SEAD | Super-efficient Equipment and Appliance Deployment

Motor Repairs:
Potential for Energy Efficiency Improvement

Task 3 Report

May, 2014

Motor Repairs:

Potential for Energy Efficiency Improvement

Final Report

May, 2014

Developed in support of the
APEC Expert Group on Energy Efficiency & Conservation
Collaborative Assessment of Standards and Testing

Prepared by Econoler
with the Research and Development (R&D) Laboratory of ABB

ECONOLER

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ABBREVIATIONS

AC	Alternating current
ADC	Aluminum die cast
AES	Annual Electricity Savings
AEMT	Association of Electrical and Mechanical Trades
APEC	Asia-Pacific Economic Cooperation
CLASP	Collaborative Labeling and Appliance Standards Program
CEE	Consortium for Energy Efficiency
CuDC	Copper die cast
DC	Direct current
DOE	U.S. Department of Energy
DSM	Demand-side management
EASA	Electrical Apparatus Service Association
EGEEC	Expert Group of Energy Efficiency and Conservation
EIA	U.S. Energy Information Agency
EU	European Union
EuP	Energy Using Product
GMI	Green Motor Initiative
GMPG	Green Motors Practices Group
ICA	International Copper Association
IEA	International Energy Agency
NZ	New Zealand
ODP	Open drip proof
PEV	Proven Efficiency Verification
SKF	Svenska Kullagerfabriken
TEFC	Totally enclosed fan-cooled
US	United States of America
VFD	Variable frequency drive
VPI	Vacuum pressure impregnation
WSU	Washington State University

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EXECUTIVE SUMMARY

Background of Study

Motors in various sectors of activity fail during operation every year. As a result, most failed motors are repaired and put back into service. Poor[1] practices are typically used in repairing failed motors, degrading the initial efficiency of motors when they are still recently new. By contrast, advanced repair and re-winding practices allow maintaining or slightly increasing the efficiency of motors. Quite often, advanced repair techniques do cost the same as less refined repair techniques. Adopting improved motor repair practices could generate considerable energy savings in any country.

The primary aim of this study was to estimate the energy efficiency improvement potential arising from adopting best motor repair practices in five selected economies, namely China, Japan, New Zealand (NZ), the United States (US) and Vietnam. The study can benefit policy-makers and standardization bodies by helping to raise their awareness about the potential for energy savings likely to arise from the repair and preventive maintenance of installed motors. The study team brought together Econoler experts and an industry specialist from the Research and Development (R&D) laboratory of ABB, one of the international market leaders in motor and electrical machinery repair techniques.

Scope of Study

Motors considered under this study have the following characteristics: (1) open drip-proof (ODP) and totally enclosed fan-cooled features (TEFC); (2) outputs of 0.75 kW (1 hp) and above; (3) 50-Hz or 60-Hz frequencies; (4) three-phases; and (5) two poles and above. The motors within scope are mostly found in the industrial sector. The remaining motors are found in the commercial, residential, transport and agricultural sectors. Motors used in industry applications particularly account for the larger portion (approximately 64%[2]) of electricity consumption by all electric motors across sectors.

Repairs with a significant effect on motor efficiency were considered under this study. In fact, the vast majority of repairs do not include rewinding; they most often include the replacement of bearings, which has little, if any, measurable effect on motor efficiency. Other repairs include stator lamination, which can significantly impact motor efficiency, as well as rewinding, which is a complete form of winding repair.

The study focused on three types of repair: (a) rewinding without lamination repair; (b) rewinding with lamination repair; and (c) rotor repair. It also focused on rotor replacement as an energy efficiency measure.

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[1] Based on interviews with motor experts (March 2013)

[2] Ibid.

Methodology

Achieving the overall goal of the study comprised three interrelated tasks: Task 1 (Report 1) – Existing and Best Motor Repair Practices; Task 2 – Market Overview and Task 3 – Potential for EE Improvement in Motor Winding and Repair. Task 1 provides background information on current motor rewinding and repair best practices along with evaluations of the gap between these best practices and the practices currently followed in the five economies. As part of this task, a survey form was developed to collect data on current repair practices employed by repair shops and the motor failure and repair market. The data served as a basis for Task 2 in establishing the market characteristics of motor failure and repair in the five economies. Findings from Tasks 1 and 2 were then used as input data in Task 3 to estimate energy savings resulting from employing best practices to repair motors and from replacing aluminum rotors with copper rotors.

Country-specific Data Collection

Mainly for New Zealand and the US, two national studies on electric motors were identified to collect data on the number, type and size of motors installed, their applications and purposes, and their number of operating hours per year. Other data provided by the studies include either the number of motor failure cases each year or the number of failed motors repaired and put back in service. The first study was conducted in 1998, in the US and the second, in 2006, in NZ. For China, Japan and Vietnam, no information was available.[3]

To collect recent country-specific market data on motor sales, use, failure and repair, email and telephone interviews were conducted as a primary research strategy with stakeholder countries. Their feedback not only confirmed that there is no field data on motor failure and repair in China, Japan and Vietnam, but also that the studies identified in New Zealand and the US were the most recent in their respective economies.

Due to the difficulty of obtaining recent market data, in-person interviews at repair shops were conducted in each country to collect data on motor failure and repair market characteristics, such as the percentage of failed motors repaired and put back in service, the type of failure, motor rewind intervals, and the distribution of failed motors in terms of power class, enclosure type and pole number. Because shops did not keep any specific records in the survey form format, some questions were answered based on respondents' practical experience in motor repair.

Summary of Key Findings

The main study findings include the following:

- The most common poor practices observed include removing windings by using hand tools and mechanical stripping by cold process. Other poor practices are related to stator lamination repair and include visually inspecting the stator lamination to determine whether it needs repair and

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[3] This does not mean that reports or statistics do not exist in these three countries; it only means that they were not public or available to us.

ignoring any defects detected in the lamination before proceeding with the repair. These poor practices were often combined with the use of inappropriate tools and equipment, such as burn-out ovens, vacuum pressure impregnation (VPI) systems, insulation resistance testers, hipot test kits and thermo-graphic cameras.

- Stator winding failure (without or with lamination damage) is the leading reason for sending motors for repair, accounting for nearly 100% of failures in all countries under study, except China. Whereas in China, 70%-75% of failures were winding failures and rotor failures accounted for the remainder.
- Most failed motors are repaired rather than replaced. The larger the motor, the more likely it is to be repaired instead of replaced. Motors are typically rewound between one and three times during their 16- to 30-year lifetimes, with smaller motors at the bottom and larger motors at the top of this lifetime range.
- Individual poor motor repair practices reduce motor energy efficiency only in a small percentage, but result in significant energy losses when considered as an aggregate. Employing recommended best practices to rewind and repair motors could result in an average annual savings potential between 8 GWh and 3,800 GWh in the five economies, with New Zealand at the bottom and China at the top of the range. In percentage terms, this potential ranges between 0.06% and 0.17% of annual motor electricity consumption in the economies.
- Energy efficiency degradation can be avoided altogether with better, highly cost-effective motor repair practices. In fact, end users' investment in improving motor repair practices can be paid back in energy savings in as little as two years.
- End users seldom choose to retrofit their motors with copper rotors, as doing so can be time consuming and expensive when a suitable replacement must be ordered or fabricated.
- Energy savings from replacing aluminum rotors with copper rotors in small motors can be significant, particularly in the largest economies under study: China and the United States. Assuming that aluminum rotors are replaced with copper ones in all eligible motors in 2015, electricity savings are estimated at 31,100 GWh and 15,900 GWh for China and the US, respectively. New Zealand would have the lowest electricity savings estimate with 180 GWh. Motors that provide constant torque to linear loads (such as reciprocating compressors, conveyor belts and crushers) are the most likely to generate for energy savings; they do not require any VFD control, which can be expensive to add.

Causes of Uncertainty in Energy Savings Estimates

Uncertainty in the energy savings estimates is dependent on the availability and quality of the data on operation parameters. Operation parameters include annual motor running hours, efficiency, and rated power by power rating category. Ideally, these parameters should be country-specific and recent, because technology, materials, manufacturing techniques or weather conditions change over time. Instead, information drawn from relevant literature addressing these parameters was used as proxy for economies where relevant data was not available.

Barriers to Employing Best Practices in Motor Repair/Rewind and Replacing Aluminum Rotors with Copper Rotors

Several barriers impede the transition to and rapid market promotion of copper rotors and best practices for motor repair and rewind.

Barriers to introducing best motor repair and rewind practices are as follows:

- Lack of harmonized repair standards in the five economies – Motor repair is neither regulated nor centralized, and no harmonized or uniform standard exists for the entire range of services that can be performed on a motor. Some international standards, such as the IEC standards cover only a limited scope of motor servicing. Repair shops in the five economies surveyed do not follow any established standards. Although significant efforts have been undertaken in this regard in the US and New Zealand, more still needs to be done for market adoption of repair and rewind best practices.
- Lack of simple certification programs – Across all the economies surveyed, fewer than one in three shops was ISO 9001 certified. None of the shops surveyed in the US had ISO certification. All US respondents made it clear that the ISO certification has virtually nothing to do with the AC motor repair/rewind business. Other certification programs exist in the US. However, many US repair shops perceive those certification programs as too complex and expensive.
- Customers' preference for fast turnaround over Repair quality – Customers usually do not have spare motors; this means that production facilities are shut down while motors are being repaired. As a result, customers tend to choose the fastest options to get their motors back into service, even if shops suggest buying replacement motors or repairing motors as per manufacturers' original specifications as a cheaper solution. Repairing as per manufacturers' original specifications takes longer, and minor additional work is likely required to make motors operate satisfactorily.[4]
- Lack of experienced motor repairers – As years go by, key rewind staff grow older and few people are being trained to take their places, because few workers wish to learn motor rewind as a trade or even committed to learning the trade fully. Also, no training program is offered in community colleges and no short-term course is specifically dealing with the technique.
- Lack of appropriate tools and equipment – Shops in emerging economies like China and Vietnam are not as well equipped as their counterparts in industrialized economies, such as Japan, New Zealand and the US. Unlike large shops across the five economies, most small and medium shops do not have any appropriate tools and equipment to ensure high-quality rewind/repair.

Barriers to replacing aluminum rotors with copper rotors include the following:

- Lack of copper rotor inventory and specialized equipment at repair shops – Few repair shops replace aluminum rotors with copper bars by fabricating the copper bars and inserting them in

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[4] Anibal de A. et al, 2012, *Electric Motors and Drives: Consumer Behaviour and Local Infrastructure*, Second Draft

the slots. This process is not common practice, since bars to fit the slots are hard to acquire and the core is difficult to reassemble since it is normally held together by the rotor cage. In terms of workmanship quality, as far as a typical well-equipped repair shop is concerned, rotors are not repaired or replaced on a regular basis because such work involves using some amount of design knowledge.

- Inexistence of mass copper rotor production – Replacing aluminum rotors with copper rotors is time consuming and expensive – Replacing aluminum rotors with copper rotors implies manufacturers having to make technology changes. This process can take quite some time and manufacturing costs can be higher. Hence, copper rotors are usually unavailable in the market and can only be supplied by their manufacturers.

Recommendations

Without any policy implementation in the current motor repair market, the barriers discussed above will make it difficult or even impossible to achieve the estimated electricity savings. Therefore, the following recommendations are made to help remove the barriers.

- Developing repair quality standards and certification programs in the economies – Rewind/repair standards and quality labels should be created and implemented in the economies covered by the study. Efforts should be made to fill any gaps in existing standards. The labels can be applied to motors repaired in accordance with established standards and should serve as the quality image of repair shops in the future, enabling users to easily identify and choose the best repair shops.
- Designing and implementing awareness campaigns – Awareness campaigns should be carried out among motor users to help them understand the benefits of appropriate motor repair and choose qualified repairers.
- Creating training facilities and developing training materials – Training facilities and materials should be developed for current employees and new employees entering the repair industry. The training and materials should focus on energy-efficient motor rewind/repair practices. These efforts should be undertaken in the five economies.
- Designing and implementing financing schemes to help repair facilities upgrade their equipment – In the five economies, a financing scheme needs to be designed and implemented to help SMEs deal with costs involved in upgrading their equipment and increasing return on their investment.
- Speeding up the transition from aluminum rotors to copper rotors – Two possible ways to speed up the transition to copper rotors would be for motor repair shops and distributors to keep copper rotors with common specifications in stock and for end users to time motor maintenance, refurbishment and repair to coincide with planned down times.

INTRODUCTION

Generally speaking, repair shops employ poor maintenance and repair practices, which negatively impacts electric motor efficiency. It was believed that in the early 2000s, rewinding or repairing AC induction motors would systematically reduce original efficiency by up to 2 percent depending on motor size.[5] Unlike poor practices, best motor rewinding and repair practices have been developed to partially or totally eliminate motor efficiency degradation. Nonetheless, most repair shops in developing economies still employ poor practices. Employing poor practices results in substantial electric energy waste caused by reduced efficiency.

Electric motors account for the largest proportion of electricity consumed globally. According to the International Energy Agency (IEA), electric motors account for between 43 percent and 46 percent of the global electricity consumption.[6] Such a high level of electricity consumption is not surprising, since electric motors are used not only in a wide range of industrial systems, but also in many types of application, such as pumping, ventilation and compressors in the commercial, residential and agricultural sectors.

During this study, (1) current best practices in selected APEC countries (China, Japan, New Zealand, the United Stated and Vietnam) were documented and analyzed; (2) the market characteristics of motor repair in each country were identified; and (3) the potential for energy efficiency improvement associated with repair and refurbishment using the best available technical solutions and adopting best industry practices was estimated. The study will benefit national policy-makers and standardization bodies, since it will raise awareness regarding the potential for energy savings related to the repair and preventive maintenance of installed motors.

The study team brought together Econoler experts and an industry specialist from the Research and Development (R&D) laboratory of ABB, one of the international leaders in motor and electrical machinery repair techniques.

The report, the third in a series of three (1) summarizes the findings from the first two reports on the review of best motor repairing/rewinding practices and the market overview and (2) presents energy savings estimates for the abovementioned five economies. The first two reports prepared as part of this study are listed below.

Report 1: Existing and Best Practices in Motor Repair – The report summarizes the findings from a literature review of studies and documents published by manufacturers and repair industry associations or published under efficient motor market transformation and demand-side management (DSM) programs implemented by government agencies and not-for-profit organizations. The report also identified current best practices recommended for motor rewinding and repair and evaluated gaps between these recommended best practices and practices used in the five economies.

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[5] Motor Challenge Fact Sheet at http://www1.eere.energy.gov/manufacturing/tech_deployment/pdfs/mc-0382.pdf

[6] International Energy Agency at http://www.iea.org/newsroomandevents/news/2011/may/name,19833,en.html

Report 2: Market Overview – This second report describes the market characteristics of motor failure and repair in the targeted economies. The report describes the installed stock of three-phase squirrel cage AC induction motors in operation in each country and the number of motors failing per year. It also presents a description of key market characteristics concerning electric motor failure and repair in the five economies.

1 STUDY SCOPE AND METHODOLOGY

The purpose of this study was to estimate energy savings resulting from the adoption of best practices in electric motor repair/rewind and to raise awareness among policy makers and standard and labeling regulators using these energy savings estimates. This section presents the scope and methodology of the study.

1.1 SCOPE

Electric motors are classified according to the type of power supply (AC single or three phases and DC) and other design and construction characteristics. AC induction motors largely dominate the electric motor market in terms of sales and stock installed. These motors have become popular because of their reliability and low cost, compared with DC, synchronous and universal motors. Therefore, this study mainly focuses on AC induction motors. Table 1 presents the characteristics of AC induction motors selected to define the scope for the study.

Table 1: Range of AC Induction Motors

Characteristics	Range	Observation
Type of enclosure	Open drip-proof (ODP) and totally enclosed fan cooled (TEFC)	Both are widely used and are included in the study.
Output (kW)	0.75 to 1000	The study focused on medium-size (0.75 to 375 kW) and large-size motors (> 375 kW). The scope does not cover smaller size motors (< 0.75). The motors within scope have outputs of 1 hp and above.
Frequency (Hz)	50 or 60	This is the typical range available on the market.
Voltage (V)	220 to 13,200 (50 Hz) or 208 to 13,800 (60 Hz)	A wide range is necessary to capture the complexity of motor design at different voltages.
Number of phases	3	Unlike three-phase motors, single-phase motors are quite small and are replaced rather than repaired. Therefore, the number of single-phase motors rewound is very small and does not represent a significant potential.
Number of poles	2 to 12	In general, the number of motor poles varies between 2 and 12. This is the typical range covered for similar studies.

The motors within scope were mostly found in the industrial sector. At the global level, motors in industry applications account for approximately 64%[7] of electricity consumption by all electric motors across sectors. The remainder of motors were found in the commercial, residential, transport and agricultural sectors.

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[7] Ibid.

Motors can be rewound or repaired. Repairs with a significant effect on motor efficiency were considered under this study. In fact, the vast majority of repairs do not include rewinding and most often include replacement of bearings with little, if any, measurable effects on motor efficiency. Other repairs include stator lamination repair, which can have a significant effect on motor efficiency. The same applies to motor rewind, which can change motor characteristics if not done according to the best repair practices.

Therefore, the study focused on three types of repair, as discussed in APPENDIX II to this report: (1) Rewinding without lamination repair, (2) rewinding with lamination repair and (3) rotor repair. It also includes complete rotor replacement as a potential energy efficiency measure.

Throughout the report, the AC induction motors included in the scope of the study are referred to as motors.

1.2 METHODOLOGY

The study includes the three tasks below.

Task 1 (Report 1): Existing and Best Practices in Motor Repair

During this particular task, current best practices in rewinding and repairing AC motors were analyzed and the gap between these best practices and practices used in the five APEC economies were evaluated. The task included the following activities:

- Selecting eight countries to consider in the study based on six APEC economies (Australia, China, Japan, New Zealand, South Korea and the United States) suggested by CLASP and on the international experience of the study team members. The selection resulted in a list consisting of the initial six economies and two other APEC economies in Southeast Asia: Indonesia and Vietnam. After project inception, the study team reduced the list by excluding Australia, Indonesia and South Korea under the agreement of CLASP and its partners[8], because of insufficient data gathered through literature review and surveys. Hence, the study covers five APEC economies, including China, Japan, New Zealand, United States and Vietnam.
- Selecting the size and type of electric motors to consider in the study, with input from CLASP and its partners. This activity resulted in the identification of AC motors. Their characteristics area presented in detail in Table 1 above.
- Collecting data on motor repair practices and market through literature review and field surveys. Analyzed during this activity were publications by motor manufacturers and repair industry associations, as well as government agencies and not-for-profit organizations under efficient motor market transformation and demand-side management (DSM) programs. With regard to the field surveys, the study team customized survey forms for each stakeholder to solicit specific information. More precisely, email and telephone interviews were conducted with motor

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[8] CLASP partners in this project include the APEC Expert Group of Energy Efficiency and Conservation (EGEE&E), the China National Institute of Standardization (CNIS) and the International Copper Association (ICA).

manufacturers' associations, public agencies in charge of electric motor standards and labeling programs, and non-profit organizations engaged in energy-efficient motor promotion. The team also had native speakers conduct in-person interviews with repair shops.

