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EU-MORE

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Deliverable D4.4 – Report on non-energy benefits in electric motors

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EU-MORE

EU-MORE is an acronym for
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Executive summary

The EU-MORE project, under Deliverable D4.4, explores the significant non-energy benefits (NEBs) of replacing old, inefficient motors by high-efficiency electric motors and motor systems across industries. Beyond the conventional focus on energy savings, this report highlights the broader advantages of high-efficiency motor technologies, such as improved operational reliability, productivity, environmental sustainability, and workforce conditions.

Key findings:

1. **Energy benefits – Reduce energy consumption and production costs:**
    - High-efficiency motors, namely IE4 and IE5 classes, deliver energy savings of 3-12% (depending on the power range) compared to older standard motors (IE2, IE1 and below), typically reducing the losses from 30 to over 50%.
    - Much large efficiency gains (typically in the range 20-50%) can be achieved by motor systems optimization.
    - Lifecycle analyses reveal substantial cost savings, with payback periods as short as less than 3 years for high-efficiency motors.
    - At EU level, the application of energy-efficient motor systems (including the replacement of old motors) has the potential to save 100 TWh per year.
2. **Non-energy benefits – Economic and operational advantages**:
    - Utilities can defer transmission and distribution system upgrades and achieve more electricity price stability.
    - Reduced maintenance costs, extended equipment lifespans, and minimized downtime.
    - Improved reliability, enhanced productivity and quality, as well as reduced unplanned outages.
    - The application of digitization can additionally optimize system performance, quality and productivity.
3. **Non-energy benefits – Environmental impact:**
    - Transitioning to higher efficient motors and motor systems aligns with global net-zero targets by significantly lowering industrial energy demand and the associated greenhouse gas emissions.
    - At EU level, the application of energy-efficient motor systems (including the replacement of old motors) has the potential to achieve a reduction of 200 Mtonnes of CO_2 emissions.
4. **Non-energy benefits – Workforce and societal impacts**:
    - Quieter and more stable motor operations improve workplace conditions, contributing to worker safety, reduced absenteeism, and increased productivity.
    - Widespread adoption of high-efficiency motors and motor systems has been linked to job creation, especially in SMEs and industries focused on energy efficiency.

5. **Policy and market trends**:
   - The EU's Ecodesign Directive and national programs provide strong regulatory and financial support for motor market transformation. The inclusion of NEBs will make this transformation more cost-effective, and therefore promoting a faster adoption of energy efficient motors and motor systems
   - Despite technological advancements, challenges such as high upfront costs, limited awareness, and material supply barriers need to be addressed. Besides the financial benefits associated with NEBs a variety of other benefits described in this report can be achieved.

Recommendations:

- **For policymakers**: Integrate NEBs into energy efficiency policies, expand financial incentives, and establish robust monitoring frameworks to evaluate policy effectiveness.
- **For manufacturers**: Emphasize NEBs in product development and provide training for stakeholders on the complete spectrum of lifecycle benefits.
- **For end-users**: Conduct lifecycle analyses including NEBs and leverage incentives to transition to high-efficiency systems.

Conclusions:

High-efficiency motors and motor systems offer a transformative solution to industrial challenges, driving energy efficiency, cost savings, productivity and sustainability. By leveraging technological innovations and robust policies, industries can unlock the full potential of both energy and non-energy benefits, contributing significantly to climate goals and economic competitiveness.

1. Introduction

1.1 Background and objectives of the EU-MORE project

The **EUropean MOtor REnovation (EU-MORE)** project is an EU-funded initiative designed to accelerate the adoption of highly efficient electric motors across industries. The project addresses the dual objectives of reducing energy consumption and greenhouse gas emissions while promoting the broader advantages of **non-energy benefits (NEBs)**—including enhanced operational reliability as well as productivity, reduced maintenance costs, improved workplace safety, and minimized environmental impacts [1][2][3].

The EU-MORE project aims to overcome key barriers to the adoption of highly efficient electric motor systems, such as high upfront costs, lack of information on technology options, retrofitting challenges, and limited awareness of NEBs among stakeholders. By providing quantitative and qualitative evidence of these benefits, the project equips policymakers, manufacturers, and industrial operators with the tools to make informed decisions, fostering sustainable growth and competitiveness [4][5].

There is a notable lack of technical literature focusing on the inclusion of non-energy benefits (NEBs) in cost-effectiveness analyses specific to electric motors. Reference [30] presents an evaluation of energy and non-energy benefits through 23 pilot assessments in various European industries. While electric motors are not explicitly addressed, the study reveals that NEBs accounted for 66% of the total financial flows generated by energy efficiency improvement projects, compared to 34% from energy benefits. These findings underscore the critical role of NEBs in enhancing the financial viability of energy efficiency investments and highlight the need for further investigation into their impact in the context of electric motors [30].

Since the 1990s, USA utilities have carried out large scale demand-side management programmes to promote energy-efficient motors and motor systems in industry. Figure 1 shows the inclusion of NEBs in Cost-Effectiveness Testing[1] in USA energy efficiency programs, using the following evaluation approaches:

- **Adder:** Standardized fixed amount or percentage of value added to the benefits of an energy efficiency program.
- **Quantification:** Inclusion of certain specified NEBs or all NEBs that can be quantified.
- **Hybrid:** Use of an Adder to represent certain NEBs, while also allowing for the inclusion of other NEBs based on quantification.

[1] Source: Midwest Energy Efficiency Alliance. *The Trusted Source on Energy Efficiency: Non-Energy Benefits of Energy Efficiency.* Midwest Energy Efficiency Alliance, n.d. Web. (Source: Link).

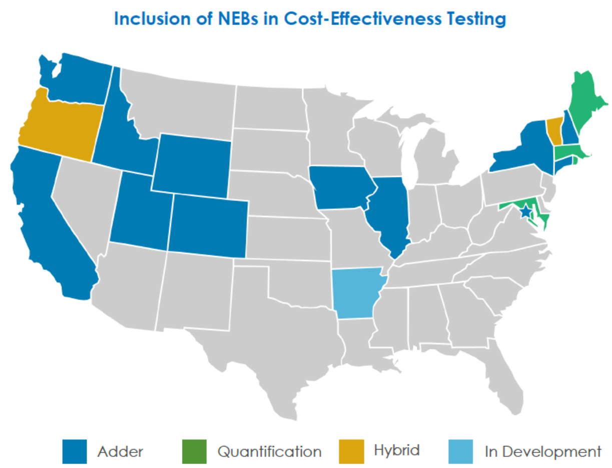

Figure 1: Inclusion of NEBs in Cost-Effectiveness Testing (Source: Midwest Energy Efficiency Alliance. *The Trusted Source on Energy Efficiency: Non-Energy Benefits of Energy Efficiency.* Midwest Energy Efficiency Alliance, n.d. Web. PDF File) (Source: Link).

1.2 The role of electric motors in global energy systems

Electric motors are key components of industrial production systems, consuming approximately 70% of global electricity in industry [6]. They drive essential processes in manufacturing, transportation, and infrastructure, making their efficiency a critical factor in terms of energy and environmental performance. Conventional industrial motors, namely three-phase induction motors, have been widely adopted due to their fairly high efficiency, reliability and cost-effectiveness. However, some of these motors are old and have low efficiency, or operate at suboptimal efficiencies (namely in part-load operation), leading to avoidable energy losses and higher operational costs [5][7][8].

In the past decades, Minimum Efficiency Performance Standard (MEPS) were upgraded to IE3 and IE4, but a large share of the existing motor stock still has an efficiency below IE2 [41]. Additionally, the shift to high-efficiency technologies, such as permanent magnet synchronous motors (PMSMs) and synchronous reluctance motors (SynRMs) reaching IE5 level, presents an opportunity to significantly enhance energy savings and reduce lifecycle environmental impacts.

1.3 non-energy benefits (NEBs): Definition and relevance

Non-energy benefits (NEBs) refer to the secondary advantages gained from energy-efficient technologies beyond direct energy savings. These benefits include operational improvements, economic gains, environmental benefits, and workforce-related improvements [1][3].

1.4 The importance of non-energy benefits

While energy and cost savings are often emphasized when evaluating efficiency projects and programs, policymakers, utilities, and consumers do occasionally also take non-energy benefits (NEBs) into account when deciding to adopt efficiency measures [33]. For example:

- **Policymakers** value benefits such as pollution reduction and economic growth (e.g., economic competitiveness, job creation).
- **Utilities** focus on advantages like deferring distribution system upgrades and achieving price stability.
- **End-users** appreciate enhanced system performance and increased comfort.

Understanding and quantifying NEBs play a critical role in:

- Supporting **cost-effectiveness analysis** to determine the overall value of efficiency improvement measures.
- Improving **program design and marketing** by addressing the non-energy priorities of stakeholders, thereby encouraging greater adoption of efficiency initiatives.

1.5 NEB perspectives and real-world applications

NEBs can be viewed from three distinct perspectives: utility, societal, and participant. Each perspective emphasizes unique aspects of how high-efficiency electric motors contribute to other benefits beyond energy savings. Table 1 provides a summary of these perspectives, along with practical examples and best practices for implementation.

Table 1: NEB perspectives and practical impacts [33].

Perspective	Examples of NEBs	Key impacts / applications
Utility	Fewer service interruptions (shutoffs/reconnects) - Improved power reliability	Efficient motors reduce strain on utility infrastructure, minimizing maintenance and operational costs while improving service continuity and grid stability.
Society	- Economic development (job creation) - Environmental benefits (GHG emission reductions) - Public health improvements	Lower emissions contribute to cleaner air, reduced healthcare costs, and economic growth through job opportunities associated with sustainable energy projects.
Participant	- Lower equipment maintenance costs - Extended motor lifespans - Improved workplace safety and comfort - Enhanced property value	Users experience tangible financial and operational benefits, such as reduced downtime, better air quality, and increased productivity due to quieter, safer equipment.

1.6 Classification of electric motor projects based on the share of NEBs

Electric motor projects can be classified by the percentage of total savings attributed to non-energy benefits (NEBs). This categorization helps in understanding the relative contribution of NEBs to the overall value of each project, providing a clear framework for assessing their impact.

Table 2 provides a concise summary of NEB shares and their potential implications for project outcomes. Projects with higher shares of NEBs often demonstrate transformative benefits, emphasizing the importance of including these in cost-benefit analyses.

Table 2: Classification of projects by share of NEBs [33].

Level of NEB	Share of NEBs in total savings	Examples of NEBs
None	0%	No measurable NEBs

Level of NEB	Share of NEBs in total savings	Examples of NEBs
Low	1%-20%	Minor noise reduction, slightly improved reliability
Medium	20%-50%	Reduced maintenance costs, extended equipment lifespan
High	Over 50%	Significant safety improvements, enhanced comfort

1.7 Barriers to adoption of high-efficiency motors

A comprehensive overview of barriers related to motor replacement is provided in "**EU-MORE D2.3 Policy Recommendations Report**". Despite the advantages of high-efficiency motors and motor systems, their adoption faces several challenges, including:

1. **Perceived low importance of motor efficiency.** When considering options for efficiency improvements in a company, motor efficiency is seen as being of low interest.
2. **Payback times are not properly assessed** – If NEBS are not considered, the payback times are not properly evaluated, leading to longer paybacks and reduced investments.
3. **Economic barriers**. Low budget for energy efficiency projects and, in some case, relatively long payback times.
4. **Higher upfront costs.** Companies often decide based on purchase cost instead of life-cycle costs. Advanced motor technologies often require significant upfront investments [1][4].
5. **Lack of awareness about the NEBs of energy efficient motors.** The advantages of motors with higher efficiency, such as lower maintenance due to lower operating temperatures, and process improvements, are often not taken into account in the decision-making process [3] [9]. The improvement of motor systems leading to much larger benefits requires expertise, which is often lacking.
6. **Goals split between different company departments.** Different departments within a company (production, energy, maintenance, financial, etc.) may have different short-term goals. Sometimes, miscoordination between these departments, in addition to the low budgets for energy efficiency projects, may lead to inaction.
7. **Quick availability.** The need for vital plant equipment to be brought on-line again as soon as possible after motor failure, leads to choosing the fastest solution without further evaluation. This often means repairing the motor, or replacing it with an old motor in stock. Repairing a motor is also seen as the lowest risk option.
8. **Stocks of old motors.** Many sites have stocks of older motors, and there is a natural tendency to use these "free" motors rather than purchase new ones.
9. **Energy audits.** Energy audits are, sometimes, not fully anchored in the reality of installations and failing to identify NEBs, leading to recommendations that are not the most ambitious and cost-effective.
10. **Technical retrofitting challenges**: Compatibility with existing systems may present difficulties [2]. Some high-efficiency motor technologies have more active material than less efficient motors, and may need an extended stator frame. Those longer motors may not fit into all applications.

Policy and market gaps: Policies often focus exclusively on energy savings, neglecting NEBs [4].

Table 3 outlines these barriers and the strategies recommended to overcome them.

Table 3: Barriers and strategies for high-efficiency motor adoption.

Barrier	Description	Strategy to overcome
High initial investment	Upfront costs deter SMEs.	Financial incentives, tax credits, and grants.
Payback times are not properly assessed	If NEBS are not considered, the payback times are not properly evaluated, leading to longer paybacks and reduced investments.	Energy audits should identify NEBs
Lack of awareness	Limited understanding of NEBs among stakeholders and of motor systems improvement potential.	Awareness campaigns, workshops, and training.
Retrofitting challenges	Compatibility issues with existing systems.	Modular designs and flexible integration kits.
Policy gaps	Regulatory focus limited to energy savings.	Integrating NEBs into policy frameworks.

