EFFICIENCY FOR ACCESS

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THE BENEFITS OF PERMANENT MAGNET MOTORS

Efficiency opportunities in off- and weak-grid appliance markets

MARCH 2021 EFFICIENCY FOR ACCESS COALITION **VOLUME 1**

CONTEXT

Permanent magnet (PM) direct current motors have the potential to revolutionise the market for solar-compatible appliances by significantly improving their energy-efficiency and performance. Despite this potential, PM motors are not the prevailing technology employed in off- and weak-grid markets. This report characterises current and future global markets for PM motors in South Asia and Sub-Saharan Africa. It provides the first comprehensive exploration of the off- and weak-grid PM motor market through an evaluation and segmentation of the addressable market and analysis of quantifiable benefits and technology trends. Finally, this report identifies avenues for market growth, including a summary of existing drivers and barriers for PM motor adoption and opportunities for demand aggregation and standardisation.

pManifold Business Solutions (with support from Dr. Evan Murimi and the Jomo Kenyatta University of Agriculture and Technology) developed this report in close collaboration with CLASP and the Energy Saving Trust (EST) on behalf of the Low Energy Inclusive Appliances (LEIA) Programme. LEIA is a research and innovation programme that seeks to double the efficiency and halve the cost of a range of electrical appliances suited for off- and weak-grid household, small business and industrial consumers. LEIA is the flagship programme of Efficiency for Access, a global coalition working to promote high performing appliances that enable access to clean energy for the world's poorest people. It is a catalyst for change, accelerating the growth of off-grid appliance markets to boost incomes, reduce carbon emissions, improve quality of life and support sustainable development.

The Efficiency for Access Coalition is coordinated jointly by CLASP, an international appliance energy efficiency and market development specialist not for-profit organisation and Energy Saving Trust, which specialises in energy efficiency product verification, data and insight, advice and research.

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ACRONYMS AND ABBREVIATIONS

AC	Alternative Current
ASIC	Appliance Specific Integrated Circuit
BLDC	Brushless Direct Current
CAGR	Compound Annual Growth Rate
DC	Direct Current
DRE	Distributed Renewable Energy
DSM	Demand Side Management
ECU	Electronic Controller Unit
EV	Electric Vehicle
FOC	Field Oriented Control
GHG	Greenhouse Gas
ICE	Internal Combustion Engine
IOT	Internet of Things
KW	Kilowatt
LEIA	Low Energy Inclusive Appliances
LED	Light-Emitting Diode
LVDC	Low-Voltage Direct Current
M&E	Monitoring and Evaluation
MEPS	Minimum Energy Performance Standard
MFI	Microfinance Institution
NDC	Nationally Determined Contribution
OEM	Original Equipment Manufacturer
PAYGO	Pay-As-You-Go
PM	Permanent Magnet
PMS	Permanent Magnet Synchronous
POS	Point-of-Sale
POC	Proof of Concept
PV	Photo-Voltaic
R&D	Research and Development
SMC	Soft Magnetic Composite
SWP	Solar Water Pump
TCO	Total Cost of Ownership
W	Watt

Executive Summary

Introduction

The off-grid solar energy market currently serves 420 million people, the majority of whom reside in Sub-Saharan African and South Asia.[1] As the availability and affordability of higher-power solar power systems has increased in the past five years, more consumers have begun to purchase motor-driven household appliances and productive use equipment to improve their quality of life. For example, the market for fans, televisions and refrigerators is predicted to grow to US$25.3 billion by 2030,[2] while the market for solar water pumps is estimated at US$11 billion in 2030.[3] As the market evolves, appliance companies are anticipated to adopt more energy-efficient technologies such as permanent magnet (PM) motors that have the potential to drive the market toward better performing products and lift millions more people out of energy poverty.

As the 'prime movers' in many appliances, motors determine the capabilities, power demand, energy consumption and reliability of most off-grid appliances. PM motors have the potential to revolutionise the market for solar-compatible appliances in off- and weak-grid setting by significantly improving the energy efficiency, performance, reliability and cost of a wide range of products. By switching to appliances using PM motors and light-emitting diode (LED) lighting, a typical off-grid household would save 30% in the net cost of their system compared to a household using standard alternating current (AC) appliances and incandescent lighting.

This report provides the first comprehensive analysis of PM motor applications in off-and weak-grid markets. It estimates the global addressable market for PM motors, quantifies PM motor benefits, identifies key drivers for adoption, assesses potential demand aggregation strategies.

Benefits of adopting PM motors in off-grid appliances

PM motors are superior to conventional AC motors in all critical parameters of off- and weak-grid compatibility. Generally speaking, appliances using PM motors are more energy-efficient, serviceable and reliable than traditional AC motor appliances.

The benefits of switching to appliances using PM motors are substantial. PM motor appliances consume between 22% and 42% less energy than conventional AC motor appliances. These savings reduce total energy consumption, deliver 30% net cost savings to off-grid consumers, and allow for the use of additional appliances that deliver greater energy service. In addition to energy savings, PM motors appliances offer a more reliable service and expanded set of features coveted by consumers. This benefits may translate into a larger market potential for off- and weak-grid appliances, as consumers may be willing to pay more for products with enhanced functionality.

Market trends for PM motor appliances[4]

PM motor market penetration is asymmetric across appliance categories and geographies. In *South Asia*, PM motor adoption is low across small household appliances and 2 wheelers (see Figure 1 on page 10). PM motor adoption is higher in large household and productive use appliances (refrigerators, washing machines and solar water pumps). The market potential for these products is high, with market penetration expected to exceed 80% in 2025.

Like in South Asia, PM motors are not commonly used in small household appliances in *Sub-Saharan* Africa and are more commonly found in large household and productive use appliances (washing machines, air conditioners and solar water pumps). PM motor use in key cooling technologies, i.e. refrigerators and air conditioners, is significantly lower in Sub-Saharan Africa than South Asia. This study finds PM motor adoption will be slower in Sub-Saharan Africa for most appliances, with only solar water pumps surpassing 80% market penetration in 2025 (see Figure 1 on page 10).

Electric vehicles (EVs) represent a major segment for PM motor application in the transportation sector. Nearly all electric 2-wheelers (e-2w) and electric 3-wheelers (e-3w) use PM motors. Unfortunately, these vehicles make up a relatively small market share of registered 2- and 3-wheelers. The market share of 2- and 3-wheelers using PM motors is expected to grow in South Asia and Sub-Saharan Africa, with the largest growth projected in 2-wheelers. In 2025, 3-wheelers using PM motors are expected to make up over 50% of the market share in South Asia, the highest of any vehicle type included in this study (see Figure 1 on page 10).

1. https://www.worldbank.org/en/topic/energy/publication/off-grid-solar-market-trends-report-2020
2. https://efficiencyforaccess.org/publications/2019-state-of-the-off-grid-appliance-market-report
3. https://efficiencyforaccess.org/publications/solar-water-pump-outlook-2019-global-trends-and-market-opportunities
4. The figures represent the appliances which run directly on 220V AC with applications in on-, weak- and off-grid which constitute the majority appliance market in both regions. Appliances designed to run on direct DC sources has limited data availability.

Figure 1: Market penetration of PM motors appliances in South Asia (2020 and 2025)

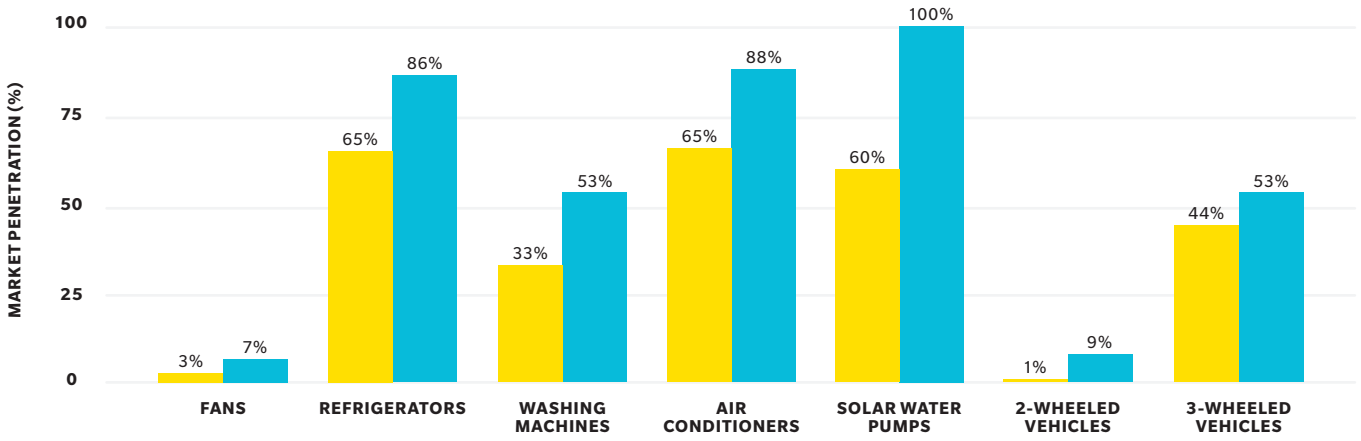
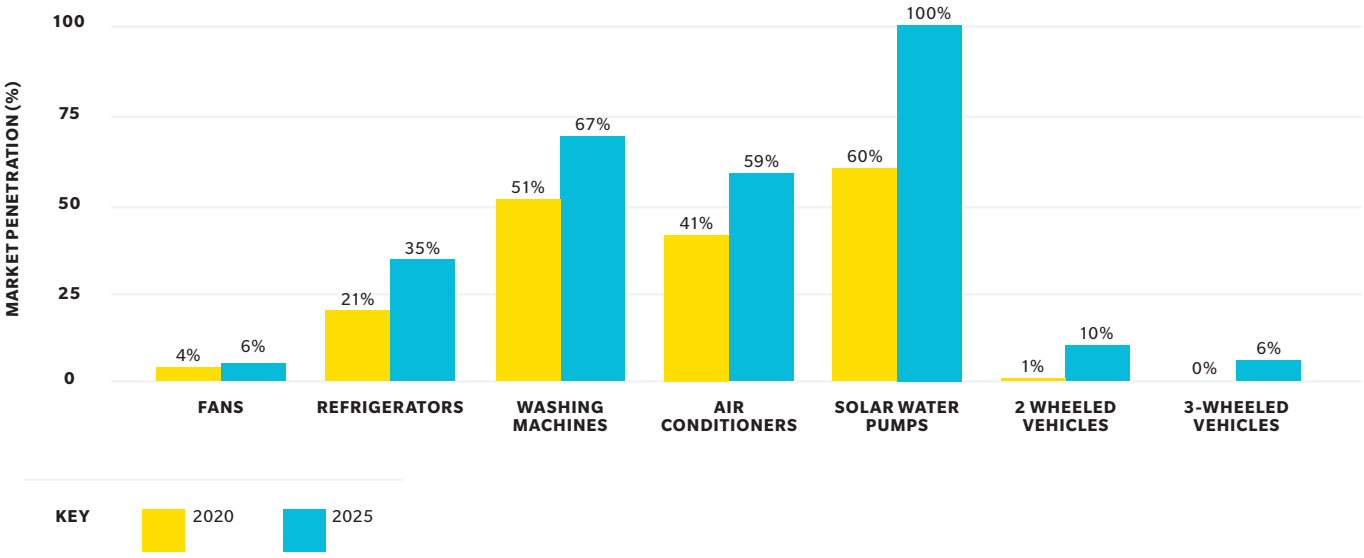


Figure 2: Market penetration of PM motor appliances in Sub-Saharan Africa (2020 and 2025)



Market barriers and strategies to accelerate PM motor adoption in appliances

If widely adopted, PM motors have the potential to transform off- and weak-grid appliance markets in Sub-Saharan Africa and South Asia. A switch to PM motors across the appliance and transportation sectors would reduce total energy consumption and improve the reliability of a wide array of products. However, this study finds significant barriers to the widespread adoption of PM motor appliances in off- and weak-grid markets persist.

High purchase prices are one of the most significant factors limiting PM adoption motors in high-performing appliances. Percentage cost premiums vary by appliance type. The price premium for a deep freezer using a PM motor is just 3%, while price premium in fans and two-wheeled EVs may be as high as 63% and 67%, respectively. Other significant barriers to PM motor adoption in appliances include:

1. Lack of access to finance
2. Low awareness of the technology
3. Lack of post-sale services

In order to increase PM motor adoption in appliances across South Asia and Sub-Saharan Africa, market actors should take the following actions:

1. Standardise PM motors, controllers and appliance interfaces
2. Establish standards and labelling programmes
3. Strengthen the local manufacturing capacity, supply chain and ecosystem
4. Develop demand aggregation and bulk procurement models for PM motor appliances
5. Provide fiscal incentives and subsidies
6. Improve consumer awareness of the benefits of energy efficient appliances
7. Develop and grow consumer financing
8. Create a quality-assured market platform for PM motor appliances
9. Provide quality post-sales services at lower costs
10. Improve customers' experiences and confidence in PM motor appliances
11. Build capacity of motor and appliance original equpment manufacturers (OEMs), integrators and distributors

Introduction

INTRODUCTION

The Low Energy Inclusive Appliances programme (LEIA) aims to accelerate the availability, affordability, efficiency and performance of a range of low energy inclusive appliances particularly suited to lesser developed countries. LEIA supports market, consumer, impacts, and technology research that furthers the programme's goal to double the efficiency and halve the costs of a suite of off- and weak-grid technologies.

