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Energy demand and savings opportunities in the supply of limestone and olivine-rich rocks for geochemical carbon dioxide removal

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Abstract

The large-scale implementation of geochemical Carbon Dioxide Removal (CDR) approaches such as Enhanced Weathering (EW) and Ocean Liming (OL) will require the extraction and processing of large amounts of limestone and olivine-rich rocks. Based on a literature review, surface mining, comminution, their related sub-stages, and long-haul transportation have carefully been surveyed to elucidate the order of magnitude of the energy demand, the technical challenges posed by each operation, and the potential energy-savings achievable by applying opportune strategies. This work confirms the significant energy-saving opportunities in fine and ultrafine grinding (one of the most energy-consuming activities along the raw material supply chain) as underlined by previous studies, and, in addition, it focuses on limestone and olivine-rich rocks providing new outcomes, it analyses data from a climate change perspective and extends calculations and discussion to transportation. The results show that the implementation of energy-saving strategies (cutting-edge energy efficiency solutions and best practices) to comminute such materials for OL and EW purposes in the near-medium term (2025–2050) would reduce the average electricity demand by 33%–65% in case of low carbon removal target (up to 27 MtC yr^{-1}) and substantial energy efficiency improvement, and by 33%–36% in case of high carbon removal target (up to 69 MtC yr^{-1}) and poor energy efficiency improvement.

1. Introduction

Meeting the Paris Agreement temperature goal requires ambitious reductions of greenhouse gas emissions, as well as carbon dioxide removal (CDR) from the atmosphere at the gigaton scale. CDR technologies are expected to sequester cumulative amounts of CO_2 ranging from 450 to 1 100 Gt between 2020 and 2100 (Smith *et al* 2023).

Enhanced Weathering (EW) and Ocean Liming (OL) are two examples of negative emission technologies (NETs) that have been gaining increasing attention because of their CDR potential of 2–4 and 1–100 GtCO2 yr^{-1}, respectively (Hartmann *et al* 2013, Beerling *et al* 2020, Caserini *et al* 2021a, Smith *et al* 2023). OL may also help reduce ocean acidification, another alarming environmental issue that we are facing (Butenschön *et al* 2021). Other ways to support the natural buffer capacity of the ocean and to store industrial CO_2 emissions in seawater as bicarbonates are the accelerated weathering of limestone proposed by Rau and Caldeira (1999) and the more recent buffered accelerated weathering of limestone proposed by Caserini *et al* (2021b) and De Marco *et al* (2023).

Each of these technologies has individual limitations and challenges, but all rely on the availability and utilization of primary raw materials at the gigaton scale. Limestone by-products (e.g. calcium hydroxide), and olivine, are currently considered the most suitable candidates to perform OL and EW respectively, given the appreciable carbon removal potential upon dissolution (Moosdorf *et al* 2014, Stler *et al* 2018, Caserini *et al* 2021a).

Hence, the order of magnitude of energy consumption caused by the extensive use of mining and processing of such raw materials for CDR purposes, and the potential to lower the related requirements, will shape the extent to which the mentioned NETs will be employed.

Based on a literature review, we highlight the technical challenges and strategies to achieve energy savings in surface mining, comminution, and long-haul transportation, we estimate the maximum energy-saving potential practically achievable and we propose two new relationships (one for limestone and the other for olivine-rich rocks) to calculate the energy demand of comminution depending on the grain size.

Finally, we present evaluations on the future energy demand of grinding limestone and olivine-rich silicate rocks for OL and EW purposes, the impact on the global electricity grid, and the potential energy-saving practically achievable.

2. Materials and methods

2.1. Geological properties of limestone and olivine-rich rocks

Overall, the energy demand of mining and grinding is highly site-specific, rock resource-dependent, and it suffers from a lack of publicly available data.

We focused on limestone and olivine-rich rocks not only for climate change purposes but also to be consistent with the types of data effectively gathered. The full datasets are reported in tables SM1, SM3, and SM4 of the Supplementary Material (SM).

Limestone is a sedimentary rock, mainly composed of calcite ($CaCO_3$) and occasional traces of other minerals like magnesium carbonates (Renforth *et al* 2013) or chemical impurities (e.g. silica, alumina, iron oxide), often in the form of clay or quartz (Jena *et al* 2013). About 10% of the Earth's land surface is covered by limestone deposits (Renforth *et al* 2013). It is widely used around the world, especially for cement and lime production. In 2017, the yearly worldwide production of limestone was estimated at 6.6 Gt (Caserini *et al* 2022).

Olivine is a magnesium-iron silicate mineral (Renforth 2012, Kremer *et al* 2019) and can be found within a range of ultramafic rocks including harzburgite, lherzolite, and dunite. These rocks are distinguished based on their olivine, orthopyroxene, and clinopyroxene content and belong to the peridotite group (Foteinis *et al* 2023).

The abundance and the industrial use of olivine are not as large as limestone but the forsteritic (magnesian) olivine [content of forsterite (i.e. an end-member of olivine) $>$ 85%] is commonly employed to remove impurities from steel and to produce refractories. In 2017, the annual worldwide production of olivine was estimated at 8.4 Mt (Kremer *et al* 2019, Caserini *et al* 2022). It is worth specifying that:

- The total production of olivine does not include 'pure olivine' only but the worldwide complex of peridotite (Kremer *et al* 2019).
- For commercial use, olivine is mainly extracted from dunite, the upper olivine-rich variety of peridotite.
- The term 'olivine' is often commercially used to comprise both the mineral and other olivine-bearing rocks (e.g. dunite, serpentinite).

Additional information about the geological and industrial properties of the raw materials analyzed in this work can be found in section S1 of SM.

2.2. Stages and sub-stages of the raw material supply chain

The reviewed activities over the raw material supply chain have been framed in two macro-phases (i.e. surface mining and comminution) and subdivided into micro-phases as illustrated in figure 1. Screening has been excluded from discussion and calculations since it shows negligible energy consumption in comparison with the other activities surveyed.

Transportation is a recurring operation needed to move ore and waste from one site to another, with significant energy consumption. Road transportation (today mainly carried out by diesel-powered trucks), railway, and marine transportation are the macro modes surveyed.

We collected data on the energy demand for each activity, sub-activity, and transport mode.

2.3. Assessment of the energy-saving potential

The energy-saving strategies have been surveyed by considering:

1. The implementation of technological improvements and/or optimization of processes deriving from research and development (R&D) findings (e.g. advanced materials/equipment/processes).
2. The implementation of best practices (BPs).
3. The utilization of renewable energy sources and/or low carbon footprint energy alternatives.

Following the methodology proposed by USDOE (2007), the total energy-saving potential (ES_T) has been estimated as:

$$ES_T = ES_{PA} + ES_{LP}.$$

The first contribution (ES_{PA}), also called practically achievable energy-saving opportunity, is given by:

$$\begin{aligned} ES_{PA} &= (ED_{av} - ED_{BP}) + (ED_{BP} - ED_{PM}) \\ &= ES_{BP} + ES_{R\&D} \end{aligned}$$

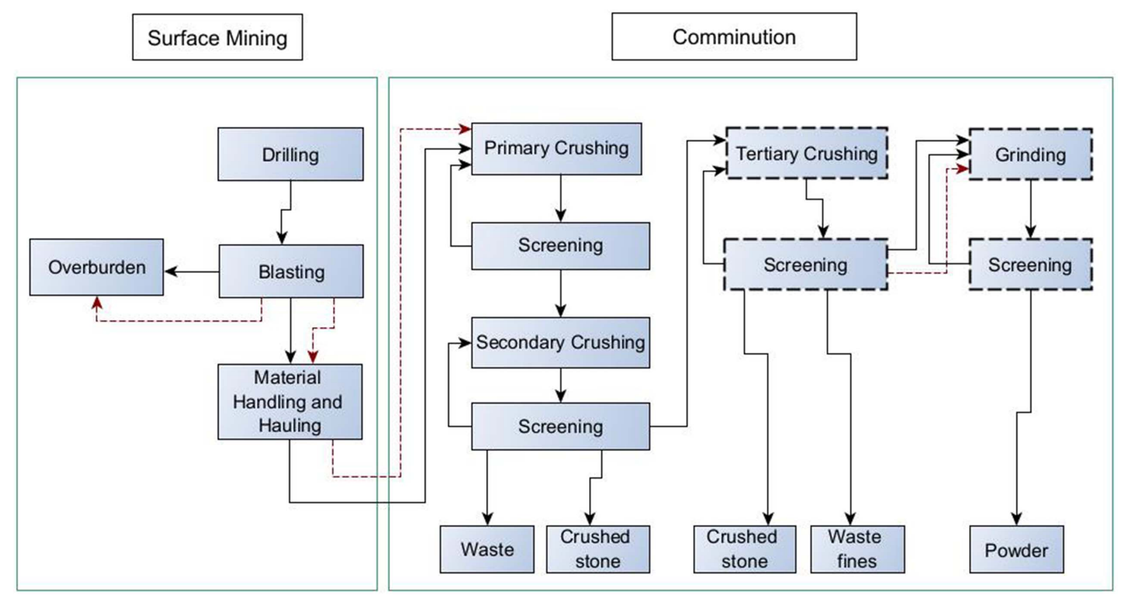

Figure 1. Diagram of stages and sub-stages of limestone and olivine-rich silicate rock process chain. Dashed arrows: transportation. Solid line arrows: output/input. Boxes with solid boundaries: necessary phases or end-products. Boxes with dashed boundaries: optional phases. Information is drawn from Metso: Outotec (2021) and adapted to this work.

