ENERGY MANAGEMENT
IN EUROPEAN AGGREGATES SITES
A GUIDE TO GOOD PRACTICE

AGGREGATES EUROPE

R8TATE
CIRCULAR ECOLOGICAL ESSENTIAL
& CRITICAL RAW MATERIALS



1 Contents

1 Contents 2
2 President's foreword 3
3 Executive summary 6
4 Why does energy matter? 9
4.1 Business benefits of effective energy management 9
4.2 Energy as a production variable 11
4.3 Energy efficiency and climate neutrality 11
4.4 Ten principles for good energy management 13
5 Energy in EU policies 14
5.1 From the internal energy market to climate neutrality 14
5.2 Energy, the Single Market and European competitiveness 14
5.3 From the Clean Industrial Deal to electrification 14
5.4 What does this mean for aggregates operations? 15
6 Understanding energy performance 16
6.1 Energy: forms and measurement 16
6.2 Energy saving and energy efficiency 17
6.3 Indicators that support decisions 19
7 Energy through the aggregates production process 20
7.1 Energy in the production process 20
8 Quarry design, drilling and blasting 25
8.1 Land preparation and quarry design 25
8.2 Drilling and blasting as one production subsystem 25
8.3 Fragmentation links extraction and processing 26
8.4 A practical quarry-to-crusher optimisation loop 26
9 Loading, haulage and material movement 28
9.1 Material movement is the energy driver 28
9.2 Direct excavation and loading 29
9.3 Haulage 29
9.4 Haul roads and quarry geometry 30
9.5 Trucks, conveyors and transport architecture 30
9.6 Progressive rehabilitation as material-flow optimisation 32
10 Processing: crushing, screening and classification 33
10.1 Comminution: reduce only what the product requires 33
10.2 Crushing stages and circuit configuration 33
10.3 Screening: a small drive with a large system effect 33
10.4 Open and closed circuits 34
10.5 Practical questions for processing energy performance 34
11 Conveying, storage, washing and auxiliary systems 36
11.1 Conveying and internal material flow 36
11.2 Washing, classification and dewatering 36
11.3 Pumping and water circuits 38
11.4 Thermal drying of specialised aggregates 38
11.5 Storage and buffers 39
11.6 Ancillary facilities and support services 40
11.7 Product loading and dispatch 40
11.8 External transport and organisational boundaries 41
12 How to improve energy performance 42
12.1 Improvement hierarchy 42
12.2 Operations and maintenance 44
12.3 Correct sizing and equipment matching 46
12.4 Procurement and life cycle thinking 47
13 Efficient equipment, electrification and low-carbon energy 49
13.1 Electricity generation mix and time-dependent carbon intensity 49
13.2 Electricity supply and motor-driven systems 52
13.3 Mobile equipment and powertrains 53
13.4 Electrification 53
13.5 Renewable fuels for residual combustion-engine demand 53
13.6 Onsite energy generation, storage and energy resilience 55
14 Monitoring, digitalisation and energy economics 59
14.1 Measurement and digital support 59
14.2 Energy audits 62
14.3 Energy economics and investment 65
14.4 Electricity costs and energy procurement 66
14.5 Core management scorecard 69
15 Managing energy systematically 70
15.1 The practical management cycle 70
15.2 Energy review, SEUs, EnPIs and baselines 71
15.3 Action plans and verification 71
15.4 Energy audit and EnMS internal audit 71
15.5 A practical implementation roadmap 71
15.6 EU energy-management requirements 72
16 People and environmental co-benefits 73
16.1 Environmental interactions 73
16.2 People, competence and energy culture 74
17 Recommendations and route to action 76
17.1 Route to action for an aggregates site 76
17.2 Recommendations for industry associations 77
17.3 Recommendations for companies and operations 77
17.4 Recommendations for equipment manufacturers and technology suppliers 79
17.5 Recommendations for policymakers 80
17.6 Enabling regulatory and policy conditions for the sector's energy transition 81
Annex A – Illustrative applications of energy-management principles 86
A.1 Purpose and scope 86
A.2 Illustrative example 1 — Haul-road and dispatch optimisation 87
A.3 Illustrative example 2 — Crushing and screening circuit optimisation 88
A.4 Illustrative example 3 — Water recirculation and pumping optimisation 90
A.5 Illustrative example 4 — Onsite photovoltaic generation, electrification and load management 91
A.6 Common lessons from the illustrative examples 93
Annex B – Core terminology, source evidence and bibliography 94
B.1 Core terminology 94
B.2 Bibliography 95

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Environment Committee - Climate Change Mitigation and Adaptation Task Force

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This guide represents a sector-specific adaptation and further development of relevant outcomes from the ROTATE project, tailored to the particular characteristics, operational conditions and energy-efficiency challenges of the aggregates industry. It builds on the knowledge and results generated throughout the project, with the ROTATE Handbook – Volume 1: Energy Efficiency used as a supporting reference.

It has been developed in collaboration with Aggregates Europe, a member of the ROTATE International Advisory Board (IAB), to support the practical transfer and application of the project's results within the European aggregates sector.

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2 President's foreword



Aggregates are indispensable to Europe. They form the physical foundation of our homes, transport networks, energy infrastructure, water systems and the many other assets on which modern society depends. Every year, 26,000 quarries, sand and gravel operations, recycling facilities and processing plants across Europe transform locally available natural mineral resources and secondary materials into 3,000 million tonnes of essential construction materials. Increasingly, aggregates producers also recover construction and demolition waste and suitable industrial materials to produce recycled and manufactured/artificial aggregates, extending the sector's contribution to Europe's circular economy. Doing so requires energy at every stage of the production chain.

Energy has therefore become a strategic issue for our sector. It is a production input, a competitiveness factor, a source of exposure to volatile costs and, increasingly, one of the principal levers available to reduce the greenhouse-gas footprint of aggregates production. The challenge is not simply to purchase different energy or more efficient machines and production facilities. It is to understand why energy is required, where it is consumed, what useful production it delivers and how the complete quarry and processing system can be improved.

This is also a central climate issue. The Spanish DAPÁridos sectoral EPD dataset, covering around 500 production sites, approximately 90 million tonnes of production and more than 270,000 verified data points, shows that fuel and electricity consumption account for 79.29% of cradle-to-gate Global Warming Potential within modules A1–A3. For communication purposes, this Guide refers to this as approximately four-fifths of production-stage greenhouse-gas emissions being energy-related. Energy management

is therefore one of the principal direct levers available to reduce the production-stage carbon footprint of aggregates. This means that appropriate energy management in quarries, sand and gravel operations and aggregates processing plants is not a secondary environmental action but one of the main practical pathways available to minimise the sector's production-related emissions. This makes appropriate energy management one of the principal practical levers available to reduce the production-stage carbon footprint of aggregates.

This conclusion also explains why energy efficiency and decarbonisation must be addressed together but not confused. We must first reduce unnecessary physical work, improve material flows, optimise fragmentation, loading, haulage, crushing, screening, conveying, washing and pumping, and maintain equipment close to its efficient operating condition. We must then combine these improvements with electrification, production and use of renewable electricity, lower-carbon fuels and other suitable energy solutions where they are technically and economically appropriate.

The size and diversity of our industry makes a single prescription impossible. A hard-rock quarry with long internal haulage routes faces different energy challenges from a sand and gravel operation with intensive washing and pumping. Geology, quarry geometry, plant configuration, production requirements, available grid capacity and remaining site life all matter. This Guide therefore does not promote one technology or one universal benchmark. It provides a practical framework for understanding energy performance, identifying significant uses, prioritising opportunities and verifying improvement under real operating conditions.

The extractive industry is particularly sensitive to the availability, cost and volatility of energy, as a significant share of its operating costs is directly or indirectly linked to fuels and electricity. This exposure can be amplified by geopolitical tensions, supply disruptions, dependence on imported fuels or technologies, grid congestion and insufficient electricity-network capacity, volatility in energy and carbon markets, taxation and regulated charges, or rapid changes in regulatory frameworks. A lack of technology neutrality may create an additional risk when particular solutions are favoured or restricted before viable alternatives are technically mature, economically competitive and available at the required scale. For industries operating long-life assets, these factors can increase both production costs and investment uncertainty, making an orderly and competitive energy transition more difficult.

This vulnerability is particularly relevant to the aggregates industry, which is characterised by relatively low unit-value products, large production volumes and a limited capacity to absorb significant increases in energy costs. Extraction, loading, internal haulage, crushing, screening, washing and material handling all require energy, while the location-specific nature of mineral resources and proximity-to-market requirements constrain the ability to relocate or reorganise production. Energy policy for the sector should therefore combine energy efficiency, diversification and security of supply, electrification where technically and economically viable, renewable generation and self-consumption, flexibility, technology neutrality, and access to different low-carbon energy solutions, while avoiding the creation of new dependencies or losses of competitiveness during decarbonisation. In this context, sound energy management is not only a means of reducing costs and emissions; it is also a strategy for strengthening industrial resilience.

In an increasingly volatile energy environment, managing energy means not only using less and using it better, but also securing reliable, competitive and resilient energy supplies for our aggregates sites.

This is particularly important for a sector composed largely of small and medium-sized enterprises. Good energy management must be technically robust, but it must also be usable. It should help operators and managers make better everyday decisions, support investment planning, strengthen resilience and progressively embed energy performance alongside safety, quality, productivity, cost and environmental management. This Guide is aimed at the aggregates sector, which accounts for more than 80% of all extraction sites in Europe and European raw material operations, but it is fully applicable to the rest of the EU open-cast extractive industry.

Aggregates Europe is committed to supporting its members in this transition. By improving energy performance, our industry can reduce costs, strengthen resilience, reinforce competitiveness, lower emissions and contribute to Europe's climate and energy objectives while continuing to supply the essential mineral materials on which society depends. I hope this Guide will provide companies, associations, workers, technology providers and policymakers with a common basis for action and continual improvement.



Antonis Antoniou Latouros
President of Aggregates Europe

3 Executive summary

Energy is a fundamental production input in aggregates operations. The industry needs to extract, move and process mineral raw materials and to deliver products that meet demanding specifications. Because aggregate production is based on large material flows, apparently small inefficiencies in fragmentation, loading, haulage, crushing, screening, conveying or pumping can accumulate into significant energy use over the life of a site.

The scope of this Guide includes aggregates produced from natural (88% of total demand), recycled (10% of total demand) and manufactured/artificial sources (2% of total demand). Recycled aggregates may be produced from construction and demolition waste (CDW) and other suitable secondary materials, while manufactured/artificial aggregates may originate from industrial processes, including suitable slags and other mineral residues. These materials may be processed at existing quarry or sand-and-gravel sites, where natural and secondary aggregates can share part of the same production infrastructure, or at dedicated standalone facilities.

This is also a central climate issue. Sectoral Environmental Product Declaration calculations, including DAPÁridos [1], indicate that approximately 80% of the CO_2 and other greenhouse-gas emissions associated with aggregates production are linked to the energy consumed across the successive production stages. The DAPÁridos work draws on data from around 500 production centres. Energy management is therefore one of the principal and most direct vectors available to reduce and minimise production-related greenhouse-gas emissions in the aggregates sector.

The purpose of this Guide is not to prescribe a single technology or a universal energy bench-

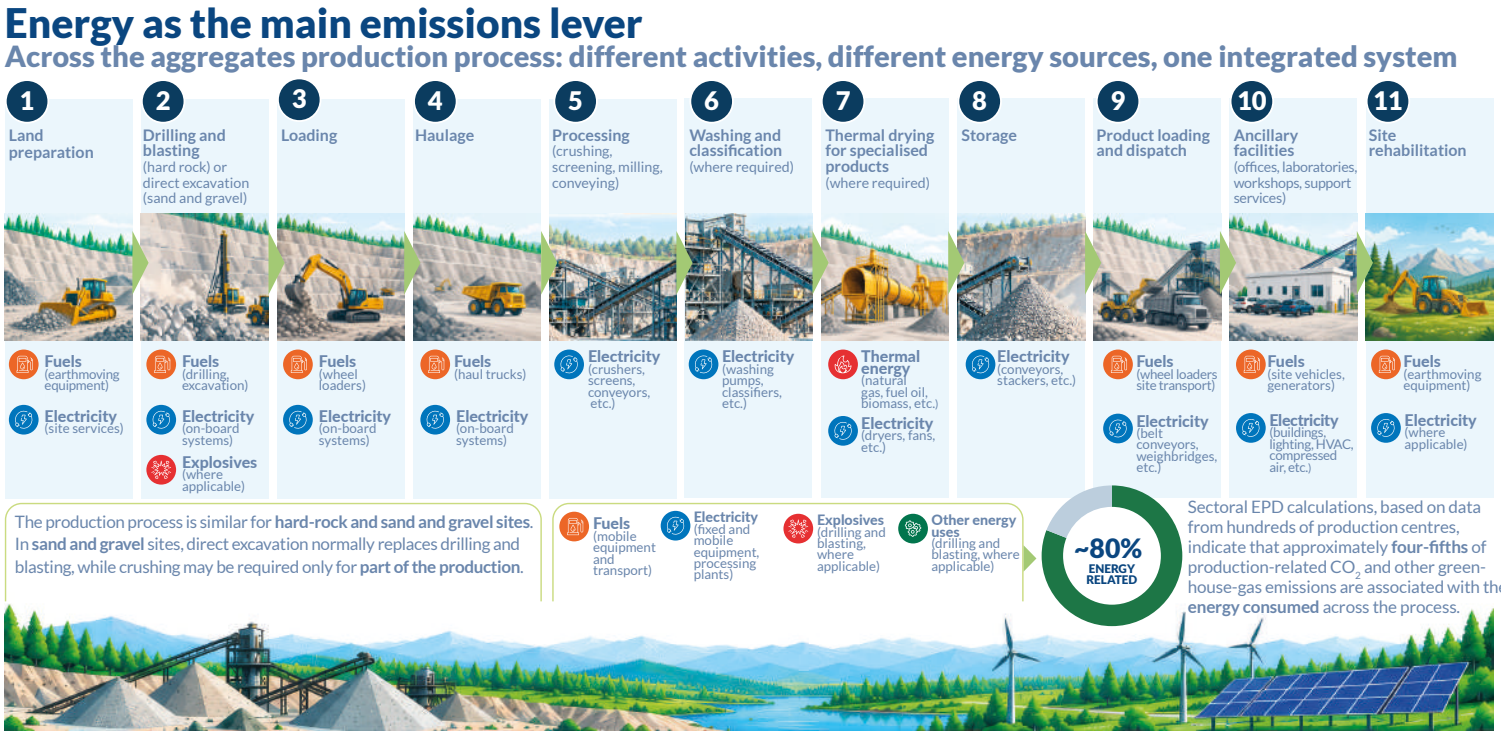


FIGURE 1. — Energy as the main emissions lever

[1] See Annex B.2 Bibliography reference n. 40.

mark. Quarries and sand and gravel operations differ substantially in geology, geometry, haul distance, processing configuration, product mix, production rate, water requirements and access to electricity. The correct objective is therefore to improve the energy performance of each production system under its actual operating conditions.

The central principle of this Guide is simple: optimise the production system before optimising the individual machine or production facility.

Energy saving, energy efficiency and decarbonisation are related but distinct. Energy saving concerns a reduction in energy consumption. Energy efficiency concerns the useful output obtained from that energy. Decarbonisation concerns the greenhouse-gas emissions associated with supplying and using energy. A site may reduce emissions through electrification or renewable electricity without necessarily reducing energy consumption; equally, a decline in total consumption does not demonstrate improved efficiency if production has fallen more rapidly.

For this reason, energy performance should be measured in relation to useful production and, where necessary, normalised for the variables that materially influence consumption. Typical indicators include kWh/t for processing, l/t or kWh/t for mobile equipment, l/t·km for haulage and kWh/m^3 for pumping. Site-level indicators should normally be related to saleable production rather than only to material handled.

The largest opportunities are frequently found before the point of energy conversion. Quarry development, crusher location, haul distance, vertical lift, fragmentation, process configuration, recirculating loads, storage location and the number of times material is handled determine how much physical work the operation requires. Good energy management therefore starts by avoiding unnecessary work, simplifying material flows and stabilising production before investing in more efficient equipment.

The Guidance applies the following hierarchy throughout: avoid unnecessary work; simplify material flows; optimise operation; improve maintenance and control; upgrade equipment; and redesign the system where justified. Electrification, renewable energy, storage and alternative fuels can then be evaluated within this system context rather than as isolated decarbonisation measures.

Monitoring and digitalisation support this approach by connecting energy data with production and operational variables. Their value lies not in collecting data for its own sake, but in identifying Significant Energy Uses, detecting deviations, establishing Energy Performance Indicators and baselines, prioritising actions and verifying improvement.

An Energy Management System provides the management framework for making this improvement continual. ISO 50001 is the principal international reference, but the core logic is accessible to every operation: understand energy use, prioritise significant uses, define indicators and targets, implement actions, measure results and repeat. Energy management should be integrated into quarry planning, production, maintenance, procurement and investment rather than operate as a parallel administrative system.

Effective energy management must combine physical efficiency with sound energy procurement: reducing specific consumption, managing peak demand and reactive energy, making intelligent use of tariff periods and flexibility, and selecting supply arrangements that control costs, risks and exposure to energy-market volatility.

The transition towards lower-energy and lower-carbon aggregates production will require coordinated action by companies, industry associations, technology providers and policymakers. Companies can improve process design, operating practices, maintenance, measurement and investment decisions. Associations can provide common tools, evidence, training and knowledge transfer. Policymakers can support grid access, technology-neutral investment, skills, innovation and proportionate requirements that recognise the site-specific nature of aggregate production.

ENERGY-MANAGEMENT HIERARCHY

From less work to cleaner energy

A structured approach to reduce energy use and emissions in aggregates sites

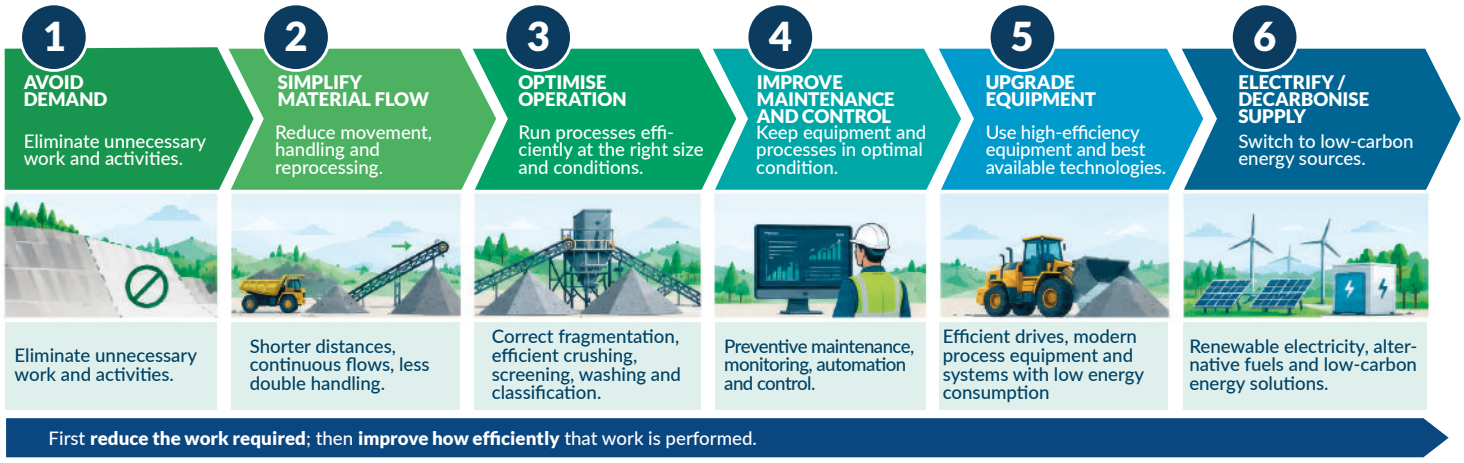


FIGURE 2. — Energy-management hierarchy

4 Why energy matters?

4.1 Business benefits of effective energy management

Effective energy management is not only an environmental or decarbonisation measure. For aggregates producers, it can contribute directly to cost control, productivity, operational reliability, competitiveness and business resilience.

Energy is required throughout the production chain and represents a significant operating cost for many sites. Inefficient energy use is frequently associated with unnecessary physical work, poor material flows, idling, recirculation, rehandling, equipment condition or unstable production. Improving energy performance can therefore generate benefits well beyond the direct value of the energy saved.

The principal potential business benefits include:

- **Lower operating costs**. Reducing fuel and electricity consumption per tonne of saleable product reduces production costs and exposure to energy-price increases.
- **Higher productivity and process efficiency**. Measures that eliminate unnecessary movement, reduce recirculation, improve fragmentation, stabilise plant feed or optimise equipment utilisation can simultaneously reduce energy consumption and increase throughput.
- **Improved equipment reliability and availability**. Good energy performance is closely linked to correct equipment selection, operation and maintenance. Detecting abnormal energy consumption can also help identify wear, misalignment, blockages, poor lubrication or other developing equipment problems before they result in failure.
- **Reduced maintenance and equipment wear**. Avoiding unnecessary operating hours, excessive loads, repeated handling and inefficient operation can extend component life and reduce maintenance requirements.
- **Better investment decisions**. Energy measurement and life cycle costing provide a stronger basis for equipment selection and capital investment than purchase price alone. They help companies distinguish between measures that genuinely improve whole-system performance and those that merely improve the nominal efficiency of an individual machine.
- **Reduced exposure to energy-price volatility**. Lower energy demand reduces the financial impact of changes in electricity and fuel prices. Electrification, demand management, onsite renewable generation, storage and appropriate energy procurement can provide additional options for managing energy-related business risk.
- **Lower carbon footprint**. Energy use is a major contributor to the production-stage carbon footprint of aggregates. Improving energy performance can therefore provide a direct means of reducing energy-related greenhouse-gas emissions.
- **Improved ability to respond to customers and markets**. Reliable energy and emissions data can support EPDs, customer information, public procurement requirements and

other forms of environmental reporting. As carbon performance becomes increasingly relevant along the construction value chain, this information can become commercially important.

- **Greater resource efficiency and circularity**. Efficient processing of construction and demolition waste and suitable industrial materials can recover valuable mineral fractions as recycled or manufactured/artificial aggregates while also separating metals and other materials for recovery through appropriate recycling routes. Energy management helps ensure that this additional circular-economy activity is performed with the minimum necessary handling and processing.

- **Greater regulatory and strategic preparedness**. Systematic energy management helps companies respond to evolving energy-efficiency, climate, reporting and industrial-policy requirements and provides a structured basis for identifying and prioritising future decarbonisation investments.

- **Greater operational resilience**. Understanding when, where and why energy is consumed helps sites assess their dependence on different energy carriers, grid capacity and fuel supply, and supports better planning for electrification, renewable generation, storage and other changes in energy supply.

The magnitude of these benefits will vary between operations and not every energy-saving measure will improve every aspect of performance. Measures should therefore be assessed against energy performance, production, product quality, safety, reliability, maintenance, environmental performance and life cycle cost.

Good energy management is therefore not simply about buying cheaper energy or reducing kWh. It is about producing the required quantity and quality of aggregates with less unnecessary work, lower cost, lower emissions and greater operational resilience.

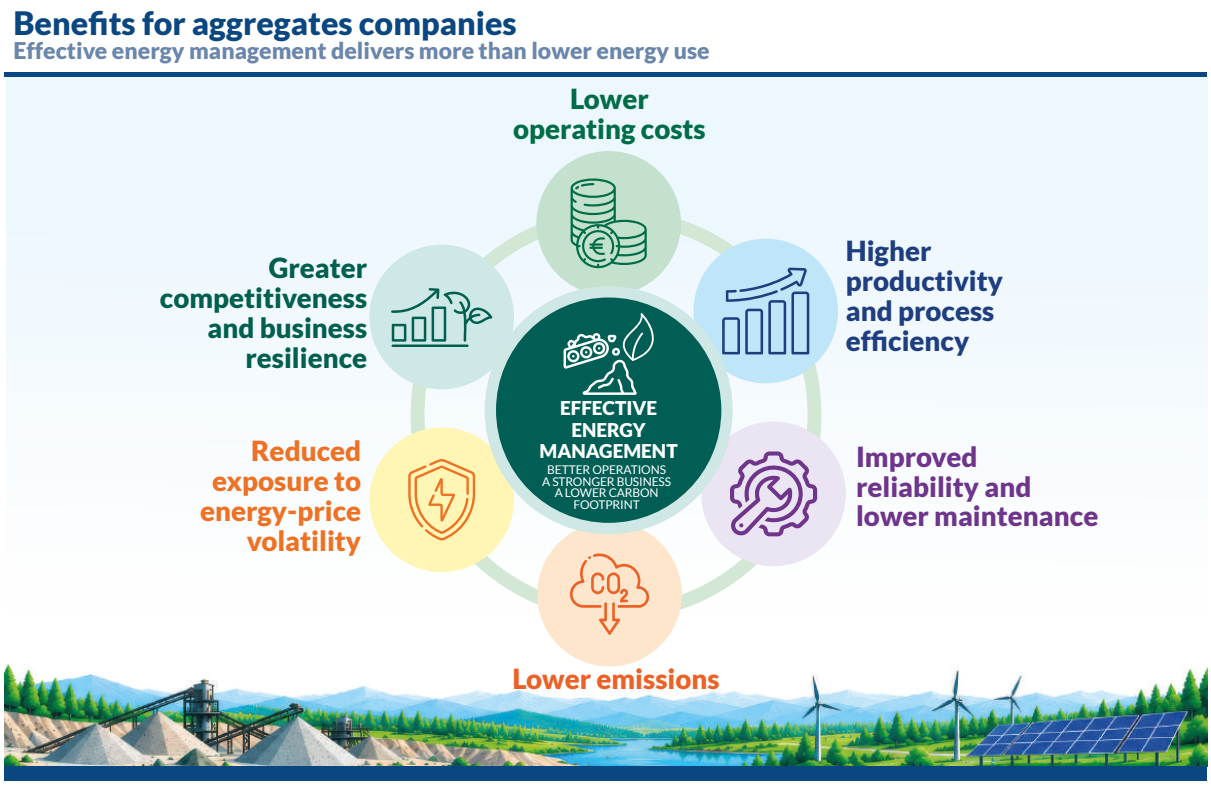


FIGURE 3. — Benefits for aggregates companies

4.2 Energy as a production variable

Energy should be treated as a production variable rather than only as a utility cost. It is embedded in the physical work required to extract or receive materials, sort and separate them where necessary, drill, fragment, excavate, load, transport, crush, screen, wash, pump and handle material. The amount of energy required depends not only on installed equipment but also on the work imposed by quarry geometry, material characteristics, product requirements and operating strategy.

Treating energy as a production variable makes the relationship between energy use, process conditions and useful output visible to operators and management, providing the basis for systematic improvement.

4.3 Energy efficiency and climate neutrality

Energy efficiency is an essential component of the transition towards climate neutrality because it reduces the energy required to deliver useful production. It should nevertheless remain conceptually separate from decarbonisation. The emissions associated with energy use depend on the energy carrier, the carbon intensity of electricity, the life cycle characteristics of fuels and the accounting boundary applied.

For aggregates production, this relationship is especially significant. The reference Spanish sectoral EPD dataset covers around 500 production sites, approximately 90 million tonnes of production and more than 270,000 verified data points. Within its cradle-to-gate boundary (modules A1–A3), fuel and electricity consumption contribute 79.29% of GWP-total. This

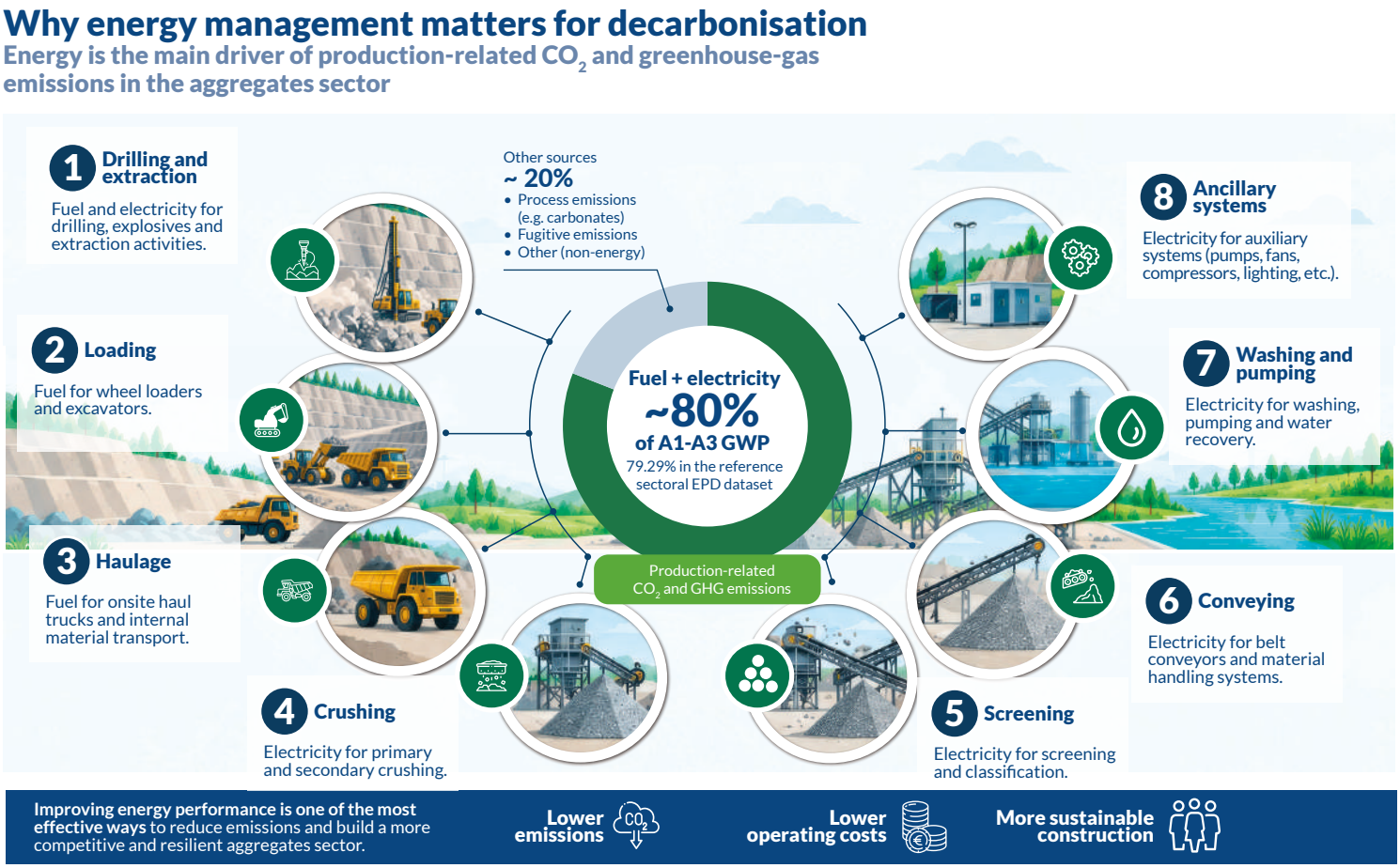


FIGURE 4. — Why energy management matters for decarbonisation?

Guide therefore uses the rounded expression 'approximately 80% energy-related' when communicating the significance of energy management for production-stage emissions. The figure should not be interpreted as 80% of the complete life cycle carbon footprint of aggregates, particularly where downstream transport or other modules are included. This places energy management at the centre of the sector's practical decarbonisation strategy: every verified reduction in unnecessary fuel or electricity demand can contribute directly to reducing the emissions generated by producing aggregates, while changes in the carbon intensity of the remaining energy supply can provide an additional reduction.

A robust strategy therefore combines three questions: How much energy does the operation require? How effectively is that energy converted into saleable production? How carbon-intensive is the energy supplied? Keeping these questions distinct prevents improvements in one area from being mistaken for improvements in another.



Three concepts to distinguish

Different but complementary pathways to a more sustainable aggregates sector

ENERGY SAVING
Reducing energy consumption

Use less energy to carry out the same activity by eliminating unnecessary use and reducing demand.



LOWER ENERGY CONSUMPTION

Examples:
- Avoiding unnecessary movements
- Optimising processes and scheduling
- Reducing idle time

ENERGY EFFICIENCY
Obtaining more useful output per unit of energy

Do more with the same energy input, by improving equipment, processes and operational practices.



MORE OUTPUT PER UNIT OF ENERGY

Examples:
- High-efficiency equipment and drives
- Process optimisation and control
- Operator training and best practices

DECARBONISATION
Reducing greenhouse-gas emissions associated with energy use

Lower the carbon intensity of the energy used, by switching to low-carbon energy sources and alternative fuels.



CO_2

LOWER EMISSIONS PER UNIT OF OUTPUT

Examples:
- Renewable electricity (e.g. solar, wind)
- Alternative fuels (e.g. biofuels, hydrogen)
- Electrification of mobile and fixed equipment

The three objectives **can reinforce each other**, but they are **not equivalent**.

FIGURE 5. — Three concepts to distinguish

4.4 Ten principles for good energy management

1. Measure energy together with production and the variables that explain it.
2. Avoid work that does not contribute to saleable production.
3. Minimise unnecessary material movement, distance and vertical lift.
4. Optimise the complete production chain rather than individual machines.
5. Match equipment and systems to the required duty.
6. Operate and maintain equipment close to its efficient operating condition.
7. Remove correctly sized material from the process as early as practicable and avoid unnecessary recirculation.
8. Use electrification and low-carbon energy where technically and economically appropriate.
9. Use digital tools to support decisions, not simply to generate data.
10. Verify improvement and make energy performance a continual management process.