1.8 Future trends and policy implications

The adoption of high-efficiency motors is increasingly supported by policy frameworks, such as the EU's Ecodesign Directive and Energy Efficiency Directive, which set mandatory efficiency standards [3][4]. However, these standards primarily focus on energy savings, often overlooking the broad spectrum of non-energy benefits (NEBs). To fully maximize the potential of high-efficiency motors, NEBs should be systematically incorporated into energy efficiency policies and their impact assessments. This can be achieved by providing evaluation criteria to include NEBs, such as reduced maintenance costs, improved operational reliability, and enhanced workplace safety. For example, policymakers could employ a hybrid approach, quantifying measurable NEBs and incorporating these into cost-benefit analyses used for MEPS development. This would not only promote broader adoption, but also provide industries with a more comprehensive justification for transitioning to advanced motor systems, such as those meeting IE3, IE4 and higher standards, as outlined in the 2019 EU MEPS regulations.

The availability of cost-effective IE5 motor technologies coupled with motor systems optimization can lead to much larger energy and NEBs. Digital technologies such as IoT-enabled monitoring and predictive maintenance systems will further amplify NEBs impacts, offering real-time monitoring and optimizing the motor systems performance were addressed in "**EU-MORE D4.1 Motor System Efficiency Trends"** report" the chapter on digitalisation [5][10][42].

2. Non-energy benefits: conceptual framework

2.1 Comprehensive understanding of non-energy benefits (NEBs)

Non-energy benefits (NEBs) are the additional advantages gained through the adoption of energy-efficient technologies, such as high-efficiency electric motors (HEMs) and motor systems, beyond their direct energy savings. NEBs include economic improvements, enhanced operational reliability, environmental sustainability, and better workplace conditions [1] [2]. While energy savings are a primary motivator for transitioning to high-efficiency systems, NEBs can help to provide a more comprehensive assessment on the value of such investments.

Over the past decade, research has shown that NEBs often contribute more to the overall financial and operational returns than the energy savings itself [3]. By recognizing and quantifying NEBs, industries can justify upfront investments in energy-efficient equipment, enabling decision-makers to prioritize long-term benefits [4].

2.2 Categories of non-energy benefits

NEBs can be classified into four major categories, each addressing specific industrial, environmental, and social impacts [1] [3]:

1. **Economic benefits**:
    - Reduced maintenance costs
    - Lower operational and production downtime, leading to higher productivity
    - Extended motor lifespan and reduced replacement frequency
    - Reduced workshop cooling costs
2. **Operational benefits**:
    - Enhanced system reliability and process efficiency
    - Improved process control and precision
3. **Environmental benefits**:
    - Reduced greenhouse gas emissions
    - Reduced resource consumption and waste
4. **Workforce benefits**:
    - Reduced noise and vibration levels
    - Improved thermal comfort and air quality
    - Enhanced worker safety and productivity

Figure 2 provides a visual representation of these NEB categories.

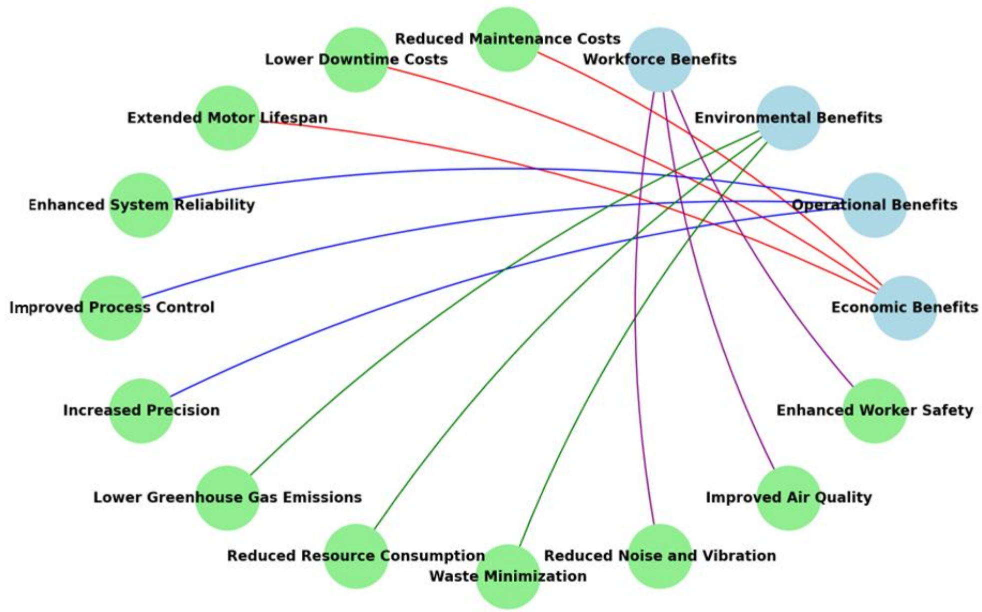

Figure 2: Categories of non-energy benefits (Source – ISR).

2.3 Economic benefits

Economic NEBs can provide industries with additional measurable cost savings that enhance financial returns on energy-efficiency investments. These benefits arise from improved process performance, reduced maintenance, longer motor lifespan, and minimized production interruptions.

Key economic benefits:

- Reduced maintenance costs: High-efficiency motors experience less mechanical stress, reducing the need for frequent repairs and maintenance.
- Extended motor lifespan: Optimized design and lower operating temperatures improve motor longevity, reducing replacement costs.
- Decreased downtime: Reliable motor performance minimizes unplanned failures, enhancing production continuity [4].

2.4 Operational benefits

Operational NEBs refer to the improvements in process reliability, control, and system efficiency resulting from high-efficiency motor adoption. These benefits directly impact production quality and system operation [6][7].

Key operational benefits:

- Improved process performance: High-efficiency motors, particularly IE5 synchronous reluctance motors (SynRMs) and IE5 permanent magnet synchronous motors (PMSMs) offer precise speed and torque control, in addition to their higher efficiency, enhancing production consistency.
- Reduced downtime: Enhanced motor reliability lowers the frequency of breakdowns, increasing system availability.

- **Optimized system performance**: Advanced motors integrate with modern automation systems, enabling process optimization and increased productivity.

2.5 Environmental benefits

Environmental NEBs align closely with global climate targets, including the EU Green Deal and Circular Economy Action Plan. By reducing energy consumption and improving resource efficiency, high-efficiency motors contribute significantly to sustainability [3][5].

Key Environmental Benefits:

1. **Lower carbon emissions**: Reduced energy consumption leads to significant reductions in CO_2 emissions.
2. **Reduced resource usage**: Longer motor lifespans minimize material demand for replacements.
3. **Waste minimization**: Improved reliability reduces waste generation from repairs and disposal.

2.6 Workforce benefits

Workforce related NEBs improve working conditions and employee satisfaction by addressing safety and comfort concerns. High-efficiency motors and motor systems operate with lower noise levels, reduced vibrations, and minimal heat generation, enhancing workplace conditions [4][6].

Key workforce benefits:

- **Noise reduction**: High-efficient motors produce less noise, minimizing worker fatigue and health risks (e.g. related to hearing problems, fatigue and mental stress).
- **Improved ambient conditions**: Lower heat emissions provide increased worker comfort and reduce the need for ventilation and cooling on the work floor.
- **Enhanced safety**: Stable motor operation minimizes risks of accidents and injuries [9].

2.7 Quantifying NEBs in the decision-making process

2.7.1 Quantifying NEBs

Industries should integrate NEBs into the decision-making frameworks to fully realize the value of energy-efficient investments. Traditional cost-benefit analyses often neglect NEBs, limiting the scope of the investment evaluation [2][4].

Table 4 outlines approaches for quantifying NEBs and incorporating them into investment evaluations.

Table 4: Approaches for quantifying NEBs [1].

Approach	Description
Lifecycle Cost Analysis (LCCA)	Quantifies lifecycle economic and operational NEBs.
Monetization of NEBs	Converts NEBs into financial terms.
Sustainability Metrics	Measures environmental benefits (e.g., CO_2).
Workforce Productivity Metrics	Assesses productivity gains from NEBs.

By quantifying NEBs, decision-makers can better justify high-efficiency motor investments, ensuring alignment with economic, operational, and sustainability goals [3].

2.7.2 Monetizing NEBs

Monetizing NEBs is critical to integrating them into cost-benefit (B/C) or return on investment (ROI) calculations. The monetization process, illustrated in Figure 3, involves translating NEBs into financial terms [33]:

1. **Direct approach**: Attributable changes (e.g., recorded savings) are multiplied by their monetary value.
2. **Secondary approach**: Indirect benefits (e.g., emissions savings) are calculated using proxy values.
3. **Modeling and surveys**: Statistical and survey-based methods assess NEBs and allocate financial values proportionally.

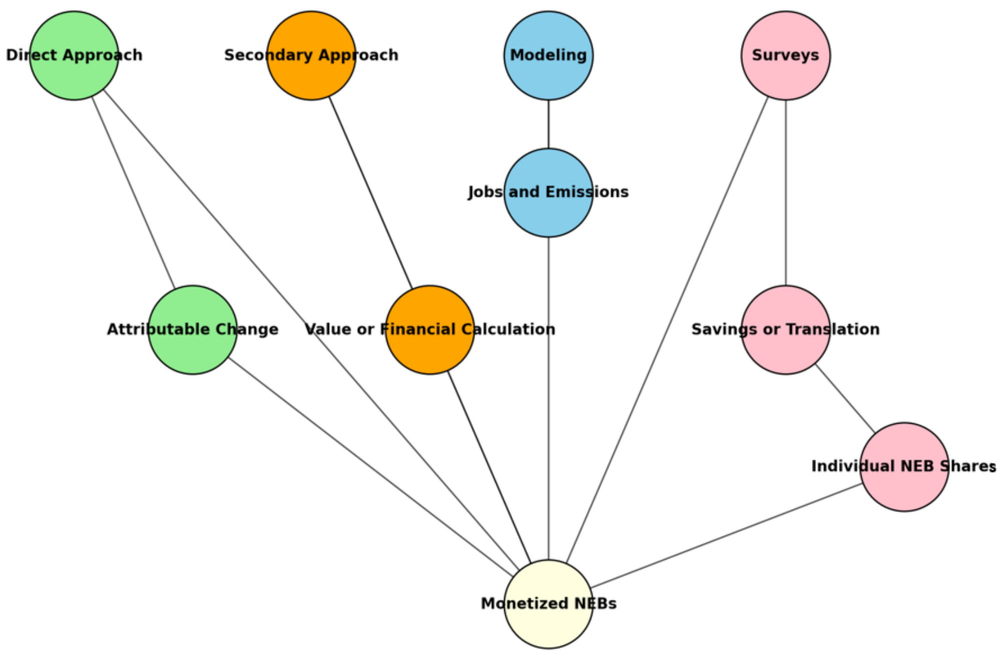

Figure 3: Monetization process for NEBs (Source – ISR).

The integration of NEB measurement and monetization into electric motor evaluations is essential for capturing their full value. By combining direct measurements, secondary data, and survey insights, stakeholders can develop a comprehensive understanding of how these benefits contribute to economic, environmental, and social improvements. Proper monetization further ensures that NEBs are appropriately accounted for in decision-making processes.

2.8 Customer perspective on NEB project economics

From the customer's perspective, non-energy benefits (NEBs) may play a pivotal role in improving the financial feasibility of electric motor projects. By complementing energy savings, NEBs reduce the payback period and enhance the overall value of investments in high-efficiency technologies.

Figure 4 illustrates the economics of NEBs from a customer perspective:

1. **Costs and benefits over time**: The left section of the figure demonstrates how project costs (black) are offset over time by discounted energy savings (blue) and non-energy benefits (red). This gradual offset indicates the cumulative impact of both energy and non-energy savings on financial outcomes.
2. **Monetized vs. untapped NEBs**: The right section of the figure highlights the total discounted benefits (including energy and non-energy benefits) relative to project costs. It distinguishes between NEBs that are currently monetized and those not yet monetized, emphasizing opportunities for future cost optimization and untapped value creation.

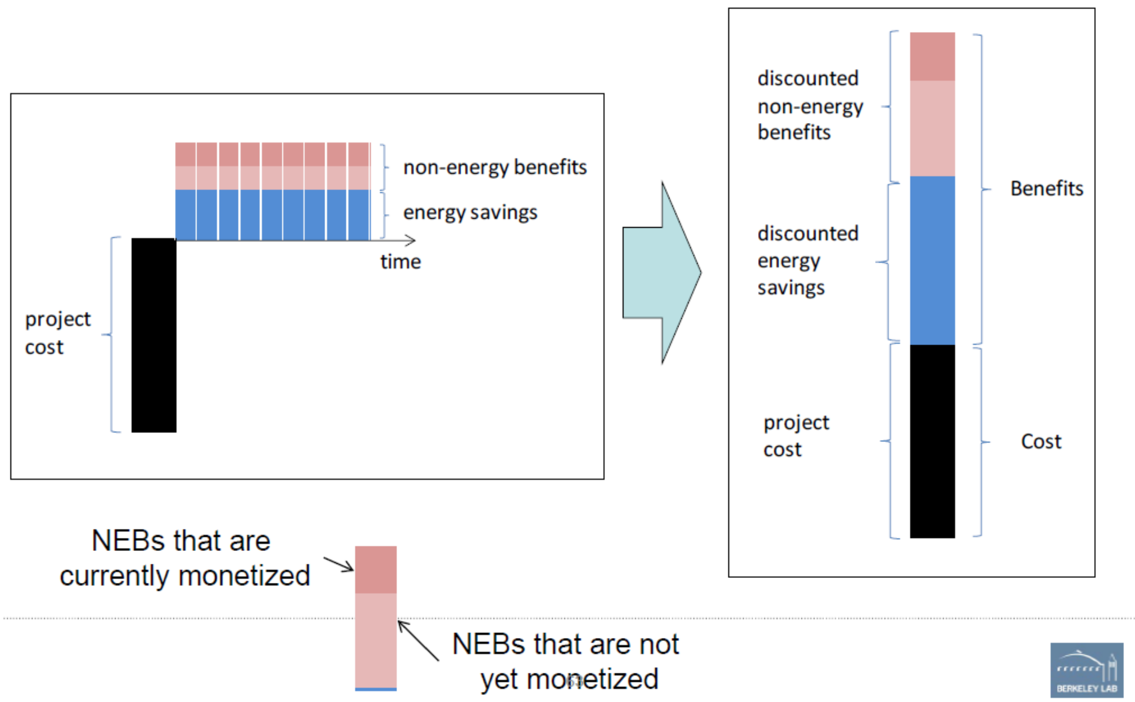

Figure 4: NEBs project economics from a customer perspective [33].