where:

- ED_{av}: current average energy demand (kWh t^{-1})
- ED_{BP}: energy demand achievable by implementation of best practices (kWh t^{-1})
- ED_{PM}: practical minimum of energy demand attainable by implementation of more efficient technologies (kWh t^{-1})
- ES_{BP}: the energy-saving opportunity or the energy reduction deriving from implementation of best practices (kWh t^{-1})
- $ES_{R\&D}$: the energy-saving opportunity or the energy reduction deriving from implementation of more efficient technologies (kWh t^{-1})

The current average energy demand is considered the mean value of each energy dataset gathered in this work. Refer to tables SM1 (section 2), SM3 (section 3), SM4 (section 3), and SM6 (section 4) of SM for the full datasets.

The second contribution (ES_{LP}) is called less practical energy-saving opportunity and is described by:

$$ES_{LP} = ED_{PM} - ED_{th}$$

where:

- ED_{th}: theoretical energy demand (kWh t^{-1})

The theoretical energy demand is the energy consumption that a process would require if no energy loss existed. It has been put into relation with the current average energy demand, ED_{av}, by:

$$ED_{th} = ED_{av} \cdot \eta_{av}$$

where:

- η_{av}: current average energy efficiency of the process (−).

The improved energy requirements deriving from application of BPs and R&D advances have been calculated as:

$$ED_{BP} = \frac{ED_{th}}{\eta_{BP}}$$

$$ED_{PM} = \frac{ED_{th}}{\eta_{PM}}$$

where:

- η_{BP}: best practice energy efficiency (−)
- η_{PM}: maximum practically attainable energy efficiency (−)

The energy efficiency η_{PM} is that obtainable when both BP and R&D technological advances are fully implemented. η_{BP} is an intermediate level between the current average energy efficiency η_{av} and η_{PM} and is achieved when BPs are implemented alone.

The complete overview of the energy efficiencies used in this work can be found in table SM7, section 5 of SM.

2.4. Potential energy reduction of grinding for future deployment of OL and EW

The energy cost of grinding limestone and olivine-rich rocks for future deployments of OL and EW, along with the potential energy-saving practically

Table 1. Share of CDR sequestered by OL and EW only, share of OL and EW deployment to achieve the CDR targets, average and maximum energy efficiency of grinding. The values in brackets refer to the low energy efficiency scenario.

Parameter	Unit	Year					
		2025	2030	2035	2040	2045	2050
Share of CDR exclusively sequestered by OL and EW	%	0.1	1	2	3	4	5
Share of deployment of OL	%	0	20	40	50	60	70
Share of deployment of EW	%	100	80	60	50	40	30
Current average energy efficiency excluding energy-saving strategies	%	2	2	2	2	2	2
Current average energy efficiency including energy-saving strategies	%	2 (2)	3 (2)	3 (2)	4 (3)	4 (3)	5 (4)
Maximum energy efficiency	%	3 (3)	4 (3)	5 (3)	7 (4)	8 (4)	10 (5)

achievable (ES_{PA}), have been evaluated over the time frame 2025–2050 under two different energy efficiency conditions.

The first condition represents the High Energy Efficiency scenario. Here, we suppose that, due to the rapid and radical implementation of BPs and R&D improvements, the maximum level of energy efficiency (η_{PM}) in grinding becomes sufficiently high to keep both the energy demand and the use of OL and EW, low.

The electricity requirements to comminute each raw material down to a target grain size of 5 μm (i.e. 125 kWh t^{-1} for limestone and 207 kWh t^{-1} for olivine-rich rocks) have been estimated using the new energy relationships derived from this work (section 3.4 of SM). They account for the first two baseline parameters against which improvements are compared since the energy reduction due to the application of energy-saving strategies is not included. The other baseline parameter is the energy efficiency and it is assumed to be 2% (table 1).

The total practical energy-saving potential (ES_{PA}) and the other energy-saving contributions (i.e. theoretical energy demand, ED_{th}, and practical minimum of energy, ED_{PM}) have been calculated following the method described in section 2.3 and assuming that implementation of BPs and R&D advances led the current average energy efficiency (i.e. the energy efficiency relative to each year) and the maximum energy efficiency, to gradually increase as shown in table 1. Moreover, to include the effects of energy-saving actions in the current average energy demand over time, this latter has been reduced by 10% for each unitary increase of the current average energy efficiency (i.e. the average energy efficiency relative to each year) versus the baseline value (2%). The 10% reduction was chosen given the findings of Gagnon *et al* (2023).

The annual amount of CDR from novel technologies (Bioenergy with Carbon Capture and Storage—BECCS, biochar, Direct Air Carbon Capture and Storage—DACCS, EW and OL) has been retrieved from Smith *et al* (2023), figure 7.1, 2 °C pathway (67% chance that global warming remains below 2 °C).

The yearly amount of CDR sequestered by OL and EW only has been calculated assuming that the coupled deployment of these two technologies could gradually remove from $\sim$0.1% of the total annual CO_2 captured by novel technologies in 2025%–5% in 2050 (table 1). We also assume that from 0.0% (in 2025) to 70% (in 2050) of this total will be achieved by OL given the wider availability of limestone, and the remaining parts by EW via olivine-rich rocks or peridotites (table 1).

The amount of rock has been assessed considering a CO_2 drawdown of 0.8 kg for each kg of peridotite (Foteinis *et al* 2023).

The second condition represents the Low Energy Efficiency scenario. In this case, both the current average energy efficiency and the maximum efficiency of grinding vary and increase slowly due to poor investments in technological advancements (table 1, table SM13, section 6 of SM) but OL and EW are used on a larger scale given the high energy requirements and a better Technology Readiness Level achieved by these and novel CDR technologies.

The annual amount of CDR from novel technologies has been retrieved from Smith *et al* (2023), figure 7.2 A, Focus on carbon removal.

The share of this total that is exclusively sequestered by OL and EW, the share of deployment of OL and EW as well as the way to derive the electricity requirements including or excluding energy-saving strategies and the energy-saving potential have not been changed.

A complete overview of the results obtained in this study can be found in tables SM12 and SM13, section 6 of SM.

3. Results and discussion

3.1. Surface mining

The extraction of an ore body may be performed by open pits, underground mines, or a combination of these (Ridley 2013). Methods and equipment used to extract the rock are influenced by both technical (e.g. production capacity, market price of the commodity) and natural constraints (i.e. nature and location of the deposits, size, depth, hardness of the rock) (OEERE 2002).

Limestone as well as olivine are generally mined from open pits or quarries (USDOE 2007).

3.1.1. Drilling and blasting

3.1.1.1. Overview, technical challenges

The main purpose of drilling and blasting is to release the rock from the mine face and to decrease the resistance to crushing and grinding by generating internal fractures.

Before blasting, cylindrical holes are drilled in the rock by hammering and rotation. The equipment usually employed are top and down-the-hole hammers, tricone rotary drills, diamond drills, percussion drills, and drill boom jumbos (OEERE 2002, USDOE 2007). The energy carriers are compressed air, electricity, or diesel.

After drilling, explosives are used to blast the rock for further processing. At this stage, it is crucial to minimize the loss of energy by interaction with the atmosphere.

Maximizing the efficiency of blasting is essential since well-fragmented rocks increase the productivity of loading, hauling, crushing, and grinding, reduce the wear of the equipment, and lower the energy demand of loading (Tosun and Konak 2014).

3.1.1.2. Energy consumption

The average energy demand of drilling and blasting is lower than 1 kWh t^{-1} for both limestone and olivine-rich rocks (table 2). For these latter, the energy demand of drilling and blasting exceeds that of limestone by 30% and 60% respectively, on average.

Drilling and blasting account for 16%–20% of the total energy consumption of mining and less than 1% of the total if we include comminution.

