Renewables and mining activities: the case study of Piedmont Region (NW Italy)

Renewable Energy 268 (2026) 125819

Contents lists available at ScienceDirect

Renewable Energy

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

Renewables and mining activities: the case study of Piedmont Region (NW Italy)

Martina Gizzi [a], Federico Vagnon [a,*], Glenda Taddia [a], Alessandro Berta [a,b], Stefano Paolo Corgnati [b], Stefano Lo Russo [a]

[a] Department of Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino, Corso Duca degli Abruzzi 24, Turin, 10129, Italy
[b] Department of Energy (DENERG), Politecnico di Torino, Corso Duca degli Abruzzi 24, Turin, 10129, Italy

ARTICLE INFO

Keywords:
Mining industry
Renewables
Energy challenges
Solar energy
Piedmont

ABSTRACT

Mining activities have high energy demand, significantly impacting the climate and environment due to reliance on fossil fuels, and accounting for about 30% of operating costs. Consequently, integrating renewable energy into the mining sector has been promoted by international agreements aimed at reducing carbon footprints. However, challenges remain in terms of technical and policy barriers to widespread implementation. A positive example comes from the Piedmont Region (NW Italy), where the Regional Plan for Mining Activities (PRAE) encourages the use of renewable energy through regional incentives, with ambitious goals for 2030 and 2050. This paper analyzes active mining operations in Piedmont, exploring the potential for converting some activities to renewable energy systems. It evaluates the feasibility of solar, wind, hydropower, and geothermal energy, discussing their strengths and limitations based on the energy needs of each mining operation. The study found significant potential for hydropower (including mini-hydro) in mountainous areas and geothermal energy for plain mining activities through ground-source heat pump systems. Additionally, the installation of floating solar panels on quarry lakes shows promise.

1. Introduction

The mining industry is highly energy-intensive. It has been estimated that all the mining processes, from exploration to refining, account for 10 percent of global energy consumption [1] and it is expected to increase in the next future due to the increasing of worldwide population and the progressive declining mineral ore grades [2]. All sectors of consumer society are inextricably linked to mining activities: the laptop used to write this paper contains more than 60 minerals mined from the Earth.

In terms of energy-use, the mining activities can be divided into two main categories: off-grid and grid-connected. Regardless of this classification, most of the energy (especially in off-grid mines) comes from burning fossil fuels, such as coal, natural gas and oil. Consequently, mining has a large carbon footprint [3]. However, compared to other energy-intensive sectors, mining has received much less attention (except in cases of conflict) regarding the reduction of environmental impacts. In fact, even if renewables have many potential applications in mining [2–9], only in recent years they have been considered as alternative source of energy. In particular, Igogo et al. [2] show that the integration of renewables in mining can significantly reduce emissions and operating costs, although their deployment is still constrained by technical and economic barriers [9]. Advantages are particularly evident in off-grid contexts, where renewables can be more competitive [7]. The importance of cost competitiveness and site-specific conditions is also emphasized by Zharan and Bongaerts [3]. Van der Merwe and Brent [4] demonstrate that solar PV can cover a substantial share of the energy demand in mining operations, as also highlighted by Choi and Song [5] and Strazzabosco et al. [6], who underline the potential contribution of both solar and wind systems.

The recent increase in the adoption of renewables in the mining sector is also driven by several factors, including: i) an overall reduction of the cost of renewable equipment, ii) the reduction of maintenance related to renewable plants, iii) a governance stimulation and support to renewable conversion to achieve global decarbonization goals [8], iv) the volatile prices of fossil fuels. As a consequence, the renewable capacity on mine sites has grown up from 600 MW in 2015 to 5 GW nowadays [10].

There are several global examples where renewables have been

* Corresponding author.
E-mail address: federico.vagnon@polito.it (F. Vagnon).

https://doi.org/10.1016/j.renene.2026.125819
Received 27 January 2025; Received in revised form 24 March 2026; Accepted 18 April 2026
Available online 20 April 2026

List of abbreviations

A	Surface area
a.s.l.	above sea level
b	Groundwater height
DEM	Digital Elevation Model
Δh	Difference in the hydraulic head
ΔT	Difference of temperature
E-SE	East-South East
G	Amount of heat
GIS	Geographic Information System
GW	Giga Watt
I	Hydraulic gradient
K	Hydraulic conductivity
L	Length
n_e	Effective porosity
NW	North West
PRAE	Regional Plan for Mining Activities
PV	Photovoltaic
P_{wind}	Potential power generated by wind
ρ	Density
$S_{VC_{wat}}$	Volumetric heat capacity of water
T	Transmissivity
v_{wind}	Wind velocity
W-SW	West-South West
Z	Discharge

Unit measure

h	Hour
K	Kelvin
kg	kilogram
kW	Kilo Watt
J	Joule
m	meter
m^2	square meter
m^3	cubic meter
MW	Mega Watt

successfully integrated with conventional energy systems. In a recent review paper, Strazzabosco et al. [6] identified and analyzed 27 projects, some already operational and others planned or financed, in Australia that will contribute to cover an energy production of about 200 MW. Most of these systems are based on solar PV and wind turbine technologies, others on battery storage and very few on geothermal energy. The authors highlighted that renewables are mostly adopted in off-grid mines, with a large variability in power capacity, spanned from 0.1 to 60 MW, reflecting the site-specific characteristics of these systems. Analogously, Votteler and Brent [9] highlighted the suitability of solar PV, on-shore wind and geothermal technology as potential renewables in mining operations in South Africa. Booth III and Bixley [11] reported the use of geothermal energy for the generation of electrical power in a gold mine in Papua New Guinea.

Renewables can be involved not only during mining working life but as a potential means of redevelopment of dismissed mining sites. On this purposes, many projects have been financed and realized. For instance, a 200 MW solar installation on a former coal mine at the border of Kentucky and West Virginia (USA) will go online by early 2024 and it will represent a first attempt to reduce the energy power demand by coal in the country [12]. In Queensland (Australia), a dismissed gold mine will be converted to a hydroelectrical power plant to satisfy the energy demand of about 100000 buildings. At present, one of the biggest PV solar plant (about 352 ha and 150 MW installed) is located in a ex lignite mine in Germany. Analogously in Italy, there are some examples of solar fields in dismissed mines.

In the Italian context, the Piedmont Region (NW Italy) has recently adopted the revised version of the "Regional Plan for Mining Activities" [13], setting ambitious goals for technological innovation related to energy supply and the use of renewables in its mining sectors. In particular, in synergy with the "Regional Environmental Energetic Plan" [14], the Piedmont Region aims to achieve the following targets before the 2030:

- an overall reduction of about 30% of the energy demands, with a particular focus on the activities most energy consuming, such as mining industry;
- an increase, estimated in 28%, of renewables.

Moreover, the European Commission has approved the REPowerEU [15] initiative to reduce dependence on Russian fossil fuels and supported the widespread adoption of renewables, setting the following targets:

- increase the PV solar power installed up to 600 GW before 2030;
- double the diffusion of heat pumps for thermo-solar and geothermal uses for heating and cooling;
- reducing the bureaucracy related to the authorization iter for renewable energy installation;
- speed up the production of hydrogen to replace the use of fossil fuels in strategic sectors.

Within the European and Italian regulatory framework, the permitting process typically includes several administrative steps, such as environmental impact assessments, land-use compatibility checks, grid connection authorizations, and approvals from regional and local authorities. These procedures can significantly slow down the deployment of renewable energy plants. One of the objectives of the REPowerEU initiative is therefore to simplify and accelerate these permitting procedures [15].

As a result, governance bodies have made public funds available to promote the use of renewables (mainly hydro, geothermal and solar power), as potential sources of energy cogeneration. In particular, financial support mechanisms have been introduced or reinforced within the framework of European and national energy transition policies, including the REPowerEU initiative and related national and regional programs. These measures aim to facilitate the deployment of renewable energy technologies by strengthening existing financial instruments, such as incentives for renewable installations, energy efficiency programs, and innovation funding schemes (e.g. FER2 Decree of the Italian Ministry of Environment and Energy Security).

Rather than representing a single additional funding allocation, these policy initiatives have expanded access to previously established financial resources, including funds from the Recovery and Resilience Facility and other European funding programs dedicated to the energy transition.

Although detailed data on the exact amounts allocated specifically to renewable energy projects in the mining sector are not publicly available, these policy instruments have contributed to increasing the overall availability of public funding to support the development and integration of renewable energy systems.

This paper analyses the possible strengths and limitations in the use of renewables as energy suppliers in mining activities in the Piedmont Region. In particular, renewable options were identified based on the type, size and geographical location of the mines.

2. An overview of the mining industry and its operations in the Piedmont Region

Mining and quarrying materials can be classified into: industrial minerals, metal minerals, aggregates and mineral fuels. The energy demand for each sector is undoubtedly different and depends also by the mine type (underground, open-pit, etc.), its size (included the related plants) and the means used for the exploitation.

In the Piedmont Region, according to the PRAE, three mining sectors (in the following named as “Comparto”) were identified (Fig. 1):

- “Comparto I”, which includes mining activities that produced aggregates for constructions and infrastructures. The geomaterials belonging to this sector are: no siliceous sands, gravels, pebbles and, more in general, alluvial quaternary deposits used for concrete, asphalt and ballast production.