Energy efficient motors are an area of great interest for LEIA given their importance in a wide range of off- and weak-grid appliances. This study was commissioned to better understand the characteristics of the current and future market for these products. Permanent magnet (PM) direct current motors, particularly brushless direct current (BLDC) motors and permanent magnet synchronous (PMS) motors are an area of interest in terms of the total potential demand for motor appliances in off- and weak-grid applications, and the potential energy efficiency, performance, and reliability improvements they offer over competing motor technologies. This report focuses on the following aspects of adoption of PM motors in various appliances:

1. Characterisation of the current and future global market of PM motors as used in the following appliances:
   - A *Household appliances:* Fans, refrigerators, mixer-grinders, washing machines, and air conditioners
   - B *Productive use appliances:* Solar water pumps, deep freezers and commercial mixer-grinders
   - C *Transportation:* 2-wheelers and 3-wheelers
2. Evaluation and segmentation of the potential addressable market for PM motors in off- and weak-grid applications listed in Point 1
3. Quantification of the benefits of PM motors versus conventional legacy motors (alternating current (AC) induction motors, universal motors, etc.) in off- and weak- grid applications, in terms of enhanced efficiency, performance, reliability, maintainability and total life cycle costs
4. Identification of barriers to the adoption of PM motors in appliance market segments, and strategies to accelerate adoption in off- and weak-grid applications at scale
5. Opportunities for implementing standardisation and demand aggregation strategies to upscale adoption of PM motors in different appliances
6. Brief discussion on technology trends in PM motors focused on further improving the energy efficiency and adding user perceived value features to the appliance or equipment through incorporation of PM motors

The results of this study are intended to provide an important component of the evidence base for future Efficiency for Access Coalition activities to support PM motor use in appliances and equipment.

The report consists of two volumes. The first volume focuses on appliance-agnostic topics like the compatibility of PM motor appliances with off- and weak- grid power systems, market trends of adoption of PM motors in South Asian and Sub-Saharan Africa, and upscaling strategies for PM motor adoption. The structure of Volume 1 is as below:

- The study starts by evaluating the impact of drive motors on appliance energy efficiency, power needs, and off- and weak-grid compatibility
- Next, PM motors are compared against conventional AC induction and universal motors for their benefits and impact on the appliance cost as well as sizing of a solar PV based off-grid system
- Finally, the study identifies the primary barriers for PM motor adoption in selected appliances and provides recommendations for overcoming each

Volume 2, published separately, addresses each appliance in more specific detail including market status and trends, price-performance characterisation, and total life cycle cost comparisons.

PM motors in off-and weak-grid applications

There has been be a marked rise in global off-grid solar system sales as consumers have become more aware of the benefits of off-grid power supply in terms of operating cost and reliability compared to the central utility grid. The off-grid solar sector is a US$1.75 billion annual market. Between 2017 and 2019, sales of solar photovoltaic (PV) panel systems grew by 10% annually.[5] By 2030, the off-grid solar sector is expected to serve 823 million people globally.[6] This growth underscores the increasing importance of off-grid compatibility of among appliances.

Motor Technology

Electric motors are the prime movers in many appliances. Motors work by transforming electric energy into useful work fulfilling the purpose of the appliance. Thus, they determine the appliance capabilities, power demand, energy consumption and reliability. In addition, motors also contribute to an appliances ease of use, features, refinement, etc.

A *motor* primarily consists of a *stator* and a *rotor*. Both the stator and the rotor have electromagnetic fields and at least one of them changes constantly. The generation of changing or rotating magnetic fields required to start and run the motor is called *commutation*. It is achieved by continuously changing the direction of the current flowing through the electromagnetic coils. If both the fields use electromagnetic *induction,* the motor is called an induction motor. If permanent magnets are used in one of the fields, the motor is called a *permanent magnet* (PM) motor. If the motor runs on *alternating current* (AC), it is called an AC motor. On the other hand, if the motor works on *direct current* (DC), it is called a DC motor.

In an AC *induction motor*, the alternating current supplied to the motor's stator creates an electromagnetic field that rotates with the AC oscillations (based on the number of poles). This changing magnetic field creates a rotor flux with magnetic polarity opposite to the stator, dragging the rotor behind stator flux, with the currents in the rotor induced at the slip frequency. Thus, there is always a slip or lag between the stator and rotor fields. This is one of the main reasons for relatively lower efficiency of AC induction motors.

DEFINITIONS

Off-grid energy system Refers to stand-alone systems that typically employ small-scale renewable energy supply and do not connect to a centralised electricity supply grid. Off-grid energy systems help improve the overall standard of living in remote rural areas where the grid does not have reach. They are often much more efficient (grid transmission losses and thefts can be as high as 10-20%[7]) – particularly in the remote rural or sub-urban regions.

Weak-grid Refers to installations which, although connected to a central electricity supply grid, experience extensive reliability issues in terms of power supply duration, power-cut frequency, and supply voltage.

A *universal motor* typically uses AC in both the field coils and the armature (electromagnetic coils producing the changing field). Thus, both can alternate (reverse polarity) synchronously with the supply and the rotor field does not lag the stator field – making it a *synchronous motor*. This design necessitates a commutator - usually a sliding brush – to selectively apply and switch-off the stator current to different rotor sections. These basic commutators cause frictional losses thereby reducing the motor efficiency.

In PM motors,[8] the armature conductors are separated by a gap and the direction of current is maintained perpendicular to the field of the permanent magnets using electronic switching circuits. The interaction of such an armature field with the magnets provides commutation. In these motors, the magnets and the armature fields can rotate at the same speed, making them synchronous motors. Thus, PM motors do not have slip losses. Electronic switching commutators eliminate commutation friction making PM motors more efficient compared to the AC induction or universal motors.

5. https://www.lightingglobal.org/wp-content/uploads/2020/03/VIVID%20OCA_2020_Off_Grid_Solar_Market_Trends_Report_Summary_High%20res.pdf
6. https://www.worldbank.org/en/topic/energy/publication/off-grid-solar-market-trends-report-2020
7. https://www.cea.nic.in/reports/others/planning/pdm/growth_2019.pdf Pg. No 58
8. Brushless DC motors (BLDC motors), permanent magnet synchronous motors (PMS motors), etc.

PM MOTORS IN OFF- AND WEAK-GRID APPLICATIONS

The primary comparisons drawn in this report are for AC (induction or universal) motors traditionally used in appliances due to their simplicity and lower cost, versus the permanent magnet DC motors, which although more complex, can be significantly more energy efficient and enable enhanced functions and features in appliances.

The primary function of a *motor controller* is to enable commutation. Motors must often operate on duty-cycles (on-off, clockwise-anticlockwise, variable speed-torque, etc.) for a product to provide useful energy service. The controller ensures the motor caters to those demands. Another function often handled by motor controllers is power conversion. The accuracy and versatility of a controller tends to define the efficiency, effectiveness, noise, and quality of the appliance. Hence, product designers often focus on controller features and tuning.[9]

Table 1: Comparison of different motor types with respect to performance attributes

	AC INDUCTION MOTOR		UNIVERSAL MOTOR		PM MOTOR[10]	
Attribute	**Motor**	**Controller**	**Motor**	**Controller**	**Motor**	**Controller**
Construction	Simple	Simple	Medium	Simple	Simple	Complex
Cost	Low	Low	Medium	Low	Medium	High
Efficiency	Low	Low	Medium	Medium	High	High
Smart features[11]	Low	Low	Medium	Low	Many	Many
Versatility[12]	Low	Low	Medium	Low	High	High
Noise levels	Medium	Medium	High	High	Low	Low

9. From technical consultations with LG India
10. PM motors broadly include BLDC and PMS motors. The comparison is drawn on average cost of these two motors.
11. IoT compatibility, app connectivity, programmability, self-diagnostics, etc.
12. Usability in all operating conditions and various modes of operations.

The commutation in a PM motor uses electronic switching circuits, so controllers are inherently more complex and thus more expensive than those of AC motors. This complexity provides an opportunity to integrate enhanced functionalities and features adding to the user-perceived value of the appliance. These enhanced features continue to drive sales of PM motor appliances, particularly in urban markets, as customer spending capacity and willingness to pay improves along with the perceived value of these features, examples include:

1. Smart and programmable controls – optimisation of appliance operation time based on utility tariffs, user convenience, energy consumption and energy availability in case of solar off-grid supply.
2. Internet of Things (IoT) – monitoring and rescheduling operational (e.g. washing machine cycles) or maintenance tasks from remote locations using a smartphone application and internet.
3. Variable speed smart duty-cycles – ability to tune the appliance to adapt changes in ambient conditions, time of the day, energy usage, user preferences, etc.
4. Self-diagnostics and serviceability prompts – simple maintenance tasks can be handled easily by users following controller prompts, particularly for productive use appliances and transportation devices.
5. Detection of and optimisation for running on backup power supply – extended period low-voltage running can be optimised by appropriately adjusting motor duty-cycle.

Motor application challenges

High startup current, power conversion efficiency, low voltage performance, and maintenance are major barriers to greater adoption of PM motors in off-grid appliances. Despite these barriers, PM motors are more compatible with off- and weak-grid settings than other motor types, see Table 2 on page 18).

High startup current The most common power source in off-grid setups is the solar PV system. PV systems have an inherent cyclicity in terms of the magnitude of power generated (morning, noon and evening) and periods of zero power generation (night). This cyclicity is often compensated by using an auxiliary battery to store energy. The battery is an additional system cost as illustrated in the case study on page 31.

Some appliances have an on/off duty cycle in their operation. For example, refrigerator compressors, washing machines and mixer-grinders are designed to run either in some sort of start-stop mode or require frequent reversals in the direction of rotation. The starting current of AC induction motors can be as high as seven times the rated current.[13] This can cause a momentary surge in current demand, causing the appliance power supply to trip.

Power conversion efficiency The energy required to run a motor appliance is directly influenced by the efficiency of the motor and the number of energy conversions involved. Power conversions might be required for compatibility between a power source and motor as well as auxiliaries like convective fans, lights, displays, etc. Unlike engine-generators powering AC grids, solar PV cells produce DC power. Using PM motors, appliances can be easily designed to run directly on DC power. This can minimise or even eliminate conversion losses[14] from household inverters, and enable a more simple (and therefore more reliable and less expensive) product design with fewer components.

Performance at low voltage The next major challenge in off- and weak grid systems is ability to run on low voltage. Often, when a DC energy source like solar panels or a battery is loaded, the voltage tends to drop. Thus, in off- or weak-grid applications, appliances must be capable of running at low voltage for a substantial portion of their operational life. AC induction motors are relatively more vulnerable to poor performance as well as reduced lifetimes while running on low voltage.

Maintenance Off-grid sites are often remote, posing challenges for service, maintenance, and repair of appliances as well as power supplies. Thus, appliances with better reliability and easier maintenance are preferred by consumers.

Overall, for off- and weak-grid systems, the parameters that influence appliance-motor compatibility are:

- *Power to start and run the appliance* affects the sizing and cost of solar PV panels
- *Energy to start and run the appliance* determines the capacity and cost of the auxiliary battery
- *Low voltage operability* heavily influences appliance performance and lifetime
- *Reliability* of the appliance determines the frequency of breakdowns and thus, its service requirements
- *Maintainability* determines the technical capability required of the operator or the service personnel

13. BLDC vs AC motor comparison
14. https://efficiencyforaccess.org/publications/performance-and-efficiency-of-off-grid-appliances-with-power-converters-phase-2-testing-of-multipleappliances-and-an-inverter-compressor-refrigerator

Table 2: Analysis of compatibility of different motor types for off- and weak-grid applications

	AC INDUCTION MOTOR		UNIVERSAL MOTOR		PM MOTOR	
Compatibility parameters	**Start**	**Run-time**	**Start**	**Run-time**	**Start**	**Run-time**
Power consumption	Very High	High	Very High	High	Low	Low
Energy consumption	Very High	High	Very High	High	Low	Low
Low voltage operability	Poor	Average	Poor	Average	Good	Excellent
Reliability	Average	Average	Average	Average	Good	Good
Maintainability	Easy	Easy	Average	Average	Easy	Easy

PM motor technology trends

While PM motors are currently more expensive than conventional AC and universal motors, there are several technological improvements on the horizon which may bring PM motor appliances to cost parity while saving energy and adding value for the user. Some of the technological advancements expected to be implemented in the next 2-5 years are:

1. Using axial flux design instead of conventional radial flux – can provide higher torque and power density, making the designs much more compact.[15]
2. Using Field Oriented Control (FOC) – can make motors more efficient (high power factor and ~ 10% better light-load / low-speed efficiency), smoother (lower torque ripples) and more responsive.[16]
3. Using Soft Magnetic Composites (SMC) instead of laminated steel in the core – can reduce eddy current losses but have to be traded-off with hysteresis losses.[17]
4. Enabling advanced remote monitoring and servicing capabilities – this is particularly relevant for remote customer in sites that are difficult to service, as it can provide early warnings of failures along with utilisation data.
5. Ability to run on DC source directly – enables bypassing the inverter when connected to an appropriate DC power source, thereby increasing the appliance efficiency by cutting down conversion losses.

Apart from the new technologies, various existing technological alternatives are being actively pursued. These have the potential to make the PM motor appliances more cost-effective. Alternatives of note include:

1. Use of ferrite magnets instead of neodymium, leading to reduced materials cost with equivalent performance.
2. Use of a single inverter for all motors in appliances like air conditioner and refrigerator, which use multiple motors, leading to reduced complexity and cost.
3. General purpose integrated circuit-based controllers (ASIC) instead of dedicated controllers, leading to lower costs.
4. Sensor-less control techniques to eliminate the rotor speed sensor, leading to reduced component count and lower costs.