3. Multiple impacts of high-efficiency electric motors and motor systems

3.1 Economic impact

The economic impact of adopting energy-efficient motors and motor systems extends beyond energy savings and also includes maintenance cost reductions, improved reliability, and extended equipment lifespans [2][5].

Operational cost savings

In addition to reducing energy costs, high-efficiency motors and motor systems also optimize motor performance and offer a variety of advantages, including:

- Reduction of component wear, as well as lower maintenance frequency and cost.
- Reduction of noise (less fan power is required due to lower losses and by matching the operation speed to process requirements).
- Enhanced reliability minimizes unplanned breakdowns and production stoppages.
- Improved thermal management, lower mechanical stress, and advanced design extend the operational lifespan, reducing the need for replacements over time.
- Improved productivity and production quality.

3.2 Impact on industrial productivity and reliability

High-efficiency motors improve industrial productivity by ensuring stable and reliable operations. Enhanced motor performance reduces downtime caused by failures, which is critical for industries operating under tight production schedules [4][9].

- **Reduced downtime**: HEMs experience fewer mechanical failures, reducing unplanned stoppages and production losses.
- **Improved process control**: Advanced motor technologies enable precise speed and torque regulation, enhancing product quality and reducing material waste.
- **Optimized systems**: Integration with modern automation systems enhances overall process efficiency.

3.3 Societal and Workforce Impact

High-efficiency motors contribute to better working conditions and employee well-being through noise reduction, vibration minimization, and improved thermal comfort.

3.3.1 Noise and vibration reduction

High-efficient motor systems (HEMs) operate with greater efficiency, reducing noise and vibrations:

- **Noise levels**: Decreased as much as 10 dB.
- **Vibration levels**: Lower vibration reduces worker fatigue and equipment wear [6][9].

Table 5 summarizes the workforce benefits provided by HEMs.

Table 5: Workforce benefits of high-efficiency motors in the 20-30 kW power range [10].

Workplace Factor	IE3 IM Standard Motor	IE4/IE5 PMSM or PMSynRM/SynRM High-Efficiency Motor	% Improvement
Noise level (dB)	85 dB	75 dB	12%
Vibration level	Moderate	Low	Significant
Heat generation (°C)	50°C	40°C	20% Reduction

These improvements create a safer and more comfortable working environment, which enhances productivity and reduces absenteeism [9][10].

3.3.2 Improved safety and comfort

Reduced heat and vibrations improve workplace safety, lowering the risk of injuries and health-related absences [9][10]. These benefits contribute to higher worker productivity and reduced absenteeism.

3.4 Advancing motor efficiency in developing countries: a case study in Pakistan within global perspectives on energy efficiency initiatives

Some developing countries are already promoting the replacement of old motors. Pakistan's electric motor industry is undergoing a significant transformation, driven by initiatives such as the Industry Accelerator Program, a collaboration between CLASP and SAMA Verte. Focused on Gujranwala, the country's fourth-largest city, the program introduces advanced manufacturing capabilities, enabling local production of high-efficiency motor components.

Key achievements include [26]:

1. **Local innovation:** Twenty-one motor manufacturers have collaborated to acquire a multi-alloy stamping machine, enabling the production of efficient motor cores locally.
2. **Economic benefits:** By reducing dependency on imported components, manufacturers are saving costs and increasing their global competitiveness.
3. **Environmental impact:** High-efficiency motors produced through this initiative reduce electricity consumption, contributing to significant carbon savings.
4. **Increase the reliability due to availability of lower cost high-efficiency motors** leading to multiple benefits, including higher reliability, namely in hot weather conditions (in Pakistan the outside temperature can reach 50 °C, and well above inside some industrial facilities).

The program has demonstrated how capacity building, such as upskilling engineers and fostering collaboration, can achieve substantial non-energy benefits, including increased operational reliability and economic savings for end-users [26].

Figure 5 showcases a collection of old motors stored in Pakistan, symbolizing the ongoing transformation of the local motor industry toward high-efficiency standards.

Figure 5: Old motors in Pakistan: preparing for a future of efficiency [26].

4. Tools and methodologies for the assessment of NEBs

4.1 Frameworks for analyzing NEBs

The analysis of **non-energy benefits (NEBs)** requires structured frameworks that enable the identification, categorization, and quantification of non-energy benefits. NEBs, such as economic savings, operational improvements, and environmental contributions, often require multi-dimensional approaches to assess their full value [1].

4.1.1 Categorization Framework for NEBs

NEBs can be systematically categorized into four primary dimensions: Economic Benefits, Operational Benefits, Environmental Benefits, and Workforce Benefits. See Section 2.2 for more details.

4.1.2 Lifecycle Framework for NEBs

The **Lifecycle Framework** examines NEBs across the entire lifecycle of electric motors, including manufacturing, operational use, and end-of-life stages [3].

- **Manufacturing phase**: Environmental NEBs include reduced material waste and enhanced recycling opportunities.
- **Operational phase**: Economic and operational NEBs dominate this phase, such as maintenance savings and energy optimization.
- **End-of-life phase**: Benefits include resource recovery, recyclability, and disposal cost reduction.

4.2 Tools for quantifying social, economic, and environmental benefits

Various tools enable the accurate quantification of NEBs, providing industries with measurable evidence to justify investments in high-efficiency motors.

4.2.1 Lifecycle Cost Analysis (LCCA)

LCCA evaluates the total ownership costs of equipment, considering initial investment, operational costs, and NEBs over the equipment's lifespan [4]. See Chapter 7 for more details.

4.2.2 Multi-Criteria Decision Analysis (MCDA)

MCDA provides a structured method to evaluate and compare NEBs by assigning weights to multiple criteria, such as economic, operational, and environmental impacts [7].

Steps in MCDA Implementation:

1. **Identification of NEBs**: List of benefits such as downtime reduction, emissions savings, and workplace safety.
2. **Assign weights**: Prioritize NEBs based on their relative importance to stakeholders.
3. **Score technologies**: Compare motor technologies options against each NEB, considering the old systems and the new systems.
4. **Rank options**: Aggregate scores to determine the best-performing technology.

4.3 Case studies and validation techniques

4.3.1 Case study: multiple benefits in the food processing industry

A food processing plant upgraded its motor systems to high-efficiency electric motors [6]. The following NEBs were observed:

- **Downtime reduction**: Substantial improvement in equipment availability.
- **Workforce benefits**: Noise levels are reduced, enhancing worker safety.

4.3.2 Online monitoring techniques:

Motor system digitization, not available in most old installations, is being increasingly adopted to bring a variety of energy and non-energy benefits. Online sensor monitoring techniques, including vibration, temperature, rotor flux, stator endwinding vibration, and partial discharge (PD) monitoring, as well as motor current signature analysis (MCSA), have demonstrated effectiveness in early fault detection. These methods provide actionable insights into bearing degradation, insulation degradation, rotor bar conditions, and mechanical stress, reducing unplanned outages and maintenance costs [24].

Advancements in online monitoring technologies have significantly enhanced the ability to detect and address potential issues in electric motor systems, contributing to operational efficiency and a range of non-energy benefits (NEBs). Various tools and methodologies are now available to monitor thermal, mechanical, and electrical stresses in motor components, providing actionable insights for maintenance planning and system optimization [24].Table 6 summarizes the key online monitoring techniques, the types of stresses they monitor, the NEBs they deliver, and practical examples from real-world applications. These tools not only help in identifying early warning signs of equipment degradation, but also minimize unplanned downtime, extend equipment life, and improve overall reliability. For instance, bearing degradation is the main cause of motor failure and vibration sensors can be used to monitor the bearing condition (Figure 6). Partial discharge (PD) monitoring is instrumental in detecting insulation degradation early, preventing costly rewinds and extending motor lifespan. Similarly, Electrical signature analysis (ESA) effectively identifies rotor bar issues, allowing operators to plan maintenance during scheduled downtimes, as evidenced in the case study of an 8,000 hp motor in a gas plant [24].

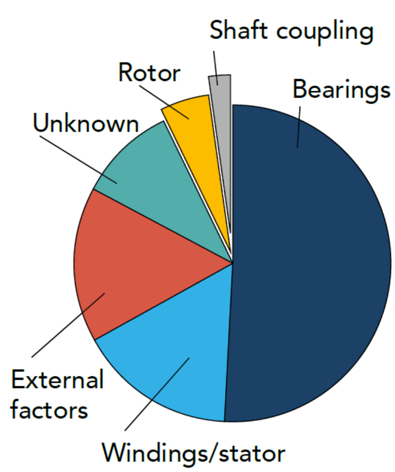

Figure 6: Failure causes in electrical motors. Source: Total Cost of Ownership Guide, AEMT.

These tools ensure that NEBs are effectively measured and integrated into decision-making, providing industries with robust justification for investing in high-efficiency motors.

Table 6: In-service online monitoring techniques and associated NEBs [24].

Monitoring technique	Stress monitored	Key benefits (Indirect NEBs)	Case study / example
Thermal monitoring using RTDs or TCs	Thermal	Tracks temperature trends, preventing overheating and enabling optimized motor efficiency.	A 28,750 kVA generator was diagnosed with overheating due to restricted airflow, which was mitigated by cleaning and optimizing the cooling systems.
Proximity probes	Mechanical	Detects vibrational anomalies, reducing wear and tear on components, extending lifespan.	Vibration-related bearing issues in a 4,000 V, 2,500 hp motor were successfully identified.
Electrical signature analysis (ESA)	Mechanical	Identifies rotor cage health issues, reducing unscheduled downtime and maintenance costs.	Broken rotor bars were detected in an 8,000 hp motor at a gas plant, enabling scheduled rotor refurbishments.
Rotor telemetry	Thermal and mechanical	Ensures rotor insulation health, improving reliability and reducing operational risks.	Used in large synchronous machines to monitor rotor performance, avoiding insulation degradation.
Partial discharge (PD) monitoring	Electrical	Assesses insulation failure risks, minimizing costly rewinds and ensuring system reliability.	Trending PD data on a 22,110 hp motor revealed the degradation of the corona suppression system, enabling refurbishment.
Cross-coupled impedance measurement	Electrical	Detects stator interturn faults, avoiding catastrophic failures and enhancing safety.	Identified interturn faults in a 1 MVA, 2,300 V motor, leading to timely repairs before severe damage occurred.
Negative sequence current monitoring	Electrical	Identifies unbalanced phases, enabling proactive correction and reducing energy losses.	The stator health of high-voltage generators was monitored, establishing baseline fault indexes for trending.
Fiber-optic accelerometers	Mechanical	Monitors endwinding vibrations, mitigating mechanical degradation and improving durability.	Installed on a 288 MVA generator, it detected vibration peaks of 315 μm and guided towards corrective actions.

Monitoring technique	Stress monitored	Key benefits (Indirect NEBs)	Case study / example
Flux probe for rotor flux monitoring	Electrical	Detects rotor turn-to-turn shorts, maintaining motor performance and efficiency.	Turn-to-turn shorts in a 35,000 hp synchronous motor were successfully identified, preventing further damage.

Case study – Stator endwinding monitoring

A case study on stator endwinding monitoring using fiber-optic accelerometers demonstrated the ability to detect mechanical stresses early, allowing for corrective actions. This intervention not only successfully mitigated potential failures, but also extended the machine's operational life [24].

4.3.4 Validation techniques for the assessment of NEBs

Validation techniques ensure that NEBs assessments are credible, accurate, and applicable across industries. Common methods include:

1. **Benchmarking**: Compare NEBs data across similar facilities to establish standard performance benchmarks [8].
2. **Simulation models**: Use existing software tools and lifecycle assessment platforms to simulate **non-energy benefits (NEBs)** over the motor lifecycle. Tools such as **MotorMaster+**, **GaBi**, and **RETScreen** integrate NEBs like reduced maintenance costs and extended equipment lifespans, alongside energy efficiency benefits. These tools provide a comprehensive analysis, helping stakeholders evaluating lifecycle impacts and associated cost savings [6].
3. **Stakeholder feedback**: Conduct interviews and surveys with facility managers and operators to validate qualitative NEBs, such as safety improvements and worker comfort or well-being [8].

These methods ensure that NEB data are both measurable and reliable, supporting a broader adoption of high-efficiency motor technologies.