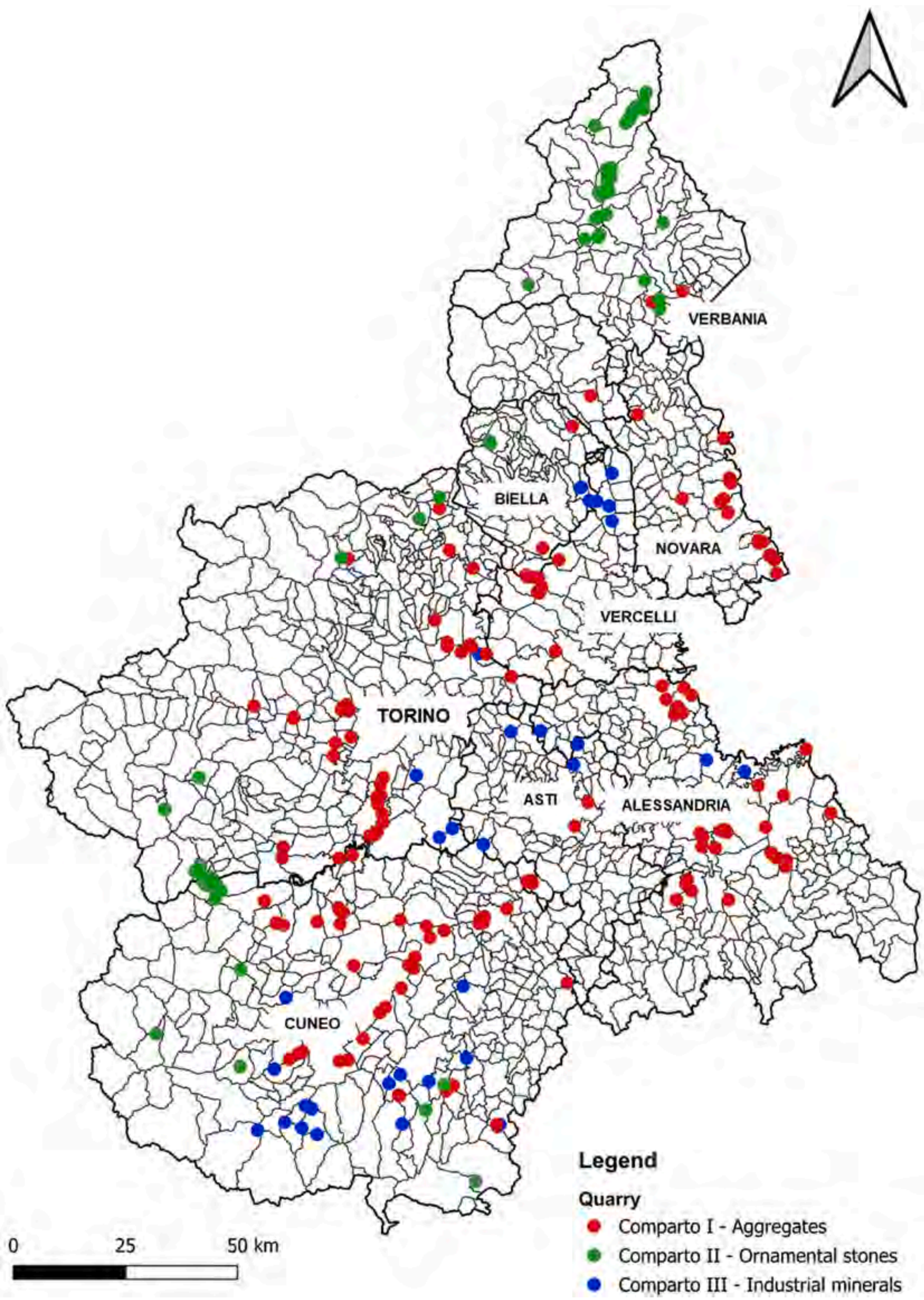

Fig. 1. Distribution of the active quarries in Piedmont Region, divided in mining sectors: Comparto I – Aggregates (red markers), Comparto II – Ornamental stones (green markers) and Comparto III – Industrial minerals (blue markers). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

- “Comparto II”, which includes ornamental stone quarries. Acid metamorphic rocks, such as gneiss and michaschist, or igneous rocks, such as granite, sienite and diorite, are mainly exploited; marbles and sedimentary rock quarry are a marginal percentage (less than 6%).
- “Comparto III”, which includes industrial materials, subdivided in clays materials, limestones and dolomites, gypsum and other siliceous minerals (siliceous or feldspar sand, quartzite).

At present, 279 active mining enterprises [16] are locate in Piedmont Region (dots in Fig. 1). The 52% belongs to the sector of aggregates (Comparto I), followed by the 37% who exploits ornamental stones (Comparto II) and the 11% is involved in the production of industrial materials (Comparto III). These mining enterprises have a moderate to small economic impact compared to the average at European scale. As it is shown in Fig. 2a, there is a wide heterogeneity in terms of economic dimensions (blue bars in Fig. 2a) and number of employes (red bars in Fig. 2a) between each mining sector: the industrial materials leads over the other two sectors. However, by analyzing the economic output per employee (Fig. 2b), the variation is not so significant. These two aspects highlight a different susceptibility to counteract economic crisis and also a different propensity to face energy transition challenges.

Although the relative small size of the mining enterprise, in terms of economic availability and numbers of employees, might suggest that the Piedmont mining sector is less inclined to innovation and research, local and national incentive programs have supported the transition from traditional to modern and highly specialized enterprises. In the framework of renewables, these factors should not be considered drawbacks, as smaller operations mean lower energy demands, which in turn facilitate the exploration of different green energy solutions.

In the next Sections, opportunities and limitations about the integration of renewables into mining operations will be discussed. Based on open datasets, the potential application of solar, wind, geothermal and hydro power will be investigated for each active mining activities located in the Piedmont Region.

3. Material and methods

The evaluation of the possible integration of renewables into mining processes for the active mining activities in the Piedmont Region requires the definition of mining archetypes. Three criteria were selected for this purpose:

- Elevation above the sea level;
- Total annual energy consumption for each mining sector;
- Percentage of annual energy demand that possibly could be covered by electrical power.

For the first criterion, mining activities were classified as “mountain quarries” if located at an altitude higher than 600 m and “plain quarries” if locate at an altitude below 600 m. Although there is no real distinction between mountain and plain quarries, this classification follows the Italian law (Law No. 991/1952), which recognizes 600 m a.s.l. as the boundary between plain and mountain areas. This distinction is important not only for selecting the most suitable renewables, whose potential might be matched to the existing energy source, but also for considering possible access limitation and morphological issues in these areas.

The second criterion estimates the total energy required to conduct all mining activities. This parameter, as will be discussed in the next sections, includes the total power used for exploiting the material, transportation, possible secondary activities such as washing, crushing, and classification, and the presence of power generators, whether in an off-grid configuration or to supplement energy deficits. These data were provided by the Mineral Police Sector, Quarries and Mines of the Piedmont Region and refer to the 2022. However, the dataset does not include data relating to the energy demand of administrative offices and changing rooms.

The last criterion assesses the percentage of energy that could hypothetically be supplied by renewables. Currently, many mining operations, especially those related to exploitation (drilling and excavations) and transport (mostly road-transport), are based on fossil fuel, making it difficult to substitute them with renewables. However, some mining operation such as wire drilling or processes like washing, crushing and sorting could potentially be partially or fully powered by renewables.

Once the mine archetypes were defined, the potential renewable energy sources were identified and evaluated. Based on the availability in the Piedmont Region, four renewables were identified as potential for integrating energy in mining operations: solar power, hydropower, ground source low-enthalpy geothermal energy, and wind power. Since, at present, there are no available regional scale maps of these renewables (except for the closed-loop ground source geothermal system potential map), the analyses were based on the comparison of selected parameters with the location and energy demand of each mining activity. In particular, under the criteria of free and public access, the following public databases (Fig. 3) were taken into account:

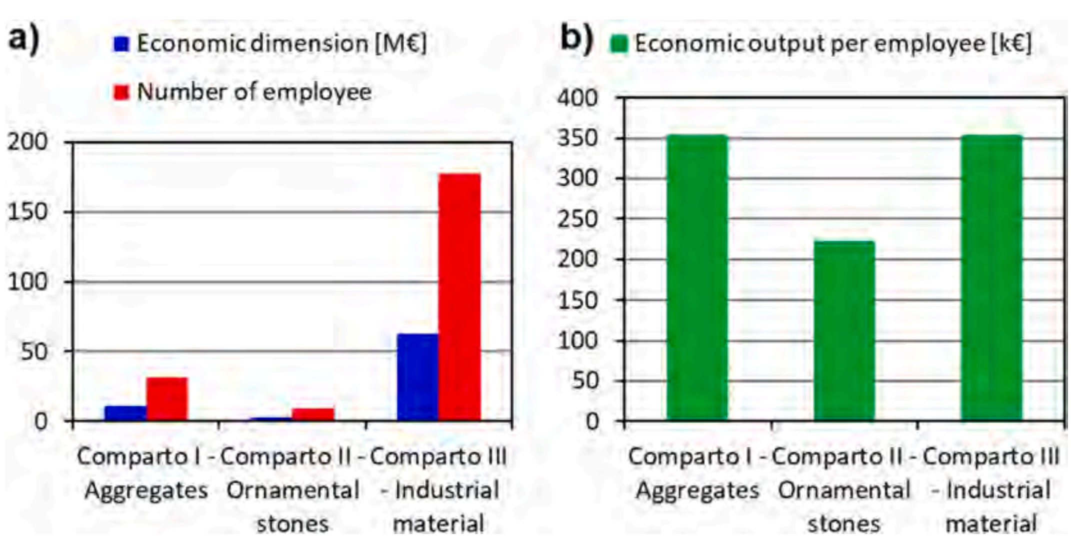

Fig. 2. Trends of the a) average number of employees and economic dimension and b) the economic output per employee of the Piedmont mining enterprises for each mining sectors.

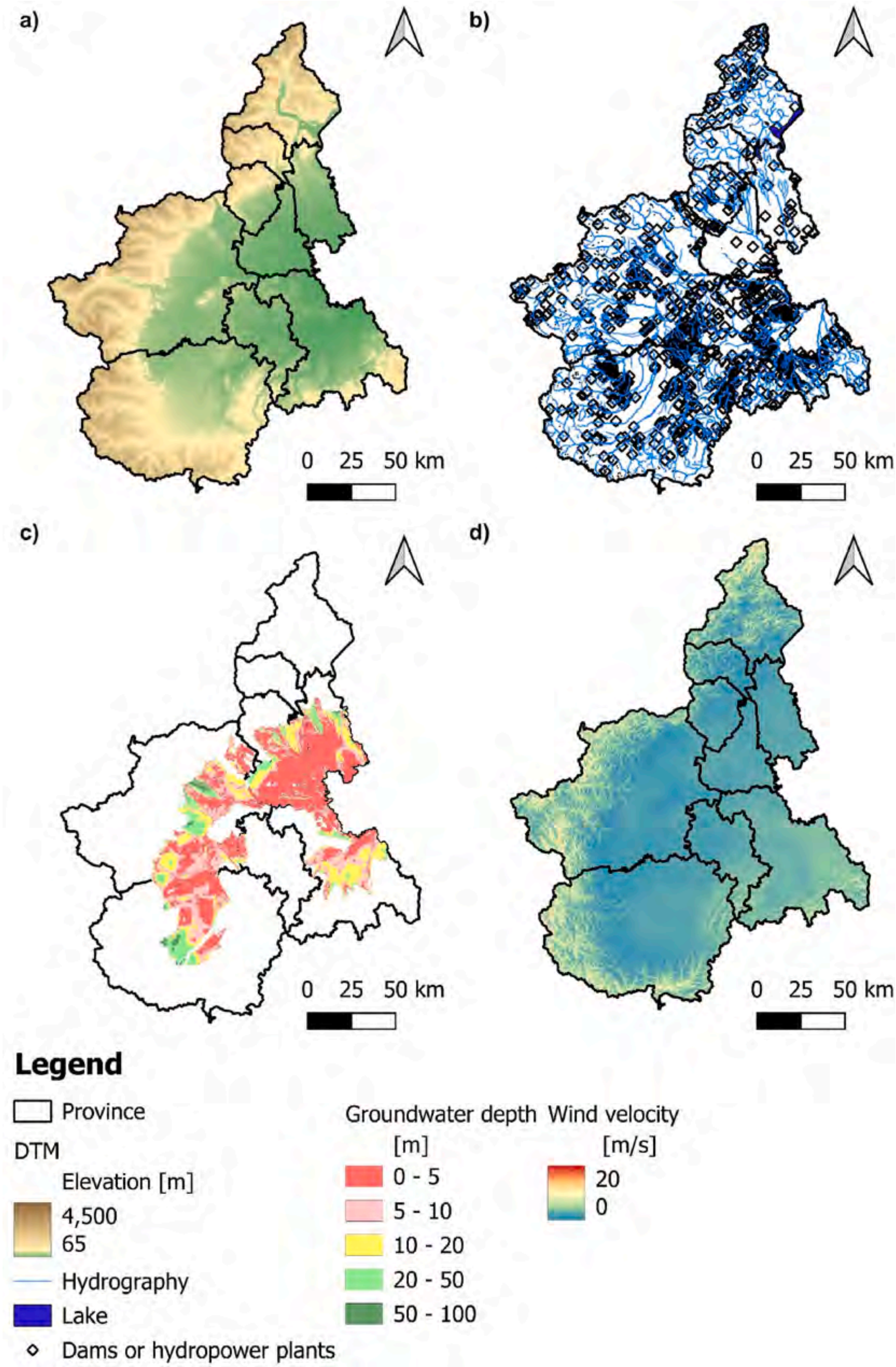

Fig. 3. a) 25 × 25 m resolution DTM and map of the b) regional hydrography, c) groundwater depth of the plain sectors of the region and d) distribution of the wind velocity at 50 m high from the ground.