15. https://www.magnax.com/magnax-blog/axial-flux-vs-radial-flux.-4-reasons-why-does-axial-flux-machines-deliver-a-higher-power-density.
16. https://www.ti.com/lit/an/slva939b/slva939b.pdf?ts=1602157243428andref_url=https%253A%252F%252Fwww.google.com%252F#:~:text=FOC%20control%20makes%20the%20stator,speed%20using%20field%20weakening%20technique.
17. https://www.horizontechnology.biz/blog/lamination-steel-soft-magnetic-composite

PM MOTORS IN OFF- AND WEAK-GRID APPLICATIONS

KEY TAKEAWAYS

PM motors were identified to be superior to conventional AC motors in all parameters critical for off- and weak-grid compatibility. Thus, with the off-grid solar market poised to grow significantly in the coming years especially in developing regions like Sub-Saharan Africa and South Asia, where appliance manufacturers are expected to switch to PM motor technology for higher value products.

With continuous technological innovations and advancements, PM motors are expected to realise improvements in cost, energy efficiency and value added features. Analysis of current PM motor market size and future trends will be useful to vet the market sentiments towards current PM motor technology and assess if the motor technology is advancing in coherence with OEMs' and end-users' requirements and expectations.

PM motor market trends and price performance

Market size and demand drivers

This section discusses annual sales[18] and PM motor penetration rates for household appliances, productive use appliances, and transportation in Sub-Saharan Africa and South Asia. For each of these appliance categories, key demand drivers to increase PM motor adoption are presented. Analysis of the current market, future trends, and key demand drivers for PM motor appliances highlights the most critical parameters for decision makers and aids in creating a supportive environment for promoting energy efficient technologies.

In order to estimate the current and future market size for PM motor appliances, baseline appliance baseline appliances sales numbers irrespective of motor technologies from 2017-2019 and growth rates were identified. We combined these figures with PM motor penetration rates to estimate annual sales of PM motor appliances in 2020 and 2025.

Household appliances

Fans Fans have the largest total market of all household appliances included in this report, but the penetration of PM motor fans is lowest among the appliances included in this study; only 2% in 2017 in Sub-Saharan Africa and South Asia.

One primary reason for this low market share is that the fan market is highly price-sensitive, and PM motor fans are expensive. A PM motor accounts for approximately 40% of a fan's price. PM motor fans do not currently cater to the mass market. Low volumes cause PM motor fans to be sold at a price premium. PM motor adoption will be mainly driven by growth in the solar off-grid market and by government standards and incentives that push for energy efficient appliances.

Refrigerators In South Asia, the refrigerator market is estimated to grow from 22.5 million units in 2020 to 32.2 million units in 2025, a CAGR of 7.4% (see Table 3 on page 22). The market in Sub-Saharan Africa is expected to develop along similar lines, reaching 6.3 million units by 2025.

In South Asia, PM motor adoption for refrigerator compressors is among the highest of any application. In the region, the market share of PM motor refrigerators (also referred to as inverter refrigerators) is expected to increase from 65% (14.7 million units) in 2020 to 86% (27.8 million units) in 2025. In Sub-Saharan Africa, the penetration rate is expected increase to 21% in 2020 and 35% in 2025.

One of the key reasons of the high penetration rate in refrigerators is the PM motor's ability to provide value added features such as quiet operation. Consumer value, along with higher energy efficiency and increasing disposable income, are the drivers with the highest impact on adoption of PM motors in refrigerators.

Washing machines There is limited or no adoption of PM motors in semi-automatic washing machines[19] and thus this research focuses on fully automatic washing machines, which currently constitute about 46% of the total washing machine market for both regions. However, with rising disposable incomes and lifestyle changes, the market share of fully automatic washing machines is expected to increase. The fully automatic washing machine market is estimated to grow at a CAGR of 11% in South Asia to reach 10.5 million units by 2025 and 7% in Sub-Saharan Africa to reach 1.4 million units by 2025.

The washing machine market presents the only example for which PM motor penetration is higher in Sub-Saharan Africa (51% in 2020 and estimated to reach 67% in 2025) than in South Asia (33% in 2020 and estimated to reach 53% in 2025). The key demand drivers for PM motor washing machines are similar to that of refrigerators. A PM motor's ability to enable value add features, increase disposable income and increase the working population will drive adoption in washing machines.

Air conditioners In both South Asia and Sub-Saharan Africa, the air conditioner market is estimated to grow at a CAGR of 10%, reaching 16.3 million units in South Asia and 2.6 million units in Sub-Saharan Africa in 2025. In Sub-Saharan Africa and South Asia, split air conditioners are more popular than window air conditioners, with market share well above 90% in both regions. PM motor air conditioners (also referred to as inverter air conditioners) have flooded the market, especially in South Asia with current penetration rate of 65%, estimated to reach 88% by 2025. In Sub-Saharan Africa, the PM motor penetration rate is expected to grow from 41% in 2020 to 59% in 2025.

Increasing disposable income and rising temperature and humidity are contributing to greater air conditioner use. Consumer preference towards energy efficient appliances is driving the inverter air conditioners market. Like in other white goods products, a PM motor's ability to enable value added features is a key demand driver for PM motor application.

18. Irrespective of the motor technology. Also, the numbers are total appliance sales and not just in off- and weak-grid regions.
19. Stakeholder consultations with Appliance OEMs

Table 3: Household appliance market trend and PM motor penetration rate-South Asia and Sub-Saharan Africa

		ESTIMATED ANNUAL SALES[20] (THOUSANDS)			ESTIMATED PM MOTOR PENETRATION	
HOUSEHOLD APPLIANCE	REGION	2020	2025	CAGR (2020-2025)	2020	2025
Fans	South Asia	76,669	104,550	6%	3%	7%
	Sub-Saharan Africa	1,316	1,656	5%	4%	6%
Refrigerators	South Asia	22,549	32,288	7%	65%	88%
	Sub-Saharan Africa	4,348	6,338	8%	41%	59%
Washing Machines	South Asia	6,337	10,541	11%	33%	53%
	Sub-Saharan Africa	949	1,355	7%	51%	67%
Air Conditioners	South Asia	10,148	16,293	10%	65%	86%
	Sub-Saharan Africa	1,606	2,570	10%	21%	35%

20. The estimated sales are inclusive of all types of motors that includes induction motors, PM motors, and others.

Productive use appliances

Solar water pumps Much of the demand for solar water pumps (SWPs) is in South Asia and is driven by subsidy programmes managed by government agencies. However, the commercial opportunity for the broader productive use market is also growing due to falling costs of technology, innovations in system design (controller, portability, etc.), better product reliability, increasing sales and service network, and innovations in business models. The SWP market is estimated to grow at a CAGR of 27% and 18% in South Asia and Sub-Saharan Africa, respectively (see Table 4).

Higher energy efficiency and better compatibility with solar technology has ensured very high PM motor penetration rates for SWPs. In both South Asia and Sub-Saharan Africa, the current PM motor penetration rate is 60% and estimated to reach 100% in 2025.

These factors along with high government subsidies and availability of external financing will continue to drive the demand for PM motors for SWPs, primarily in South Asian markets.

Deep freezers[21] The deep freezer market in South Asia is expected to grow at a CAGR of 25% reaching annual sales of 5.6 million units in the year 2025 (see Table 4). Growth in food storage facilities to reduce food wastage and growth in healthcare facilities will be the key demand drivers for deep freezers.

Unlike household refrigerators, PM motor penetration of deep freezers is quite low in South Asia. One of the reasons for this is lack of energy labelling programmes. In March 2020, India introduced the first voluntary energy labelling programme in the region. In South Asia, PM motor penetration is currently estimated to be 5% and is estimated to reach 8% in 2025.

In Sub-Saharan Africa, there was limited baseline data available for deep freezers with conventional motors. The PM motor deep freezer market is estimated to reach annual sales of 120 thousand units in the year 2025, growing at a CAGR of 19%.

Energy-labelling programmes and supportive governmental policies can be used to push for more energy efficient and reliable cold storage facilities, especially in the healthcare sector. These actions are expected to drive the demand for PM motor adoption in deep freezers.

Table 4: Productive use appliance market trend and PM motor penetration rate-South Asia and Sub-Saharan Africa

		ESTIMATED ANNUAL SALES[22] (THOUSANDS)			ESTIMATED PM MOTOR PENETRATION	
	REGION	2020	2025	CAGR (2020-2025)	2020	2025
Solar Water Pump	South Asia	86	374	27%	60%	100%
	Sub-Saharan Africa	55	153	18%	60%	100%
Deep Freezer[23]	South Asia	1,805	5,592	25%	5%	8%
	Sub-Saharan Africa	5	11.7	19%	NA	NA

21. Deep freezers are a standalone freezer with a hinged lid that opens from the top
22. The estimated sales are inclusive of all types of motors that includes induction motors, PM motors, and others.
23. The represented figures for Deep Freezers in Sub-Saharan Africa are estimated PM motor appliance sales and not overall appliance sales

Transportation

Electric 2- and 3-wheelers Nearly all electric 2-wheelers (e-2W) and electric 3-wheelers (e-3W) use a PM motor and thus higher adoption of PM motor transportation is expected to occur alongside higher adoption of electric vehicles in general.

2W and 3W vehicle segments have seen phenomenal growth over the last decade. The growing demand in both urban and rural areas has been primarily due to increasing population, growing income, increasing urbanisation, and poor public transport networks. In the next five years, 2W are estimated to reach annual sales of 30.7 million units in South Asia and 3.6 million units in Sub-Saharan Africa (see Table 5). The 2W market landscape of South Asia and SSA are quite different. In South Asia, two-wheelers are primarily used for personal travels, while in many countries of SSA they are operated primarily as commercial taxis.

The e-2W market is expected to be the next big market for PM motors. In contrast with the 4% and 8% CAGR for all 2W in South Asia and Sub-Saharan Africa, respectively, the e-2W market is expected to grow by 58% and 68% CAGR over the next five years in South Asia and Sub-Saharan Africa, respectively.

The e-3W market is already a large market for PM motors in South Asia with annual sales estimated to be 0.74 million units in 2020. The e-3W market is expected to grow at a more modest rate of 11% CAGR. In Sub-Saharan Africa, the market volumes are expected to be very low until 2025.

The key demand drivers for growth of e-2W and e-3W are global awareness of climate change, lower operating cost as compared to fossil fuel-powered vehicles, and favorable government policies and incentives. Improved customer awareness and facilitation of financing will be the key growth drivers for electric vehicles and a major market opportunity for PM motors.

Table 5: Transportation market trend and PM motor penetration rate-South Asia and Sub-Saharan Africa

		ESTIMATED ANNUAL SALES[24] (THOUSANDS)			ESTIMATED PM MOTOR PENETRATION	
	REGION	2020	2025	CAGR (2020-2025)	2020	2025
2-Wheeler	South Asia	21,881	30,689	4%	1%	9%
	Sub-Saharan Africa	2,661	3,661	8%	1%	10%
3-Wheeler	South Asia	1,694	2,331	7%	44%	53%
	Sub-Saharan Africa	576	1,937	11%	~0%	6%

24. The estimated sales are inclusive of all types of motors that includes induction motors, PM motors, and others.

Characterisation of off- and weak-grid markets

To assess the market potential of PM motor appliances for off- and weak-grid regions, the following parameters are considered for qualitative analysis:

- *Current adoption trends*: The current penetration of PM motor appliances
- *Customer affordability:* The customer's ability to purchase the appliance
- *Priority of the appliance:* The purchase priority of the appliance from the end-user perspective
- *Supply chain:* The strength of the supply chain including local manufacturing, sales and post-sales support

This section highlights the market potential for each PM motor appliance in off- and weak-grid markets.

Fans have a very price sensitive market. Fan manufacturers sometimes compromise on the quality of air delivery to meet a specific price point. PM motor fans are also popular for solar applications. Due to their low energy consumption, and there will be increased demand from grid-connected households that seek to reduce energy costs.

Air conditioners and washing machines have low market potential in off- and weak-grid applications. This is primarily due to high price and lower priority for purchase compared to other appliances.

Refrigerators and deep freezers have high potential for solar applications due to government/donor interest and the potential to improve livelihoods. The pressing need to distribute COVID-19 vaccines is expected to further increase the demand for cold storage solutions. Demand aggregation and access to financing are important parameters to address end-user affordability.

Water pumps also have high potential for solar application due to government/donor priorities and potential to improve livelihoods. Sub-Saharan Africa has a limited history of mechanised irrigation, however with growing income levels more farmers are expected adopt solar water pumps.

The **e-2W** market is expected to grow significantly as the technology matures, battery prices fall and competition among OEMs increases. Solar-based systems can charge vehicles in off- and weak-grid areas. The business models need to be further developed through pilots.

The market for **e-3W** varies for South Asia and Sub-Saharan Africa. In Sub-Saharan Africa, 2W are used as commercial taxis, lowering the priority of the 3W vehicle segment. In South Asia, customer affordability of commercially used 3W is driving the market potential of e-3W.

Looking across all applications in South Asia, PM motor productive use appliances and transportation are expected to have the greatest market potential (see Table 6). Among household appliances, refrigerators are expected to have high market potential and fans are expected to have medium potential.

In looking across all applications in Sub-Saharan Africa, refrigerators and fans have high market potential among household appliances and solar water pumps and deep freezers have high potential among productive use appliances. The potential of PM motors in transportation is considered medium to low due to low sales volumes of electric vehicle.