3.1.1.3. Energy-saving opportunity

Performing the extraction of limestone or olivine-rich rocks carrying out drilling and blasting at their maximum level of practical efficiency (η_{PM}) i.e. 53% and 64%, respectively (table SM7, section 5 of SM) and maintaining material handling and hauling at its average energy efficiency (30%), assure around 11% energy-saving and less than 1% if comminution is included (table SM8 and table SM9, section 5 of SM).

The ways to reduce the energy requirements are discussed below, following the order highlighted in section 2.3

1. R&D advances and/or optimization of processes.

An example of automatic equipment in drilling is the semi-autonomous drill or the robotic drill with simultaneous online sampling and analysis of the deposit (Curry *et al* 2014, Holtec 2019). It maximizes rock fragmentation, reduces the production of waste, and minimizes the need to redrill.

Other examples of advanced technologies are microwaves to generate intergranular and transgranular fractures by thermal expansion, polycrystalline diamond percussion bits to improve the durability and efficiency of equipment, high-pressure water and abrasive water jets to improve the drilling efficiency in soft and hard rock, radio wireless and wired communication systems to provide information about the inclination angle of the hole and the directional trajectory of the drilling (Karpuz 2017).

In blasting, software packages with image capture systems (e.g. WipFrag, Split, PortaMetrics, GoldSize, Fragscan, PowerSieve, BLASTFRAG), modeling software, vibration monitoring systems, and high-speed video are used to control rock fragmentation, vibration, airblast, and wall damage (Johnson 2017, CEEC 2023). Images are taken by portable cameras and placed on loader-mounted systems.

Planning an appropriate stemming can increase the average blasting efficiency by at least 41% (Konya and Konya 2017). Stemming consists of placing liquid (e.g. water), semiliquid (e.g. mud), or solid materials (e.g. concrete) or plugs (e.g. plastic molded plugs) on top of the blast hole at direct contact with the explosive powder column to maximize the bore-hole pressure, improve the fragmentation and reduce gas pressure losses (Konya and Konya 2017).

2. Best practices.

Cleaning the wellbore through sweeps or high-viscosity pills, planning scheduled monitoring and maintenance of equipment, and performing accurate analyses on porosity, permeability, and other geomechanical properties before drilling, could reduce loss of energy and the risk of instability caused by drilling hard formations (Singh and Nayak 2023).

3. Renewable energy sources and/or low carbon footprint alternatives.

The upscaling of renewables in the mining sector, such as photovoltaic (PV) cells to produce electricity, solar heating systems to produce thermal energy, and concentrated solar power to produce alternatively thermal or electrical energy is crucial, especially for remote mines due to the high cost to transport diesel for on-site electricity generation (Awuah-Offei 2016, Paredes Sànchez 2017). Overall, promoting the use of renewables reduces the reliance on diesel generators and/or fossil fuel sources, and this has benefits such as lower greenhouse gas emissions, lower operating costs, new jobs as well as social and economic sustainability (Pouresmaieli *et al* 2023).

Sustainable mining can be also achieved by changing the concept of life cycle of a mine with the more recent concept of life cycle of a mined material (Gorman and Dzombak 2018). Life cycle assessment of a mineral entails accurate evaluations of the extraction efficiency, rate of resource depletion, recovery rates, assessment of losses, dissipation, and recycling rates.

3.1.2. Material handling and hauling

3.1.2.1. Overview, technical challenges

Material handling consists of digging, loading, unloading, transferring, storing, and feeding the blasted material.

Digging, loading, unloading, and feeding are carried out by cable shovels, hydraulic excavators, front-end loaders, continuous miners, longwall mining machines, and drag lines (OEERE 2002, Norgate and Haque 2010). Hydraulic excavators can be either front shovels or backhoe shovels.

In surface mines, the use of diesel to power equipment has varied from 49% to 41% in the last ten years, mostly due to the development of natural gas and grid electricity infrastructures and continuous fluctuations in the oil price (Soofastaei *et al* 2017, Soofastaei and Fouladgar 2022); 56% of this total is attributable to haul trucks (Sahoo *et al* 2017).

Hauling, at this stage, serves to move ore and waste from the quarry to the mill facilities or the disposal area, which are generally close to each other. If the raw material is dry, it is performed by several types of heavy vehicles (e.g. haul trucks, bulldozers, service trucks, bulk trucks, pick-up trucks, rear-dump trucks, bottom trucks, articulated trucks, and shuttle cars) or conveyor belts. In the case of wet material (i.e. slurry handling), the operations are carried out by slurry pumps and hoses.

The fossil-fuel reliance is still strong given the poor adaptability to automation, natural or imposed operating conditions (e.g. the resistance to digging, bench and haul road profile, mine geometry and topography, quantity, and size of the rock to be transferred to the truck), lack of investment in more advanced technologies (Awuah-Offei 2016).

3.1.2.2. Energy consumption

Material handling and hauling is the most cost and energy-intensive activity in mining since it is responsible for at least 50% of the total energy required in this macro-phase (Soofastaei *et al* 2017, Ribeiro Souza *et al* 2019). According to the data collected in this work, it covers almost 80% of the total energy requirement of mining (table 2).

3.1.2.3. Energy-saving opportunity

Performing the extraction of limestone or olivine-rich rocks carrying out material handling and hauling at its maximum level of practical efficiency (η_{PM}) i.e. 63% (table SM7, section 5 of SM), and maintaining drilling and blasting at their average energy efficiency (53% and 64% respectively), can lead to around 43% energy-saving (table SM8 and table SM9, section 5 of SM). The percentage declines to only 1% if comminution is included, given the high energy consumption associated with fine and ultrafine grinding (see section 3.2).

The technological options to reduce the energy requirements in such a sector are presented below.

1. R&D advances and/or optimization of processes.

Electrolytic double-layer capacitors (EDLCs) and hydraulic drive and electromechanical flywheel storage systems are examples of energy recovery systems (ERS) mostly used in diesel-electric mine haul trucks, loading shovels, and hybrid excavators. These are designed to capture the energy in the descending part of the haul track or during braking, and, re-inject it when the vehicle accelerates or the load is raised.

A hydraulic drive flywheel storage system can lead to a 10%–30% reduction in the fuel consumption of a hybrid excavator, EDLCs to 25% fuel cost saving in a shovel, and an electromechanical flywheel storage system to 20% fuel consumption saving in a mobile gantry crane (Terblanche *et al* 2017).

For haul trucks, ERS solutions are seen as more suitable than chemical battery-based solutions mostly due to a faster charging rate (hours for chemical batteries and minutes for supercapacitors and electromechanical flywheel; Xu *et al* 2023) and longer service life (three times higher than a Li-ion battery; Terblanche *et al* 2017).

Electric trolley assists combined with electric drive systems are other alternatives to diesel-powered equipment and are commonly used to facilitate the uphill of the haul track (Jeswiet *et al* 2015, Awuah-Offei 2016, ABB 2021).

In-pit crushing and conveying systems allow the crushed rock to be transferred by conveyor belts. They can be fixed, semi-mobile, or fully mobile. However, technical limitations such as a proper level of fragmentation of the hauled rock (limit size = 300 mm; Soofastaei *et al* 2017), the lack of flexibility in the management, high investment costs, and frequent maintenance and repairs, limit the utilization (Hill *et al* 2012).

Other examples of electric systems are pipe conveyors or RopeCon® (Doppelmayr 2021).

Intelligent automated loading systems are regenerative alternate current (AC) drives, semi-automated load assistance, collision avoidance systems, shovel load assist program, and autonomous driverless dump trucks (Soofastaei *et al* 2017). Potential benefits are the increase in energy efficiency and safety, reduction of the operator's downtime, and greenhouse gas emissions (Awuah-Offei 2016, WEF 2021). The energy saving attainable by AC drives could be about 26% (Soofastaei *et al* 2017).

2. Best practices.

It has been shown both theoretically and experimentally that investing in the initial and periodic training of operators to improve habits and perform BPs, especially in material loading, can lead to 40% energy saving (Awuah-Offei 2016, Soofastaei *et al* 2017).

Equipment monitoring systems and simulator training tools can be used to control operator behavior and verify the effectiveness of training programs (Awuah-Offei 2016).

Other BPs consist of matching the shallowest depth of cut with the optimal fill factor of loading, optimizing the position between the shovel and the truck and loading, and filling the truck tray with 3 or 4 passes (Soofastaei *et al* 2017).

3. Renewable energy sources and/or low carbon footprint alternatives.
Renewable-powered systems are difficult to integrate into this sector due to high investment costs, lack of constant energy supply, and limited energy storage capacity (Igogo *et al* 2021).