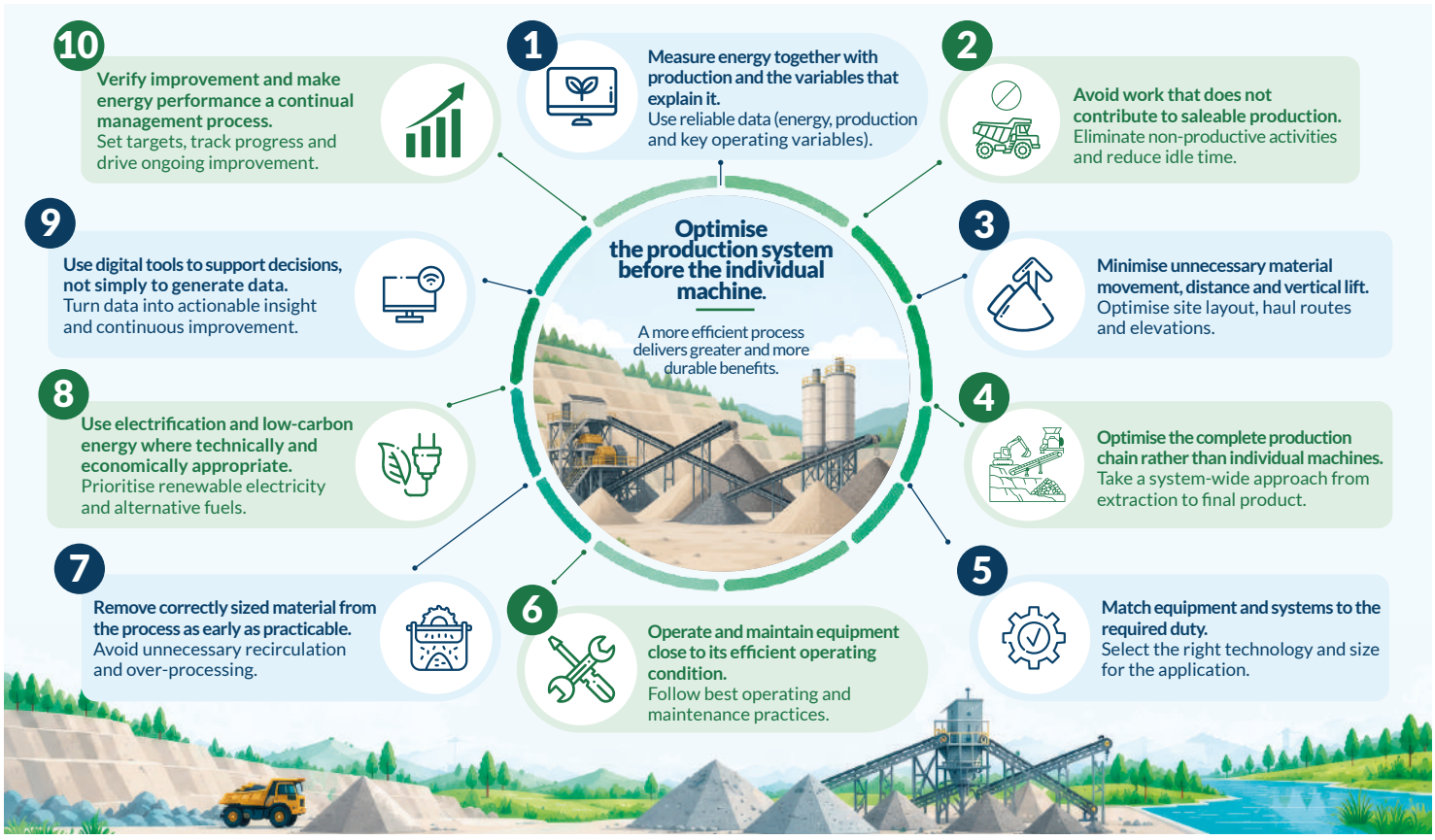


FIGURE 6. — Ten principles of good energy management

5 Energy in EU policies

EU energy policy has evolved from market integration and security of supply into a central pillar of climate, industrial and competitiveness policy. For aggregates producers, this matters because energy is simultaneously a production input, a source of greenhouse-gas emissions, an infrastructure constraint and a factor in investment and competitiveness.

5.1 From the internal energy market to climate neutrality

The European Green Deal placed energy policy within the objective of climate neutrality, subsequently made legally binding for 2050 by the European Climate Law (European Commission, 2019; Regulation (EU) 2021/1119). The "Fit for 55" cycle translated that direction into sectoral legislation. For industry, the recast Energy Efficiency Directive reinforces the "energy efficiency first" principle and enterprise obligations for audits and energy-management systems, while the revised Renewable Energy Directive accelerates renewable deployment across the economy (Directive (EU) 2023/1791; Directive (EU) 2023/2413).

REPowerEU added energy security to this framework after Russia's invasion of Ukraine. Its priorities—energy savings, diversification of supply, faster renewables and reduced dependence on imported fossil fuels—made efficiency a resilience and competitiveness issue as well as a climate measure (European Commission, 2022).

5.2 Energy, the Single Market and European competitiveness

The competitiveness debate intensified in 2024. Enrico Letta's Much More Than a Market calls for a deeper Single Market in strategic sectors and specifically for more efficient European energy and climate policies. Its diagnosis is that fragmented infrastructure and national barriers prevent Europe from fully exploiting its scale (Letta, 2024).

Mario Draghi's report on The Future of European Competitiveness identifies high and volatile energy prices, fossil-fuel import dependence, insufficient grids and slow clean-technology deployment as structural constraints on European industry. It therefore presents decarbonisation and competitiveness as mutually dependent: cleaner energy must also become more affordable, investable and available at industrial scale (Draghi, 2024).

This diagnosis shaped the 2024–2029 Commission agenda. The Competitiveness Compass makes "decarbonisation and competitiveness" one of three transformative imperatives and links industrial performance directly to affordable energy and clean-technology deployment (European Commission, 2025a).

5.3 From the Clean Industrial Deal to electrification

The Clean Industrial Deal and the Action Plan for Affordable Energy, adopted in February 2025, make the industrial-energy link explicit. They combine lower energy costs with faster clean-energy investment, greater efficiency, stronger grids, deeper market integration and reduced fossil-fuel dependence (European Commission, 2025b; European Commission, 2025c). The revised electricity-market design

strengthens long-term contracting and reduces exposure to short-term fossil-fuel price volatility, while the Net-Zero Industry Act supports European manufacturing of strategic clean technologies (Regulation (EU) 2024/1747; Directive (EU) 2024/1711; Regulation (EU) 2024/1735).

In July 2026 the Electrification Action Plan placed direct electrification at the centre of competitiveness, decarbonisation and energy security, with an indicative objective of increasing electricity to 46% of final energy use by 2040 (European Commission, 2026). For aggregates operations, this is directly relevant to mobile equipment, charging, fixed processing, pumping, onsite renewables, storage and local grid capacity.

5.4 What this means for aggregates operations?

The implications for quarries, sand and gravel operations and processing plants are practical and site-specific:

- Energy efficiency is increasingly a competitiveness, resilience and decarbonisation issue, not only a utility-cost issue.
- Electrification must be assessed together with grid capacity, demand peaks, charging strategy, production continuity and remaining site life.
- Energy audits and energy-management systems are increasingly relevant as EU requirements become linked to measured enterprise energy consumption.
- Renewable electricity, long-term procurement, storage and flexibility should complement—not replace—understanding and reducing underlying demand.
- SMEs need proportionate requirements, practical tools, technical assistance and access to finance.

This context reinforces the central message of this Guide: better energy management is one of the most direct ways in which aggregates operations can combine improved competitiveness, resilience and production-stage decarbonisation.

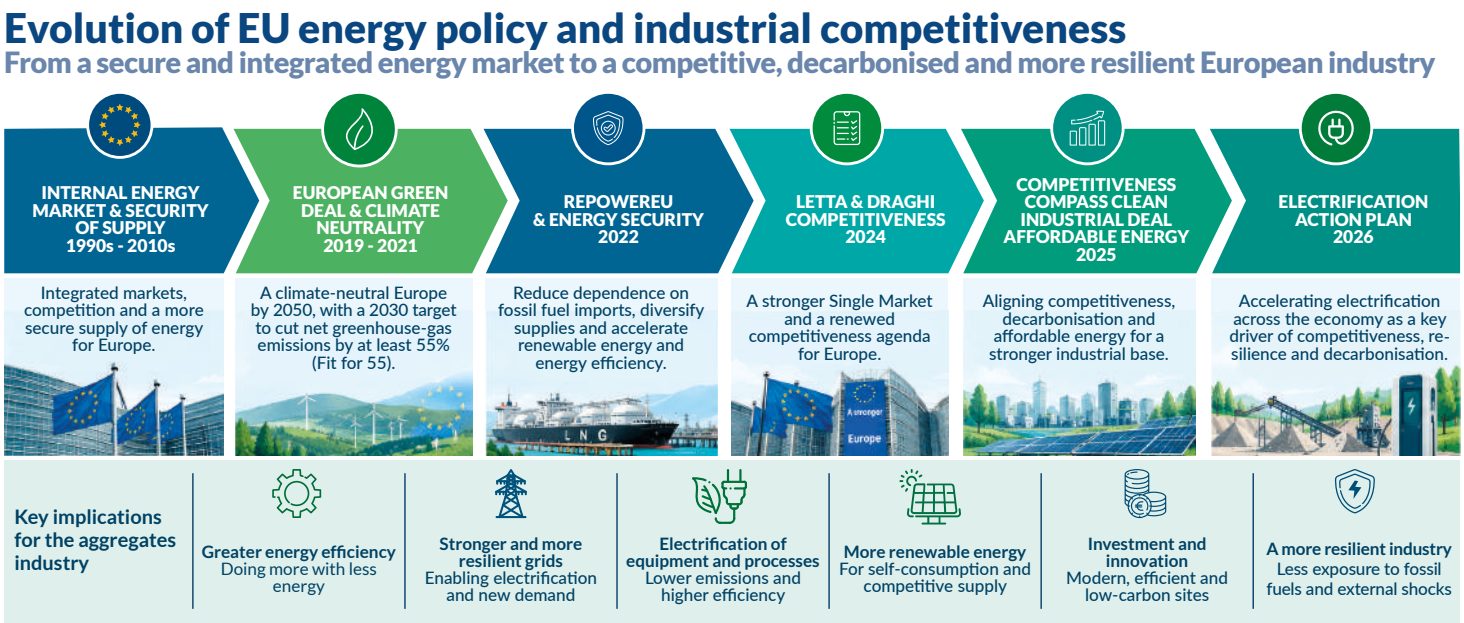


FIGURE 7. — Evolution of EU energy policy and industrial competitiveness

6 Understanding energy performance

6.1 Energy: forms and measurement

Energy is the capacity of a physical system to perform work or bring about change. In aggregates production, it is an essential operational resource, required to extract, transport and process raw materials into saleable products.

Energy sources can be classified as:

- **Renewable energy sources**, which are naturally replenished on a human timescale, including solar, wind, hydropower, geothermal, marine energy and biomass.
- **Non-renewable energy sources**, which rely on finite resources depleted through use, principally fossil fuels and nuclear fuels.

Energy generally undergoes conversion and distribution before reaching the point of use. It is therefore useful to distinguish between **primary energy** and **final energy**.

Primary energy is energy from natural sources before conversion or transformation into other energy products. Final energy is the energy supplied to end users after the relevant conversion and distribution processes. At quarry level, this includes principally the electricity delivered to the site and fuels supplied for mobile plant and other equipment.

This distinction is relevant because reducing final energy consumption at an aggregates operation contributes to reducing energy demand across the wider energy system, although the two are not directly equivalent because energy conversion and distribution also involve energy consumption and losses.

The physical forms of energy most relevant to aggregates production are:

- **Mechanical** energy, associated with motion and position.
- **Thermal** energy, associated with the thermal state of matter and transferred as heat.
- **Electrical** energy, which can be converted into mechanical energy, heat and other useful forms.
- **Chemical** energy, stored in fuels and explosives and released through chemical reactions.

At site level, the principal purchased energy inputs are generally electricity and fuels. These are converted into useful energy for drilling, excavation, loading, haulage, crushing, screening, conveying, pumping and ancillary operations. Explosives introduce chemical energy directly into the extraction and fragmentation process.

Understanding these energy conversions, and the losses associated with them, is fundamental to identifying opportunities for improved energy performance.

6.1.1 Measuring energy

The SI unit of energy is the joule (J). In industrial applications, larger units such as the megajoule (MJ) and gigajoule (GJ) are commonly used, while electrical energy consumption is normal-

ly expressed in kilowatt-hours (kWh) or megawatt-hours (MWh).

For energy statistics and comparisons between different energy carriers, the **tonne of oil equivalent (toe)** is also widely used:

- 1 toe = 41.868 GJ ≈ 11.63 MWh.
- When different energy carriers are compared or aggregated, they should be converted to a consistent energy basis.

Absolute energy consumption alone provides limited information on the performance of an aggregates operation. It should therefore be complemented by appropriate specific energy consumption or energy-performance indicators, for example:

- kWh/t of saleable product.
- l/t of material handled or produced.
- fuel or energy consumption related to both material moved and haul distance.

The appropriate indicator depends on the process being assessed and should account, where necessary, for the operational variables that materially influence energy use.

6.2 Energy saving and energy efficiency

Although closely related, **energy saving** and **energy efficiency** are different concepts.

Energy savings are reductions in energy consumption resulting from an improvement measure, taking into account the relevant conditions affecting consumption.

Energy efficiency expresses the relationship between the useful output obtained - whether performance, service, goods or energy - and the energy input required to achieve it. Improved energy efficiency therefore means obtaining the same useful output with less energy, or greater useful output from a given energy input.

This distinction is particularly important in aggregates production. A reduction in total site energy consumption does not necessarily demonstrate improved efficiency: production may simply have fallen. Conversely, total energy consumption may increase while efficiency improves if useful production increases proportionately more.



Energy performance should therefore be assessed using indicators that relate energy consumption to a meaningful production or operational variable and, where necessary, account for relevant operating conditions.

6.2.1 Improving energy efficiency in aggregates production

Energy performance can be improved through a combination of:

- Operational measures, including production scheduling, equipment utilisation and haulage optimisation.
- Technical measures, including efficient equipment, drives, controls and appropriate process modifications.
- Maintenance, keeping equipment and processes close to their intended operating performance.
- Monitoring and management, based on measuring, analysing and controlling significant energy uses.
- Workforce practices, supported by appropriate training, competence and engagement.

In aggregates production, energy performance is determined by the complex interaction of extraction planning, fragmentation, loading, haulage, processing, material flow, equipment utilisation, maintenance practices and final product requirements. Each of these elements influences not only its own energy consumption but also the operating conditions and efficiency of subsequent stages. Understanding these interdependencies is essential for identifying opportunities to improve energy performance throughout the production process.

Consequently, energy efficiency initiatives should be evaluated from a system-wide perspective rather than focusing exclusively on individual machines or operations. Measures that reduce energy consumption at one stage may increase energy demand, create operational constraints or introduce inefficiencies elsewhere in the production chain. The ultimate objective should therefore be to achieve a sustained improvement in the overall energy performance of the entire production system, while maintaining the required production capacity, product quality and operational reliability.

Effective energy management can contribute to:

- Lower energy consumption and costs.
- Improved specific energy performance.
- Identification of inefficient operating conditions and avoidable losses.
- Improved process and equipment performance.
- Reduced exposure to energy-price volatility.
- Improved control of production costs.
- Lower greenhouse-gas emissions where energy savings reduce the use of carbon-intensive energy sources.

6.2.2 Energy efficiency and decarbonisation

Energy efficiency and decarbonisation are related, but they are not synonymous.

Energy efficiency reduces the energy required to provide a given useful output. Decarbonisation reduces the greenhouse-gas emissions associated with supplying that energy.

Consequently, measures such as electrification, renewable electricity or alternative fuels may re-

Energy flow in aggregates sites

From energy inputs to saleable aggregates - and where energy is lost

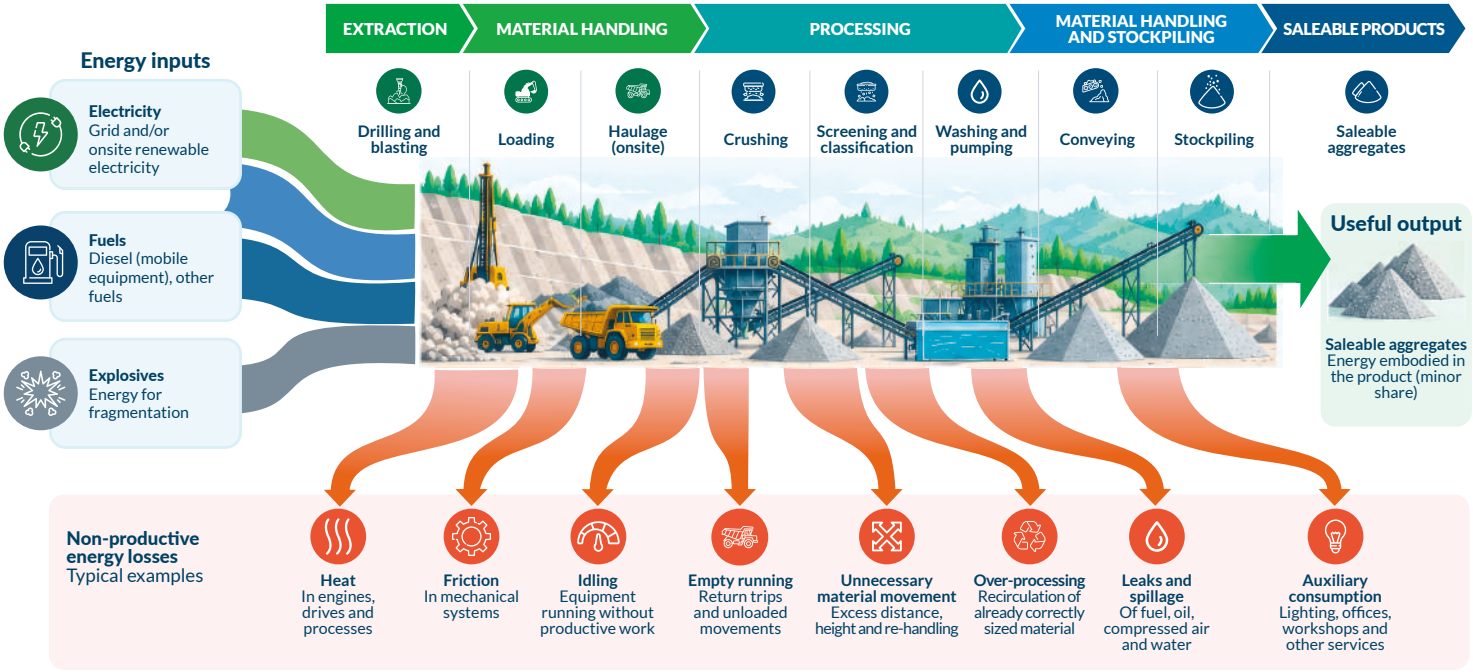


FIGURE 8. — Energy flow in an aggregates site

duce emissions without necessarily reducing energy consumption. Similarly, the emissions benefit of an energy-efficiency improvement depends on the energy carrier whose consumption is reduced.

Good energy management should therefore consider both how much energy is consumed and how effectively that energy is converted into useful production.

6.3 Indicators that support decisions

Absolute consumption is necessary for accounting but insufficient for evaluating performance. Indicators should relate energy use to the useful output or physical duty of the process. A small set of stable indicators is generally more useful than a large dashboard that is not linked to management decisions.

Indicators should be normalised when changes in relevant variables would otherwise obscure underlying performance. For example, l/t may not be sufficient for comparing haulage performance if average haul distance or vertical lift changes as the quarry develops.

TABLE 1 Aggregates sites typical indicators

Area	Typical indicator
Whole site	kWh/t or MJ/t of saleable product
Electric processing	kWh/t processed and/or saleable product
Mobile equipment	l/t or kWh/t
Haulage	l/t·km or kWh/t·km
Pumping	kWh/m^3
Economics	€/t saleable product
Renewables	MWh generated and self-consumption %

7 Energy through the aggregates production process

7.1 Energy in the production process

7.1.1 Energy throughout the aggregates production process

Energy requirements vary substantially between aggregates operations according to deposit characteristics, extraction method, quarry geometry, haul distances, plant configuration and the products manufactured.

The relative contribution of each component is site-specific. It depends not only on installed power but also on operating hours, equipment loading, production rate, material characteristics and the configuration of the production process.

For this reason, generic percentages for the distribution of installed power or energy consumption should not be used as sector benchmarks. Each operation should establish its own energy balance using measured or otherwise reliable site data.

7.1.1.1 Natural aggregates

The basic production cycle in an **aggregates hard-rock quarry** typically comprises:

land preparation → drilling → blasting → loading → haulage → processing (feeding, crushing, milling, screening, and conveying) → where required, washing and classification → where required, thermal drying for specialised products → product storage → product loading and dispatch → ancillary facilities (Offices • Laboratories • Workshops • Support services) → site rehabilitation.

In **sand and gravel sites**, direct excavation normally replaces drilling and blasting, while crushing may be required only for part of the production.

land preparation → direct excavation → loading → haulage → processing (feeding, crushing, milling, screening, and conveying) → where required, washing and classification → where required, thermal drying for specialised products → storage → product loading and dispatch → ancillary facilities (Offices • Laboratories • Workshops • Support services) → site rehabilitation.

Each stage involves specific equipment and energy inputs. Mobile extraction, loading and haulage equipment has traditionally relied predominantly on diesel fuel, while most stationary crushing, screening, conveying, washing and pumping equipment is electrically driven. Explosives provide the chemical energy required for rock fragmentation where drilling and blasting are used.

The distinction between these energy carriers is important, but energy consumption should be considered primarily from the perspective of the complete production system.

Some specialised aggregates may require additional processing stages. In particular, **thermal drying** may be used for certain sands for mortars, specialised applications and fine or micronised mineral products. Although uncommon in con-

ventional aggregates production, drying can represent a significant energy use where it is required and should therefore be included explicitly in the site's energy balance and Significant Energy Uses, where applicable.

For an aggregates site (hard-rock quarry or sand and gravel quarry), total energy consumption can be expressed conceptually as:

$$E = E_{lp} + E_{de} + E_d + E_b + E_l + E_h + E_p + E_w + E_{td} + E_s + E_{ld} + E_{af} + E_{sr}$$

where:

- E = total energy consumed.
- E_{lp} = energy consumed in land preparation.
- E_{de} = energy consumed in direct excavation.
- E_d = energy consumed in drilling.
- E_b = energy consumed in blasting.
- E_l = energy consumed in loading.
- E_h = energy consumed in hauling.
- E_p = energy consumed in processing (feeding, crushing, milling, screening, and conveying).
- E_w = energy consumed in washing and classification.
- E_{td} = energy consumed in thermal drying (where required for specialised products).
- E_s = energy consumed in storage.
- E_{ld} = energy consumed in product loading and dispatch.
- E_{af} = energy consumed in ancillary facilities (Offices, laboratories, workshops, support services).
- E_{sr} = energy consumed in site rehabilitation.

7.1.1.2 Recycled and manufactured/artificial aggregates

Aggregates production may also use secondary materials rather than extracted natural mineral resources. Recycled aggregates are commonly produced from construction and demolition waste and other suitable mineral waste streams, while manufactured/artificial aggregates may originate from industrial processes such as iron and steel slags and other suitable mineral residues.

These materials may be processed within an existing quarry or sand-and-gravel operation, sometimes using adapted sections of the same processing plant on an intermittent or campaign basis, or at a dedicated standalone recycling or aggregates-processing facility.

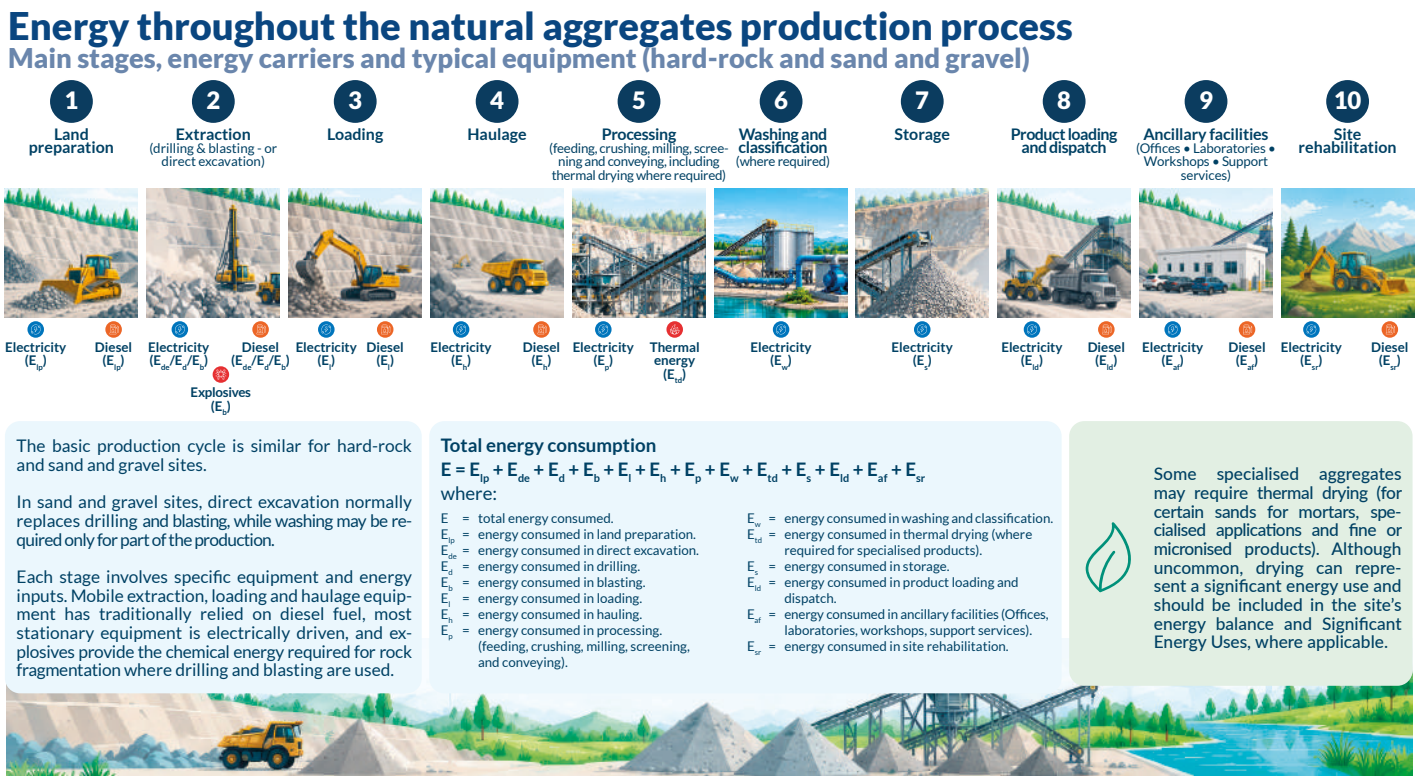


FIGURE 9. — Energy throughout the natural aggregates production process

A simplified production sequence is:

material reception → segregated storage → inspection and pre-sorting, removal and recovery of unwanted or separately recyclable materials → processing (feeding, crushing where required, screening and conveying) → washing and classification where required → further separation where required → product storage → product loading and dispatch → ancillary facilities (Offices • Laboratories • Workshops • Support services)

Incoming materials should normally be stored separately according to their origin, characteristics and intended treatment. Before or during processing, non-mineral components and materials intended for other recycling routes may need to be separated. Depending on the incoming material, these can include ferrous and non-ferrous metals, wood, paper and cardboard, plastics, glass and other unwanted components.

Once the appropriate mineral fraction has been obtained, the principal energy-consuming operations—feeding, crushing, screening, conveying, washing, classification, storage and product handling—are broadly analogous to those used for natural aggregates. The energy-management principles developed in the following chapters therefore apply equally to these production routes.

$$E = E_{so} + E_p + E_w + E_s + E_{ld} + E_{af}$$

where:

- E = total energy consumed;
- E_{so} = energy consumed in inspection and pre-sorting, removal and recovery of unwanted or separately recyclable materials
- E_p = energy consumed in processing (feeding, crushing, milling, screening, and conveying).
- E_w = energy consumed in washing and classification.
- E_s = energy consumed in storage.
- E_{ld} = energy consumed in waste unloading, product loading and dispatch.
- E_{af} = energy consumed in ancillary facilities (Offices, laboratories, workshops, support services).

7.1.2 Energy considerations for recycled and manufactured/artificial aggregates

From an energy-management perspective, processing secondary materials introduces several

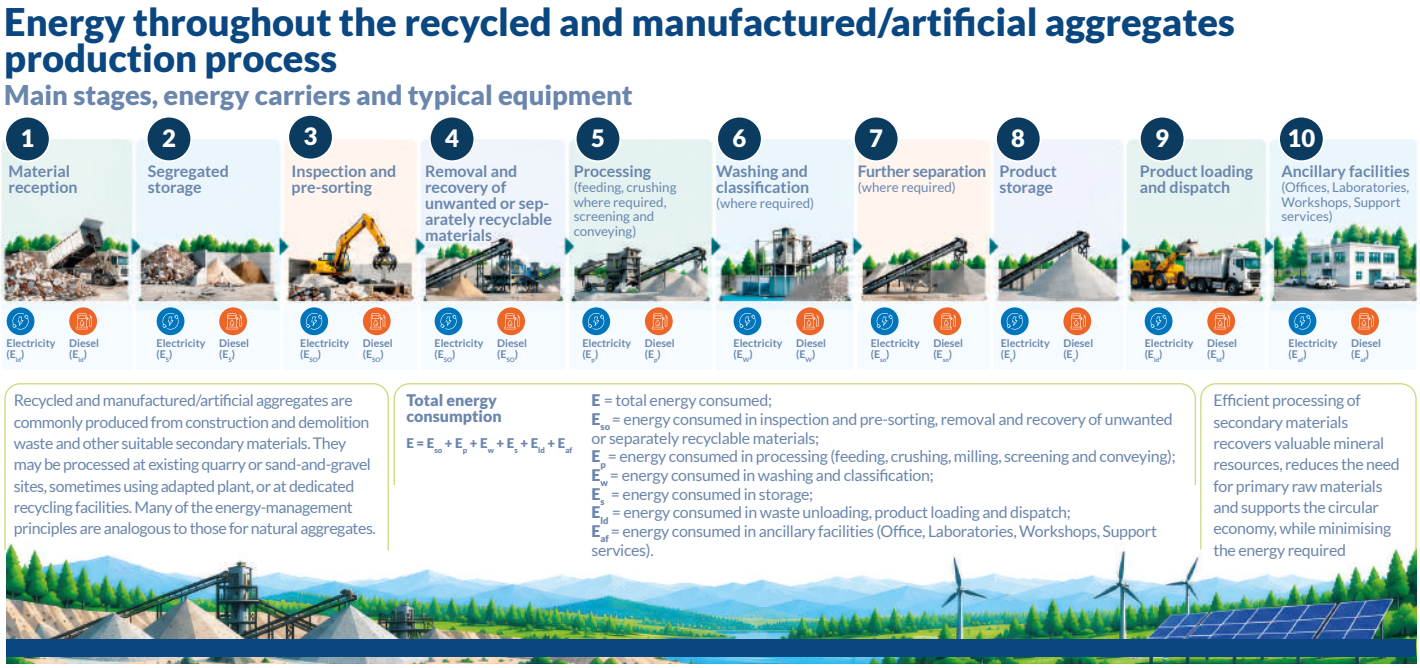


FIGURE 10. — Energy throughout the recycled and manufactured/artificial aggregates production process

variables that may differ from natural aggregates production. Incoming materials can be more heterogeneous in composition, particle size, moisture and contamination, and different batches may require different levels of sorting, crushing, screening or washing.

The objective should be to avoid processing material unnecessarily. Effective reception control, selective stockpiling and early separation of unwanted components can reduce downstream crushing, screening, conveying, washing and rehandling. Valuable materials such as metals should be recovered as early as practicable where technically appropriate, while materials requiring other recycling routes should be removed before they impose unnecessary processing demand.

Where an existing natural-aggregates plant is used intermittently for secondary materials, energy performance should be evaluated separately for each relevant production campaign or material family. Differences in feed characteristics, saleable yield, recirculation, cleaning requirements and operating rate can otherwise make whole-site kWh/t indicators misleading.

The same principle applied throughout this Guide remains valid: first reduce unnecessary material movement and processing, then optimise the required treatment, and finally improve the efficiency and carbon intensity of the energy used.

7.1.3
Influence of quarry and plant design

The production process is a system of interconnected operations. Decisions affecting one stage can alter energy requirements, productivity and costs elsewhere in the process.

Fragmentation is a clear example. Changes in drilling and blasting can affect:

- Loading performance.
- Truck payload and cycle time.
- The occurrence of oversize.
- Primary-crusher performance.
- Energy requirements in subsequent crushing and grinding stages.

Similarly, quarry geometry and plant location influence haul distance and elevation, while the choice between discontinuous and continuous transport systems changes both the quantity and the form of energy required.

This systemic relationship means that the lowest energy consumption in an individual operation does not necessarily correspond to the lowest energy consumption for the production system as a whole.