4.4 Summary of tools and methodologies

The systematic assessment of NEBs relies on structured frameworks, tools, and validation techniques. The following tools are essential for NEB quantification:

- **Categorization framework**: Classifies NEBs into economic, operational, environmental, and workforce benefits.
- **Lifecycle cost analysis (LCCA)**: Quantifies savings in energy, maintenance, and downtime costs over the lifecycle of the motor.
- **Multi-criteria decision analysis (MCDA)**: Evaluates and ranks technologies based on NEBs.
- **Development of a decision-making tool that incorporates multiple benefits**: A robust methodology has been developed to integrate technical, socio-economic, and investment-related aspects into a web-based decision-making tool tailored for motor system retrofits. This tool is designed to emphasize multiple benefits, including energy savings, improved operational reliability, reduced maintenance requirements, and broader business advantages such as enhanced workplace safety and improved process quality, thereby supporting decision-makers in achieving higher efficiency and competitiveness [16]. Werle et al. (2019) classify multiple benefits into three categories: overserved, served appropriately, and underserved. While benefits like reduced energy costs and improved system reliability are well-

realized and widely recognized, other critical non-energy benefits—such as process optimization, reduced unscheduled downtime, and increased employee productivity—are often underserved. Bridging these gaps could significantly enhance the overall business case for motor efficiency upgrades by highlighting their full value, extending beyond energy savings, and fostering organizational buy-in [16].

- Case Studies and Validation: Further data collection from real-world demonstrations is needed to improve the accuracy of NEB validation models. There is lack of data on the quantification of NEBs.

5. Policy and market perspectives

5.1 Market trends and challenges in high-efficiency motor adoption

A comprehensive overview of motor system efficiency trends is provided in "EU-MORE D4.1 Motor System Efficiency Trends Report". The adoption of high-efficiency motors is accelerating due to a combination of regulatory mandates, technological innovations, and the recognition of both energy and non-energy benefits (NEBs). These drivers are reshaping the market landscape, encouraging the integration of advanced motor technologies into industrial systems. Key trends include:

- Technological advancements: Continuous innovation in motor technologies, such as permanent magnet synchronous motors (PMSMs) and synchronous reluctance motors (SynRMs), has significantly enhanced motor performance, enabling efficiency levels surpassing IE5 [7]. These motors deliver substantial NEBs, such as lower operational noise, reduced maintenance costs, extended lifespan, and improved reliability, making them attractive to industries seeking comprehensive efficiency improvements.
- Increased demand for energy-efficient motors: The demand for IE4 and IE5 motors is expected to grow as industries strive to meet stricter efficiency standards and reduce carbon footprints. The integration of IoT and smart technologies into these motors further enables predictive maintenance, process optimization, and increased productivity—key non-energy benefits that improve operational efficiency and competitiveness.
- Growth in the PMSM and SynRM markets:
  - The market for IE4 and IE5 PMSMs was valued at $10.1 billion in 2024 and is projected to grow at a compound annual growth rate (CAGR) of 8.6%, reaching $19.35 billion by 2031 (Figure 7).
  - The IE5 SynRM market is expected to grow at a CAGR of 12.7%, reaching $0.6 billion by 2032. SynRMs are increasingly favored for their cost-competitiveness, reduced heat generation, and minimal maintenance requirements, which contribute to reduced system downtime and improved productivity.
- Cost competitiveness: For variable-speed applications requiring electronic drives, IE5 SynRMs are becoming cost-competitive with IE3 induction motors while offering superior energy efficiency and NEBs, such as reduced wear and tear and greater control over speed and torque.
- Impact of digitization: The growing adoption of digitization is reducing the prevalence of fixed-speed applications, which have traditionally relied on induction motors due to their direct on-line starting capability. This shift is driving demand for electronically controlled motors, further strengthening the market for IE4 and IE5 technologies.

- **Circular economy practices**: Increasing emphasis on motor recycling, material recovery, and remanufacturing aligns with the European Union's sustainability goals. These practices not only contribute to environmental benefits but also reduce resource dependency, lower waste, and support the adoption of more sustainable motor technologies. More detailed information on this subject can be found in the report "**EU-MORE D2.4 Analysis of end-of-life practice of electric motors**". .

5.2 Policy framework and its role in unlocking non-energy benefits

The European policy landscape plays a pivotal role in promoting the adoption of high-efficiency motors and unlocking the full range of energy and non-energy benefits. Policies that combine regulatory measures with financial incentives are essential for accelerating market growth and addressing existing barriers.

1. **Ecodesign directive and minimum efficiency standards**:
   - The **Ecodesign Directive** establishes minimum efficiency requirements for electric motors, mandating the use of high-efficiency technologies like IE4 and IE5 motors. This regulatory framework ensures that energy savings and NEBs, such as reduced maintenance and extended equipment life, are prioritized across industries.
2. **National incentive programs**:
   - Several EU member states offer **financial incentives** to overcome cost-related barriers. These include subsidies for motor replacements, tax benefits for energy-efficient investments, and grants for research and development. Such programs also emphasize the importance of NEBs, including improved system reliability, reduced unplanned downtime, and enhanced safety standards.
3. **Promotion of circular economy initiatives**:
   - Policies supporting material recovery and motor recycling strengthen the circular economy, reducing the environmental impact of motor production and disposal. These initiatives also contribute to NEBs by improving supply chain resilience and reducing dependency on scarce materials, such as rare earth elements used in PMSMs.
4. **Awareness campaigns and knowledge dissemination**:
   - Awareness programs targeting industry stakeholders aim to bridge the gap in understanding NEBs. These campaigns emphasize benefits like process optimization, enhanced workplace safety, and long-term cost reductions, highlighting the broader value of motor efficiency upgrades.

5.3 Challenges and opportunities

Despite favorable policies and market trends, several challenges must be addressed to fully unlock the potential of high-efficiency motors and their associated NEBs:

- **High upfront costs**: While advanced motor technologies offer significant long-term benefits, their initial costs remain a barrier, especially for SMEs. Addressing this issue requires innovative financing mechanisms, such as leasing models or energy performance contracts, that tie payments to realized savings and NEBs.
- **Material scarcity**: The reliance on rare earth materials for PMSMs presents supply chain risks. Diversifying motor technologies and promoting SynRMs, which do not require rare earth elements, can mitigate these challenges while offering comparable efficiency and NEBs.

- **Awareness gaps**: Many stakeholders are unaware of the full spectrum of NEBs associated with high-efficiency motors, such as reduced health and safety risks, improved working conditions, and enhanced system control. Expanding education and training programs for decision-makers is critical to addressing this gap.
- **Integration into existing systems**: Retrofitting high-efficiency motors into legacy systems can pose technical challenges. Policies promoting the development of interoperable technologies and providing technical support for integration can reduce these barriers.

5.4 Summary of policy and market perspectives

The intersection of policy and market dynamics is pivotal in driving motor system renovations and realizing both energy and non-energy benefits. Key conclusions include:

1. **Policy-driven growth**: The Ecodesign Directive and national incentive programs create a robust framework for the adoption of energy-efficient motor technologies. By emphasizing NEBs in these policies, such as operational reliability and reduced maintenance costs, adoption rates can be accelerated.
2. **Market trends supporting NEBs**: Advancements in motor technologies, combined with increasing digitization and circular economy practices, are driving demand for IE4 and IE5 motors. These trends not only improve energy efficiency but also deliver NEBs that enhance industrial productivity, safety, and competitiveness.
3. **Challenges to overcome**: Addressing cost barriers, material scarcity, and awareness gaps is essential to unlock the full potential of high-efficiency motors. Policy measures and market incentives must address these challenges comprehensively to enable widespread adoption.

By addressing these challenges and leveraging effective policies, industries can unlock significant NEBs, contributing to enhanced cost-effectiveness, industrial competitiveness, and sustainability. This combined approach ensures a balanced focus on energy savings and broader benefits, fostering long-term success in achieving environmental and economic goals.

Figure 7: IE4 and IE5 permanent magnet synchronous motors market (Source: www.verifiedmarketresearch.com).

6. Technological innovations and materials

Technological advancements in electric motor designs and material innovations play a pivotal role in achieving energy efficiency, operational sustainability, and environmental goals. In addition to their energy-saving potential, these technologies offer significant **non-energy benefits (NEBs)**, such as reduced operational costs, increased reliability, enhanced workplace safety, and contributions to policy objectives like the EU Green Deal and Circular Economy Action Plan.

6.1 Advances in motor design: permanent magnets vs. synchronous reluctance

Advancements in electric motor design have primarily focused on improving efficiency, reducing material dependency, and achieving operational sustainability. Two prominent motor designs—**permanent magnet synchronous motors (PMSMs)** and **synchronous reluctance motors (SynRMs)**—demonstrate significant potential for industrial and commercial applications [11][6][42].

6.1.1 Permanent Magnet Motors (PMSMs)

Most PMSMs utilize **rare-earth magnets**, such as neodymium-iron-boron (NdFeB), to achieve higher efficiency, torque plus power density, and compact designs compared to traditional induction motors [6], but these IE5 motors cost about 40-70% more than similar power IE3 induction motors.

Key NEBs of PMSMs include:

- Lower maintenance costs and minimal rotor losses result in reduced operational downtime.
- IE5-IE6 efficiency levels: Up to 60% lower energy losses compared to IE3 motors, mainly through reducing rotor losses.
- Improved speed and torque control enabling simpler or direct drive transmission, which besides reducing energy losses, also significantly reduces maintenance costs.

6.1.2 Synchronous reluctance motors (SynRMs)

SynRMs have emerged as a **rare-earth-free alternative** to PMSMs, addressing supply chain and environmental concerns [2]. They achieve high efficiency through optimized rotor designs with laminated steel barriers to produce reluctance torque.

Key benefits of SynRMs include [2]:

- **NEBs:** Lower maintenance costs and minimal rotor losses result in reduced operational downtime.
- **Policy relevance:** SynRMs support the EU's circular economy objectives by reducing material dependencies and improving recyclability.
- **IE5 efficiency levels**: Up to 40% lower energy losses compared to IE3 motors, mainly through reducing rotor losses.
- **Cost-effectiveness**: They use about the same amount of active materials as IE3 induction motors. Eliminates rare-earth magnets, reducing costs.
- **Improved speed control through synchronous operations.**
- **Thermal management**: Much lower rotor losses leading to lower operating temperatures and motor lifespan.

Table 7 compares PMSMs, SynRMs, and traditional induction motors across key performance metrics.

Table 7: Comparison of PMSM, SynRM, and Induction Motors [6][2][14].

Feature	PMSMs	SynRMs	Induction Motors
Efficiency	IE5-IE6	IE5	IE3/IE4
Material Dependency	Rare-earth magnets	Non-critical Copper/Aluminum	Non-critical Copper/Aluminum
Cost	High	Moderate	Low
Need of VFD to Operate	Yes	Yes	No
Rotor Losses	Minimal	Minimal	Large About 20% of motor
Applications	Direct drive loads, elevators, Motion control, Robotics	HVAC, Conveyors, Pumps	General Industry

6.2 Recycling and circular economy contributions

Recycling plays a critical role in ensuring the sustainability of electric motors, particularly in reducing the **environmental impact** of rare-earth extraction and addressing **material scarcity** [3].

6.2.1 Rare-earth magnet recycling

Innovative processes such as **hydrogen decrepitation** and **hydrometallurgical recycling** are improving recovery rates for critical materials. For instance:

- **Hydrogen decrepitation**: Achieves up to **70% recovery** of rare earth elements by breaking down magnets into reusable materials [5][21].
- **Direct magnet reuse**: Allows for the recovery of entire magnet assemblies without material degradation [20].

Table 8 provides an overview of key recycling technologies.

Table 8: Advanced recycling technologies for rare-earth materials in motors [3][20].

Technology	Recovery efficiency (%)	key Benefits
Hydrogen decrepitation	70%	Low energy use, high purity
Pyrometallurgical	50%	Suitable for mixed materials
Hydrometallurgical	65%	Cost-effective for large volumes

6.2.2 Design-for-recycling

Innovations in motor design support circular economy goals by facilitating material recovery. Key strategies include (see "EU-MORE D2.4 Analysis of end-of-life practice of electric motors report"):

1. **Disassembly-friendly construction**: Modular designs that allow for quick disassembly and sorting [6].
2. **Material simplification**: Reducing the diversity of components to streamline recycling processes [3].

Table 9 highlights recovery rates for motor materials.

Table 9: Recovery rates of common motor materials [6] [17].

Material	Recovery rate (%)	Challenges
Copper	95	Insulation removal
Electrical Steel	98	Sorting efficiency
Aluminum	90	Contamination issues
Rare-Earth Magnets	70	Separation complexities

6.2.3 Smart recycling systems

Industry 4.0 technologies, including AI, machine learning, robotics, and automated sorting systems, are enhancing the efficiency and precision of recycling operations [4] [20]. These technologies reduce labor costs, improve material purity, and minimize waste.

6.2.4 Policy and industry integration

- **NEBs:** Enhanced material recovery reduces supply chain vulnerabilities, contributing to economic stability.
- **Policy implications:** EU initiatives like the *Circular Economy Action Plan* incentivize industries to adopt sustainable recycling practices.

6.3 Material efficiency and design optimizations

Material efficiency involves reducing resource consumption without sacrificing performance. Advances in motor design have enabled significant efficiency improvements through:

- Improved coil and winding designed to minimize the use on non-active copper parts (e.g. coil heads)
- **Optimized rotor shapes**: Enhanced lamination techniques and magnetic flux management reduce energy losses [2] [14].
- **Additive manufacturing**: 3D printing allows for lightweight, customized motor components while minimizing production waste.

These innovations deliver tangible NEBs, including:

- **Economic impact:** Lower production costs through material optimization.

- **Policy relevance:** Aligning with the EU's Ecodesign Directive by reducing waste and increasing material circularity.