Table 6: Qualitative analysis of off- and weak-grid market potential of PM motor appliances[25]

	REGION	CURRENT ADOPTION TREND	CURRENT AFFORDABILITY	PRIORITY OF THE APPLIANCE	SUPPLY CHAIN	MARKET POTENTIAL OF PM MOTOR APPLIANCE
Household appliance						
Fans	South Asia	High	High (price sensitive market and quality can be compromised)	High	Medium	Medium (price conscious)
	Sub-Saharan Africa	High	High (price sensitive market and quality can be compromised)	High	Low	High (lower HH electrification rate)
Air conditioners	South Asia	Negligible	Low	Low	Low	Negligible
	Sub-Saharan Africa	Negligible	Low	Low	Negligible	Negligible
Washing machines	South Asia	Negligible	Medium	Low (other appliances are top priority)	Negligible	Negligible
	Sub-Saharan Africa	Negligible	Medium	Low (other appliances are top priority)	Negligible	Negligible
Refrigerators	South Asia	Low	Medium	High	Low	High (use in food and vaccine storage)
	Sub-Saharan Africa	Low	Medium	Medium	Low	High (use in food and vaccine storage)
Transportation						
E-2w	South Asia	Low for all 2w	Medium (affordability is expected to improve with volumes)	High	Medium	High
	Sub-Saharan Africa	Low for all 2w	Low (dependent on suitability of electric vehicle for commercial use as taxis)	High	Low	Medium (volumes are small at a country level)
E-3w	South Asia	High for all 3w	High (commercial usage and lower LCC)	High	High	High
	Sub-Saharan Africa	Negligible for all 3w	Low (market need is limited)	Low (as 2W are used as taxis)	Negligible	Low
Productive use appliance						
Solar water pumps	South Asia	Medium	Medium (due to favorable subsidies)	High	High	High (heavily dependent on government policy)
	Sub-Saharan Africa	Low	Low (lack of subsidies)	High	Medium	High (high unirrigated land)
Deep freezers*	South Asia	Low	Medium (provided access to finance is available)	High	Low	High (use in food and vaccine storage)
	Sub-Saharan Africa	Low	Medium (provided access to finance is available)	High	Low	High (use in food and vaccine storage)

25. Scale: Negligible (0), Low (1), Medium (2), High (3).

PM motor characteristics for various appliance types appliances

Basic motor technical parameters like size, speed, duty-cycle, etc. are listed for each appliance type in the table below. Further, the key technical advantages of switching to PM motor are identified for each application.

Motors can range from as small as 20 W for a fan to as high as 10 kW for a solar water pump. Motor speed requirements for each application vary significantly depending on the function performed by the appliance. High speed operation is required for mixer-grinders and washing machines, whereas refrigerators, air conditioners, and deep freezers operate at a low motor speed.

Variable speed operation is only critical for transportation applications, though in general, a PM motor's ability to enable variable speed control along with low voltage operability emerges as a key technical advantage across applications.

Table 7: Study of PM motor functional parameters for different applications

APPLIANCE NAME	NUMBER OF MOTORS	MOTOR SIZE RANGE(W)	MOTOR SPEED RANGE (RPM)	TYPICAL DUTY-CYCLE	KEY ADVANTAGE OF PM MOTOR
Household appliances					
Fans	1	20-60	100-2,500	Constant speed	Low voltage operability as speed doesn't drop at low voltage
Air conditioners	3[26] (compressor, IDU fan, ODU fan; depends on model)	750-1,800	750-2,500	On/off at constant speed	Variable speed control can avoid on/off duty-cycle
Mixer-grinders	1	250-750	8,000-15,000	Constant speed	Better control on acceleration and deceleration during grinding
Washing machines	Maximum 2 (separate for wash and spin cycles; depends on model)	120-350	8,000-12,000	On/off and speed reversal for wash cycle, constant speed for spin cycle	Eliminating belt drive through broader range speed control
Refrigerators	Maximum 3[27] (compressor, evaporator unit fan, condenser unit fan; depends on model)	90-250	1,800-4,200	On/off at constant speed	Variable speed control can avoid on/off duty-cycle
Transportation					
E-2W & E-3W	1	250-6,000	300-5,000	Completely transient for speed and load	Better control of acceleration and deceleration during transients and accurate torque response
Productive use appliances					
Solar water pumps	1	250-10,000	1,000-3,000	Constant speed	Low voltage operability and early start-ability as speed doesn't drop at low voltage
Deep freezers	2[28] (compressor, condenser unit fan)	90-230	1,800-4,200	On/off at constant speed	Variable speed control can avoid on/off duty-cycle
Commercial mixer-grinders	1	750-1,500	8,000-15,000	Constant speed	Increase in duration of continuous operation through lower blade speed

26. In this report, only compressor motor is considered
27. In this report, only compressor motor is considered
28. In this report, only compressor motor is considered

Price-performance analysis

Price-performance analysis is used to quantify the benefits of PM motors versus conventional motors in each application. For performance analysis, other than energy consumption, one key functional parameter highly relevant to the appliance has been compared. The figures represented in Table 8 (page 28) and Table 9 (page 29) are for household appliances, productive use appliances, and transportation in South Asia, as it is reasonable to assume that the same trends will be seen in other regional markets as they continue to mature. A detailed price-performance analysis along with each appliance's total life cycle cost (LCC) comparison is documented in Volume 2 of this report.

The price premium for PM motor appliances ranges from 3% for a deep freezer to 63% for a ceiling fan. However, due to the significantly reduced operational costs of energy efficient PM motor appliances, the life-cycle costs of PM motor appliances are lower than conventional AC motor appliances.[29] The price-premium is 67% for an e-2W when compared with an internal combustion engine (ICE) 2W.

The PM motor and controller constitutes 2% to 16% of the overall appliance, cost with the exception of fans where it is 35% to 45%. For fans a reduction in cost of PM motor will translate to substantial reductions in price and thus faster adoption of energy efficient technologies.

One of the primary advantages of PM motors is that they are more energy efficient than conventional AC or universal motors. The energy savings for PM motor appliances range from 22% in refrigerators to 42% for deep freezers. An e-2W is 83% more efficient than a conventional ICE 2W.

Excluding washing machines, the payback period for all appliances ranges from 4 months to 6 years. Washing machines can have a payback period of 26 years due to the relatively low number of operating hours during which efficiency benefits can be accumulated. Despite the longer payback, washing machines have 33% to 51% PM motor penetration. This indicates that customer purchase decisions are based on the superior performance and additional features enabled by PM motors rather than the payback period. From a manufacturer's perspective, the switch to PM motors may be driven by the elimination of a second motor or belt drive for spin-dry function, thus reducing product complexity and increasing reliability.

ELECTRIC 2-WHEELERS AND 3-WHEELERS

Electric 2-wheelers and 3-wheelers are a unique case, as they are the only products in this study where PM motors directly compete with Internal Combustion engines (ICE) instead of a different type of electric motor. Although the energy efficiency advantage of electric 2-wheelers over ICE 2-wheelers is extremely high (~83% energy savings), the customer perceives the value of a vehicle in terms of its range, or the distance that can be travelled per refill or recharge. Even the most advanced battery technology is an order of magnitude lower in energy density (kWh/kg) than the poorest of fossil fuels, to a point that even the most efficient electric 2-wheeler is sometimes perceived by the customer to be less valuable than a typical ICE 2-wheeler due to the former's lower range. Manufacturers compensate for the lack of range by maximising the amount of battery storage and using the most efficient motor possible. Therefore, most electric 2-wheelers already utilise PM motors, and battery capacity tends to be the biggest driver of product price. Any additional market growth for PM motors in electric vehicles will not come from a transition in motor technology, rather from the growth of the entire electric mobility market in general.

29. Except for washing machine

FANS IN PAKISTAN

Tamoor Fans is a Pakistan based company that sells ceiling and pedestal fans. Tamoor incorporated brushless DC (BLDC) motors into their ceiling fan product line in 2016 but had delayed upgrades to their pedestal fan product line due to costs. In 2019, their pedestal fan was tested by the Low Energy Inclusive Appliances (LEIA) programme. The results of this testing demonstrated that energy efficiency improvements were needed if the fan was to be able to operate on a smaller solar home system, thereby opening up new market opportunities. Tamoor proceeded to develop a pedestal fan with a BLDC motor which reduced energy consumption by nearly 50%, from 35 watts to 18 watts. Notably the cost of the fan increased by about US$6, or 32%. This cost increase is partially offset by the reduction in the size of the solar home system required to power the fan.

Table 8: Price-performance analysis of PM motor productive use appliances and transportation (South Asia)

CATEGORY	PRICE PERFORMANCE ATTRIBUTES	CEILING FAN (1.2 M)	DIRECT COOL REFRIGERATOR (200 L)	WASHING MACHINE (7.5 KG)
Price	Price premium for PM motor appliance (%)	63%	9%	12%
	Price of PM motor and controller in appliance price (%)	35% to 45%	~3%	~8%
Performance	Energy efficiency savings by PM motor (%)	~38%	~22%	~28%
	Other functional advantage from PM motor	38% reduction in input power[30] [W]	27% reduction in minimum operating voltage [V]	28% reduction in water utilisation[31]
Returns	PM motor appliance Payback	3.5 years	6.2 years	26.2 years
	Total LCC[32] of PM motor appliance against conventional motor appliance (%)	17% lower	3% lower	4% higher

30. Input power at medium speed (W)
31. Litres of water consumed per kg capacity
32. Life cycle costs

Table 9: Price performance analysis of PM motor productive use appliances and transportation (South Asia)

CATEGORY	PRICE PERFORMANCE ATTRIBUTES	SOLAR WATER PUMP (3HP)[33]	DEEP FREEZER (100 L)	ELECTRIC 2-WHEELER (100 KG)[34]
Price	Price premium for PM motor appliances (%)	~106%	3%	67%
	Price of PM motor and controller in appliance price (%)	2% to16%	4%	6%
Performance	Energy efficiency savings by PM motor (%)	Not relevant	42%	82%[35]
	Other functional advantage from PM motor	9% greater water output [litres per day][36]	34% improvement in minimum operating voltage [volts][37]	84% reduction in cost per 100 kilometers
Returns	PM motor appliance pay back	11 monts	4 months	3.5 years[38]
	Total LCC of PM motor appliance against conventional motor appliance (% lower)	~89%	25%	6%

Adoption drivers for PM motor appliances

This analysis identifies six key adoption drivers for PM motor appliances ranging from better product performance and cost savings to voluntary and mandatory programmes to incentivise the purchase of energy-efficient products.

1. **Improved energy efficiency** which saves operating costs in exchange for higher upfront cost. In this analysis we found efficiency to be an important factor for most appliances, but especially those with a high duty cycle, e.g., electric 2-wheelers that operate for long periods away from a charging station, and cold chain appliances that operate continuously throughout the day.

2. **Superior functional performance and value-added features.** For consumers, PM motors can enable quieter operation of washing machines and fans and can enable low-voltage performance for devices like solar water pumps to allow operation in early-mornings and overcast days. For manufacturers, PM motors can make for a better business case, for example by eliminating the need for belt drives in washing machines (thereby reducing component counts, complexity, and cost) or by enabling use of aluminium instead of copper cooling coils in refrigerators (reducing component costs).

3. **Higher reliability and improved serviceability.** PM motors have higher reliability than AC and Universal motors since they employ electronic commutation which is much less prone to wear and tear; an especially important factor for products like electric 2-wheelers and solar water pumps that are used in challenging environments. PM motors also do not require a starting capacitor – one of the most common failure points for fans with induction motors. PM motors deliver improved serviceability through IOT-enabled remote diagnostics, which can identify product performance degradation before the event of failure.

4. **Energy labelling.** Voluntary and mandatory energy labelling programmes can help drive the market for PM motors in grid-connected environments by highlighting the difference in performance between efficient and inefficient products. Developments in PM motor technology has enabled stricter energy efficiency norms and improved re-rating of energy labels.

5. **Cost savings in off-grid applications.** A net cost savings up to 30% is expected for off-grid households using energy efficient PM motor appliances over conventional motor appliances. The higher price of efficient appliances is outweighed by cost reductions at the system level, in particular the reduction in solar PV and battery capacity required to operate motor appliances.

33. Comparison with Diesel operated AC Induction motor pump
34. e-2W is compared to an ICE 2W
35. Petrol vs battery energy
36. Compared with AC Motor Solar Water Pump
37. Due to non-availability of data for selected appliance size, data for 325 litres deep freezer was selected for analysis
38. Assuming 30 kms per day and 37,000 kms payback mileage

Case study for an illustrative off-grid household using energy-efficient appliances The case study is for an illustrative off-grid two-room household in South Asia, to understand the impact of using energy efficient PM motor appliances versus conventional AC motor alternatives. The comparison evaluates peak power demand, average energy consumption and purchase cost. Subsequently, a sizing of solar PV off-grid system is done for both conventional and EE appliance scenarios.

The household runs appliances[39] for the assumed durations as illustrated in Figure 3 and Table 10. In this example, it is assumed the appliances are designed to run on 110 / 220 V AC and that the household uses an inverter for converting solar PV DC output to 110 / 220 V AC for household utilisation. This case study only considers the effect of appliance energy efficiency and not the additional savings possible by eliminating inverter and conversion losses by using DC supply compatible appliances. For sizing the off-grid system, there are typically two alternatives: series configuration where panels charge the battery and the battery runs the appliances (for peak demand) and parallel configuration where panels run the appliances during the day and simultaneously charge the battery for nighttime backup. The series configuration typically requires a larger battery and the parallel configuration a larger PV panel array. Even though the overall upfront cost comes out to be similar, a larger battery requires higher replacement cost (as the battery will never outlast the PV panel). Hence, the parallel configuration is chosen in the case study.