Nevertheless, the level of technology maturity (capacity to meet supply and demand challenges) of electric short-haul construction vehicles and short and medium-haul vehicles has reached defined results and indicates there is potential to replace diesel-powered technologies in the near-medium term (DNV 2023). Where full electrification cannot be pursued, hybrid solutions made of electric batteries and hydrogen fuel cells, solar PV or wind-battery-diesel systems, or the use of drop-in fuels (fuels produced by sustainable feedstocks with low carbon intensity, e.g. biofuel, biomethane) could compensate the gap (Igogo *et al* 2021, DNV 2023).

At present, most of these technologies are either at a prototype scale or only implemented by large mine companies (Igogo *et al* 2021).

3.2. Comminution

Technically, this term is often used to include the whole process of particle size reduction from the mine to the mill. Within this work, we consider only crushing and grinding since the highest amount of energy consumed to reduce the particle size, is performed by these two activities.

3.2.1. Crushing and grinding

3.2.1.1. Overview, technical challenges

Crushing brings fragmented rock from large boulders (750 mm) to coarse pieces of 5–20 mm (Mitchell *et al* 2008). It is typically carried out in two stages (primary and secondary crushing, figure 1), sometimes followed by an additional step (tertiary crushing, figure 1). Electricity is the energy carrier (refer to section 3.1 of SM for a detailed overview of equipment).

Grinding carries out the disruption of the crystal structure of the mineral. In the lime industry, it is generally required to obtain high-quality products.

The aim of both phases is the creation of a new surface area to increase the reactivity of the material.

The main difference between crushing and grinding is that the energy demand of the former is much lower than the latter since large particles can be easily captured and thus broken. By contrast, small particles require more particle-particle collisions and/or particle–grinding media interactions, to be adequately intercepted (Wang and Forssberg 2007). These events are also called 'breakage events'.

Comminution is also known as a very low-efficiency process. The energy efficiency (i.e. the ratio of the effective amount of energy spent for generating new surface area to the total energy consumed by the machine) of any kind of equipment is well below 10%, and the net power spent for rock breakage is always several orders of magnitude lower than the theoretical capacity (power input) of the machine itself (Radziszewski 2013, Yang *et al* 2016, Góralczyk *et al* 2020, Kelemen *et al* 2020).

Reasons explaining significant energy consumption are the energy dissipation in the form of heat occurring during the breakage events, the nature of the rock (hard-soft, abrasive—non-abrasive), the hardness of the mineral compounds, the circuit configuration of the mill, the type of grinding media used, noise, vibration, the geometry of the stirrer and the grinding chamber, its peripheral speed, the grinding time, the throughput (Stamboliadis 2007, Yang *et al* 2016, Mannheim and Kruszelnicka 2022). Moreover, about 30% of the bodies of a grinding machine remain in a 'boundary dead zone' since they are not practically involved in the breakage processes (Góralczyk *et al* 2020).

3.2.1.2. Energy consumption

The energy demand of crushing depends on the level of rock fragmentation achieved by blasting and affects the grinding requirements. The trend steeply increases with the decrease of the target grain size, P_{80} (80% passing size of the product) (figure 2, Strefler *et al* 2018). Further details about the mathematical relationships found in this study are reported in section 3.4 of SM.

A statistical analysis has been carried out to make comparisons between the two datasets (limestone and olivine-rich rocks) in terms of diameters, to verify deviations from the normal distribution, to identify potential outliers, and to highlight in which range of diameters the majority of data fall.

Shapiro–Wilk test and histogram of frequencies (figures 3 and 4) confirm that both datasets are not normally distributed. From the boxplots, it is also evident that, for each sample, the areas within the box, and, whiskers are not equal in size and length, respectively. In the case of olivine-rich rocks, the number of outliers (data points less than $Q(0.25) - 1.5 \cdot IQR$ or greater than that $Q(0.75) + 1.5 \cdot IQR$ with Q (0.25) = first quartile, Q (0.75) = third quartile and IQR = interquartile range) is 12 out of 68 and all the outliers are greater than 500 kWh t^{-1}; in the case of limestone, the number of outliers is 15 out of 128 and all of these are greater than 208 kWh t^{-1}. Hence, the majority of data falls in the range of 0–400 kWh t^{-1} in both cases.

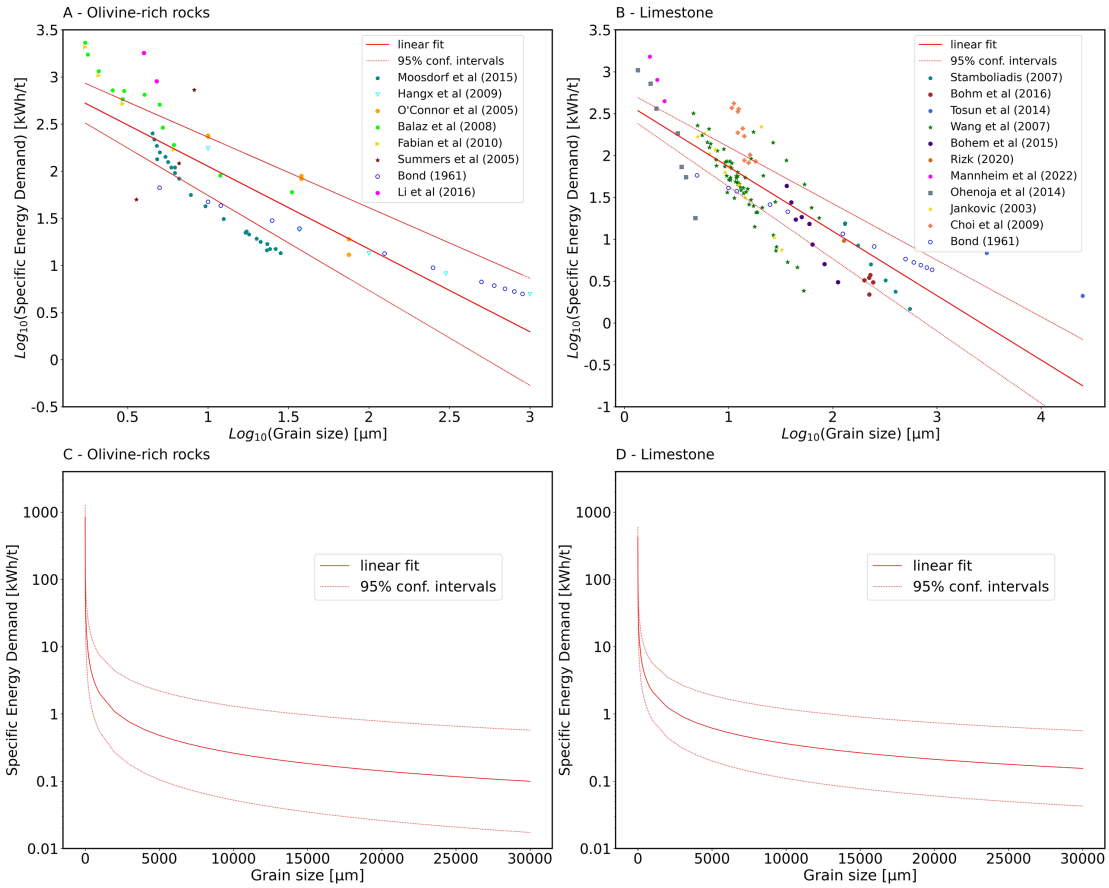

Figure 2. Relationships between the energy demand of comminution and the target grain size in logarithm form (top) and rational form (bottom) in the case of olivine-rich rocks (A and C, left side) and limestone (B and D, right side). Data and mathematical calculations are reported in section 3.3 and 3.4 of SM.

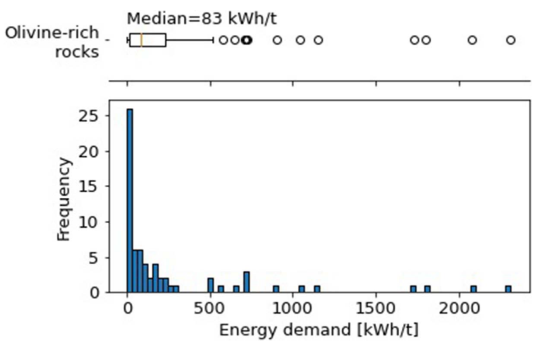

Figure 3. Histogram of frequencies and boxplot of energy consumption in the comminution of olivine-rich rocks. Histogram bin size calculated as dataset width range/30 (Afifi *et al* 2020). The extensive dataset is reported in table SM3 of SM.