The same principle applies to plant design. Crushing, screening, conveying, washing, pumping and intermediate storage interact through material flow. Bottlenecks, excessive recirculation, unstable feed and unnecessary handling can increase energy consumption even when the individual machines operate efficiently.

The objective should therefore be to optimise the complete extraction and processing chain, taking account of the interactions between upstream and downstream operations.

This integrated approach has also been demonstrated in the European DIGIECOQUARRY project, which addressed the quarry value chain as a connected system and developed digital tools for real-time monitoring and optimisation across extraction, processing and related operations.

At this stage, the purpose is to establish the principle of interdependence between the different

production operations. The specific measures available to optimise drilling and blasting, loading and haulage, continuous transport, crushing and screening, electrification and other energy-consuming systems are developed in subsequent chapters.

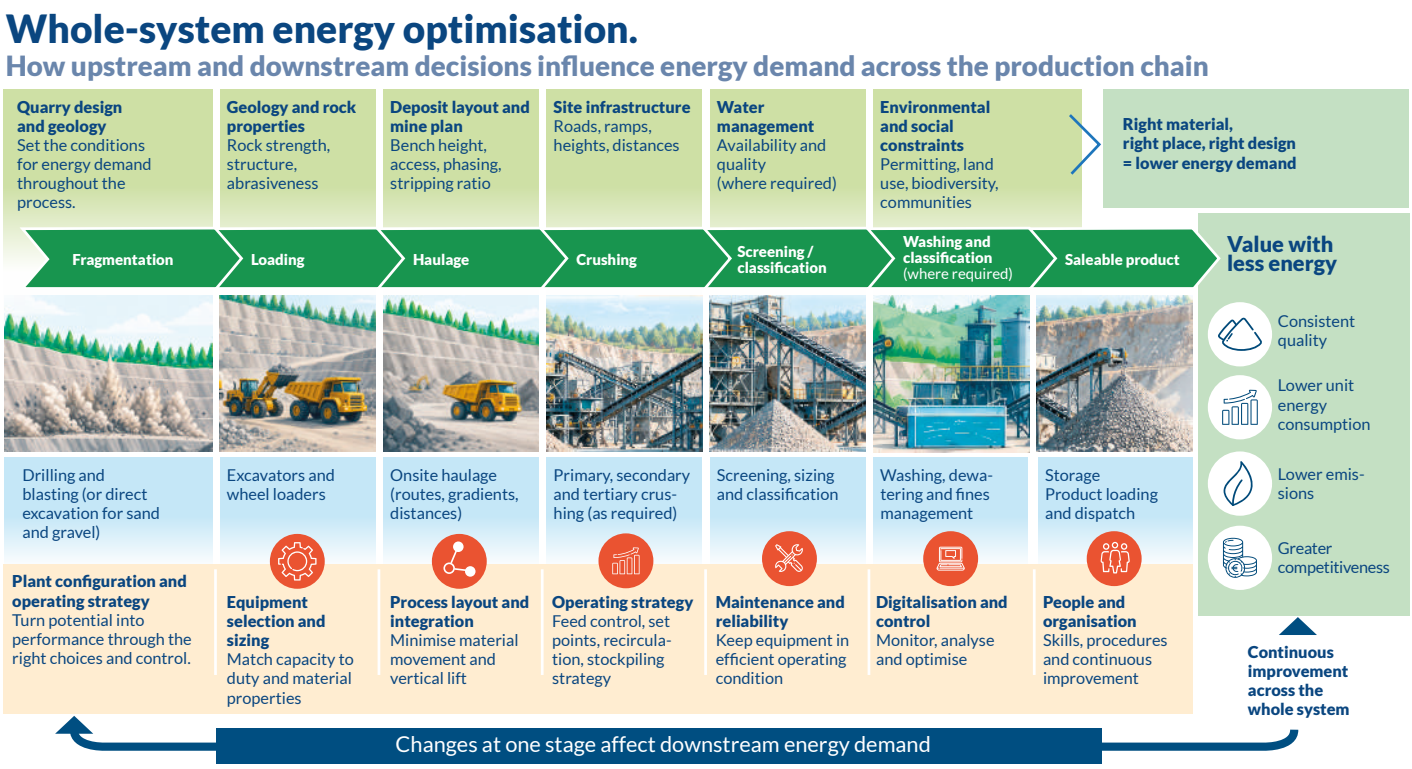


FIGURE 11. — Whole-system energy optimisation

8 Quarry design, drilling and blasting

8.1 Land preparation and quarry design

Land preparation is the first energy-consuming stage of the aggregates production cycle. Depending on the site, it may involve vegetation clearance, selective stripping of topsoil and subsoil, overburden removal, initial access construction and preparation of working areas. From an energy perspective, the principal objective is to minimise unnecessary excavation, handling, haulage and temporary storage while preserving the materials required for subsequent site rehabilitation. Quarry phasing should therefore consider land preparation, extraction and rehabilitation as interconnected material-flow operations. Quarry design establishes much of the physical work that the production system will have to perform throughout the life of the site. Extraction sequence, bench development, crusher location, access roads, haul profiles, elevation change and the relationship between mobile and continuous transport all influence energy demand. These decisions should therefore be treated as energy decisions as well as planning and production decisions.

System design determines how much work is required. Equipment technology determines how efficiently that work is performed.

8.2 Drilling and blasting as one production subsystem

Drilling and blasting should be managed as a single upstream subsystem whose purpose is to deliver a muckpile that can be excavated, loaded, transported and processed efficiently. The objective is not to minimise drilling energy or explosive consumption in isolation, but to optimise the performance of the complete quarry-to-crusher chain.



The appropriate drilling and blast design is site-specific. It depends on geology, rock structure, bench geometry, production requirements, drilling accuracy, explosive characteristics, environmental constraints and the equipment used downstream. Top-hammer, down-the-hole and other drilling configurations should therefore be selected for the actual duty rather than from a universal diameter threshold.

For energy management, the most useful drilling indicators relate consumption to productive output and operating conditions rather than installed engine power.

- Fuel or electricity per metre drilled.
- Energy per tonne or cubic metre of rock blasted.
- Penetration rate under comparable geological conditions.
- Equipment utilisation and avoidable idle time.
- Compressor demand where compressed-air drilling is used.

Drilling accuracy is itself an energy-relevant variable. Hole deviation, poor collar positioning or an inappropriate pattern can increase oversize, secondary breakage, loading effort and crusher disruption even where the drill rig appears efficient when assessed only in litres or kWh per metre.

8.3 Fragmentation links extraction and processing

Blast performance affects the size distribution, shape and displacement of the muckpile. These characteristics influence diggability, bucket fill, loading cycle time, truck utilisation, oversize, secondary breakage and primary-crusher performance. Fragmentation is therefore the principal connection between drilling and blasting and downstream energy consumption.

A blast designed solely to minimise explosive consumption can transfer cost and energy demand to excavation, haulage or crushing. Conversely, a higher or better-distributed drilling-and-blasting input can improve downstream performance under some conditions. Neither direction is universally preferable: the optimum must be demonstrated from site data.

- Fragmentation and oversize.
- Toe and floor conditions.
- Muckpile shape and diggability.
- Loading productivity and truck cycle time.
- Primary-crusher throughput and interruptions.
- Specific energy in downstream processing.
- Overall production cost and energy performance.

8.4 A practical quarry-to-crusher optimisation loop

Digital drilling records, blast-design tools and fragmentation measurement can strengthen energy management when they form a feedback loop rather than a stand-alone data exercise. A practical sequence is: design the blast, record actual drilling, execute the blast, measure the result, evaluate loading and crusher performance, and use the findings to adjust the next blast.

The optimum blast is the one that supports the best overall quarry performance within safety and environmental constraints—not necessarily the one with the lowest explosive or drilling input.

Explosives contain chemical energy, but their treatment in site energy indicators should be defined explicitly. For many operational energy-management purposes it is more useful to track explosives as a production input and assess their effect on downstream fuel and electricity use than to add their nominal chemical energy automatically to purchased electricity and fuel.

Quarry-to-crusher energy chain

From the rock mass to the processing plant - decisions at each stage influence energy use downstream

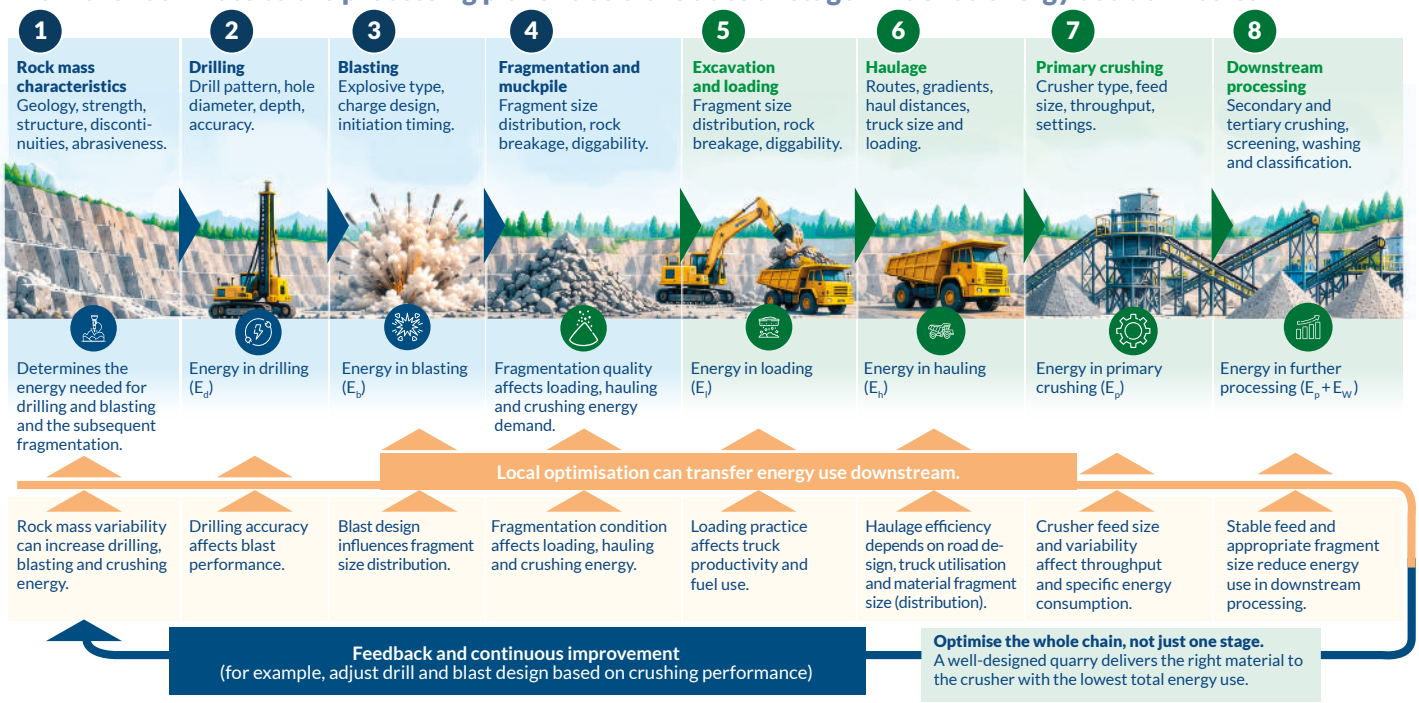


FIGURE 12. — Quarry-to-crusher energy chain

Fragmentation optimisation loop

Use information from downstream to design better blasts and reduce total energy use



FIGURE 13. — Fragmentation optimisation loop

9 Loading, haulage and material movement

9.1 Material movement is the energy driver

Mobile equipment can represent one of the largest energy uses in an aggregates operation, particularly where extraction faces are distant from the processing plant or where material must be lifted through significant elevation. The principal energy-management question is therefore not only how efficiently each machine operates, but how much material must be moved, how far, how high and how many times.

Every unnecessary tonne-metre of material movement represents avoidable energy use.

Quarry planning should seek to reduce physical transport work before optimising the machine that performs it. This applies to overburden, natural raw feed, incoming secondary materials, intermediate products, separated fractions, finished aggregates, rejects and rehabilitation materials.

At recycling facilities, unnecessary rehandling between reception areas, sorting zones, temporary stockpiles and the processing plant can become an important source of avoidable fuel and electricity consumption. Site layout should therefore seek to minimise movement while preserving the segregation required for material quality and regulatory compliance.

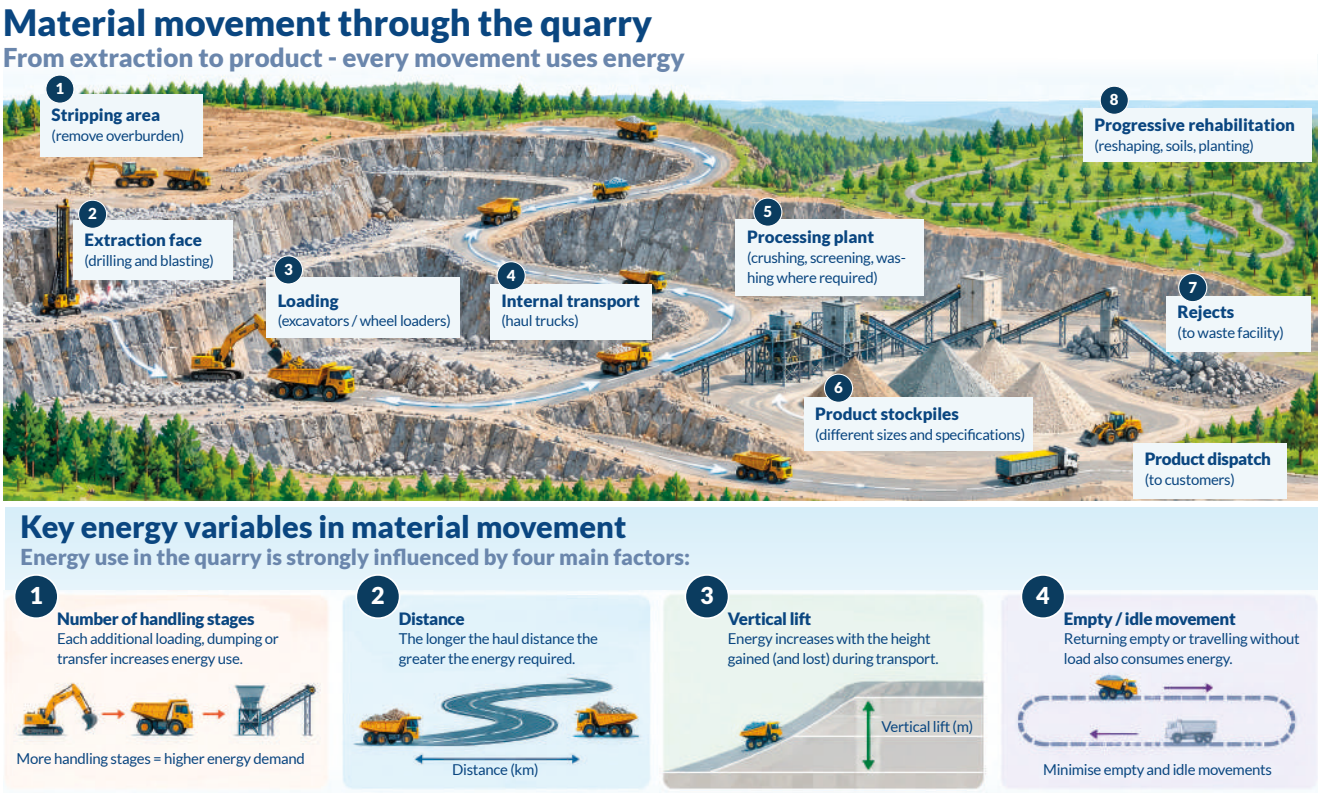


FIGURE 14. — Material movement through the quarry

9.2 Direct excavation and loading

In sand and gravel sites, and in other directly extractable deposits, mechanical excavation replaces the drilling-and-blasting stage. Energy performance therefore depends strongly on digging resistance, face conditions, excavation method and the coordination between excavation, loading and the downstream transport system. Where excavation and loading are performed by the same machine, their energy performance should be assessed as a combined production duty rather than artificially separated.

Excavators and wheel loaders should be matched to the material, production rate and downstream transport system. Their specific energy performance depends on fragmentation or digging resistance, bucket fill, cycle geometry, travel or swing distance, machine utilisation and coordination with trucks, hoppers and stockpiles.

- Relate fuel or electricity to tonnes loaded rather than machine-hours alone.
- Reduce unnecessary swing, travel, reversing and repositioning.
- Maintain appropriate bucket fill and avoid persistent under-loading.
- Coordinate loader and truck capacity so that neither stage causes queueing or waiting.
- Use load-and-carry only where its flexibility justifies the additional travel work.

Dozers and auxiliary mobile equipment should be managed with the same principle: use them where their function adds value, but avoid repeated pushing, rehandling or road work caused by poor material-flow planning.

9.3 Haulage

A haulage cycle includes positioning, loading, loaded travel, manoeuvring and tipping, empty return and the next positioning movement. Energy is consumed during the complete cycle, including periods that do not move useful material. The most useful indicators therefore combine consumption with payload and, where route conditions change materially, distance.

- Payload and payload consistency.
- Haul distance and empty-return distance.
- Vertical lift and road gradient.
- Rolling resistance and road condition.
- Queueing and waiting.
- Truck-loader matching and fleet size.
- Cycle time and avoidable idling.

l/t is useful where the route is broadly stable. l/t·km or kWh/t·km can be more informative where haul distance changes as the quarry develops. Where elevation is a major driver, the site may also need a normalised model that accounts for gradient or vertical lift.



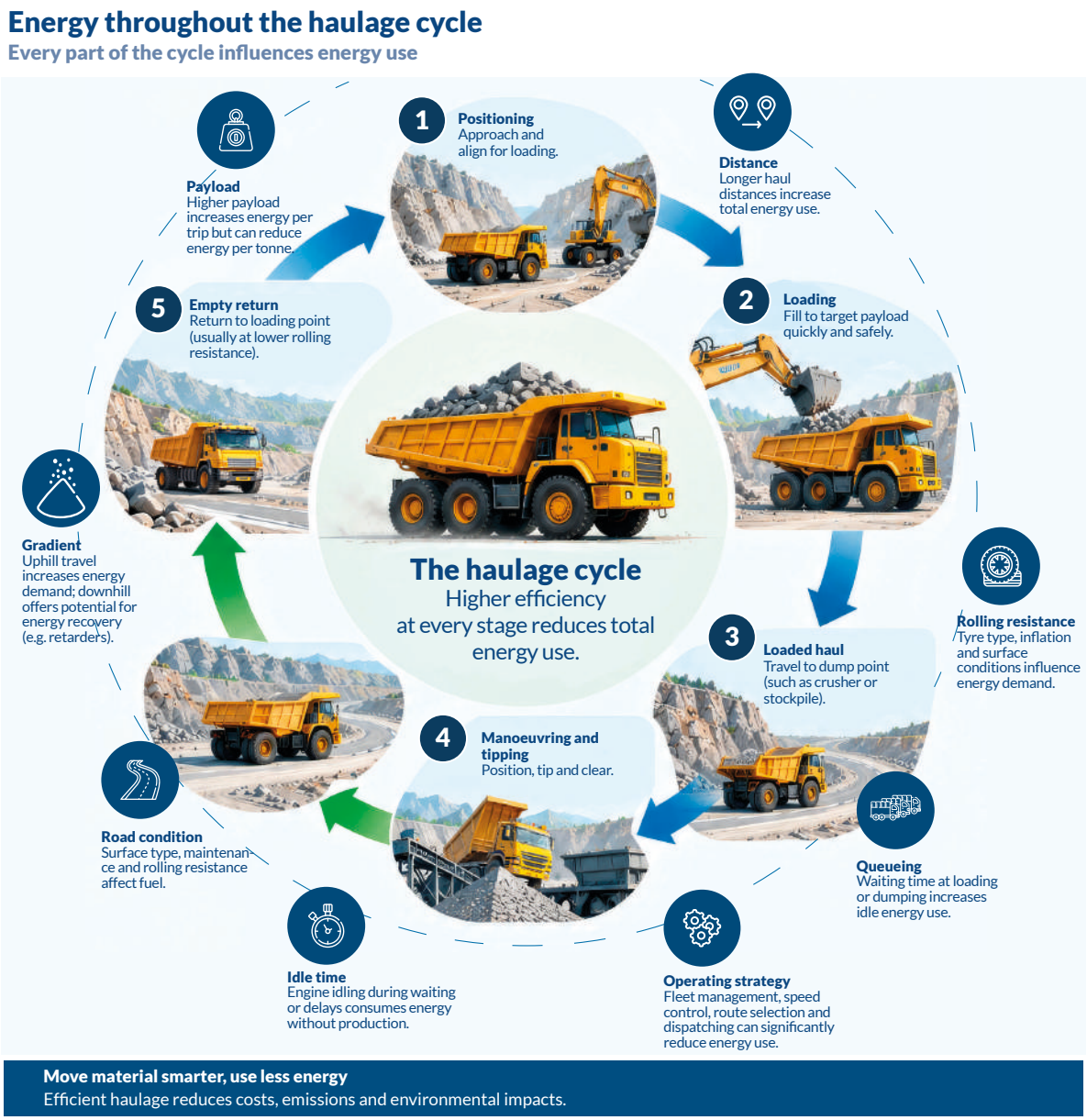


FIGURE 15. — Energy throughout the haulage cycle

9.4 Haul roads and quarry geometry

Haul-road condition affects the energy demand of the entire fleet. Excessive gradient, loose or deformed running surfaces, poor drainage, potholes, rutting and inefficient junctions increase tractive effort and may reduce payload productivity. Road maintenance should therefore be treated as an energy-performance measure as well as a safety and production requirement.

The same principle applies at planning scale. Crusher location, bench access and the sequence of quarry development can lock in transport work for many years. An efficient powertrain cannot remove the energy penalty created by an unnecessarily long or steep route.

9.5 Trucks, conveyors and transport architecture

Trucks provide flexibility as extraction faces move. Conveyors provide continuous, predominantly electric transport where material size, throughput, route geometry and quarry development permit. Neither system is universally pref-

erable. The choice should be based on site-specific operational, energy and life cycle analysis.

- Required production rate and variability.
- Distance and elevation change.
- Material size and crusher location.
- Required mobility and future quarry development.
- Remaining site life.
- Electrical infrastructure and power demand.
- Capital, maintenance and operating costs.

Transport architecture should be evaluated only after the underlying transport duty—distance, vertical lift, rolling resistance and avoidable movement—has been minimised as far as practicable.

Transport-system optimisation hierarchy

Step by step to lower energy use and higher efficiency

Greater impact

Lower cost

1 Avoid movement
- Do not move material if it is not necessary.
- Optimise quarry design and sequencing
- Locate processing and stockpiles close to the face
- Use in-pit processing and conveyors where viable
- Reduce rehandling and double handling



The most sustainable tonne is the one not moved.

2 Minimise distance

Keep haul distances as short as possible.
- Optimise pit layout, access ramps and haul routes
- Locate waste and product stockpiles strategically
- Use direct routes and avoid unnecessary detours



Shorter distances, lower energy use, lower costs.

3 Minimise vertical lift and rolling resistance

Reduce the energy needed to overcome gravity and rolling resistance.
- Optimise ramp gradients and bench heights
- Design and maintain road surfaces
- Minimise curves and avoid steep inclines
- Use appropriate tyre types and pressures



Less uphill. Less resistance. Less energy per tonne.

4 Select transport architecture

Choose the most appropriate material transport system for the site conditions and production scale.
- Trucks (rigid or articulated)
- Conveyor belts, in-pit crushers and conveying systems
- Hybrid solutions (e.g. truck to conveyor)
- Consider flexibility, reliability and total cost of ownership



The right system for the right site.

5 Optimise loading, dispatch and utilisation

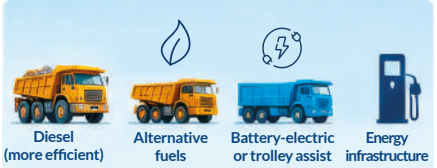
Make every movement as efficient as possible.
- Match excavators and trucks (payload and cycle time)
- Minimise queueing and idle time
- Optimise fleet size, route management and dispatching
- Use real-time monitoring and data analytics



More tonnes per litre/kWh.

6 Optimise powertrain and energy supply

Use the most efficient and lowest-emission energy solutions for the operating conditions.
- High-efficiency engines and drivetrains
- Alternative fuels (e.g. HVO, biomethane)
- Electrification (battery, trolley, or hybrid)
- Smart energy management and charging/refuelling infrastructure



Cleaner energy. Higher efficiency. A lower-carbon future.

More specific

Higher cost

FIGURE 16. — Transport-system optimisation hierarchy

9.6 Progressive rehabilitation as material-flow optimisation

Site rehabilitation is the final stage of the production cycle, but progressive rehabilitation means that its energy requirements should be considered throughout the operational life of the site rather than only after extraction has ceased.

Rehabilitation materials are part of the quarry material-flow system. Where technically, environmentally and legally practicable, coordinating stripping and progressive rehabilitation can avoid temporary stockpiling, rehandling and a second haul to the final placement area.

- Preserve the required segregation and quality of topsoil, subsoil and overburden.
- Coordinate quarry phasing with areas ready for rehabilitation.
- Compare direct placement with intermediate storage on a tonne-metre basis.
- Maintain ecological, geotechnical, landscape, safety and regulatory requirements as overriding constraints.

The objective is not to reduce energy at the expense of rehabilitation quality, but to achieve the required rehabilitation outcome with the minimum necessary handling and transport.

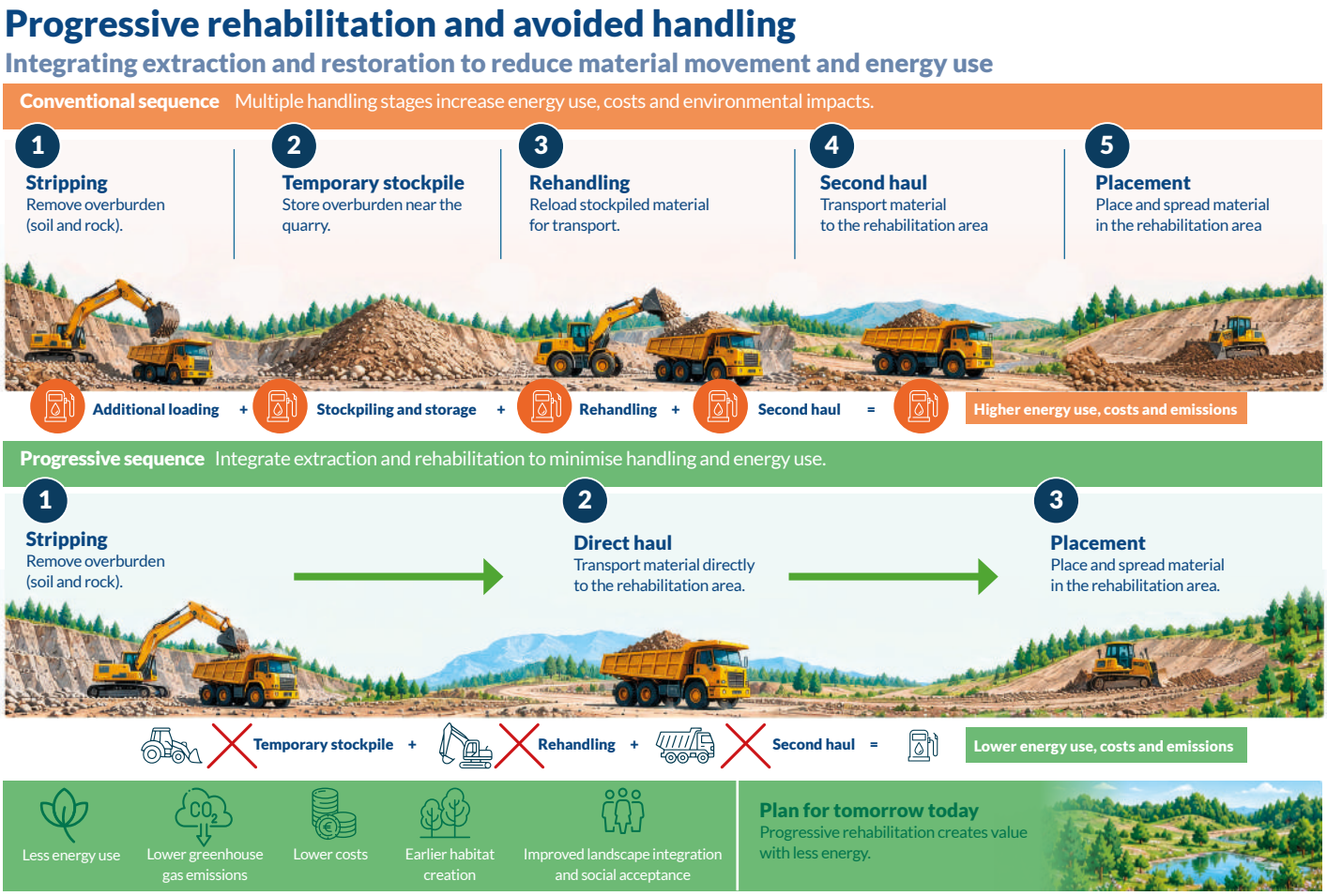


FIGURE 17. — Progressive rehabilitation and avoided handling

10 Processing: crushing, screening and classification

The principles in this chapter apply both to natural mineral feed and to suitable mineral fractions recovered from construction and demolition waste or industrial materials. Secondary feed can be more heterogeneous, making effective upstream sorting, controlled feeding and early removal of unwanted components particularly important for stable and energy-efficient processing.

10.1 Comminution: reduce only what the product requires

Crushing is one of the principal electricity uses in many hard-rock aggregate plants. Its purpose is not to maximise size reduction, but to produce the required grading, particle shape and product quality at the lowest practicable specific energy consumption.

The correct indicator is normally expressed in kWh/t processed for a machine or stage and, at whole-plant level, in kWh/t of saleable product. Interpretation should consider feed size distribution, rock strength and abrasivity, moisture, crusher setting, circulating load, utilisation and the required product specification.

- Avoid over-crushing material beyond the required size or shape.
- Avoid crushing material that already meets the required product specification or that should instead be separated for another recovery route.
- Maintain stable, controlled feed rather than repeated starvation and surging.
- Match crusher type and operating setting to the feed and required product.
- Maintain wear components so that throughput and product quality do not deteriorate progressively.
- Evaluate the complete circuit rather than the nominal motor efficiency of the crusher alone.

10.2 Crushing stages and circuit configuration

Large reductions are normally achieved in stages. Primary, secondary and, where required, tertiary crushing should be combined with screening so that correctly sized material leaves the circuit as early as practicable. Additional stages can improve control of grading or shape, but they also add crushers, screens, conveyors and drives. The optimum is therefore the simplest reliable circuit capable of producing the specified products efficiently.

Reduce only as much material, and only to the size and shape, required to produce the saleable product.

10.3 Screening: a small drive with a large system effect

The direct electrical demand of a screen is often lower than that of major crushing equipment, but poor separation can increase total plant energy use by returning material unnecessarily for further crushing. Screening performance should

therefore be assessed both by the power consumed by the screen and by its influence on circulating load, crusher utilisation, saleable yield and reprocessing.

Energy-relevant screening variables include feed distribution, bed depth, proportion of near-size material, aperture and open area, moisture, screen motion and the condition of screening media. The objective is not to maximise vibration intensity; it is to achieve the required separation and throughput reliably.

- Remove correctly sized material before it reaches another crushing stage.
- Investigate persistent high circulating load rather than accepting it as normal.
- Prevent blinding, pegging and poor feed distribution.
- Keep screening media and drives in suitable condition.
- Relate screening performance to product recovery and crusher duty, not only to screen kWh.

10.4 Open and closed circuits

Open circuits are operationally simple but provide less control of final size. Closed circuits return screen oversize for further crushing and can improve product control, but recirculation itself consumes energy. The objective is therefore not to eliminate recirculation, but to maintain the lowest effective circulating load compatible with the required production and specification.

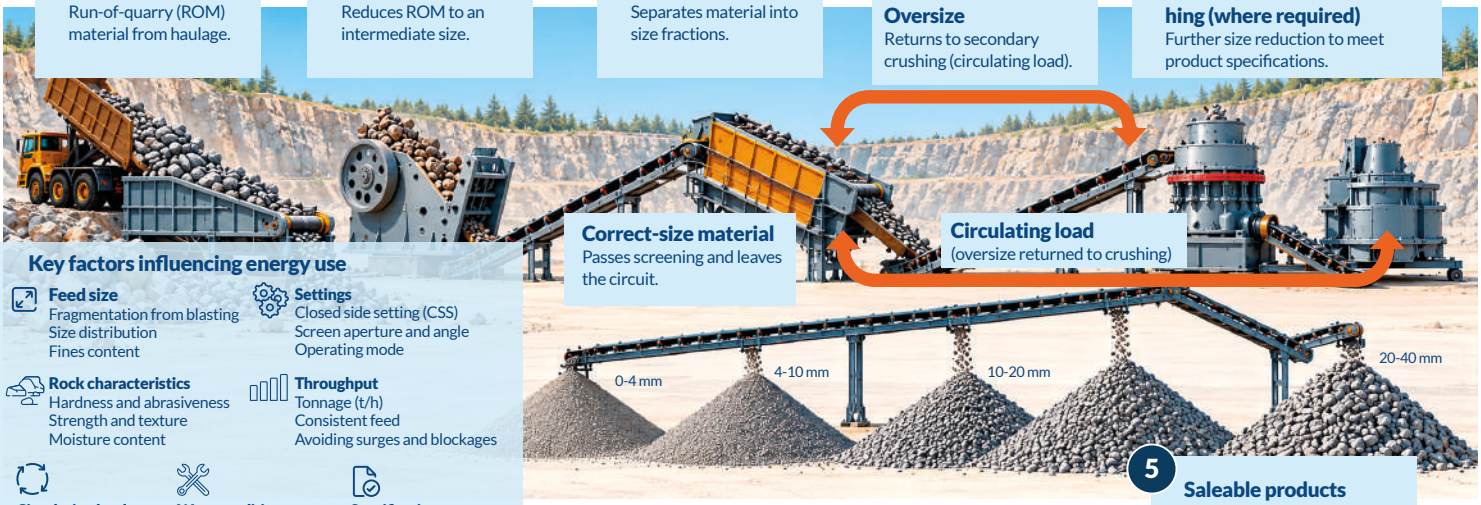
10.5 Practical questions for processing energy performance

- Is quarry fragmentation appropriate for the primary crusher?
- Is the plant being fed consistently?
- Are crusher settings appropriate to the required product?
- Does screening remove correctly sized material before further crushing?
- Is material circulating unnecessarily?
- Are worn components reducing throughput or increasing kWh/t?
- Is the plant producing material finer than the market specification requires?
- Is electricity use measured together with tonnes processed and tonnes sold?