Even after accounting for a 20% higher upfront cost for energy-efficient appliances, there is still an *overall cost saving potential of 30%*. If higher capacity PV panels are installed, a spare capacity of 0.75 kW, freed up by PM motor appliances, can be used to charge an electric 2 or 3-wheeler, virtually eliminating its operating cost.

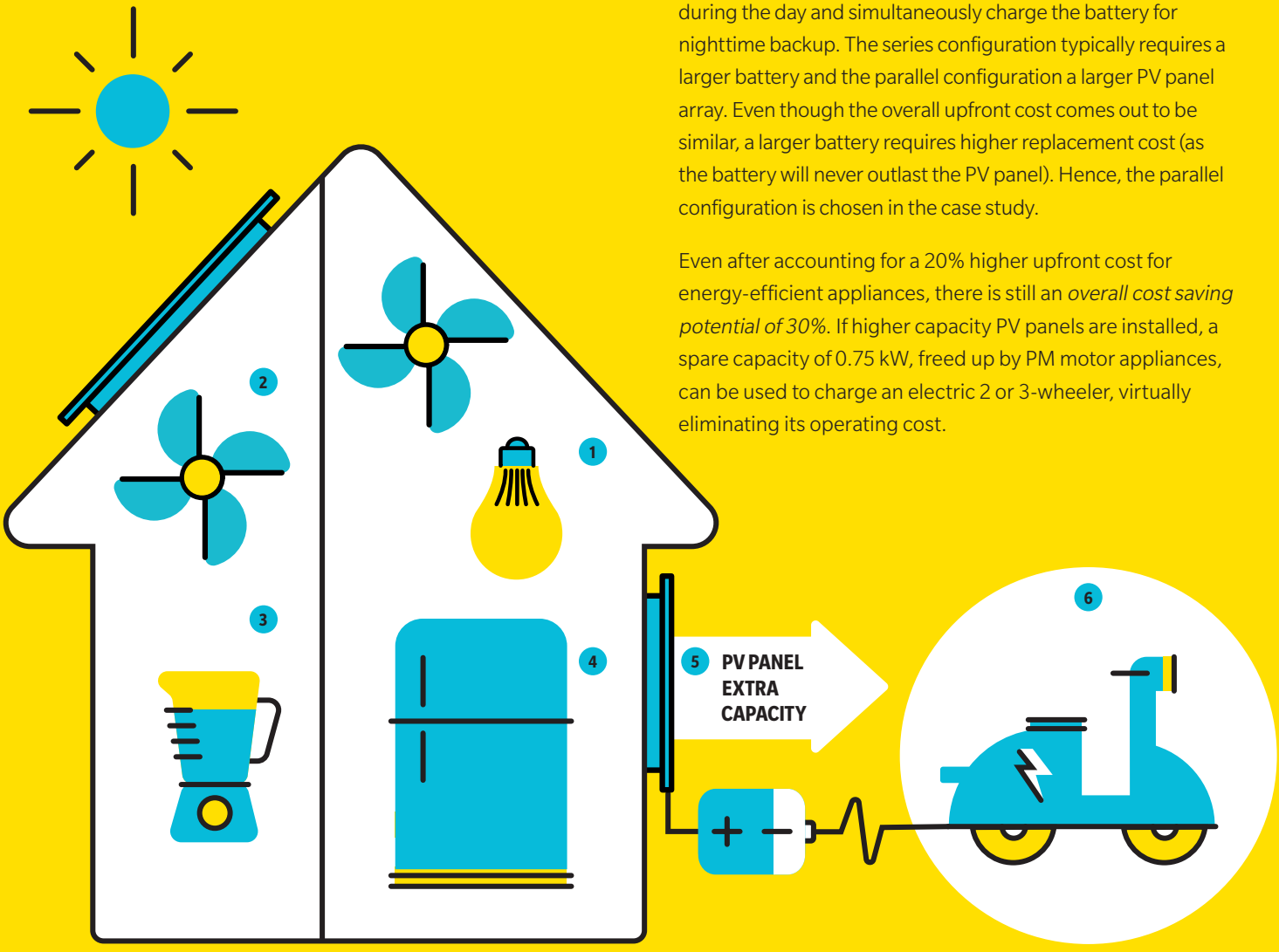


Figure 3: Illustration of an off-grid 2-room household with basic household appliances

1. 2 lights (450 lumens) Incandescent 80W vs. LED 10W
2. 2 1.2m sweep ceiling fans AC induction motor vs. 104Wpm motor 64W
3. 1 mixer-grinder universal motor 510W vs. PM motor 340W
4. 1 200L direct cool refrigerator AC induction motor vs. 100W PM motor 78W
5. PV panel extra capacity
6. Electric 2-wheeler (PM motor and 3 kw-hr battery; charge at 600 W for 6 hrs)

39. Motor driven appliances have been considered consistent with the focus of this report. Lighting has also been included.

Table 10: Power, energy and cost comparisons for conventional and energy efficient off-grid household appliances

	CONVENTIONAL APPLIANCE		ENERGY-EFFICIENT APPLIANCE		EXTRA COST FOR ENERGY-EFFICIENT APPLIANCE[40] [$US]
	Power [W]	Energy [kW-hr/yr]	Power [W]	Energy [kW-hr/yr]	
2 ceiling fans[41]	104	304	64	186	2*19 = 38
Mixer-grinder[42]	510	6	340	4	19
Refrigerator[43]	100	170	78	133	19
2 lights[44]	80	219	10	22	2*0.75 = 1.5
Mobile charger[45]	20	7.3	20	7.3	0
Inverter / battery charger[46]	395	1,154	193	562	0
TOTAL	**1,209**	**1,890**	**705**	**930**	**77.5**
NET % REDUCTION/SAVINGS	**–**	**–**	**42%**	**51%**	**20%**

A solar PV based off-grid power supply sized for this household with off-the-shelf sub-systems is as below:

Table 11: Solar PV and lead-acid battery sizing for conventional and energy efficient off-grid household appliances[47]

PARAMETER	HOUSE WITH CONVENTIONAL APPLIANCES	HOUSE WITH EFFICIENT APPLIANCES
PV panel peak wattage [W][48]	1,814	1,057
Recommended PV panels set	2.0 kW = 250 Wp x 8	1.25 kW = 250 Wp x 5
Spare capacity if already installed for conventional [W]	–	0.75 kW
Cost of PV panel [$US]	$US 107 x 8 = $US 855	$US 107 x 5 = $US 535
Cost savings on PV panel [$US]	–	320
Recommended battery [kW-hr] / [A-hr] 10 hr backup	2.5 kWh/ 220 Ah	1.5 kWh/ 150 Ah
Cost of battery [$US]	276	147
Cost savings on battery [$US]	–	129
TOTAL COST SAVINGS [$US]	**–**	**449**
NET REDUCTION/ SAVINGS [%]	**–**	**40%**

40. Details of cost premium for individual appliances are elaborated in Volume 2 of this report
41. 1200 mm sweep ceiling fan – 1-Ø AC induction motor v/s BLDC motor for usage of 8 hrs/day
42. 1.5L jar and actual mechanical power at blade of ~ 175 W – universal motor v/s BLDC motor for usage of 2 mins/day
43. 200L direct cool – 1-Ø AC induction motor v/s BLDC motor- Duty-cycle of 60% of rated power for AC and 80% for DC
44. Incandescent lights v/s LED lights for usage of 8 hrs/day41. 20 W charger for 3 hours/day
45. 20 W charger for 3 hours/day
46. Battery charging for 8 hrs/day during period of availability of sunlight
47. Solar PV and battery costs assumed for Luminous™ models as sold in India
48. The power required to charge battery in 8 hrs is added and a cushion of 50% is applied over the peak rated power of solar PV panels for cloudy days.

Barriers to PM motor adoption and strategies to drive market uptake

Barriers to PM motor adoption

PM motor penetration in most appliances is low. Though the identified demand drivers (page 30) will continue to push the appliance market towards energy efficient technologies, there are barriers to large scale adoption of PM motors whose impact can be mitigated, summarised in Table 12.

All of the identified barriers are highly relevant for Sub-Saharan Africa. For South Asia, only high unit economics/cost, product performance gaps and lack of purchase incentives are highly relevant. It is important to lower these barriers to ensure large scale adoption of PM motors in appliances. Addressing these barriers (high upfront cost of appliances using PM motors, increasing their ease of repair and maintenance, and improving consumer awareness) can encourage further PM motor adoption.

High upfront cost Challenges for PM motor adoption, like higher costs and poor access to finance, can be mitigated through initiatives like standardisation of appliance architecture, manufacturing processes, quality and reliability. These aspects are discussed in greater detail in the next section on standardisation.

Ease of repair and maintenance Remote monitoring systems and internet connectivity enabled by PM motor controllers contributes to making the task of servicing easier. Many appliances running on PM motors already have self-diagnostic abilities which, once connected to the internet, can send out prompt (and in some cases predictive) notification of product failures, thus reducing the number of service calls required by service providers.

Consumer awareness The hurdles of lower consumer awareness levels are being addressed through various regulations for efficiency ratings and federal regulations. Several global initiatives, including Efficiency for Access (a global coalition to accelerate clean energy access through high-performing appliances), Global LEAP (an energy efficiency awards programme) and VeraSol (a quality assurance programme), maintain databases of high-quality, energy efficient appliances or run campaigns to increase consumer awareness regarding energy efficient technologies.

Table 12: PM motors adoption barriers for Sub-Saharan Africa & South Asia

BARRIER CATEGORY	BARRIERS	SUB-SAHARAN AFRICA	SOUTH ASIA
Supply side	High unit economics/cost	✓	✓
	Product performance gaps	✓	✓
	Lack of access to finance (working capital and retail consumer financing)	✓	×
Customer side	Low awareness	✓	×
	Low priority for energy efficiency	✓	○
Policy side	Lack of purchase incentives	✓	✓
	Lack of performance standards	✓	×
	Lack of mass media driven consumer information	✓	○

KEY ✓ HIGHLY RELEVANT ○ SOMEWHAT RELEVANT × NOT RELEVANT

Table 13: Impact of standardisation interventions on various motor and controller parameters

STANDARDISATION INTERVENTION	RELIABILITY IMPROVEMENT	EASE OF REPAIR AND SPARE PART AVAILABILITY	BILL OF MATERIAL COST REDUCTION
Utilisation voltage	Low	High	High
ASIC[49] as motor controller	High	High	High
Power converter	Medium	High	High
Connector	Medium	Medium	Medium
Frame size	Low	High	High
Common motor design across select appliances	Medium	Medium	High

Standardisation opportunities and their impact on PM motor adoption

Standardisation aims to consolidate and simplify the technical aspects of an appliance. For PM motor appliances, standardisation may help to create new market opportunities and drive competition among OEMs to help reduce component and appliance costs. Standardisation can also lead to increased product reliability and serviceability, thereby protecting consumers and building trust in PM motor appliances. Standardisation of PM motor design and manufacturing will increase energy efficiency, cost-effectiveness, and reliability, while making the manufacturing and servicing processes more predictable. Table 13 identifies the impact of different standardisation interventions on various performance attributes of motor and controller.

It can be seen that standardisation will have maximum impact on cost reduction of motor and controller and ease of repair and spare part availability. A lesser impact is expected on reliability. Specific standardisation opportunities include: utilisation voltage, application specific integrated circuits (ASIC) as a motor controller, the power converter, connectors, frame size, and a common motor design for certain appliances.

Utilisation voltage Standardisation of utilisation voltage will reduce the proliferation of appliances with unique utilisation voltage requirements. Currently, utilisation voltages of 48V, 60V, and 72V are prevalent, with 48V being the most popular. Some international standards specify a maximum current of 20A for 48V systems; this translates to a power limitation of 1kW, which is insufficient for some motor applications. For appliances with rated power over 1 kW, efforts are underway to standardise around a Utilisation voltage of 380V. For community-level appliances in off- and weak-grid regions, this could be beneficial as 380V can be derived directly from solar PV arrays. Within this context, we recommend a 48V utilisation voltage for low power appliances and a 380V utilisation voltage for high-power appliances.

Application specific integrated circuits (ASIC) as a motor controller The present-day small market for PM motor appliances has led manufacturers to use Electronic Controller Units (ECU) as motor controllers in many appliances. ECUs tend to be large and costly, as they are generic devices meant to serve a wide range of applications, and thus may contain unnecessary or redundant features. With greater market demand for PM motor appliances, there will be opportunity to replace ECUs with lower footprint and less expensive ASIC. Standardisation of utilisation voltage (as noted above) will help drive standardisation of ASIC and its hardware and software architecture which will allow numerous different manufacturers to calibrate changes for different application before mass production. Globally, some big OEMs are working on the development of ASICs and progress should be visible in another 2-3 years. We recommend further engagement by PM motor stakeholders, standards bodies, etc. in ASIC standardisation efforts.

49. Application specific integrated circuit, an integrated circuit chip designed for a particular use.

Power converter Many PM motor appliances used in weak-grid applications are powered by AC and hence require AC to DC power conversion, which induces energy losses of 5-10% in each conversion step. If a DC solar power system is used as a power source for PM motor appliances, there are sometimes additional DC to AC and AC to DC power conversion losses in the ECU. Standardisation of utilisation voltages and connector specifications will help with the standardisation of power converters. This standardisation will allow for modular designs in which power converter circuitry is separated from appliance circuitry, so the same appliance will be capable of operating on AC or DC power sources with only a change to (or removal of) the power converter module.

Connectors The AC or DC main supply controller, converters, and appliances will benefit from standard connectors (plugs and sockets) for electrical interface. Standard connectors will allow improved interoperability across different (or multiple) appliances and integration with power and communication networks.