Task 2 (Report 2): Market Overview

This particular task aimed at establishing the market characteristics of motor failure and repair in the five economies. For that purpose, the survey forms developed under Task 1 and containing a series of questions to collect market data were used. As part of this task, the study team analyzed responses to these questions to provide an overview of motor failure and repair market characteristics, such as the percentage of failed motors repaired and put back in service, motor rewind intervals and the distribution of failed motors among horsepower rating classes, enclosure types and number of poles.

Task 3 (Report 3): Potential for Energy Efficiency Improvement

The aim of this particular task was to estimate energy efficiency savings arising from implementing best practices in AC motor rewind and repair, based on Task 1 and Task 2 findings combined. For that purpose, the study team developed a technical model aimed at determining the gain in efficiency associated with the introduction of best repair techniques for single-phase motors. Thereafter, the energy efficiency savings in economic terms were extrapolated from the gain associated with single-phase motors.

1.3 COUNTRY-SPECIFIC DATA COLLECTION

To collect information on motors, the research team combined three approaches: literature research, telephone interviews and emailing, and in-person interviews at repair shops.

Literature Research

With regards to the five countries under study, the team identified studies on electric motors conducted in New Zealand and the US.

The New Zealand study[9] was conducted in 2006 to assess motor replacement in the industrial sector, as part of the Electricity Commission pilot project on motor system operation efficiency improvement. Field data collected during this study provided information on the number of motors failing every year and the number of failed motors repaired and returned to service. The data also provided information on motor rewind intervals, based on survey results obtained as part of this study and a Canadian study[10] conducted in 2001.

In 1998, the US Department of Energy (DOE) commissioned a major market assessment study[11] on the US electric motor population and use as part of its Motor Challenge Program.[12] Upon completion,

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[9] Electricity Commission, *Industrial Motors Efficiency: Motor Replacement*. 2006.

[10] Ibid, p 37

[11] USD OE, *United States Industrial Electric Motor Systems: Market Opportunities Assessment*.1998.

[12] Motor Challenge is an industry/government partnership designed to help industrial businesses capture significant energy and cost savings by increasing motor system efficiency.

the study provided a detailed profile of the stock of motor-driven equipment in US industrial facilities, including an estimate of the number of motors failing every year, the percentage of failed motors repaired and put back in service, and the operation parameters of motors in use, such as the average load factor, annual operating hours and service lifetime. However, the study contains little information on motor failure or repair. In addition, the only information provided seems more of a rule of thumb than factual information. Since then, no other study of this kind has been conducted in the US.[13] But other study reports refer to the 1998 DOE study regarding projections of current motor stocks in the US, confirming that the DOE study is the most recent comprehensive assessment of motors in the US.

The report[14] on motor shipment analysis issued by the DOE is another important source of information on motors in the US. The report presents data on the share of motors by horsepower rating based on the distribution available in the database of the Washington State University (WSU) Extension Energy Program, during which data was collected from extensive field measurements.

The study team also identified as a source of data a handbook on energy efficient motor systems published by the American Council for an Energy-Efficient Economy (ACEEE) in 2002. The handbook provides a profile of the motor population and use in the US based on past field motor surveys conducted in commercial and industrial facilities in the 1980s and 1990s. The profile contains data on motor population, distribution, and use by size and type. It also contains motor distribution by speed, enclosure, duty and load factors, and motor life.

For China, Japan and Vietnam, no information was available[15] with regards to the number of electric motors installed, their types and sizes, their applications and purposes, or their number of operating hours per year. Very little data was available on the number of motor failing every year or the number of failed motors repaired and put back in service.

The team also identified the preparatory studies conducted on motors under The Energy Using Product (EuP) Directive (2005/32/EC) in Europe.[16] Even though those studies focused on European countries not covered by this particular study, the information they contained was considered as a benchmark to cross-check other information collected in the five stakeholder countries.

Email and Telephone Interviews

To collect recent country-specific market data on motor sales, use, failure and repair, email and telephone interviews were conducted with stakeholders (motor manufacturers' associations, motor experts from public agencies in charge of electric motor standards and labeling programs, non-profit organizations engaged in energy-efficient motor promotion, etc.). Stakeholder feedback confirmed that no field data on motor failure and repair exists in China, Japan or Vietnam. Also, the feedback confirmed that the 1998 and 2006 studies carried out in the US and NZ, respectively, were the most recent.

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[13] Interview with the Office of Energy Efficiency & Renewable Energy within the USD OE on March 4, 2013

[14] DOE, 2012, *Shipments Analysis*

[15] This does not mean that no reports or statistics were available in the countries surveyed, but that they were not public or available to us.

[16] See the preparatory studies under The Energy Using Product (EuP) Directive (2005/32/EC) by Anibal T. de Almeida et al, 2008

In-person Interviews

Due to the difficulty of obtaining recent market data during the activity described above, in-person interviews and repair shop visits were organized at a limited number of sites in each target country. Participating shops were recruited based on their size (large, medium and small) to constitute a cross-sectional picture of the market. Where shops exist, a large shop is defined as one with more than 50 employees, a medium-sized shop, as a shop with 20 to 50 employees, while a small-sized shop, as a shop with fewer than 20. Out of all shops in each size category identified and contacted, Table 2 shows the number that took part in the survey. At the time the interviews were conducted, there were no single shops of more than 50 employees in New Zealand.

Table 2: Surveyed Shop Size in Each Country

Size of Shop Surveyed	China	Japan	New Zealand	US	Vietnam	Total
Number of Small Shops	4	7	3	3	4	**21**
Number of Medium Shops	4	2	7	3	2	**18**
Number of Large Shops	2	1	0	1	2	**6**
Total	**10**	**10**	**10**	**7**	**8**	**45**

The visits allowed the research team to collect data on motor failure and repair market characteristics, such as the percentage of failed motors repaired and put back in service, the frequency of each type of failure, motor rewind intervals and the distribution of failed motors by power class, enclosure type and pole number. Because shops did not keep specific records in the required survey format, some questions were answered based on respondents’ practical experience in motor repair.

2 EXISTING AND BEST MOTOR REPAIR PRACTICES

Shops in the countries covered by the study apply non-optimal rewinding or repair motor practices that increase losses in motor energy, thereby degrading their original efficiency. This section reviews both existing rewinding and repair motor practices in the countries based on shop survey and best practices based on motor repair industry recommendations. Appendix I of this report discusses the energy losses and associates them with motor repair practices that cause the loss increases. Motor failures causes are classified in Appendix II.

2.1 EXISTING REWIND/REPAIR PRACTICES IN SURVEYED ECONOMIES

This section describes the major survey findings on current repair techniques based on information[17] collected at repair shops during the in-person interviews in the five economies. Participating shops were recruited based on their sizes (large, medium and small).

2.1.1 Rewind/Repair Techniques in the Five Surveyed Countries

In this section presents an analysis of, rewind/repair techniques used by service shops in the five surveyed countries.

Winding Removal and Stator Core Testing

The survey findings show that shops use different methods to remove winding. In all the economies, none of the shops surveyed use chemical stripping, a method that has probably been phased out over time for health, safety and environmental issues. Approximately 40 percent of shops in Vietnam remove windings manually, which is the least technically advanced technique that likely results in greater efficiency degradation in repaired units. A far greater percentage of shops (approximately three quarters) in China use the mechanical stripping by cold process method[18] than in any other economies. One possible explanation for this difference is that the cold process method is significantly more labor intensive than other processes and may not be financially viable in countries where workers' wages are higher. In all countries surveyed, a larger percentage of medium-sized shops use burn out ovens compared with large-sized and small-sized shops. Using burn out ovens is a standard practice among the Electrical Apparatus Service Association (EASA)[19] member shops; it has the additional benefit of reducing repair time. Ideally, a winding removal procedure in a burn out oven is followed by a stator core test. Surprisingly, fewer shops surveyed in the United States test stator cores compared with shops in other countries, even though all shops in the United States use burn out ovens. All Chinese and Vietnamese shops reported testing stator cores before repair.

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[17] See Section II[17] of the survey form presented in Appendix III for information about repair techniques.

[18] The manual process differs from the cold process: hand tools are used for the first process, while more elaborate tools like hydraulic fixtures or even small cranes are used for the second.

[19] EASA is an international trade organization of more than 1,900 electromechanical sales and service firms in 62 countries. The organization is headquatered in the US.

Measuring Burn Out Oven Temperature

This practice refers to the burn out oven process control. If the temperature in a burn out oven is not controlled accurately, there is a high probability that the stator core lamination insulation will overheat and be damaged. It was observed that slightly less than one-third of small shops do not control oven temperature. Whereas, only a few large-size and medium-size shops do not control oven temperature. Control cost and the lack of awareness about the negative impact of high temperatures in stator cores during burn-outs likely contributed to this observation.

Determining the Need for Stator Lamination Repair

As part of best motor rewind practices, shops should test stator lamination for evidence of damage or missing components to repair any defects revealed during testing. Testing stator cores with appropriate test equipment is associated with good practice, while performing a simple visual inspection is generally considered bad practice. Approximately two-thirds of all shops visually inspect motors to determine whether stator lamination needs repair or not. This is not surprising, as visual inspection is the first-level check for obvious damage. A large majority (more than two-thirds) of shops in all the countries under study, except China, supplement with other methods. United States shops use the widest variety of methods, while Chinese shops use only a few methods. None of the shops surveyed in New Zealand use a commercial core loss tester. This is more likely to be a matter of awareness or local industry culture than technical capability. Shops are probably more focused on preventing recurrent failures than preventing excessive core losses. Recurrent failures are connected with localized hot spots and identified more easily with the core loop flux test, which only requires inexpensive test equipment. Three shops (one in New Zealand, one in the United States and one in Japan) use advanced equipment for testing. These shops rely on thermal imaging, infra-red scanning and sound inspection techniques, respectively, for motor inspection.

Thermal imaging or infrared scanning is used while performing the core flux loop test. Using measurement tools such as these help decide whether a stator core with hot spots is acceptable or not. “Sound” or magnetic noise tests are used to indicate looseness of the stator core (not necessarily the presence of hot spots or insulation damage) and are seldom implemented.

Method to Repair Lamination Damage

In case any defects are detected in the iron core before proceeding with rewind/repair, the best practice is to correct the defect by grinding and de-burring the lamination core plate, replacing removed laminations with the same material, applying the chemical inter-laminar re-insulation process or applying mica between the laminations. It is important to note that the existing material should be identified by testing its chemical properties.

All large-size shops surveyed reported repairing lamination damage, whereas approximately one-fifth of small- and medium-size shops reported not generally repairing lamination damage. The most popular method (about half of all shops) is to grind and separate damaged lamination. This method does not involve removal of laminations and is the most cost-effective method. Grinding is the most popular way to remove ‘drag’ or ‘flash’ in the damaged area. None of the shops in Vietnam use the ‘grinding’ method, likely due to lack of awareness. Similarly, none of the shops surveyed in Japan reported replacing defective laminations, probably due to difficulty in obtaining replacement stampings. A far lower quantity of shops in Japan reported using the repair method involving the removal of laminations, staggering and re-stacking the same or new laminations, as compared with shops in other countries. Although the most reliable, the method of restacking a stator core is the most labor-intensive. Shops in the United States (1) use the widest variety of methods and (2) always report repairing lamination damage. The application of best repair practices among those shops is evidenced by this finding. Finally, in all the economies, medium-sized shops use the widest variety of methods, as opposed to small- and large-sized shops.

Change in Copper Size

During rewind procedure, making sure that the new copper-conductor size is identical to the original size is considered best practice. Also, the size can be changed by increasing the conductor cross-sectional area to enhance motor efficiency. None of the shops in China reported changing copper size, as opposed to more than half of shops in all the other countries combined. Quite possibly, this finding is related to the local repair culture, where Chinese shops probably focus on the exact duplication of winding, which is a simple process without having to redesign the winding.

Replacement Wedges

Magnetic wedges, if not designed and used correctly, can lead to reliability problems. Shops are likely to replace them with non-magnetic wedges to avoid recurrent failures. Also, there is a general lack of awareness in the motor repair industry about the benefits of using magnetic slot wedges.

An approximately equal percentage of shops use magnetic and non-magnetic wedges to replace magnetic wedges. In China, the large and medium-sized shops use non-magnetic wedges, while most small-sized shops use magnetic wedges.

Repairing Rotor Windings

Rotor windings consist of rotor bars and short-circuiting rings. All shops in the United States replace damaged rotor windings, and this practice is prevalent among shops in other countries (more than two-thirds reported replacing damaged rotor windings). Among the large-sized shops, none of the Chinese shops reported following this practice, but this may be due to the small sample of interviewed shops. All medium-sized shops reported replacing rotor windings. Approximately 15 percent of all shops replace rotors outright when rotor windings are damaged.

2.1.2 Availability of Tools and Equipment in Repair Shops

Using particular tools and equipment allows electric motor repair shops to perform higher-quality rewind/repair. The absence of adequate tools and equipment could be an indication of poor repair practices.

Tool Use

Some tools and their repair processes presented in Table 3 were considered in the survey. Except for a bearing oil bath, the absence of these tools in a repair shop is a strong indication of poor rewind/repair practice. For instance, bearing oil bath is an old technology that could be replaced by more efficient tooling; hence, its presence in a repair shop is associated with a poor practice.

Table 3: Surveyed Tools

Repair Process	Tool
Rotor removal	Bearing/pulley pullers
	Single-gantry crane
	Two-gantry cranes
Record winding data	Micrometer screw gauge
Rewinding	Semi-automatic coil winding machine
	Crimping tool
Impregnation	Vacuum pressure impregnation (VPI) system
	Varnish dip tank (When VPI is not used)
Bearing assembly during reassembly	Bearing/pulley pullers
	Bearing induction heaters
	Bearing oil bath

Among all shops in the surveyed countries, bearing oil baths and VPI systems were the least common tools, followed by two-gantry cranes. However, micrometer gauges were the most common tool. It was also observed that U.S. shops have the widest variety of tools, while Chinese shops have the smallest variety of equipment. The main trends observed are summarized as follows:

- Large majorities (80 percent and 100 percent, respectively) of shops in China did not have any bearing/pulley pullers or two-gantry cranes.
- Not surprisingly, all shops had single-gantry cranes.
- None of the Japanese shops had crimping tools.
- Semi-automatic coil winding machines were far more prevalent in large-sized and medium-sized shops than small-sized shops.
- More than 90 percent of small-sized shops did not have any VPI systems. To perform resin impregnation, a shop must ideally have either a varnish dip tank or a VPI system, which is a very expensive piece of equipment. There are other impregnation methods, such as spray or pour methods. However, these methods are not favorably compared with VPI or Varnish Dip methods, as the VPI system allows much better deposition of varnish.

With regards to shop size, large shops had a wider variety of tools, as compared with small and medium shops; this makes perfect sense. It was also observed that slightly less than one-third of all the shops surveyed in the five economies had none of the tools mentioned in the above table. This finding indicates a lack of appropriate equipment to perform repair according to best practices.

To conclude, it the phasing-out of old bearing heating methods (in oil baths) and the reliance on newer induction heating methods shops was observed in a large number of shops, interestingly enough. In fact, based on a literature review, the study team's knowledge and the survey, the old methods used extensively in the past are now less popular in the shops. This is certainly an indication of the shops adopting better repair practices.

Equipment Use

The survey also looked into a certain number of equipment pieces owned by repair shops. The equipment presented in Table 4 is associated with good-quality electric motor repair.

Table 4: Surveyed Equipment

Repair Process	Equipment
Record winding data	Winding resistance meter (digital ohm meter)
	Surge comparison tester
Rewinding	Surge comparison tester
	Winding resistance meter
	Insulation resistance tester <500V
	Insulation resistance tester >500V
	Hipot test kit (status voltage)
Stator core test	Thermo-graphic camera
	Test panel
	Watt meter
	Power analyzer

Since stator windings are most commonly replaced during motor repair, winding resistance is a good, simple check to test for winding uniformity. It was observed that winding resistance meter instruments are the most commonly used equipment, while power analyzers and thermo-graphic cameras are the least commonly used equipment.

Other trends in equipment use are presented as follows:

- In the United States it was observed that small shops tend not to use thermo-graphic scanning. Using power analyzers was not frequent in the shops surveyed. Although one shop reported measuring efficiency, in general most of the shops did not consider efficiency testing as a very important factor for their customers. The shops certainly understand the importance of motor efficiency, but maintaining horsepower output and motor speed through repair seemed to be their customers' prevailing expectations. Those two factors dominated all other repair criteria, including first repair cost.

- Shops in the United States use the widest variety of equipment, while Chinese shops use the fewest type of equipment.
- All shops surveyed in Japan, the United States and New Zealand have a hipot test kit and test panel, respectively. One of the hypotheses to explain this observed practice is customer awareness of service processes and/or the standard expected of EASA member shops.
- A large majority of shops in China and Vietnam do not have any high-voltage insulation resistance testers[20], while none of these shops have any surge comparison testers. This situation could be because high-voltage motors do not form a significant share of failed equipment serviced in China.
  - As expected, the large shops have the widest variety of surveyed equipment, as compared with small and medium shops.

2.2 BEST PRACTICES IN MOTOR REWIND/REPAIR

According to best practice recommendations issued by the repair industry association, in all cases where rewind/repair is called for, electric motor repair facilities should follow specific procedures to retain the efficiency of rewound/repaired motors closer to a new motor's. The procedures include the following:

- Record winding data prior to winding removal to reproduce initial winding configuration. Only rewinding data related to winding connections can be obtained without removing the windings. Details on the number of turns, wire size, the number of parallels and coil pitch can only be noted during winding removal.
- Perform a core loss test before and after rewind/repair. Core losses can be measured in a dismantled motor, using a flux loop test.
- When installing a new winding, ensure that no mechanical modification or change is made to the length and cross-sectional area of the conductor, as designed by the original manufacturer.
- Avoid lamination damage when removing the winding.
- Perform mechanical repair according to manufacturer specifications, if available. Mechanical repair includes shaft checking for wear, cracks, scoring and straightness, as well as bearing repair.