Crushing, screening and recirculation

Efficient processing turns rock into the right product with less energy



Key factors influencing energy use

Feed size
Fragmentation from blasting
Size distribution
Fines content

Settings
Closed side setting (CSS)
Screen aperture and angle
Operating mode

Rock characteristics
Hardness and abrasiveness
Strength and texture
Moisture content

Throughput
Tonnage (t/h)
Consistent feed
Avoiding surges and blockages

Circulating load
Proportion of oversize
Screen efficiency
System balance

Wear condition
Liner and blow bar wear
Screen media condition
Maintenance strategy

Specification
Product size distribution
Shape requirements
Customer needs

FIGURE 18. — Crushing, screening and recirculation

Processing energy checklist

Is the plant reducing only what needs to be reduced?

Is the plant reducing only what needs to be reduced?
The right material, to the right size, in the right way, with the lowest energy use.

1 Stable feed



- Consistent feed size and quality
- Minimise variability (blast design, selective mining)
- Avoid oversize and uncrushable material
- Use surge bins where needed

A stable feed allows steady operation and lower energy use.

2 Crusher settings



- Closed side setting (CSS) appropriate for target size
- Correct speed and operating mode
- Adjust settings to rock characteristics
- Avoid over-crushing

Crush only what needs to be reduced.

3 Early screening

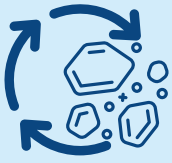


- Remove fines as early as possible
- Use efficient, well-maintained screens
- Correct aperture and screen angle
- Avoid sending correctly sized material to further crushing

Screen early, crush less.



4 Circulating load



- Keep circulating load as low as practical
- Minimise recirculation of near-size material
- Use effective screening and classification
- Monitor and control return loads

Less recirculation means lower energy use.

5 Wear condition



- Maintain liners, blow bars and screens
- Use wear-resistant materials
- Replace at the right time
- Monitor wear and its impact on performance

Good wear control maintains efficiency.

6 Energy performance



- Monitor specific energy (kWh/t)
- Benchmark against targets
- Identify and address inefficiencies
- Consider the whole circuit (not just individual machines)

Track kWh/t and look for continuous improvement.

FIGURE 19. — Processing energy checklist

11 Conveying, storage, washing and auxiliary systems

11.1 Conveying and internal material flow

Within the processing plant, energy performance depends strongly on how material is transferred between stages. The preferred arrangement is the shortest practical flow path that preserves production reliability, product quality, maintenance access and safe operation.

- Avoid unnecessary transfers and repeated elevation changes.
- Use gravity where site topography and process control allow it.
- Use short, direct continuous transfer where fixed flow is appropriate.
- Stop or modulate conveyors and feeders when no useful material is being transferred, where process conditions permit.
- Maintain alignment, idlers, belt condition and transfer points to limit avoidable mechanical resistance.



The energy performance of a conveyor depends on throughput, length, elevation, belt speed, mechanical resistance and drive efficiency. Motor efficiency is only one component of the complete transport system.

11.2 Washing, classification and dewatering

Wet processing should be used only to the intensity required by the deposit and product specification. Its energy demand arises principally from pumps, screens, scrubbers, classifiers, dewatering equipment and the repeated movement of water and slurry through the circuit.

- Match water flow and pressure to the washing duty.
- Use the least intensive treatment that reliably achieves product quality.
- Recover correctly sized and saleable material as early as practicable.
- Dewater effectively before unnecessary water is transported with the product.
- Avoid excessive recirculation of water or slurry.

Hydrocyclones and other hydraulic classifiers should be evaluated as complete circuits rather than isolated items: sump, pump, classifier, dewatering and water recovery all contribute to energy performance.

Energy hierarchy for material handling

Move less material, use less energy

1 Avoid the movement

Do not move material if it is not necessary.

- Optimise quarry and plant design.
- Locate processing and stockpiles close to the face.
- Use in-pit processing and conveyors where viable.
- Plan extraction and product allocation to minimise handling.



The most sustainable tonne is the one not moved.

2 Use gravity

Let gravity do the work.

- Optimise levels and layouts.
- Use drops, chutes and gravity flow where possible.
- Design to minimise lifting and pumping.



Use natural potential energy to reduce mechanical energy input.

3 Short direct continuous transfer

Keep it simple, short and continuous.

- Minimise transfer points.
- Use direct routes and avoid detours.
- Design for continuous flow.



Shorter, simpler routes reduce energy use, costs and spillage.

4 Conveyors and controlled feeders

Use efficient, reliable and well-designed conveying systems.

- Select appropriate conveyor type and size.
- Use controlled feeders and variable speed.
- Maintain good alignment, clean belts and low rolling resistance.



Continuous conveying is usually the most energy-efficient way to move material.

5 Mobile handling (where flexibility is required)

Use mobile equipment only where needed.

- Choose the right equipment and size.
- Optimise fleet management and utilisation.
- Minimise loading cycles, travel distances and idle time.
- Consider hybrid or electric options.



Mobile handling gives flexibility but usually higher energy use. Use only where it adds value.

6 Minimise rehandling

Handle material as few times as possible

- Design integrated flows from face to product.
- Avoid unnecessary stockpiling and double handling.
- Use appropriate stockpile locations and reclaim systems.
- Plan for direct delivery to final product or use.



Fewer handling stages mean lower energy use, lower costs and less environmental impact.

Smarter material handling for a more sustainable tomorrow.
Plan, design and operate to move less, use less energy and create more value.

FIGURE 20. — Energy hierarchy for material handling

11.3 Pumping and water circuits

Pumping energy is driven by flow, head, system resistance, pump efficiency and operating time. The first priority should be to reduce the hydraulic duty imposed on the system before improving the motor or pump in isolation.

- Avoid unnecessary pumping height.
- Reduce avoidable pipe length, restrictions and pressure losses.
- Select pumps close to the required duty point.
- Control flow according to actual process demand.
- Maintain pumps, pipes, valves and hydro-cyclones in suitable condition.
- Monitor kWh/m^3 together with flow and head.

Water efficiency and energy efficiency are related but distinct. Increasing water recirculation can reduce freshwater demand while increasing pumping, clarification or sludge-dewatering energy. Both effects should therefore be measured.

11.4 Thermal drying of specialised aggregates

Thermal drying is not a common operation in conventional aggregates production, but it may be required for certain sands used in mortars, specialised applications and fine or micronised mineral products. Where present, it can constitute a Significant Energy Use because water must be evaporated from the material and the required heat is normally much greater than the mechanical energy associated with conveying or classification.

Energy performance depends principally on the initial and required final moisture content, tonnes

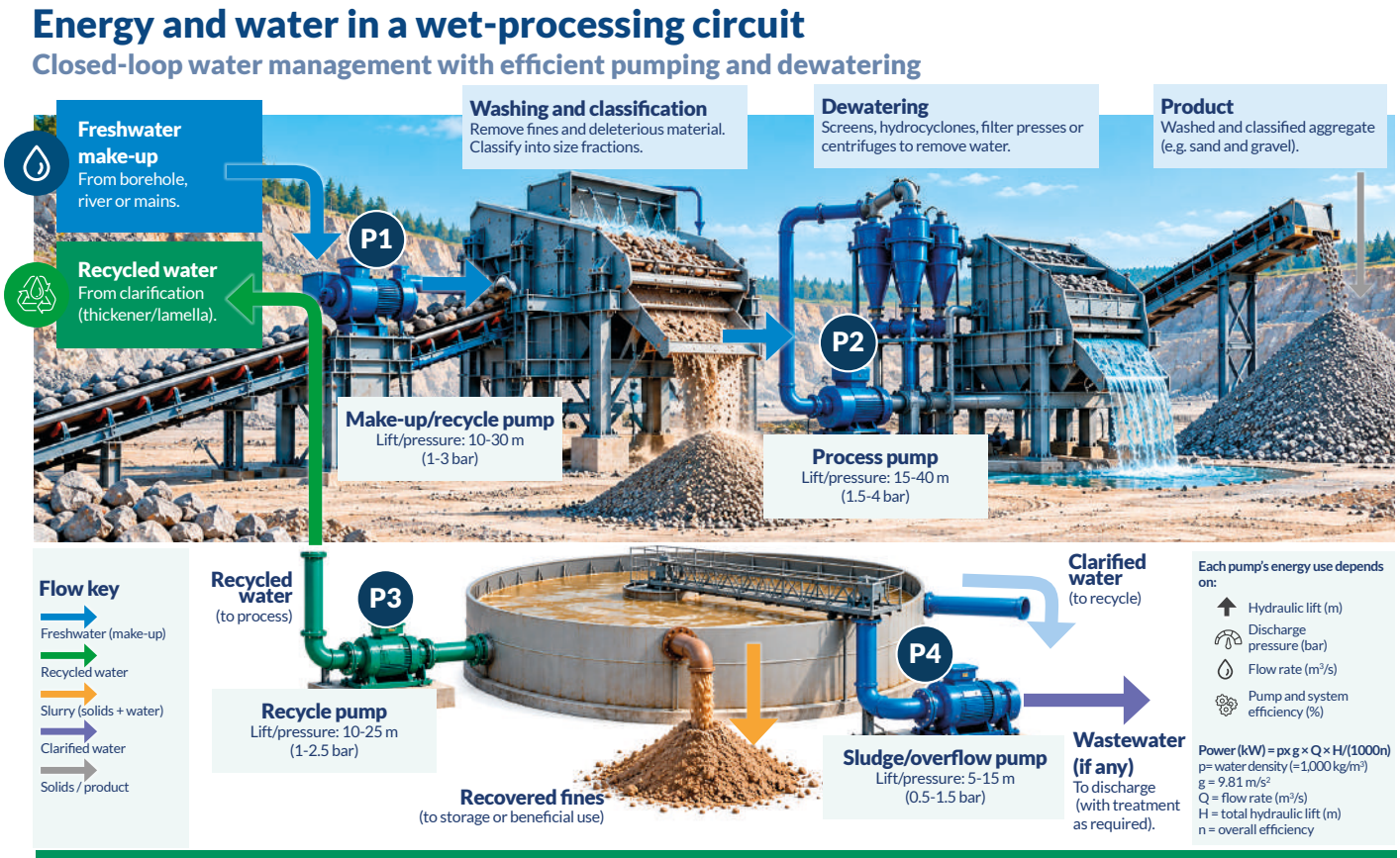


FIGURE 21. — Energy and water in a wet-processing circuit

dried, drying temperature, dryer design, heat-generation efficiency, exhaust losses, air flow, insulation, operating stability and the energy carrier used.

The first objective should be to minimise the thermal duty rather than simply improve the efficiency of the heat source. Where technically compatible with product requirements, priority should therefore be given to:

- Avoiding unnecessary drying.
- Reducing the amount of water entering the dryer through effective drainage or mechanical dewatering.
- Avoiding over-drying below the moisture level required by the product.
- Maintaining stable feed and appropriate throughput.
- Minimising air leakage and unnecessary exhaust losses.
- Maintaining burners, heat exchangers, insulation and controls in suitable condition.
- Evaluating heat recovery, electrification or lower-carbon heat sources where technically and economically appropriate.

Performance should preferably be monitored as thermal energy per tonne of dried product, together with inlet and outlet moisture. Comparing kWh/t without accounting for the quantity of water evaporated can give misleading conclusions.

Specific thermal energy = thermal energy consumed / tonnes of dried product

Specific evaporation energy = thermal energy consumed / kg of water evaporated

11.5 Storage and buffers

Storage is valuable when it stabilises material flow, separates products and decouples process stages. It becomes an energy penalty when poor location or operating practice creates repeated loading, long loader travel, contamination, degradation or unnecessary transfer.

- Locate stockpiles to reduce cumulative travel between processing and dispatch.
- Use buffers to stabilise feed and reduce stop-start operation.
- Select reclaim methods according to capacity, flexibility and energy implications.
- Control stockpile formation and reclaim to limit segregation and avoid reprocessing.

A correctly designed hopper or buffer can have a greater indirect energy benefit than its own direct consumption by reducing surges, blockages, idle operation and unstable crusher or screen loading.





FIGURE 22. — Storage as a process stabiliser

11.6 Ancillary facilities and support services

Ancillary facilities—including offices, laboratories, workshops and other support services—form part of the site's total energy balance and should therefore be included in energy measurement and management.

Auxiliary services should be prioritised according to measured significance rather than assumed importance. Lighting, workshops, offices, HVAC and compressed air may offer straightforward savings, but they should not displace attention from major production uses unless site data justify it.

- Match lighting and HVAC operation to occupancy and safe operating requirements.
- Avoid unnecessary standby or out-of-hours operation in workshops and laboratories.
- Treat compressed air as an energy service: eliminate leaks, avoid excessive pressure and question inappropriate end uses.
- Include significant auxiliary loads in the site metering and action plan.

11.7 Product loading and dispatch

Product loading and dispatch form the final material-handling stage within the aggregates production site. Although the energy consumed per tonne may be lower than in extraction, haulage or crushing, inefficient stockyard layout and dispatch practices can create substantial cumulative loader travel, rehandling, idling and vehicle waiting.

Energy management should therefore consider the complete stockpile-to-dispatch movement. Stockpiles should, where practicable, be located and managed to minimise loader travel and repeated handling while maintaining product segregation, quality and safe traffic flows. Loader capacity should be matched to dispatch requirements, unnecessary load-and-carry movements should be avoided, and loading operations should be coordinated with weighbridges and vehicle arrivals to reduce queues and idle time. Where automated reclaim, conveyors or loading

systems are technically and economically justified, their whole-system energy performance should be compared with mobile handling.

Useful indicators may include energy or fuel per tonne dispatched, loader travel distance per tonne, tonnes per loading cycle, vehicle waiting time and avoidable idle time.

The objective is simple: once the product has been manufactured, do not add unnecessary energy consumption before it leaves the site.

11.8 External transport and organisational boundaries

External transport can be a significant part of the delivered energy and carbon footprint of aggregates, but it may fall outside the direct operational boundary of the quarry. The energy-management boundary and the greenhouse-gas accounting boundary should therefore be defined separately and consistently.

Where the producer operates the fleet, transport can be monitored directly. Where transport is subcontracted or customer-controlled, procurement and logistics can still influence performance through vehicle selection, payload utilisation, route planning, dispatch coordination and reduction of empty running.

- l/t delivered.
- kWh/t delivered.
- l/t·km or kWh/t·km where distance varies.
- Payload utilisation.
- Empty kilometres and waiting time.

Optimise the efficiency of the transport service, not only the efficiency of the vehicle.



12 How to improve energy performance

Improvement opportunities should be prioritised according to their effect on the complete production system. The first question should not be "Which more efficient machine can we buy?" but "Why is this work being performed, and can it be reduced or avoided?"

12.1 Improvement hierarchy

12.1.1 Optimisation of production areas and operating practices

The different areas of an aggregates operation offer opportunities to improve energy performance, but not every measure will be appropriate or equally important at every site.

Potential measures should therefore be screened and prioritised according to:

- Applicability to the specific operation.
- Expected effect on energy performance.
- Effect on production, product quality and reliability.
- Technical complexity.
- Investment, implementation and maintenance cost.
- Interaction with other processes.
- Implementation timescale.
- Availability of data to verify the result.
- Allocation of responsibility for implementation and coordination.

Priority should be given to measures that reduce the work required by the production system before measures that improve only the efficiency of individual machines.

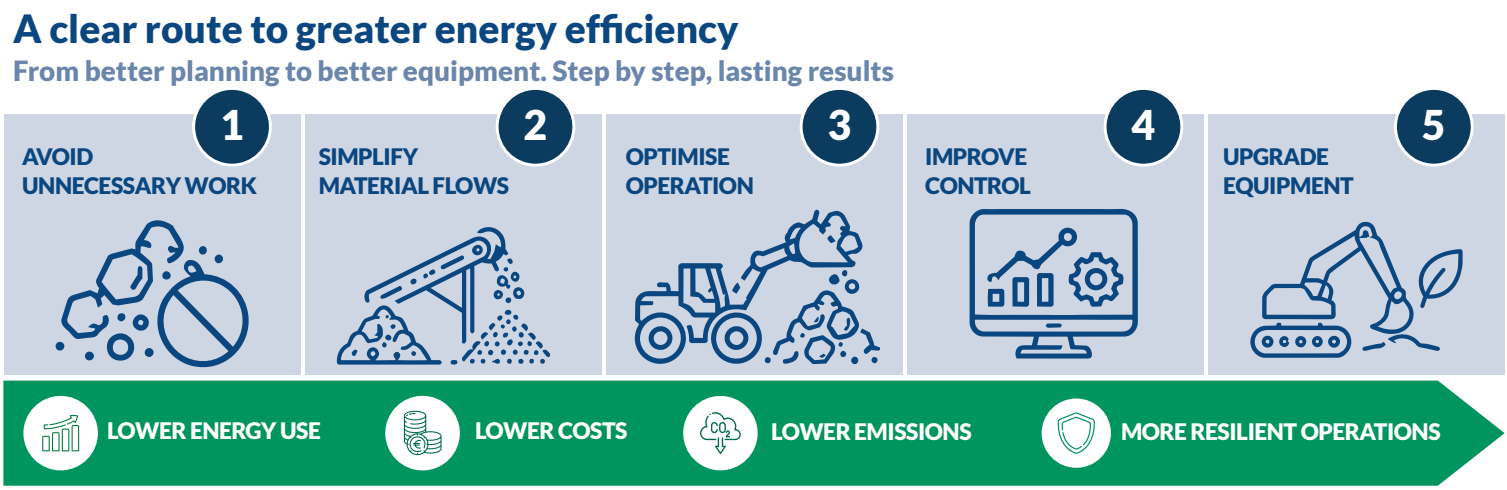


FIGURE 23. — A clear route to greater energy efficiency

A useful hierarchy is: Avoid unnecessary work → Simplify material flows → Optimise operation → Improve control → Upgrade equipment.

For secondary aggregates, avoid processing contaminants or fractions that should be separated or recovered by another route and separate materials as early as practicable and minimise rehandling between reception, sorting, processing and storage.

Measures can also be considered according to their nature: System design | Operational | Maintenance | Technology

And, where appropriate, according to the level of intervention required: No/low CAPEX → process optimisation → maintenance and control → targeted investment → major system redesign.

Hierarchy for prioritising improvement measures

Start with the simplest solutions and work towards larger investments

1 Avoid unnecessary work

Do not use energy for work that is not needed.

- Remove non-value-adding activities
- Avoid unnecessary handling and rehandling
- Optimise production planning
- Eliminate losses and inefficiencies



The cleanest and cheapest energy is the one you do not use.

2 Improve system design

Design for lower energy use and higher efficiency.

- Optimise quarry layout, material flows and elevations
- Use gravity and shorter transport routes
- Size and locate stockpiles appropriately
- Select efficient process configurations



Good design reduces energy use for the Lifetime of the operation.

3 Improve operating practices

Get more from what you already have.

- Optimise loading, dispatch and routing
- Avoid queues and reduce idle time
- Maintain equipment properly
- Control feed quality and operating conditions
- Train and engage the workforce



Better practices deliver real savings now.

4 Improve measurement and control

You cannot manage what you do not measure.

- Monitor energy use (kWh/t, l/t)
- Use data and KPIs to identify opportunities
- Implement control systems (e.g. load, speed, process stability)
- Review performance and drive continuous improvement



Data turns opportunities into results.

5 Upgrade technology

Invest in more efficient equipment and systems.

- Use high-efficiency motors, drives and hydraulics
- Consider electrification and alternative fuels
- Adopt advanced process equipment
- Integrate automation and optimisation systems
- Plan for fleet renewal and major upgrades



New technology enables step changes in energy efficiency.

TYPICAL INVESTMENT LEVEL

Low CAPEX
Operational changes (no or very low cost)

Moderate CAPEX
Process and control improvements

Major redesign
New equipment and systems

A stepwise approach delivers the greatest impact.
Start simple, build momentum and invest where it delivers most value.

FIGURE 24. — Hierarchy for prioritising improvement measures

12.2 Operations and maintenance

12.2.1 Maintenance and energy performance

Maintenance and energy performance are closely linked.

Equipment that deteriorates from its intended operating condition may require more energy to provide the same useful output, even before the deterioration becomes severe enough to cause failure.

Maintenance should therefore be integrated into energy management rather than treated solely as a reliability function.

An appropriate maintenance strategy may combine:

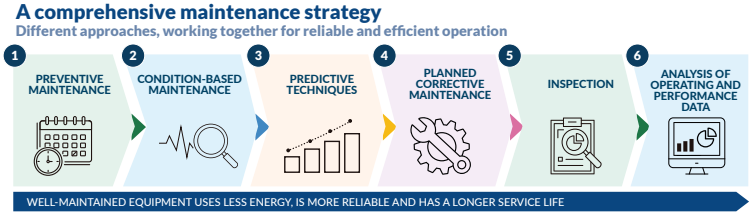


FIGURE 25. — A comprehensive maintenance strategy

The level of monitoring should reflect both equipment criticality and energy significance.

12.2.1.1 Fixed and electrically driven equipment

Energy-related maintenance may include, as appropriate:



FIGURE 26. — Examples of energy-related maintenance activities for fixed equipment

Energy efficiency classes for motors and variable-speed drives do not remove the need to maintain the complete driven system correctly.

A high-efficiency motor connected to a poorly maintained pump, conveyor or transmission remains part of an inefficient system.

Condition-monitoring techniques may include:

- Vibration analysis.
- Temperature monitoring.
- Thermography.
- Oil analysis.
- Electrical measurements.
- Performance trending.



FIGURE 27. — Condition monitoring techniques

These techniques should be applied where equipment criticality, failure mode and potential benefit justify them rather than as universal requirements.

12.2.1.2 Mobile equipment

For mobile equipment, factors affecting energy consumption include:



FIGURE 28. — Key factors affecting energy consumption in mobile equipment

Maintenance intervals should follow manufacturer requirements and actual operating conditions.

For quarry equipment, operating hours, tonnes handled, duty cycle and component condition may be more meaningful maintenance variables than road kilometres alone.

Tyres require particular attention because their condition and inflation influence rolling resistance, energy consumption, safety and component life.

12.2.1.3
Energy performance as a maintenance indicator

Energy data can provide valuable diagnostic information.

An unexplained deterioration in the following indicators may reveal an operational or mechanical problem:

- l/t.
- kWh/t.
- kWh/m^3 pumped.
- Compressor specific power.
- Conveyor power at comparable throughput.
- Other relevant EnPIs.

For example, a sustained increase in fuel consumption per tonne transported should be investigated where there has been no corresponding change in:

- Haul distance.
- Gradient.
- Rolling resistance.
- Payload.
- Production conditions.
- Material characteristics.
- Operating schedule.

Likewise, increasing electrical power at an unchanged production rate may indicate wear, friction, blockage, poor adjustment or deterioration of a driven system.

Energy trends should therefore be evaluated alongside conventional maintenance data.

This allows energy performance to become part of condition monitoring rather than merely an accounting result.

12.2.1.4
Maintenance prioritisation

Not every component requires the same level of monitoring.

Maintenance resources should be prioritised according to:

- Safety significance.
- Production criticality.
- Energy consumption.
- Consequence of failure.
- Condition.
- Failure history.
- Economic value of early detection.

Significant Energy Uses should receive particular attention because even relatively small deterioration can lead to substantial cumulative energy losses.

Maintenance should also be coordinated with production planning so that equipment can be restored to an appropriate operating condition without creating unnecessary disruption or inefficient temporary operating modes.

The central principle is: Energy performance is an operating condition that should be maintained, not merely a value measured when equipment is commissioned.

Maintenance should therefore be linked to energy performance. A deterioration in kWh/t, l/t or other relevant indicator can be a symptom of wear, poor adjustment, leakage, misalignment, changing process conditions or measurement error. Energy data can consequently support condition-based maintenance and prioritisation.

12.3 Correct sizing and equipment matching

12.3.1 Correct sizing and matching of equipment

Correct equipment sizing is fundamental to energy, operational and economic performance.

Equipment should be selected for its expected operating duty rather than solely for the maximum theoretical demand that could occur.

Excessive oversizing may result in:

- Unnecessary capital investment.
- Low utilisation.
- Inefficient part-load operation in some equipment types.
- Excessive cycling.
- Poor control.
- Unnecessary auxiliary losses.

Undersizing may result in:

- Persistent overload.
- Inability to meet production requirements.
- Extended operating hours.
- Accelerated wear.
- Bottlenecks.
- Reduced process stability.
- Unplanned shutdowns.

The effect of load on efficiency differs between equipment types. Pumps, fans, motors, crushers, conveyors and combustion engines do not necessarily respond in the same way to part-load operation.

Sizing should therefore be based on equipment-specific performance characteristics and the expected load profile.

The correct design question is: What operating range will the equipment experience most of the time, and how efficiently can it perform within that range?

12.3.1.1 Equipment matching

Correct sizing must also consider the relationship between adjacent stages of the process.

Typical examples include:

- Excavator capacity and truck payload.
- Truck fleet and loading capacity.
- Primary crusher capacity and quarry feed.
- Crusher discharge and downstream screening.
- Screens and recirculating load.
- Conveyors and actual material flow.
- Pump capacity and hydraulic-system requirements.
- Motor capacity and driven load.
- Washing equipment and water circuit.
- Buffer-storage capacity and production variability.

A technically efficient machine can still contribute to poor overall energy performance if it causes:

- Queues.
- Starvation of downstream equipment.
- Excessive recirculation.
- Repeated start-stop operation.
- Unnecessary idle time.
- Persistent underutilisation elsewhere in the process.

Sizing should therefore consider both the equipment duty and its interaction with adjacent process stages.

12.3.1.2 Spare capacity and future requirements

Some spare capacity may be justified to provide:

- Operational resilience.
- Maintenance flexibility.
- Peak production capability.
- Future production growth.
- Adaptation to changing quarry conditions.

This should not be confused with indiscrimi-

nate oversizing.
Sizing should consider foreseeable changes in:

- Production rate.
- Quarry geometry.
- Haul distance.
- Electrification.
- Product mix.
- Washing requirements.
- Processing configuration.
- Remaining quarry life.

For example, future electrification may significantly increase the required capacity of transformers, substations, chargers and site electrical infrastructure even where current electricity demand is relatively modest.

The central principle is: Size equipment for the expected duty, provide justified flexibility and match each component to the system in which it operates.

12.4 Procurement and life cycle thinking

12.4.1 Energy-efficient equipment procurement

Energy performance should be incorporated into procurement and replacement decisions for significant energy-consuming equipment.

Selection based only on initial purchase price can favour equipment with substantially higher operating costs over its useful life.

A simplified life cycle perspective is: Life cycle cost = Purchase + Installation + Energy + Maintenance + Downtime + End-of-life costs, where relevant.
Energy performance deserves particular attention for equipment with:

- High installed power.
- High annual operating hours.
- Long service life.
- Significant influence on overall process efficiency.

This may include motors, crushers, screens, conveyors, pumps, compressors, mobile equipment, drives, transformers, lighting and HVAC systems.

Where practical, technical specifications should require suppliers to provide:

- Efficiency data.
- Performance curves.
- Part-load performance.
- Expected consumption under defined duty conditions.
- Control options.
- Maintenance requirements.
- Relevant eco-design or efficiency information.
- Assumptions underlying performance guarantees.

For significant equipment and systems, suppliers should be engaged not only as vendors but as technical partners in defining the duty, selecting and sizing the solution, integrating it with adjacent processes and verifying energy performance after commissioning.

Comparisons should be made under equivalent operating conditions.

The lowest-capital-cost option is not necessarily the lowest-cost option over the equipment lifetime.



Before replacing equipment

Explore all lower-cost options first, then make an informed decision

1 Can the work be avoided?
Is the activity necessary?
Can material be moved, processed or handled less, or not at all?

YES → Avoid the work and save energy, costs and emissions.

NO ↓

2 Can the duty be reduced?
Can throughput, size reduction, transport distance, lifting height or operating hours be lowered while still meeting requirements?

YES → Reduce the duty and avoid unnecessary energy use

NO ↓

3 Can the process be stabilised?
Are there opportunities to improve feed consistency, remove bottlenecks, increase storage, or better control flow and operating conditions?

YES → Stabilise the process and improve efficiency.

NO ↓

4 Is the equipment correctly sized and maintained?
Is the equipment the right size for the duty? Is it well maintained and operating as intended?

YES → Optimise operation and maintenance before considering replacement.

NO ↓

Correct sizing or maintenance issues and review performance.

If replacement is still being considered...
Evaluate all relevant factors, not just purchase price.

Energy use
- Lower energy consumption (kWh/t, l/t)
- More efficient drive systems and control

Productivity
- Higher capacity or better availability
- Meets future production requirements

Reliability
- Reduced breakdowns and downtime
- Proven performance in similar applications

Maintenance
- Lower maintenance requirements
- Easier and safer to maintain

Emissions
- Lower direct and indirect emissions (CO^2, NO_x, particulates, etc.)
- Supports environmental and regulatory goals

Life cycle cost
- Consider total cost of ownership (CAPEX, energy, maintenance, downtime and residual value)
- Compare realistic alternatives

Make the decision
Choose the option that delivers the best overall value for your operation and its long-term sustainability.



The most sustainable equipment is the equipment you do not need to replace.
Optimise first. Replace only when it clearly delivers better overall performance.

FIGURE 29. — Before replacing equipment

13 Efficient equipment, electrification and low-carbon energy

13.1 Electricity generation mix and time-dependent carbon intensity

Electricity supplied by the grid is not produced from a single energy source. It comes from a changing combination of generation technologies connected to the electricity system, including wind, solar photovoltaic, hydropower, biomass and biogas, geothermal energy, nuclear power, natural gas, coal and lignite, oil and other combustible fuels, together with electricity imported through interconnections.

In 2024, the EU electricity mix as a whole comprised approximately 48% renewable electricity, 23% nuclear and 29% fossil generation, but the composition differed substantially between Member States. For example, some national systems are dominated by hydro or wind, others have a major nuclear contribution, while others continue to rely significantly on natural gas or solid fossil fuels.

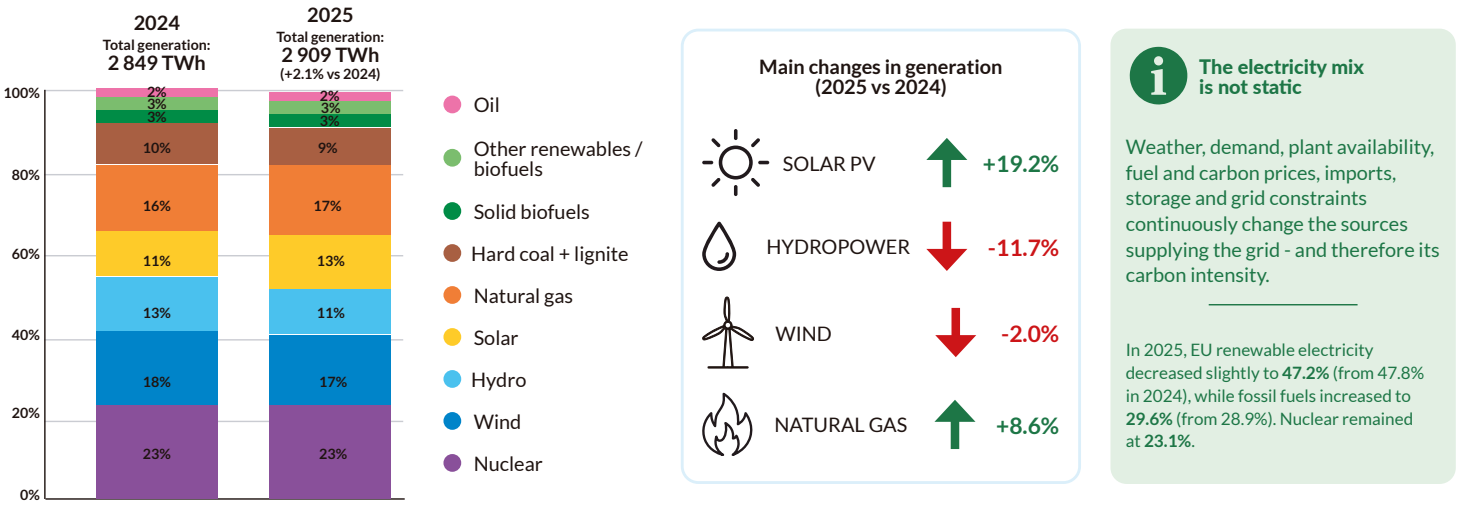
The generation mix also changes continuously within the same country. Solar output varies with solar irradiation, cloud cover, season and time of day; wind generation depends on wind conditions; hydropower depends on precipitation, snowmelt, river flows and reservoir levels; thermal and nuclear generation are affected by maintenance and outages, fuel availability and, in some cases, cooling-water conditions.