Some standardisation efforts are already underway for connectors. For example, GOGLA is currently leading an effort to develop standard connector specifications and communication protocols for household appliances, with a focus on two types of connectors, one that can handle power up to 100W and another for greater than 100W. For electric vehicles, particularly electric 4-wheelers, standardisation of the AC plug connector is already established. However, for 2-wheelers and 3-wheelers no common global standard has been established.

Frame size The distance between the center of the shaft of the motor to the base of the motor, expressed in millimeters, is called the frame size. National Electrical Manufacturers Association (NEMA) frame size refers to mounting only and has no direct bearing on the motor body diameter. NEMA and the International Electrotechnical Commission (IEC) have established standards for motor frame size. NEMA standards are typically followed in North America whereas IEC standards are followed in the rest of the world.

Air conditioners provide a good example of frame size[50] standardisation. The following standard frame sizes are used irrespective of the size (tonnage) of the system and are the same for both AC and DC motor types. PM motors use an additional 88 mm standard frame size for indoor units.

- Outdoor unit fan motor: 95mm
- Commercial and window ACs: 42 mm
- Mainly for commercial ACs: 48 mm

The IEC has developed a series of standard frame sizes, several of which could be agreed upon for use in PM motor appliances. Few manufacturers adhere to these standards currently. We recommend further efforts to support manufacturer adoption of IEC standards for off-grid and weak-grid appliances.[51]

Common motor design for select appliances Motor applications are typically characterised by power rating (watts) and speed (rpm) for required torque/load (N-m) across the operating spectrum. Multi-use motors are those which can be used in different appliances or applications. A multi-use motor may have to be over-designed to meet varying requirements of different applications and are generally sold as off-the-shelf components, versus being custom-designed for the application. Benefits of a multi-use motor include a significant reduction in cost due to higher volumes, greater spare part availability, and easier maintenance. The comparison in Figure 4 (page 37) shows some overlaps in motor speed and power requirements for different appliances.

50. Stakeholder consultation with Motor OEM
51. IEC 60072-1:1991, http://webstore.iec.ch/peblication/584

Figure 4: Mapping of typical motor rated power and speed ranges for various appliances

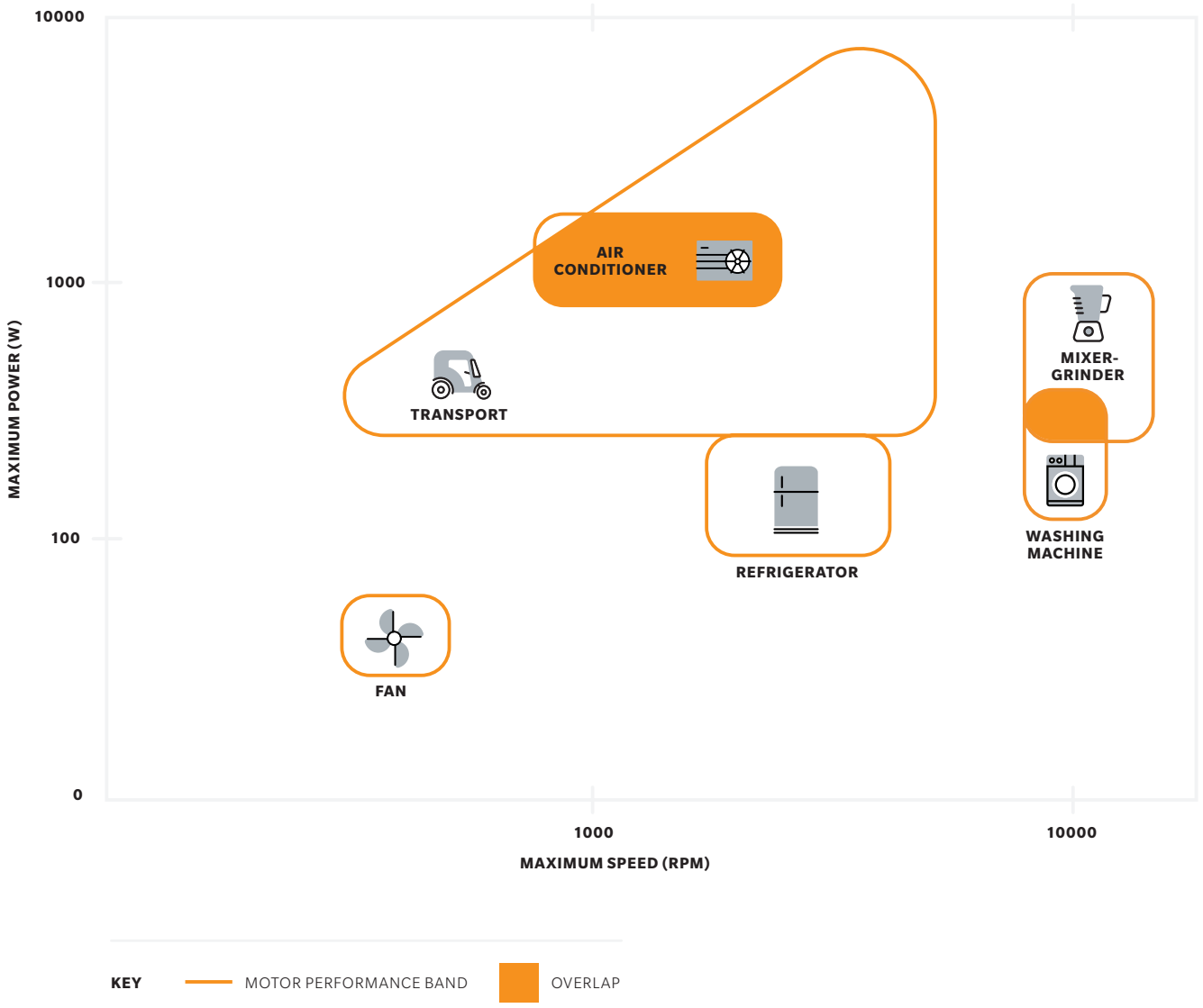


Table 14: Comparison of a 1300W motor application in electric vehicle and air conditioner compressor motors

	ELECTRIC VEHICLE MOTOR[52]	AIR CONDITIONER COMPRESSOR MOTOR[53]
Rated power [W]	1,300	1,250
Axial dimension [mm]	190	220
Radial dimension [mm]	160	150
Speed range [rpm]	0-3,200	1,800-3,000[54]
Rated torque [Nm]	4	4[55]
Utilisation voltage [V]	36 V DC Li-ion battery	110 / 220 V 1-Φ AC mains

As indicated in Figure 4 (page 37), there are two areas of potential overlap in PM motor performance, first between air conditioners and transport applications, and second between washing machines and mixer-grinders. As detailed in Table 14, a 1300 W motor could serve both an electric vehicle and air conditioner application, though a unique controller design would be required to cater to the highly transient operation of an electric vehicle compared to the steady-state operation of an air conditioner compressor. Further study is required to assess the potential benefits of a common motor for these two applications.

A similar analysis of washing machine and commercial mixer-grinder applications illustrates an overlap in rated power and operating speed. Other important parameters like axial and radial dimensions (important for packaging into a household mixer-grinder) and rated torque (washing machines require higher torque at low speed for wash-cycles, whereas mixer-grinders require only moderate torque) are quite different. Thus, despite the overlap between rated power and speed range of the motors in these applications, interchangeability is not readily apparent.

52. http://www.volanomotor.com/products/1300x_36v_3200rpm_electric_bldc_motor-en.html
53. LG Rotary and Scroll compressor spec sheet https://www.lg.com/global/business/download/resources/cm/Aircon_Compressor_1207.pdf
54. 50 Hz x 120 / 2 = 3000 rpm.https://www.airconditioning-systems.com/air-conditioner-motors.html
55. 1250 W @ 3000 rpm (314 rad/s) = 1250 / 314 = 4 Nm of torque

Strategies to accelerate adoption of PM motor appliances

To accelerate the adoption of PM motor appliances concerted actions are required across an appliance lifecycle, illustrated in Figure 5.

To overcome the barriers to PM motor adoption discussed earlier, key stakeholders like governments/regulatory institutions, standards organisations, OEMs, and financing institutions will have to work in collaboration to strengthen the supply-demand ecosystem, see Figure 6.

Figure 5: Strategies to accelerate adoption of PM motor appliances

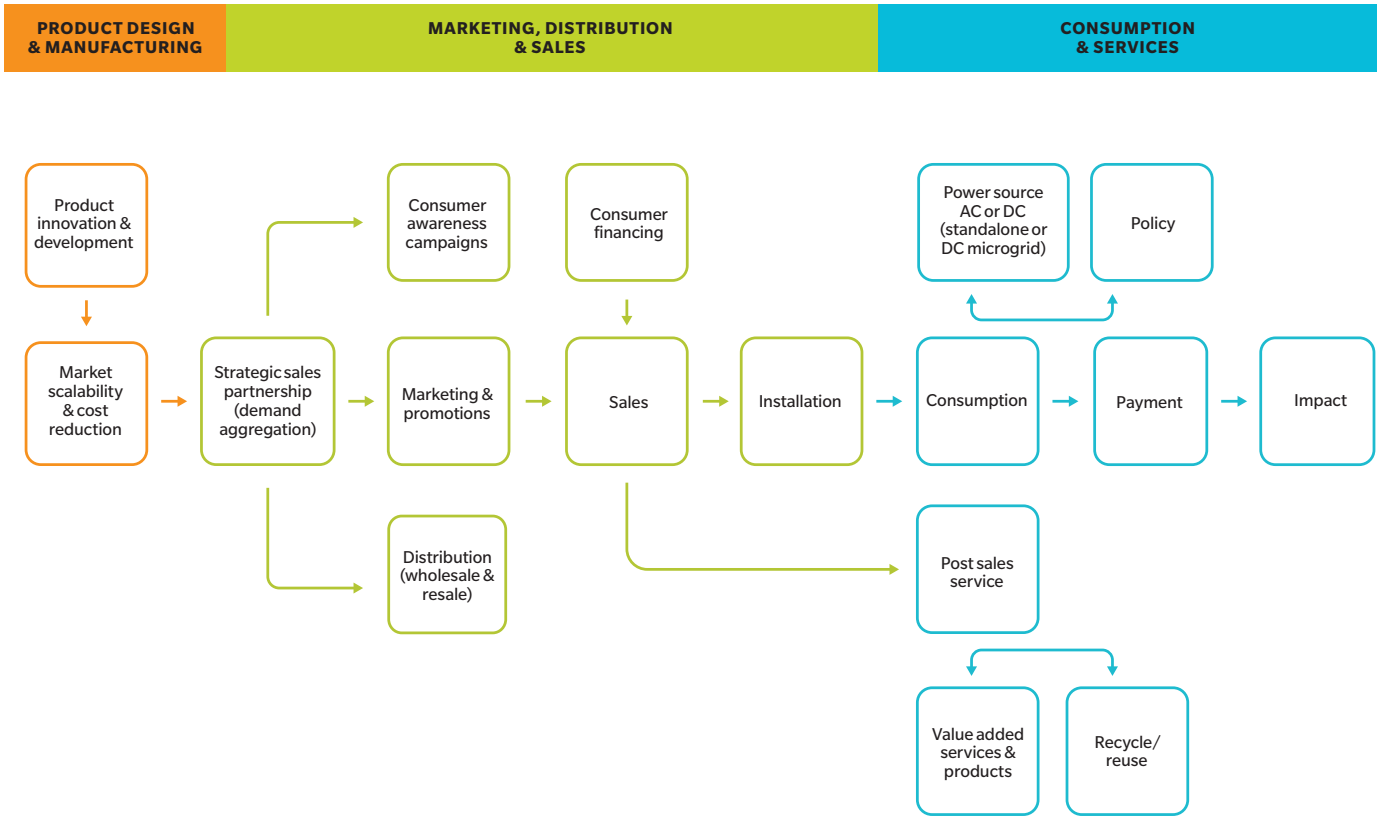


Figure 6: Key stakeholders and their roles to increase adoption of PM motor appliances

Governments/Regulatory bodies

Support with effective policy interventions like fiscal incentives, R&D funding, programmatic financing, demand aggregation

Standards organisations[56]

Develop globally harmonised standards to meet the global quality standards for sustainable PM motor appliances

OEMs

Innovate on both the technology front (to reduce the upfront cost of the PM motor appliances) and business model front for last mile availability of the PM motor appliances

Financing institutions

Innovate sustainable financing models to help markets mature and unlock or encourage private investments

56. The Industry body includes standadisation organisations like IEEE, NEEMA, ISO, IEC, BIS etc.

Standardise PM motors, controllers and appliance interfaces Standardisation of PM motors and controllers (as discussed previously) could play an important role in mitigating the higher upfront cost of PM motor appliances and improving overall post-sales serviceability and reliability. Standardisation of Utilisation voltage across different appliances, motor control ASICs and power converters for different applications, and plugs and connectors (for AC and DC sources and different power ratings) all have high potential to drive scale and reduce costs for appliance components. Reduced component costs will in turn reduce the price premium of PM motor appliances, leading to increasing sales volumes and further economies of scale. Standardisation will also allow greater interoperability and compatibility with AC and/or DC supply systems. Standards and industry bodies including Efficiency for Access, GOGLA, IEC, the Institute of Electrical and Electronics Engineers (IEEE) and others should work closely with influential OEMs from key countries in South Asia and Sub-Saharan Africa to timely build consensus on common standards for PM motor appliances.