Unlike best repair practices, poor practices overlook these procedures, thereby degrading the original efficiency of motors.

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[20] During the study, it was found that two types of insulation resistance checker exist, with one having higher voltage ratings than the other. HiPot tester (not to be confused with IR checker) is mentioned separately in the survey.

3 MARKET OVERVIEW REGARDING ELECTRIC MOTOR FAILURE AND REPAIR

This section summarizes key data on the types of failure observed on electric motors that workshops regularly receive in the five economies surveyed. The data collected and analyzed in this section resulted from in-person interviews with repair shops in the five economies. Information from the NZ study on motor failure was also used as a coherence check of survey results obtained in this particular country. The section also summarizes key market data on AC motor failure and repair in the five economies. Market data was collected from literature review and in-person interviews with repair shops in the economies.

3.1 MOTOR FAILURE MODES

3.1.1 Winding Failure

The study covered repair practices associated with stator and rotor failure. For each country, information about the percentage of failed motor population affected by either winding failure with/without lamination damage or rotor failure was collected during the survey.

Winding failure is mainly caused by electrical factors and overload conditions. As for lamination, there are several potential causes for damage, including unreliable winding, inadequate external protection systems, stator damage while dismantling a failed bearing, and poor maintenance practices. Rotor failure is discussed in the next section.

Table 5 presents the survey results with respect to winding and rotor failure at the shops surveyed in the economies. Each value in the table is the simple average of the values reported by each shop surveyed in the different economies. For a given country in the table, each block of three values can exceed 100%, because rotor failure was reported to likely occur together with stator winding failure.

Table 5: Winding and Rotor Failure Modes by Power Rating

Power Rating	Failure Modes	Percentage				
		China	Japan	NZ	US	Vietnam
Under 50 kW (67 hp)	Winding failure with lamination damage	25%	7%	23%	98%	28%
	Winding failure without lamination damage	46%	88%	76%		72%
	Rotor failure	29%	7%	5%	1-3%	9%
51 to 200 kW (68 – 268 hp)	Winding failure with lamination damage	24%	8%	25%	98%	28%
	Winding failure without lamination damage	45%	87%	77%		72%
	Rotor failure	31%	6%	5%	1-3%	11%
201 to 375 kW	Winding failure with lamination damage	34%	9%	25%	98%	35%

Power Rating	Failure Modes	Percentage				
		China	Japan	NZ	US	Vietnam
(269 – 502 hp)	Winding failure without lamination damage	41%	87%	73%		66%
	Rotor failure	29%	4%	7%	1-3%	11%
Above 375 kW (502 hp)	Winding failure with lamination damage	33%	9%	22%	98%	30%
	Winding failure without lamination damage	41%	87%	78%		70%
	Rotor failure	30%	3%	8%	1-3%	4%

As shown by the survey, most electric motors sent to repair shops (excluding motors with a simple mechanical problem) had failed due to winding problem. As for winding failure with or without lamination damage, the situation was slightly different across the surveyed economies. Among all the failed motors received at the shops surveyed in NZ and Vietnam, approximately 75% simply had failed due to winding failure without lamination damage and 25% had failed due to winding failure with lamination damage. In the US, most shops surveyed indicated that approximately 98% of failed motors were due to winding failure with and without lamination damage. These shops did not distinguish between cases with and without lamination damage.

In China, the prevalence of lamination damage was slightly higher than in the abovementioned economies. However, in Japan, the prevalence of lamination damage was lower (less than 10%). Better condition-monitoring practices, preventive maintenance practices, machine design and winding quality were possible causes of this trend in that particular country.

3.1.2 Rotor Failure

According to an expert from a leading international motor manufacturer who was interviewed as part of the present study, rotor failure accounted for approximately 5% to 7% of all motor failures, with increasing motor power rating. In other words, for powerful machines (above 375 kW), rotor failure typically accounted for 7% of all failures; as for smaller motors (less than 375 kW), rotor failure accounted for 5%. This general trend is more or less in line with the one revealed by the shop survey results for most economies covered by the study.

In fact, as shown by the survey results (See Table 5), all the US respondents made it clear that motor failure strictly due to rotors were in the range of 1% to 3% at most. Also, the average was approximately 5% for the other economies surveyed except China, where the prevalence of rotor failure was higher (approximately 30%). This phenomenon could be explained by the fact that none of the shops surveyed in China reported using repair standards, guidelines, procedures or specifications. This could result in poor handling of rotors during repair. In addition, this could be due to poor rotor quality.

3.2 MARKET CHARACTERISTICS OF MOTOR FAILURE AND REPAIR

This section covers three major topics, including: (1) the percentages of failed motors repaired versus motors replaced; (2) the characteristics (power rating, enclosure type, number of poles and rewind intervals) of failed motors received by the shops; and (3) the characteristics of repair shops.

3.2.1 Failed Motors Repaired versus Replaced

As shown by the survey results (see Figure 1), most failed motors are repaired rather than replaced. The larger the motor, the more likely it is to be repaired rather than replaced. Overall average results suggest that 54% of failed motors under 50 kW (67 hp) were repaired, 69% for 51 - 200 kW (68 - 268 hp), 87% for 202 - 375 kW (269 - 502 hp) and 89% for motors above 375 kW (502 hp).

Past study results found during the literature review also confirm this trend for opting for repairing or replacing motors. The US survey in the manufacturing sector quoted in de Almeida *et al* (2002: p. 243) is an example of a past study. A juxtaposition of data from this survey and the current study is presented in the figure below.

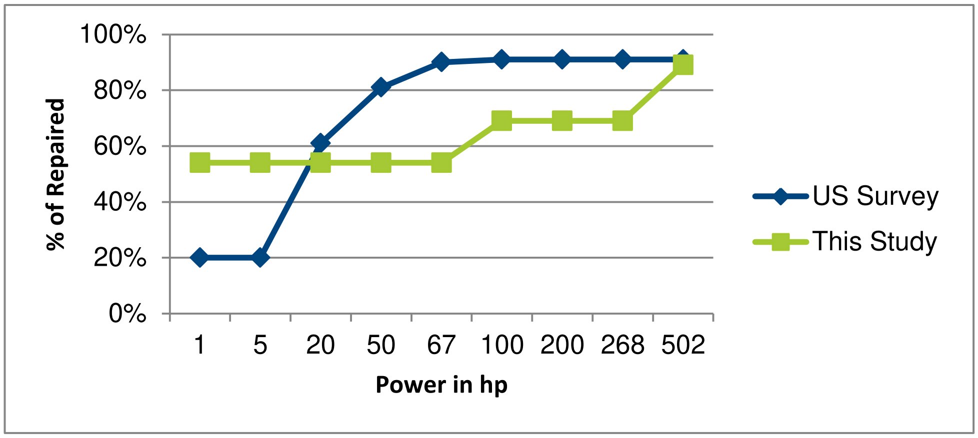

Figure 1: Percentage of Failed Motors Repaired

As shown in Figure 1 based on the US survey, most failed motors 20 hp (15 kW) and above were repaired rather than replaced. By contrast, a large portion (80%) of failed motors 5 hp (4 kW) and below were replaced instead of being repaired.

Data from studies on electric motors undertaken in the EU[21] suggests that rewinding is less competitive and less cost effective on smaller equipment while more competitive on larger equipment, which explains the trend described above.

In conclusion, the proportion of failed motors repaired instead of replaced increased across the economies as the rated power increased.

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[21] See the preparatory studies under The Energy Using Product (EuP) Directive (2005/32/EC) by Anibal T. de Almeida *et al*, 2008, p. 87.

3.2.2 Characteristics of Failed Motors Sent for Repair

This section examines the distribution of the failed motor population by power rating category, according to their power rating, enclosure type and number of poles. It also describes other characteristics, such as rewind interval and motor lifetime.

Distribution of Failed Motors by Power Category

According to the survey results (see Figure 2), the proportion of failed motors below 50 kW (67 hp) from all motors sent to repair shops varied between 56% and 67% for most of the economies surveyed except for the US, where the proportion was approximately 43%. Motors with a power rating from 51 kW to 200 kW (68 hp to 268 hp) accounted for an average of 25% of failed motors in China, Japan, NZ and Vietnam and for 44% in the US. Larger motors accounted for a very low share of failed motors across the five economies.

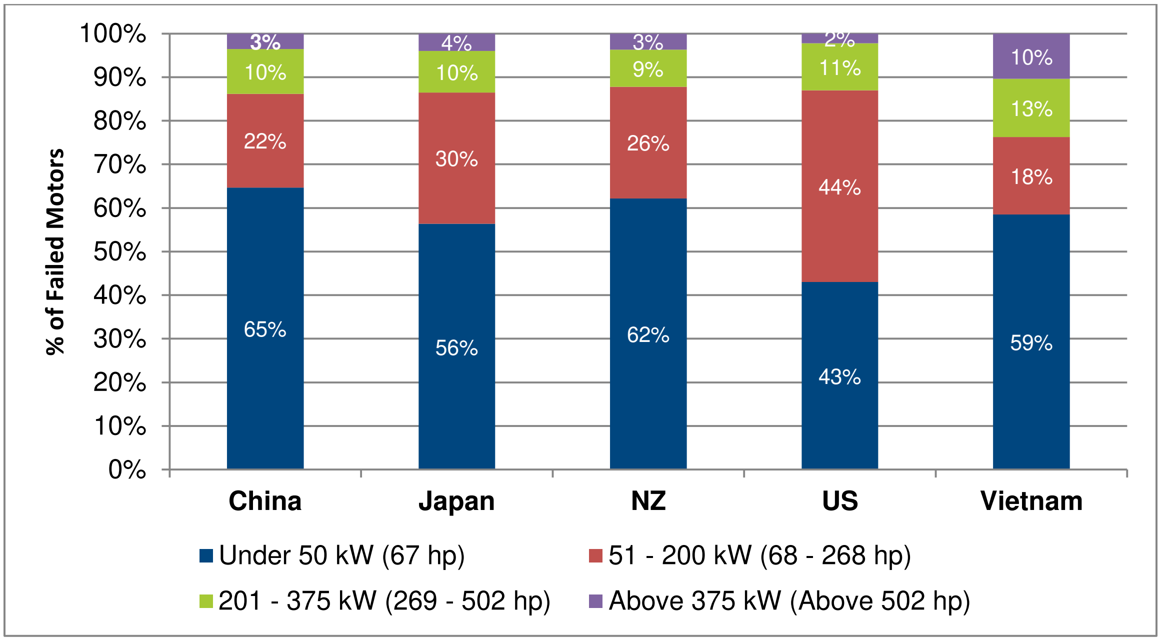

Figure 2: Distribution of Failed Motors by Power Category

Interestingly enough, motors in the first two power rating categories - i.e., motors below 50 kW (67 hp) and motors from 51 kW to 200 kW (68 to 268 hp) – together accounted for 79% to 90% of all failed motors sent to repair shops across the economies. In the US, the first two categories of motors evenly accounted for 43% and 44% of failed motors respectively.

Distribution of Failed Motors by Enclosure Type

There are two main enclosure types used for motors: totally enclosed fan-cooled (TEFC) and open drip-proof (ODP). The survey mainly focused on motors with TEFC enclosure type. The survey results (see Table 6) show significant variations in their nominal efficiencies across the economies.

Table 6: Distribution of Failed Motors with TEFC Enclosure

Power Rating	Percentage (TEFC)				
	China	Japan	NZ	US	Vietnam
Under 50 kW (67 hp)	84%	69%	94%	49%	73%
51 - 200 kW (68 - 268 hp)	83%	63%	86%	51%	49%
201 - 375 kW (269 - 502 hp)	76%	46%	83%	51%	31%
Above 375 kW (Above 502 hp)	74%	47%	83%	56%	30%

In China and NZ, TEFC motors accounted for more than three quarters of motors received by repair shops. US shops received a smaller percentage of TEFC motors under 50 kW (67 hp) than shops in the other countries.

Also, regardless of size class, TEFC motors accounted for approximately half of failed motors sent to repair shops surveyed in the US. This pattern was not consistent with the distribution of installed motors by enclosure type, as shown by data on the US. In fact, past studies in the US indicated that 21% to 30% of installed motors were models with TEFC housings, while 56% to 73% were with ODP enclosures.[22] It is also possible that TEFC motors have become more common in the last 12 years and fail more frequently than ODP motors.

The smallest percentage of TEFC motors among the higher rating categories (201 - 375 kW or 269 - 502 hp) and above 375 kW (502 hp) was observed in Vietnamese shops. In Japan, for motors 200 kW (269 hp) and below and motors 200 kW (269 hp) and above, TEFC motors accounted respectively for 66% and 46% of motors received by shops.

Distribution of Failed Motors by the Number of Poles

AC motors exist in different pole configurations, ranging from 2 to 12 poles. For the purpose of the present study, motors were divided into two categories: motors with four or fewer poles and motors with more than four poles. This choice was made because there is a clear difference in energy Efficiency and other characteristics between these two motor categories as shown in Table 7 below.

Table 7: Number of Poles and Motor Characteristics

	Reliability	Efficiency	Prevalence
Four Poles or Fewer	Less reliable	More efficient	More common
More than four Poles	More reliable	Less efficient	Less common

The survey results are presented in Table 8 below.

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[22] T de Almeida, 2002, 201

Table 8: Distribution of Failed Motors with Four Poles or Fewer

Power Rating	Percentage				
	China	Japan	NZ	US	Vietnam
Under 50 kW (67 hp)	82%	77%	89%	73%	72%
51 - 200 kW (68 - 268 hp)	76%	70%	88%	73%	45%
202 - 375 kW (269 - 502 hp)	75%	68%	87%	65%	39%
Above 375 kW (Above 502 hp)	73%	73%	84%	65%	39%

The survey results suggest that most (approximately 70%) motors, regardless of the power rating category, received by repair shops had four or fewer poles in all the surveyed economies except Vietnam, where approximately 40% of motors above 50 kW (67 hp) had four or fewer poles.

The trend observed in the economies (except Vietnam) was consistent with results of past US surveys,[23] which indicated that 70% to 97% of installed motors had four or fewer poles. This observation is coherent with our survey results and would explain why motors with four or fewer poles accounted for a large majority of motors received by repair shops.

Motor Lifetime and Rewind Intervals

Motor lifetime depends largely on whether motors are properly selected and maintained or not. More specifically, factors such as the number of operating hours, load factor, the number of start/stop cycles, power quality and environmental conditions (temperatures, vibrations, humidity, chemical and corrosive pollutions) influence motor life. Consequently, there is variation in motor lifetime, as shown by the data available from two studies[24] presented in Table 9.

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[23] Ibid, 201

[24] The first was a survey of motor repair shops conducted in 1995 in the US and the results are quoted in Anibal T. de Almeida *et al*, 2002, *Energy-Efficient Motor Systems: A Handbook on Technology, Program, and Policy Opportunities*, Second Edition. The second source is the final report of the preparatory studies on electric motors undertaken under The Energy Using Product (EuP) Directive (2005/32/EC). For the second study, see Anibal T. de Almeida *et al*, 2008, "*EuP Lot 11 Motors*", Final Report, ISR – University of Coimbra.

Table 9: Motor Lifetime (including Repair)

Power Rating	Average Life (Years)[25] (EuP Study on Electric Motors in 2008)	Average Life (Years)[26] (Repair Shop Survey in 1995 in the US)	Life Range (Years)[27] (Repair Shop Survey in 1995 in the US)
0.75 – 3.75 kW (1 – 5 hp)	12	17.1	13 - 19
3.75 – 7.5 kW (5 – 10 hp)	12	19.4	16 - 20
7.5 – 15 kW (10 – 20 hp)	15	19.4	16 - 20
15 – 37.5 kW (20 – 50 hp)	15	21.8	18 - 26
37.5 – 75 kW (50 – 101 hp)	15	28.5	24 - 33
75 – 93 kW (101 – 125 hp)	20	28.5	24 - 33
93 – 250 kW (125 – 335 hp)	20	29.3	25 - 38
Above 250 kW (Above 335 hp)	-	29.3	25 - 38

Data on US motor life span is available, though not recent. By contrast, this data is not available from the literature of the other countries (China, Japan, NZ and Vietnam) covered by the study.

Rewinding intervals or average time between rewindings is another key factor influencing motor lifetime. The survey results show a significant variation across the five economies. The rewind intervals vary from 3 to 21 years across the economies and is not consistent with existing survey results reported in the literature.

Data from a Canadian study quoted in the New Zealand study suggests that rewinding occurs between 3.8 and 7.3 years, with the interval between rewinds decreasing with larger motor sizes.[28] According to a study by the International Energy Agency (IEA), large motors are repaired one, two or even three times during their lifetime.[29] A survey of 12 New Zealand repair shops showed a variation of motor life between rewinds. The survey results suggest a time between rewinds of 12 to 16 years.[30] These figures, collected from available literature, showed a significant variation of the number of times motors are repaired during their lifetime.

Specific data from surveys in China, Japan, the US and Vietnam is not available from the literature. As a result, assumptions based on motor lifetime and rewind interval information mentioned in the previous paragraph will be used as proxy for these economies when estimating the EE potential resulting from the adoption of best practices in motor repair.

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[25] Anibal T. de Almeida *et al*, 2008, p. 63.
[26] Anibal T. de Almeida *et al*, 2002, p. 206.
[27] Ibid.
[28] Electricity Commission, 2006, p. 16.
[29] IEA, 2011, p. 75
[30] Electricity Commission, 2006, p. 16.

3.2.3 Characteristics of Repair Shops

In each economy, understanding the characteristics of the motor repair market requires an analysis of motor repair workshops. To collect country-specific market data, 45 repair shops were interviewed in the five economies. More specifically, 10 shops were interviewed in China, 10 in Japan, 10 in NZ, 7 in the US and 8 in Vietnam. The main findings from the analysis of those surveys are presented as follows.