- Digital Elevation Model (DEM) of the Piedmont Region at scale 1:25000 with 25m × 25m resolution cells (Fig. 3a);
- Map of the regional hydrography at 1:100000 and distribution of the existing dams and hydropower plants (Fig. 3b);
- Map of the regional groundwater depth of the superficial aquifer at scale 1:50000 (Fig. 3c);
- Map of distribution of the wind velocity at 50 m high from the ground at scale 1:50000 (Fig. 3d).

These databases, in the form of raster or shape files, were analyzed within a GIS environment using QGIS software, version 3.34.1-Prizren.

For solar power, the analyses was conducted considering both the elevation of the quarry above the sea level and its average exposure. Specifically, quarries with southern exposure (ranging from W-SW to E-SE) were considered more favorable compared to those exposed to the north. Based on these assumptions, the QGIS plugin r.sun [17] was used to evaluate the global irradiance/irradiation at the mining site. Subsequently, the annual potential electricity generation from a 1 kWp (1 kWh/kW_{peak}) solar system by considering the optimally-inclined photovoltaic modules with a performance ratio of 0.75 was estimated using the PVGIS tool developed by the EU Commission's Joint Research Centre (JRC Photovoltaic Geographical Information System (PVGIS) - European Commission).

The hydropower potential was analyzed at two levels: one taking into account the distances from the most important hydrographical sources (lakes and streams of all orders), while the second considered the proximity to existing dams and hydropower plants. This was done to explore the potential for new hydropower plants or mini-hydro projects or the enhancement of existing ones (if feasible), to increase the mining energy supply.

For wind power potential, it has been estimated from the map of wind velocity at 50 m height above the topographical surface by using the following equation:

$$P_{wind} = \frac{1}{2}\rho v_{wind}^{3} A \tag{1}$$

where P_{wind} is the potential power generated by wind in W, A is the surface area of the air swept by a rotor in m^2, ρ is the air density and equals to 1.225 kg/m^3 and v_{wind} is the wind velocity in m/s. Analogously to the previous renewables, this power per unit area of the rotor was directly compared with the location of the quarry.

For the geothermal potential, the analysis is more complex: a map of the potential distribution of available fluid temperature at depths greater than 1000 m exists [18], but it is at an European scale and consequently affected by scale issues and applicability. However, the estimated temperatures are not satisfactory for high enthalpy geothermal plants and limited to specific area of the Piedmont region, as discussed in the next sections. Ground-source heat pump system, both in open and closed loop, might represent an interesting renewables due to the development and the technological maturity of these technologies. While a regional map of the geothermal potential has been developed for closed loop system (Politecnico di Torino 2021), no such map is yet available for open-loop systems. Consequently, for geothermal energy potential, the closed-loop map, based on the G.POT method [19] was used.

For the open loop, a preliminary potential map was developed, under the following assumption:

- the amount of heat, G, that can be extracted from the superficial aquifer is based on the equation:

$$G = S_{VC_{wat}} \cdot Z \cdot \Delta T$$

where $S_{VC_{wat}}$ is the volumetric heat capacity of water, equal to 4.18 $MJK^{-1}m^{-3}$, Z is the water discharge that can be utilized and ΔT is the maximum temperature difference between the undisturbed aquifer temperature and the reinjected water.

- In accordance with current regional regulations [20], the maximum allowable temperature difference is 7 K.
- Since Z depends on the aquifer yield, Darcy's law was used to estimate it. Specifically, Z can be calculated as:

$$Z = \frac{K}{n_e} \cdot A \cdot \frac{\Delta h}{L} = \frac{K}{n_e} \cdot b \cdot L \cdot i = \frac{T \cdot L \cdot i}{n_e}$$

where K is the hydraulic conductivity of the aquifer lithology, ne is the effective porosity (assumed to be 20%), A is the considered flowing area, Δh is the hydraulic head difference between two adjacent DEM cells, L is the length of the section considered assumed to be 50 m in this study, b is the superficial aquifer thickness and T is the aquifer transmissivity.

- Δh and b can be evaluated from the groundwater depth map (Fig. 3c).
- Since a K map is not available, K values were evaluated using an existing database of K values measured from pumping test at wells.

For all the previously generated maps, a direct analysis and evaluation of renewable energy potential was performed by comparing the archetypes of active mining activities, which will be described in the following sections.

4. Analysis of the active mining activity archetypes in piedmont

Fig. 4 shows the distribution of Piedmont mining activities based on the topographic criterion of 600 m a.s.l. Specifically, Fig. 4a presents the mining activities located above 600 m a.s.l., hereafter referred to as "mountain" activities, while Fig. 4b shows the so-called "plain" activities. Out of a total of 279 mining activities, 92 (33%) are located in mountain areas, and 187 (67%) are located in plain areas. As expected, due to the Piedmont geological context, most of the mountain mining activities involve ornamental stones (80 out of 92 - 87%) and industrial mineral (10 out of 92 - 11%). In contrast, aggregates are predominantly exploited in plain areas (142 out of 187 – 76%), while the distribution of ornamental stones and industrial mineral is nearly equal (23 and 22 out of 187, respectively).

For what it concerns the amount of energy installed (and consequently consumed) at the mining activities in Piedmont, based on the 2022 database provided by the Mineral Police Sector, Quarries and Mines of the Piedmont Region, the results are shown in Fig. 5 for each mining sector. Box plots were used to better illustrate the statistical distribution of the dataset, highlighting the mean, median and the first and third quartile values. Specifically, mining energy consumption was subdivided into the following subcategories:

- Excavation machinery (Fig. 5): this category includes all the equipment used for mining operation such as dozers, draglines, excavators, loaders, drilling machines and diamond wire cutting machines. Additionally, excavation machinery was further categorized by power source: fossil fuel (Fig. 5a) and electrical power (Fig. 5b - such as diamond wire cutting machine and dragline).
- Material handling: this category includes all the equipment used for the movement and transport of the exploited material, such as dump trucks and derricks. Analogously to the previous category, material handling was categorized based on power source (Fig. 5c and d).
- Mining operations (Fig. 5e): this category includes all the secondary mining processes, such as crushing and washing of the material and pumping operations.
- Conveyor belt (Fig. 5f): it was excluded from the material handling category due to is specific application.
- Power generators (Fig. 5g): this category includes the off-grid or portable power generation systems.

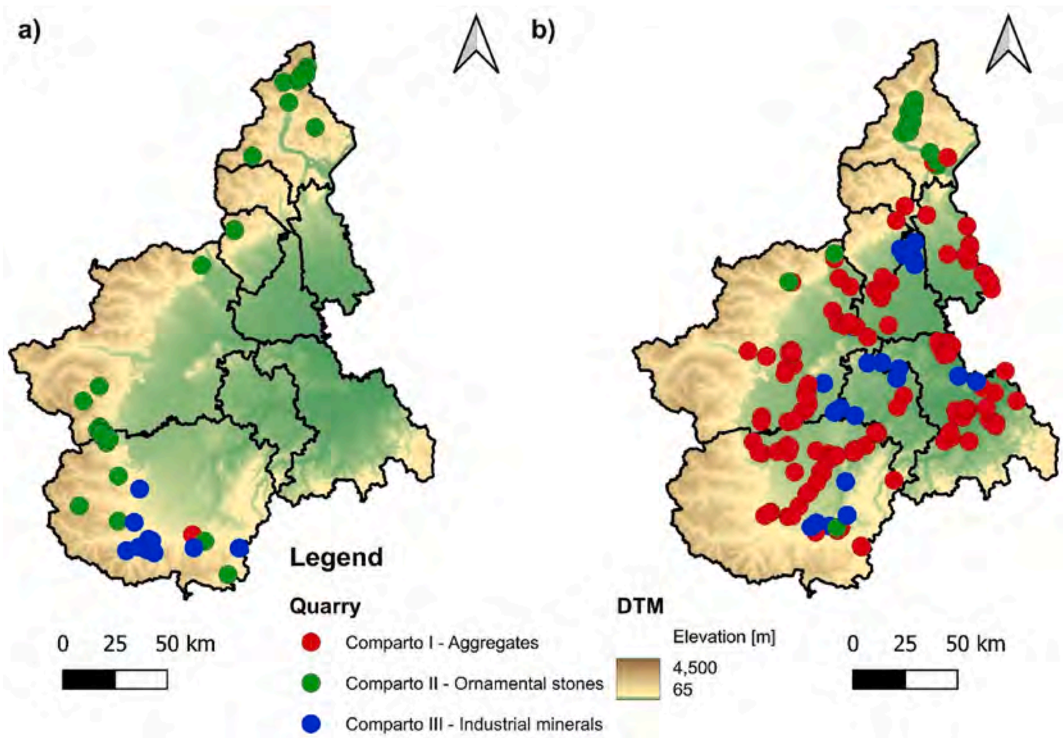

Fig. 4. Distribution of a) "mountain" and b) "plain" mining activities, subdivided by mining sector (red, blue and green dots). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 5 and Table 1 illustrate that the energy consumption of mining activities in the Piedmont Region is relatively moderate compared to other mining operations worldwide. As expected, the three sectors have an average power consumption of around 1.5 MW, with peaks reaching up to 16 MW in the industrial minerals sector (Comparto III). Overall, the exploitation of industrial minerals is the most energy-intensive sector, followed by the aggregates sector and the ornamental stone extraction. This is primarily due to the energy demands of secondary mining processes, as seen in Fig. 5e. Excavation machinery (Fig. 5a) also represents a significant portion of energy consumption across all mining sectors.

Fig. 6 shows the total installed power (Fig. 6a) and the electrical power (Fig. 6b) installed at each mining site, confirming the general findings previously discussed. The installed power refers to the total power capacity allocated for the mining operations. It is sourced from grid power and diesel generators, and encompasses all power requirements for machinery, processing facilities, ventilation systems, and auxiliary services necessary for the mine's functioning. In detailed, the analysis of Fig. 6 highlights two main aspects: the relatively small scale of operations, most of which are conducted at a local or familiar level, and the limited use of processes and machinery powered by electricity.

While this might initially appear to be a limitation, it presents a significant opportunity to transition from fossil fuels to renewable energy sources in certain mining activities, particularly within the aggregates and industrial minerals sectors, especially considering that the potential for renewable energy production represents 20% on average. For instance, power generators could potentially be replaced by renewable energy solutions. Additionally, there is potential for renewables to support the transition in areas such as conveyor belts, power generation, and certain mining operations, particularly in secondary processes like crushing and cutting.

5. Opportunities and challenges for integrating renewable energy in mining operations

5.1. Solar

The first renewable energy source analyzed was solar power. Following the procedure outlined in Section 3, a map of the potential solar electricity production for the Piedmont Region was developed (Fig. 7a). The potential solar production was then assigned to each mining site based on the location of its centroid.