6.4 Future trends and innovations

The future of electric motor technologies focuses on ultra-efficiency and smart capabilities to support Industry 4.0 initiatives [14] [18]:

1. **IE5 Motors**: Offering up to 50-60% energy savings over IE2 motors, IE5 motors will dominate industrial applications by **2030** [14]. The exact value of energy savings varies depending on the operating hours, lifespan, failure rates for existing motors, application, and the operating point of the motors.
2. **Alternative materials:** Use of ferrites or other new materials under development as alternatives to rare-earths in PMSM motor design.
3. **Hybrid designs**: Combining PMSMs and SynRMs to achieve high efficiency (IE5 and above) and torque performance over a wide speed range, while reducing reliance on rare-earth materials [2].
4. **Smart motors**: Integration of **IoT sensors** for predictive maintenance, energy optimization, process control and real-time monitoring [17].
5. **Policy recommendations:** Integrating NEBs into energy efficiency policies will accelerate the adoption of sustainable motor systems.

7. Economic and business impacts

7.1 Return on investment (ROI) from NEBs

The economic justification for adopting high-efficiency electric motors is often focused on energy savings. However, a comprehensive evaluation must include **non-energy benefits (NEBs)** such as operational cost reductions, increased productivity, reduced environmental impacts and enhanced equipment lifespan, which collectively improve the **return on investment (ROI)** [11][2].

7.1.1 Economic justification of NEBs

A study by [2] categorized NEBs into operational savings, maintenance cost reductions, and risk minimization, as described below:

- **Reduced downtime**: High-efficiency motors experience **fewer failures** due to better thermal management and reduced wear [2][3].
- **Improved productivity**: Enhanced reliability ensures uninterrupted production cycles, which directly impacts revenue [12].
- **Maintenance savings**: Fewer breakdowns reduce maintenance labor and spare parts costs [3].

7.2 Enhancing competitiveness through NEBs

The adoption of high-efficiency motors is a strategic move that enhances business competitiveness by lowering production costs and improving product quality [3][4].

7.2.1 Operational efficiency and competitiveness

High-efficiency motors reduce energy consumption and operational costs, enabling businesses to achieve:

- **Lower unit costs**: Energy efficiency improvements lead to up to 10% (IE5 VS IE1) reduction in energy expenses [11][4]. This amount of energy saving is based on the assumption of equal operating hours, lifespan, and failure rates for IE1 to IE5 motors. Considering the longer operating hours, extended lifespan, and lower failure rates of IE5 motors, the percentage of energy savings will increase. However, the exact value also varies depending on the application and the operating point of the motors.
- **Product quality gains**: Enhanced control in motor operations leads to consistent output and fewer defects [2].

For example, industries implementing IE4 and IE5 motors have reported increased production yields and reduced customer complaints [4].

7.4 Economic assessment of motor upgrades

Quantifying multiple benefits is essential to demonstrate the economic viability of motor efficiency upgrades. Werle et al. (2019) highlight a case where a $20,000 investment in a motor system yielded $130,000 in multiple benefits within one year. This included energy savings, increased production reliability, and reduced maintenance costs [16].

7.5 Broader economic and societal impact

The widespread adoption of high-efficiency motors brings macroeconomic and societal benefits, including job creation, reduced energy demand, and enhanced energy security [7]. As detailed in Table 10, Table 11, and Table 12, energy-efficient motor systems deliver substantial economic and environmental benefits. For example, across 191 facilities in Ohio, these measures have led to $702 million in energy savings, avoided 2.7 million metric tonnes of CO_2 emissions, and created 3,445 jobs [25]. These impacts highlight the significance of energy-efficient motor systems in driving sustainable economic development and achieving societal goals.

Table 10: Key energy-efficient motor system recommendations [25].

Recommendation	Efficiency gain	additional Benefits
Replace standard V-belts with notched V-belts or synchronous belts	2-8%	Reduced maintenance costs, extended lifespan of belts
Install Variable Frequency Drives (VFDs)	20-30%	Enhanced reliability, reduced thermal and mechanical stresses
Trim impellers on oversized pumps	~10-15% savings in power	Optimized flow, significant energy and cost savings, reduced CO_2 emissions

Table 11: Case studies demonstrating energy and cost savings in motor systems [25].

Facility	Intervention	Annual Savings	CO_2 Reduction
Ferroalloy manufacturing plant	Replaced standard V-belts with notched V-belts	106,313 kWh, $3,836	95 tonnes
Burial casket manufacturing facility	Trimmed pump impellers	11 kW, $2,932	51.8 tonnes

Table 12: Economic and environmental impacts of energy-efficient motor systems [25].

Metric	Implemented	Potential (all facilities)
Energy cost savings	$702M	$4.3M annually
Avoided CO_2 emissions	2.7M metric tonnes	1,161,070 metric tonnes
Created jobs	3,445	Significant

7.5.1 Job creation and economic growth

The production, installation, and maintenance of high-efficiency motors require skilled labor, contributing to job creation. Even larger impacts can be achieved with energy-efficient motor systems. For example:

- The transition to IE4 and IE5 motors has created over 30,000 jobs in the EU energy efficiency sector since 2018 [3].
- SMEs participating in energy efficiency programs reported a 15% increase in local employment [4].

- In Ohio, energy efficiency measures in 191 facilities created 3,445 jobs, demonstrating the potential for employment growth through widespread adoption of motor system interventions, as shown in Table 12 [25].

This reinforces the importance of integrating energy efficiency into industrial operations to generate economic growth and local employment opportunities

7.5.2 Contribution to climate goals

Widespread motor renovations contribute to climate action goals through reduced energy demand and CO_2 emissions. For instance:

- Replacing IE2 motors with IE4/IE5 models reduces CO_2 emissions due to motor losses by 4–50% annually [11].
- Implementing energy-efficient motor systems across Ohio facilities prevented 2.7 million metric tonnes of CO_2 emissions, with additional potential savings of 1,161,070 metric tonnes if adopted more broadly [25].

These benefits align with the EU's Net-Zero Emissions Goals by 2050 [13] and emphasize the critical role of energy-efficient motor systems in achieving sustainability targets.

8. Environmental and sustainability aspects

8.1 Contribution to net-zero goals

The shift to high-efficiency electric motors and motor systems is a significant enabler for achieving global **net-zero emissions targets** by 2050, as outlined in frameworks such as the **Paris Agreement** and the **European Green Deal** [3][11]. Electric motor systems account for **53% of global electricity consumption**, making them a primary focus for emission reduction strategies [14].

Replacing traditional motors with energy-efficient motor systems reduces energy consumption by up to **25%**, significantly lowering greenhouse gas (GHG) emissions [3][13]. This transition could globally save over **1,000 TWh annually** [14].

8.2 Lifecycle emissions and end-of-life management

A comprehensive **lifecycle assessment (LCA)** reveals that the **use phase** of electric motors dominates emissions, contributing to over 90% of total lifecycle impact [6]. The is phase emphasizes the critical importance of energy-efficient technologies

As an example, CO_2 emissions for 22 kW motors have been calculated, demonstrating the observable impact of high-efficiency motors on reducing CO_2 emissions. These improvements are detailed in Table 13, which provides calculations based on motor efficiencies outlined in [27]. For this analysis, **IE2 is used as the baseline efficiency class**, and the impact of upgrading to IE3, IE4, and IE5 motors is quantified.

Table 13: Energy and Emissions Savings in the 22 kW Power Range (Case 1: Single Motor Context) [11] [4] [27].

Efficiency class	Energy savings (%)	CO_2 emission reduction (kg/year)
IE2 (Baseline)	-	-
IE3	1.5%	300
IE4	3.0%	600
IE5	4.1%	900
Operating time assumed: 3000 hours/year.		

Case 1: Single motor context

This case assumes the energy savings and CO_2 emission reductions are calculated for a single motor operating under specified conditions.

Assumptions:

1. Operating characteristics:
   - Load power: 22 kW
   - Operating time: 3000 hours/year
   - Grid CO_2 intensity: 0.28 kg CO_2/kWh (EU average for electricity generation)

2. Efficiency levels (from [27]):
   - IE2 Efficiency: 91.6%
   - IE3 Efficiency: 93.0%
   - IE4 Efficiency: 94.5%
   - IE5 Efficiency: 95.6%
3. Baseline emissions:
   - CO_2 emissions for IE2 motor are calculated based on the baseline annual energy consumption:

$$Energy\ Consumption\ (IE2) = \frac{Load\ Power \times Operating\ Hours}{Efficiency} \quad (1)$$

$$CO_2\ Emissions\ (IE2) = Energy\ Consumption \times Grid\ Intensity \quad (2)$$

Calculations:

1. Annual energy consumption:

- IE2:

$$Energy\ Consumption = \frac{22 \times 3000}{0.916} = 72{,}052\ \frac{kWh}{year}$$

- IE3:

$$Energy\ Consumption = \frac{22 \times 3000}{0.93} = 70{,}968\ \frac{kWh}{year}$$

- IE4:

$$Energy\ Consumption = \frac{22 \times 3000}{0.945} = 69{,}841\ \frac{kWh}{year}$$

- IE5:

$$Energy\ Consumption = \frac{22 \times 3000}{0.956} = 69{,}038\ \frac{kWh}{year}$$

2. CO_2 emissions:

$European\ Union\ Grid\ Intensity\ (average)$:
$\sim 0.28\ kg \frac{CO^2e}{kWh}\ (due\ to\ signiicant\ renewable\ energy\ contributions)$

- IE2:

$$CO_2\ Emissions = 72{,}052 \times 0.28 \approx 20{,}174\ kg/year \approx 20.2\ tonnes/year$$

- IE3:

$$CO_2\ Emissions = 70{,}968 \times 0.28 \approx 19{,}871\ kg/year \approx 19.9\ tonnes/year$$

- IE4:

$$CO_2\ Emissions = 69{,}841 \times 0.28 \approx 19{,}555\ kg/year \approx 19.6\ tonnes/year$$

- IE5:

$$CO_2\ Emissions = 69{,}038 \times 0.28 \approx 19{,}330\ kg/year \approx 19.3\ tonnes/year$$

3. CO_2 emission reduction compared to IE2:

- IE3:

$$Reduction = 20.2 - 19.9 = 0.3\ tonnes/year$$

- IE4:

$$Reduction = 20.2 - 19.6 = 0.6\ tonnes/year$$

- IE5:

$$Reduction = 20.2 - 19.3 = 0.9\ tonnes/year$$

4. Energy savings (%):

$$Energy\ Saving\ (\%) = \frac{Baseline\ Consumption\ (IE2) - Current\ Consumption}{Baseline\ Consumption\ (IE2)} \times 100 \qquad (\mathbf{3})$$

- IE3:

$$Energy\ Saving\ (\%) = \frac{72{,}052 - 70{,}968}{72{,}052} \times 100 \approx 1.5\ \%$$

- IE4:

$$Energy\ Saving\ (\%) = \frac{72{,}052 - 69{,}841}{72{,}052} \times 100 \approx 3\ \%$$

- IE5:

$$Energy\ Saving\ (\%) = \frac{72{,}052 - 69{,}038}{72{,}052} \times 100 \approx 4.1\ \%$$

8.3 Synergies with broader climate goals

8.3.1 Circular economy contributions

The integration of **circular economy principles** in motor design and recycling is critical for reducing environmental impacts and conserving resources [4]. Key strategies include:

- **Design-for-disassembly**: Simplified motor designs allow for easier recycling and material recovery [2].
- **Closed-loop recycling**: Recovering and reusing critical materials, such as copper and rare earth metals, reduces the need for virgin resource extraction [20]. Recycling should be made in the same region or country to minimize transportation energy and environmental impacts.
- **Motor refurbishment and reuse**: Extending motor lifespan through refurbishment reduces waste and lowers production-related emissions [15]. One option is the remanufacturing of an induction motor with an interior permanent-magnet rotor [36].

8.3.2 Energy security and resource conservation

Upgrading to high-efficiency motors reduces energy consumption, enhancing energy security by decreasing dependency on fossil fuels.

This also mitigates the environmental and geopolitical challenges associated with the mining of critical materials, such as rare earth elements and copper [5] [22]. The reuse of recycled materials further reduces the strain on supply chains, contributing to long-term resource conservation [21].

9. Recommendations and implementation guidelines

9.1 Strategies for increasing awareness for NEBs in industry

To achieve widespread adoption of high-efficiency electric motors and promote non-energy benefits (NEBs), there is a strong need to increase awareness among stakeholders. Companies must understand the broader benefits such as improved operational efficiency and productivity, reduced maintenance costs, and enhanced sustainability outcomes [3]. Awareness campaigns can focus on:

- **Education and training**: Training programs for industrial users, particularly small and medium enterprises (SMEs), are essential for demonstrating NEBs and dispelling misconceptions about upfront costs [11].
- **Information dissemination**: Publishing case studies and success stories involving NEBs can serve as a motivation for industry adoption [14].
- **Stakeholder engagement**: Collaborating with trade associations, energy consultants, and policymakers to integrate NEB-messaging into broader energy efficiency campaigns [13].

9.2 Steps for effective policy implementation

Effective implementation of policies to promote NEBs requires a structured and multi-tiered approach. This can be divided into three key phases:

9.2.1 Policy design and integration

Policymakers must design policies that integrate NEBs alongside energy savings into evaluation criteria. Policies should include incentives for high-efficiency motor adoption and recognize NEBs' value [6]. For example, integrating NEBs into the Ecodesign Directive can expand its impact across sectors [11].