Shops surveyed in China and in the US have similar motors received/employee metrics across different shop sizes. A higher number of motors received/employee number in Japan and NZ could suggest that subcontracting was carried out by some of these shops. Shops affiliated to a manufacturer averaged a higher motor/employee level, as compared with independent shops; this difference was more pronounced in small shops. It was likely that many of these shops catered to the replacement motor market.

In addition, less than one in three shops surveyed was ISO 9001 certified. None of the shops in the US had ISO certification. In Japan and Vietnam, the average age of shops ISO certified differed significantly from the age of shops not ISO certified. While the ISO certified shops were 20 years older on average than shops not ISO certified in Vietnam, Japanese shops ISO certified were 30 years younger than shops not ISO certified. It is worth mentioning that ISO 9001 is a quality system standard that applies to daily management operations within certified shops. A repair shop implementing the ISO 9001 does not necessarily employ the best practices when repairing or rewinding motors. All US respondents made it clear that the ISO certification has virtually nothing to do with the AC motor repair/rewind business. Therefore, test certificate from some of their larger customers and motor manufacturers mean much more to these shops.

4 ENERGY SAVINGS POTENTIAL

This section discusses the energy savings achievable through the adoption of best practices in rewinding and repairing motors. It first looks into improvement potential on individual motors and for the entire motor population in the five economies. It also looks into the savings that can be achieved by replacing aluminum rotors with copper rotors in each economy.

4.1 ENERGY LOSS INCREASE AFTER REPAIR

Unlike the best practices recommended by the motor repair industry, current practices of shops in rewinding and repairing motors cause an increase in energy loss after motor rewind and repair. To estimate the increase, the study team applied the algorithm presented in Section 4 of Task 1 report. The table below presents the average energy loss increase by motor power rating category and by country. APPENDIX III presents detailed energy loss figures by power rating, the number of poles and frequency.

Table 10: Percentage Increase in Energy Loss after First Repair Using Current Standard Practices

Power Rating Category	Loss Increase in % after Rewinding without Lamination Repair					Loss Increase in % after Rewinding with Lamination Repair				
	China	Japan	New Zealand	US	Vietnam	China	Japan	New Zealand	US	Vietnam
Under 50 kW (67 hp)	4.38	4.73	2.81	3.24	4.78	4.74	4.91	2.93	3.25	5.03
51 – 200 kW (68 - 268 hp)	4.90	5.53	3.44	3.75	5.34	5.40	5.77	3.62	3.78	5.67
201 – 375 kW (269 – 502 hp)	4.90	5.68	3.54	3.87	5.39	5.42	5.94	3.72	3.91	5.76
Above 375 kW (502 hp)	4.83	5.84	3.60	4.01	5.40	5.38	6.12	3.79	4.05	5.80

The figures in the table above suggest that energy loss increases after rewinding with lamination repair are higher than that after rewinding without lamination repair. In fact, employing poor practices to determine if lamination has any defects and to repair lamination damage is a source of energy loss increase in motors. Poor practices still being employed by some shops include visual-inspecting stator laminations for evidence of damaged or missing components and not repairing the lamination damage before proceeding with the rewind/repair.

Increases in motor energy loss after repairs in New Zealand and the US are generally lower than those in China, Japan and Vietnam. The levels of increase in motors energy loss after repair in Japan are high and counter-intuitive, given that this country is technologically as developed as New Zealand and the US. This is because most shops (90%) interviewed in Japan reported removing stator windings by mechanical stripping after heating with an open flame, which is a poor practice that weighs significantly in the algorithm mentioned in Section 4.1 above. This could be due to the fact that small shops interviewed in Japan account for 70% of total shops, as opposed to 40% in the other economies covered by the study; hence, small shops are likely to use good practices.

It is worth mentioning that the figures in the table above account for the impact on the original efficiency after rotor repair, because all the shops interviewed reported that rotor failure could coincide with stator winding failure. Rotor failure is not treated as a separate practice, because very few motors are sent to repair shops just because of those failures. In general practice, repair shops use motor rewind or repair as an opportunity for repairing rotors.

In conclusion, when considering motors individually, the estimated increases in energy loss after repair range from 2.81% to 6.12%.

4.2 SAVINGS POTENTIAL FROM EMPLOYING BEST PRACTICES TO REPAIR MOTORS

This section discusses the energy savings potential achievable through rewinding/repairing motors, using recommended best practices on the market by considering the total population of motors in a country.

4.2.1 Assumptions

Estimating the energy savings potential requires making a number of assumptions regarding the existing motor repair market in the five countries. The assumptions are summarized as follows.

Assumption 1: Motors are Repaired Three Times at Most over their Lifetimes.

To estimate the number of times they are repaired during their lifetimes, motors are assigned a lifetime and a rewind/repair interval, based on the data available from the literature and presented in Section 3.2.2 above. Particularly large motors (above 50 kW), are repaired more than once during their lifetimes. Also, after the second repair, there is an increment of a certain percentage in energy loss increase, as explained in Assumption 2 below. After operating over the assigned lifetime, motors are assumed to be replaced and not repaired. Table 11 presents the lifetimes and rewind intervals assigned to motors by power rating categories.

Table 11: Lifetimes and Repair Intervals Assigned to Motors by Power Rating Category

Power Rating Category	Lifetime (Years)	Rewind Interval (Years)	Number of Repairs during Lifetime
Under 50 kW (67 hp)	16	13	1
50 – 200 kW (68 - 268 hp)	26	10	2
200 – 375 kW (269 – 502 hp)	30	8	3
Above 375 kW (502 hp)	30	8	3

Assumption 2: Increase in Energy Loss after Repeated Repairs Does not Exceed 125% of the Estimated Loss Increase after the First Repair.

To account for the impact of past repairs on the original efficiency of motors, it is assumed, based on the experience of the ABB research center, that after repeated repairs, the energy loss increase does not exceed 125% of the estimated loss after the first repair. Therefore, to determine the increase in energy loss of motors after the second repair, a factor of 1.20 was applied to the loss increase of motors after the first repair, as presented in Table 10. Similarly, a factor of 1.24 is used for the same motor after the third repair.

Assumption 3: Employing Best Motor Repair Practices Maintains their Original Efficiency.

Some motor repair industry associations have recommended best practices for motor rewinding and rebuilding. These practices are based on lessons learned from a scientific study[31] conducted by two prominent motor repair industry associations: EASA and the Association of Electrical and Mechanical Trades (AEMT).[32] The study looked into the impact of repair/rewinding on motor efficiency. Study results proved that motors repaired following best practices can maintain and even improve their nominal efficiency. Table 12 presents results for motors rewound under controlled conditions (recommended best practices) during the study.

Table 12: Results of Motor Rewinds under Controlled Conditions[33]

Motor Description	Efficiency before Rewind	Efficiency after Rewind	Efficiency Change*	Comments
200 hp, 60 Hz, 4 poles	95.7%	95.1%	-0.6%	1st rewind
		95.6%	-0.1%	2nd rewind
150 hp, 60 Hz, 2 poles	95.9%	95.9%	0.0%	1st rewind
		95.9%	0.0%	2nd rewind
		95.8%	-0.1%	3rd rewind

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[31] EASA/AEMT, 2003, *The Effect of Repair/Rewinding on Motor Efficiency*, pp.1-6

[32] EASA and AEMT intended to find definitive answers to efficiency issues for motor users and others, since there were claims that rewinding inevitably decreases motor efficiency.

[33] The table is adapted from A. Bonnett and B. Gibbon, *The Results Are in: Motor Repair's Impact on Efficiency*, p.6

Motor Description	Efficiency before Rewind	Efficiency after Rewind	Efficiency Change*	Comments
110 kW, 50 Hz, 4 poles	94.8%	94.6%	-0.2%	1st rewind
		94.6%	-0.2%	2nd rewind
75 kW, 50 Hz, 4 poles	93.0%	93.6%	0.6%	1st rewind
		93.6%	0.6%	2nd rewind
		93.7%	0.7%	3rd rewind
5.5 kW, 50 Hz, 4 poles	86.7%	86.9%	0.2%	Five burnouts at 360°C, one rewind only
5.5 kW, 50 Hz, 4 poles	83.2%	84.0%	0.8%	Five burnouts at 360°C, one rewind only

* Each of the percent changes is relative to the "before rewind" efficiency

The table above demonstrates clearly that, even after multiple rewinds, maintaining and even improving the nominal efficiency of motors is technically feasible.

Based on these results, it was assumed that the original energy loss of motors does not increase after it is repaired using best practices. Therefore, the energy savings achievable through employing best practices to repair motors are considered to be equal to the increase in energy loss of motors after applying current practices for repair.

Assumption 4: Motors Are Sent to Repair Shops due to Winding Failure with or without Lamination Damage.

This assumption was made for simplification reasons and is based on the survey results suggesting that the majority of failed motors (excluding motors with only mechanical damage) received at repair shops are due to winding failures with or without lamination damage. Rotor failure alone is never reported as the reason why motors are sent to the repair shops. Motors are sent for repair only when there is winding failure. Table 13 presents the percentages of failed motors by type of winding failure considered for each economy in this study, based on the survey results presented in Table 5 in Section 3.1.1.

Table 13: Breakdown by Winding Failure

Winding Failure	China	Japan	New Zealand	US	Vietnam
Without lamination damage	45%	85%	75%	50%	75%
With lamination damage	55%	15%	25%	50%	25%
Total	**100%**	**100%**	**100%**	**100%**	**100%**

Assumption 5: Not All Motors Failing Every Year Are Sent to Repair Shops

This assumption was based on the findings presented in Section 3.2.1. To estimate the percentage of failed motors sent every year to shops, a proportion of these motors in each power rating category in each economy was assumed, based on the findings. Table 14 presents the values considered for the five economies. Failed motors not sent for repair are taken out of service (and usually replaced).

Table 14: Failed Motors Repaired versus Replaced

Power Rating Category	Percentage of All Motors Sent to Shops
Under 50 kW (67 hp)	65%
50 – 200 kW (68 - 268 hp)	90%
200 – 375 kW (269 – 502 hp)	91%
Above 375 kW (502 hp)	91%

Assumption 6: As of 2015, All Motors Sent to Repair Shops Are Repaired Using Best Practices.

A time horizon starting from 2015 and lasting throughout the lifetimes of motors was considered for the energy savings analysis, for which savings were calculated. In other words, starting from 2015, the savings were estimated over a period of 16 years for motors under 50 kW (68 hp), over 21 years for motors with a rated power between 50 – 200 kW (68 - 268 hp), and over 30 years for motors between 200 – 375 kW (269 – 502 hp) as well as motors above 375 kW (502 hp). Therefore, to estimate the savings volume, the energy savings achievable through employing best motor repair practices were compared with the total electricity consumption of motors in 2015 in each of the five economies.

4.2.2 Electricity Savings Estimate

The methodology for calculating the electricity savings achievable through using best motor repair practices is discussed in Appendix IV of this report. Using the savings estimation resulting from this methodology, an estimate of the electricity savings potential associated with the adoption of best practices for rewinding without or with lamination repair can be established. Figure 3 presents the savings potential over the lifetimes of all the motors in operation in each country by power rating category. The estimated savings take into account the installed stock in 2015, as shown in Table 23 in APPENDIX IV. The savings potential is inclusive of two repair practices: rewinding without and with lamination repair. The figure also presents the additional cost that end users could avoid if their motors were repaired using best practices. APPENDIX V of this report presents the detailed savings calculation results.

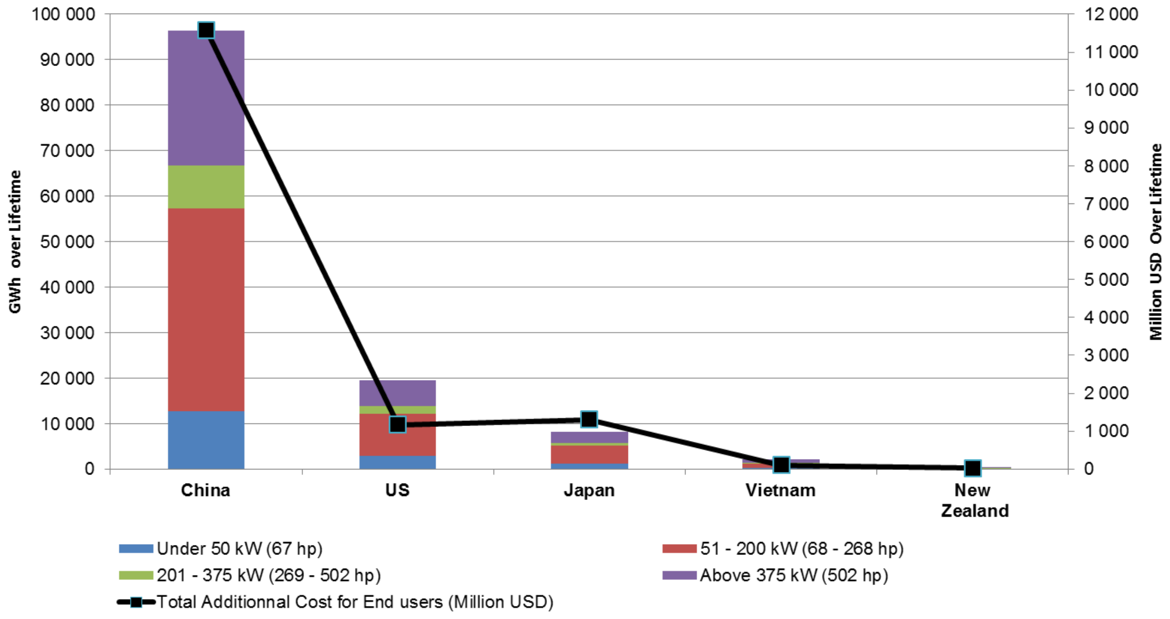

Figure 3: Annual Electricity Savings after Repair Using Best Practices

The total amount of electricity savings associated with the adoption of best motor repair practices up to the lifetime of total motor stock in each of the five economies varies widely, from 219 GWh (for New Zealand) to 96,000 GWh (for China) which is understandable considering the large difference in size for those economies. As of 2015, on an annual basis, these savings will range from an average 8 GWh (for New Zealand) to 3,800 GWh (for China). The estimated savings takes into account the potential growth of the installed stock.

In addition, employing best motor repair practices over their lifetimes can help motor users avoid additional electricity costs, which range from USD 26 million in New Zealand to USD 11,000 million in China. The additional costs to motor users become higher in countries such as Japan, where electricity price is higher than that in the other countries covered by the study, as presented in Table 15 below. It is worth noting that electricity prices for industrial consumers is used, since motors in this sector account for the majority (64%) of electricity consumption of all motors across sectors.

Table 15: Electricity Prices for Industrial Consumers in USD/kWh

Country	Price
China	0.12
Japan	0.16
New Zealand	0.12
US	0.06
Vietnam	0.05

Figure 4 shows the estimated average savings potential (in %) achievable annually in each country covered by the study. For each economy, the percentage is relative to the total motor electricity consumption in 2015.

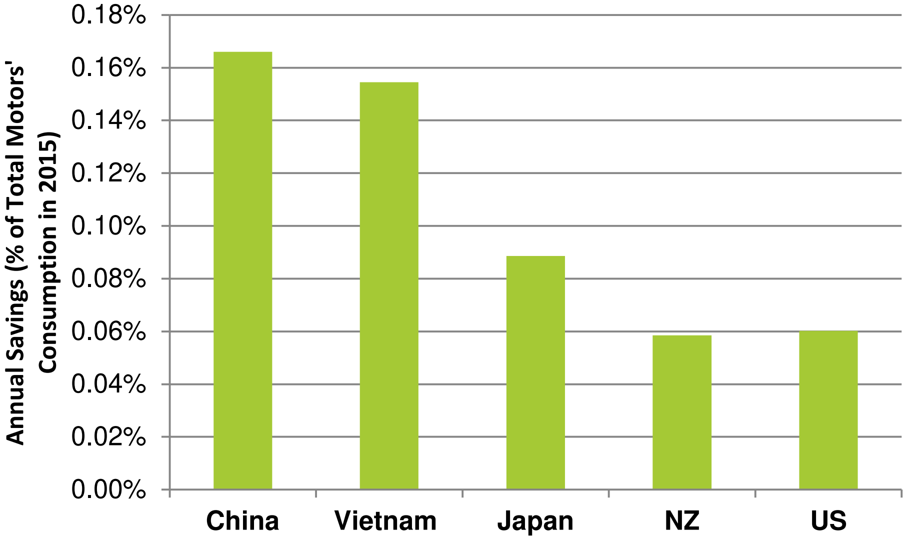

Figure 4: Electricity Savings Potential

Annual electricity savings will range from 0.06% to 0.17% of the total electricity consumption by motors in 2015. The savings potential is higher in China and Vietnam than in Japan, New Zealand and the US. As suggested by the findings of the survey conducted under this study, shops in Japan, New Zealand and the US are better equipped and use a wider variety of tools to repair motors. By contrast, shops in Vietnam and China have a limited variety of tools for motor repair. Therefore, increases in energy loss in repaired motors in Japan, New Zealand and the US are lower than those of repaired motors in China and Vietnam.

4.3 ROTOR REPLACEMENT

There are four types of rotor construction: (1) aluminum die cast (ADC); (2) copper die cast (CuDC); 3) fabricated aluminum bar; and 4) fabricated copper bar. In general, only the ADC, fabricated aluminum bar and copper bar rotors are in common use today. The CuDC rotor, hereinafter referred to as copper rotor, is a new technology.

One potential avenue to reducing overall loss in electric motors and improving their efficiency is to replace aluminum rotors with copper rotors during repair. To estimate the potential for this measure, results from laboratory studies on the key operation parameters of copper-rotor motors have been analyzed.

This section presents some key findings of selected ICA[34] studies that focus on the efficiency and speed improvement of motors associated with rotor replacement. Also, it presents the estimated electricity savings achievable by replacing their aluminum rotors with copper rotors, assuming that the technology is available.

4.3.1 Key Findings from Motor Rotor Replacement Tests

In a recent study conducted by the ICA, motor testing allowed to measure the efficiency improvement of motors equipped with copper rotors. The results of those tests were then used to develop a model to simulate energy efficiency improvement of motors as a result of changing aluminum rotors with copper ones. According to the simulation results of the model built by the ICA, replacing aluminum rotors with copper ones can improve motor efficiency from IE1 to IE2[35] and even from IE1 to IE3[36], representing 2 and 3 percentage points in improvement, respectively.