Fig. 7a illustrates the spatial distribution of global solar irradiation across the Piedmont Region. It highlights the distinct differences between mining sites in the plains (circle markers) and those in mountainous areas (diamond markers). Generally, mining sites located in the plains exhibit higher potential for solar power utilization, benefiting from more consistent solar exposure, less topographical shading, and larger, more suitable areas for solar panel installation. This trend is particularly evident across central and northern plains, though some exceptions are observed in the southern region, where favorable solar conditions exist even in more elevated areas.

Fig. 7b complements this by visually correlating the average potential solar production (represented by marker colors) with the electrical power consumption of each mining site (indicated by marker diameters). Sites with higher potential solar production tend to be located in flatter regions with fewer geographical obstacles to solar capture, thus displaying larger colored markers. However, larger diameters (indicating higher electricity consumption) suggest that some mining sites with greater power demands may not fully meet their energy needs through solar power alone, particularly in mountainous regions where solar potential is lower.

This visualization offers a clear comparison between solar power potential and current energy demands. However, limitations remain: the analysis does not account for the precise available surface area for solar installations at each site, nor does it incorporate variations in the efficiency of solar technologies. These factors could significantly affect the

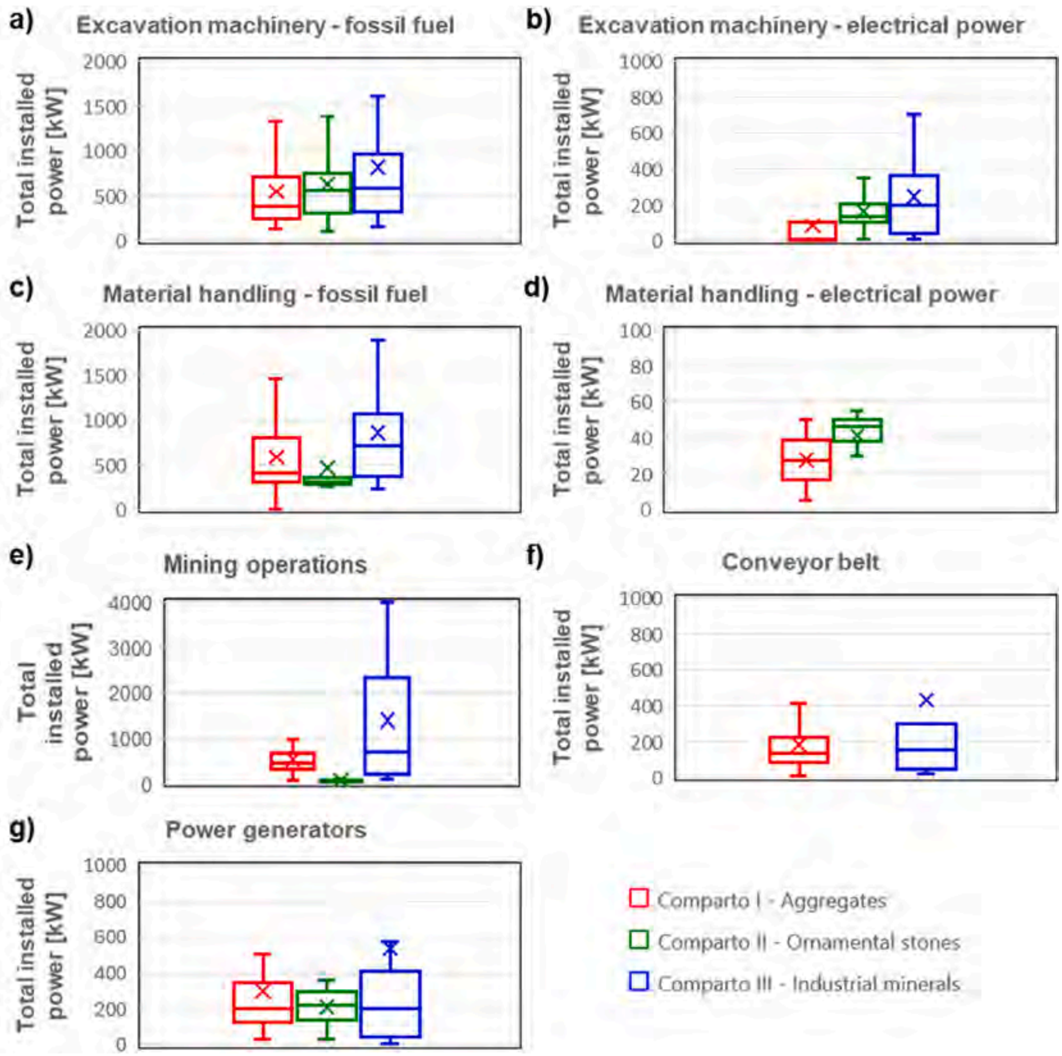

Fig. 5. Box plots for each mining category. a) and b) excavation machinery, using with fossil fuel and electrical power, respectively, c) and d) material handling using with fossil fuel and electrical power, respectively, e) mining operations, f) conveyor belt and g) power generators.

Table 1
Statistical characteristics of the total installed power in the mining activities in Piedmont Region.

	Total power installed			
	Installed Power [kW]			
	Average	Min	Max	Median
Comparto I - Aggregates	1447	122	4342	1249
Comparto II - Ornamental stones	979	194	3523	817
Comparto III - Industrial minerals	2345	150	15959	1193

actual energy production. Despite this, the map provides a solid preliminary understanding of where solar energy production might be most feasible, laying the groundwork for more detailed site-specific studies.

5.2. Wind

Assuming a potential rotor radius of 50 m, as outlined in Section 3, a map of potential wind production for the Piedmont Region was developed (Fig. 8a). Similar to Fig. 7a, the potential wind production was then assigned to each mining site based on the location of its centroid.

However, it is clear that wind energy is not the most suitable renewable option for the majority of mining sites in the Piedmont Region. Most mining operations, especially those located in the plains, exhibit limited potential for harnessing wind as a viable source of transition energy. Only a small number of sites, mainly situated in the northern and eastern parts of the region, along with a few in the southern mountainous areas, show some potential for wind energy generation. Even at these locations, however, the expected production capacity remains modest, typically below 2.5 MW.

As a result, the electrical power demands of these mining sites cannot be adequately met by wind energy alone (Fig. 8b). The disparity between wind energy potential and the energy consumption of the mining sector indicates that alternative renewable energy sources or supplementary energy strategies must be considered to achieve sustainable energy transitions in these areas.

5.3. Geothermal energy

Fig. 9 shows the distribution of temperature at a depth of 1000 m below the surface in Piedmont Region. The temperature values indicate that the potential for high-enthalpy geothermal applications, such as electrical power production, is neither technically nor economically viable in this region. A limited area in the southern part of the region exhibits temperatures higher than 80 °C, which could potentially be considered for some medium-enthalpy applications. However, there are no active mining activities in that area.

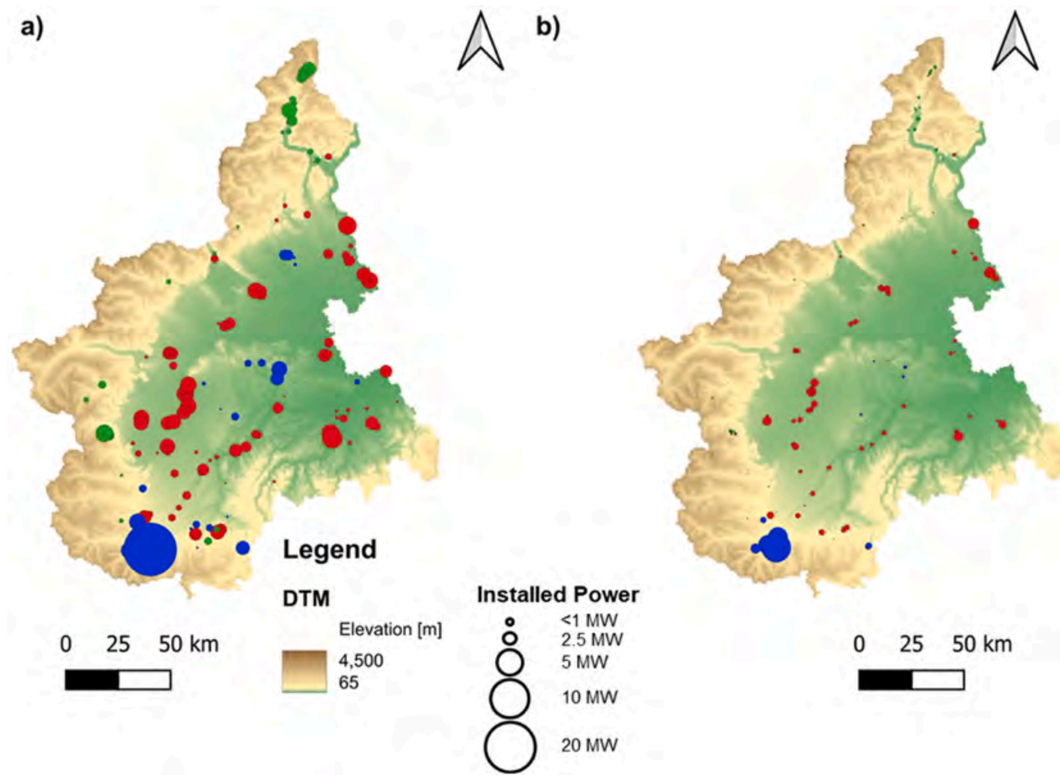

Fig. 6. a) Total and b) electrical power installed at each mining site in the Piedmont region. The marker colors represent different mining sectors: red for aggregates (Comparto I), green for ornamental stones (Comparto II), and blue for industrial minerals (Comparto III). The diameter of the circles corresponds to the installed power. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

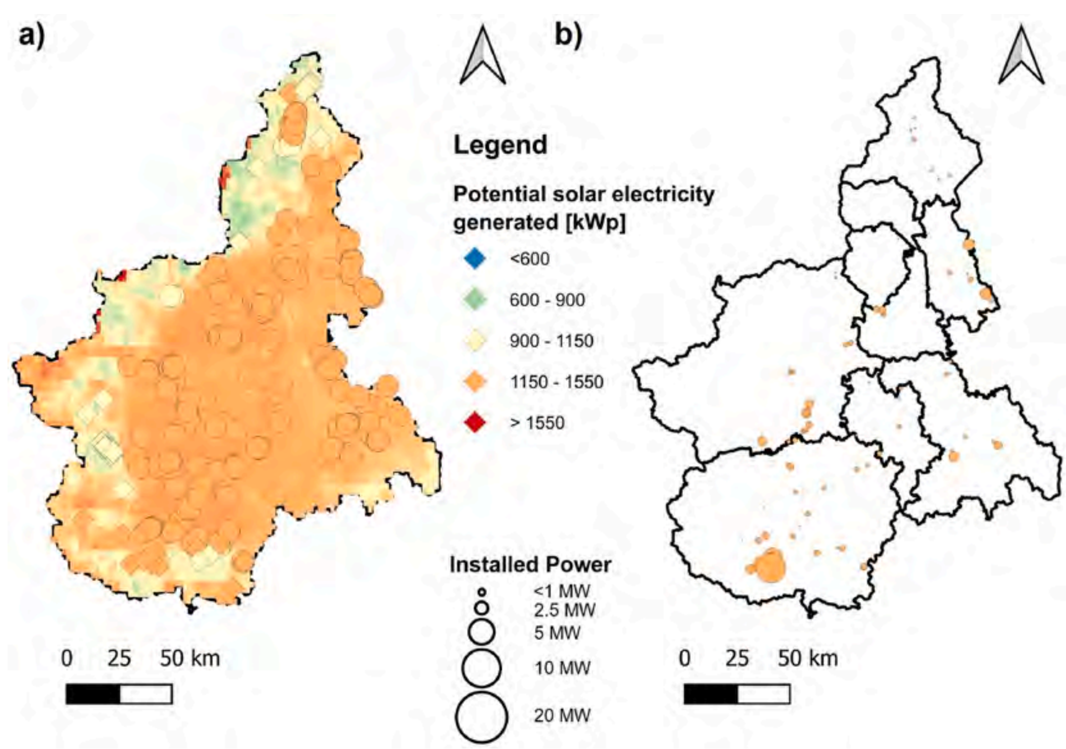

Fig. 7. a) Map of annual potential electricity generation from a 1 kWp (1 kWh/kW$_{peak}$) solar system by considering the optimally-inclined photovoltaic modules with a performance ratio of 0.75 in the Piedmont Region, showing the distribution of plain (circle markers) and mountain (diamond markers) mining sites. b) Comparison of average potential solar production (marker colors) and electrical power consumption (marker diameters). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