The dispatch of available plants is further influenced by electricity demand, fuel and carbon prices, network constraints, interconnector flows, storage availability, renewable curtailment and balancing requirements. Consequently, the greenhouse-gas intensity of grid electricity can vary materially between seasons, days, hours, minutes, seconds and milliseconds. The sharp fall in EU hydro generation in 2025, while solar generation increased strongly, illustrates how the generation mix can change significantly from one year to another.



EU-27 electricity generation mix: 2024 vs 2025

The generation mix changes from year to year. Even at EU level, the contribution of different sources varies, which affects the carbon intensity of grid electricity



Source: Eurostat, Energy statistics - quantities (nrg bal_peh), EU-27.
2025 data provisional (June 2026). Percentages are rounded and may not sum to 100%
Year-on-year changes refer to electricity generation by source.

FIGURE 30. — EU-27 electricity generation mix 2024 - 2025

This distinction matters for aggregates operations. Reducing electricity consumption remains an energy-efficiency improvement irrespective of the generation mix, but the associated avoided greenhouse-gas emissions depend on the carbon intensity of the electricity displaced. Similarly, electrification transfers part of the site's energy demand from fuels to the electricity system: its decarbonisation benefit therefore depends partly on the present and future electricity mix. Onsite renewable generation, storage, flexible operation and appropriate procurement can reduce exposure to this variability, but physical electricity flows, contractual renewable-energy attributes and greenhouse-gas accounting should not be treated as interchangeable concepts.

The JRC therefore provides separate country-specific factors for electricity generation and electricity consumption, distinguishing direct CO_2, operational GHG and life cycle GHG factors.

Grid electricity is an energy carrier with a changing carbon intensity: the same kWh consumed at different locations or times does not necessarily have the same generation mix or greenhouse-gas footprint.

TABLE 2 Electricity sources potentially supplying an aggregates site

Electricity source potentially supplying an aggregates site	Site access	Main factors determining availability/output	Direct operational CO_2 indicative g CO_2/kWh	Life cycle GHG, indicative g CO_2e/kWh	Indicative annual utilisation in Europe
Solar PV	Grid / onsite	Solar irradiation; latitude; season; day/night; clouds; module temperature; orientation; shading; snow/soiling; curtailment	≈0	8–83	~11–18%; EU-2024 fleet ≈16%
Wind — onshore	Grid / onsite where resource and permitting allow	Wind speed distribution; turbulence; terrain; cut-in/cut-out speeds; icing; storms; curtailment; maintenance	≈0	7.8–16	~20–35%
Wind — offshore	Mainly grid	Wind resource; storms; marine access; cable availability; turbine outages; curtailment	≈0	12–23	~35–50%
Hydropower — run-of-river/ reservoir	Mainly grid; occasionally onsite/small hydro	Rainfall; snowmelt; river flow; reservoir level; drought; water-use constraints; environmental flows; dispatch strategy	≈0*	6–147 in UNECE study; highly site-specific	~20–45%; EU-2024 aggregate ≈28%
Biomass / solid biofuels	Grid / possible onsite CHP	Sustainable feedstock availability; moisture; transport/logistics; storage; boiler availability; competing uses; sustainability requirements	Biogenic stack CO_2 occurs; accounted separately under applicable method-ology	Commonly ~50–110 for several sustainable wood pathways; much wider ranges possible	Typically, ~50–85% where operated as dis-patchable generation
Biogas	Grid / possible onsite CHP if feedstock exists	Feedstock supply; digester production; gas storage; methane losses; engine availability; heat demand for CHP	Fossil CO_2 usually low; biogenic carbon treated separately	Strongly pathway dependent; municipal -waste biogas about 49–57 in representative JRC pathways; some waste/manure pathways can be much lower	Often ~50–90% when continuous feedstock is available
Geothermal	Grid; very site-specific onsite potential	Geological resource; reservoir tem-perature and flow; well productivity; reinjection; scaling/ corrosion; outages	Usually low but not necessarily zero because some reser-voirs release gases	Roughly 6–79 in IPCC literature	Typically, ~70–95% where a viable resource exists
Nuclear	Grid	Planned refuelling; maintenance; unplanned outages; reactor fleet; cooling-water constraints; regulatory operation	≈0	5.1–6.4 in UNECE assessment	EU-2024 ≈75%
Natural gas — CCGT	Grid / possible onsite CHP or generation	Gas availability; pipelines/LNG; stor-age; gas price; EU ETS/carbon price; plant efficiency; demand; renewable output; outages	~350–490	403–513	EU-2024 fleet utilisation ≈25–30%; technically dispatchable
Hard coal / lignite	Grid, not normally appropriate onsite	Fuel supply; coal/lignite availability; carbon price; environmental con-straints; maintenance; demand; com-petition from gas and renewables	Coal ~670–870; lignite generally toward/higher than upper end	~751–1,095 for coal technologies in UNECE assessment	EU-2024 combined uti-lisation roughly ~30%
Oil / diesel-fired electricity	Grid in some systems / onsite backup generator	Fuel availability; logistics; storage; price; emissions constraints; operating need; island/backup use	Fuel-oil generation around ~800; diesel depends strongly on generating efficiency	Typically, among the highest-carbon electricity options; broadly ~700–1,000+	Usually low for conti-nental-grid generation; potentially high tempo-rarily for backup/island operation

NOTES

Hydropower can have reservoir-related methane emissions. They are highly site-specific and are one reason life cycle estimates show much greater dispersion than wind or nuclear.

The life cycle ranges for coal, gas, nuclear, hydro, PV and wind above come from the UNECE comparative LCA, which reports 751–1,095 g CO_2e/kWh for coal, 403–513 for gas CCGT, 5.1–6.4 for nuclear, 6–147 for hydro, 8–83 for PV, 7.8–16 for onshore wind and 12–23 for offshore wind. IPCC data similarly distinguish direct emissions from life cycle emissions; for example, gas CCGT has indicative direct emissions around 350–490 g CO_2/kWh and coal around 670–870 g CO_2/kWh.

Batteries, pumped-storage hydropower or hydrogen are not included as "**primary energy sources**" in this table. They are **energy storage systems or energy carriers**: they may be highly relevant to a quarry, but the carbon intensity of the electricity they deliver depends on the energy used to charge them or, in the case of hydrogen, to produce them.

13.2 Electricity supply and motor-driven systems

Most fixed aggregates processing equipment is electrically driven. Electricity management therefore has two complementary objectives: reduce the electricity required by the process and ensure that the remaining demand is supplied and distributed efficiently.

Site assessment should distinguish purchased electricity, onsite generation and any fuel used for local electricity generation. Physical consumption and cost should also be reported separately because price changes can alter expenditure without changing energy performance.

13.2.1 Electrical distribution and power quality

Transformer loading, conductor sizing, voltage drop, connections, phase balance, harmonics and power factor can influence losses, available capacity and equipment reliability. Power-factor correction should be based on actual measurements and treated primarily as an electrical-distribution and commercial issue, not as a universal process-energy saving.

13.2.2 Motor-driven systems

A motor should be assessed as one component of a complete system: electrical supply → drive/control → motor → transmission → driven equipment → process duty. Correct sizing, operating load, driven-equipment efficiency, transmission losses, maintenance and control strategy can be as important as nominal motor efficiency class.

13.2.3 Variable-speed drives

Variable-speed drives can be highly effective where process demand varies and changing speed is an efficient control method, particularly in suitable pump and fan applications. They should not be assumed to save energy automatically on every crusher, conveyor or fixed-duty machine. Selection should follow the actual load profile and process requirement.

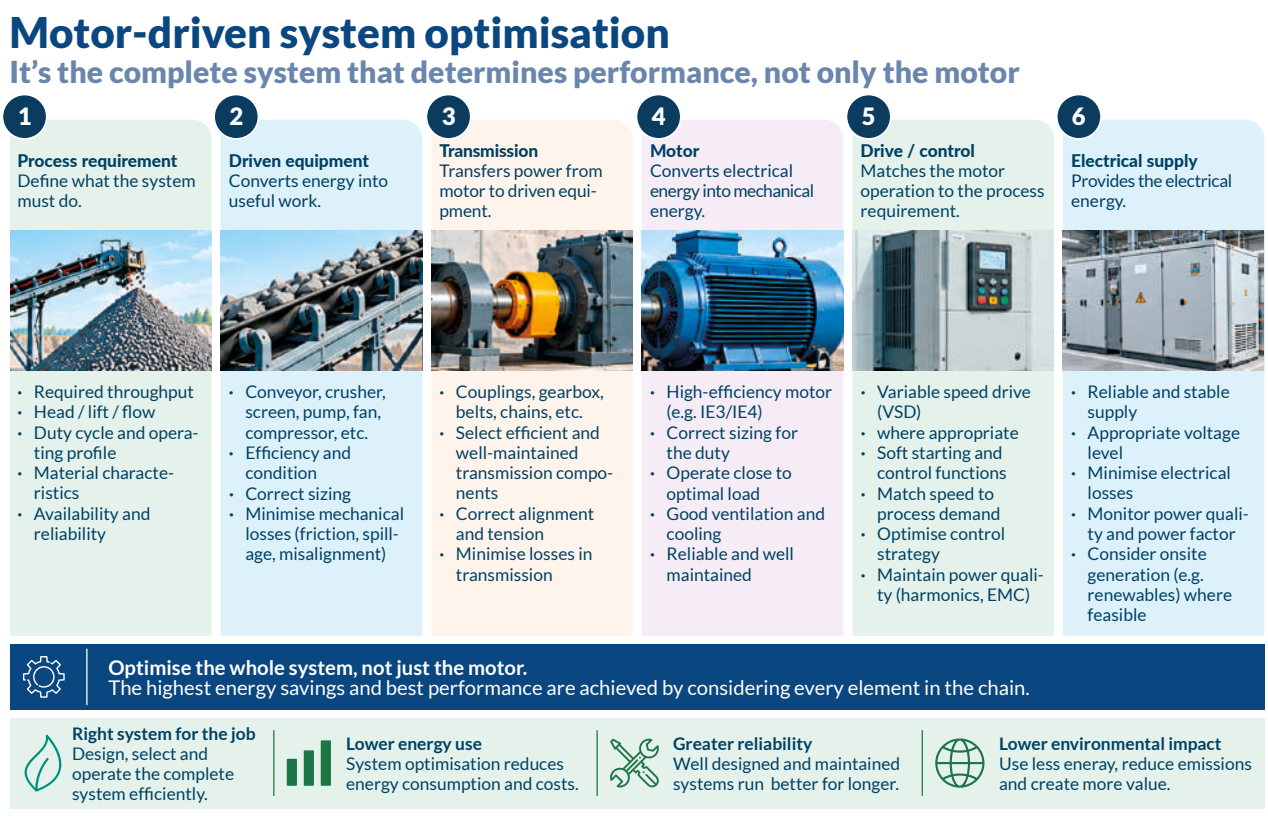


FIGURE 31. — Motor-driven system optimisation

13.3 Mobile equipment and powertrains

For mobile equipment, the first priority remains the work and operating cycle. Equipment selection, payload, haul distance, gradient, road condition, queueing, idling and maintenance can have a greater influence on energy per tonne than the nominal efficiency of the engine or drivetrain.

- Optimise the loading and haulage cycle before changing powertrain.
- Match equipment capacity to the duty and adjacent process stages.
- Maintain roads, tyres or tracks, hydraulics and drivetrain condition.
- Reduce avoidable idling and waiting while respecting equipment and safety requirements.
- Use telemetry to relate energy to payload, distance, cycle time and operating state.
- Relevant indicators include l/t or kWh/t, l/t·km or kWh/t·km, payload utilisation, cycle time and avoidable idle time. Consumption per machine-hour alone is not a sufficient efficiency indicator when productivity differs.

13.4 Electrification

Electrification can improve conversion efficiency and reduce dependence on liquid fuels where suitable equipment and infrastructure are available. Stationary processing, conveyors and pumping are already largely electric; the next opportunities increasingly concern mobile and semi-mobile equipment, charging systems and the electrical infrastructure needed to support them.

A site-specific assessment should consider duty cycle, required autonomy, charging opportunities, grid and transformer capacity, maximum demand, production continuity, equipment availability, remaining site life and total life cycle cost. Electrification changes the energy carrier; it does not remove the need to reduce transport work, idling, recirculation or other avoidable demand.

13.5 Renewable fuels for residual combustion-engine demand

Where direct electrification is not yet technically or economically appropriate, approved renewable liquid fuels can reduce the life cycle greenhouse-gas intensity of residual combustion-engine demand. Fuel substitution should come after demand reduction and should not be presented as an energy-efficiency measure in itself.

Compatibility must be verified for the specific machine and engine. FAME biodiesel and paraffinic renewable diesel such as HVO have different fuel properties, storage requirements and equipment-approval conditions and should not be treated as interchangeable.

- Manufacturer approval and permitted fuel or blend level.
- Fuel specification and warranty conditions.
- Storage, contamination and cold-weather requirements.
- Actual fuel/energy consumption per tonne of production.
- Verified life cycle greenhouse-gas information and feedstock sustainability.
- Reliable availability, logistics and life cycle cost.

A lower-carbon fuel is not necessarily a more energy-efficient fuel. Assess its energy, carbon and economic effects separately.

Energy-transition hierarchy for mobile equipment

Use less energy, then cleaner energy, for a more sustainable operation

1 Avoid machine work

Do not use fuel or electricity for work that is not needed.

- Optimise quarry layout and sequencing
- Reduce haul distances
- Use gravity and in-pit crushing where possible
- Avoid unnecessary handling and reworking
- Improve planning, scheduling and material flow



2 Improve operating efficiency

Get more from the machines you already have.

- Avoid idling and reduce non-productive time
- Use the right size machine for the job
- Optimise payloads, speeds and cycle times
- Maintain tyres, hydraulics and engines properly
- Use operator training, guidance systems and telematics



- Higher productivity
- Lower fuel use
- Less wear and maintenance
- Skilled operators

3 Electrify where appropriate

Use electric drives and charging infrastructure where it is technically and economically feasible.

- Battery-electric equipment (e.g. excavators, wheel loaders, site vehicles)
- Trolley-assist for haul trucks
- Fixed and mobile charging solutions
- Integrate with renewable electricity supply
- Consider total cost of ownership and operational needs



- Zero tailpipe emissions
- Lower noise
- Lower total energy cost (where feasible)

4 Use approved lower-carbon fuels for residual combustion-engine demand

For applications that cannot yet be electrified, use lower-carbon fuels.

- Sustainable biofuels (e.g. HVO)
- Renewable diesel and other approved fuels
- Ensure fuel quality, supply and compatibility
- Monitor performance, emissions and cost
- Keep up to date with regulations and standards



- Lower life cycle emissions
- Use approved and compatible fuels
- Maintain performance and reliability

Demand reduction comes before fuel substitution.

The cleanest and lowest-cost energy is the energy you do not use.

Use lower-carbon fuels only after you have avoided unnecessary work, improved efficiency and electrified where appropriate.



A STEPWISE APPROACH DELIVERS REAL PROGRESS.

Cleaner, more efficient mobile equipment.
Less energy. Lower emissions. A more resilient future.

FIGURE 32. — Energy-transition hierarchy for mobile equipment

13.6 Onsite energy generation, storage and energy resilience

Onsite energy generation can complement energy-efficiency measures and electrification by supplying part of an aggregates site's electricity or thermal-energy demand. Aggregates operations can offer favourable conditions for some forms of onsite generation because they may have relatively large land areas, significant daytime electricity demand, roofs and other built surfaces, electrical infrastructure and, in some cases, areas that have already been worked or progressively rehabilitated.

Onsite generation should complement, not substitute for, demand reduction and energy-efficiency improvement.

13.6.1 Most relevant onsite generation options

The suitability of onsite energy generation varies significantly between aggregates sites.

Solar photovoltaic generation is generally the most widely applicable option, particularly where suitable ground, roofs, infrastructure areas or progressively rehabilitated land are available, due to its technological maturity, modularity, relatively low operating requirements and potential alignment with daytime processing demand.

Wind generation can also provide substantial output at sites with a favourable wind resource, although its feasibility is more dependent on local conditions, permitting, environmental constraints and grid connection, while small wind installations tend to have more limited applications.

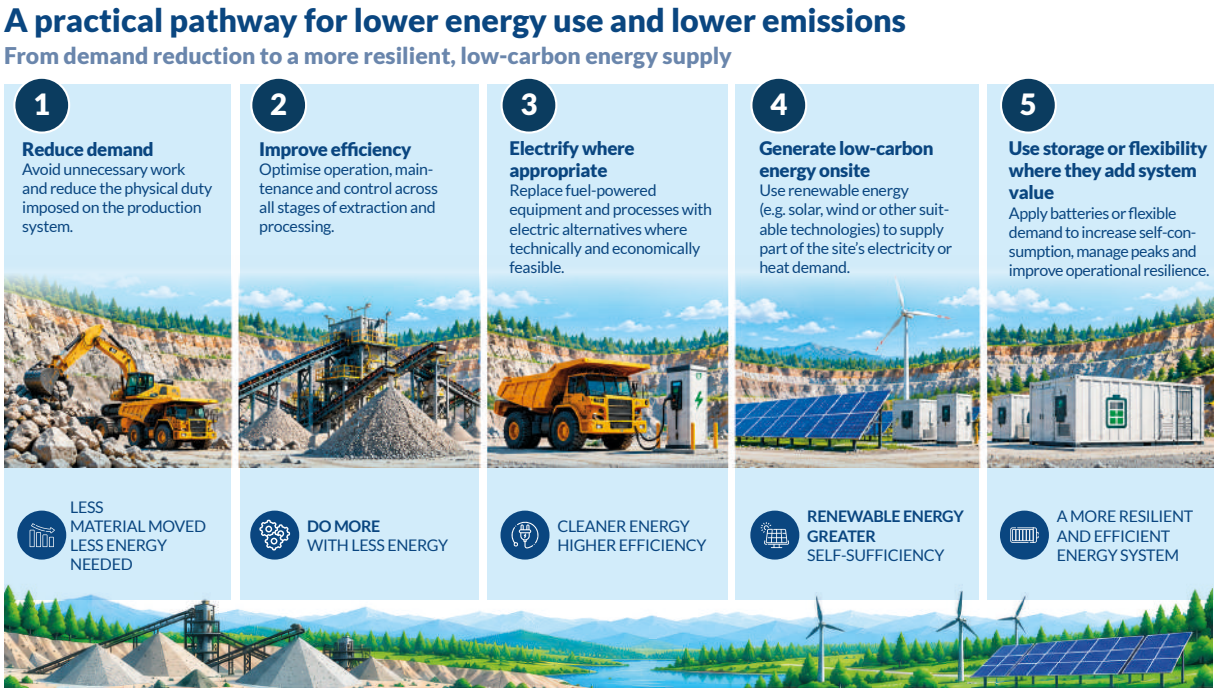


FIGURE 33. — A practical pathway for lower energy use and lower emissions

The objective should not necessarily be to maximise installed renewable capacity. In many operations, the more useful objective is to maximise the technical, environmental and economic value of the energy generated, taking account of the site's actual and future demand profile.

Hydropower or micro-hydro, biomass or biogas CHP, and renewable heat systems are more site-specific options and are likely to be justified only where suitable local resources and energy demands exist.

Waste-heat recovery may also reduce purchased energy where a sufficiently continuous and useful heat source is available, although it should be regarded as energy recovery rather than primary energy generation.

Consequently, technology selection should be based on the site's energy-demand profile, available renewable resources, land and infrastructure constraints, permitting conditions, grid capacity, remaining operational life and whole-life economics, rather than on a predetermined preference for a particular technology.

13.6.2 Why aggregates sites can offer particular opportunities

Aggregates sites may present particular opportunities for renewable generation because the land required by extraction changes progressively over the life of the operation. Depending on national and local planning and permitting requirements, renewable installations may potentially be located on processing and infrastructure areas, roofs and buildings, land not required for current extraction, previously disturbed areas and progressively or finally rehabilitated land.

TABLE 3 Most relevant onsite generation options in an aggregates site

Option	Applicability to aggregates sites	Principal advantages	Main constraints
Solar photovoltaic — ground-mounted	High where suitable land or disturbed/restored areas are available	Mature technology; modular; relatively rapid deployment; low operating requirements; good match with daytime processing demand	Land availability; permitting; grid connection; seasonal/daytime variability; dust/soiling; shading; remaining site life
Solar photovoltaic — roofs, workshops, offices, carports and other structures	High where suitable surfaces exist	Uses existing built surfaces; close to loads; limited additional land occupation	Available surface; structural capacity; orientation; dust; fragmented installations
Solar photovoltaic on rehabilitated or non-operational areas	Potentially high	Can give an additional productive use to land no longer required for extraction; capacity may increase progressively as rehabilitation advances	Restoration objectives; biodiversity/landscape requirements; planning and permitting; electrical connection
Wind power	Site-specific	Potentially high generation where wind resource is good; may complement solar generation seasonally and temporally	Wind resource; permitting; landscape/ecology; aviation/radar constraints; setbacks; grid connection; greater project complexity
Small wind turbines	Generally, more limited	Modular and potentially useful at particularly favourable sites	Economics and output are highly dependent on local wind conditions and turbulence
Hydropower / micro-hydro	Niche	Dispatchable or predictable generation may be possible where a suitable continuous hydraulic resource already exists	Very site-specific; water flow and head; environmental permits; seasonal availability
Biogas / biomass CHP or heat generation	Niche / site-specific	Dispatchable energy; can provide useful heat as well as electricity	Sustainable local feedstock; logistics; emissions; maintenance; economics; generally, not intrinsic to aggregates production
Solar thermal / renewable heat	Specific thermal applications	Can displace part of purchased thermal energy	Requires a compatible heat demand and temperature level; intermittency
Waste-heat recovery	Where significant heat is available	Recovers energy that would otherwise be lost	Not primary generation; source temperature, continuity and heat sink must justify recovery

This creates an opportunity to consider renewable generation as part of quarry development and rehabilitation planning, rather than as an independent energy project added later. Temporary, relocatable or phased installations may also be appropriate where the configuration of the quarry changes over time.

13.6.3 Solar photovoltaic as the first option to assess

For many aggregates operations, solar photovoltaic generation is likely to be the most readily applicable onsite renewable-electricity option. Processing plants commonly operate during daylight hours, which can provide a useful degree of coincidence between PV generation and electricity demand.

Potential locations include roofs, workshops, offices, parking or vehicle shelters, processing and infrastructure areas, suitable non-operational land and, where compatible with restoration objectives and permitting, progressively or finally rehabilitated areas.

The preferred design should be based on the site's hourly or sub-hourly electricity demand, rather than annual consumption alone. A plant that generates the same annual electricity as the site consumes does not necessarily make the site electrically self-sufficient because generation and consumption occur at different times.

13.6.4 Self-consumption, export and sizing

The value of onsite electricity depends strongly on how much can be consumed directly by the operation.

Relevant indicators include:

- Onsite renewable electricity generated, MWh/year.
- Electricity consumed directly onsite, MWh/year.
- Self-consumption ratio = onsite renewable electricity consumed onsite / onsite renewable electricity generated.
- Renewable coverage = onsite renewable electricity consumed onsite / total site electricity consumption.
- Electricity imported from the grid.
- Electricity exported to the grid.

Maximising renewable generation is not necessarily equivalent to maximising economic value. Oversizing generation relative to site demand may increase exports at times when their value is lower than the avoided cost of electricity consumed onsite.

13.6.5 Combining onsite generation with electrification

Electrification and onsite renewable generation should be planned together. Electrification of mobile equipment, pumping, conveying or thermal processes may substantially change the site's future load profile and increase the proportion of onsite renewable electricity that can be used directly.

Conversely, controlled charging of battery-electric equipment or flexible operation of selected loads may allow part of electricity demand to be shifted towards periods of high onsite generation, provided that production, safety, equipment availability and overall energy performance are not adversely affected.

13.6.6 Storage: supporting generation, not generating energy

Batteries and pumped-storage systems are not energy sources. They store energy generated elsewhere and return less energy than was originally stored because conversion losses occur.

Storage may nevertheless create value by increasing renewable self-consumption, managing peak demand, supporting controlled charging of mobile equipment, reducing grid-connection constraints, providing backup capability or improving operational resilience. Storage should therefore be evaluated according to the service it provides to the complete site energy system, not simply according to installed battery capacity.

13.6.7 How to evaluate an onsite generation project

Onsite generation should be designed around the energy needs and evolution of the quarry — not the other way round. First reduce unnecessary demand, then determine how much of the remaining demand can be supplied efficiently with locally generated low-carbon energy.

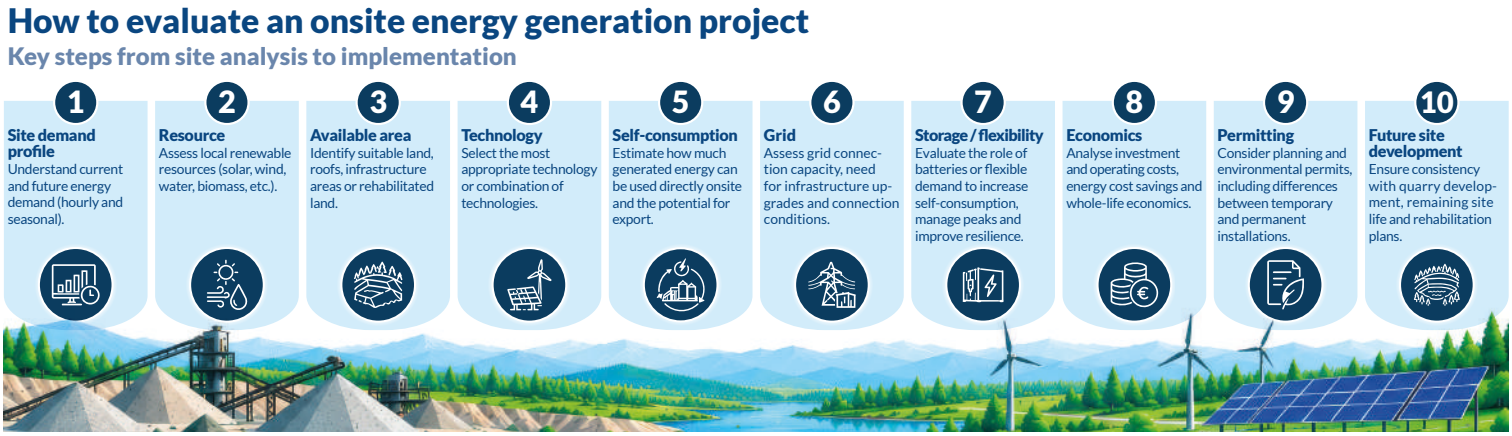


FIGURE 34. — How to evaluate an onsite generation project

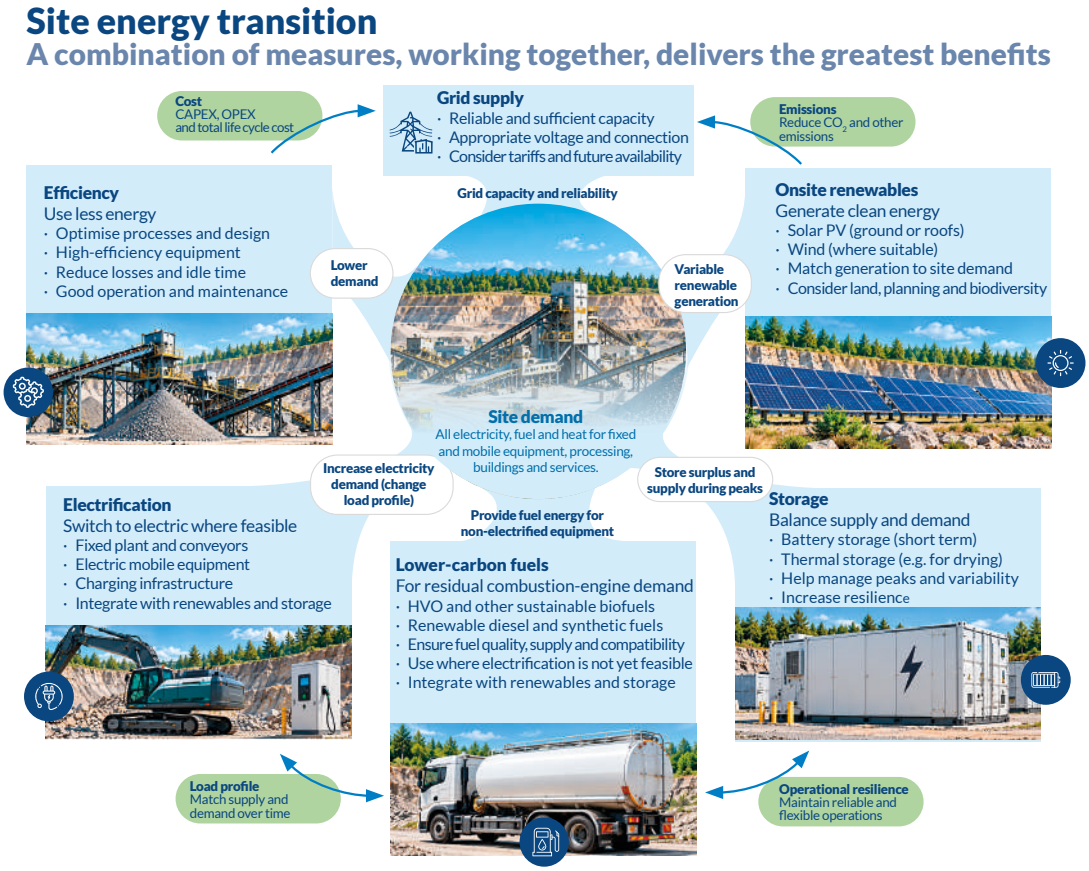


FIGURE 35. — Onsite energy transition options

14 Monitoring, digitalisation and energy economics

14.1 Measurement and digital support

14.1.1 Digitalisation and energy management

Digital technologies can improve energy performance by increasing the visibility, coordination and control of production.

Their value does not arise from digitalisation itself, but from their ability to support better decisions and control actions.

A useful hierarchy is:
Measurement → Communication → Contextualisation → Analysis → Decision → Control → Verification

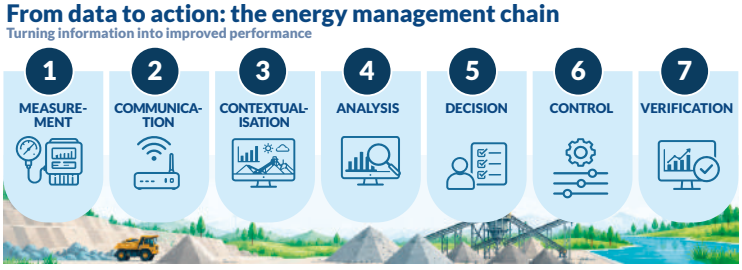


FIGURE 36. — From data to action: the energy management chain

Reliable measurement and process understanding should therefore precede advanced analytics.

14.1.1.1 Measurement and connected equipment

Modern equipment and sensors can provide data on:

- Electrical power and energy.
- Fuel consumption.
- Throughput.
- Operating hours and operating state.
- Load and speed.
- Pressure and flow.
- Temperature and vibration.
- Equipment location.
- Payload.

For energy management, data become particularly valuable when consumption can be associated with production, operating state and relevant process variables.

14.1.1.2 Plant control

Integrated plant-control systems can coordinate feeders, crushers, screens, conveyors, pumps, stockpiles and auxiliary equipment.

Appropriate control can reduce:

- Empty running.
- Excessive recirculation.
- Unstable feed.
- Poor equipment coordination.
- Unnecessary starting and stopping.
- Operation outside appropriate process conditions.

Automation must preserve safe operating logic and appropriate human supervision and intervention.

14.1.1.3 Production measurement

Reliable production measurement is essential for specific-energy indicators.

Relevant systems may include:

- Belt weighers.
- Weigh feeders.

- Onboard payload systems.
- Weighbridges.
- Other process weighing systems.

For an indicator such as kWh/t or l/t, the quality of the production measurement is as important as the quality of the energy measurement. Relevant measuring systems should therefore be maintained and calibrated appropriately.

14.1.1.4
Fleet management

Telematics and fleet-management systems can combine location, payload, cycle time, queueing, idle time, speed, fuel or electricity consumption and equipment condition.

These data can help identify:
- Excessive queueing.
- Unnecessary travel.
- Underloading.
- Poor dispatch.
- Excessive idling.
- Inefficient haul-route segments.

The objective should be optimisation of the complete load-and-haul system rather than isolated vehicle performance.

14.1.1.5
Digital maintenance

Maintenance-management and condition-monitoring systems can combine equipment history, work orders, inspections, condition data and energy-performance trends.

Depending on equipment criticality, deterioration may be detected through vibration, temperature, oil condition, electrical signals, pressure, flow or other performance variables.

Energy consumption can itself be a useful condition indicator when interpreted against production and relevant operating variables.