Similarly, data available from other studies suggest that installing copper rotors in motors initially fitted with aluminum rotors generally results in improved efficiency and increased motor speed. Table 16 compiles measured values of these performance characteristics as reported in some selected studies. The figures in the table show that overall motor nominal efficiency increases when replacing aluminum rotors by copper rotors. It also shows that copper rotors allow running motors at a slightly higher speed compared with their aluminum counterparts. This is expected because motors with higher energy efficiency have lower slip and, therefore, run at a higher speed.

Table 16: Performance Characteristics of CuDC Rotor and Aluminum from Other Studies[37]

Rated Power	Efficiency (%)		Full Load Speed (rpm)		Difference (%)	Difference (rpm)
	CuDC Rotor	Aluminum Rotor	CuDC Rotor	Aluminum Rotor		
1.5 kW (2 hp)	82.54	81.14	2,949	2,926	1.4	23
3.7 kW (5 hp)	87.09	83.99	2,947-	2,925-	3.1	22
5.5 kW (7.5 hp)	79.0	74.0	-	-	5.0	-
7.5 kW (10 hp)	86.5	85.0	-	-	1.5	-
11.2 kW (15 hp)	90.7	89.5	1,775	1,760	1.2	15
18.8 kW (25 hp)	92.5	90.9	-	-	1.6	-
200 kW (270 hp)	93.0	92.0	-	-	1.0	-

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[34] ICA is an international association with a mission to defend and grow markets for copper, based on its superior technical performance and contribution to a higher quality of life worldwide.

[35] For three-phase motors, IE1, IE2 and IE3 are efficiency classes defined by the international standards IEC 60034-30:2008

[36] ICA simulation results were kindly provided by Daniel Liang.

[37] Compilation of data from D.T Peters et al, *Performance of Motors with Die-cast Copper Rotors in Industrial and Agricultural Pumping Applications* and E. Brush et al, *Die-cast Copper Motor Rotors: Motor Test Results, Copper Compared to Aluminum.*

The figures in the table above provide the background information required to predict the energy savings potential associated with replacing aluminum rotors with copper rotors in each of the five economies covered by the study.

4.3.2 Savings Estimates

Centrifugal Loads

For centrifugal loads such as pumps, blowers and centrifugal air compressors, the power of the equipment is proportional to the cubic power of the impeller (pump and air compressor) or wheel (fan) speed. As mentioned in the previous section, copper-rotor motors operate at a slightly higher speed than their aluminum counterparts. This implies that the power drawn by centrifugal equipment could increase by the cube of the ratio of the motor speed after the replacement to the prior motor speed, thereby offsetting the gains resulting from the higher copper-rotor motor efficiencies. In extreme cases, the results could be energy losses.

Higher speed after an aluminum rotor is replaced with a copper rotor can induce operational problems for certain processes, for which a precise speed is required. Hence, increase in speed and flow could create a problem when an aluminum rotor is replaced with a copper rotor for motors driving pumps and blowers; this effect must be considered when repairing motors, which is not a trivial task.

However, combining a copper-rotor installation with variable frequency drive (VFD) technology has the potential to mitigate the issue related to speed increase in centrifugal equipment by adjusting the speed back to what is really needed by the process. Combining copper-rotor motors with a VFD will increase energy savings, but will require a larger upfront capital expenditure.[38]

In conclusion, centrifugal devices and their operating conditions must be examined carefully before considering a rotor replacement. Therefore, for centrifugal loads, the energy savings associated with the measure will be considered only for the fraction of motors in the market equipped with VFD control.

Other Load Types

For constant torque loads such as reciprocating compressors, conveyor belt and crushers, a reduction in rotor loss resulting from replacing the aluminum rotor with a copper rotor improves motor efficiency with a similar increase in rotor speed. However, the negative effect is much less significant, since this load power requirement varies linearly with the speed instead of by a cubic power of its variation. This is especially true if the equipment is controlled by a feedback from a mass or volume signal (a higher speed means that a higher volume or mass will be moved in less time, so the equipment could operate a shorter time).

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[38] Copper Development Association Inc. http://www.copper.org/environment/sustainable-energy/electric-motors/case-studies/a1357.html. Consulted on February 14, 2014.

Savings Estimates

Based on the methodology presented in Appendix VI, the electricity savings associated with the rotor replacement measure are calculated and presented in Table 16.

Table 17: Savings From Replacing Aluminum Rotors with Copper Rotors in all Eligible Motors in 2015

	Power Rating	China	US	Japan	Vietnam	New Zealand
Electricity Savings (1,000 GWh)	Under 50 kW (67 hp)	21.0	10.7	3.1	0.4	0.127
	51 - 200 kW (68 - 268 hp)	10.0	5.1	1.5	0.2	0.061
	201 - 375 kW (269 - 502 hp)	0.07	0.04	0.01	0.001	0.0004
	Above 375 kW (502 hp)	0.23	0.12	0.03	0.005	0.001
	Total	**31.3**	**16.0**	**4.6**	**0.6**	**0.2**
Electricity Cost Savings in 2015 (Million USD)	-	3,700	960	700	30	20
Motors Electricity Consumption in 2015 (GWh)	-	2,300,000	1,300,000	370,000	52,000	15,000
Savings (% of Motors Electricity Consumption in 2015)	-	1.36%	1.23%	1.23%	1.23%	1.27%

Replacing aluminum rotors with copper rotors can result in an estimated savings ranging between 200 GWh and 31,300 GWh, depending on the economy considered. Those savings are cumulative for the two following motors applications:

1 Motors that drive centrifugal loads (pumps and blowers) and are controlled by an VFD; and
2 Motors that drive other types of loads (compressors, conveyors, etc.).

This is equivalent to 1.23% to 1.36% of the total electricity consumption of AC motors in 2015 in the five economies. It is worth noting that the savings estimate assumes that aluminum rotors in all eligible motors are replaced in 2015. This assumption was made to determine the technical savings potential achievable from replacing aluminum rotors with copper rotors in eligible motors.

Electricity savings from replacing aluminum rotors with copper rotors in small motors (50 kW or 67 hp and below) are significant, approximately 67% of total electricity savings achievable from rotor replacement in each economy.

5 CAUSES OF ESTIMATE UNCERTAINTY

Uncertainty in the energy savings estimates is dependent on the availability and quality of data on the quantity of motors and their operation parameters in the surveyed economies. Operation parameters include annual motor operating hours and efficiency by power rating category. Ideally, these parameters should be country-specific and recently updated, because technology, materials, manufacturing techniques, weather conditions, etc. change over time. As there are little hard facts from previous studies in most surveyed economies, proxies had to be used for economies with data unavailable. For instance, most values attributed to the operating parameters were taken from past surveys conducted in the US industrial sector and applied to the other four countries covered by the study.

6 PAYBACK ANALYSIS

This section looks into the economics of repair using best practices for winding and rotor replacement for a typical motor representing each power category considered in this study.

6.1 MOTOR REPAIR USING BEST PRACTICES

This section examines the characteristics of motors considered for the economic analysis of using best practices to repair motors and the associated results by focusing on the payback.

6.1.1 Characteristics of Analyzed Motors

The basic characteristics of the baseline motors used in the analysis are presented in the following table.

Table 18: Basic Assumptions for the Economic Analysis

Parameters	Power Rating			
	Under 50 kW (67 hp)	51 – 200 kW (68 – 268 hp)	201 – 375 kW (269 – 502 hp)	Above 375 kW (502 hp)
Nameplate power (kW)	50	150	375	775
Enclosure type (ODP or TEFC)	TEFC	TEFC	TEFC	TEFC
Number of poles	<= 4	<= 4	<= 4	<= 4
Nameplate efficiency (%)	91.6%	92.2%	93.3%	93.3%
Loading (%)	75%	75%	75%	75%
Type of load (fixed or variable)	Fixed	Fixed	Fixed	Fixed
Hours of operation (hours/year)	3200	5250	6132	7186

Other inputs, such as the escalation rate of electricity prices and the cost of repairs considered for the analysis, are presented in Table 27 and Table 28, respectively in APPENDIX VII of this report. As for the electricity prices, refer to Table 15 above.

6.1.2 Economic Analysis Results: Best Practices Versus Current Practices

The analysis considers a period of 10 years and a discount rate of 12%. Based on these assumptions, Figure 5 presents the estimated payback of the incremental investment if shops employed the best practices recommended by repair industry associations, for the repair of the population of motors mentioned in Table 18 for the five economies covered by the study. For simplification purposes, the only repair practice considered for the economic analysis is rewinding without lamination repair. A detailed example of payback calculation is presented in Appendix VIII of this report.

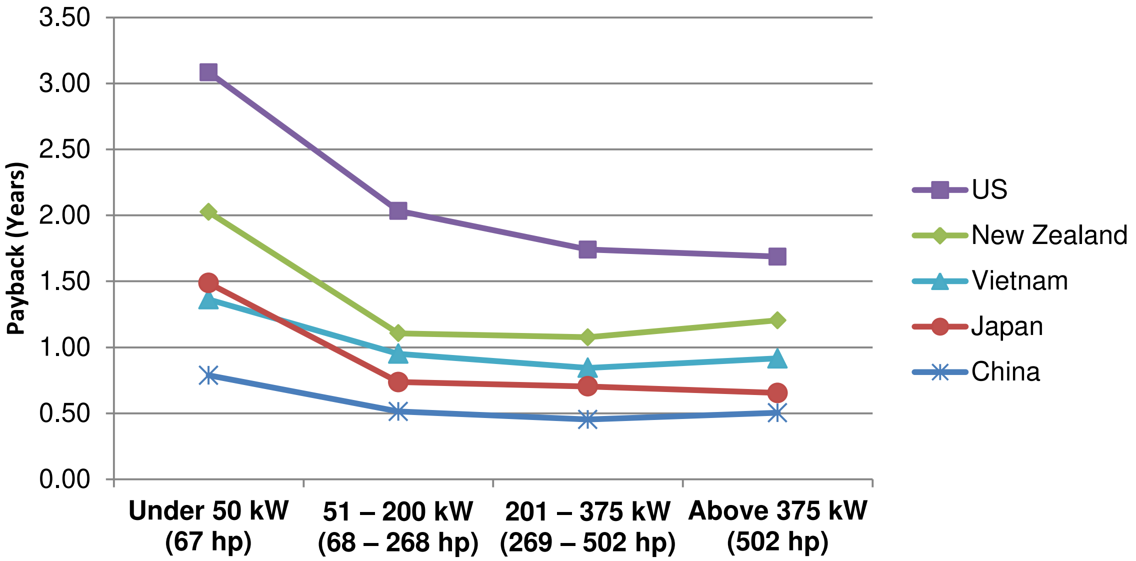

Figure 5: Payback Period by Rated Power Category

As can be seen from the figure above, the payback ranges from 0.56 to 2.92 years, depending on the rated power category and the economy.

Payback periods in the United States are longer than those in the other economies due to relatively low electricity prices and higher labor costs. Unlike in the US, the labor cost in China is lower but electricity prices are high. Therefore, the payback in China is shorter compared to the other economies.

Across the rated power categories, the payback improves as rated power increases. Hence, motors more powerful than 50 kW (67 hp) have a shorter payback compared with those under 50 kW due to longer operations and higher electricity savings.

6.1.3 Impact of Variation in Labor and Material Cost

In this section, the impact of increases in labor and material costs on the payback estimated in the previous section is analyzed. Motor repair costs consist of labor and material costs. The costs of copper, which is the main material used for winding repair, account for almost the totality of the material costs. Table 19 presents the ratio of labor to material costs for motor repairs by category of motor power for each of the five economies. The ratios are compiled based on data collected from experts from a leading motor business (repair shop), interviewed as part of the present study.

Table 19: Ratio of Labor to Material Prices

Power Rating	US	China	Vietnam	New Zealand	Japan
Under 50 kW (67 hp)	3	0.3	0.3	1.7	2.5
51 – 200 kW (68 – 268 hp)	1.5	0.15	0.15	0.8	1.2
201 – 375 kW (269 – 502 hp)	1.2	0.1	0.1	0.9	1.3
Above 375 kW (502 hp)	1	0.1	0.1	1	1

To estimate the effect of labor and material cost increases, two scenarios were considered. The first scenario (Scenario 1) considers 15% and 10% annual increases in labor and material cost, respectively. The second scenario (Scenario 2) considers 30% and 20% annual increases in labor and material cost, respectively. These scenarios are coherent with international repair cost trends as analysts predict that the upward trend in the labor and copper costs will continue in the coming years.

Figure 6Figure 6 below presents payback increases under Scenarios 1 and 2.

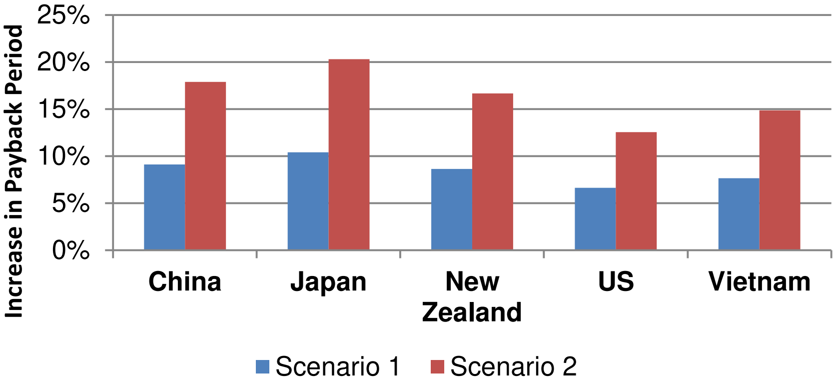

Figure 6: Payback Increases under Both Scenarios

It can be seen from the figure above that across the economies, the payback period lengthens as labor and material costs increase. The payback increase ranges between 7% and 10% to 13% and 20% under Scenarios 1 and 2, respectively. The payback is sensitive to changes in labor and material costs.

6.2 ROTOR REPLACEMENT

As mentioned in Section 4.3.1 above, the ICA conducted a study with the objective of testing rotor replacement on some motors and preparing a mathematical model to simulate energy efficiency improvement for motors, for which aluminum rotors are replaced by copper rotors. This section presents the economics of rotor replacement for a 7.5 kW motor manufactured and operated in China, as taken from the results of the study.

Table 20: Economics of Rotor Replacement for a 7.5 kW Motor in China[39]

Items	Value
Price of new Y-series (IE1) 7.5KW	RMB[40] 1900 (USD 312)
Price of copper rotor of 7.5 KW motor	RMB 750 (USD 123)
Price of new IE3 7.5 KW motor	RMB 3500 – 4000 (USD 576 – 658)
Labor cost to replace rotor (excluding shaft and bearing)	RMB 250 (USD 41)
Motor efficiency improvement from 87% (before rotor replacement) to 90.4% (after rotor replacement)	3.4%
Annual Operating Hours	4,000 hours
Annual Electricity Savings	1297 kWh
Annual Electricity Cost Savings	RMB 1,297 (USD 213)
Payback Period for Rotor Replacement	**0.77 years**
Payback Period for Replacing Motor with a New IE3 Unit	**2.7 years**

As Table 20 shows, the payback period is 0.77 years, which is much shorter than replacing the motor with a new one with an IE3 efficiency level.

The study has not looked into the economics of rotor replacement for large motors (above 50 kW) for the following reasons: These motors are low in number (fewer than 7% of total motors in use in the economies); and their energy savings associated with replacing their aluminum rotors with copper rotors are smaller than for lower capacity motors. In addition, one of the ICA study findings suggests that production of copper rotor for large motors will be too expensive and, therefore, difficult to promote. In fact, according to motor repair experts interviewed as part of study, the cost of a new rotor can be at least 60% of that of a new motor above 50 kW, which will reduce the economic interest of this type of energy efficiency measure.

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[39] Results provided by ICA
[40] Chinese renminbi (1 RMB is USD 0.16)

7 SUMMARY OF FINDINGS

Based on Task 1 and 2 findings, this report presents the energy efficiency savings feasible by employing best practices in repairing motors in the five economies under study, namely China, Japan, New Zealand, the US and Vietnam. The report also provides expected savings from replacing aluminum rotors with copper rotors in motors in operation in the said economies. The main findings of the study are as follows:

- The most common poor practices identified include removing windings by using hand tools and mechanical stripping by cold process. Other poor practices involve stator lamination repair and include the lack of visual inspection of stator lamination to determine whether it needs repair or not and overlooking repair defects usually detected by visual inspection. These poor repair practices were often associated with a lack of proper tools and equipment, such as burn-out ovens, vacuum pressure impregnation (VPI) systems, insulation resistance testers, hipot test kits and thermo-graphic cameras.
- Stator winding failure (without or with lamination damage) is the leading reason for sending motors for repair (excluding motors with only mechanical damage) and accounts for nearly 100% of failures in all countries under study, except China. Whereas in China, 70%-75% of failures were winding failures and rotor failure accounts for the remainder. When broken down to take into account occurrence of lamination damage, the general trend observed in New Zealand and Vietnam is that winding failure without and with lamination damage accounts for 75% and 25%, respectively of winding failure. The prevalence of lamination damage was slightly higher in China (up to 35%) than in the other four economies covered by the study. However, in Japan, the prevalence of lamination damage was quite low (less than 10%).
- Most failed motors are repaired rather than replaced. The larger the motor, the more likely it is to be repaired instead of replaced. Motors are typically rewound between one and three times during their 16- to 30-year lifetimes, with smaller motors at the bottom and larger motors at the top of this lifetime range.
- Poor motor repair practices reduce motor energy efficiency only in a small percentage, but result in significant energy losses when several poor practices are aggregated, thereby degrading the efficiency of repaired motor. Adopting recommended best practices to rewind and repair motors could result in an average annual electricity savings potential between 8 GWh and 3,800 GWh in the five economies, with New Zealand at the bottom and China at the top of the range. In percentage terms, this potential ranges between 0.06% and 0.17% of annual motor electricity consumption in the economies. These savings represent the additional motor electricity consumption that would be avoided if repair shops adopted best practices to repair and rewind motors.
- Adoption of better motor repair practices is a highly cost effective investment. In fact, end users' investment required for the adoption of best motor repair practices are generally paid back in energy savings in less than two years.