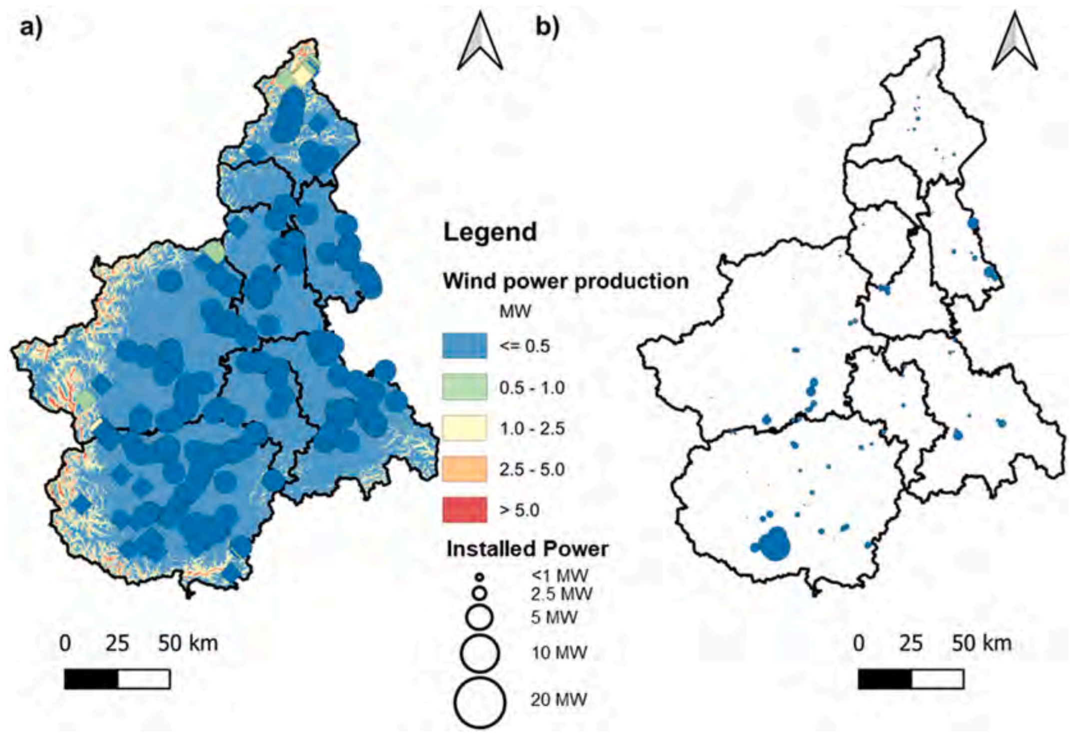

Fig. 8. a) Map of wind power in the Piedmont Region, showing the distribution of plain (circle markers) and mountain (diamond markers) mining sites. b) Comparison of average potential wind production (marker colors) and electrical power consumption (marker diameters). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

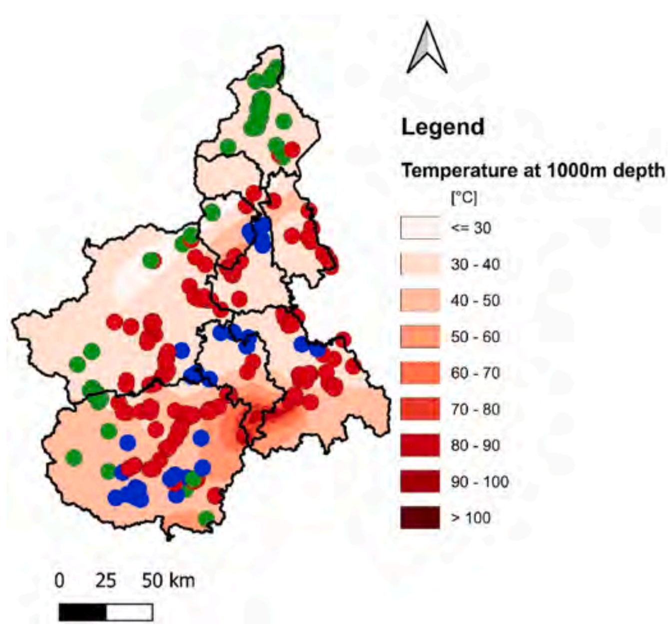

Fig. 9. Temperature at a depth of 1000 m below the ground surface. The marker colors represent different mining sectors: red for aggregates (Comparto I), green for ornamental stones (Comparto II), and blue for industrial minerals (Comparto III). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

For these reasons, Figs. 10 and 11 analyze the low-enthalpy geothermal potential of the region as a potential renewable resource for energy generation in mining activities. In particular, Fig. 10a shows the regional map of closed-loop geothermal potential based on the G. POT method [19]. This method assumes that heat transfer in the ground occurs solely through conduction, neglecting the effects of advection and thermal dispersion. Although conservative, as groundwater flow can increase thermal power by 20-30%, this estimation provides a cautious measure of the geothermal potential.

In the alluvial plains, the geothermal potential is conservatively estimated, yet these areas show excellent potential for closed-loop geothermal systems. In low-altitude mountainous areas (below 1200 m), geothermal potential can reach up to 1 MWh/year, driven by high thermal conductivity of the lithologies and moderate ground temperatures. However, potential decreases with altitude as temperatures drop. Overall, the median geothermal potential for the region is 10.5 MWh/year, with no particularly low-potential areas identified below 2000 m in elevation. Consequently, closed-loop geothermal systems can be considered a potential renewable energy source, although they may not fully meet the energy demands of Piedmont's mining activities (Fig. 10b).

The development of an open-loop geothermal plant requires a thorough and site-specific evaluation, in addition to the fulfilment of extensive well authorisation procedures. Regulatory authorities mandate the use of numerical simulations as a standard requirement [21]. However, applying such simulations at a regional scale presents significant challenges, particularly due to the lengthy computation times involved. As outlined in the methodology section, in the absence of an existing regional-scale geothermal map for open-loop systems, a new map was generated based on the approach previously described, incorporating the following assumptions:

- Only plain areas where considered since they host porous and shallow aquifers.
- Areas with groundwater depths (Fig. 3d) greater than 50 m were excluded from the calculations, as they were deemed economically unfeasible for well drilling. According to the official regional cost list [22], drilling a well with a 500 mm diameter costs approximately €400 per meter. Considering that open-loop systems typically require two wells, the total cost becomes economically prohibitive.

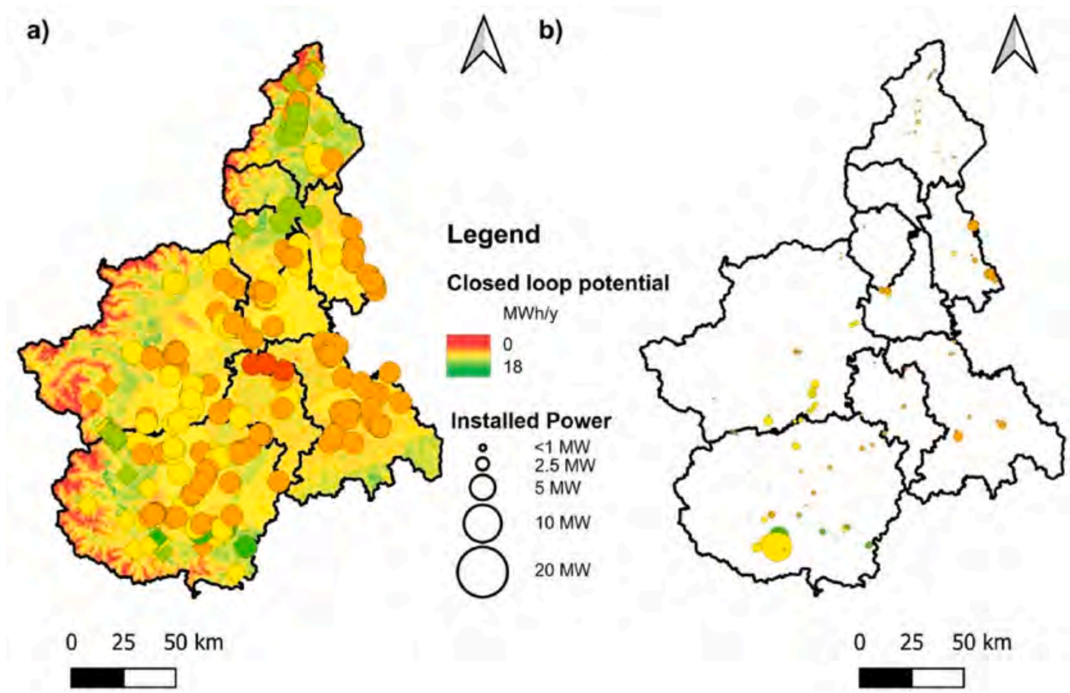

Fig. 10. a) Map of closed-loop geothermal potential in the Piedmont Region, showing the distribution of plain (circle markers) and mountain (diamond markers) mining sites. b) Comparison of average geothermal potential for closed-loop systems (marker colors) and electrical power consumption (marker diameters). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