Establish standards & labelling programmes Standards and labelling programmes are an effective way to build energy efficiency, performance and overall quality governance in appliance markets. On the demand side, these programmes create a 'pull' by increasing public awareness and acceptance of energy efficient appliances. On supply side, they create a competitive 'push' to improve appliance innovation and performance to meet compliance, and aid manufacturers to sell quality products across global markets.

Energy labelling systems are becoming common practice in many parts of the world. They are more common for household appliances like refrigerators, air-conditioners and fans. There are few standards and labelling programmes in place for off-grid productive use appliances, like solar water pumps and deep freezers, likely due to their small market size.

Strengthen the local manufacturing capacity, supply chain and ecosystem The widespread usage of motorised appliances in household and productive use segments, and increasingly for electric mobility, is creating high market potential for PM motors across South Asia and Sub-Saharan Africa. This creates a favourable case for countries to build local manufacturing capacity for PM motors and controllers. This will further boost PM motor driven local appliances manufacturing and systems engineering capabilities, which in turn will help improve quality and bring down the price premium of these appliances.

Governments should consider taking the following actions already in alignment and consensus with the private sector:

- Localising the development and manufacturing of PM motors and driven different appliances
- Providing funds, grants and/or incentives for undertaking R&D, manufacturing, new start-ups and innovations, distribution and exports in PM motor appliances
- Providing appropriate programmatic financing for enterprises to drive PM motors and appliances supply

STANDARDS AND LABELLING PROGRAMME, INDIA

The Standards and Labelling (S&L) programme in India provides the consumer an informed choice about the energy saving and thereby the cost saving potential of the relevant marketed product. The scheme targets display of energy performance labels on high energy end use equipment and appliances, and lays down minimum energy performance standards. This programme has led to change in consumer choice, i.e. more efficient purchases for refrigerators and air conditioners in particular, and has also impacted manufacturers decisions by encouraging them to eliminate inefficient models.

India's Bureau of Energy Efficiency (BEE) revamped its Star Rating scheme for ceiling fans (IS 374:2019) in August 2019. As part of this revision, fans with size 1200 mm and up must meet a service value of 6.0 to achieve a 5-star rating.[57] This performance level is very difficult to meet with an induction motor, so all of the latest 5-star rated fans on the Indian market are powered by brushless DC motors.

VERASOL QUALITY ASSURANCE PROGRAMME

VeraSol is a quality assurance programme for solar home systems, pico solar lighting products and off-grid appliances. Building upon the rich history of Lighting Global Quality Assurance, VeraSol develops and certifies products to internationally-recognised quality, durability, and truth-in-advertising standards. VeraSol is the trusted source of this information in the off-grid solar industry, connecting buyers with sellers of quality-verified products. VeraSol recently expanded its quality assurance services now meet the industry's growing need for high-quality off-grid appliance and productive use data. As of 2019, more than 42 million certified products have been sold, benefiting 180 million people worldwide.

57. Service Value indicates the amount of air delivered per wattage of energy consumed

Develop demand aggregation models and bulk procurement models for PM motor appliances

The current state of low demand and disaggregated manufacturing for PM motor appliances sustains high unit costs. For OEMs, these unit costs result from factors beyond the cost of the PM motor itself, including i) manufacturing overheads, ii) marketing, iii) distribution and sales overheads, iv) inventory overhead and v) post-sales services and warranty provisions. One important strategy to improve unit economics and support early market development for PM motor appliances is to drive government-supported demand aggregation models. These would provide bulk sales volumes through select aggregators to targeted end-customer segments, including governments (for electric vehicle fleets), farmer co-operatives (for solar water pumps and cold storage chillers) and retail users (for household appliances).

The bulk procurement model reduces fixed costs for OEMs and has been shown to bring down bulk prices by 20% to 40%. This is also win-win for the OEMs: higher volumes and competition allows them to build greater manufacturing capacity and deliver higher quality products and services. A demand aggregation model for PM motor appliances has to be rightly designed with the following important considerations in mind:

1. Deep understanding of customer needs and appropriate matching of appliance variants to customer segments
2. Detailed technical specifications and standardisation of appliances across segments
3. Well engagement of OEMs to discuss specifications, business model and procurement contract terms and conditions
4. Right selection of OEMs on design, manufacturing and servicing capabilities
5. Right selection of operator or aggregator (for example, distribution utility company for demand aggregation of PM motor ACs) to aggregate demand and service distribution, sales, services, payments and manage end-user relationships
6. Appropriate business model design for win-win of all parties involved including the OEM, bulk procurement agency, operator and the end-user

There is great potential to involve distribution utility companies in building strong demand side management (DSM) programmes around PM motor energy-efficient appliances. PM motor and controller characteristics allow lower starting torque, thus reducing start-up current. They can operate at variable current and speed, which can enable peak power management and electricity savings for the utility. Bunding PM motor appliances with solar provides further electrification and grid management benefits in off- and weak-grid markets.

ENERGY EFFICIENCY SERVICES LIMITED SUPER-EFFICIENT AIR CONDITIONER PROGRAMME, INDIA

Energy Efficiency Services Limited (EESL), an Energy Saving Company (ESCO) in India Energy Efficiency Services Limited (EESL), an Energy Saving Company (ESCO) in India initiated a first of its kind, Super-Efficient Air Conditioning programme. EESL plans to distribute 50,000 super energy-efficient and environment-friendly air conditioners across India by partnering with different state distribution companies. Consumers can buy the Super-Efficient Air Conditioners distributed by EESL at 30% less than the retail prices of BEE 5-Star air conditioners. These Super-Efficient air conditioners provides 1.5-TR cooling capacity at high ambient temperature while also reducing the cost of cooling by 50%. To date, around 1,300 Super-Efficient Air Conditioners have been sold.

Similarly, EESL is facilitating implementation of 5,00,000 solar water pumping systems in ISA (International Solar Alliance) member countries. This movement has led to a global disruption that brought down the price of solar-powered agricultural pumps by 50% per horsepower (hp).

Provide fiscal incentives and subsidies to reduce the upfront cost of PM motor appliances The price premium of PM motor appliances varies from 3% to 63% across different types of appliances.[58] Much of this differential is due to low sales volumes and value-add pricing by OEMs. Due to electricity savings, the operating cost of PM motor appliances is 22-42% less than conventional appliances.[59] Fiscal incentives support to the end-consumer by governments or other entities can help drive early market development for these efficient appliances. This can take the following forms:

1. *Supply side:* Reduced taxation on input raw materials and on output final appliance sales to OEMs allowing reduced price to end-customers
2. *Demand side:* Direct capital subsidy to end-customers on purchase of efficient appliances and also its integration with solar DRE

Further innovations like appliance replacement programmes led by OEMs (in which discounts on PM motor appliances are extended to accelerate replacement of old inefficient appliances) can also be implemented. Governments can enact targeted policy to promote efficient appliances to specific beneficiaries including households and enterprises in off- and weak-grid (or rural and remote) regions, then phase out subsidies after the market (demand and supply) is established and efficient appliances achieve price parity. The extent of subsidy can vary for different appliances depending on their price premium, need of targeted customer segments (household vs. productive use appliances), volumes (niche vs. mass use) and government commitments (like reducing fossil fuel import bills and air pollution through electric vehicles).

Some appliance types are better suited to direct subsidy. For example, fans are a highly price sensitive market and consumers' willingness to pay a price premium of 63% is low. Subsidising high price productive use appliances like solar water pumps and deep freezers will create significant income addition to farmers and improve overall agriculture production and efficiency. For appliances like washing machines, air conditioners and refrigerators, subsidy may not as relevant since the price premium for efficiency is low and affordable to the segment of the population capable of purchasing these appliances. Instead of subsidy an appliance replacement discount may be more appropriate to accelerate replacement of old inefficient models.

58. 67% for an electric 2W when compared to an ICE 2W
59. Service Value indicates the amount of air delivered per wattage of energy consumed

SELECT EXAMPLES OF FISCAL INCENTIVES SUBSIDIES TO DRIVE ADOPTION OF ENERGY-EFFICIENT APPLIANCES

Promoting energy-efficient appliances for the benefit of people programme, China[60]

In 2012, the Government launched a year-long incentive phase of the Promoting Energy-Efficient Appliances for the Benefit of People programme, which subsidised consumer purchases of six energy-efficient household appliances. The subsidies began in June 2012 and covered air conditioners, flat-panel television sets and refrigerators that meet energy-saving standards. Consumers can get subsidies ranging from 20% to 30% when purchasing these appliances.

KUSUM Scheme, India

In July 2019, the Ministry of New & Renewable Energy (MNRE), Government of India, notified the guidelines for implementation of Kisan Urja Suraksha Utthaan Mahabhiyan (KUSUM) Scheme for implementation of DRE systems, solar agriculture water pumps and solarisation of existing grid connected agriculture pumps, approving almost 90% (central & state) subsidy.

Appliance replacement with new energy efficient model, New South Wales (NSW), Australia[61]

The NSW Government offers official appliance replacement offer to upgrade old television or fridge to a new energy efficient model at 40% off the cost of a fridge and 50% off the cost of a television.

Refrigerator rebate, turn-in and replacement programme, Ghana[62]

The Government of Ghana implemented a “rebate, turn-in, and replacement” refrigerator bounty programme in 2012. The scheme encouraged consumers to exchange their old refrigerators for new efficient ones, available at a discounted price through a rebate. Upon completion of the programme, the market share of imported new refrigerators was over 80%, while 32,257 old refrigerators were replaced and transported to recycling facilities for disposal.

60. https://c2e2.unepdtu.org/kms_object/impacts-of-chinas-energy-efficient-appliance-subsidy-programme-on-consumer-behavior/
61. https://www.energy.gov.au/rebates/energy-efficient-fridge-and-television-discounts
62. https://www.buildup.eu/sites/default/files/content/manual-financing-mechanisms_25-06-19_web.pdf

BARRIERS TO PM MOTOR ADOPTION AND STRATEGIES TO DRIVE MARKET UPTAKE

Improve customer awareness of the benefits of energy efficient appliances The role appliance energy efficiency plays in climate mitigation is well-established in policy circles. However, there is a need to drive further adoption of appliance energy efficiency policies and improve their integration with distributed renewable energy systems. While OEMs are conducting individual marketing and promotions in limited forms, the issue requires much deeper and wider mass behavioral change management process. Energy efficiency in household appliances, productive use appliances and transportation should be picked up as a government priority, and regular mass media promotions across channels (television, radio, newspaper, hoardings, other prints, cinema halls, demonstration camps, replacement campaigns, social media, etc.) can be supported. Governments could also support OEMs through tax credits for consumer education and promotions.

Develop and grow consumer financing for PM motor appliances A lack of access to finance is one of the major challenges preventing the adoption of PM motors in appliances for the following reasons:

1. Perceived high credit risk of off-grid and rural customers
2. Missing organised financing players, systems and infrastructure in remote/ rural regions
3. Lack of understanding and appreciation of energy efficiency appliances financing in financial institutions, and hence not best fit financing instruments available
4. Appliances quality, performance and aesthetics do not generate demand 'pull' from customers
5. Lack of evidence of claimed savings and benefits to the end-users
6. Lack of post-sales services and warranty management because the current market is supported by small OEMs, innovative start-ups and non-profits with operational limitations
7. Missing organised big OEMs in energy efficient appliances catering to niche off-grid and rural markets

Financing solutions for energy efficient appliances, like microfinance institutions (MFIs) and non-banking financial companies (NBFCs) are available. However, a slow and people centric approval process; EE not being part of priority sector lending; and lack of enough back-end risk mitigation for EE lending (like sourcing from climate financing funds at reduced interest rate) has kept their overall scale limited. Pay-As-You-Go (PAYGO) models have demonstrated success in sub-Saharan Africa but have not yet been taken up in South Asia. All these models need to be scaled up and made win-win for financial institutions, end-customers and OEMs.

Retail end-user financing made available at the point-of-sales (POS) has a high impact on sales. If the financing interest rate for energy efficient appliances can be kept lower than other equipment, this can create higher customer attraction and conversion. Such retail financing is available for high-end household appliances like refrigerators and washing machines in urban markets but is missing for small household appliances like fans and mixer-grinders, for productive use appliances like SWPs and deep freezers, and in rural markets more broadly. A good programmatic financing structure will leverage strengths of multilateral and public sector institutions, organised national banks, and remote/rural financial institutions to develop appropriate business and operational model for sales and services of EE appliances at attractive interest rates.

SAMPLE FINANCING INSTRUMENTS

PAYGO Model, Africa In Africa, players have introduced pay-as-you-go (PAYGO) model. In this model, consumption is smartly measured by an in-built technology that shuts down the system once all the prepaid credits are used up by the consumer. This leads to a better awareness and understanding of financing in the users and avoids the issues of faulty readings via the meters and non-payment of dues by the users for a long time.

KfW partners with commercial banks to make financing attractive and affordable, Germany[63] The German Energy Savings Ordinance (EnEV) defines minimum energy efficiency standards, based on primary energy use and heat loss calculations, which all new buildings must comply with. KfW labels its House Efficiency standard based on these minimum national regulatory standards, setting these as the baseline on an energy consumption scale of 100, and KfW lines of credit flow through German banks to homeowners providing attractive interest rates on lending as well as grants. The KfW mortgage products are available for new buildings and energy efficiency improvements for existing buildings. The less energy that the home uses, the more attractive the lending rates and the higher the KfW grant component is for the homeowner.

63. https://www.buildup.eu/sites/default/files/content/manual-financing-mechanisms_25-06-19_web.pdf

Create a quality-assured market platform for PM motor appliances While creating regional or national level demand aggregation programme for PM motor appliances is one way to drive initial demand, a parallel and dedicated online market platform listing sellers with credible quality assurance mechanism can help to drive B2C and B2B retail sales and build a community of credible OEMs. VeraSol is currently developing quality standards for off-grid appliances. Quality assurance programmes like VeraSol create healthy competition amongst sellers and drive improvement in innovation and quality of products.