- End users seldom choose to retrofit their motors with copper rotors, as doing so can be time consuming and expensive when a suitable replacement is not readily available in stock or if it must be custom fabricated. Energy savings from replacing aluminum rotors with copper rotors in motors can be significant, particularly in the largest economies under study: China and the United States. Assuming that aluminum rotors are replaced with copper ones in all eligible motors in 2015, the electricity savings are estimated at 31,300 GWh and 16,000 GWh for China and the US, respectively. New Zealand would have the lowest electricity savings estimate with 200 GWh. Motors that provide constant torque to linear loads (such as reciprocating compressors, conveyor belts, and crushers) are the most likely to generate savings, as they are less affected by the power penalty associated with the slight speed increase caused by copper rotors. Electricity savings from replacing aluminum rotors with copper rotors in small motors (50 kW, or 67 hp or below) can be significant, with approximately 67% of total electricity savings feasible through rotor replacement in each economy.

8 DISCUSSION AND RECOMMENDATIONS

This section discusses barriers to adoption of best practices in motor repair and rewind and adoption of copper rotors in motors. It also provides recommendations to mitigate those barriers.

8.1 BARRIERS

As shown in the previous sections, the average annual savings potential associated with employing best practices to repair motors and replacing aluminum rotors with copper rotors is significant. But several barriers impede adoption and rapid market promotion of these energy efficiency measures.

8.1.1 Barriers to Adoption of Best Practices in Motor Repair and Rewind

The barriers include: lack of harmonized repair quality standards, lack of simple certification programs, customers' preference for fast turnaround over repair quality, lack of experienced motor repairers, and lack of appropriate tools and equipment required to apply the best practices. These barriers were mentioned by several stakeholders during the in-person interviews discussed in Section 1.3.

Lack of Harmonized Repair Standards

Motor repair is neither regulated nor centralized, and no harmonized or uniform standard exists for the entire range of services that can be performed on a motor on a global scale. Some international standards cover only a limited scope of motor repair activities. For example, IEC standards 60034-23 cover specifications for the refurbishing of rotating electrical machines. IEC standards 60079-19 applies to equipment repair, overhaul in explosive and hazardous atmosphere and is not specific to motors. IEEE standard 6080 only applies to motor repair and rewind for the petroleum and chemical industry. Service shops that intend to adopt these standards must have their facilities audited and their processes and staff evaluated.

In the US, motor repair industry specifications include both the Electrical Apparatus Service Association (EASA) specifications (ANSI/EASA AR100) and the motor repair specifications of the Consortium for Energy Efficiency (CEE).

Some repair shops in New Zealand, EASA members, indicated during the interviews that they repair motors in accordance with EASA-recommended best practices. Of an estimated 58 motor repair workshops, 24 (19 businesses) were members of the New Zealand EASA chapter in 2006.[41] Currently, 19 businesses are chapter members.

In China and Vietnam, most repair shops reported not following any repair standards, guidelines, procedures or specifications for motor repair or rewind. In Japan, some shops follow manufacturer standards, while others rely on their own standards.

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[41] Electricity Commission, *Industrial Motors Efficiency: Motor Replacement*. 2006

In conclusion, no widely established and adopted standards were followed by any of the repair shops in the five economies. Although significant efforts have been undertaken in this regard in the US and New Zealand, more still needs to be done for market adoption of repair and rewind best practices.

Lack of Simple Certification Programs

Of all the 45 shops interviewed in the five economies, less than one third was ISO 9001 certified. None of the shops surveyed in the US had ISO certification. It is worth mentioning that ISO 9001 is a quality system standard that applies to daily management operations at certified shops. A repair shop implementing the ISO 9001 standard may not necessarily employ best practices when repairing or rewinding motors. All US respondents made it clear that the ISO certification has virtually nothing to do with the AC motor repair/rewind business. Therefore, test certificates from some of their larger customers and motor manufacturers mean much more to these shops.

In the US, quality assurance programs include the well-known EASA-Q, created by the EASA to help its members implement ISO 9001 quality system standards and the SKF[42] Certified Rebuilder Program[43], under which motor service centers are periodically audited. In addition, there is a focus on training motor shop personnel on issues and topics regarding bearing failure and replacement, as well as motor failure root cause analysis. Other quality assurance programs include the Green Motor Initiative (GMI) and the Proven Efficiency Verification (PEV) program developed by the Green Motors Practices Group (GMPG) and the private firm Advanced Energy, respectively.

These certification programs are perceived by many repair shops as too complex and expensive, which militates for the creation of a simplified approach more attractive to the market stakeholders.[44]

In the other economies (China, Japan, New Zealand and Vietnam), there is no national certification program for repair shops.

Customers' Preference for Fast Turnaround over Repair Quality

Several shops interviewed described a large part of their customer base as being generally sole sourced. Their customers usually do not have any spare motors on the shelf. This means that production facilities are either shut down while motors are being repaired or standby equipment are used, but without any other options if this equipment fails in turn. Therefore, customers want to quickly get the motor back in service even if servicing shops suggest buying a replacement motor or repairing the motor as per original manufacturer specifications as a more cost-effective solution. Ordering new motors or repairing units as per their original specifications induce delays and minor additional work is likely to be required to make them operate satisfactorily.[45] Customers' preference for fast service over quality of repair could be due partly to a lack of information; however, in many instances, even informed customers prefer shorter delays to quality of repair.

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[42] SKF stands for Svenska Kullagerfabriken in Swedish.
[43] Electric Motor Rebuilding on SKF website at http://www.skf.com/group/index.html?contentId=687952
[44] Anibal T. de Almeida *et al*, 2002, p. 206.
[45] Anibal de A. et al, 2012, *Electric Motors and Drives: Consumer Behaviour and Local Infrastructure*, Second Draft

The costs of unscheduled facility shutdowns are usually much greater than costs avoided after implementing motor repair and rewind best practices. Therefore, speed overrides repair quality mainly based on cost concerns associated with production equipment downtime.

Lack of Experienced Motor Repairers

Several interviewees in the US and Japan raised concerns about the long-term viability of the rewind industry, given the ever-changing job market and the interests of a new generation of workers. According to the interviewees, mostly in their 60s, as time goes by, every year key rewind people grow older and few new employees are being trained to take their places because of workers' lack of interest in fully learning motor rewind as a trade and lack of commitment in time and effort.

The lack of training programs in community colleges or short courses specifically geared to on this topic is another reason explaining the lack of experienced rewinders. And yet, rewind skills are absolutely critical in reworking electrical motors. Only very experienced, focused and dedicated technicians can properly perform such work. The rewind industry requires employees with not only excellent mechanical skills, but also the ability to master a combination of mechanical, electrical and rewinding expertise. Therefore, finding replacement resources is an acute challenge for the motor rewind shop industry.

Lack of Appropriate Tools and Equipment

As mentioned in Section 2.1.2, owning and using the appropriate tools and equipment allows motor repair shops to perform high-quality rewind/repair, thereby maintaining or even improving motor efficiency. The in-person interviews suggest that shops in emerging economies, like China and Vietnam are not as well equipped as their counterparts in industrialized economies, such as Japan, New Zealand and the US. Unlike large shops across the five economies, most small and medium shops lack appropriate tools and equipment to ensure high-quality rewind/repair.

This is a significant barrier impeding adoption and market promotion of best practices in motor repair and rewind.

8.1.2 Barriers to Adoption of Copper Rotors to Retrofit Motors

Two key barriers are preventing repair shops and end users from retrofitting motors with copper rotors. First, most repair shops lack an inventory of copper rotors and specialized equipment to replace aluminum rotors. The second barrier is related to longer delays in motor repair and additional cost to order or fabricate copper units.

Lack of Copper Rotor Inventory and Specialized Equipment at Repair Shops

Few repair shops build copper rotors from existing aluminum rotors by machining copper bars that are then inserted into the rotor slots. This approach is not common, since it is difficult to purchase bars that fit exactly into the slots and to reassemble the core, as it is normally held together by the rotor cage. In addition, even for well-equipped repair shops, rotor repair/replacement is not routine because it involves a fair amount of design knowledge. This finding is confirmed by a recent International

Copper Association (ICA) study,[46] revealing that rotor replacement was offered by Chinese motor manufacturers instead of repair shops.

Inexistence of Mass Copper Rotor Production

Mass production of copper rotors requires manufacturers to change their manufacturing processes. Actually, it is very difficult for other market stakeholders to enter this market due to the initial investment required and a relatively small existing market. Hence, high-volume production copper rotors are usually not available in the market unless offered by manufacturers. Custom rotor orders to manufacturers are quite often limited to large motors. Orders could also be limited to small motors, but repair shops prefer making rotor bars themselves. In addition, shops mainly replace rotors themselves with new units to shorten downtime, since it may take quite some time to get new rotors.

8.2 RECOMMENDATIONS

The potential savings associated with replacing aluminum rotors with copper rotors and employing best practices in motor repair and rewind are significant. However, as discussed in the previous section, there are many existing barriers, making it difficult to unlock this potential on a global scale. The following recommendations are made to mitigate these barriers.

Developing Repair Quality Standards and Certification Programs in the Economies

Because of significant efforts undertaken in various economies to promote the shift to energy-efficient motors, retaining efficiency gains from the application of energy efficiency programs achieved by maintaining the original efficiency of motors after repair has become a major challenge. If best practices are not adopted widely by repair shops, increasing energy loss after repair will offset, if not eliminate entirely the energy savings associated with the introduction of a greater number of efficient motors. Therefore, rewind/repair standards and quality labels should be created and implemented in the economies covered by this study and other jurisdictions. The motor repair quality labels can be applied to motors having been repaired in accordance with established standards. The labels could also promote the image of participating shops in the future, enabling users to easily identify and choose the best repair shops in their market.

The EASA and the GMPG have already issued two important reference documents, respectively: the ANSI/EASA AR100 (Recommended Practice for the Repair of Rotating Electrical Apparatus) and the Rewind/Repair Processes for Electric Motor Efficiency Retention. Some of their recommended best practices should be considered in the development of future standards in China, Japan and Vietnam. In the US and New Zealand where existing repair shop certification programs are perceived as complex and expensive, there is a need to develop simpler, less expensive certification programs to facilitate the successful transformation of the motor repair market.

Designing and Implementing Awareness Campaigns

To address the lack of information about the impact of repair techniques on motor efficiency, awareness campaigns targeting motor users should be carried out to help them better understand the benefits of best motor repair practices and selecting qualified repairers. Several programs have already been developed and implemented in New Zealand and the US to raise awareness among motor users regarding good motor management practices, including selecting an appropriate motor repair shop and developing good repair specifications to obtain quality repair. Similar efforts should be pursued in the other economies.

Creating Training Facilities and Developing Training Materials

As mentioned by many repair shops interviewed, there is general concern about the long-term viability of the rewind industry, given the ever-changing job market and the diverging interests of a new generation of workers. To address the lack of experienced motor repairers, training facilities and materials should be developed with a view to encourage new employees to enter the repair industry as well as for existing employees who are still using older repair techniques. Training and materials should focus on energy-efficient motor rewind/repair practices. These efforts should be undertaken in the five economies.

Designing and Implementing Incentive and/or Financing Schemes to Help Repair Facilities Upgrade Their Equipment

To address the lack of appropriate tools and equipment for high-quality repair, repair shops, especially small and medium enterprises (SMEs) will need to upgrade their equipment, such as their burnout, impregnation and test equipment. Therefore, there is a need to design and implement incentive and/or financing schemes to help SMEs in the five economies to proceed with the investment needed.

Speeding Up the Transition from Aluminum Rotors to Copper Rotors

Two possible ways to speed up transition to copper rotors would be for motor repair shops and distributors to keep an inventory of available copper rotors to reduce delays in motor repair. End-users can adopt a motor management practice where they can plan rotor replacement to coincide with planned downtime. This practice allows more time for the shops to work on a motor compared with urgent situations where motors have to be back on line as soon as possible.

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3 Copper Development Association Inc. http://www.copper.org/environment/sustainable-energy/electric-motors/case-studies/a1357.html

4 Electric Motor Rebuilding on SKF website at http://www.skf.com/group/index.html?contentId=687952

APPENDIX I
MOTOR ENERGY LOSS

The difference between the electrical input and shaft output power of an AC induction motor determines the motor efficiency and the amount of energy loss. Energy loss in AC induction motors can be classified into five main categories: (1) stator copper loss (stator "I^2 R"[47] loss); (2) rotor copper loss; (3) stator iron loss; (4) friction and windage loss; and (5) stray loss.

Table 21: Types of AC Motor Energy Loss

Loss	Description	Factor Causing Loss Increase
Stator copper	Appears as heat generated by resistance to the electric current flowing in the stator windings. Of all the types of losses in an AC induction motor, I^2 R loss is the heaviest.	Reducing conductor cross-sectional area and/or increasing its length.
Rotor copper	Caused by heat that occurs as the current flows through the rotor conductor bars and end rings. Stator and rotor I2 R losses together usually account for 50% to 60% of the total losses that occur in a motor.	Damaged rotor cage, poor connections between bars and end rings and wrong or improperly installed bars.
Stator iron	Occurs in the stator and is caused by either hysteresis or eddy currents.	Winding removal operation by: (1) applying improper burnout temperature, (2) overusing abrasive blasting with sand or a similar material; and (3) hammering the core.
Friction and windage	Includes the energy used to overcome bearing friction and energy used to overcome air movement from the rotor and cooling fan.	Motor reassembly by damaging or improperly installing the bearings, applying excess greasing to the bearings and by using poor quality grease and the wrong size or type of fan. Proper balancing of fan and rotor is important
Stray	Includes all residual losses not fully accounted for by the sum of the four types of losses above.	Use of poor repair techniques for motor dismantling, winding removal, core cleaning and motor rewinding.

In the literature, testing procedures and research papers, stator and rotor copper losses are often grouped under the label of Joule losses, because they appear as heat generated by resistance to electric current flowing in the stator windings and the rotor conductor bars and end rings (for a squirrel cage design). However, with respect to motor repair, the two sources of joule losses are discussed separately in this report, because different repair techniques apply to stator and rotor.

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[47] The "I" symbol refers to ampere current while "R" refers to winding resistance.

APPENDIX II
CLASSIFICATION OF MOTOR FAILURE CAUSES

AC induction motors have two major components: the stationary or static component called the stator, and the rotating component, which is the rotor. The stator is made up of laminations of high-grade electric sheet steel. The rotor consists of laminations of slotted ferromagnetic material; the rotor might be either the squirrel-cage type or the wound-rotor type. The latter is of a form similar to that of the stator winding, while the squirrel-cage consists of a number of bars embedded in the rotor slots and connected at both ends by means of end rings.[48] It is worth noting that the bars and the rings are made from either copper or aluminum.

Most motor failures are due to mechanical, electrical and misapplication causes. A major energy research consortium study conducted in 1985 covering 6,000 utility industry motors revealed that 53 percent of motor failures are due to mechanical factors[49], the largest proportion of which are associated with bearing failures (41 percent). Stator-related, rotor-related and other mechanical failures account respectively for 37 percent, 10 percent and 12 percent of problems. In conclusion, the primary cause of motor mechanical failure is a bearing problem, which can be caused by any combination of contamination, lubrication, improper assembly, misalignment or overloading. With regard to electrical causes, they are mainly associated with winding failures, mostly due to poor ventilation and excessive winding temperature increases caused by overload conditions. Other factors that can also contribute to winding failures are supply voltage variations, improper or poor electrical connections, excessive vibrations and insulation contamination. Sometimes, electrical failures also occur in motors because of misapplication, which is the failure to correctly match motor characteristics with the load requirements of driven equipment (e.g. starting torque requirements).

Based on the prevalence of failure modes in electric motors and the potential effect of each failure repair methods on the repaired unit efficiency, this study focuses on three types of failure: (a) stator winding failure with lamination damage, (b) stator winding failure without lamination damage and (c) rotor failure. Bearing failure is covered in the study, as this is not a significant issue for motor efficiency improvement or degradation.

For the previously mentioned failures, motor owners always face the choice of either repairing or replacing failed units with new motors. Therefore, the study covers the following repair practices: (1) Rewinding (winding removal, rewinding configuration and modification, impregnation, etc.); (2) Lamination repair or replacement; and (3) Rotor repair or replacement.

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[48] Edward J. Thornton and J.Kirk Armintor, 2003, “The Fundamentals of AC Electric Induction Motor Design and Application”, Proceedings of the 20th International Pump Users Symposium, available at http://turbolab.tamu.edu/proc/pumpproc/P20/11.pdf

[49] Ibid

APPENDIX III
ADDITIONAL INFORMATION ABOUT REPAIR TECHNIQUES

Table 22: Energy Loss Increase after Motor Rewind and Repair

Power Rating	Number of Poles	Frequency (Hz)	Loss Increase in % after Rewinding without Lamination Repair					Loss Increase in % after Rewinding with Lamination Repair				
			CN	JP	NZ	US	VN	CN	JP	NZ	US	VN
Under 50 kW (67 hp)	<=4	50	4.43	4.54	2.81	-	4.77	4.79	4.71	2.94	-	5.00
		60	-	4.81	-	3.16	-	-	4.99	-	3.17	-
	>4	50	4.32	4.58	2.81	-	4.80	4.68	4.75	2.93	-	5.05
		60	-	4.99	-	3.32	-	-	5.18	-	3.33	-
51 – 200 kW (68 - 268 hp)	<=4	50	4.88	5.46	3.46	-	5.36	5.38	5.70	3.63	-	5.71
		60	-	5.79	-	3.87	-	-	6.04	-	3.89	-
	>4	50	4.93	5.37	3.42	-	5.31	5.42	5.61	3.60	-	5.63
		60	-	5.49	-	3.63	-	-	5.73	-	3.66	-
201 – 375 kW (269 – 502 hp)	<=4	50	4.92	5.64	3.57	-	5.45	5.45	5.90	3.76	-	5.82
		60	-	5.88	-	3.94	-	-	6.15	-	3.97	-
	>4	50	4.88	5.51	3.50	-	5.34	5.40	5.76	3.68	-	5.69
		60	-	5.70	-	3.80	-	-	5.96	-	3.84	-
Above 375 kW (502 hp)	<=4	50	4.83	5.87	3.70	-	5.49	5.40	6.15	3.89	-	5.91
		60	-	6.13	-	4.14	-	-	6.43	-	4.18	-
	>4	50	4.83	5.55	3.51	-	5.31	5.35	5.81	3.70	-	5.68
		60	-	5.80	-	3.89	-	-	6.08	-	3.93	-

APPENDIX IV
ESTIMATING SAVINGS ASSOCIATED WITH BEST REPAIR PRACTICES

This Appendix presents the equation used to calculate the annual electricity savings from using best motor repair practices and the sources of the parameters involved in the equation.

