, M., Tonne, C., Thondoo, M., Jephcote, C., Gulliver, J., Woodcock, J., Nieuwenhuijsen, M., 2022. Impact of road traffic noise on annoyance and preventable mortality in European cities: a health impact assessment. Environ. Int. 162, 107160.
Kuss, P., Nicholas, K.A., 2022. A dozen effective interventions to reduce car use in European cities: lessons learned from a meta-analysis and transition management. Case studies on transport policy 10 (3), 1494–1513.
Lebrusán, I., Toutouh, J., 2021. Car restriction policies for better urban health: a low emission zone in Madrid, Spain. Air Quality, Atmosphere & Health 14 (3), 333–342.
Liu, J., Yuan, Y., 2024. Exploring dynamic urban mobility patterns from traffic flow data using community detection. Spatial Sci. 1–20.
Mapelli, C., Dall'Osto, G., Mombelli, D., Barella, S., Gruttadauria, A., 2022. Future scenarios for reducing emissions and consumption in the Italian steelmaking industry. Steel Res. Int. 93 (5), 2100631.
Michelsen, O., Cherubini, F., Strømman, A.H., 2012. Impact assessment of biodiversity and carbon pools from land use and land use changes in life cycle assessment, exemplified with forestry operations in Norway. J. Ind. Ecol. 16 (2), 231–242.
Milijögiraff, A.B., 2015. LCA of Elevator Lifting Service in Property.
Mio, A., Petrescu, L., Luca, A.-V., Galusnyak, S.C., Fermeglia, M., Cormos, C.-C., 2022. Carbon dioxide capture in the iron and steel industry: thermodynamic analysis, process simulation, and life cycle assessment. Chem. Biochem. Eng. Q. 36 (4), 255–271.
Mio, A., Barbera, E., Pavan, A.M., Danielis, R., Bertucco, A., Fermeglia, M., 2023. Analysis of the energetic, economic, and environmental performance of hydrogen utilization for port logistic activities. Appl. Energy 347, 121431.
Molina-Besch, K., Wikström, F., Williams, H., 2019. The environmental impact of packaging in food supply chains—does life cycle assessment of food provide the full picture? Int. J. Life Cycle Assess. 24, 37–50.
Palantas, P., 2015. Multicriteria Analysis as a Tool for Assessing Transport Projects: ART Line in Mountain Pellion Greece. Institutional Repository - Library & Information Centre - University of Thessaly.
Papadopoulou, I., Tzanetatos, D., 2022. Evaluating transport sustainability in metropolitan Athens through a cable car proposal as a partial alternative to the announced metro Line 4. IOP Conference Series: Earth and Environmental Science. IOP Publishing, 012050.
Phuyal, S., 2020. Developing a Tourism Opportunity Index Regarding the Developing a Tourism Opportunity Index Regarding the Prospective of Overtourism in Nepal Prospective of Overtourism in Nepal.
Puhar, J., Krajnc, D., Čuček, L., Vujanović, A., 2022. Review and environmental footprint assessment of various formalin production pathways. J. Clean. Prod. 377, 134537.
Rowe, J., Narey, T., 2014. Delivering the emirates air line, London, UK: north and south stations. Proceedings of the Institution of Civil Engineers-Structures and Buildings 167 (10), 581–590.
Sandanayake, M.S., 2022. Environmental impacts of construction in building industry—a review of knowledge advances, gaps and future directions. Knowledge 2 (1), 139–156.
Sintagma, 2019. Piano Urbano della Mobilità Sostenibile (PUMS) di Trieste Fase II - Attivita' di raccolta dati. analisi e valutazioni della situazione attuale - Allegato: rilievo dei flussi di traffico.
Sutopo, Y., Jinca, M., Azmy, M., Maramis, M., Amin, M., 2020. Aerial cable car in the city centre of Makassar: the potential routes, technology and station locations. IOP Conference Series: Materials Science and Engineering. IOP Publishing, 012002.
Tahmasseby, S., 2021. Aerial ropeway system—feasibility study in Doha, Qatar. J. Unmanned Veh. Syst. 9 (2), 92–111.
Teodorović, D., Janić, M., 2017. Chapter 11 - transportation, environment, and society. In: Teodorović, D., Janić, M. (Eds.), Transportation Engineering. Butterworth-Heinemann, pp. 719–858.
Teufel, B., Sushama, L., Poitras, V., Dukhan, T., Bélair, S., Miranda-Moreno, L., Sun, L., Sasmito, A.P., Bitsuamlak, G., 2021. Impact of COVID-19-related traffic slowdown on urban heat characteristics. Atmosphere 12 (2), 243.
Težak, S., Sever, D., Lep, M., 2016. Increasing the capacities of cable cars for use in public transport. Journal of Public Transportation 19 (1), 1–16.
Tiessler, M., Engelhardt, R., Bogenberger, K., Hessel, C., Serwa-Klamouri, M., 2019. Integration of an Urban ropeway into Munich's transit system demand modeling. Transport. Res. Rec. 2673 (10), 47–57.
Urban Planning Committee, 2018. Urban gondolas in public transit - is this a viable option for edmonton. https://www.edmonton.ca/sites/default/files/public-files/assets/transit/ETSAB_Urban_Gondolas_in_Public_Transit.pdf.
Venter, Z.S., Aunan, K., Chowdhury, S., Lelieveld, J., 2020. COVID-19 lockdowns cause global air pollution declines. Proc. Natl. Acad. Sci. U. S. A. 117, 18984–18990. https://doi.org/10.1073/PNAS.2006853117/SUPPL_FILE/PNAS.2006853117.SAPP.PDF.
Verones, F., Hellweg, S., Antón, A., Azevedo, L.B., Chaudhary, A., Cosme, N., Cucurachi, S., de Baan, L., Dong, Y., Fantke, P., Golsteijn, L., Hauschild, M., Heijungs, R., Jolliet, O., Juraske, R., Larsen, H., Laurent, A., Mutel, C.L., Margni, M., Núñez, M., Owsianiak, M., Pfister, S., Ponsioen, T., Preiss, P., Rosenbaum, R.K., Roy, P.-O., Sala, S., Steinmann, Z., van Zelm, R., Van Dingenen, R., Vieira, M., Huijbregts, M.A.J., 2020. LC-IMPACT: a regionalized life cycle damage assessment method. J. Ind. Ecol. 24 (6), 1201–1219.
Woods, J.S., Damiani, M., Fantke, P., Henderson, A.D., Johnston, J.M., Bare, J., Sala, S., Maia de Souza, D., Pfister, S., Posthuma, L., Rosenbaum, R.K., Verones, F., 2018. Ecosystem quality in LCIA: status quo, harmonization, and suggestions for the way forward. Int. J. Life Cycle Assess. 23 (10), 1995–2006.
World Wildlife Fund (WWF), 2020. Living Planet Report 2020 - Bending the curve of biodiversity loss. WWF, Gland, Switzerland.
Zara, L., Tordoni, E., Castro-Delgado, S., Colla, A., Maccherini, S., Marignani, M., Panepinto, F., Trittoni, M., Bacaro, G., 2021. Cross-taxon relationships in Mediterranean urban ecosystem: a case study from the city of Trieste. Ecol. Indicat. 125, 107538.