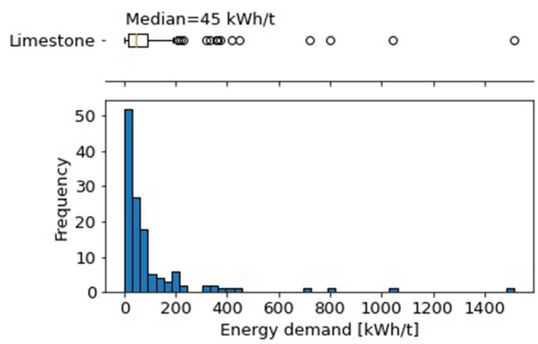

Figure 4. Histogram of frequencies and boxplot of energy consumption in the comminution of limestone. Histogram bin size calculated as dataset width range/30 (Afifi *et al* 2020). The extensive dataset is reported in table SM4 of SM.

Moreover, the consistency of data between the two datasets mostly differs for what regards the crushing phase; the range of variability is 100–1 000 μm for olivine-rich rocks and 112–25 000 μm for limestone. It has been calculated that from $P_{80} = 20\,000$ μm the energy demand of limestone starts exceeding that of olivine-rich rocks by 10% and the share rises with the increase of the diameter (figure 2). No equal variances have also been found by Leven Test.

The overall conclusion is that olivine-rich rocks and limestone datasets significantly differ in the energy demand and, despite the common scarcity of data for both types of rocks in the crushing segment, the olivine-rich rocks' energy relationship is affected by a gap of data ($P_{80} > 1\,000$ μm) more than that of limestone.

Previously it has been stated that the energy input increases by 8%–10% for every 1 m^2 g^{-1} of new surface area created (Renforth *et al* 2013). Based on 68 data for olivine-rich rocks and 128 for limestone, it has been found that 1 $m^2\ g^{-1}$ increase in new surface area corresponds to percentage increases in the energy demand, ranging from 100% ($P_{80} > 2\,500\ \mu m$) to less than 7% ($P_{80} < 10\ \mu m$) depending on the grain size bandwidth we refer to (in other words, 10% increase in new surface area corresponds to 6.1% increase in energy input in case of limestone and 6.8% in case of olivine-rich rocks).

3.2.1.3. Energy-saving opportunity

Grinding offers the greatest energy-saving opportunity along the raw material process chain. It covers 97% of the total energy-saving potential (ES_{PA}) which is practically achievable in comminution (103 kWh t^{-1}) in the case of limestone and 99% of the total practical energy-saving potential ($ES_{PA} = 272$ kWh t^{-1}) in the case of olivine-rich rocks (table SM8 and table SM9, section 5 of SM).

Strategies to reduce the energy requirement in comminution are discussed below.

1. R&D advances and/or optimization of processes.

Advanced technologies are mills equipped with vibration and eccentric, impact and centrifugal actions, high-pressure roller mills (HPRMs) or high-pressure grinding rolls (HPGRs), and stirred media mills (Wang and Forssberg 2003, Gorman and Dzombak 2018). Stirred media mills are 30%–40% more energy-efficient than ball mills for fine and ultrafine grinding (Taylor *et al* 2020) since the use of an agitator allows the feed to be mixed with small-size media (Yang *et al* 2016) and the type and properties of the grinding beads can be adapted to the type of rock, the level of fineness to achieve and the feed size (Mannheim 2011). A study shows that the replacement of a Semi–Autogenous mill (SAG) with HPGR in a conventional SAG-Ball circuit leads to 15%–20% energy savings, 23%–25% cost savings, and 26%–39% reduction in carbon footprint (Daniel *et al* 2010).

Low energy consumption can also be attained by coupling different technologies or equipment. Wet and dry HPRM can be combined with ball mills, stirred media mills (Wang and Forssberg 2007), or ultrasonic energy (Wang and Forssberg 2003). The Ultrasonic Wet-Milling and Micro-Grinding technology as provided by Hielscher (2021) could be a suitable alternative for calcium carbonate and metal oxides.

Smart energy management entails control and real-time optimization by automation to reduce the risk of over-grinding and improve the quality of a product (Klein *et al* 2017). Control and optimization can be achieved by employing new techniques to analyze the mill's internal dynamics (e.g. analytical and discrete element methods to simulate the internal load motion, 3D modeling to monitor the behavior of grinding media and intra-mill materials, online monitoring and diagnostics of internal liners' wear; Góralczyk *et al* 2020) and/or adopting improved classifiers (e.g. air classifier and centrifuges, optical and sensor-based ore sorting, coarse particle flotation, flash separation) to optimize the circulation of loads (Napier-Munn 2015, Bouchard *et al* 2017, Klein *et al* 2017). An interesting analysis regarding the recovery of heat loss from comminution in SAG and ball mills is provided by Radziszewski (2013). The author highlights how the comminution efficiency of these machines could rise from 1% to around 4%–11% if the heat could be properly recovered and converted into electricity.

2. Best practices.

Examples of best practices are an appropriate selection of equipment, adoption of energy management systems, adequate training of operators, use of flexible flowsheet and speed control, and operating at high capacity (Napier-Munn 2015, Klein *et al* 2017, Engeco 2021).

3. Renewable energy sources and/or low carbon footprint alternatives.

A recent study has tested a solar PV with a battery energy storage system to supply electricity for grinding. The solution has shown to be cost-effective albeit the hardness of a rock has a relevant impact on the size of the system (Pamparana *et al* 2019).

3.3. Long-haul transportation

3.3.1. Overview, technical challenges

At present, the most prominent modality to transport bulk commodities is road transportation by heavy-duty trucks (Wetzel 2021). Railways would offer better opportunities for energy efficiency and cost but are underutilized given the poor flexibility in terms of time, location, routes, the high costs for using the tracks, the dependence of the speed on the rail infrastructure.

3.3.2. Energy consumption

Road transport by diesel-powered trucks accounts for the highest energy-intensive transport mode among all the types surveyed (table 2; Lefebvre *et al* 2019). On average, a train requires around 87% less energy than a diesel-powered truck, and a ship around 95% less (table 2). Moreover, a truck is 30%–40% less efficient than a train (see table SM7, section 5 of SM for comparisons).

3.3.3. Energy-saving opportunity

The total practical energy-saving opportunity (ES_{PA}) in long-haul road transportation amounts to 26 kWh t^{-1} per 100 km (table SM9, Section 5 of SM). Railway and maritime transport follow with 2.4 kWh t^{-1} and 0.9 kWh t^{-1}, respectively.

The energy-saving strategies are described below.

1. R&D advances and/or optimization of processes.
In road transportation, experimental simulations have shown that truck platooning can lead to 8%–15% energy saving (Tsugawa *et al* 2016). Truck platooning consists of arranging a set of trucks into groups (platoons) and letting them work connected, eventually supported by smart technologies (e.g. vehicle-to-vehicle communication, vehicle-to-infrastructure communication, radar) and controls, according to the level of automation which is possible to achieve (Atasayar *et al* 2022). Additional benefits are the reduction of road congestion and CO_2 emissions and an increase in road capacity (Neuweiler and Riedel 2017).

In the railway sector, driverless e-trains, digital signaling, rolling motorways, and automated road/rail transshipment systems are examples of new technologies that could decrease labor costs, increase the network capacity, promote the modal shift from road to rail (Paddeu *et al* 2019).

In maritime transportation, the combined use of automated guided vehicles and automated stacking cranes would reduce the number of empty trips, optimize energy consumption and allow easy relocation of freight from the quay to storage areas inside the port (Široký 2011, Flämig 2016, Duan *et al* 2023).

Agile Port System is the technical term used to perform intermodal ship-to-rail convey of cargo in the form of containers at the quay. It consists of interconnected container-carrying vehicles and cranes, working on semi-automated systems (e.g. semi-automated, ship-to-shore cranes, semi-automated, cantilevered, rail-mounted gantry cranes, rail-mounted, automated shuttle cars) (Beškovnik and Twrdy 2011, Paddeu *et al* 2019). Another example of automation is autonomous shipping. It consists of replacing the management of traditional vessels with the remote control of autonomous vessels equipped with electronic devices (i.e. detectors, sensors, high-resolution cameras, advanced satellite communication systems), all located in a center, onshore (IMO 2023). However, the real feasibility of these options is conditioned by solving technical issues such as safety during navigation and liability of these types of vessels under different weather conditions (IMO 2023).

2. Best practices.
In road transportation, an efficiently planned payload combined with high-capacity vehicles (more than 26 m long) can reduce fuel consumption by 25%–35% (Lindqvist *et al* 2020).

In maritime transport, the interconnection of marine terminals ashore with interface centers inland produces a gain in efficiency of 2%–8% since waiting times at berth and turnaround time are reduced (ISU 2013).

3. Renewable energy sources and/or low carbon footprint alternatives.
In road transport, biofuels could potentially replace fossil fuels, but, at present, their use is limited by the high cost of production (DNV 2023).