EQUATION FOR CALCULATING SAVINGS

The annual electricity savings are calculated using the following equation for each category and failure type (winding failure without or with lamination damage) considered in this study.

$$\boldsymbol{AES = N_{yr} * FR_{yr} * FMR_{yr} * FT_{failure\ yr} * H_{yr} * LF * P_{avg} * 0.735 * \left(\frac{1}{Eff_{after}} - \frac{1}{Eff_{before}}\right)} \tag{Equation 1}$$

Where:

AES	Annual electricity savings in GWh
N_{yr}	Average annual number of motors in use (millions)
FR_{yr}	Percentage of motors in use that fail annually
FMR_{yr}	Percentage of failed motors that are repaired every year
$FT_{failure\ yr}$	Percentage of repaired motors that undergo a rewinding without or with lamination repair
H_{yr}	Annual hours of operation
LF	Average annual load factor
P_{avg}	Average rated power of motors (hp) in the power rating category for which the savings are calculated.
Eff_{before}	Average efficiency of motors in the power rating category before repair using current practices
Eff_{after}	Average efficiency of motors in the power rating category after repair using recommended best practices
yr	Stands for year
avg	Stands for average
0.735	Conversion rate from hp to kW

Figure 7 presents the electricity savings calculation structure.

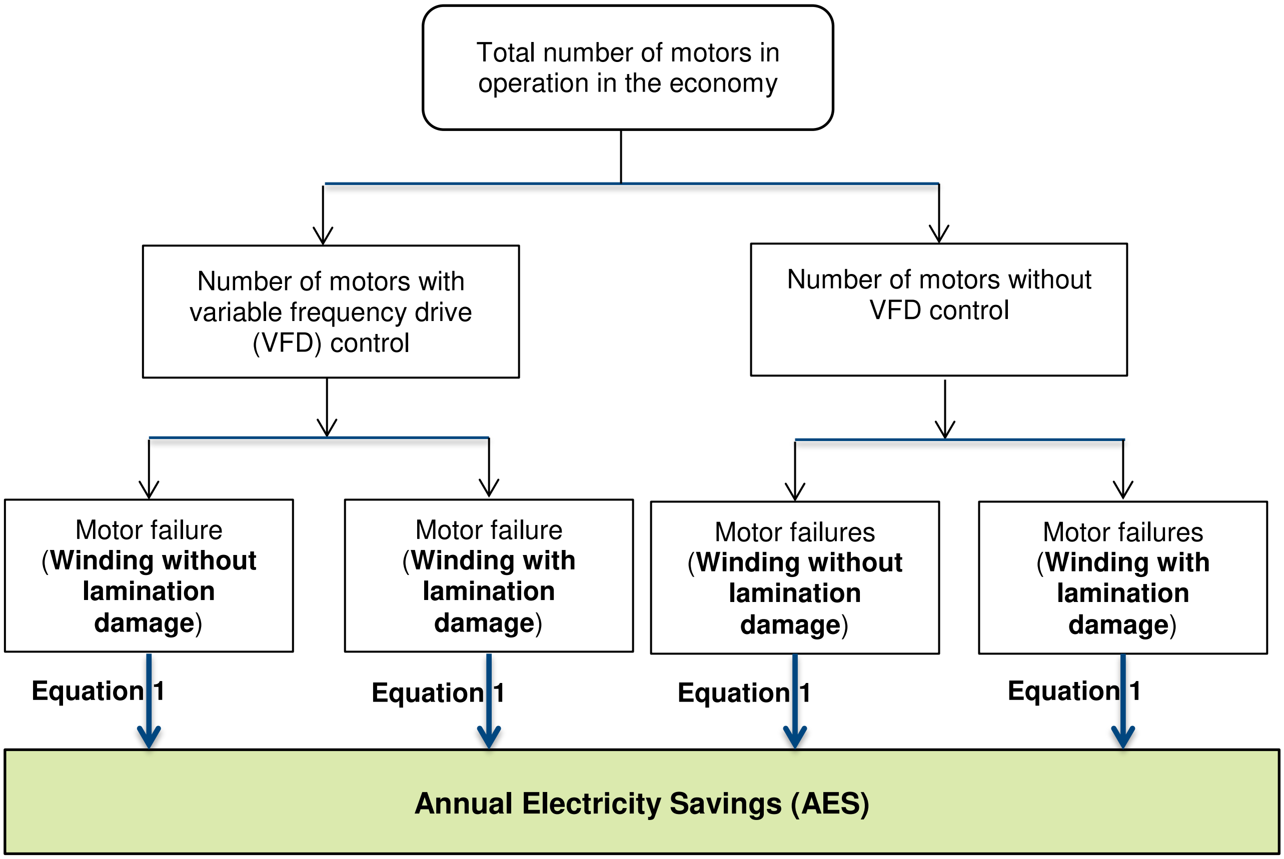

Figure 7: Savings Calculation Structure

SOURCE OF EQUATION PARAMETERS

Average Annual Number of Motors in Use (N_{yr})

The annual number of motors is based on the installed stock and is estimated through a top-down approach, as described and presented in Appendix II of the Task 2 report. The values (N_{yr}), used for each power rating category for each economy, are related to the year 2015 and presented in the table below.

Table 23: Number of Motors (Million) in Use by Power Class

Power Rating	China	Japan	New Zealand	US	Vietnam
Installed Stock in 2012					
Under 50 kW (67 hp)	39.9	7.2	0.30	30.7	0.96
51 - 200 kW (68 - 268 hp)	2.7	0.5	0.020	2.0	0.06
201 - 375 kW (269 - 502 hp)	0.11	0.02	0.001	0.08	0.003
Above 375 kW (Above 502 hp)	0.08	0.01	0.001	0.07	0.002
Total (Installed Stock 2012)	**42.8**	**7.7**	**0.32**	**32.9**	**1.0**
Potential Annual Growth Rate (%) of Installed Stock[50]	7%	0.5%	0.9%	0.5%	8%
Installed Stock in 2015 (N_{yr})					
Under 50 kW (67 hp)	48.9	7.4	0.31	31.1	1.1
51 - 200 kW (68 - 268 hp)	3.3	0.5	0.02	2.1	0.07
201 - 375 kW (269 - 502 hp)	0.13	0.02	0.001	0.08	0.003
Above 375 kW (Above 502 hp)	0.10	0.02	0.001	0.06	0.002
Total (Installed Stock 2015)	**52.4**	**7.9**	**0.33**	**33.3**	**1.2**

Percentage of Motors in Use Failing Every Year (FR_{yr})

$\mathrm{FR}_{\mathrm{yr}}$ is equivalent to the failure rate estimated based on the rewind interval set to the values in Table 11 in Section 4.2.1. The values set for $\mathrm{FR}_{\mathrm{yr}}$ are presented in Table 24.

Table 24: Percentage of Annual Motor Failure Used in the Calculations by Power Class

Power Rating	Rewind Interval	$\mathrm{FR}_{\mathrm{yr}}$
Under 50 kW (67 hp)	13	8%
51 - 200 kW (68 - 268 hp)	10	10%
201 - 375 kW (269 - 502 hp)	8	13%
Above 375 kW (Above 502 hp)	8	13%

Percentage of Failed Motors Repaired Every Year (FMR_{yr})

See discussion under Assumption 5 in Section 4.2.1.

Percentage of Repaired Motors That Undergo Rewinding without or with Lamination Repair ($FT_{failure\ yr}$)

See discussion under Assumption 4 in Section 4.2.1.

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[50] For each of the five economies, the potential growth rate was considered to be the annual electricity consumption growth rate over 2007 and 2010, which was then used to estimate motor electricity consumption in 2012. However, since China and Vietnam had a high growth rate (9.57% and 13.27%, respectively) over 2007 and 2010, the rates considered for the period beyond 2012 was adjusted to be conservative.

Annual Hours of Operation (H_{yr})

$\boldsymbol{H_{yr}}$ is set to values presented in Table 25 below.

Average Annual Load Factor (LF) and Average Rated Power of Motors (P_{avg})

In each economy, a portion of the installed motors that fail and are sent to repair shops operate with adjustable speed drive (ASD) control. Therefore, the energy savings are calculated for motors with and without ASD control. The average rated power ($\boldsymbol{P_{avg}}$) is estimated based on data available from the literature and set to values presented in Table 25 below. The load factor ($\boldsymbol{LF}$) is the average load (considering all hours of operation throughout the year) divided by the peak load or power rating of the motor. As shown in the table below, the load factor was estimated for motors under and without ASD control.

Table 25: Annual Hours of Operation, Load Factor and Average Rated Power Used in Savings Calculations

Power Class	China	Japan	NZ	US	Vietnam	Source
Average annual operating hours						DOE, 1997, as cited in T. de Almeida et al, 2002, p. 197. The average annual operating hours figures are from the US DOE motor market study conducted in 1997. These values are used as a proxy for the other countries.
Under 50 kW (67 hp)	3,200	3,200	3,200	3,200	3,200	
51 - 200 kW (68 - 268 hp)	5,250	5,250	5,250	5,250	5,250	
201 - 375 kW (269 - 502 hp)	6,132	6,132	6,132	6,132	6,132	
Above 375 kW (Above 502 hp)	7,186	7,186	7,186	7,186	7,186	
Average load factor (LF)						› China: IEA Motor Study, 2011, p. 43. › Japan: Ibid. › US: T. de Almeida et al, 2002, p. 197. › Vietnam: Ibid. (Mexico's LF in the source used as a proxy) New Zealand: Industrial Motors Efficiency Project, 2006, p. 8.
Under 50 kW (67 hp)	62%	60%	60%	50%	56%	
51 - 200 kW (68 - 268 hp)	62%	60%	60%	50%	56%	
201 - 375 kW (269 - 502 hp)	62%	60%	60%	50%	56%	
Above 375 kW (Above 502 hp)	62%	60%	60%	50%	56%	
LF Motors without VFD control						Estimated based on the percentage of motors with and without VFD control. In fact, the results from the DOE 1997 study on motor use in the industrial sector suggested that only fewer than 10% of the motors in use in the US have VFD control. A study[51] on the savings potential of variable speed drive in China estimates that approximately 10% of the motors in use have VFD control. Refer to Table 28 for the percent of motors in each power rating class with VFD control. The LF of motors with VFD control and that of motors without VFD control are estimated in such a way that their weighted average equals the average LF above.
Under 50 kW (67 hp)	66%	63%	63%	52%	59%	
51 - 200 kW (68 - 268 hp)	66%	63%	63%	52%	59%	
201 - 375 kW (269 - 502 hp)	66%	63%	63%	52%	59%	
Above 375 kW (Above 502 hp)	66%	63%	63%	52%	59%	
LF Motors with VFD Control						
Under 50 kW (67 hp)	30%	30%	30%	30%	30%	
51 - 200 kW (68 - 268 hp)	30%	30%	30%	30%	30%	
201 - 375 kW (269 - 502 hp)	30%	30%	30%	30%	30%	
Above 375 kW (Above 502 hp)	30%	30%	30%	30%	30%	
Average power rate in hp (P_{avg})						US values are estimated based on T. de Almeida et al, 2002. US values are used as proxies for the other economies.
Under 50 kW (67 hp)	16	16	16	16	16	
51 - 200 kW (68 - 268 hp)	152	152	152	152	152	
201 - 375 kW (269 - 502 hp)	370	370	370	370	370	
Above 375 kW (Above 502 hp)	1,500	1,500	1,500	1,500	1,500	

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[51] Energy Research Institute, 2011, *Energy – saving Potential Analysis of VSD Reconstruction of Motor System in China: Current situation, potential and advice.*

Average Efficiency of Motors in the Power Rating Category before Repair (Eff_{before})

Eff_{before} is set to values presented in Table 26 below.

Table 26: Average Efficiency before Repair Used in Savings Calculations

Power Rating - kW (hp)	Value	Source
Motors without VFD Control		
Under 50 (67)	86%	T. de Almeida et al, 2002. The average efficiency by horsepower category is the figure for the US and is used as a proxy for the other countries.
51 - 200 (68 - 268)	89%	
201 - 375 (269 - 502)	90%	
Above 375 (502)	91%	
Motors with VFD Control		
Under 50 (67)	90%	Estimate
51 - 200 (68 - 268)	91%	
201 - 375 (269 - 502)	93%	
Above 375 (502)	93%	

Average Efficiency of Motors in the Power Rating Category after Repair (Eff_{after})

The efficiency of motors after repair is based on the increase in energy losses as a result of the repair and is determined by using the following equation:

$$Eff_{after} = 100\% - \left(\left(100\% - Eff_{before}\right) * (1 + IEL)\right) \quad \textbf{Equation 2}$$

IEL is the average increase in energy losses and is expressed in %, as presented in Table 22. Table 27 presents an example of efficiency estimates of a four-pole motor without ASD control sent to a shop for rewinding without lamination repair in the US.

Table 27: Example of Estimating the Efficiency of a Given Motor after Repair

Power Rating - kW (hp)	Number of Repairs	Loss Increase after First Repair (%) A	Loss Increase after Second Repair (%) B = A x 1.20	Loss Increase after Third Repair (%) C = A x 1.24	Average IEL (%) Average (A, B, C)	Efficiency Before Repair (%)	Efficiency after Repair (%)
Under 50 (67)	1	3.16	-	-	3.16	86.0	85.6
51 - 200 (68 - 268)	2	3.87	4.64	-	4.25	89.0	88.5
201 - 375 (269 - 502)	3	3.94	4.73	4.88	4.52	90.0	89.5
Above 375 (502)	3	4.14	4.97	5.13	4.75	91.0	90.5

APPENDIX V
DETAILED SAVINGS CALCULATION RESULTS

Motor Size by Horsepower	Lifetime in Years	Annual Total Energy Consumption (2015)	Stator Winding without Lamination Damage		Stator Winding with Lamination Damage		Total Annual Savings (a+c)	Total Lifetime Savings (b+d)	Potential Savings
			Total Annual Savings (a)	Total Lifetime Savings (b)	Total Annual Energy Savings (c)	Total Lifetime Savings(d)			
kW (hp)		GWh/Year	GWh/Year	GWh	GWh/Year	GWh/Lifetime	GWh/Year	GWh/Lifetime	%(Relative to electricity consumption in 2015)
CHINA									
Under 50 (67)	16	380,672	344	5,508	455	7,282	799	12,790	3.40%
51 - 200 (68 - 268)	26	744,792	729	18,961	983	25,566	1,712	44,527	6.00%
201 - 375 (269 - 502)	30	873,522	135	4,039	182	5,470	317	9,509	1.10%
Above 375 (502)	30	395,384	418	12,527	570	17,116	988	29,643	7.50%
Total		**2,394,370**	**1,626**	**41,035**	**2,190**	**55,434**	**3,816**	**96,469**	**4.19%**
JAPAN									
Under 50 (67)	16	59,763	64	1,030	12	189	76	1,219	2.04%
51 - 200 (68 - 268)	26	116,928	126	3,277	23	604	149	3,881	3.32%
201 - 375 (269 - 502)	30	137,138	19	560	3	103	22	663	0.48%
Above 375 (502)	30	62,073	68	2,033	12	376	80	2,409	3.88%
Total		**375,902**	**277**	**6,900**	**50**	**1,272**	**327**	**8,172**	**2.21%**

Motor Size by Horsepower	Lifetime in Years	Annual Total Energy Consumption (2015)	Stator Winding without Lamination Damage		Stator Winding with Lamination Damage		Total Annual Savings (a+c)	Total Lifetime Savings (b+d)	Potential Savings
			Total Annual Savings (a)	Total Lifetime Savings (b)	Total Annual Energy Savings (c)	Total Lifetime Savings(d)			
kW (hp)		**GWh/Year**	**GWh/Year**	**GWh**	**GWh/Year**	**GWh/Lifetime**	**GWh/Year**	**GWh/Lifetime**	**%(Relative to electricity consumption in 2015)**
NEW ZEALAND (NZ)									
Under 50 (67)	16	2,494	1	23	0.5	8	1.5	31	1.26%
51 - 200 (68 - 268)	26	4,881	3	77	1	27	4	104	2.13%
201 - 375 (269 - 502)	30	5,724	0.4	14	0.1	4	0.5	18	0.32%
Above 375 (502)	30	2,591	1.6	49	0.5	17	2	66	2.54%
Total		**15,690**	**6**	**163**	**2.1**	**56**	**8**	**219**	**1.46%**
US									
Under 50 (67)	16	209,778	90	1,442	91	1,450	181	2,892	1.38%
51 - 200 (68 - 268)	26	410,436	178	4,631	179	4,663	357	9,294	2.26%
201 - 375 (269 - 502)	30	481,375	26	785	27	791	53	1,576	0.33%
Above 375 (502)	30	217,886	96	2,874	97	2,903	193	5,777	2.65%
Total		**1,319,475**	**390**	**9,732**	**394**	**9,807**	**784**	**19,539**	**1.50%**
VIETNAM									
Under 50 (67)	16	8,284	12	189	4	67	16	256	3.08%
51 - 200 (68 - 268)	26	16,208	26	665	9	236	35	901	5.56%
201 - 375 (269 - 502)	30	19,009	5	145	2	52	7	197	1.04%
Above 375 (502)	30	8,604	17	511	6	184	23	695	8.07%
Total		**52,105**	**60**	**1,510**	**21**	**539**	**81**	**2,049**	**3.94%**

APPENDIX VI
ESTIMATING SAVINGS ASSOCIATED WITH ROTOR REPLACEMENT

This Appendix presents the equation used to calculate the annual electricity savings associated with replacing aluminum rotors with copper rotors and the sources of the parameters involved.