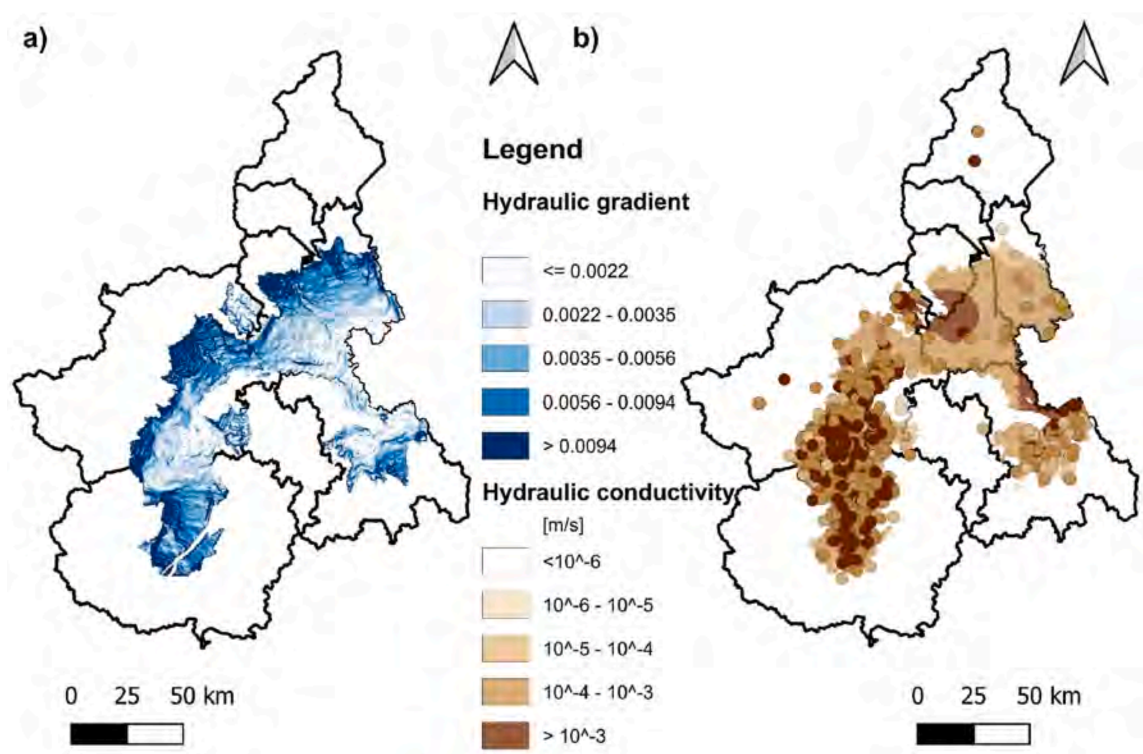

Fig. 11. Maps of a) hydraulic gradient, i, and b) hydraulic conductivity, K, distribution with the locations of the wells used for the estimation (circle markers).

- Grid cells with a hydraulic gradient greater than 0.1 were also excluded (Fig. 11a). These cells were located at the boundary of the study area and were likely the result of errors in mathematical approximations rather than actual values.
- The hydraulic conductivity distribution (Fig. 11b) was developed by performing a kriging of the K values measured from pumping test at wells (Fig. 11b).
- The maximum temperature difference was set to 7 K to comply with regional regulations [11].

Fig. 12 shows the open-loop geothermal potential for the plain sector of the Piemonte region. The areas with higher geothermal potential (red and orange zones) could be particularly advantageous for activities that demand heat, such as heating for administrative offices, workers' changing rooms, and canteens, or electricity for machinery, processing, and extraction activities, thereby reducing reliance on external energy sources.

The ability to harness geothermal energy in these regions can significantly lower energy costs for extraction enterprises, offering a sustainable energy source to support operations and enhance overall efficiency. However, this renewable resource can also be considered for supplying smaller-scale or localized operations where the aquifer yield is particularly high.

5.4. Hydro power

Mapping the potential for renewable energy from hydropower presents significant challenges due to the complexity of factors that influence the viability of such systems. Unlike solar or wind energy, where potential can often be correlated directly with environmental conditions (such as solar radiation or wind speed), hydropower potential is highly dependent on site-specific factors. These include: i) topography, which affects the energy that can be harnessed from water flows, ii) hydrology that can vary seasonally and geographically and iii) existing infrastructures, which significantly influence the feasibility of energy production in a given area.

Due to these complexities, it is not feasible to create a straightforward map showing hydropower potential based solely on environmental factors. Instead, a more practical approach was adopted, focusing on proximity to key hydrological features (Fig. 13). Specifically, we used the distance from main drainage systems (Fig. 13a and b) and existing dams (Fig. 13c and d) as proxy indicators for potential hydropower exploitation.

Fig. 13 illustrates this approach. The rationale behind this approach is that areas closer to these features are more likely to have favorable conditions for hydropower, as they already demonstrate the necessary water flow and infrastructure.

This method allows for an approximation of potential locations for hydropower expansion, despite the inherent complexity and variability in the natural and built environment that influences actual energy production capabilities.

The results show that there is good potential for implementing this renewable energy source, particularly for more energy-efficient mining activities in the southern part of the region.

6. Discussions

In the previous section, the energy demands of mining activities were highlighted, along with the potential of wind, solar, geothermal, and hydropower to contribute to the energy transition of mining operations in Piedmont. Mining is traditionally an energy-intensive activity due to the heavy machinery and extraction processes involved, as confirmed by Fig. 6. However, this data may have limitations because it is based on self-reported information from mining activity owners and is also incomplete.

The results obtained in this study are consistent with previous international research on renewable energy integration in the mining sector, which highlights the strong potential of hydropower and solar energy [8], while indicating a more limited and site-dependent role for wind [5] and geothermal resources [11]. Similar findings have been reported in studies conducted in Australia [6], South Africa [4], and other regions [2], where renewable energy adoption in mining is largely influenced by local climatic, geological, and infrastructural conditions.

Table 2 lists the number of active power plants located in the Piedmont region. As noted, wind power plants are relatively limited in number, yet they exhibit higher average energy outputs compared to solar, with a mean installed capacity of 1.25 MW. Similarly, hydropower plants have an average power output of 1.837 MW, making them more

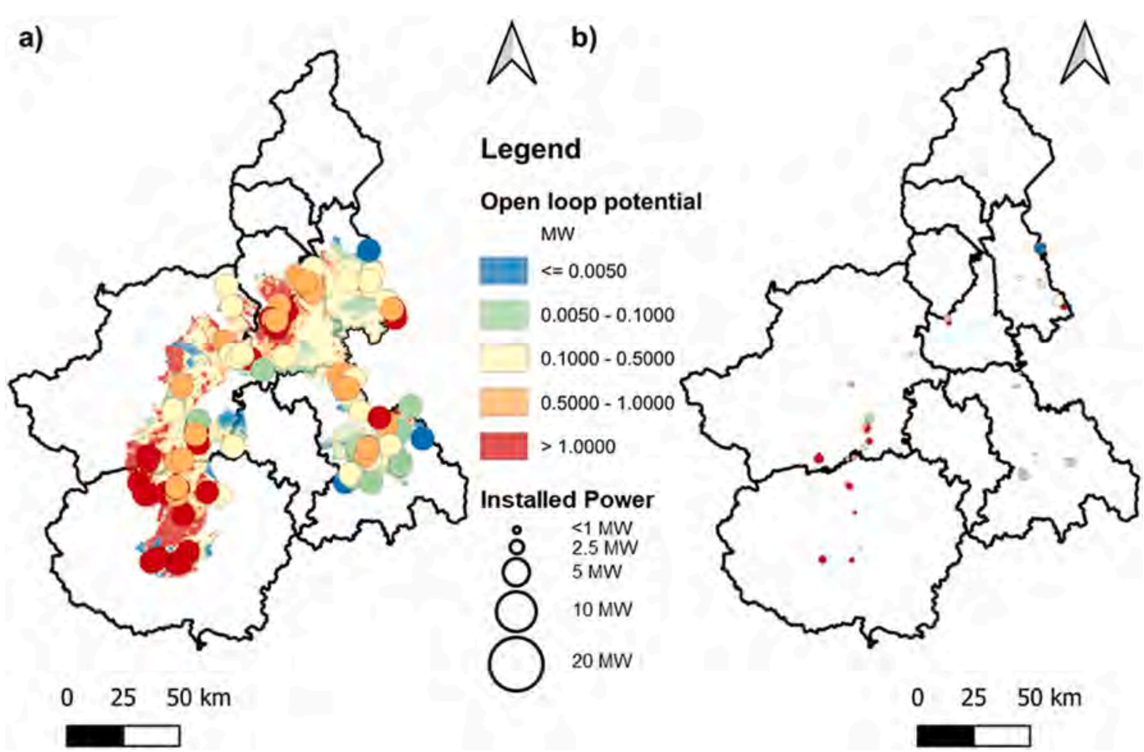

Fig. 12. a) Map of open-loop geothermal potential in the Piedmont Region, showing the distribution of plain (circle markers) mining sites. b) Comparison of average geothermal potential for open-loop systems (marker colors) and electrical power consumption (marker diameters). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

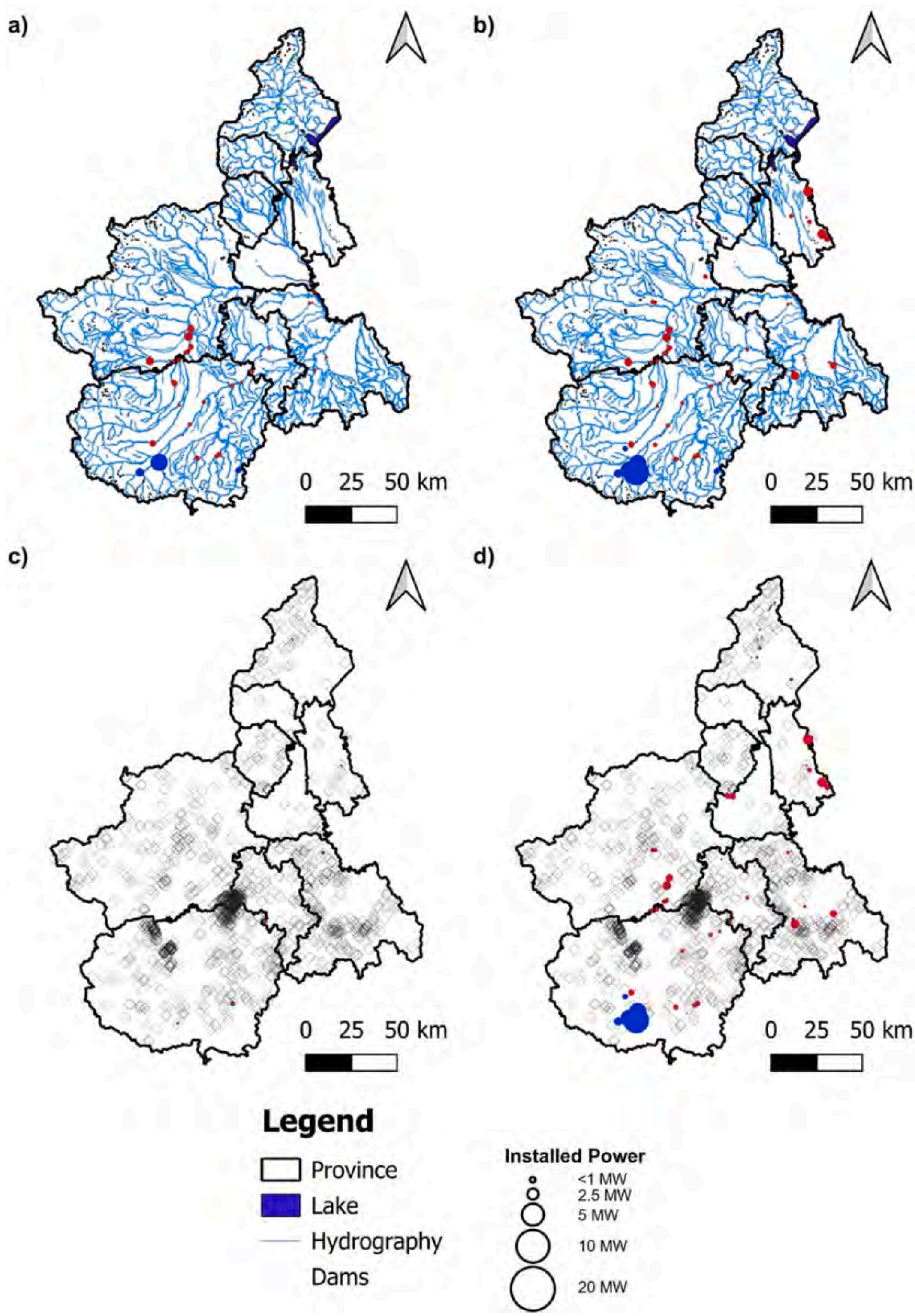

Fig. 13. Quarry distribution subdivided by installed electrical power within a distance of 1000 m and 5000 m respectively from the principal hydrographic channel or lake (a and c) and dams (b and d).

compatible with the high energy demands of mining operations. In contrast, although there are many solar power installations, each has a much smaller average capacity per plant, currently limiting their application to local uses such as buildings. This pattern is in line with broader European trends, where solar energy is often implemented in distributed configurations, while hydropower remains one of the most reliable large-scale renewable sources [23].