Electric medium-duty trucks have already been considered feasible alternatives to diesel engines. By contrast, the upscale of electric heavy-duty rigid trucks, semitrailers, and heavy articulated truck-trailer combinations has been undergoing multiple challenges. Some of these are the high upfront costs, the low energy content per unit of weight of the battery, the impact of the weight of the battery on the payload, the impact of the space occupied by a battery onboard, the existence of fast-charging infrastructure at affordable prices, the battery lifetime, restrictions on the gross vehicle weight imposed by countries' regulations, insufficient renewable generation capacity (Liimatainen *et al* 2019, DNV 2023).

Overall, the technology maturity of commercial heavy-duty trucks in the production of batteries and infrastructure has reached partial results but the level of policy in sustaining the upscale of production and infrastructure and in satisfying the demand across all transport sub-sectors is at an early stage (DNV 2023). Despite that, electrification is predicted to power road transport for 78% by 2050, since the gain in operating cost will offset the high capital cost (DNV 2023). Cummins and Tesla are examples of manufacturing industries, that are currently committed to the production of all-electric semi-trailer trucks (Hodgkinson and Smith 2018).

In maritime transport, alternative fuels are pure or blue and green hydrogen (i.e. hydrogen produced by fossil fuels but with carbon capture and storage systems, the former, by electrolysis, the latter), biomethane, bio-methanol, synthetic electrofuels (e-fuels) such as ammonia, e-methanol, e-methane. Each of those poses significant challenges for the implementation at a large scale such as the variability of the cost with the feedstock availability and market price (e.g. biomethane), the limited usability to cover long distances (e.g. green H_2), availability of renewable electricity and sustainable CO_2 at low cost for the production (e.g. e-methanol), toxicity (e.g. ammonia), possibility of using the existing infrastructure for storage and distribution to the port (IRENA 2021, DNV 2023).

Electrification is hardly applicable to maritime transportation, given the lack of adequate knowledge around the supply and demand challenges, lack of supporting policy, and limitations due to the low energy density of batteries (DNV 2023).

3.4. Summary and comparisons

The total average energy demand to mine limestone and olivine-rich rocks is 2.5 and 4 kWh t^{-1}, respectively (table 2).

Table 2. Average energy demand and descriptive statistics on each stage and sub-stage of limestone and olivine-rich rocks supply chain and long-haul transportation per 100 km. The extensive datasets can be found in tables SM1, SM3, SM4, and SM6 of SM. CI is the confidence interval.

Rock	Macro-phase	Sub-phase/ transport mode	Mean kWh t^{-1}	Minimum kWh t^{-1}	Maximum kWh t^{-1}	Std deviation	75% CI lower bound	75% CI upper bound	Number of data
Olivine-rich rocks	Surface mining	Drilling	0.3	0.1	0.6	—	—	—	2
		Blasting	0.4	0.3	0.5	—	—	—	2
		Material handling and hauling	3.1	0.8	5.3	1.4	2.7	3.5	18
		Sub-total	3.8	1.2	6.4	—	—	—	22
	Comminution	Crushing[a]	7.8	4.9	13.4	3.3	6.6	9	10
		Grinding[b]	335	13	2 310	531	254	415	58
		Sub-total	343	18	2 323	—	261	424	68
	Total		347	19	2 330	—	—	—	90
Limestone	Surface mining	Drilling	0.2	0.1	1.6	0.3	0.2	0.3	26
		Blasting	0.2	0.1	0.2	0.03	0.2	0.2	32
		Material handling and hauling	2.1	0.6	4.7	1	1.9	2.3	26
		Sub-total	2.5	0.8	6.5	—	2.3	2.8	84
	Comminution	Crushing[c]	5.8	1.5	15.5	4	4.8	6.7	23
		Grinding[d]	125	2	1 515	211	101	149	105
		Sub-total	131	3	1 531	—	106	156	128
	Total		134	4	1 538	—	108	159	212
Olivine-rich rocks/limestone	Long-haul transportation (100 km)	Road transport	86	22	161	28	85	91	39
		Railway	11	6	19	7	6	16	3
		Maritime transport	5	2	6	2	4	6	5

[a] Average, Lowest and Highest target grain size P_{80}: 528, 100, 1 000 μm respectively, table SM5 of SM.
[b] Average, Lowest and Highest target grain size P_{80}: 14, 2, 75 μm respectively, table SM5 of SM.
[c] Average, Lowest and Highest target grain size P_{80}: 1 530, 112, 25 000 μm respectively, table SM5 of SM.
[d] Average, Lowest and Highest target grain size P_{80}: 18, 1, 83 μm respectively, table SM5 of SM.

The total average energy demand for comminution is 343 kWh t^{-1} (final target size of $\sim$ 14 μm) in the case of olivine-rich rocks and 131 kWh t^{-1} (final target size of $\sim$ 18 μm) in the case of limestone (tables 2, SM5 section 3 of SM).

The energy consumption of mining is at least 80% less than that of comminution, especially if it is compared with fine ($P_{80} < 50$ μm) and ultrafine grinding ($P_{80} < 10$ μm). Similar conclusions can be drawn if the energy demand of road transportation is included (figure 5).

Overall, the more energy is used for grinding or to transport the commodity for long distances (>50 km) by diesel-powered trucks, the higher the energy impact of these two activities in comparison with the others. If comminution is limited to a final target size of 100 μm, the energy demand of road transportation per 100 km is 80%–85% of the total energy demand (mining, comminution, and transportation), whereas, in the case of 5 μm, it falls to 30%–40%.

The impact of long-haul transportation can be also understood if we consider that the saleability of widespread and low-value commodities like limestone, is profitable only if transportation costs are low.

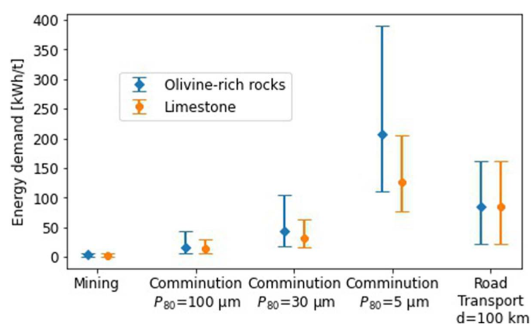

Figure 5. Average, minimum, and maximum energy demand along the raw material process chain and of road transportation, given three types of target grain size P_{80} (100, 30, 5 μm) for grinding and a transport distance of 100 km. The energy demand of crushing is included in the total comminution and refers to only one target grain size (3 000 μm). Data on mining and road transport are taken from table 2. The energy demand of comminution has been calculated by applying the energy relationships found in this work (section 3.4 of SM).