EQUATION FOR CALCULATING SAVINGS

The annual electricity savings are calculated using the following equation for motors driving constant and variable torque loads. It is assumed that the rotor replacement measure is implemented in 2015 for all operating motors equipped with aluminum rotors. The savings are calculated using the following equations:

Centrifugal Load (Pumps and Blowers)

$$\boldsymbol{ES_{cl} = N_{vtl} * FP_{cl} * FP_{Al} * H_{yr} * LF_{vl} * P_{avg} * 0.735 * \left(\frac{1}{Eff_{before\ (vs)}} - \frac{1}{Eff_{after\ (vs)}}\right)} \quad \textbf{Equation 3}$$

Where:

ES_{cl}	Electricity savings associated with motors driving centrifugal loads. Expressed in GWh
N_{vtl}	Number of motors driving pumps and blowers (in millions). According to the DOE 1997 study on motors, motors driving pumps and blowers account for 31% of the total motors in operation in the US. A study[52] by the International Energy Agency (IEA) on motors estimated that globally 38% of the motors in use drive pumps and blowers. These percentages are then applied to China, New Zealand and Vietnam. According to a paper published in 2013 in the *Energy Policy Journal*, motors driving pumps and blowers account for 52% of all the motors installed in Japan[53].
FP_{Al}	Percentage of operating motors equipped with an aluminum rotor. According to motor industry experts, at least 80% of all the motors installed in all the five economies or globally use only aluminum rotors. For motors above 200 kW, the percentage is set at 5%. In fact, most motors more powerful than 200 kW and a few smaller special-purpose motors are built with copper squirrel cage structures manufactured by a time-consuming and costly fabrication process.[54]
FP_{cl}	Percentage of operating motors equipped with a VFD. According to the DOE 1997 study, these motors account for approximately between 0.3% to 9.1% of all the motors installed in the US, depending on the size of the motor. The percentage is used as a proxy for the other economies. See Table 28 in this Appendix.
H_{yr}	Average annual hours of operation. See Table 28 in this Appendix.
LF_{vl}	Average Load Factor of motors with VFD. See Table 28 in this Appendix.
P_{avg}	Average rated power (hp) in a power rating category. See Table 28 in this Appendix.

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[52] Paul Waide et al, 2011, *Energy Efficiency Policy Opportunities for Electric Motor-Driven Systems*, IEA

[53] Chun Chun Ni, 2013, *Potential of energy savings and reduction of CO2 emissions through higher efficiency standards for polyphase electric motors in Japan*, Energy Policy 52 (2013) 737-747

[54] E. Brush et al, *Die-cast Copper Motor Rotors: Motor Test Results, Copper Compared to Aluminum*

0.735	Conversion factor from hp to kW
$\boldsymbol{Eff_{before\ (vs)}}$	Average efficiency of motors with VFD. See Table 28 in this Appendix.
$\boldsymbol{Eff_{after\ (vs)}}$	Average efficiency of motors with VFD control after rotor replacement. Determined by adding the increase in efficiency after replacement (percentage point), as presented in Table 28 in this Appendix.

Other Types of Load (Compressors, Conveyors, etc.)

$$\boldsymbol{ES_{ol} = N_n * FP_{Al} * H_{yr} * LF_{nVFD} * P_{avg} * 0.735 * \left(\frac{1}{Eff_{before\ (nASD)}} - \frac{1}{Eff_{after\ (nASD)}}\right)} \quad \textbf{Equation 4}$$

Where:

ES_{ol}	Electricity savings associated with motors without ASD control and not driving a centrifugal load. Expressed in GWh
N_n	Number of motors driving other types of load (in millions).
FP_{Al}	See Equation 3.
H_{yr}	See Equation 3.
LF_{nVFD}	Average Load Factor of motors without ASD control. See Table 28 in this Appendix.
P_{avg}	Average rated power (hp) as per motors power rating category. See Table 28 in this Appendix.
$Eff_{before\ (nVFD)}$	Average efficiency of motors without VFD control. See Table 28 in this Appendix.
$Eff_{after\ (nVFD)}$	Average efficiency of motors without VFD control after rotor replacement. Determined by adding the increase in efficiency after replacement (percentage point), as presented in Table 28 in this Appendix.

The structure of the savings calculation is presented in Figure 8.

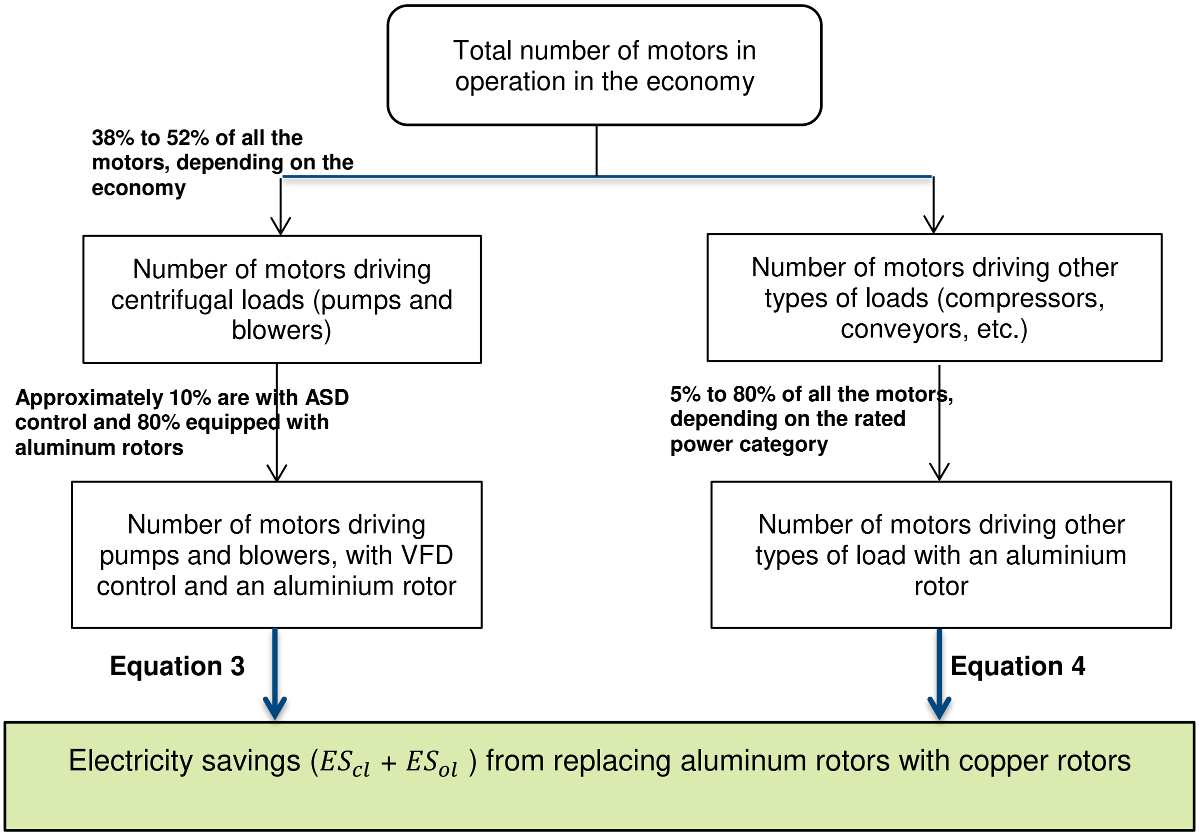

Figure 8: Structure of Savings Calculations Associated with Rotor Replacement

Table 28: Inputs Used in the Calculation of Savings Associated with Rotor Replacement

	Under 50 kW (67 hp)	51 – 200 kW (68 – 268 hp)	201 – 375 kW (269 – 502 hp)	Above 375 kW (502 hp)
Percentage of motors with VFD control	9.1%	4.4%	2.0%	0.3%
Percentage of motors driving a variable torque load	25.0%	25.0%	25.0%	25.0%
Percentage of motors driving a variable torque load and without VFD control	15.9%	20.6%	23.0%	24.7%
Percentage of motors with aluminum rotors (FP_{Al})	80.0%	80.0%	5.0%	5.0%

	Under 50 kW (67 hp)	51 – 200 kW (68 – 268 hp)	201 – 375 kW (269 – 502 hp)	Above 375 kW (502 hp)
Percentage of motors driving a centrifugal load (% of motors with VFD)	20.0%	20.0%	20.0%	20.0%
Increase in efficiency after replacement (percentage point)	2.0%	1.0%	1.0%	1.0%
Hours of operation	3 200	5 250	6 132	7 186
Average efficiency of motors without VFD control before rotor replacement	86.0%	89.0%	90.0%	90.0%
Average efficiency of motors with VFD control before rotor replacement	90.0%	91.0%	93.0%	93.0%
Average load factor of motors without VFD control	63%	63%	63%	63%
Average load factor of motors with VFD control	30.0%	30.0%	30.0%	30.0%
Average rated power (hp) of motors	16	152	370	1 500

SAVINGS ESTIMATES

Power Rating - kW (hp)	Number of Poles	Number of Motors in Use in 2015	CENTRIFUGAL LOAD (PUMPS AND BLOWERS)			LINEAR LOAD		
			Number of Motors Driving Pumps and Blowers with VFD Control and an Aluminium Rotor	Efficiency after Rotor Replacement	Anuual Energy Savings GWh per Year	Number of Motors Driving other Types of Load with Aluminium Rotors	Efficiency after Rotor Replacement	Energy Savings GWh in 2015
CHINA								
Under 50 (67)	<=4	43,981,035	642,327	92.0%	172.4	28,957,928	88.0%	18,710
Under 50 (67)	>4	4,886,782	71,370	92.0%	19.2	3,217,548	88.0%	2,079
51 - 200 (68 - 268)	<=4	2,943,581	20,502	92.0%	43.5	1,848,158	90.0%	9,008
51 - 200 (68 - 268)	>4	327,065	2,278	92.0%	4.8	205,351	90.0%	1,001
201 - 375 (269 - 502)	<=4	118,963	24	94.0%	0.1	4,556	91.0%	61
201 - 375 (269 - 502)	>4	13,218	3	94.0%	0	506	91.0%	7
Above 375 (502)	<=4	90,437	3	94.0%	0.1	3,212	91.0%	205
Above 375 (502)	>4	10,049	5	94.0%	0.1	395	91.0%	25
Total		**52,371,130**	**,**		**240**			**31,096**
JAPAN								
Under 50 (67)	<=4	6,646,267	97,066	92.00%	26.3	4,376,025	88.00%	2,722
Under 50 (67)	>4	738,474	10,785	92.00%	2.9	486,225	88.00%	302
51 - 200 (68 - 268)	<=4	444,824	3,098	92.00%	6.6	279,287	90.00%	1,310
51 - 200 (68 - 268)	>4	49,425	344	92.00%	0.7	31,032	90.00%	146
201 - 375 (269 - 502)	<=4	17,977	4	94.00%	0	689	91.00%	9

Power Rating - kW (hp)	Number of Poles	Number of Motors in Use in 2015	CENTRIFUGAL LOAD (PUMPS AND BLOWERS)			LINEAR LOAD		
			Number of Motors Driving Pumps and Blowers with VFD Control and an Aluminium Rotor	Efficiency after Rotor Replacement	Anuual Energy Savings GWh per Year	Number of Motors Driving other Types of Load with Aluminium Rotors	Efficiency after Rotor Replacement	Energy Savings GWh in 2015
201 - 375 (269 - 502)	>4	1,997	0	94.00%	0	77	91.00%	1
Above 375 (502)	<=4	13,667	0	94.00%	0	485	91.00%	30
Above 375 (502)	>4	1,519	1	94.00%	0	60	91.00%	4
Total		**7,914,150**			**36.5**			**4 524**
NEW ZEALAND								
Under 50 (67)	<=4	277,412	4,051	92.00%	1.1	182,653	88.00%	114
Under 50 (67)	>4	30,824	450	92.00%	0.1	20,295	88.00%	13
51 - 200 (68 - 268)	<=4	18,567	129	92.00%	0.3	11,657	90.00%	55
51 - 200 (68 - 268)	>4	2,063	14	92.00%	0	1,295	90.00%	6
201 - 375 (269 - 502)	<=4	750	0	94.00%	0	29	91.00%	0
201 - 375 (269 - 502)	>4	83	0	94.00%	0	3	91.00%	0
Above 375 (502)	<=4	570	0	94.00%	0	20	91.00%	1
Above 375 (502)	>4	63	0	94.00%	0	2	91.00%	0
Total		**330,333**	**,**		**1.5**			**189**
US								
Under 50 (67)	<=4	27,995,331	408,861	92.00%	111.7	18,432,644	88.00%	9 554
Under 50 (67)	>4	3,110,592	45,429	92.00%	12.4	2,048,072	88.00%	1 062
51 - 200 (68 - 268)	<=4	1,873,683	13,050	92.00%	28.2	1,176,411	90.00%	4 597
51 - 200 (68 - 268)	>4	208,187	1,450	92.00%	3.1	130,712	90.00%	511
201 - 375 (269 - 502)	<=4	75,724	15	94.00%	0.1	2,900	91.00%	32

Power Rating - kW (hp)	Number of Poles	Number of Motors in Use in 2015	CENTRIFUGAL LOAD (PUMPS AND BLOWERS)			LINEAR LOAD		
			Number of Motors Driving Pumps and Blowers with VFD Control and an Aluminium Rotor	Efficiency after Rotor Replacement	Anuual Energy Savings GWh per Year	Number of Motors Driving other Types of Load with Aluminium Rotors	Efficiency after Rotor Replacement	Energy Savings GWh in 2015
201 - 375 (269 - 502)	>4	8,414	2	94.00%	0	322	91.00%	4
Above 375 (502)	<=4	57,566	2	94.00%	0	2,044	91.00%	105
Above 375 (502)	>4	6,396	3	94.00%	0.1	251	91.00%	13
Total		**33,335,893**			**155.6**			**15,878**
VIETNAM								
Under 50 (67)	<=4	1,001,281	14,623	92.00%	3.9	659,262	88.00%	383
Under 50 (67)	>4	111,253	1,625	92.00%	0.4	73,251	88.00%	43
51 - 200 (68 - 268)	<=4	67,014	467	92.00%	1	42,076	90.00%	184
51 - 200 (68 - 268)	>4	7,446	52	92.00%	0.1	4,675	90.00%	20
201 - 375 (269 - 502)	<=4	2,708	1	94.00%	0	104	91.00%	1
201 - 375 (269 - 502)	>4	301	0	94.00%	0	12	91.00%	0
Above 375 (502)	<=4	2,059	0	94.00%	0	73	91.00%	4
Above 375 (502)	>4	229	0	94.00%	0	9	91.00%	1
Total		**1,192,291**	**,**		**5.4**			**636**

APPENDIX VII
INPUTS USED IN THE ECONOMIC ANALYSIS

Table 29: Cost of Repair in USD (Rewinding without Lamination Repair)

Category	Current Practices			Best Practices (15% higher than current practices[55]		
	Labor	Material	Total Cost	Labor	Material	Total Cost
CHINA						
<50 kW	126	421	547	145	463	608
50-200 kW	227	1,514	1,741	261	1,665	1,926
200-375 kW	342	3,422	3,764	394	3,764	4,158
Over 375 kW	924	9,241	10,166	1,063	10,166	11,228
JAPAN						
<50 kW	1,053	421	1,474	1,210	463	1,673
50-200 kW	1,816	1,514	3,330	2,089	1,665	3,754
200-375 kW	4,448	3,422	7,870	5,116	3,764	8,880
Over 375 kW	9,241	9,241	18,483	10,628	10,166	20,793
NEW ZEALAND						
<50 kW	716	421	1,137	823	463	1,286
50-200 kW	1,211	1,514	2,724	1,393	1,665	3,057
200-375 kW	3,080	3,422	6,501	3,542	3,764	7,306
Over 375 kW	9,241	9,241	18,483	10,628	10,166	20,793
US						
<50 kW	1,263	421	1,684	1,452	463	1,916
50-200 kW	2,270	1,514	3,784	2,611	1,665	4,276
200-375 kW	4,106	3,422	7,528	4,722	3,764	8,486
Over 375 kW	9,241	9,241	18,483	10,628	10,166	20,793
VIETNAM						
<50 kW	126	421	547	145	463	608
50-200 kW	227	1,514	1,741	261	1,665	1,926
200-375 kW	342	3,422	3,764	394	3,764	4,158
Over 375 kW	924	9,241	10,166	1,063	10,166	11,228

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[55] Based on the study team members' experience

APPENDIX VIII
PAYBACK CALCULATION OF BEST VERSUS CURRENT PRACTICES (EXAMPLE OF CHINA)

Scenario	Parameters	Under 50 kW (67 hp)	51 – 200 kW (68 – 268 hp)	201 – 375 kW (269 – 502 hp)	Above 375 kW (502 hp)
Existing Setup	Nameplate power (kW)	50	150	375	775
	Enclosure type (ODP or TEFC)	TEFC	TEFC	TEFC	TEFC
	Number of poles	<= 4	<= 4	<= 4	<= 4
	Nameplate efficiency (%)	91.6%	92.2%	93.3%	93.3%
	Loading (%)	75%	75%	75%	75%
	Type of load (fixed or variable)	Fixed	Fixed	Fixed	Fixed
	Annual hours of operation (hrs.)	3200	5250	6132	7186
Repair Case (Conventional method or current practices)	Type of Repair	Rewind without Lamination Repair	Rewind without Lamination Repair	Rewind without Lamination repair	Rewind without Lamination repair
	Cost of repair (kUSD)	0.5	1.7	3.8	10.2
	Annual increase in maintenance cost (%)[56]	3.00%	3.00%	3.00%	3.00%
	Increase in motor losses after repair (%)	4.38%	4.90%	4.90%	4.83%
	Efficiency after repair	91.23%	91.82%	92.97%	92.98%
	Maintenance cost of repaired motor (kUSD/yr)	0.016	0.052	0.113	0.305
	Increase in input power (kW)	0.22	0.68	1.42	2.89
	Total increase in annual energy consumption after repair (kWh)	528	2 668	6 528	15 585

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[56] Efficiency losses from repairs can lead to higher maintenance costs.

Scenario	Parameters	Under 50 kW (67 hp)	51 – 200 kW (68 – 268 hp)	201 – 375 kW (269 – 502 hp)	Above 375 kW (502 hp)
	Additional cost for customer (kUSD/yr)	0.06	0.31	0.75	1.80
	% increase in energy consumption	0.44%	0.45%	0.38%	0.37%
Repair Case (Best Practice)	Cost of repair (kUSD)	0.6	2.0	4.3	11.5
	Annual increase in maintenance cost compared to conventional method (%)	0.00%	0.00%	0.00%	0.00%
	Efficiency after repair	91.6%	92.2%	93.3%	93.3%
	Increase in maintenance cost after motor repaired motor (kUSD/year)	0	0	0	0
	Increase in input power (kW)	0.00	0.00	0.00	0.00
	Total increase in annual energy consumption after repair (kWh)	0	0	0	0
	Additional cost for customer (kUSD/yr)	0.00	0.00	0.00	0.00
	Payback Period	0.92	0.63	0.56	0.63
Energy	Country	China	China	China	China
	Cost of energy (USD/kWh)	0.12	0.12	0.12	0.12
	Annual increase in cost of energy (%)	5%	5%	5%	5%

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