9.2.2 Financial incentives and support mechanisms

Financial barriers often prevent widespread motor upgrades. Policymakers can consider:

- **Subsidies and grants**: Incentive programs can provide financial support for SMEs to adopt efficient motor systems [12].
- **Tax incentives**: Offering tax credits for motor replacement projects that deliver measurable NEBs [13].
- **Low-interest loans**: Financial mechanisms that enable long-term investments in energy efficiency [4].

Table 14 summarizes key financial incentives that have been successful in Europe.

Table 14: Examples of financial incentive mechanisms.

Policy / Program	Country	Incentive type	Impact on NEBs
PIUS Program [6]	Germany	Subsidies and advice	Increased SME adoption
NECP Policies [8]	Spain	Grants and funding	Accelerated motor renovation
Ecodesign Directive [2]	EU-Wide	Regulatory framework	Enhanced energy savings & NEBs

9.2.3 Monitoring and evaluation

Effective policy implementation relies on robust monitoring systems to evaluate NEBs and adjust policies accordingly [7]. Monitoring frameworks should include:

- **Quantitative metrics**: Evaluating improvements in maintenance costs, emissions reductions, and operational efficiencies [6].
- **Qualitative metrics / stakeholder feedback**: Gathering insights from industries on policy effectiveness and challenges faced [13].

9.3 Recommendations for stakeholders

9.3.1 Recommendations for policymakers

Policymakers play a central role in driving NEBs adoption. Key recommendations include:

- Ensuring **policy alignment** with national sustainability and energy goals [3].
- Promoting NEBs through incentives in energy efficiency regulations and climate action plans [11].
- Facilitating international collaborations to share best practices and policy tools [14].

9.3.2 Recommendations for manufacturers

Manufacturers of electric motors must emphasize NEBs as part of their product offerings. Recommendations include:

- Developing high-efficiency motors demonstrating enhanced **lifecycle benefits**, such as extended equipment life and reduced emissions [13].
- Providing training and after-sales services to highlight NEBs realization post-implementation [4].

9.3.3 Recommendations for end-users

End-users, particularly industrial users, are at the forefront of NEBs adoption. Recommendations for them include:

- Performing **comprehensive lifecycle analyses** to capture NEBs alongside energy savings [6].
- Collaborating with policymakers and energy consultants to access financial incentives [15].
- Sharing success stories and case studies to promote broader industry adoption [12].

9.4 Case studies for implementation

Case study 1: Germany's PIUS Program

The PIUS Program in Germany provides financial assistance to SMEs for implementing high-efficiency motors, resulting in significant NEBs such as reduced emissions and operational savings [12]. The combination of technical advice and financial support has helped to address the barriers for adopting high-efficiency motors.

Case Study 2: Spain's NECP Policy

Spain's National Energy and Climate Plan (NECP) includes specific measures to incentivize energy-efficient technologies in industries, focusing on achieving net-zero emissions and reducing lifecycle costs [15].

9.5 Repair vs replace [2]

[2] Source: https://eriks.com/en/.

When a motor fails, repairing it is often the first option considered, as it may appear to be a quicker and more affordable solution initially (depending on the nature of the repair). However, this can be a false economy. A low efficiency motor that is 20 years old and requires frequent maintenance and repairs may end up costing significantly more over time. Replacing an older motor with a modern, energy-efficient model can yield substantial long-term savings.

If a motor fails, you will inevitably face repair costs or the expense of purchasing a new one. The minimum investment required would be the repair cost. However, choosing to invest in a new motor allows you to offset the repair cost against the price of the replacement, effectively lowering the total investment needed to achieve a return on investment (ROI) and improving financial outcomes. Even larger savings can be obtained when motor replacement is combined with motor system optimization.

For instance, in a food industry application, replacing an old fan motor with a more efficient model demonstrated significant cost benefits. The original motor, with a power rating of 110 kW and an efficiency of 91.6%, would have cost €3,950 to repair. The replacement, a 90 kW IE3 motor with an efficiency of 95.6%, was purchased for €6,745. This upgrade resulted in savings of €65,840 over the motor's lifetime, along with a reduction of 196 tons of CO_2 emissions. Additionally, the payback period for this investment was just 10 months, making it a highly cost-effective decision.

9.6 Factors for reducing costs

While selecting the right motor is crucial for improving reliability and energy efficiency, additional measures can further reduce energy consumption and maintenance costs. To maximize cost savings, the entire drive chain must be considered. Collaborating with trusted partners who have expertise in energy-efficient solutions can provide valuable insights into the way savings can be maximized.

Much larger savings can be obtained when motor replacement is combined with motor system optimization.

Variable Frequency Drives (VFDs), for instance, play a significant role in boosting efficiency while maintaining reliable performance and lowering maintenance expenses. Pairing highly efficient electric motors with VFDs can lead to operational cost savings of up to 20%.

The greatest savings can be achieved in quadratic torque applications, such as centrifugal pumps or fans, where flow is typically regulated using a throttle valve. By replacing the throttle valve with an inverter to control motor speed, substantial savings can be realized—far exceeding the benefits of simply improving motor efficiency. The calculation of these savings determines the associated ROI, and will show which changes are required to achieve optimal performance and cost reductions[3].

9.7 The significance of sizing

Proper motor sizing is critical to ensuring the right equipment is used for a specific application. For example, it is worth assessing whether the motor is appropriately sized or if a smaller, more efficient motor could perform the task. Power analyzers are invaluable tools in this process, as they measure the actual power required by the system, enabling precise motor sizing. This is particularly important because the efficiency of an electric motor declines sharply when its load falls below 60% of the nominal load. Historically, and even today, manufacturers often oversize motors to avoid risks, leading to inefficiencies.

Beyond the motor itself, other drive train components, such as chains and belts, can also impact energy efficiency. These elements are often incorrectly sized or even plainly unnecessary. By analyzing the entire drive train, an optimized setup tailored to the customer's needs can be proposed.

[3] Source: https://eriks.com/en/.

For example, a dairy company used a 30-year-old 132 kW 4-pole motor to operate a cooling compressor. A power analyzer revealed the motor's actual power consumption was only 88.9 kW. Operating 8,000 hours annually, this resulted in total energy consumption of 711,200 kWh, with yearly energy costs of €42,672 (at €0.06/kWh).

Based on this data, the company replaced the oversized motor with a smaller, more energy-efficient IE3-rated 90 kW motor. After installation, energy measurements showed further reductions, with power consumption dropping to 82.5 kW and total annual energy use decreasing to 660,000 kWh. This reduced energy costs to €39,600 annually.

By investing in the appropriately sized IE3 motor, the company achieved annual savings of €3,072, with a return on investment (ROI) of just 1.92 years. This highlights the significant cost and energy savings that can be achieved through proper motor sizing combined with energy efficiency upgrades (Source: https://eriks.com/en/).

10. Examples of non-energy benefits of high-efficient electric motor systems

10.1 Increased equipment lifetime

Modern high-efficiency electric motors often feature improved design elements, such as superior bearing systems, better insulation, and enhanced cooling mechanisms. These improvements reduce the wear and tear on the motors themselves and the connected machinery (e.g., conveyors, pumps). For instance, when motors operate at optimal temperatures and with less vibration, they put less stress on mechanical components, resulting in reduced mechanical failures over time. This translates into fewer interruptions in production, less need for replacements, and ultimately, cost savings on maintenance and equipment over the motor's lifecycle [31].

10.2 Enhanced operational reliability

Energy-efficient motors are designed with higher-quality materials and precision manufacturing processes, resulting in motors that can handle variable loads and harsh environments more effectively. For instance, these motors might have improved moisture resistance or corrosion protection, making them ideal for applications in environments with high humidity or chemical exposure, such as food processing plants. Enhanced reliability means less downtime due to motor failures, which is critical in industries where continuous operation is essential [32].

10.3. Improved utilization of industrial non-energy benefits

The framework for effectively utilizing non-energy benefits (NEBs) in electric motor systems plays a critical role in enhancing energy efficiency while maximizing financial and operational advantages. A comprehensive approach to mapping and evaluating NEBs requires careful observation, measurement, quantification, monetization, and impact evaluation. Table 15 presents an updated version of the scheme originally presented, specifically tailored for the context of electric motor systems.

Table 15: Framework for NEB evaluation and utilization in electric motor systems [37].

Steps	Ex-post: after implementation	Ex-ante: before implementation
Observation	- Document observed NEBs post-implementation (e.g., reduced downtime, improved safety).	- Forecast potential NEBs (e.g., extended motor lifespan, reduced noise).
	- Conduct interviews or surveys with facility personnel to gather qualitative insights.	- Use historical data or case studies from similar projects for comparison.
	- Account for delayed NEBs that may manifest over time.	- Identify time-dependent factors that may influence NEBs.
Measurement	- Measure specific parameters (e.g., maintenance hours saved, noise reduction levels).	- Simulate or estimate measurable NEBs based on planned system upgrades.
	- Compare actual measurements to baseline data.	- Establish clear baseline metrics for future comparison.

Steps	Ex-post: after implementation	Ex-ante: before implementation
Quantification	- Quantify the observed NEBs through theoretical calculations or estimations when direct measurement is not feasible.	- Utilize forecasting tools and models to estimate the quantitative impact of expected NEBs.
	- Reference multiplier indexes or prior case studies for validation.	- Develop comparative scenarios to contextualize projected benefits.
Monetization	- Convert quantified NEBs into financial terms, considering maintenance cost savings and productivity gains.	- Calculate the economic value of NEBs to support decision-making processes.
	- Apply standard economic tools (e.g., lifecycle cost analysis).	- Leverage industry benchmarks and predictive financial models for monetization.
Evaluation and Impact	- Integrate NEBs into return-on-investment (ROI) or lifecycle cost analysis for a comprehensive assessment.	- Include NEBs in investment evaluations and compare projected outcomes across scenarios.
	- Assess the alignment of observed NEBs with strategic goals (e.g., sustainability targets, operational reliability).	- Use decision-support frameworks to determine the most impactful solutions.

Implementing this framework in the context of electric motor systems involves distinguishing between **ex-ante** and **ex-post** approaches. Ex-ante evaluations provide foresight into potential NEBs during the planning phase, ensuring that stakeholders have a clear understanding of the broader value proposition. On the other hand, ex-post evaluations focus on verifying and documenting the realized benefits post-implementation, offering valuable insights for future project assessments.

This structured approach also emphasizes the importance of transparency and stakeholder engagement. For instance, developing a standardized model for NEB evaluation that includes examples of both monetizable and non-monetizable benefits ensures that diverse NEBs—such as improved reliability and worker safety—are captured.

10.4 Linking non-energy benefits to investment practices in electric motors

[38] provides a range of suggestions on how various NEBs can be measured or translated into monetary terms, summarized in Table 16. These methods emphasize both cost-related benefits (e.g., reduced labor or material costs) and revenue-enhancing benefits (e.g., increased productivity).

Table 16: Suggested methods for measuring and monetizing non-energy benefits in electric motors [38].

Type of benefit	Measurement / monetization method	Type of benefit	Measurement / monetization method
Increased production	Indicator: kWh/ton output produced; measuring produced output	Safety	Reduced sick leave, lower rehabilitation costs
Fewer production disruptions	Calculate cost of disrupted production; reference industry benchmarks	Reduced material costs	Measure reduced scrap or material usage
Extended equipment life	Lower maintenance labor, reduced electricity demand, lifecycle cost (LCC) analysis	Reduced need for cooling	Pinch analysis, cost of cooling water, fewer cooling facilities
Improved product quality	Reduced scrap and fewer complaints/returns	Reduced emissions	Value of emission allowances, cost savings on filter replacements
Reduced hazardous waste	Cost of disposal savings	Reduced noise	Savings on silencers and noise enclosures
Reduced waste	Cost of disposal, landfill closure savings	Reduced need for labor	Savings on salary costs
Reduced maintenance	Lower maintenance costs	Improved air quality	Reduced production failures, improved product quality
Use of waste heat/fuel/gas	Track via measurement; reduced need for oil	Improved temperature control	Increased productivity and improved product quality
Improved worker morale	Reduced sick leave, improved productivity (e.g., man-hours per output unit)	Improved lighting	Reduced maintenance and replacement costs

In the context of electric motors, this framework can be particularly valuable in justifying investments in high-efficiency technologies. By integrating NEBs into investment evaluations—expressed as cost reductions or revenue increases—decision-makers can adopt a more holistic approach to calculating net present value (NPV), internal rate of return (IRR), and other financial metrics. This enables a more compelling case for projects with broader operational and financial benefits, aligning with both profitability goals and strategic energy management objectives.

Figure 8 illustrates the observed non-energy benefits as categorized by their perceived quantifiability and time frame, based on the framework proposed by Rasmussen (2014, p. 738). Indirect NEBs, which include benefits such as improved air quality or worker morale, are classified as long-term benefits with medium-level quantifiability. In contrast, direct benefits, such as increased production or reduced material costs, are identified as short-term benefits with high quantifiability. Additionally, NEBs that were noted by the interviewed firms but deemed not monetizable are categorized as having low quantifiability.