14.1.1.6
Advanced analytics and artificial intelligence

Advanced analytics and machine-learning techniques may be useful where sufficient reliable data and process understanding exist.

Potential applications include:
- Anomaly detection.
- Predictive maintenance.
- Process optimisation.
- Crusher and plant control.
- Fleet dispatch.
- Production forecasting.
- Energy forecasting.

However:
- Advanced analytics cannot compensate for poor instrumentation or unreliable data.
- Engineering judgement, data validation, process constraints and appropriate human oversight remain essential.

14.1.1.7
Process simulation and digital models

Process models and simulation can support equipment selection, bottleneck analysis, plant modifications, quarry development and optimisation scenarios.

The complexity of the model should be proportionate to the decision being made. A complete digital twin is not required for every energy-efficiency study.

14.1.1.8
Drones and geographic information systems

Drones, surveying technologies and GIS can support:
- topographic surveys.
- stockpile measurement.
- haul-road analysis.
- distance and elevation calculations.
- terrain modelling.
- progress surveys.
- rehabilitation monitoring.

These tools can help quantify changes in haul distance, gradient, quarry geometry and infrastructure layout and incorporate them into transport and production optimisation.

14.1.1.9 Data quality and cybersecurity

Connected operational systems require appropriate management of:

- Cybersecurity.
- Access control.
- Data ownership.
- Backups.
- System resilience.
- Sensor calibration.
- Data quality.

Digitalisation should therefore be implemented for a defined operational purpose.

- Measure what matters, convert measurements into decisions, and verify that those decisions improve performance.
- Measurement creates value only when it leads to understanding, action and verified improvement.

Energy digitalisation hierarchy

From data to decision, for real and lasting impact

Higher maturity

Greater value

More complexity

Higher capability requirements

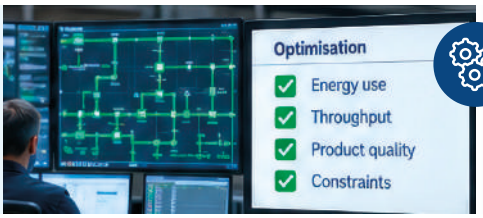
Foundation

5 Predict and simulate
Use data and models to anticipate future conditions and test options.
- Predict energy demand and variability
- Simulate process and energy scenarios
- Support investment and planning decisions



Anticipate and plan for a more resilient and efficient future.

4 Optimise control
Use advanced control and optimisation to minimise energy use while meeting operational objectives.
- Advanced process control (APC)
- Real-time optimisation
- Integrate energy and process constraints



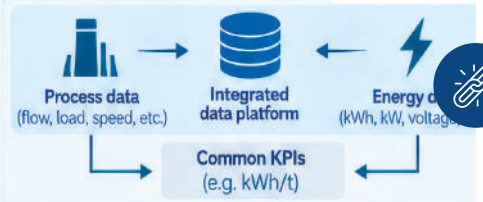
Run the plant at optimum conditions.

3 Diagnose deviations
Identify and understand abnormal energy use and performance losses.
- Monitor KPIs and set alerts
- Analyse trends and root causes
- Quantify losses and opportunities



Find and fix problems.

2 Connect energy and production
Integrate energy data with production, process and operational data.
- Combine data from multiple sources
- Use a common time base and indicators
- Visualise relationships (e.g. kWh/t, kWh/m*)



See the bigger picture.

1 Measure reliably
Install and maintain accurate and robust energy metering.
- Meter key equipment and processes
- Ensure data quality and reliability
- Establish data management and governance



Good decisions start with good data.

Better data do not automatically create better performance.
Data must be accurate, relevant, well used and combined with people, processes and the right technology to deliver real improvements.

Turn data into action.
Digital tools are a means to a more efficient, resilient and sustainable operation.

FIGURE 37. — Energy digitalisation hierarchy

14.2 Energy audits

14.2.1 Energy audits

An energy audit is a systematic assessment of how energy enters, is distributed and is consumed within an operation and of the opportunities available to improve energy performance.

It should establish:

- Where energy is consumed.
- How much is consumed.
- What useful production or service is obtained.
- Which variables influence consumption.
- Where avoidable losses or inefficient operation occur.
- Which improvements are technically feasible.
- Whether those improvements are economically justified.

The audit should cover all Significant Energy Uses within the defined boundary and should consider both electricity and fuels where applicable.

14.2.1.1 Information collection and audit boundary

Before detailed field measurements, sufficient information should be collected to understand the operation and establish an initial energy balance.

Relevant information may include:

- Electricity invoices and interval data.
- Fuel purchasing and dispensing records.
- Production records.
- Operating hours.
- Equipment inventories.
- Rated powers and performance data.
- Electrical single-line diagrams.
- Process flowsheets.
- Quarry plans.
- Haul distances and elevation changes.
- Pumping and compressed-air information.
- Maintenance records.
- Shift patterns.
- Historical energy and production data.

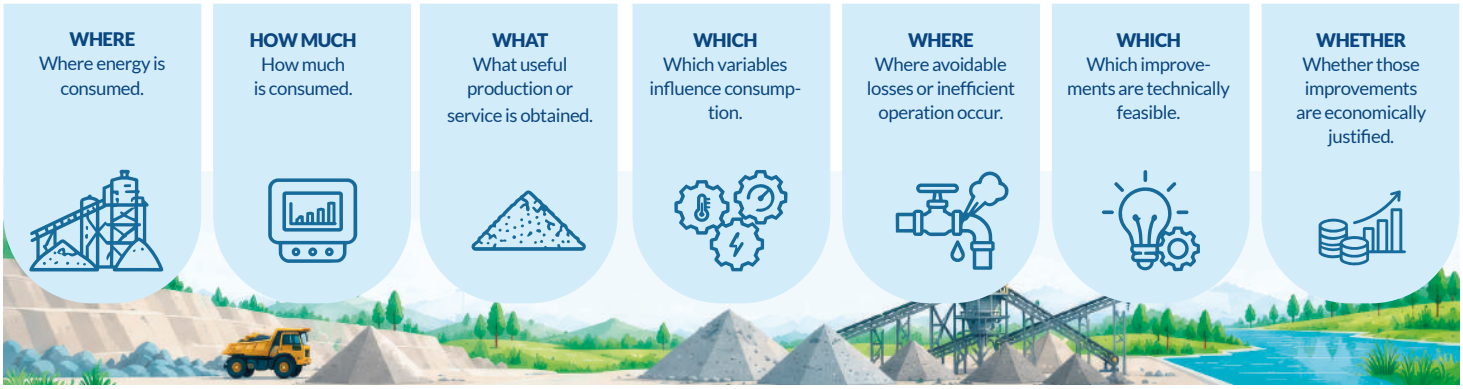


FIGURE 38. — Energy audits: Key questions

The objective is not simply to inventory equipment or estimate annual consumption. It is to relate energy to production and relevant operating variables.

The analysis period should be sufficiently representative to identify relevant changes in production, geology, haul distance, product mix, weather or other significant variables.

The energy-accounting boundary must be explicitly defined. Energy purchases should not automatically be attributed to individual processes without considering mobile equipment, subcontracted activities, stock changes, external uses and other relevant boundary effects.

14.2.1.2
Measurement

Measurement effort should be prioritised according to Significant Energy Uses and the information required to evaluate them.

For electrical systems, measurements may include:

- Voltage.
- Current.
- Active power.
- Reactive power.
- Apparent power.
- Power factor.
- Energy.
- Demand.
- Harmonics.
- Voltage unbalance.
- Operating time.

Portable power analysers can support temporary measurement campaigns, while permanent submetering may be justified for important loads requiring continuous monitoring.

Instantaneous current alone is generally insufficient to characterise a variable electrical process.

For mobile equipment, useful data may include fuel or electricity consumption, operating hours, idle time, payload, distance, cycle time and production.

Energy measurements should be combined with relevant process measurements such as:

- Tonnes processed.
- Flow and pressure.
- Crusher settings.
- Recirculating load.
- Moisture.
- Pump head.
- Conveyor load.
- Equipment speed.
- Vehicle payload.
- Haul distance.
- Elevation change.

Other techniques - including thermography, vibration, temperature, combustion analysis, leak detection or flow measurement - may be used where relevant to the Significant Energy Use being investigated.

Instrumentation should have accuracy and calibration appropriate to the intended analysis.

14.2.1.3
Energy balance

A principal audit output should be an energy balance allocating total energy input, as far as reasonably practicable, among Significant Energy Uses identified through the energy review.

Total site energy in hard rock and sand and gravel quarries = land preparation + direct excavation (where applicable) + drilling (where applicable) + blasting (where applicable) + loading + haulage + processing (feeding, crushing, milling, screening, and conveying) + washing and classification (where applicable) + thermal drying for specialised products (where applicable) + storage + product loading and dispatch + ancillary facilities (Offices • Laboratories • Workshops • Support services) + site rehabilitation.

The actual distribution must be established from site data. Historic or generic fuel/electricity percentages should not be imposed on individual operations.



FIGURE 39. — Energy balance in aggregates production

14.2.1.4

Energy Performance Indicators (EnPIs)

Absolute energy consumption alone is rarely sufficient to assess performance.

Appropriate Energy Performance Indicators – EnPIs may include:

- kWh/t processed.
- kWh/t saleable product.
- l/t transported.
- kWh/t transported.
- l/t·km.
- kWh/t·km.
- kWh/m^3 pumped.
- Compressor specific energy.
- Energy per operating hour.
- Idle-energy indicators.

Financial indicators such as energy cost per tonne may also be useful but should remain distinct from physical energy-performance indicators.

Where relevant variables change materially, performance should be normalised for factors such as:

- Production.
- Haul distance.
- Elevation.
- Material characteristics.
- Moisture.
- Product specification.
- Weather.

A power measurement becomes substantially more informative when combined with production: i.e. 400 kW at 120 t/h = 3.33 kWh/t

That value can then be interpreted against feed characteristics, product specification, settings, recirculating load and operating condition.

14.2.1.5

Identification and assessment of opportunities

Potential measures should be evaluated in terms of:

- Baseline energy use.
- Expected energy saving.
- Investment.
- Operating and maintenance implications.
- Useful life.
- Production impact.
- Reliability.
- Emissions implications.
- Implementation constraints.

Opportunities should be prioritised using the improvement hierarchy established in Section 12.1.

Simple payback may be useful for preliminary screening, but significant investments should

be evaluated using appropriate life cycle economic methods such as net present value, internal rate of return, discounted payback or life cycle cost.

14.2.1.6
Verification and continuous improvement

Implementation alone does not demonstrate an energy saving.

Performance should subsequently be compared with an appropriate baseline using measured energy, production and relevant-variable data.

The improvement cycle is therefore:
Measure → Analyse → Improve → Verify → Standardise → Monitor

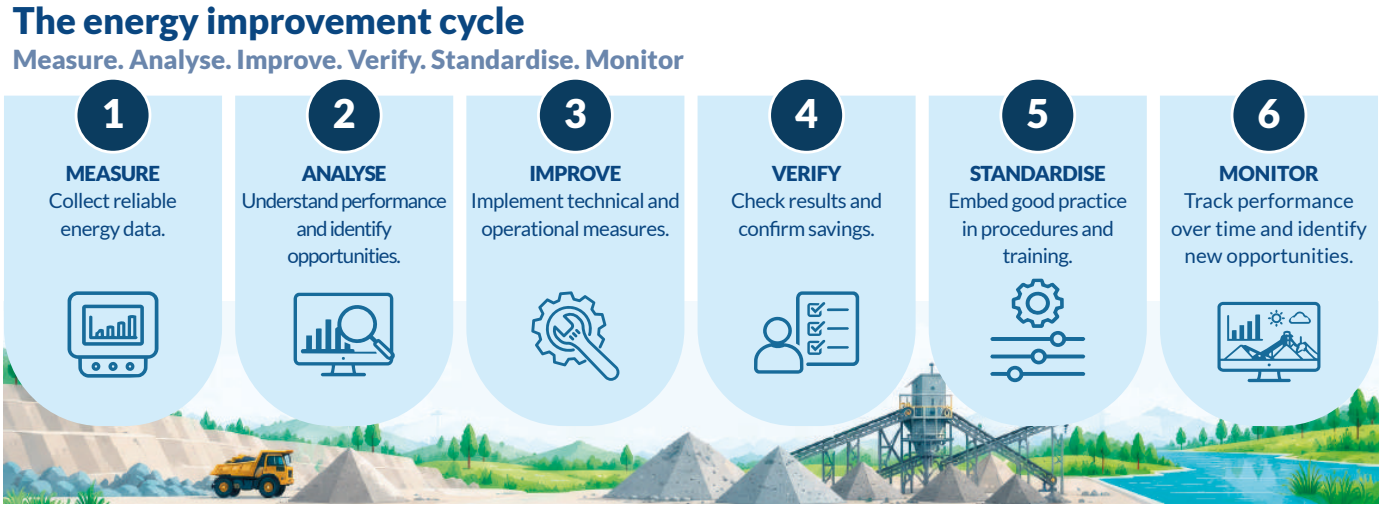


FIGURE 40. — Energy improvement cycle

Where operating conditions change significantly, the baseline or normalisation method should be reviewed so that the comparison remains meaningful.

Energy auditing should therefore form part of a continuous energy-management process rather than being treated solely as a periodic inspection.

14.3
Energy economics and investment

Energy performance is physical; energy cost is economic. They are related, but they should not be confused. A fall in expenditure may result from lower energy prices rather than better efficiency, while expenditure may rise even when kWh/t or l/t improves.

For management purposes, distinguish energy consumption, energy performance, unit price, total energy cost and energy-price risk. Where practical, both physical consumption and expenditure should be related to saleable production.

14.3.1
Investment evaluation

No- and low-cost operational measures can often be assessed directly from verified savings.

Significant investments should be evaluated over their life cycle because purchase price may represent only a small part of lifetime cost for heavily used equipment.

- Initial investment and installation.
- Energy consumption and expected price exposure.
- Maintenance, consumables and downtime.
- Production, reliability and product-quality effects.
- Equipment life and residual value.
- Emissions implications where financially relevant.

Simple payback can be useful for preliminary screening. For material investments, discounted methods such as Net Present Value, Internal Rate of Return or Life Cycle Cost provide a more complete basis for comparison. Scenario analysis should be used when electricity prices, fuel prices, production, capital cost or expected savings are uncertain.

14.3.2 Electrification and renewable electricity

Electrification changes the site cost structure rather than removing energy-price exposure. Grid capacity, maximum demand, charging profile and connection charges may become more important. Onsite renewable generation can reduce electricity purchases and exposure to future price volatility when generation is well matched to site demand. Storage should be justified by the service it provides—such as peak management, charging support, resilience or renewable integration—rather than treated as an energy source.

14.4 Electricity costs and energy procurement

14.4.1 Managing consumption and managing cost

Improving physical energy performance and reducing energy expenditure are closely related, but they are not the same. An aggregates site may reduce its electricity bill without reducing its energy consumption — for example, by changing its supply contract, shifting demand to lower-cost periods or avoiding charges associated with peak demand or reactive energy. Conversely, an improvement that reduces kWh/t may not immediately produce an equivalent reduction in the electricity bill.

Good energy management should therefore address both dimensions: how much electricity the site uses and how efficiently it uses it, and how that electricity is purchased, supplied and charged. Physical energy performance should remain the primary reference for assessing efficiency improvements, while procurement and tariff management should be used to optimise the economic value of those improvements.

14.4.2 Understanding the electricity bill

Electricity bills can contain several cost components in addition to the electricity consumed. Their structure varies between countries, network areas, suppliers and contractual arrangements, but may include:

- Energy consumed (kWh or MWh).
- Contracted capacity or power and, where applicable, maximum-demand charges.
- Transmission and distribution network charges.
- Time-dependent or tariff-period charges.
- Reactive-energy or power-factor charges, where applicable.
- Taxes, levies and other regulated charges.
- Supplier margins and other contractual components.

Sites should periodically reconcile invoices with metered consumption, operating hours and production data. Unexpected changes in the bill can reveal not only contractual issues but also changes in operating conditions, demand peaks, deteriorating power factor or abnormal consumption.

14.4.3 Contracted capacity and peak demand

The required electrical capacity should reflect the site's actual and foreseeable load profile. Excessive contracted capacity can generate unnecessary fixed costs, while insufficient capacity can result in additional charges, operational constraints or inadequate resilience.

Peak demand deserves particular attention. Large motors starting simultaneously, crushers and screens operating under unstable conditions, pumping systems, workshops and increasingly

electric mobile-equipment charging can create significant coincident loads. Load scheduling, appropriate starting and control systems, storage and smart charging can help manage peaks without compromising production.

Electrification strategies should therefore consider not only annual electricity consumption, but also when power is required, the magnitude and duration of peaks, and whether the grid connection and internal electrical infrastructure can accommodate them.

14.4.4
Tariff periods and load management

Where electricity prices or network charges vary by time period, some flexible loads may be shifted towards more favourable periods. Potential examples include water pumping, battery charging, certain stockpile-related operations and other processes with sufficient operational flexibility.

However, shifting consumption should not be pursued at the expense of overall system efficiency. A lower electricity price does not justify creating additional handling, operating equipment inefficiently or disrupting an optimised production sequence.

The objective is not simply to use electricity when it is cheapest, but to combine efficient production with intelligent management of when electricity is required.

14.4.5
Reactive energy and power factor

Many items of quarry and processing equipment — particularly induction motors, transformers and other inductive loads — require reactive power in addition to active power. A poor power factor increases current for a given useful power demand and can increase electrical losses, voltage drop and the utilisation of transformers, cables and other network components. Depending on the applicable tariff structure, it may also generate additional charges.

Power factor should therefore be monitored, particularly at sites with substantial motor-driven loads. Where justified, power-factor correction, for example through appropriately designed capacitor banks or other compensation systems, can reduce reactive-power flows and improve utilisation of the electrical infrastructure.

Correction systems must nevertheless be properly engineered. Harmonics, variable-speed drives, changing load profiles and the risk of overcompensation should be considered rather than treating capacitor installation as an automatic energy-saving measure.

Importantly, power-factor correction primarily improves the electrical system and may reduce losses and charges; it should not automatically be reported as an equivalent reduction in the useful energy required by the production process.

14.4.6
Electricity procurement and contractual strategy

Energy procurement should be aligned with the site's consumption profile, risk tolerance and expected evolution of demand. Depending on market and national conditions, supply arrangements may include fixed-price, indexed or hybrid contracts, as well as longer-term instruments such as Power Purchase Agreements (PPAs).

Price should not be the only criterion. Contract duration, indexation, volume flexibility, load profile, guarantees, imbalance exposure, renewable-energy attributes, termination provisions and counterparty risk may all affect the real value of an electricity contract.

Future changes should also be anticipated. Electrification of mobile equipment, additional pro-

cessing capacity, renewable generation, battery storage or changes in production patterns can substantially modify the load profile and therefore the most appropriate contractual strategy.

Onsite generation, storage and procurement should be considered together. A site combining grid electricity, photovoltaic or other renewable generation, storage and flexible demand may progressively move from being a passive electricity consumer towards actively managing when electricity is generated, purchased, stored and consumed.

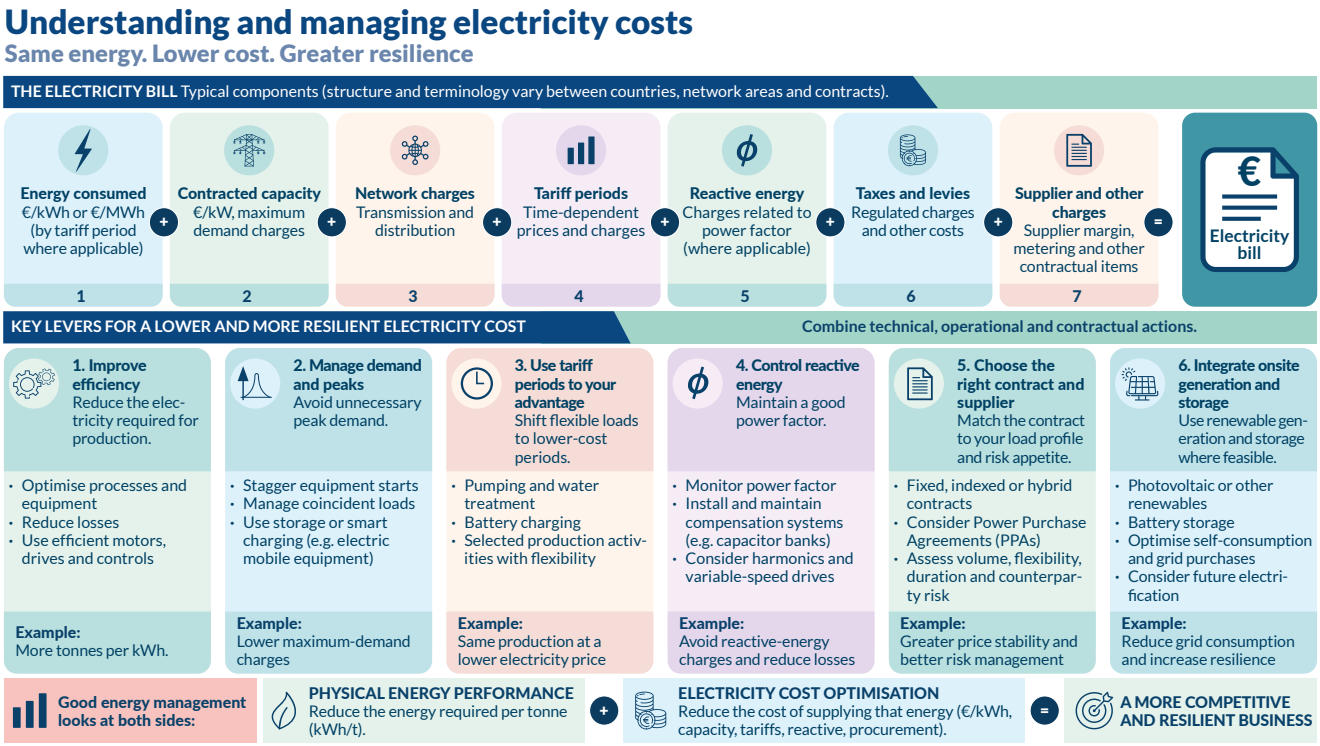


FIGURE 41. — Understanding and managing energy costs

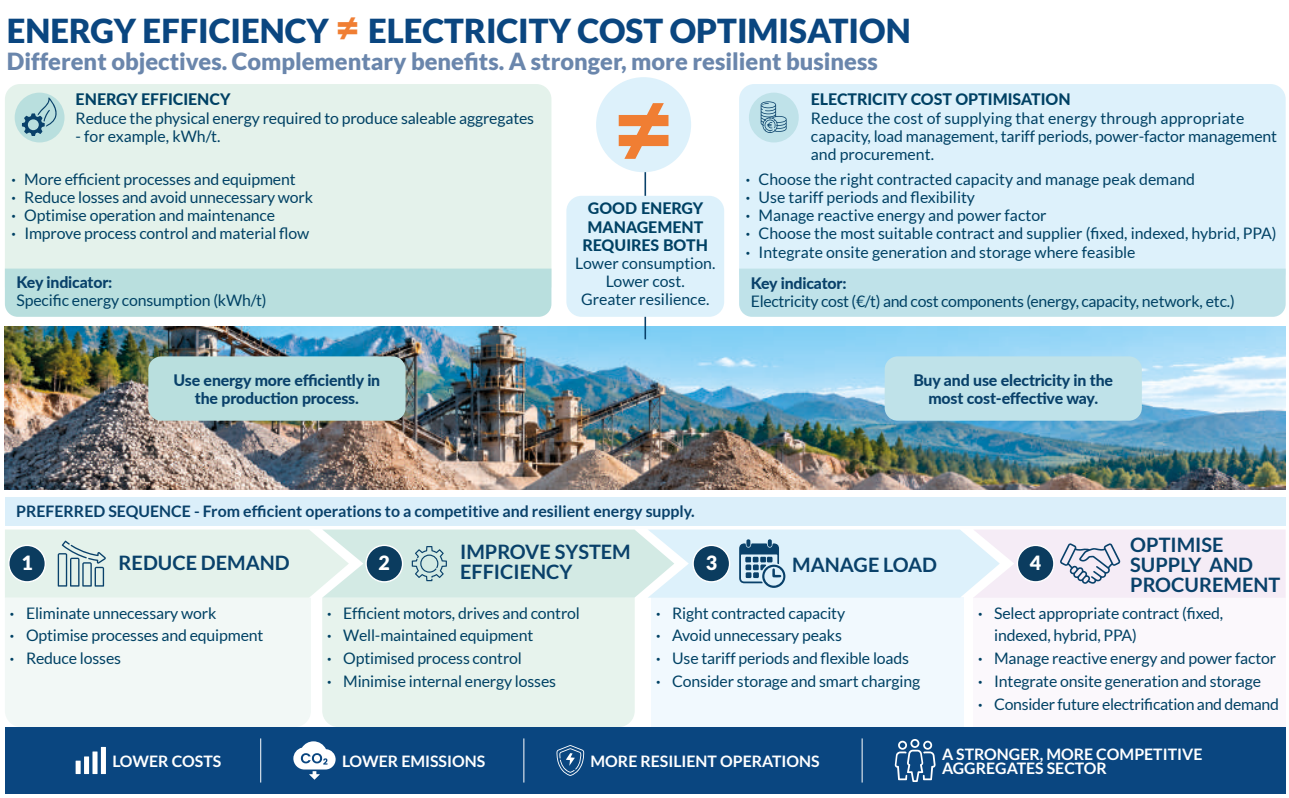


FIGURE 42. — Energy efficiency vs electricity costs optimisation

14.5 Core management scorecard

A concise management scorecard is preferable to a large set of indicators that are not used for decisions. Physical EnPIs should normally be reviewed before economic KPIs.

- Whole site: kWh/t or MJ/t of saleable product.
- Electric processing: kWh/t processed and kWh/t saleable product.
- Mobile equipment: l/t or kWh/t; haulage l/t·km or kWh/t·km where distance changes.
- Pumping: kWh/m³ together with flow and head.
- Economics: €/t saleable product and verified savings from implemented actions.
- Renewables: MWh generated and self-consumption ratio.
- Carbon: kg CO_2e/t where carbon performance is within the management scope.

For secondary-material processing:

- kWh/t incoming material and kWh/t saleable aggregate, together with material recovery or saleable-yield %.

Indicators should be normalised where relevant variables—such as haul distance, elevation, material characteristics, product mix, moisture or weather—change sufficiently to obscure underlying performance.

For recycled and manufactured/artificial aggregates, feed composition, moisture, contamination, required sorting and saleable yield may be relevant variables for interpreting energy performance.

Use the scorecard to connect physical performance with its economic significance.

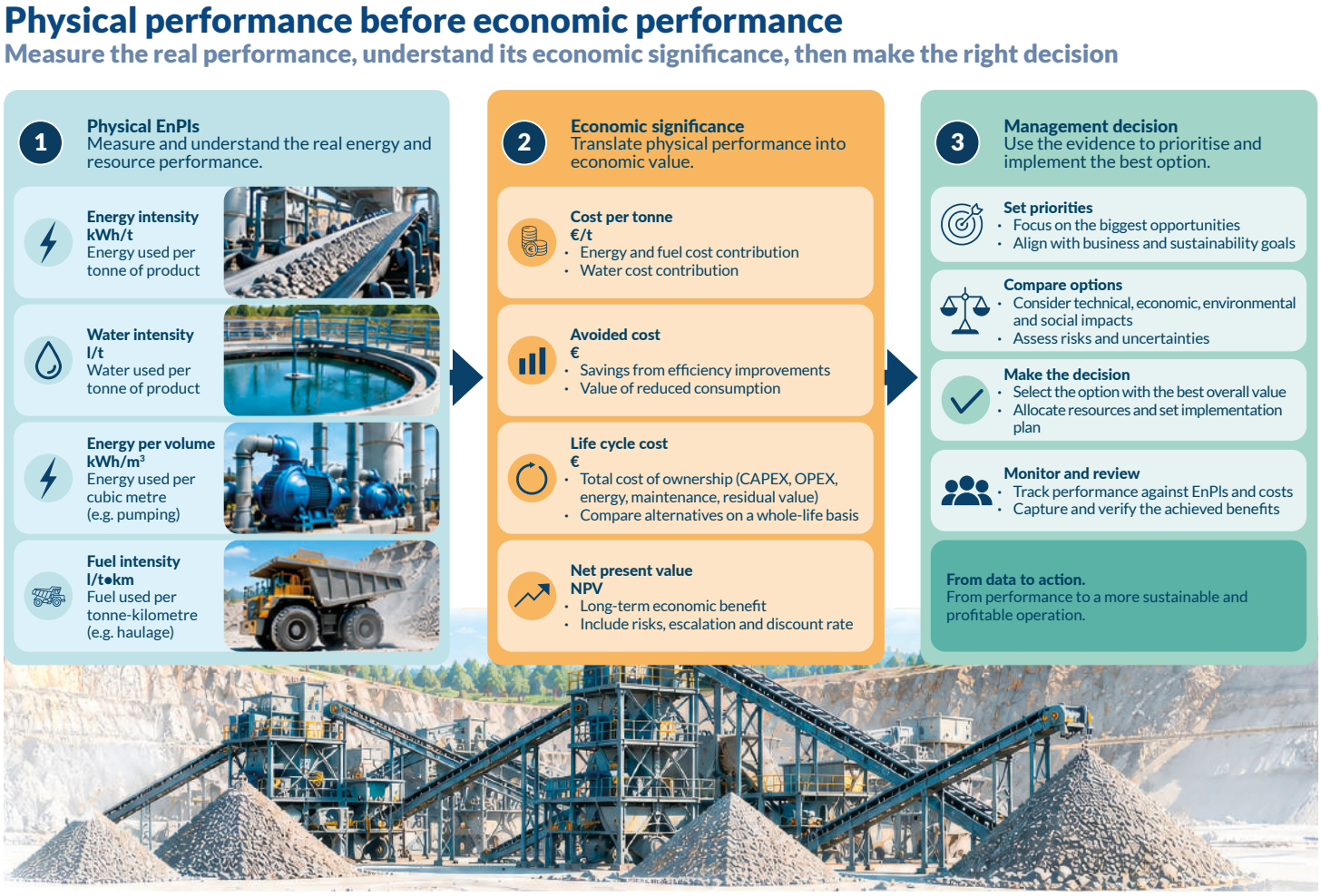


FIGURE 43. — Physical performance before economic performance

15 Managing energy systematically

Persistent improvement requires energy to be integrated into normal quarry management rather than treated as a sequence of isolated efficiency projects. An Energy Management System (EnMS) provides the framework to understand energy use, prioritise Significant Energy Uses, establish indicators and baselines, implement actions and verify improvement.

ISO 50001 is the principal international reference. It is technology-neutral and follows the Plan–Do–Check–Act logic. Certification and implementation are separate concepts: an organisation can use the management framework without voluntary certification unless certification is required by legislation or another applicable commitment.

An EnMS should manage the relationship between energy, production and decisions—not documentation for its own sake.

15.1 The practical management cycle

- PLAN — establish the energy review, identify Significant Energy Uses, relevant variables, EnPIs, baselines, objectives and action plans.
- DO — provide competence and resources, apply operational controls, maintain equipment and integrate energy into design and procurement.
- CHECK — monitor energy and production, evaluate EnPIs, verify improvements and audit the management system.
- ACT — correct deviations, review priorities, allocate resources and update the programme.

EnMS practical management cycle

Plan. Do. Check. Act. Manage energy for lasting results

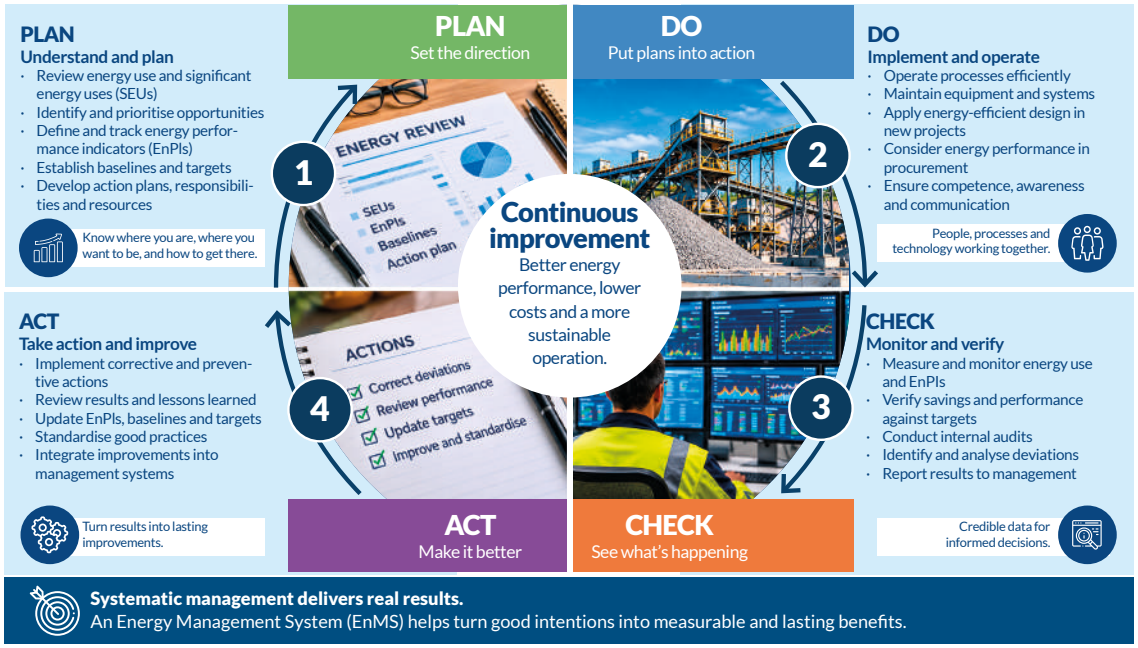


FIGURE 44. — EnMS practical management cycle

15.2 Energy review, SEUs, EnPIs and baselines

The energy review should establish where energy is used, what variables influence it and where improvement potential is significant. Significant Energy Uses must be identified from actual site information rather than generic sector assumptions.