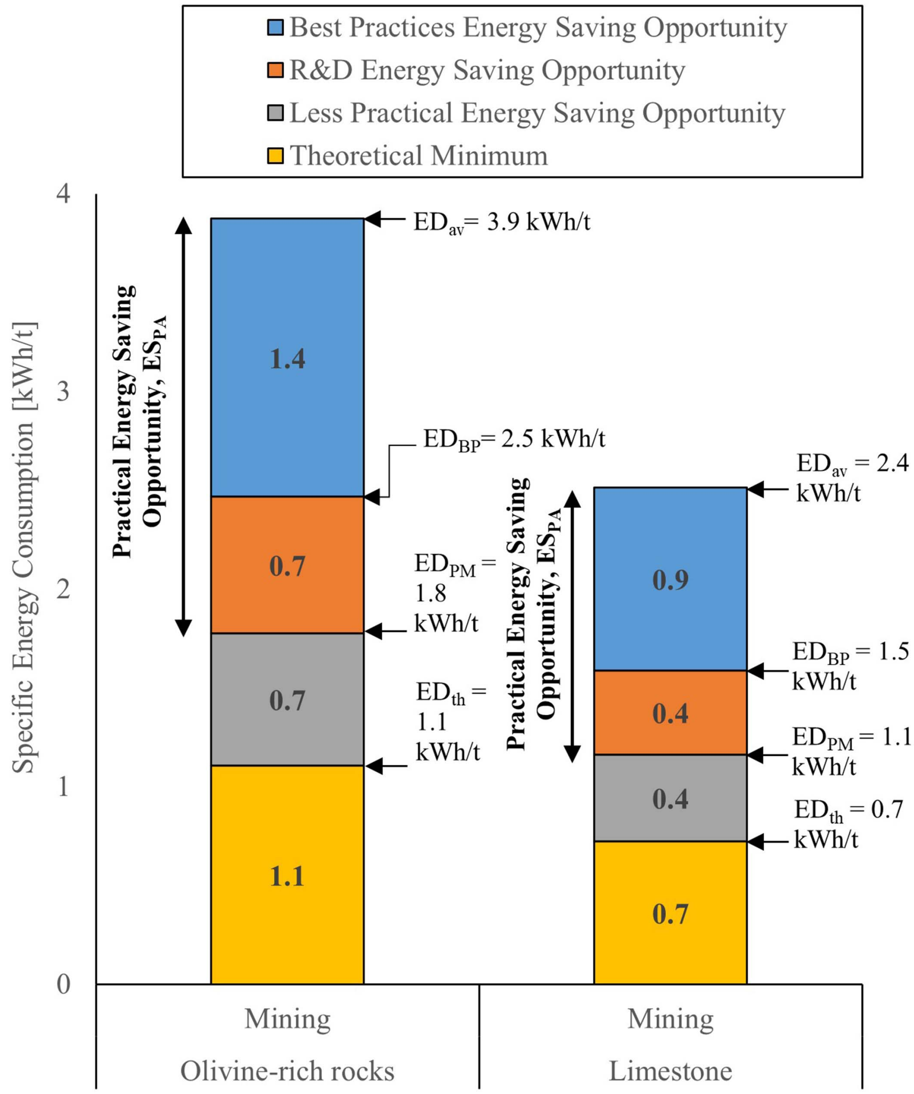

Figure 6. Energy-saving opportunity and energy contributions in the mining of olivine-rich rocks and limestone. Further details are reported in tables SM8 and SM9, section 5 of SM.

Nevertheless, both grinding and transport on road show the greatest energy-saving potential (figures 6–8; tables SM8–SM9, section 5 of SM).

If BPs and technological improvements deriving from R&D advances were applied to reduce each operation along the mine-to-mill process chain to each own practical minimum of energy, also called ED_{PM}, the total average energy-saving opportunity (ES_{PA}) would be 686 TWh yr^{-1} for the limestone industry and 2.3 TWh yr^{-1} for the olivine industry (table SM10, section 5 of SM).

Specifically, the sole implementation of BPs in mining and comminution of limestone and olivine could save a total energy of 296 TWh yr^{-1} whereas implementing energy-efficient technologies from R&D would bring an additional 392 TWh yr^{-1}.

The largest total energy-saving opportunity that is practically attainable is obtained in the grinding phase i.e. 677 TWh yr^{-1} for limestone and 2.28 TWh yr^{-1} for olivine, both equivalent to ~ 97%–98% of each total (table SM10, section 5 of SM).

The amount of energy saved by optimizing each activity of mining and comminution is nearly 0.6% of the world energy demand (407 EJ; EIA 2023) and 52% of the world mining energy demand (5 EJ; EIA 2023). Both global energy data refer to 2017 to be in line with the year of production of limestone and olivine (refer to section 2.1 for further details).

In long-haul transportation, the practical energy-saving opportunities would be 217 GWh yr^{-1}, 20 GWh yr^{-1}, and 7 GWh yr^{-1}, on average, if the annual production of olivine was transported over 100 km on road, by railway and maritime transport, respectively (table SM11, section 5 of SM). In the case of limestone, the results are 170 TWh yr^{-1}, 16 TWh yr^{-1}, and 6 TWh yr^{-1} (table SM11, section 5 of SM).

Similar to mining and comminution, the assumption is that each means of transport (truck, train,

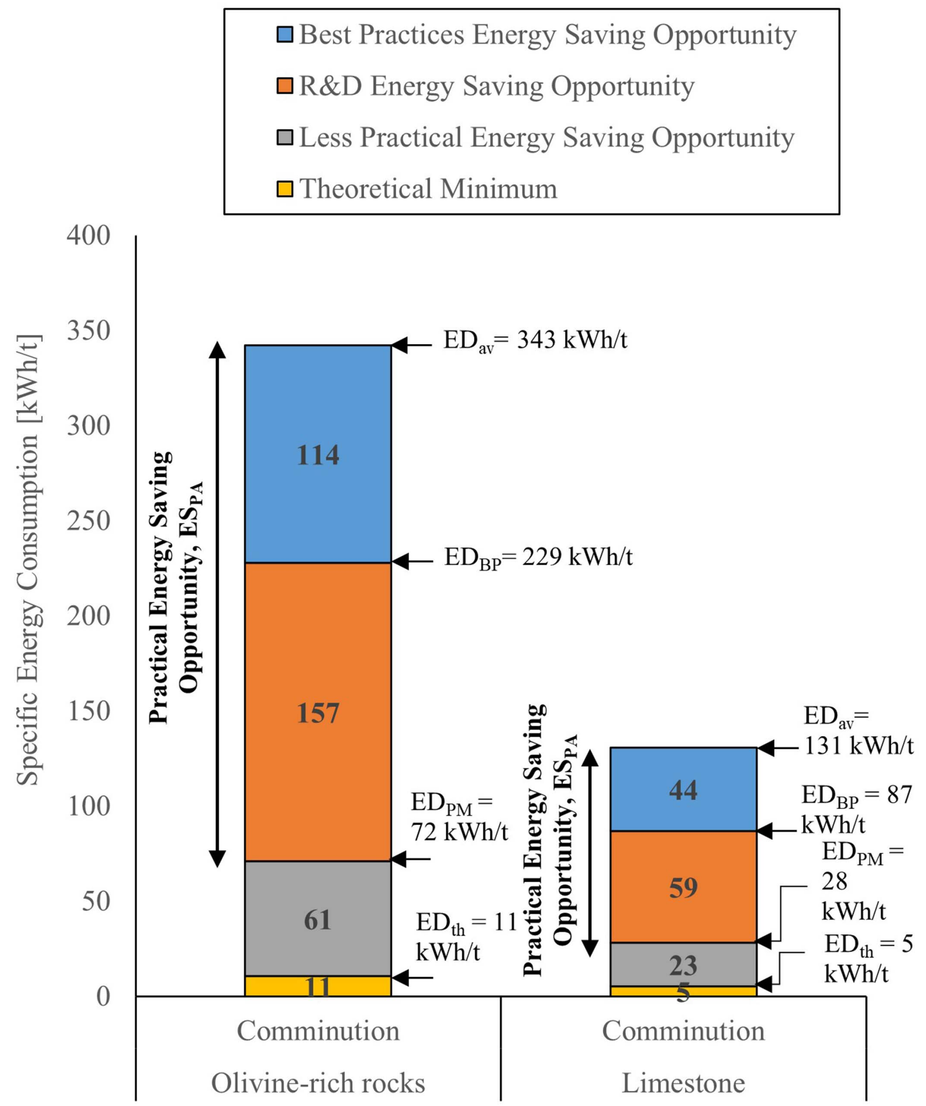

Figure 7. Energy-saving opportunity and energy contributions in the comminution of olivine-rich rocks and limestone. Further details are reported in tables SM8 and SM9, section 5 of SM.

ship) is used at its highest practically achievable energy efficiency (table SM7, section 5 of SM).

The optimization of the sole road transport of olivine and limestone accounts for 0.2% of the world's energy demand. The remaining contributions given by railway and maritime transport are much more negligible.

3.5. Future perspectives on the energy reduction of grinding for OL and EW purposes

In the High Energy Efficiency scenario the total yearly amounts of limestone and olivine-rich rocks to remove 0.002 $MtCO_2$ (in 2025)—98 $MtCO_2$ (in 2050) by OL and EW only, are 0.0–156 Mt and 0.01–37 Mt, respectively (see figure 9(A) and table SM12, section 6 of SM).

The total energy required to comminute these materials down to a target grain size of 5 μm would annually range from 0.5 GWh (in 2025) to 27 TWh (in 2050) (figure 9(C)).

If investments in BPs and R&D advances were applied, such that both the current average energy efficiency and the maximum attainable efficiency increased from 2% (in 2025) to 5% (in 2050) and from 3% (in 2025) to 10% (in 2050), respectively, the electricity demand to comminute the same amounts of raw materials would decrease by 33% −65% (figure 9(C)).

In the Low Energy Efficiency scenario, the required yearly amounts of limestone and olivine-rich rocks to sequester 0.002 $MtCO_2$ (in 2025)—252 $MtCO_2$ (in 2050) are 0.0–401 Mt and 0.0–95 Mt, respectively (figure 9(B)).