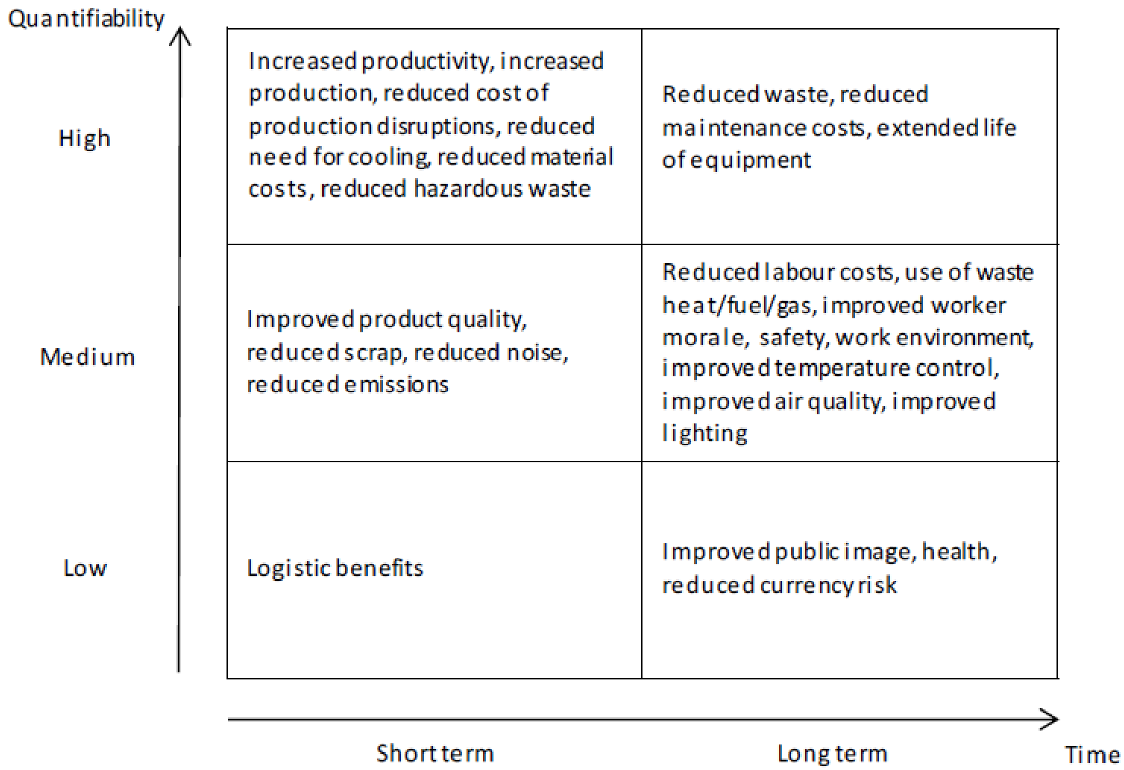

Figure 8: Suggested categorisation of the observed non-energy benefits identified in this study by level of perceived quantifiability and time frame, based on Rasmussen [38].

10.5 Case study: repair vs. replace in electric motor systems – considering NEBs

This case study evaluates the economic and operational implications of **repairing an old standard motor** versus **replacing it with a high-efficiency motor (IE3 or IE4)**. The analysis is based on scenarios involving a 75kW motor operating for 8400 hours per year at a 70% load factor, with electricity priced at €0.10/kWh. The key considerations include energy savings, payback period, and non-energy benefits (NEBs). NEBs are assumed to provide 30% of additional savings [39].

Scenario 1: repair vs. replace with IE3

- Motor efficiency:
  - Old motor (IE0): 91%
  - New motor (IE3): 95%
- Costs:
  - Repair cost: €1500
  - Replacement cost (IE3): €4500

- Electricity savings:

$$Annual\ Savings = 8400 \times 0.70 \times 75 \times \left(\frac{1}{0.91} - \frac{1}{0.95}\right) = 20{,}404\ kWh/year$$

$$Value\ of\ Savings = 20{,}404\ kWh/year \times €0.10/kWh = €2040/year$$

- Payback period:

$$Without\ NEBs: \frac{4500 - 1500}{2040} = 1.47\ years$$

$$With\ NEBs\ (30\%\ additional\ value): \frac{4500 - 1500}{2040 \times 1.3} = 1.13\ years$$

Scenario 2: repair vs. replace with IE4

- Motor efficiency:
  - Old motor (IE0): 91%
  - New motor (IE4): 96%
- Costs:
  - Repair Cost: €1500
  - Replacement Cost (IE4): €5625
- Electricity savings:

$$Annual\ Savings\ = 8400 \times 0.70 \times 75 \times \left(\frac{1}{0.91} - \frac{1}{0.96}\right) = 25{,}387\ kWh/year$$

$$Value\ of\ Savings\ = 25{,}387\ kWh/year \times €0.10/kWh = €2539/year$$

- Payback period:

$$Without\ NEBs: \frac{5625 - 1500}{2539} = 1.6\ years$$

$$With\ NEBs\ (30\%\ additional\ value): \frac{5625 - 1500}{2539 \times 1.3} = 1.25\ years$$

Analysis and insights

1. Economic feasibility:
   - Replacing the old motor with either an IE3 or IE4 model provides significant energy savings and short payback periods.
   - Including NEBs further reduces the payback period, demonstrating the added value of factors like reduced maintenance costs, improved reliability, and enhanced equipment lifespan.

2. **Non-energy benefits (NEBs)**:
   - NEBs are estimated to provide 30% of value additional to the energy savings.
   - These benefits include:
     - Lower maintenance requirements.
     - Improved operational reliability.
     - Reduced downtime and enhanced safety.
3. **Recommendation**:
   - For older motors (15+ years), replacement with IE3 or IE4 models is more economical than repair in the long term.
   - IE4 motors provide higher efficiency and greater savings but involve slightly higher upfront costs.

This case study highlights the importance of considering both energy savings and NEBs when evaluating repair versus replacement decisions for electric motors. By integrating NEBs into the analysis, stakeholders can make more informed and financially sound decisions, contributing to improved operational efficiency and sustainability.

10.6 Enhanced reliability and reduced malfunctions in electric motor systems driven by VFDs

The use of variable frequency drives (VFDs) significantly reduces the wear and tear on machinery (e.g. soft start and soft stop), resulting in fewer malfunctions and breakdowns. This improvement leads to lower downtimes and increased operational reliability of equipment.

For instance, at **Enbridge Liquid Pipelines**, a reliability study demonstrated that pumps and motors driven by VFDs are less prone to failure compared to those without VFDs (Ferrari, 2016). Approximately 50% of the company's pipeline network, which processes heavy crude oil, operates using pumps equipped with VFDs.

The following are conclusions from the company's computer maintenance management system (CMMS) [40]:

- **Pumps**: Out of a set of 154 pumps, 81 were equipped with VFDs and 73 not. The pumps with VFDs showed a **mean time between repair (MTBR)** of 995.20 days, versus 603.43 days for those without. This represents a **65% improvement in operational reliability** for pumps controlled by VFDs.
- **Electric motors**: A reliability analysis of 171 motors revealed that motors with VFDs experienced **73% less total downtime** compared to those without VFDs over a 45-year operational timeframe. Furthermore, motors with VFDs exhibited a **25% higher MTBR**, reflecting enhanced reliability and longer operating life.

This data highlights the role of VFDs in improving system performance, reducing the frequency of failures, and extending the operational life of equipment, particularly in industrial applications.

Prolonged equipment and motor lifespan

The use of variable frequency drives (VFDs) reduces wear and tear on driven systems, thereby extending the lifespan of motors and associated equipment. By minimizing mechanical stress, the need for premature replacement of machinery can be avoided, which helps prevent significant capital loss over the equipment's lifetime (Shakweh, 2007).

In particular, research shows that reducing the load speed and/or utilizing the soft start feature of a VFD significantly lowers motor winding temperatures. For every **10°C decrease in winding temperature**, the motor's lifetime can approximately **double** (Lawrence & Heron, 2016). This highlights the importance of VFDs in enhancing the durability and operational lifespan of motor systems [40].

Reduction in water losses and operational costs

The implementation of variable frequency drives (VFDs) in pump systems offers precise control over operating pressures, significantly reducing issues associated with high-pressure conditions in fixed-speed systems. According to Darweesh (2018), many water supply network problems, including leakages, are directly linked to excessive operating pressures. By mitigating these pressures, VFDs help prevent damage to the distribution infrastructure and reduce water loss [40].

Additionally, hydraulic transients, commonly caused by sudden changes in speed and pressure in fixed-speed pumps, can be minimized with VFDs. These transients often result in extra leakages and potential damage to the system. In a case study conducted by Darweesh (2018), the implementation of VFDs led to a **21% reduction in water leakages**.

Cost savings through environmental compliance

Variable frequency drives (VFDs) can help companies reduce costs associated with environmental compliance, particularly in contexts where CO_2 emissions are regulated. For instance [40]:

- **Emission Trading System (ETS) benefits**: Retrofitting motor systems with VFDs will reduce CO_2 emissions (typically by 25%), enabling the company to meet its CO_2 cap requirements under an ETS. Any surplus CO_2 allowances resulting from the reduced emissions can be sold in the ETS market, providing a direct financial benefit.

- **Utility Incentives**: In cases where industries purchase electricity from the grid and do not directly benefit from reduced emissions, they can still capitalize on utility company incentives. Many utilities offer **rebates or subsidies** for energy efficiency projects, including VFD installations, that lead to reduced electricity consumption (Durocher & Magallon, 2017).

These opportunities highlight how VFDs not only enhance energy efficiency but also provide tangible financial savings by reducing environmental compliance costs and leveraging available incentives.

Noise reduction

Variable frequency drives (VFDs) have been shown to significantly reduce noise levels in motors and driven equipment by controlling operating speeds (Wang, Astfalck, & Lai, 2002). The extent of noise reduction in the motor depends on the switching frequencies of the VFD, which regulate the rate of switching on and off during the PWM process. Higher switching frequencies, particularly below the base frequency (50 Hz or 60 Hz), achieve greater noise reductions (ABB, 1996).

Additional noise reduction is achieved by eliminating throttles used for flow control, as well as through the soft start capabilities of VFDs. These features allow pumps or fans to adjust the speed to the operating conditions, as well as ramp up to the required speed gradually, eliminating the abrupt noise typically associated with start-up (Cohen, 2007). For instance, the Metropolitan Waterworks Authority in Bangkok reported noise reductions of approximately **10-15 dB** after implementing VFDs in their water distribution pumping stations (ABB, 2006).

Reducing noise levels has several benefits, including [40]:

- **Improved workplace comfort**: lower noise levels enhance the working environment, improving employee health, focus, and morale.
- **Compliance with noise regulations**: noise reductions help industries meet strict regulatory standards.
- **Occupational health and safety**: reduced noise minimizes the risk of accidents and occupational diseases caused by prolonged exposure to high noise levels (EATON, 2015).

Extending motor and bearing lifespan through load optimization

While the implementation of variable frequency drives (VFDs) introduces new maintenance requirements due to their state-of-the-art components, well-designed systems have proven to be highly reliable. Studies indicate that VFD systems typically do not require major component replacements during the first 10 years of operation (Scheuer et al., 2007). Maintenance activities are generally limited to minor yearly checks, such as replacing air filters and small fans in air-cooled VFDs. This makes the operation and maintenance costs of VFDs minimal (Scheuer et al., 2007). The use of a VFD requires special measures to protect the motor bearing from leakage current, which can reduce its lifetime[4].

Additionally, most maintenance checks can be performed while the process is still operational, eliminating the need for costly shutdowns.

System connectivity and the internet of things (IoT)

Modern VFDs are increasingly integrated with IoT technologies, enabling real-time system monitoring and optimization. This connectivity provides actionable insights for reducing operational costs and improving performance. Examples include smart pumps that digitally monitor operational data and allow remote adjustments via cloud-based systems [35].

Case study: the impact of NEBs on the profitability of a VFD retrofit project

This theoretical case study demonstrates how including non-energy benefits (NEBs) in the evaluation of a variable frequency drive (VFD) retrofit project can enhance its profitability. The study focuses on retrofitting the condenser water-cooling system of a Dutch gas power plant. The plant currently uses throttling control for water flow, operating at 100% flow during peak hours (6 hours/day) and 70% flow during non-peak hours (18 hours/day), running 365 days a year. The analysis examines one pump in the system [40].

The system characteristics for this case study are summarized in Table 17.

Table 17: System characteristics [40].

Parameter	Details
Pump	Lowara centrifugal pump 150-400/11009
Flow	510 m^3/h
Head	56 m
Maximum head	63.9 m

[4] Source: Preventing VFD-induced bearing damage in electric motors, www. https://www.plant.ca/features/.

Parameter	Details
Pump efficiency	85.5%
Motor	Siemens GP/SD VSD10 line (Motor 1LE1503-3AB010)
Motor power	110 kW
Motor efficiency	95.4%
Insulation class	Class F
VFD efficiency	95%
Frequency	50 Hz

Key findings:

1. **Energy savings**:
   The electricity consumption and energy savings achieved by using a VFD are detailed in Table 17.
   - Electricity consumption with throttling: **694.7 MWh/year**.
   - Electricity consumption with VFD: **460.4 MWh/year**.
   - Annual energy savings: **234.2 MWh**.
   - Cost savings at €86.3/MWh: **€20,216.20/year**.
2. **CO_2 emission reductions**:

   By applying an emission factor of **0.28 tCO_2/MWh**, the annual reduction in CO_2 emissions is calculated to be **65.6 tonnes of CO_2**. These savings generate additional income through the sale of emission allowances, at a price of **€80/tCO_2**, resulting in a total annual savings of **€5,248.00/year**.
3. The impact of control methods on equipment lifespan is significant, due to reduced mechanical stress and a lower operating temperature.

In summary, the identified NEBs related to the VSD, include:

- Improved production reliability.
- Enhanced equipment performance.
- Reduced wear and tear on machinery.
- Lower operation and maintenance costs.
- Decreased malfunctions and breakdowns.
- Reduced labor requirements.
- Noise reduction, improving auditive comfort.

- Elimination of additional equipment components.
- Improved power factor, (e.g. lower voltage fluctuations) leading to higher motor reliability.