Interestingly, the maximum power production of these renewables shows that hydropower, as expected, has the highest energy output, followed by wind and solar. This suggests that each of these renewable sources could serve as a valuable supplemental energy source for mining processes, as their maximum outputs align with the electrical power demands of most mining activities (Fig. 6b).

An additional technology that may deserve consideration in future

Table 2
Number of plants in the Piedmont region that utilize wind, solar, and water as renewable energy sources, along with their corresponding average, maximum, and minimum power values (Atlaimpianti Internet (gse.it)).

Source	# Plants	Mean [MW]	SD [MW]	Max [MW]	Min [MW]
Wind	15	1.250	3.473	12.500	0.0028
Sun	62213	0.026	0.154	8.277	0.0008
Water	826	1.837	9.793	181.352	0.0011

studies is pumped storage hydropower [24]. This solution could be particularly relevant in mountainous areas of the Piedmont region, where significant elevation differences may provide favorable conditions for energy storage through upper and lower reservoir systems. In such contexts, pumped storage could help mitigate the intermittency of renewable energy sources, such as solar and wind, by storing excess energy and releasing it during periods of high demand. However, the implementation of pumped storage systems requires large-scale infrastructure, suitable topographic and hydrological conditions, and detailed site-specific feasibility analyses, including environmental and economic assessments. For these reasons, this technology was not included in the present regional-scale evaluation, which focuses on renewable solutions more directly applicable to existing mining activities. Nevertheless, pumped storage hydropower represents a promising direction for future research, particularly in areas where mining sites could potentially be integrated into multi-purpose energy systems.

Regarding solar power, an opportunity is presented by floating solar panels. In the plains of the region, many mining activities, particularly those involved in aggregate extraction, operate underwater within so-called quarry lakes. These lakes could be utilized for energy production by covering them with floating solar panels. In fact, the first floating solar plant in Italy has been installed in Piedmont and will produce 6 MW by covering 100000 m^2 of lake surface. This solution is consistent with recent studies highlighting the potential of floating PV systems in post-mining landscapes and water bodies [25], where land-use constraints can be minimized.

Regarding geothermal energy, there are currently no medium-to-high enthalpy applications in the Piedmont region, indicating a lack of economically and technically exploitable potential reservoirs. However, as shown in Fig. 9, the southern part of the region might potentially be suitable for hosting geothermal plants aimed at electrical energy production.

Although the potential energy output from low-enthalpy geothermal sources, as illustrated in Figs. 10 and 12, is insufficient to meet the full energy demands of mining operations, geothermal energy could still contribute to in the mining energy transition. Specifically, it could be used for heating and cooling buildings associated with mining activities, such as commercial offices, changing rooms, canteens, and worker accommodations.

The PRAE sets ambitious targets, particularly for the mining sector, in investigating the potential for renewable energy integration. As shown in Fig. 14, which represents the regional energy balance in ktoe (kilotonnes of oil equivalent), renewables still account for a limited share of the market in a region where most energy is imported. Moreover, the industrial sector, including mining, is the third-largest energy consumer, accounting for about half the consumption in the civil sector. Consequently, renewables are expected to represent 40% of the energy mix by 2030, as set by the PEAR. The mining sector could contribute significantly to reaching this target, particularly given the relatively small scale of these activities.

While this study presents a theoretical assessment of the technical potential for integrating renewable energy sources into mining operations, the practical implementation of such systems faces multiple real-world constraints. One of the most critical challenges is the inherent intermittency of renewable energy generation, particularly for solar and wind power, which does not always align with the consistent and often high baseload energy demand typical of mining operations [27–29]. The challenge of intermittency and system integration has been widely highlighted in the literature. Enemuo and Ogunmodimu [27] emphasize that the transition toward renewable-based mining systems requires integrated strategies to ensure reliability and continuous operation. In this context, François et al. [28] demonstrate that combining hydropower with variable sources such as wind and solar can significantly improve system stability and increase renewable penetration. Similarly, McLellan et al. [29] underline that the incorporation of sustainability principles into mineral processing design is essential to optimize energy use and reduce the environmental footprint of mining operations. Mines require a continuous power supply for the operation of heavy machinery, ventilation, water pumping, and mineral processing, requirements that are not easily met by variable energy sources without adequate storage systems or hybrid configurations incorporating conventional energy sources [30].

Moreover, the integration of renewable energy into mining operations depends heavily on appropriate business models, economic incentives, and site-specific factors, such as proximity to the power grid, local energy pricing, and regional regulatory frameworks [6,31]. Without Power Purchase Agreements (PPAs) or hybrid systems that combine renewables with storage or backup generators, relying solely on renewable energy poses significant risks to the reliability of

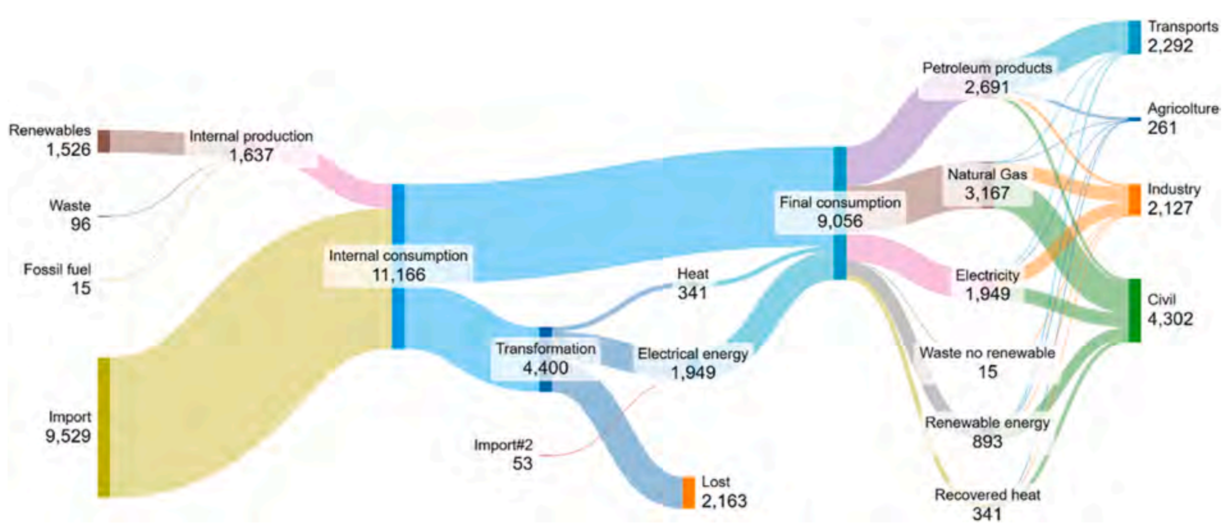

Fig. 14. Piedmont energy balance in ktoe (modified after [26]).

operations.

Therefore, while this regional-scale analysis helps to identify areas with high theoretical potential, it cannot substitute for detailed site-level feasibility studies that consider financial viability, specific load profiles, and deployment logistics. Future research should incorporate techno-economic modeling and energy system optimization to develop realistic, tailored scenarios for renewable integration in the mining sector [32]. Such analyses would also benefit from access to proprietary data on mining operations, which is currently limited and generally unavailable in public repositories.

Despite the evident potential, the adoption of renewable energy by mining companies remains low, especially among small and medium-sized enterprises. A key barrier is the lack of awareness and technical capacity to navigate complex regulatory procedures to access available funding. While programs like PEAR and other incentive schemes have successfully promoted sustainability across other industrial sectors, the mining industry faces several unique challenges. Many funding calls and support programs prioritize small and medium-sized enterprises (SMEs) that are not classified as energy-intensive, thereby unintentionally excluding mining companies, which represent some of the most energy-demanding operations. This represents a missed opportunity, particularly since mining sites, due to their remote locations and land availability, are often well-suited for hosting large-scale renewable energy installations.

Additional challenges include the large spatial requirements for significant renewable power generation systems and the high upfront capital investments involved. Although many mining sites may have the land available, the upfront capital investments and technical complexity remain significant, especially for smaller companies. However, the life span of renewable energy installations often aligns well with the duration of mining permits, suggesting that renewable energy could serve as a stable, long-term energy solution.

The assumption in this study that renewable power plants could be built in close proximity to mining operations, is not based on grid limitations or the need for off-grid systems. Instead, it reflects a strategic approach: mining sites already occupy land designated for industrial use, making them ideal for hosting renewable infrastructure without competing with agricultural or protected land.

While larger, grid-connected systems may be more efficient, the PRAE promotes direct interventions at mining sites, reinforcing the relevance of this localized approach. Targeted incentives for on-site renewable generation could enable mines to self-consume energy, reducing external energy dependence and operational costs. Establishing dedicated support offices could help guide companies through the application process, increasing participation rates in renewable energy initiatives. Furthermore, facilitating the adoption of standardized energy efficiency measures and indicators for evaluating energy performance would promote the uptake of renewable energy in mining operations. Industry-wide education campaigns and best-practice guidelines could also play an essential role in increasing renewable energy adoption.

Another interesting idea, from a regulatory standpoint, could be creating energy hubs or districts in mining regions could address logistical and energy needs. Mining operations could form energy communities, where sites exchange renewable energy between each other, ensuring that renewable generators consistently operate at nominal power. Such systems could allow for self-consumption or sharing of excess energy across multiple mining sites, optimizing energy use and efficiency.

To realize this, regulatory frameworks need to evolve to support energy sharing between different mining sites. This shift could enable mining operations to become central players in the regional energy transition toward a more sustainable energy future.

In conclusion, while the potential for renewable energy in Piedmont's mining sector is clear, the path forward requires overcoming policy gaps, increasing awareness, and facilitating the development of energy-sharing communities.

7. Conclusions

To the best of the authors' knowledge, this is the first study to explore the potential application of renewable energy technologies in the Piedmont mining sector. The analysis evaluated the technical potential of solar, wind, geothermal energy, and hydropower sources to meet the energy demands of mining operations within the broader context of energy transition.