Provide quality post-sales services at lower costs Post-sale services include issues reporting, tracking and timely resolution, spare parts availability, warranty handling, appliance reuse and recycling, etc. Currently, the trend followed by OEMs is to contract a third-party to manage post sales maintenance, service and repair. This service is an essential part of overall customer experience. Ways to provide quality service at reasonable costs are:

1. Appliance self-diagnostics and connectivity to mobile applications
2. Simple guidelines for customers to maintain and efficiently run the appliance so as to prolong both service intervals and appliance life
3. Competent first level support over phone guiding the customer through simple troubleshooting steps
4. Spares planning as per expected design life of the components and inputs from live health monitoring systems
5. Aggregating third-part service providers for multiple OEMs to reduce costs of maintaining dedicated crew as well as extending the reach of service to all remote customer locations

EFFORTS TO CONNECT BUYERS WITH SUPPLIERS OF QUALITY PRODUCTS IN INDIA

The India Renewable Energy Appliances Portal (I-REAP) by CLEAN supported by GIZ[64] The I-REAP is an open source information platform which features suppliers' details, technical specifications, contacts, and other relevant information on Distributed Renewable Energy (DRE) technologies. The portal covers a broad range of DRE appliances, including solar and biomass powered systems and provides latest information on the same. This gives last mile end users, government agencies and field organisations access to information to help make decisions for personal consumption or to promote rural livelihoods.

EESL Mart, an online platform for energy efficient appliances EESL has initiated an online platform for consumers to buy energy efficient appliances. Currently, energy-efficient, 1.5 ton inverter air conditioners are being sold and are exploring the possibility of adding more appliances, like energy efficient induction cooking stoves. They are also offering a buyback option to the consumers, on their old working air conditioner, including a 1-year comprehensive warranty on the air conditioner and 5-year warranty on the compressor.

mKisan a Government managed buyer-seller platform, India[65] mKisan is Government of India's buyer seller platform to connect farmers with the buyers (FPOs, Exporters, Traders, and Processors). Buyer registers on this platform and chooses the area from where he wants to buy the product. He can offer the price at which he wants to buy the product. Farmers of that selected location get the SMS on their mobile set. SMS contains name and mobile number of all buyers and the price which they are offering to buy a commodity. Thus, a farmer gets the negotiating power and can sell the product at better price.

64. https://www.thecleannetwork.org/off-grid-portal.php
65. https://mkisan.gov.in/BREG/Aboutbuyerseller.aspx

Improve the customer experience and build end-user confidence in PM motor appliances PM motor appliances need to be positioned better to build 'emotional desire' and win customer confidence for reasons beyond their functional energy efficiency benefits. This will require interventions by OEMs and their distribution and service partners all throughout the following value chain (see Figure 5 on page 39)

1. *Product design:* for robustness, aesthetic and value-added control features, ease of use, repair and maintenance, etc.
2. *Marketing and sales:* with clear value proposition, comparison, demonstration, warranty and credible financing support

These efforts must be customised for respective regions and countries depending on customer preferences and culture. For example, a culture of repair and maintenance for long-term use is prevalent in South Asia, while a relative lack of local trained technicians have not driven similar expectations in Sub-Saharan Africa. Vocational workforce training for breakdown and preventive repairs and maintenance is important to establish a long-term sustainable ecosystem for PM motor appliances in all markets.

Build the capacity of motor and appliance OEMs, integrators, and distributors While PM motor technology has existed for many years, there are very few local motor manufacturers in South Asia and none in Africa. Training and capacity building for OEMs, with support from industry associations, can build local skills and capacity, support local manufacturing plant investment and facilitate research and development. Training can also be provided to system integrators, to help them improve their R&D efforts and increase adoption of PM motor in appliances and end-user application integration with grid and/or solar systems. This will improve end-to-end system efficiency of PM motor appliances in integration with power supply source (grid and/or solar). These trainings should also focus on helping OEMs and their channel partners, including distributors, to improve their bundling of energy-efficient appliances for an improved customer experience.

The key stakeholders for upscaling PM motor appliance adoption are government or policymakers (G), OEMs (O), financing institutions/multilaterals (F/M), industry bodies (I), and aggregators (A), see Table 15.

Table 15: Role of different stakeholders for higher uptake of PM motor appliances

APPLIANCE LIFECYCLE STAGE	STRATEGY	DRIVE	APPROVE	SUPPORT	CONSULT
Product design & Manufacturing	Standardise PM motors, controllers and appliance interfaces	I	G		O
	Establish standards & labelling programmes	I	G		O
	Strengthen the local manufacturing capacity, supply chain and ecosystem	O	G		I
Marketing, Sales & Distribution	Develop demand aggregation models and bulk procurement models for PM motor appliances	A	G	F/M	
	Provide fiscal incentives and subsidies to reduce the upfront cost of PM motor appliances	O	G	F/M, O	I
	Improve customer awareness of the benefits of energy efficient appliances	G,O		F/M	I
	Develop and grow consumer financing for PM motor appliances	O		F/M	
	Create a quality-assured market platform for PM motor appliances	I		F/M	
Consumption & Services	Provide quality post-sales services at lower costs	O, A		O, F/M	
Common across appliance lifecycle	Improve the customer experience and build end-user confidence in PM motor appliances	O			F/M
	Build the capacity of motor and appliance OEMs, integrators, and distributors	I, A		G, F/M, O	

KEY G = GOVERNMENT/POLICYMAKERS, O=OEMS F/M=FINANCING INSTITUTIONS/MULTILATERALS, I=INDUSTRY BODIES, A=AGGREGATORS

Conclusion and recommendations

Conclusion

Use of PM motors in appliances improves energy efficiency All PM motor appliances included in this study yield significant energy efficiency savings ranging from 22% to 42% over their conventional counterparts.[66] In the transportation sector, energy savings of e-2W can reach 83% when compared with an ICE 2W. For many product types, the lifecycle cost of PM motor appliances is less than that of conventional appliances, though payback periods are quite long for appliances that do not operate frequently.[67] The simple payback of PM motor appliances with AC grid supply is: 3.5 years for ceiling fans, 6.2 years for refrigerators, 26 years for washing machines, 4 months for deep freezers, 11 months for solar water pumps and 3.5 years for e-2W. If PM motor appliances are run on solar (in case of off-grid markets), there is also a reduction in solar panel peak power demand (22% to 38%[68]) leading to savings in solar panel size and cost.

Other advantages of PM motor appliances The high energy efficiency of PM motors is a result of the technology and their construction, which allows electronic commutation through sophisticated controller circuitry and software. Advanced motor controllers give rise to many new value-added features including automatic monitoring, diagnostics and control for improved reliability and customer experience. Other advantages of PM motors in appliances include lower starting torque, reduced current requirements across the load spectrum, low voltage operability and broader speed range, which contribute to lower lifecycle costs for certain appliances.

Incremental cost of PM motor appliances
The price premium of PM motor appliances in this study ranges from 3% to 63%.[69, 70] The high purchase price of PM motor appliances is a major barrier to their adoption. However, this price premium is due to factors well beyond the PM motor and controller, which constitute only 2% to 16% of the end-price of appliances (fans are the notable exception). For some appliances (e.g., refrigerators), the use of PM motors reduces the overall bill of material cost to appliance OEMs because the design of heat exchangers and other components in the cooling circuit can be better optimised. These appliances often carry a price premium despite the lower component costs due to OEM strategies to differentiate around value-added features enabled by PM motors. In other cases, the current niche market for PM motor appliances is catered to by smaller OEMs with low volumes of PM motors purchases and a comparatively higher marketing and sales budget, resulting in higher unit prices.

Sales trends of PM motor appliances PM motor appliances have superior performance on technical, economical and environmental metrics, They are have captured increasing market share in recent years, and are expected to grow as follows from 2020 to 2025:

- **South Asia market:** Fans (3% to 7%), refrigerators (65% to 86%), washing machines (33% to 53%), air conditioners (65% to 88%), solar water pumps (60% to 100%), 2W (1% to 9%), 3W (44% to 53%)

- **Sub-Saharan Africa:** Fans (4% to 6%), refrigerators (21 to 35%) washing machines (51% to 67%) air conditioners (41% to 59%), solar water pumps (60% to 100%), 2W (1% to 10%), 3W (~0% to 6%)

The South Asia market will continue to drive PM motor adoption and is projected to be approximately 11 times the size of the Sub-Saharan Africa market by 2025.

Market share of PM motor appliances in off- and weak-grid regions Off- and weak-grid markets have a lower share of PM motor appliances than the top urban markets due to a lack of effective sales, financing and services. This situation is further aggravated by lower affordability and higher perceived credit risk of end-customers in these markets. The market potential for high quality energy-efficient appliances (with and without solar systems) in these regions is high because of continuing grid unreliability, growing customer income and falling technology costs.

66. Not considering electric vehicles
67. Except for washing machines.
68. At individual appliance level mentioned in Table 3. Only motor appliances have been considered.
69. 67% for electric 2 W when compared to an ICE 2W
70. Based on South Asia data. Other regions are expected to show similar trends as their markets continue to mature.

Major barriers for PM motor adoption and scale Key barriers to the adoption and scale of markets for PM motor appliances include low awareness among governments and consumers, a lack of effective policies (including MEPS and energy labelling) to identify and reward efficient products and high unit cost, due to their niche market and the small scale of OEMs.

For PM motors to achieve market scale, a number of strategic interventions from product design to consumption are needed, see Figure 7. These strategies should be customized for different regions and countries depending on consumer preferences and culture. They should also be fine-tuned with effective monitoring and evaluation.

Price parity with conventional motors Considering the many functional advantages PM motors contribute to appliance performance, including reducing overall bill of material costs for some appliances (e.g., refrigerators), some large multi-national appliance manufacturers have already shifted 100% of their household appliance product lines to PM motors. This is also the case for light-duty electric vehicles such as electric 2-wheelers. PM motors are projected to gradually capture 100% of the market for some appliance types even in the absence of supportive policy and financing measures, though there are many approaches available to governments and other key stakeholders to further accelerate these technology transitions.

Future trends in PM motor and controller technology The PM motor and controller cost contribution to price of the energy efficient appliance is low (2% to 16%) for all products except fans, so efforts to drive market transformation should focus on supportive policy and consumer awareness to deliver the greatest impacts. Parallel improvements in motor and appliance technologies for increased features, robustness and customer-valued performance will continue, but cost reduction will not be a major driver for OEMs. Standardisation of PM motor and controller hardware, primarily electronics, connectors and communication protocols will improve supply chain efficiency, and also allow increased interoperability for advanced home automation. Decreasing solar and battery prices and increasing DRE will drive increased use of DC home energy systems and higher overall system efficiency through DC generation and DC consumption without losses.

Figure 7: Strategies to drive PM motor adoption in off- and weak-grid markets

Recommendations

The broad objective of this report was to develop initial market intelligence regarding the technical price-performance characterisation and advantages of PM motor appliances in household, productive use and transportation segments for South Asia and Sub-Saharan Africa. This study identifies barriers to market adoption of PM motors in appliances and suggests key strategic interventions including standardisation, consumer awareness raising, demand aggregation and energy efficiency policy to drive increased penetration of these energy-efficient appliances in off- and weak-grid markets. Some recommended next steps to further these research objectives and support implementation and market development are:

1. Convene an expert industry working group for each appliance with representation from influencing countries in SA and SSA and further develop PM motor adoption roadmaps and strategies with detailed work plans, milestones, required resources and timelines. This effort should include participation from key government and institutional stakeholders to mainstream the road map implementation. Segmentation into off-grid and/or weak-grid focused activities should be clearly defined with points of differentiation.

2. Develop an analytical model for one influencing country in each of the five regions included in this study (South Asia, East/West/Central/Southern Africa) and evaluate how different adoption levels of PM motors in the next 5-10 years will impact the power grid, climate, energy access goals, government budgets, etc. This effort should model different strategies and their phase-wise implementation and impact on adoption rates, and study the impact of different policies and government commitments. This analysis could be evolved into a generic planning tool to help governments prioritise energy-efficient appliances in their nationally determined contribution (NDC) and greenhouse gas (GHG) inventory rationalisation.

3. Develop one scalable pilot for PM motor adoption in each of the 3 categories included in this study (household, productive use and transportation) in South Asia and Sub-Saharan Africa. The pilot should include the strategic elements proposed in this report, as well as those agreed by an industry working group, including i) improved design for customer centricity, ii) relevant standardisation, iii) stringent standards and labeling programmes, iv) demand aggregation in targeted segment (or online marketplace with quality assurance), v) mass media promotion and customer awareness (with government support), vi) consumer financing, vii) training and capacity building of involved stakeholders and viii) setup and growing distribution and post-sales services network.

4. Engage with international standards bodies (e.g., IEC, NEMA) to develop standardisation roadmaps for PM motors in off-grid and weak-grid appliances. Standardisation efforts should include frame size and other dimensional elements, utilisation voltage, connector designs and other elements as defined in this report.

5. Conduct a feasibility study for the inclusion of PM motors and/or PM motor appliances in VeraSol's quality assurance programme.

6. Develop a detailed technical design and proof of concept (POC) for common a PM motor design across select two appliances (for example, e-2Ws and air conditioner compressor motors).

7. Conduct a detailed techno-commercial feasibility assessment for the establishment of PM motor and appliance local manufacturing in Africa and recommend annual targets.

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