Insights and implications

This case study highlights the importance of including NEBs in the profitability analysis of energy efficiency projects. While energy savings alone provide sufficient justification for VFD implementation, NEBs further improve profitability by reducing operational costs and enhancing system performance.

Industries with large variable motor loads, such as paper, chemicals, and steel, show the greatest potential for cost-effective VFD applications.

Considerations about non-quantified NEBs related to VFDs

Non-quantified non-energy benefits (NEBs) may not always occur simultaneously across all applications. A more detailed analysis of individual processes is necessary to determine whether a specific NEB would arise in a given application. For instance, if a process implementing a VFD does not require precise control, the associated benefit of improved product quality may not materialize. Constant speed applications have in general less energy and non-energy benefits.

Moreover, the unpredictability of events like equipment failures or future productivity requirements creates challenges in accurately quantifying NEBs during ex-ante analyses. In some instances, the process becomes even more complex due to the need for detailed and specific information about the system. Despite these obstacles, the qualitative evidence presented in this study highlights the substantial potential of VFDs to provide NEBs, even when precise quantification cannot be achieved [40].

11. Conclusions

11.1 Summary of key findings

The EU-MORE project highlights the significance of **non-energy benefits (NEBs)** in the context of high-efficiency electric motors. These benefits extend beyond energy savings and include operational, economic, and environmental advantages, which strengthen the case for motor renovation initiatives. NEBs such as reduced emissions, operational cost savings, and enhanced productivity have been thoroughly demonstrated across various sectors [3][11].

From a **lifecycle perspective**, high-efficiency electric motors provide long-term environmental and economic value by significantly reducing CO_2 emissions, improving energy efficiency, and contributing to resource conservation [14][6]. Lifecycle assessment studies have consistently shown that over 90 of the environmental impact of motors occurs during the usage stage, which underscores the importance of energy-efficient designs [6][5].

The following key findings summarize the outcomes:

- High-efficiency motors reduce emissions and improve energy performance across industries [11][6].
- NEBs include enhanced operational reliability, reduced maintenance costs, reduced environmental impacts and improved workforce productivity [2][7]. Additionally, the unpredictability of certain events, such as equipment failures or future productivity demands, poses limitations on the quantification of NEBs during ex-ante analyses. In some cases, quantification is further complicated by the need for detailed and specific system information. Despite these challenges, qualitative evidence presented in this research demonstrates the significant potential of VFDs to deliver NEBs, even when precise quantification is not feasible [40].
- Policies, such as the EU Ecodesign Directive, have successfully promoted motor upgrades and sustainable practices [3][13].
- Recycling of materials, particularly critical minerals, is essential for achieving circular economy goals [5][20].
- The inclusion of NEBs in cost-benefit analysis leads to significantly shorter payback times.

11.2 Future research directions

Although significant progress has been made in recent years, a few opportunities for further exploration and improvement remain:

1. **Enhanced NEBs quantification**: Existing tools for assessing NEBs such as **lifecycle cost analysis (LCCA)** and **multi-criteria decision analysis (MCDA)** require further refinement to better capture the full spectrum of NEBs across industries [2][4]. Future research should focus on developing more robust, standardized methodologies that integrate NEBs into cost-benefit analyses.
2. **Technological innovations**: Continued research into advanced motor technologies, such as **permanent magnet synchronous motors (PMSM)** and **synchronous reluctance motors (SynRM)**, will further reduce energy losses and environmental impacts [7] [6] [5]. Innovations in motor materials and design optimization should prioritize recyclability and the reduction of rare earth dependence [20][19].
3. **Circular economy integration**: Recycling technologies for critical minerals used in motors, particularly in permanent magnets, require investment and policy support to achieve higher recovery rates. By 2040,

end-of-life magnets from clean energy technologies could provide 15-25% of the total secondary rare earth metal supply [5][23].

4. **Policy and market synergies**: To effectively enhance the renovation of electric motors, as emphasized by **the EU-MORE project**, stronger policy frameworks and market-driven incentives must be developed. Research indicates that well-designed financial mechanisms, regulatory support, and industry engagement are key to accelerating the adoption of high-efficiency motors and phasing out outdated, inefficient models [13][15]. More details on this subject can be found in the report "**EU-MORE D2.3 Policy Recommendations**"

Key strategies to improve market synergies include:

Regulatory measures: Strengthening minimum efficiency performance standards (MEPS) and enforcing stricter compliance requirements for motor replacements.

Financial incentives: Expanding subsidies, tax credits, and low-interest financing to offset the upfront costs of motor upgrades.

Industry engagement: Promoting awareness campaigns, training programs, and knowledge-sharing platforms to encourage businesses to invest in motor renovation.

Lifecycle cost considerations: Encouraging decision-making based on total cost of ownership (TCO) rather than just initial investment costs, and ensuring NEBs and long-term energy savings are factored in.

A comprehensive policy approach combining financial and regulatory mechanisms will accelerate the transition to high-efficiency motor systems, aligning industrial adoption with sustainable energy goals while delivering economic and environmental benefits.

5. **Sector-specific applications**: Detailed case studies across industrial sectors will offer better insights into sector-specific NEBs. These studies should include NEB quantification in sectors like manufacturing, food processing, and mining [2][22].

6. **Future directions for measuring and monetizing NEBs:** Profitability and short payback (PB) periods are critical factors influencing the adoption of energy efficiency improvement measures. Therefore, further research is required to develop robust methods for measuring, quantifying, and monetizing non-energy benefits (NEBs). This includes incorporating time perspectives and categorizing NEBs into direct and indirect benefits. A key challenge identified is the lack of information, which hinders effective measurement and monetization of NEBs. Future research should focus on enhancing the availability of information and developing standardized models or frameworks that integrate NEBs into investment calculations in a structured and systematic way. Additionally, to address specific barriers and leverage potential drivers, further studies should explore NEBs associated with specific energy efficiency measures and processes. These investigations should focus on identifying the drivers that encourage adoption and understanding the barriers that inhibit implementation, especially in relation to specific energy efficiency practices [34].

11.3 Concluding remarks on NEBs and electric motor renovation

The findings from the EU-MORE project emphasize that **non-energy benefits** play a vital role in driving the adoption of high-efficiency electric motors. The combined environmental, economic, and operational advantages present a compelling argument for industries to prioritize motor renovation projects [3][20].

References

1. Cagno, E., Moschetta, D., & Trianni, A. "Only Non-Energy Benefits from Energy Efficiency Measures?" Journal of Cleaner Production, 2019, 212, pp. 1319–1333.
2. Rasmussen, P. "Categorization of Non-Energy Benefits in Industrial Systems." Industrial Efficiency Studies, 2020, pp. 55–59.
3. United Nations Environment Programme. U4E Policy Guide Series on Electric Motors and Systems, 2023.
4. Waide, P., & Brunner, C. U. Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems. International Energy Agency, 2011.
5. International Energy Agency. Recycling of Critical Minerals: Outlook for Critical Minerals Recycling. 2021.
6. Estonian Research Council. "Lifecycle Analysis of Electric Motors in Industrial Applications." Motor Efficiency Reports, 2019, pp. 90–94.
7. Collaborative Labeling and Appliance Standards Program (CLASP). Energy Efficiency Standards and Policies for Electric Motors. 2020.
8. Waide, P. Market and Environmental Impacts of High-Efficiency Motors. International Energy Agency, 2019.
9. Faccio, M., & Gamberi, M. "The Environmental Benefits of Retrofitting Industrial Equipment." Sustainability, 2018, 10(6), pp. 1–12.
10. International Energy Agency. Future Trends in Industrial Energy Efficiency. 2020.
11. European Commission. *Directive 2009/125/EC on Ecodesign Requirements for Energy-Related Products*. 2009.
12. LEA Hessen. *PIUS Program Report: Production-Integrated Environmental Protection for SMEs in Germany*. 2017.
13. IEECP. *Motor Policy Review for EU-MORE Initiative*. LIFE Project Grant Agreement No. 101076631, 2023.
14. International Energy Agency. *Market Trends for High-Efficiency Motors*. 2021.
15. Spanish Ministry for the Ecological Transition and Demographic Challenge. "National Energy and Climate Plan (NECP): Strategic Goals and Industrial Contributions." 2020.
16. Werle, R., Tieben, R., Klingel, P., Rothen, A., Fleischli, L., Pyatova, V., West, S., Ackermann, K., & Phillips, R. (2019). *A decision-making tool incorporating multiple benefits of motor systems retrofits*. Presented at EEMODS 2019. Zurich University of Applied Sciences, Lucerne University of Applied Sciences and Arts, & Swiss Federal Office of Energy.
17. United Nations Environment Programme. *Recycling Rare-Earth Magnets from Motors*. 2023.
18. Ferreira de Souza, D., et al. *Life Cycle Assessment of Electric Motors*. Journal of Cleaner Production, 2024.
19. Auer, M., & Meincke, J. *Evaluation of Trade-offs in Electric Motor Lifecycle*. Sustainability, 2020.
20. Fraunhofer Institute for Material Recycling. "Recycling and Circular Economy in Electric Motor Design and End-of-Life Management." 2020.
21. International Energy Agency. *Outlook for Circular Economy in Critical Minerals*. 2024.
22. Waide, P. *Lifecycle Management of Critical Materials in Electric Motors*. 2022.
23. Orlova, N., et al. *Environmental Impact of Motors Across Lifecycle Phases*. 2016.
24. Haq, S. U., Trivedi, A., Rochon, S., & Moorthy, M. T. S. (2024). *Alternative methods of machine online condition monitoring: Recommendations for rotating machines in the petroleum and chemical industry*. IEEE Industry Applications Magazine, 30(6), 19–31. https://doi.org/10.1109/MIAS.2024.3387136.
25. Errigo, A., Choi, J.-K., & Kissock, K. (2022). Techno-economic-environmental impacts of industrial energy assessment: Sustainable industrial motor systems of small and medium-sized enterprises. *Sustainable Energy Technologies and Assessments, 49*, 101694. https://doi.org/10.1016/j.seta.2021.101694.
26. Collaborative Labeling and Appliance Standards Program (CLASP). (2024). *Innovation Ignites Pakistan's Electric Motor Future*. Retrieved from CLASP Website.

27. IEC, "IEC 60034-30-1: Efficiency classes for line operated AC motors," International Electrotechnical Commission, Geneva, 2014.
28. Association of Electrical and Mechanical Trades (AEMT). Total Cost of Ownership Guide. Version 1. Accessed January 20, 2025. Available at http://www.theaemt.com (Link).
29. Goman, V., Prakht, V., Kazakbaev, V., & Dmitrievskii, V. (2021). Comparative study of energy consumption and CO_2 emissions of variable-speed electric drives with induction and synchronous reluctance motors in pump units. *Mathematics, 9*(21), 2679. https://doi.org/10.3390/math9212679.
30. Cooremans, C., Bonardi, J.-P., Killip, G., & Lung, R. B. (2023). *Integrating the non-energy benefits of energy efficiency into business decision-making: Results of 23 pilot assessments in European companies*. ACEEE Conference Paper. Retrieved from https://www.researchgate.net/publication/373632780.
31. Copper Development Association Inc. (n.d.). *Motor management best practices: Part III - Repair specifications, and preventive and predictive maintenance*. Retrieved from www.copper.org.
32. Anderson, K. J., Ponder, M., & Ekman, A. (n.d.). *Motor projects in the Pacific Northwest*. Northwest Energy Efficiency Alliance.
33. Lawrence Berkeley National Laboratory. (2016, December 14). *Evaluating and quantifying the non-energy impacts of energy efficiency*. Webinar series facilitated by LBNL, with funding from the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability. Retrieved from https://emp.lbl.gov/emv-webinar-series.
34. Nehler, T. (2016). *The non-energy benefits of industrial energy efficiency: Investments and measures* (Licentiate Thesis). Linköping Studies in Science and Technology, No. 1760. Linköping University, Sweden. ISBN: 978-91-7685-672-7.
35. Northwest Energy Efficiency Alliance. (2020). *Power drive systems: Energy savings and non-energy benefits in constant and variable load applications*. Prepared by Cadeo Group, https://neea.org.
36. R. Ni *et al.*, "Efficiency Enhancement of General AC Drive System by Remanufacturing Induction Motor With Interior Permanent-Magnet Rotor," in *IEEE Transactions on Industrial Electronics*, vol. 63, no. 2, pp. 808-820, Feb. 2016.
37. Nehler, T. (2018). *A systematic literature review of methods for improved utilisation of the non-energy benefits of industrial energy efficiency*. Energies, 11(12), 3241. https://doi.org/10.3390/en11123241.
38. Nehler, T., & Rasmussen, J. (2016). How do firms consider non-energy benefits? Empirical findings on energy-efficiency investments in Swedish industry. *Journal of Cleaner Production, 113,* 472–482. https://doi.org/10.1016/j.jclepro.2015.11.070.
39. de Almeida, A. (2025). *Economic analysis of high-efficiency IE3 or IE4 motors versus repair or retrofit of old standard motors*. EU-MORE Project Report, 2025.
40. Serna Tamez, A. (2019). *Non-energy benefits brought by the use of variable frequency drives in pump and fan applications* (Master's thesis). Utrecht University, Utrecht, Netherlands.
41. EU-MORE Project. (2024). *European Electric Motor Market Assessment (Deliverable D2.1).* Co-funded by the European Climate Infrastructure and Environment Executive Agency under the LIFE program (Grant Agreement No. 101076631).
42. Fong, J., de Almeida, A. T., & Kulterer, K. (2024). *D 4.1. Motor system efficiency trends*. LIFE-2021-Project (Grant Agreement No. 101076631).