Among the sources considered, hydropower and solar energy emerged as the most promising, particularly due to their alignment with the energy demands and spatial characteristics of mining sites. While solar energy's average capacity remains low, its scalability and potential deployment on quarry lakes through floating systems—already piloted in Piedmont—offer innovative, site-specific opportunities. Wind energy, although currently underutilized, may be viable, particularly in the southern part of the region, where high energy production has been demonstrated. Geothermal energy, on the other hand, presents more limited potential. Medium-to-high enthalpy applications may be technically feasible in the south, but generally, low-enthalpy (open- and closed-loop) geothermal systems are better suited for thermal uses such as heating and cooling buildings associated with mining operations rather than direct electricity generation.

Beyond technical assessments, this study also offers valuable insights barriers and enablers for the adoption of renewable energy in mining. Key obstacles include a lack of awareness, limited technical capacity among small and medium-sized enterprises, and regulatory frameworks that do not adequately account for the unique needs of energy-intensive industries like mining. Furthermore, most funding programs tend to exclude mining activities from eligibility, despite the high compatibility of mine sites with renewable installations due to their remote locations, existing industrial zoning, and land availability.

Nevertheless, opportunities exist. The alignment between the lifespan of mining permits and the durability of renewable energy systems makes the integration of renewables a logical and potentially cost-effective solution. Additionally, the development of energy-sharing models, such as local energy communities or mining energy districts, could help optimize energy flows, reduce intermittency issues, and encourage collaborative approaches across multiple sites. However, realizing such models will require adaptations in regulatory frameworks, targeted financial incentives, and administrative support mechanisms, including dedicated offices to guide companies through complex procedures.

While this study provides a comprehensive analysis at regional scale, further research is necessary to translate this potential into practical implementation strategies. In particular, site-specific feasibility studies will be essential to evaluate financial viability, energy load profiles, and technical deployment strategies. Future research should incorporate techno-economic modeling and energy system optimization to develop realistic and tailored scenarios for renewable integration. These analyses would also benefit from access to proprietary data on mining operations, which is currently limited and generally unavailable in public repositories.

Moreover, addressing regulatory and financial barriers will be crucial to foster wider adoption. Raising awareness within the industry, especially among small and medium-sized enterprises, and simplifying the bureaucratic procedures for accessing incentives are key steps. Establishing dedicated support services to guide companies through funding applications, alongside promoting standardized energy performance metrics and best practices, could help drive the sector toward decarbonization.

From a strategic perspective, mining sites, due to their land availability and industrial designation, offer ideal conditions for hosting renewable energy infrastructure without conflicting with agricultural or protected land. While centralized grid-connected systems are undoubtedly more efficient in the long term, localized renewable systems on or near mining sites align well with the goals outlined in the PRAE and could facilitate self-consumption, reduce operational costs, and enhance energy independence.

In this context, innovative regulatory frameworks enabling energy sharing between mining sites could further optimize energy use and support the development of regional energy communities. By encouraging collaboration across operations, such communities could stabilize renewable generation and contribute more effectively to regional sustainability goals.

In conclusion, while the potential for renewable energy in Piedmont's mining sector is evident, realizing this opportunity will depend on overcoming policy gaps, fostering collaboration, and promoting the integration of mining into broader regional energy strategies.

CRediT authorship contribution statement

Martina Gizzi: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Federico Vagnon:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Glenda Taddia:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, Conceptualization. **Alessandro Berta:** Writing – review & editing, Validation, Methodology. **Stefano Paolo Corgnati:** Writing – review & editing, Supervision, Funding acquisition. **Stefano Lo Russo:** Writing – review & editing, Supervision, Funding acquisition.

Funding sources

This work was carried out within the framework of the research activities related to Collaborazione Istituzionale IRES Piemonte [n. 85/2018]

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.

Acknowledgements

The author wishes to thank Dr. Laura Mancuso and Dr. Eleonora Pilone of the Sector for Mining Police, Quarries, and Mines of the Piedmont Region, and Dr. Riccardo Ferrari of CSI Piemonte, for their invaluable and precious contribution in providing the energy demand data for Piedmont's mining activities.

References

[1] The world count site https://www.theworldcounts.com/challenges/planet-earth/mining/energy-use-in-the-mining-industry (online access December 2024).
[2] T. Igogo, K. Awuah-Offei, A. Newman, T. Lowder, J. Engel-Cox J, Integrating renewable energy into mining operations: opportunities, challenges, and enabling approaches, Appl. Energy 300 (2021) 117375, https://doi.org/10.1016/J.APENERGY.2021.117375.
[3] K. Zharan, J.C. Bongaerts, Decision-making on the integration of renewable energy in the mining industry: a case studies analysis, a cost analysis and a SWOT analysis, J. Sustainable Min. 16 (2017) 162–170, https://doi.org/10.1016/j.jsm.2017.11.004.
[4] W. van der Merwe, A.C. Brent, Evaluating the energy potential of solar PV located on mining properties in the Northern Cape province of South Africa, Sustainability 12 (2020), https://doi.org/10.3390/SU12145857.
[5] Y. Choi, J. Song, Review of photovoltaic and wind power systems utilized in the mining industry, Renew. Sustain. Energy Rev. 75 (2017) 1386–1391, https://doi.org/10.1016/j.rser.2016.11.127.
[6] A. Strazzabosco, J.H. Gruenhagen, S. Cox, A review of renewable energy practices in the Australian mining industry, Renew. Energy 187 (2022) 135–143, https://doi.org/10.1016/J.RENENE.2022.01.021.
[7] University of Cape Town. Energy Research Centre RG, A.C. Brent, J. Energy South Afr. 27 (2016). University of Cape Town.
[8] S. Nasirov, C.A. Agostini, Mining experts' perspectives on the determinants of solar technologies adoption in the Chilean mining industry, Renew. Sustain. Energy Rev. 95 (2018) 194–202, https://doi.org/10.1016/J.RSER.2018.07.038.
[9] R.G. Votteler, A.C. Brent, A literature review on the potential of renewable electricity sources for mining operations in South Africa, J. Energy South Afr. 27 (2016) 1–21.
[10] T. Kirk, C. Cannon, Sunshine for Mines: a Brighter Vision for Sustainable Resources. Rocky Mountain Institute, 2020. https://rmi.org/sunshine-for-mines-a-brighter-vision-for-sustainable-resources/ (online access December 2024).
[11] G. Martin Booth III, P.F. Bixley, Geothermal development in Papua New Guinea a country update report 2000-2005. World Geothermal Congress 2005, Booth III and Bixley, 2005.
[12] DIGEST E360. Kentucky to Build State's Largest Solar Project on Former Coal Mine. https://e360.yale.edu/digest/kentucky-to-build-states-largest-solar-project-on-former-coal-mine (online access December 2024).
[13] PRAE – Piano Regionale Attività Estrattive. 2022 https://www.regione.piemonte.it/web/temi/sviluppo/attivita-estrattive/piano-regionale-attivita-estrattive-prae (in Italian - online access December 2024).
[14] PEAR – Piano Energetico Ambientale Regionale. 2022. https://www.regione.piemonte.it/web/temi/sviluppo/sviluppo-energetico-sostenibile/piano-energetico-ambientale-regionale-pear (in Italian - online access December 2024).
[15] REPowerEU: energy policy in EU countries' recovery and resilience plans. https://www.consilium.europa.eu/en/policies/repowereu/, 2022 (online access December 2024).
[16] BDAE – Banca Dati Delle Attività Estrattive. https://servizi.regione.piemonte.it/catalogo/banca-dati-delle-attivita-estrattive-bdae (online access December 2024).
[17] J. Hofierka, M. Súri, The solar radiation model for open source GIS: implementation and applications. Open Source GIS - GRASS Users Conference, 2002, pp. 11–13.
[18] Sztfh. https://map.mbfsz.gov.hu/geo_DH/, 2024 (online access December 2024).
[19] A. Casasso, R. Sethi, G.POT: a quantitative method for the assessment and mapping of the shallow geothermal potential, Energy 106 (2016) 765–773, https://doi.org/10.1016/J.ENERGY.2016.03.091.
[20] A. Berta, M. Gizzi, G. Taddia, S. Lo Russo, The role of standards and regulations in the open-loop GWHPs development in Italy: the case study of the Lombardy and Piedmont regions, Renew. Energy 223 (2024) 120016, https://doi.org/10.1016/J.RENENE.2024.120016.
[21] A. Berta, G. Taddia, Exploring urban sustainability: the role of geology and hydrogeology in numerical aquifer modelling for open-loop geothermal energy development, the case of Torino (Italy), Geosciences 14 (2024) 180, https://doi.org/10.3390/GEOSCIENCES14070180.
[22] Prezziario Regione Piemonte. 2024. https://www.servizi.piemonte.it/rsr/servizi-sp/dwd/OperePubbliche/prezzario/2024/Prezzario_Regione_Piemonte_2024_omissis.pdf (in Italian - online access December 2024).
[23] G. Ronchetti, I. Galbiati, E. Garofalo, Analyzing wind and photovoltaic plant development toward the energy transition in Italy, Next Energy 8 (2025) 100265, https://doi.org/10.1016/j.nxener.2025.100265.
[24] E. Quaranta, A. Georgakaki, S. Letout, A. Mountraki, E. Ince, et al., Clean Energy Technology Observatory: Hydropower and Pumped Storage Hydropower in the European Union - 2025 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2025. https://data.europa.eu/doi/10.2760/3389272,JRC143929.
[25] C.J. Ramanan, H.L. King, Jundika Candra Kurnia, R. Sukanta, J.B. Bhaskor, J. M. Bhaskar, Towards sustainable power generation: recent advancements in floating photovoltaic technologies, Renew. Sustain. Energy Rev. 194 (2024) 114322, https://doi.org/10.1016/j.rser.2024.114322.
[26] S. De Nigris, Il Rapporto Statistico Sull'Energia Della Regione Piemonte, 2025 denigris_rapporto_statistico_2025.pdf (online access May 2025).
[27] M. Enemuo, O. Ogunmodimu, Transitioning the mining sector: a review of renewable energy integration and carbon footprint reduction strategies, Appl. Energy 384 (2025) 125484.
[28] B. François, B. Hingray, D. Raynaud, M. Borga, J.D. Creutin, Increasing climate-related-energy penetration by integrating run-of-the river hydropower to wind/solar mix, Renew. Energy 87 (2016) 686–696, https://doi.org/10.1016/J.RENENE.2015.10.064.
[29] B.C. McLellan, G.D. Corder, D. Giurco, S. Green, Incorporating sustainable development in the design of mineral processing operations – review and analysis of current approaches, J. Clean. Prod. 17 (16) (2009) 1414–1425, https://doi.org/10.1016/J.JCLEPRO.2009.06.003.
[30] K. Hund, D. La Porta, T. Fabregas, T. Laing, J. Drexhage, Climate smart mining facility. Minerals for Climate Action: the Mineral Intensity of the Clean Energy Transition, 2020. https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf (online access May 2025).
[31] L. Viscidi, A. Yépez-García, Clean Energy Auctions in Latin America. Clean Energy Auctions in Latin America, 2020, https://doi.org/10.18235/0002133.
[32] M. Bolinger, D. Millstein, W. Gorman, P. Dobson, S. Jeong, Mind the gap: comparing the net value of geothermal, wind, solar, and solar+storage in the Western United States, Renew. Energy 205 (2023) 999–1009, https://doi.org/10.1016/j.renene.2023.02.023.