Without energy-saving actions, the electricity consumption to comminute the two materials would annually increase from 0.5 GWh in 2025 to about 70 TWh in 2050, i.e. 61%–98% more than the results reported in the High Efficiency scenario (figure 9(D)). By contrast, implementation of BPs and R&D advances to improve the two types of energy

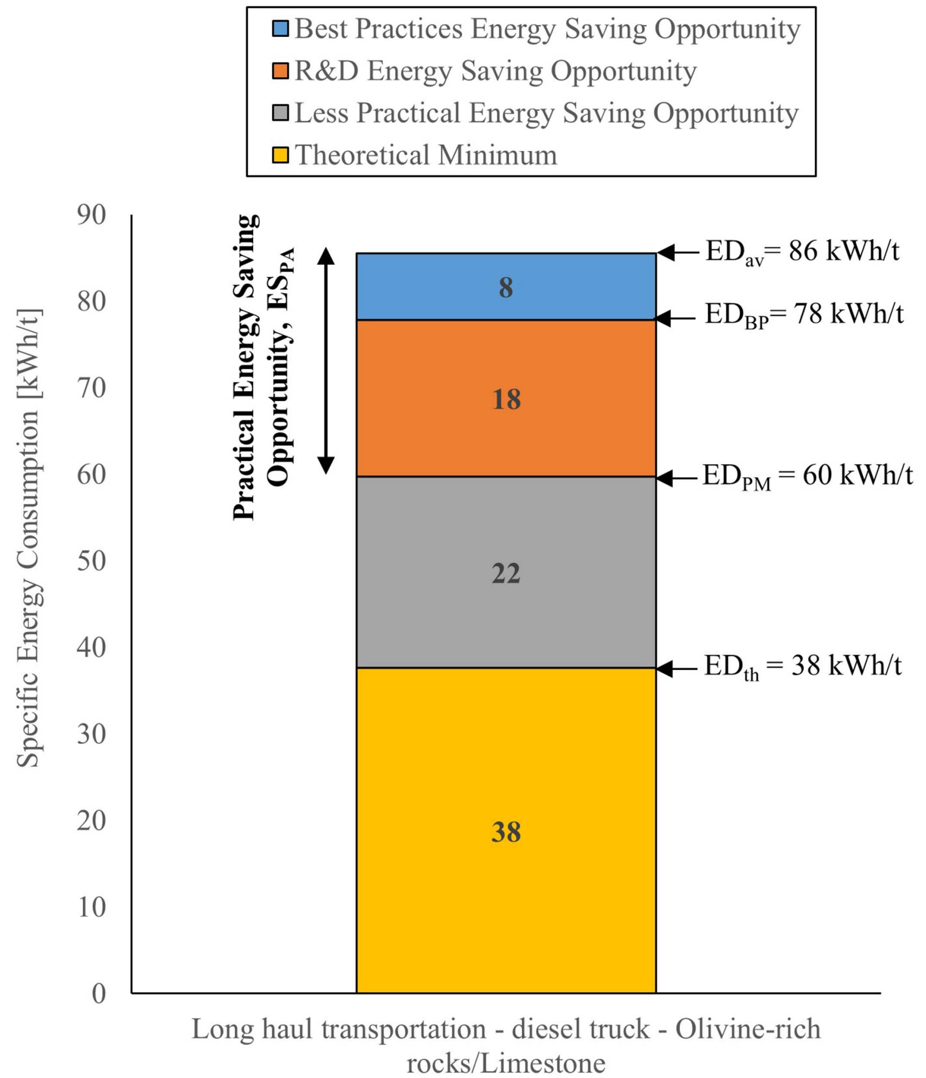

Figure 8. Energy-saving opportunity and energy contributions of limestone and olivine-rich rocks road transport by diesel-powered trucks over 100 km. Further details are reported in tables SM8 and SM9, section 5 of SM.

efficiency would reduce the energy demand by 33%–36% (figure 9(D)).

The impact of the energy consumption on the global electricity grid is less than 1% of the world electricity generation (i.e. from 32 PWh in 2025 up to 83 PWh in 2050, McKinsey and Company 2022) over the entire timeframe (2023–2050), in both scenarios, including or excluding energy-saving strategies but it is 60%–98% higher in case of low energy efficiency conditions (tables SM12 and SM13, section 6 of SM).

3.6. Conclusion

An in-depth limestone and olivine-rich rocks survey on energy consumption and potential ways to save energy along the raw material process chain and long-haul transportation has been carried out. A comprehensive understanding of all the involved steps along the supply chain and two new relationships relating the grain size to the energy demand of comminution allowed us to gather and provide more focused information and estimates.

The results show that improving the maximum level of practically achievable energy efficiency (from 3% to 10%) of fine and ultrafine grinding ($P_{80} = 5\ \mu$m) could lead to energy reduction of 33%–65% in the processing of limestone and olivine-rich rocks for OL and EW purposes.

In long-haul transportation, until electric commercial heavy trucks become an established reality, diesel-powered trucks offer the greatest practically attainable energy-saving potential, i.e. 26 kWh t^{-1} per 100 km of distance traveled.

Given the significant energy-saving potential, investments in BPs and R&D are crucial over the next decades as this would support the competitiveness of OL and EW in a portfolio of CDR methods.

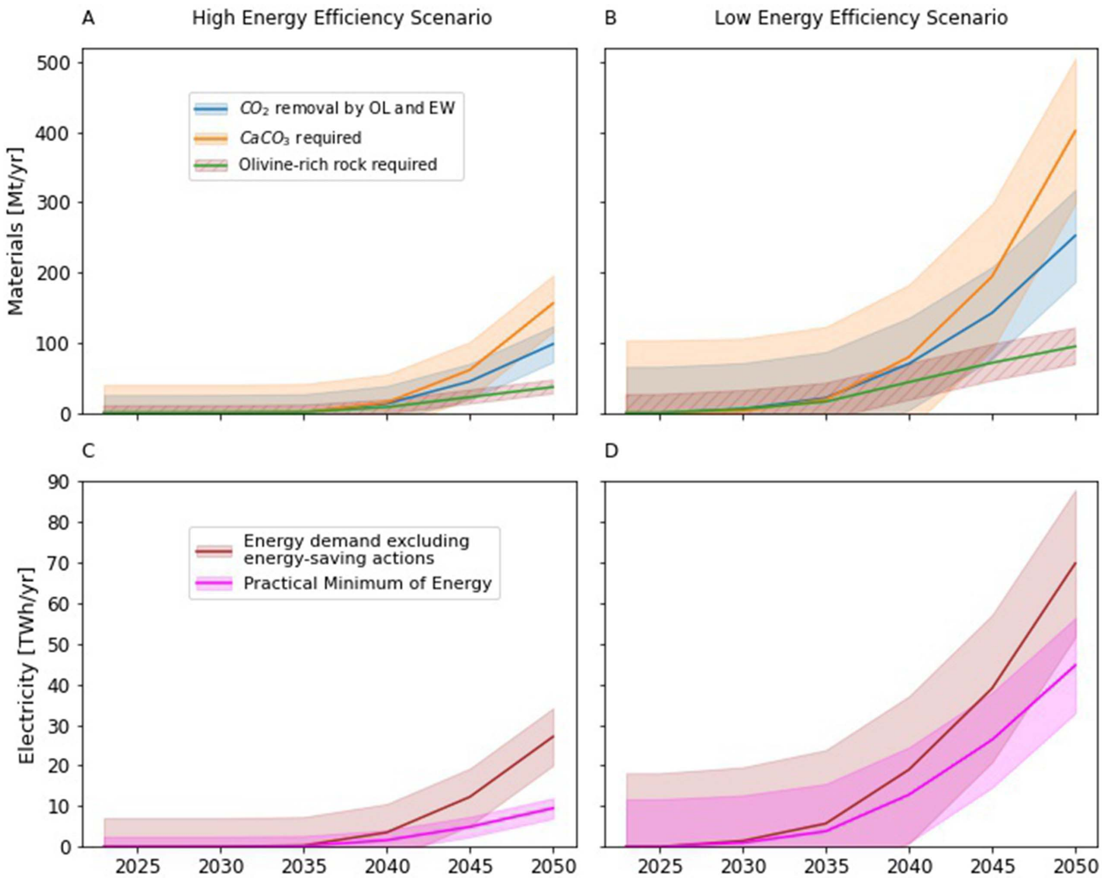

Figure 9. Projections on the future amounts of CO_2 removal from the atmosphere by OL and EW, $CaCO_3$ and olivine-rich rocks (A and B) and on the future electricity requirement to comminute limestone and olivine-rich rocks ($P_{80} = 5\ \mu$m) including and excluding energy-saving actions (C and D) for the High Energy Efficiency scenario (left side) and the Low Energy Efficiency Scenario (right side). Shaded areas are built considering 95% confidence intervals. Additional details on assumptions and calculations are reported in Section 6 of SM.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

Conceptualization, S C; Methodology, S C, T A, S D M; Formal analyses, S D M; Data curation, S D M, T A; Writing—original draft preparation, S D M; Writing—review and editing, S C, T A and M G; Supervision, T A, S C. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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