An EnPI should reflect the process duty. Examples include kWh/t for processing, l/t or kWh/t for loading, l/t·km for haulage and kWh/m³ for pumping. An Energy Baseline provides the reference against which change is evaluated. Where operating conditions change materially, the baseline or indicator should be normalised so that comparisons remain meaningful.

15.3 Action plans and verification

For each priority improvement, define responsibility, resources, timetable, expected improvement, the EnPIs to be used and the verification method. Implementation alone does not demonstrate an energy saving: the result must be compared with an appropriate baseline under comparable or normalised conditions.

15.4 Energy audit and EnMS internal audit

An energy audit and an EnMS internal audit have different purposes. The energy audit asks where and why energy is consumed and what can be improved. The internal EnMS audit asks whether the management system is appropriately implemented, maintained and effective. The two are complementary, not interchangeable.

15.5 A practical implementation roadmap

1. Define scope, boundaries, responsibilities and resources.
2. Collect energy, production and relevant operational data.
3. Prepare the site energy balance and identify Significant Energy Uses.
4. Establish EnPIs, relevant variables and Energy Baselines.
5. Prioritise opportunities using the Guide hierarchy: avoid work → simplify flow → optimise operation → improve control → upgrade equipment.
6. Set objectives and action plans with responsibilities and verification methods.
7. Integrate energy into operation, maintenance, quarry planning, procurement and investment.
8. Measure and verify results.
9. Review performance through internal audit and management review.
10. Update the energy review as quarry conditions, equipment and energy supply change.

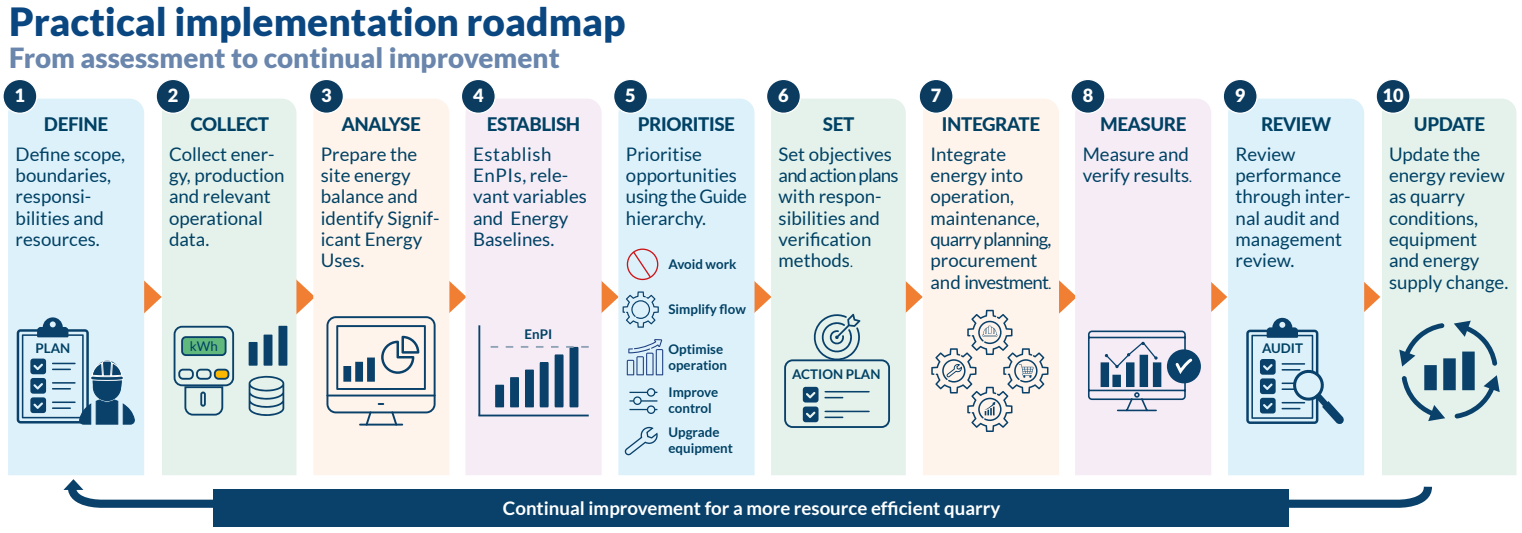


FIGURE 45. — Practical implementation roadmap

15.6 EU energy-management requirements

The EU Energy Efficiency Directive establishes enterprise-level energy-management and energy-audit obligations based on average annual energy consumption over the previous three years, taking all energy carriers together. Aggregates companies should determine the applicable enterprise boundary, verify the thresholds and deadlines in the current national transposition, and distinguish enterprise obligations from site-level energy-management practice.



FIGURE 46. — From energy data to continual improvement

16 People and environmental co-benefits

16.1 Environmental interactions

Reducing unnecessary energy demand often reduces operating cost and energy-related greenhouse-gas emissions, but energy efficiency should not automatically be equated with environmental improvement. Measures can affect water use, material recovery, waste, land use, noise, air emissions or other environmental aspects. The objective is therefore to improve energy performance within the wider requirements for safety, product quality and environmental performance.

Sectoral EPD evidence confirms the strong relationship between energy use and the production-stage carbon footprint of aggregates. Energy management therefore provides a direct operational bridge between process efficiency and emissions reduction. The strongest measures are therefore those that reduce the physical energy requirement itself and can subsequently be combined with lower-carbon energy supply.

For recycled and manufactured/artificial aggregates, energy performance should also be considered alongside material recovery. Additional sorting or separation may consume energy while enabling metals or other materials to be recovered through higher-value recycling routes and increasing the recovery of usable mineral fractions. The lowest-energy process is therefore not automatically the best environmental option; the objective is to achieve the required material recovery and product quality with the minimum necessary energy demand.

Energy and carbon performance should remain distinct indicators. Lower l/t or kWh/t can reduce Scope 1 or Scope 2 emissions, but the carbon effect depends on the energy carrier and the applicable greenhouse-gas accounting method. Conversely, switching to lower-carbon electricity or fuel can reduce emissions without improving energy efficiency.

- Reduce unnecessary material movement and rehandling.
- Avoid over-crushing and unnecessary recirculation.
- Improve saleable yield and avoid processing material that will become reject.
- Optimise water circuits without transferring excessive demand to pumping or treatment.
- Use progressive rehabilitation to reduce avoidable material movement where appropriate.

Electrification and renewable energy should also be considered in system context. They can reduce onsite exhaust emissions and carbon intensity, but require infrastructure and may introduce other life cycle, land-use or operational considerations.

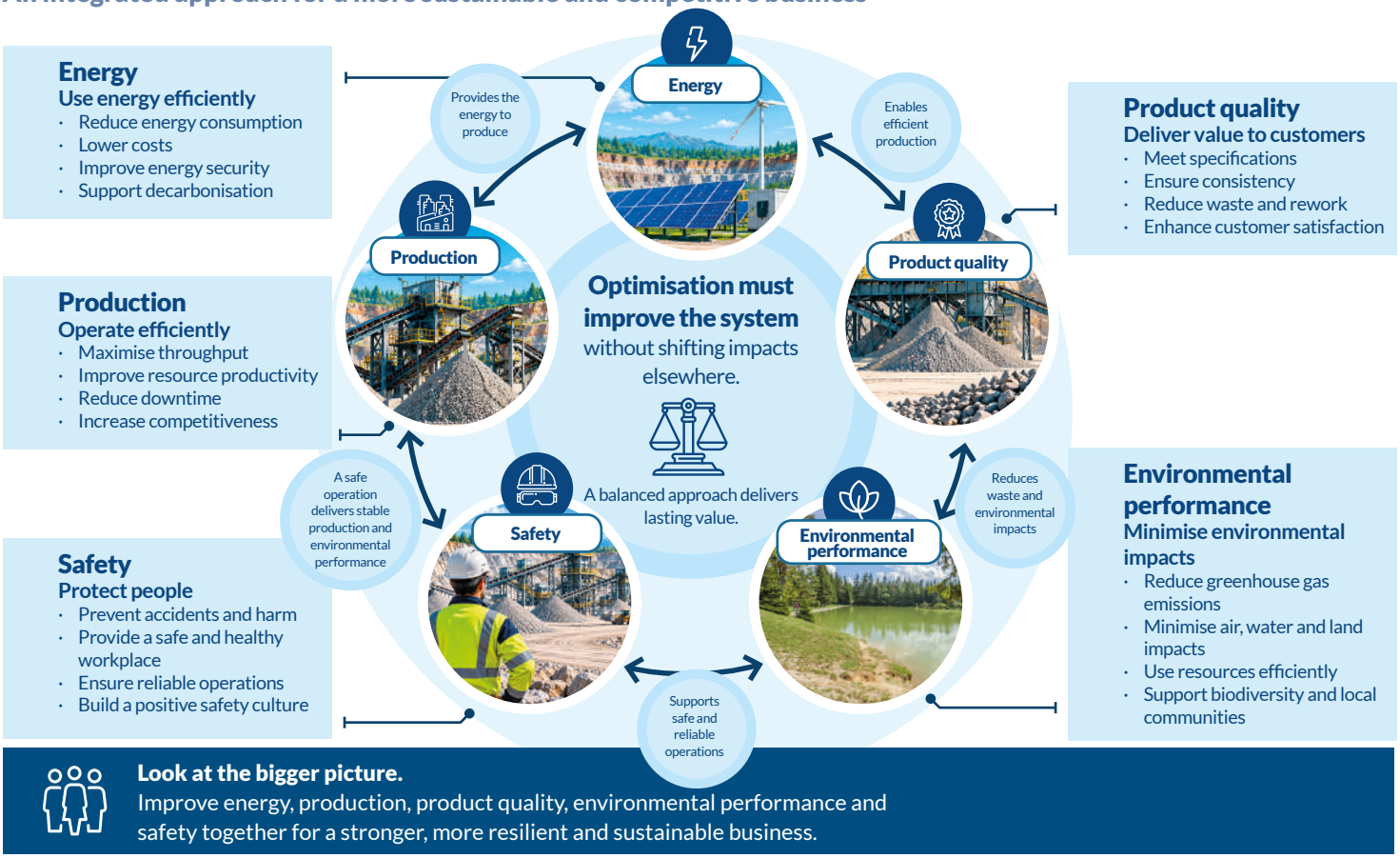


FIGURE 47. — Energy, production and environmental performance

16.2 People, competence and energy culture

Technology does not determine energy performance on its own. Operators, maintenance personnel, supervisors and managers make daily decisions that affect idling, payload, process stability, maintenance, material movement and control settings. Personnel whose work materially affects energy performance should therefore understand the variables they can influence, and the indicators used to evaluate them.

- Mobile-equipment operators: payload, positioning, idle management, operating modes and recognition of poor haul-road conditions.
- Plant operators: stable feed, sequencing, recirculation, empty running and interpretation of kWh/t alongside production.
- Maintenance personnel: condition, alignment, lubrication, leaks, wear and abnormal energy trends.
- Supervisors and managers: SEUs, EnPIs, baselines, action plans and the energy consequences of production decisions.

Worker participation is especially valuable because operating personnel often identify bottlenecks, leaks, abnormal vibration, road deterioration or unnecessary running before the issue appears in a monthly energy report. Reporting mechanisms should therefore be simple, and feedback should show whether

proposals were evaluated, implemented and verified.

Performance incentives should not reward low energy consumption in isolation. They should relate energy to useful work and preserve safety, product quality and production requirements. Management must also remove systemic inefficiencies; training cannot compensate indefinitely for persistent queues, poor roads, equipment mismatch or conflicting operating targets.

An effective energy culture exists when energy becomes a normal production variable alongside safety, quality, productivity, cost, maintenance and environmental performance.

Workers in the energy-management cycle

Everyday actions make a real difference



FIGURE 48. — Workers in the energy-management cycle

17 Recommendations and route to action

17.1 Route to action for an aggregates site

17.1.1
STEP 1 — MEASURE

Establish reliable energy and production data. Start with the significant flows; perfect sub-metering is not a prerequisite for action.

17.1.2
STEP 2 — IDENTIFY SIGNIFICANT USES

Determine which processes materially influence consumption and improvement potential.

17.1.3
STEP 3 — REMOVE AVOIDABLE WORK

Challenge rehandling, unnecessary haulage, excessive pumping, empty running, idling, over-crushing and recirculation.

17.1.4
STEP 4 — OPTIMISE THE PROCESS

Improve fragmentation, material flow, equipment matching, road condition, screening, control and maintenance.

17.1.5
STEP 5 — EVALUATE INVESTMENT

Assess equipment upgrades, conveyors, electrification, renewables and storage using system effects and life cycle economics.

17.1.6
STEP 6 — VERIFY

Compare results with an appropriate baseline using EnPIs and relevant variables.

17.1.7
STEP 7 — STANDARDISE AND REPEAT

Integrate successful measures into routine operation and update priorities as quarry conditions change.



FIGURE 49. — Route to action for aggregates sites

17.2 Recommendations for industry associations

Industry associations can accelerate improvement by creating common tools, transferring verified experience and representing sector needs. Priority actions are:

- Provide practical sector guidance, templates and training;
- Share verified case studies and comparable performance methodologies;
- Support SMEs with measurement, energy-review and investment tools;
- Maintain dialogue with equipment suppliers, grid operators and energy providers;
- Provide evidence-based input to European and national policies.
- Use available sectoral EPD evidence to communicate the central role of energy management in reducing the production-stage carbon footprint of aggregates.

17.3 Recommendations for companies and operations

Companies should manage energy as a production variable and apply the hierarchy established throughout this Guide:

- Measure energy together with production and relevant variables.
- Treat energy management as a primary production-stage decarbonisation lever: sectoral EPD evidence indicates that fuel and electricity use account for approximately four-fifths of cradle-to-gate GWP in the reference aggregates dataset.
- Identify Significant Energy Uses and establish a small set of meaningful EnPIs.

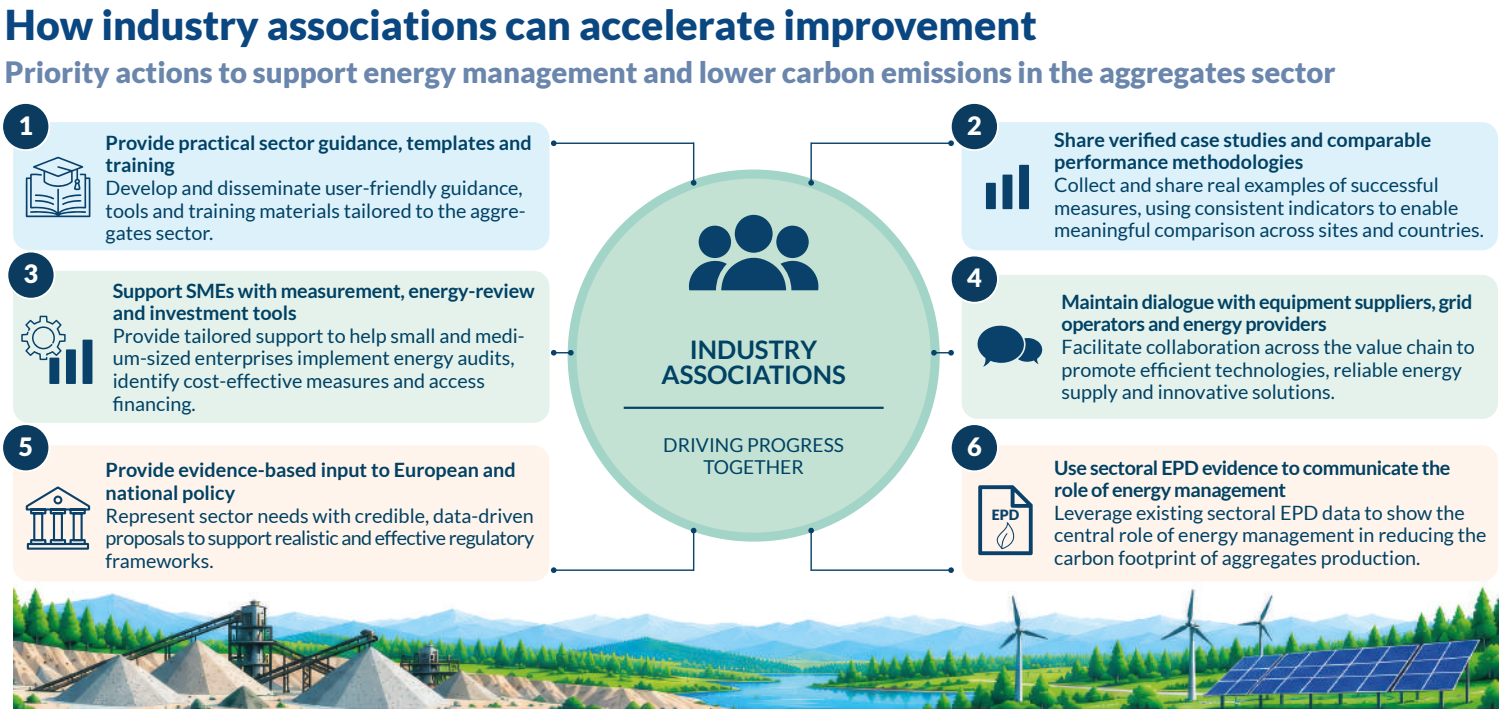


FIGURE 50. — How industry associations can accelerate improvement

- Reduce unnecessary physical work before investing in equipment efficiency.
- Optimise operating practice, maintenance, equipment matching and control.
- Include energy performance and life cycle cost in procurement and design.
- Electrify and integrate lower-carbon energy where technically and economically appropriate.
- Involve personnel and verify that implemented actions deliver measurable improvement.
- Use an EnMS or equivalent management cycle to make improvement continual.
- Integrate secondary materials into energy management. Where recycled or manufactured/artificial aggregates are produced, include reception, sorting, separation, processing and material recovery within the site energy review and establish appropriate EnPIs for the relevant production routes.

First optimise the process; then optimise the equipment and energy supply that serve it.

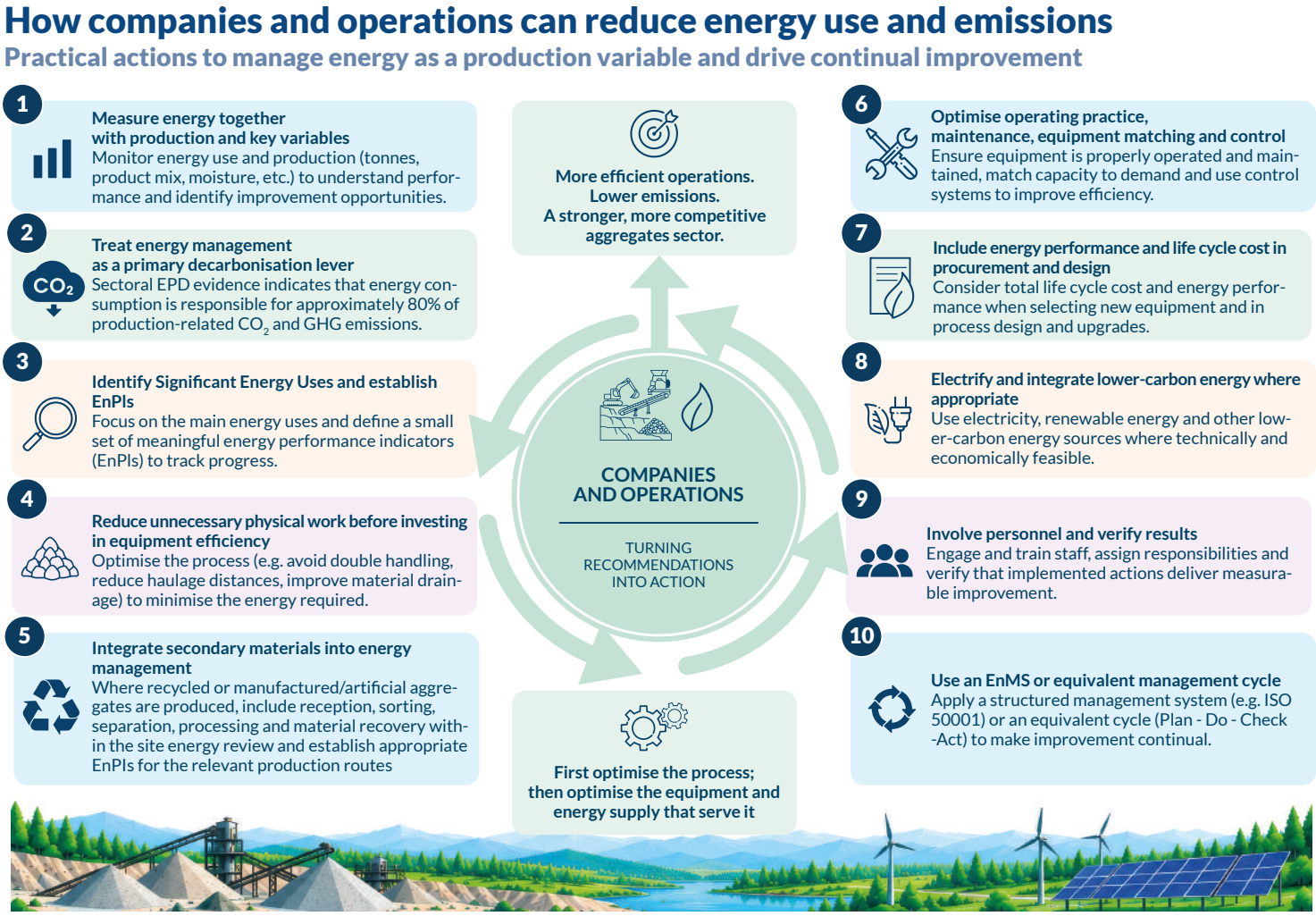


FIGURE 51. — How companies and operators can reduce energy use and emissions

17.4 Recommendations for equipment manufacturers and technology suppliers

Equipment manufacturers and technology suppliers have an important role in improving energy performance throughout the life of aggregates production systems. Their contribution extends beyond supplying more efficient individual machines: equipment selection, correct sizing, system integration, controls, commissioning, maintenance support, digitalisation and operator training can all materially influence the energy required to produce a tonne of saleable aggregate.

Priority actions are:

- Design equipment and systems for high energy performance under realistic aggregates-industry duty conditions, including part-load and variable operating conditions.
- Provide transparent and comparable energy-performance data, including efficiency curves, expected consumption, operating ranges and the assumptions underlying performance guarantees.
- Support correct equipment sizing and matching, considering interaction with upstream and downstream processes rather than optimising individual machines in isolation.
- Integrate measurement, control and digital capabilities that allow operators to monitor energy performance and identify inefficient operating conditions.

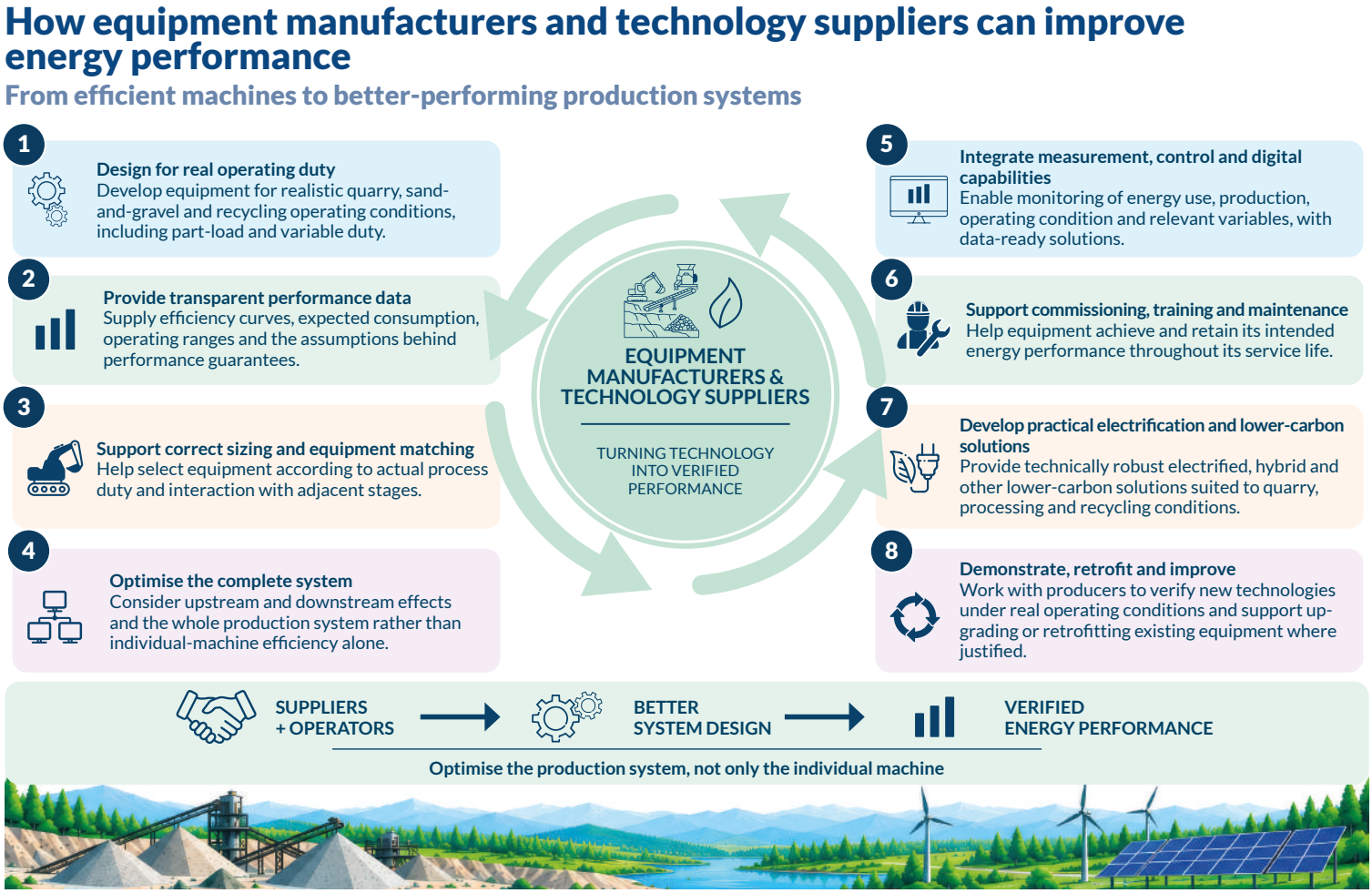


FIGURE 52. — Recommendations for equipment manufacturers and technology suppliers

- Support commissioning, operator training and maintenance practices that enable equipment to achieve and retain its intended energy performance throughout its service life.
- Develop practical electrification and lower-carbon solutions suited to the demanding operating conditions of quarries, sand and gravel sites and aggregates recycling facilities.
- Work with aggregates producers to demonstrate emerging technologies under real operating conditions and verify their energy, productivity, reliability and economic performance.
- Support equipment upgrading, retrofitting and interoperability where these can deliver cost-effective improvements without unnecessary premature replacement of existing assets.

As a shared objective, suppliers and operators should work together to optimise the production system, not simply the efficiency of individual machines.

17.5 Recommendations for policymakers

Policy can enable the sector's energy transition by recognising that quarry conditions, equipment duties and remaining site life vary substantially. Priority actions are:

- Enable timely access to adequate electricity-grid capacity and charging infrastructure.
- Maintain technology-neutral support focused on measurable performance.
- Recognise site-specific geology, haulage, product and infrastructure constraints.
- Support efficiency and demand reduction before subsidising additional energy supply.
- Recognise that energy efficiency and energy management are major emissions-reduction levers for aggregates production, as shown by sectoral EPD evidence.
- Facilitate investment in high-efficiency equipment, electrification, renewables, storage and monitoring.
- Keep administrative requirements proportionate and compatible with existing management systems.
- Provide skills, technical assistance and finance mechanisms accessible to SMEs.
- Support evidence-based pilot projects for heavy mobile equipment and other developing technologies.
- Align permitting with appropriate deployment of substations, charging, conveyors, renewable generation and storage within authorised sites.
- Support the development of efficient local networks for the recovery and processing of construction and demolition waste and suitable industrial mineral materials, recognising the potential synergies between existing aggregates sites and secondary-material processing infrastructure.

Shared objective: less energy per tonne, lower exposure to energy cost, lower emissions, higher operational efficiency and stronger competitiveness.

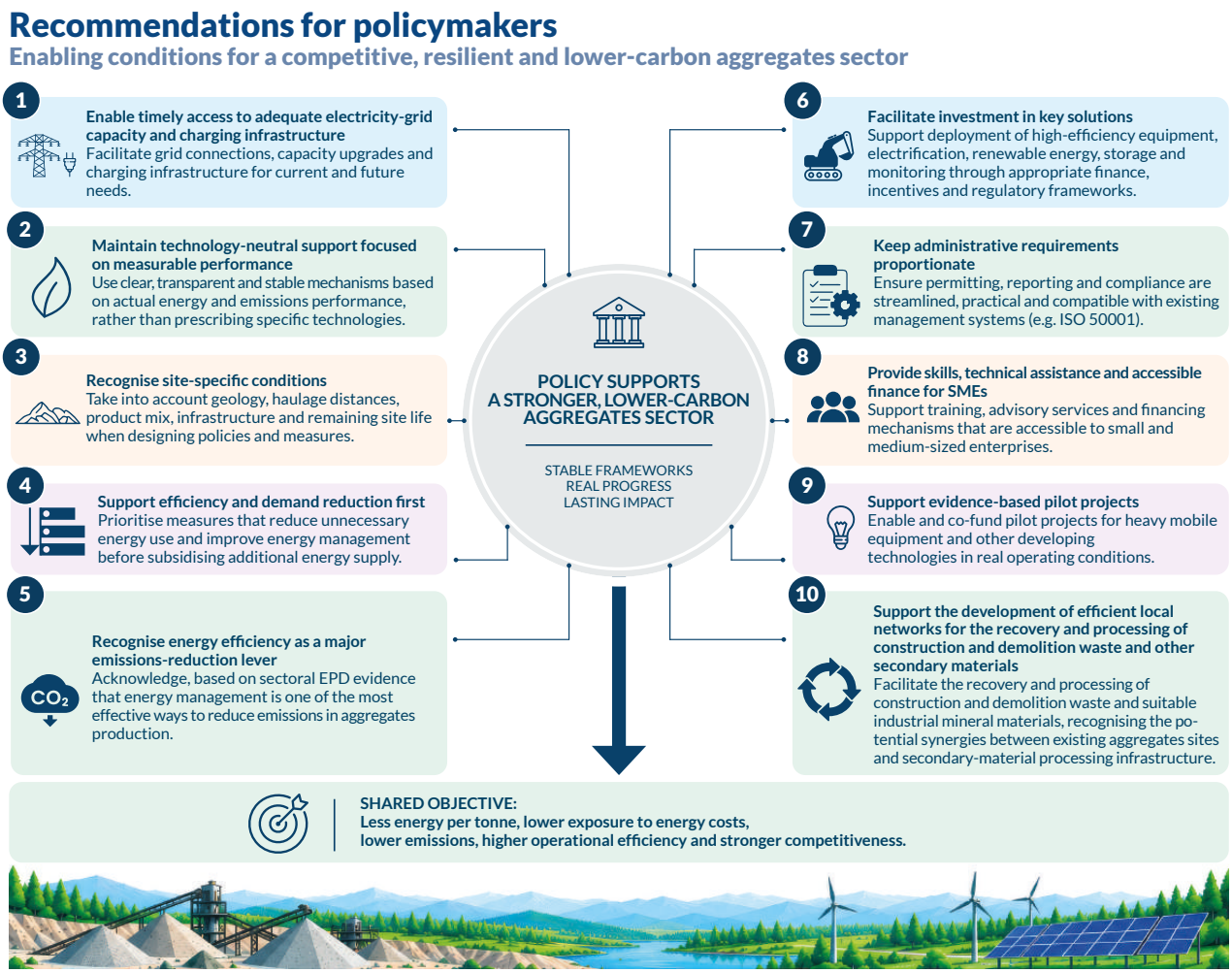


FIGURE 53. — Recommendations for policymakers

17.6 Enabling regulatory and policy conditions for the sector's energy transition

The following section presents policy conditions identified from an aggregates-sector perspective. Unlike the preceding technical guidance, these recommendations are addressed to policymakers and should not be interpreted as regulatory requirements for operators.

Improving energy performance requires action by operators, but the pace and economic feasibility of the transition are also strongly influenced by the regulatory, infrastructure and economic framework in which aggregates sites invest and operate. Grid capacity, permitting, taxation, access to finance, land-use rules, skills and the treatment of long-lived capital assets can either accelerate or delay technically sound energy improvements. Policy should therefore be technology-neutral, proportionate to the characteristics of each site and focused on measurable reductions in specific energy use, operating cost and greenhouse-gas emissions.

A coherent policy framework should combine investment support with enabling regulation. In particular, it should recognise the predominance of SMEs in the aggregates sector, the long operating life of extractive sites, the progressive movement of extraction faces and the fact that the optimum solution may differ substantially between a hard- rock quarry, a sand and gravel operation and a processing plant.

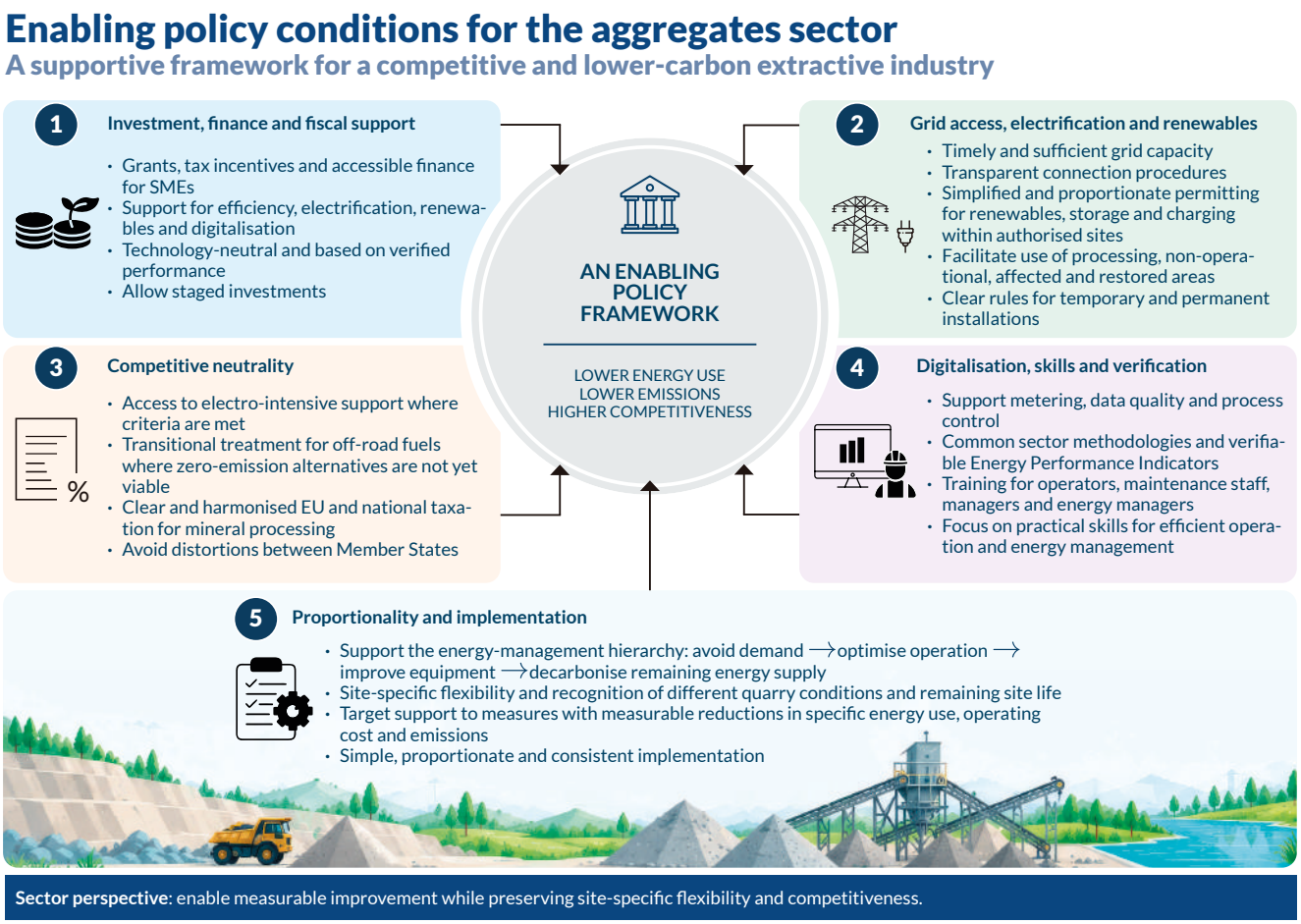


FIGURE 54. — Enabling policy conditions for the aggregates industry

17.6.1
Investment, finance and fiscal support

The sector would benefit from stable programmes of grants, investment support, tax incentives and accessible financing for verified energy-efficiency and decarbonisation projects.

Support should be accessible to SMEs and should allow staged investments rather than favouring only large projects. Eligibility should be based, as far as practicable, on verified energy and environmental performance rather than on prescribing a single technology.

Priority eligible measures should include:

- Improvements in energy efficiency throughout the different stages of extraction, internal transport and processing.
- Renewable-energy generation for self-consumption and, where appropriate, export to the grid, including photovoltaic, wind, sustainable biomass or biofuels, renewable hydrogen where technically justified, gravity-based solutions and other suitable technologies.
- Expert and industry 4.0 systems that monitor the energy consumed in each production stage and connect those data with production, process conditions and relevant variables in order to optimise specific energy consumption.
- Replacement of mobile equipment, motors and driven systems with lower-consumption, higher-efficiency, hybrid or electric alternatives where technically and economically appropriate.

- Replacement or modernisation of lighting systems where lighting represents a relevant load.

- Fleet-management, dispatch and telematics systems that reduce queueing, idling, empty running and inefficient routing.

- Upgrading and correct control of reactive-power compensation and other electrical-distribution measures, where justified by measurement and network conditions.

- Training of mobile-equipment operators in energy-efficient driving and operating practices.

- Improvement and maintenance of haul-road surfaces, drainage, gradients and access conditions to reduce rolling resistance and non-productive transport energy.

- Instrumentation, automation and control of processing plants, including reliable measurement of energy and production.

- Intelligent drilling and blast design so that fragmentation is matched to excavation, loading, haulage and primary-crusher requirements and optimises the quarry-to-crusher system rather than the blast in isolation.

- Selective treatment or pre-sorting at or close to the extraction face where it can avoid transporting and processing material that will subsequently become waste or reject.

- Replacement of discontinuous transport by continuous systems, such as conveyors, where the production rate, route, quarry development and life cycle economics justify the change.

- Mobile or in-situ refuelling systems, including appropriately designed fuel tankers, where these reduce non-productive travel by mobile equipment and comply with applicable safety and environmental requirements.

17.6.2 Grid access, electrification and renewable-energy permitting

Electrification can only progress at the pace allowed by electricity infrastructure. Timely electrification would be facilitated by transparent grid-connection procedures, realistic lead times and adequate capacity for industrial users progressively electrifying fixed and mobile processes. Permitting should facilitate substations, transformers, charging systems, storage and associated electrical infrastructure within authorised extractive sites, subject to the necessary safety and environmental controls.

Proportionate and streamlined permitting procedures could facilitate renewable-energy projects associated with authorised extractive sites, particularly where installations are compatible with existing operations, rehabilitation objectives and environmental conditions:

- Within the processing-plant or industrial area.

- In parts of the authorised site that have not yet been affected by extraction or are not expected to be affected.

- In areas already affected by extraction where renewable installations are compatible with safe operation and the approved development of the site.

- On restored areas, where the renewable use is compatible with the rehabilitation objectives and environmental conditions.

The regulatory framework should distinguish between temporary renewable installations, whose operating period is shorter than the remaining life of the extraction site, and per-

manent installations intended to remain after extraction has ceased. Temporary installations should be capable of using simplified procedures where their reversibility is demonstrated. For permanent installations, changes to rehabilitation plans and subsequent land use should be processed through clear and proportionate procedures rather than requiring the repetition of unrelated permitting steps.

European and national legislation should therefore facilitate amendments to rehabilitation plans and land-use conditions where these are necessary to integrate renewable generation, storage, charging infrastructure or other energy-transition assets, while preserving the environmental objectives and final land-use commitments of the site.

17.6.3
Taxation and competitive neutrality

The following issues are presented as sector policy considerations and remain subject to EU law, national legislation, State-aid rules and Member-State fiscal competence.

Energy taxation and industrial-support rules should avoid creating unjustified competitive disadvantages for extractive activities that supply essential construction raw materials. Three issues merit particular consideration:

- **Electro-intensive status**. European and national frameworks should allow aggregates extraction and processing activities that meet objective electricity-intensity and competitiveness criteria to access support mechanisms available to electro-intensive industries. Eligibility should depend on measured energy intensity and exposure rather than on categorical exclusion by sector label.

- **Transitional treatment of off-road fuels**. Where national systems provide reduced taxation or rebated diesel for qualifying primary-sector activities, policymakers should consider equivalent treatment for eligible off-road extractive machinery while technically and economically viable zero-emission alternatives remain unavailable. Any such measure should be designed as a transitional competitiveness instrument and should preserve incentives for efficiency, electrification and lower-carbon fuels.

- **Harmonised treatment under EU energy taxation**. The Energy Taxation Directive and its national implementation should provide clear and harmonised treatment of rock and mineral processing activities where these are comparable to mineralogical processes. Divergent national interpretations should be avoided, particularly where they create distortions in the internal market or unequal access to exemptions and reductions intended for energy-intensive mineral processing.

17.6.4
Digitalisation, skills and verification

Support mechanisms should recognise that digitalisation is an enabler rather than an end in itself. Funding should prioritise metering, data quality, production measurement, process control and interoperability before advanced analytics. Common sector methodologies for Energy Performance Indicators, normalisation and verification would make public support more robust by allowing projects to demonstrate measurable improvement under changing quarry conditions.

Training programmes should cover operators, maintenance personnel, quarry managers and energy managers. Publicly supported training in efficient driving, process optimisation, maintenance, electrical systems, digital monitoring and Energy Management Systems can deliver benefits across large numbers of SMEs at relatively low cost.

17.6.5
Proportionality and implementation

Regulation should support the hierarchy used throughout this Guide: first avoid unnecessary work and reduce the physical duty imposed on the production system; then optimise operation and maintenance; then improve control and equipment; and finally decarbonise the remaining energy supply. Aid schemes and regulatory incentives should not unintentionally favour additional energy supply over demand reduction or equipment replacement over system optimisation.

From the sector's perspective, an enabling framework would combine clear long-term decarbonisation objectives with site-specific flexibility, efficient permitting, adequate grid infrastructure, accessible finance and verifiable energy performance. Such an approach can reduce energy use and emissions while strengthening the competitiveness and resilience of a strategically important European raw-materials sector.

Annex A
Illustrative applications of energy-management principles

A.1
Purpose and scope

The following examples illustrate how the energy-management principles presented throughout this Guide may be applied to typical situations encountered at aggregates sites. They are intended to demonstrate the **reasoning process** behind energy-performance improvement: identify the physical and operational causes of energy use, measure the relevant variables, improve the production system and verify the resulting performance.

The examples are hypothetical. They do not describe specific companies or sites, and the results should not be interpreted as sector benchmarks or expected savings. Actual improvement potential depends on site geology, quarry development, production requirements, equipment, operating conditions, energy supply and other relevant variables.

The examples deliberately avoid assigning generic percentage savings. Energy-performance improvement should be demonstrated from site-specific measured data, using appropriate Energy Performance Indicators (EnPIs), Energy Baselines (EnBs) and relevant variables where necessary.

Together, the examples illustrate a recurring principle of this Guide:

Understand the work → measure performance → reduce unnecessary demand → optimise the system → verify the improvement.

Applying the Guide: four illustrative examples

Different operations, the same energy-management logic

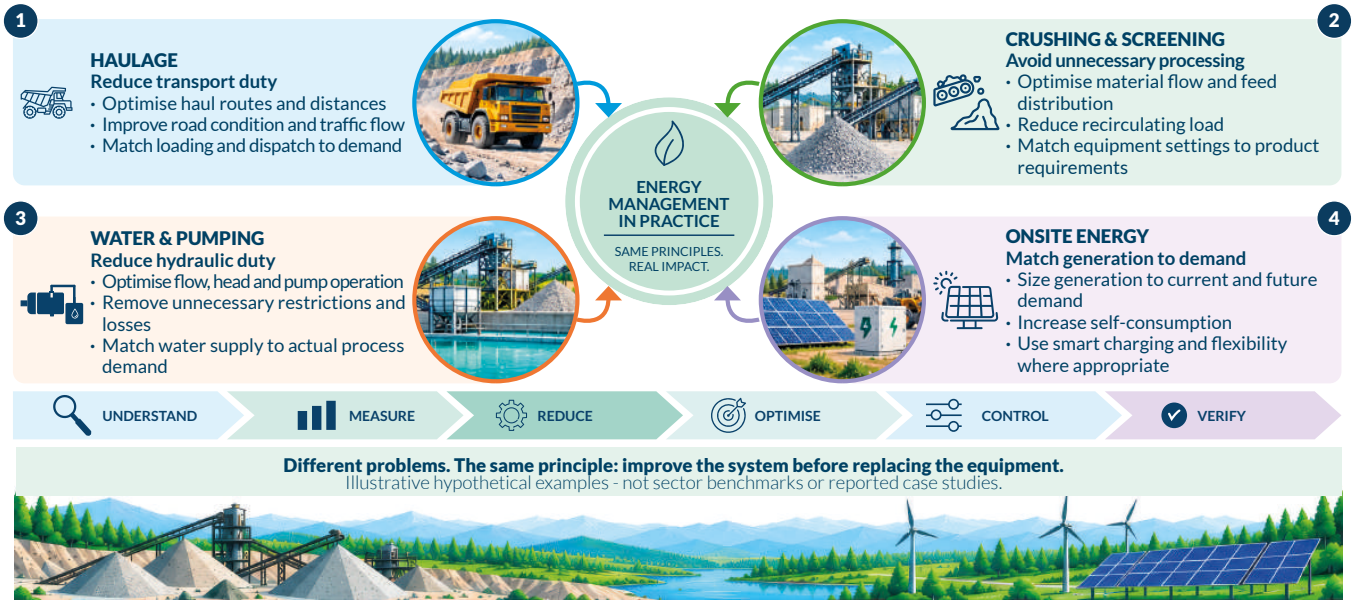


FIGURE 55. — Applying the guide: four illustrative examples

A.2 Illustrative example 1 — Haul-road and dispatch optimisation

A.2.1 THE SITUATION

A hard-rock quarry identifies a progressive increase in fuel consumption per tonne of saleable product, although production levels and the principal mobile-equipment fleet have not changed significantly.

As extraction advances, the average haul distance between the working face and primary crusher has increased. Sections of the haul road have also deteriorated, increasing rolling resistance, while trucks frequently queue before tipping at the primary crusher.

The immediate response might be to consider replacing the haul trucks with newer, more fuel-efficient equipment. However, this would address the efficiency of the machines without first determining whether the transport duty itself can be improved.

A.2.2 THE ANALYSIS

The operation measures and relates:

- Fuel consumption.
- Tonnes transported and saleable tonnes produced.
- Payload.
- Loaded and empty travel distance.
- Cycle time.
- Idle and waiting time.
- Road gradients and condition.
- Crusher feed and truck-arrival patterns.

The analysis shows that increasing fuel consumption is not primarily attributable to deteriorating engine performance. A significant part of the additional energy demand is associated with longer haul distances, increased rolling resistance and non-productive waiting.

A.2.3 THE ACTION

The site:

- Repairs and maintains critical haul-road surfaces and drainage.
- Corrects a traffic bottleneck close to the primary crusher.
- Reviews loading practice and loader–truck matching.
- Improves payload consistency.
- Coordinates truck dispatch with actual crusher demand.
- Introduces routine monitoring of fuel consumption, payload, cycle time and idle time.

The measures are implemented before considering major fleet replacement.

A.2.4 THE OUTCOME

Specific fuel consumption and non-productive operating time decrease. Truck utilisation improves and feed to the primary crusher becomes more stable.

The operation also gains a better understanding of the relationship between quarry development and future transport energy demand, allowing haulage considerations to be incorporated into subsequent quarry planning.

A.2.5 THE LESSON

Reduce transport work and operational losses before seeking efficiency improvements through a new powertrain.

The example illustrates the hierarchy: Avoid / Reduce Transport Duty → Improve Infrastructure → Optimise Operation → Improve Control → Then Consider Equipment or Powertrain Change



FIGURE 56. — Illustrative example 1 — Haul-road and dispatch optimisation

A.3 Illustrative example 2 — Crushing and screening circuit optimisation

A.3.1 THE SITUATION

A hard-rock processing plant identifies an increase in electricity consumption per tonne accompanied by a high circulating load.

The main crusher motors appear to be operating normally and there has been no major change in installed equipment. The initial assumption is therefore that more efficient motors or crusher replacement may be required.

However, energy consumption is analysed in relation to saleable production and material flow, rather than motor efficiency alone.

A.3.2 THE ANALYSIS

The site reviews:

- electricity consumption by major processing equipment.
- tonnes entering the circuit.
- tonnes of saleable product.
- crusher throughput and settings.
- screen performance.
- recirculating load.
- feed distribution.
- wear condition.
- product specifications.

Inspection identifies worn screening media and uneven feed distribution. Consequently, part of the material that already meets the required product size is not being separated efficiently and is unnecessarily returned to the crushing circuit.

The plant is therefore consuming energy to process material that does not need further size reduction.

A.3.3
THE ACTION

The operation:

- Replaces worn screening media.
- Improves feed distribution across the screens.
- Reviews crusher settings against actual product requirements.
- Stabilises feed to the circuit.
- Monitors circulating load.
- Tracks kWh/t both against material processed and saleable product.

A.3.4
THE OUTCOME

Circulating load decreases, throughput becomes more stable and specific electricity consumption falls without replacement of the principal crusher motors.

The improvement also reduces unnecessary equipment loading and wear.

A.3.5
THE LESSON

The lowest-energy tonne is often the tonne that does not need to be processed again.

The example illustrates the hierarchy: Avoid Unnecessary Processing → Improve Material Flow → Optimise Operation → Improve Control → Then Consider Equipment Upgrades

Illustrative example 2

Crushing and screening circuit optimisation

Reduce unnecessary processing, improve material flow, save energy



1 THE ANALYSIS
Review material flow and energy use

- Electricity consumption
- by major processing equipment
- Tonnes entering the circuit
- Tonnes of saleable product
- Crusher throughput and settings
- Screen performance
- Recirculating load
- Feed distribution
- Wear condition
- Product specifications

Inspection identifies worn screening media and uneven feed distribution. Consequently, part of the material that already meets the required product size is not being separated efficiently and is unnecessarily returned to the crushing circuit. The plant is therefore consuming energy to process material that does not need further size reduction.

2 THE ACTION
Improve screening efficiency and circuit stability

- Replace worn screening media
- Improve feed distribution across the screens
- Review crusher settings against actual product requirements
- Stabilise feed to the circuit
- Monitor circulating load
- Track kWh/t both against material processed and saleable product

3 THE OUTCOME
A more efficient and stable plant

- Circulating load decreases
- Throughput becomes more stable
- Specific electricity consumption falls
- Reduced unnecessary
- equipment loading and wear
- Improved resource efficiency and lower environmental impact

4 THE LESSON

The lowest-energy tonne is often the tonne that does not need to be processed again.

Improvement hierarchy for processing:

1. Avoid unnecessary processing
2. Improve material flow
3. Optimise operation
4. Improve control
5. Then consider equipment upgrades

UNDERSTAND → MEASURE → REDUCE → OPTIMISE → CONTROL → VERIFY

FIGURE 57. — Illustrative example 2 — Crushing and screening circuit optimisation

A.4 Illustrative example 3 — Water recirculation and pumping optimisation

A.4.1 THE SITUATION

A sand and gravel operation increases water recirculation to reduce freshwater abstraction.

Environmental performance in terms of freshwater use improves, but electricity consumption per tonne of saleable product increases. Investigation indicates that the additional electricity demand is associated mainly with the pumping system.

This creates an apparent conflict between water efficiency and energy efficiency.

A.4.2 THE ANALYSIS

Rather than reducing water recirculation, the operation examines the hydraulic duty required to provide it.

The site measures or assesses:

- Water flow.
- Operating pressure.
- Static and dynamic head.
- Pump operating points.
- Electricity consumption.
- Pumping hours.
- Pipe configuration and restrictions.
- Washing-plant water demand.
- Water recirculation rate.
- Production.

The review identifies avoidable hydraulic lift, pressure losses and periods during which pumping capacity exceeds actual process demand.

A.4.3 THE ACTION

The operation:

- Removes unnecessary hydraulic restrictions.
- Modifies parts of the circuit to reduce avoidable lift.
- Improves pump operation and control.
- Coordinates water supply with actual washing demand.
- Reviews pump sizing and operating points.
- Monitors both kWh/m^3 of water pumped and energy per tonne of saleable product.

A.4.4 THE OUTCOME

The site maintains a high level of water recirculation while reducing the electricity required to operate the water circuit.

Water and energy performance are consequently improved as an integrated system rather than managed as competing objectives.

A.4.5 THE LESSON

Water efficiency and energy efficiency should be optimised together; improving one should not unnecessarily penalise the other.

The example illustrates the hierarchy: Define the Required Water Duty → Reduce Head and Losses → Match Pumping to Demand → Improve Control → Then Optimise or Replace the Pump

Illustrative example 3

Water recirculation and pumping optimisation

Optimise hydraulic duty, save energy, maintain high water recirculation



1 THE ANALYSIS
Understand the hydraulic duty

- Water flow
- Operating pressure
- Static and dynamic head
- Pump operating points
- Electricity consumption
- Pumping hours
- Pipe configuration and restrictions
- Washing-plant water demand
- Water recirculation rate
- Production

The review identifies avoidable hydraulic lift, pressure losses and periods during which pumping capacity exceeds actual process demand.

2 THE ACTION
Improve the water circuit and pumping efficiency

- Remove unnecessary hydraulic restrictions
- Modify parts of the circuit to reduce avoidable lift
- Improve pump operation and control
- Coordinate water supply with actual washing demand
- Review pump sizing and operating points
- Monitor both kWh/m³ of water pumped and energy per tonne of saleable product

3 THE OUTCOME
Improved water and energy performance

- Maintains a high level of water recirculation
- Lower electricity consumption for pumping
- More efficient operation of the water circuit
- Improved integration of water and energy management
- Supports environmental performance and production efficiency

4 THE LESSON

Water efficiency and energy efficiency should be optimised together; improving one should not unnecessarily penalise the other.

Improvement hierarchy for water and pumping:

1. Define the required water duty
2. Reduce head and losses
3. Match pumping to demand
4. Improve control
5. Then optimise or replace the pump

UNDERSTAND → MEASURE → REDUCE → OPTIMISE → CONTROL → VERIFY

FIGURE 58. — Illustrative example 3 — Water recirculation and pumping optimisation

A.5 Illustrative example 4 — Onsite photovoltaic generation, electrification and load management

A.5.1 THE SITUATION

An aggregates operation is considering installing a large onsite photovoltaic system. The preliminary proposal sizes the installation primarily against the site's annual electricity consumption.

At the same time, the company expects progressive electrification of mobile equipment and other processes to increase electricity demand and alter its daily load profile.

Sizing generation solely from annual MWh would not show whether electricity is generated when the site can use it.

A.5.2 THE ANALYSIS

The operation develops an hourly or sub-hourly electricity-demand profile and evaluates:

- Current electricity consumption and peak demand.
- Daily and seasonal load profiles.
- Expected future electricity demand from electrification.
- Solar resource.
- Available roofs, infrastructure areas and suitable land.
- Expected photovoltaic generation profile.
- Direct self-consumption.
- Potential electricity exports.
- Grid-connection capacity.
- Charging requirements for electric equipment.
- Flexible loads.
- Potential role of storage.
- Project life relative to future quarry development.

Several PV capacities are compared rather than automatically selecting the maximum technically installable capacity.

A.5.3
THE ACTION

The selected photovoltaic capacity is matched to current and expected future demand. Charging of suitable battery-electric equipment is scheduled, where operationally practicable, to increase coincidence with onsite generation.

Storage is evaluated according to the services it could provide—such as increasing self-consumption, reducing peaks or supporting resilience—rather than being automatically included in the project.

The site also considers how future quarry development may affect generation areas, electrical infrastructure and load location.

A.5.4
THE OUTCOME

A greater proportion of onsite renewable generation can be used directly by the operation, while unnecessary export and potentially oversized storage are avoided.

The renewable-energy project becomes part of the site's long-term energy and electrification strategy, rather than an isolated generation investment.

A.5.5
THE LESSON

Design onsite generation around the present and future energy system of the quarry—not the other way round.

The example illustrates the hierarchy: Reduce Demand → Improve Efficiency → Understand Future Electrical Load → Generate Onsite → Match Generation to Demand → Use Flexibility / Storage where it Adds Value

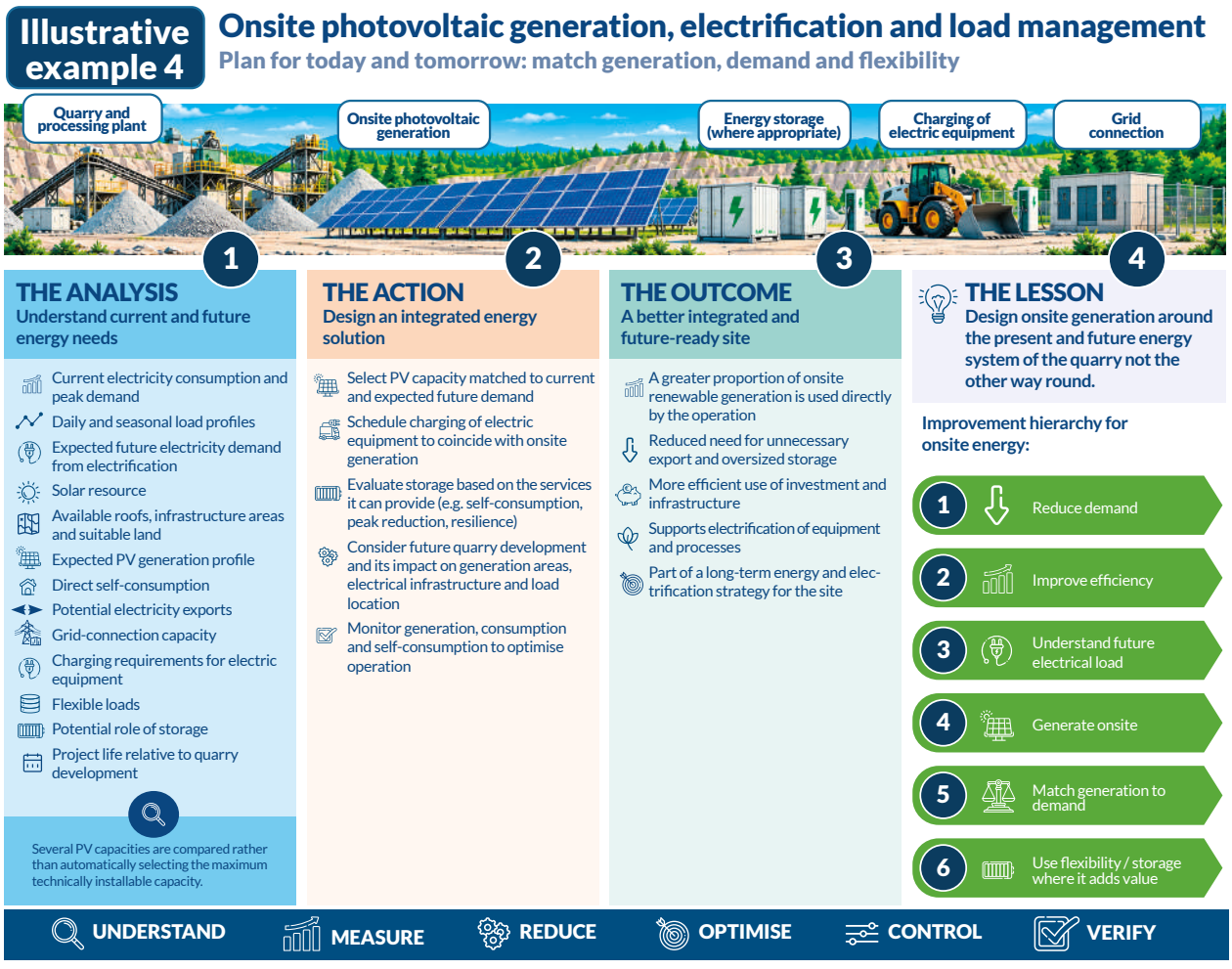


FIGURE 59. — Illustrative example 4 — Onsite photovoltaic generation, electrification and load management

A.6 Common lessons from the illustrative examples

Although the four situations involve very different parts of an aggregates operation, they demonstrate the same management logic.

In each case, the first response is not equipment replacement. The operation first determines what useful production or service is required, where energy is being consumed and which physical or operational variables are driving that consumption. Measurement is then used to identify the cause of inefficient performance and to verify whether corrective action has actually improved the relevant EnPI.

The examples also demonstrate why energy should be managed as a production variable. Fuel consumption cannot be properly understood without haul distance, payload and road condition; crushing electricity cannot be understood without throughput, screening efficiency and circulating load; pumping electricity cannot be understood without flow, head and process water demand; and onsite generation cannot be optimised without understanding the site's load profile and future electrification requirements.

A common sequence therefore emerges:
UNDERSTAND THE DUTY → MEASURE → IDENTIFY LOSSES → REDUCE UNNECESSARY WORK → OPTIMISE OPERATION → IMPROVE CONTROL → UPGRADE TECHNOLOGY WHERE JUSTIFIED → VERIFY → STANDARDISE AND MONITOR

This sequence does not prescribe a particular technology. It provides a decision-making framework that can be adapted to the characteristics of each hard-rock quarry, sand and gravel operation or processing plant.

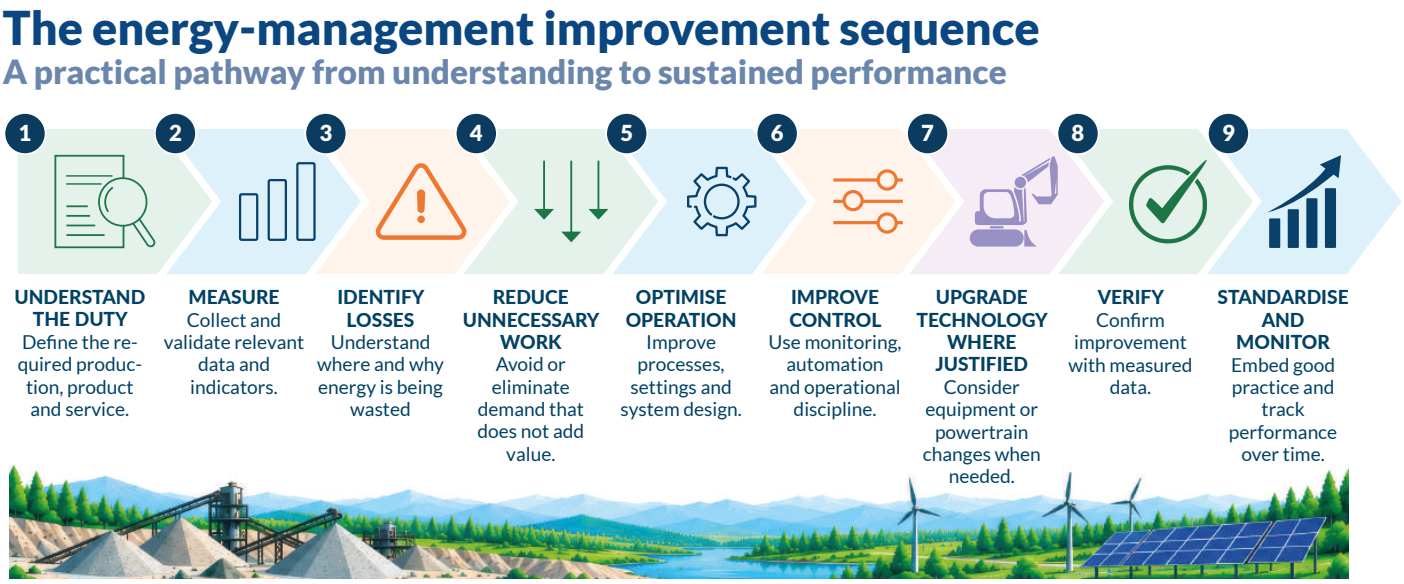


FIGURE 60. — Decision-making framework

Annex B
Core terminology, source evidence and bibliography

B.1
Core terminology

Term	Working definition for the Guide
Energy Performance Indicator (EnPI)	A measure or unit of energy performance used to quantify performance within defined conditions.
Energy Baseline (EnB)	A quantitative reference providing a basis for comparison of energy performance.
Significant Energy Use (SEU)	An energy use identified as significant because of consumption and/or potential for energy-performance improvement.
Specific energy consumption	Energy consumption related to a defined unit of useful production or process duty.
Relevant variable	A quantifiable factor that materially affects energy performance and changes routinely.
Normalisation	Modification of energy-performance data to account for relevant variables so that comparisons are meaningful.
Natural aggregates	Aggregates from mineral sources which have been subjected to nothing more than mechanical processing.
Recycled aggregates	Aggregate resulting from the processing of inorganic material previously used in construction.
Manufactured/artificial aggregates	Aggregates of mineral origin resulting from an industrial process involving thermal or other modification, including suitable slags and other industrial mineral materials.

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Environment Committee - Climate Change Mitigation and Adaptation Task Force

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This guide represents a sector-specific adaptation and further development of relevant outcomes from the ROTATE project, tailored to the particular characteristics, operational conditions and energy-efficiency challenges of the aggregates industry. It builds on the knowledge and results generated throughout the project, with the ROTATE Handbook – Volume 1: Energy Efficiency used as a supporting reference.

It has been developed in collaboration with Aggregates Europe, a member of the ROTATE International Advisory Board (IAB), to support the practical transfer and application of the project's results within the European aggregates sector.

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