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PERMANENT MAGNET MOTORS

Solar Appliance Technology Brief

AUGUST 2021

EFFICIENCY FOR ACCESS COALITION

CONTEXT

This technology brief is one in a series of insight briefs developed to synthesize the latest market intelligence and chart a pathway to commercialization for a set of off- and weak-grid appropriate appliance and productive use technologies most relevant to catalyzing energy access and achieving Sustainable Development Goals.

The first iteration of the LEIA Technology Summaries was published in 2017 to help the newly established Efficiency for Access Coalition navigate a nascent market. At the time there was limited data and research available on market trends and off/weak-grid appliance performance. This permanent magnet motors brief updates and expands on these summaries, bringing together the latest insights on market and technology trends, consumer impacts, and pathways to scale for fans. You can access briefs on all technologies that are a part of this series here.

This brief was developed by CLASP and Energy Saving Trust as part of the Low Energy Inclusive Appliances programme, a flagship programme of the Efficiency for Access Coalition. 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.

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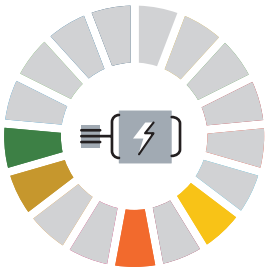
SDG INTERLINKAGES



PERMANENT MAGNET MOTORS

SDG 7: Affordable & Clean Energy
SDG 9: Industry, Innovation & Infrastructure
SDG 12: Responsible Consumption & Production
SDG 13: Climate Action

Permanent magnet motors reduce appliance energy consumption, making it possible for households and businesses to power additional products. Using PM Motors in appliances and industrial machinery directly addresses the challenge of energy efficiency in developing cities, reduces the carbon footprint of energy production especially from non-renewable sources and promotes enevironmental sustainability through quality and longer lasting appliances which can help address the growing challenge of electronic waste (e-waste).

Introduction

Electric motors are the 'prime movers' for almost all machinery and appliances that require motion. Some applications that require motors include: compressors for refrigerators, air conditioners and heat pumps; domestic appliances such as washing machines, mixer/grinders and clothes dryers; fans and blowers; water pumps; computer hard drives, DVD/CD players and other electronic appliances; electric vehicles, hybrid vehicles and electric bicycles; and industrial robots, computer numerical control machine tools and belt-driven systems.

All motors run on the principle that interacting magnetic fields in the rotor (the rotating component) and the stator (the stationary component) generate motion. They differ in how generating magnetic fields, either from coils supplied with electric current from an external source, or permanent magnets, which do not rely on electric current. Permanent magnet (PM) motors are available in alternating current (AC) and direct current (DC) and have significant efficiency advantages over AC induction and brushed DC motors.

For AC applications, the rotor comprises windings for the induction motor, while the PM motor has permanent magnets affixed to the rotor (Figure 1).

For DC applications (e.g., solar photovoltaic [PV] and/or battery-powered motors), we compare brushed and brushless DC (BLDC) motors. Figure 2 illustrates a simplified brushed PM DC motor.[1] The rotating commutator (i.e., a rotary electrical switch) rings cause the direction of current flow in the rotor to change every cycle, sustaining the rotor motion.

In PM motors, electronics replace the brushes and commutator rings (Figure 3, page 4). The absence of brushes ensures less noise and lower internal operating temperature due to lack of friction. Additionally, since brushes wear out faster than any motor components, PM motors have lower maintenance requirements. Consequently, they have a longer life span compared to brushed DC motors.

In this paper, we use the term PM motors to mean:

- In AC contexts, motors with a permanent magnet in either the rotor or the stator, as opposed to induction motors
- In DC contexts, motors with permanent magnets (in either the stator or rotor) and electronic commutation instead of brushed motors

Figure 1: Permanent Magnet AC and AC Induction Motors

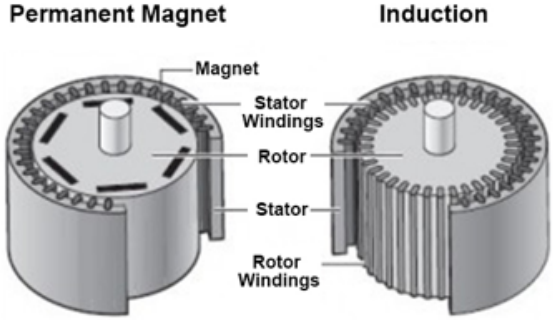
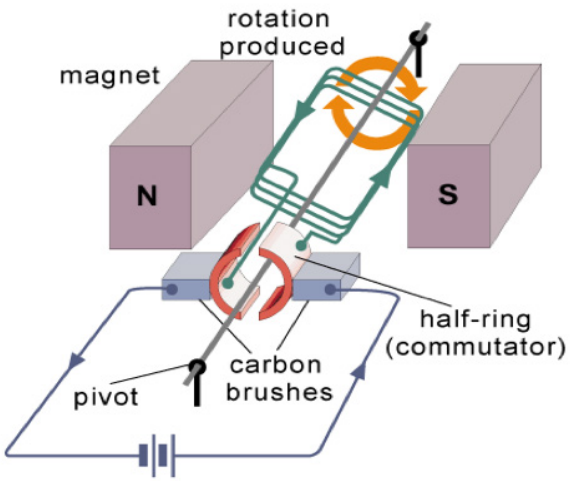


Figure 2: Example of a Brushed PM Motor with a Commutator



1. Note that in this case the current is supplied to the rotor while the permanent magnet is in the stator.

PM motors and non-PM motors have similar applications. However, PM motors are particularly suited for off- and weak-grid applications due to low starting current (are compatible with smaller power supplies), tolerance for low/fluctuating voltages and higher efficiency enabling longer runtime for a given amount of energy.

Their main drawback is the high initial cost that arises from the cost of permanent magnets and the complex controls needed to achieve electronic commutation. See Table 1 for a comparison between PM AC motors and AC induction motors.

Figure 3: Illustration of a BLDC PM Motor

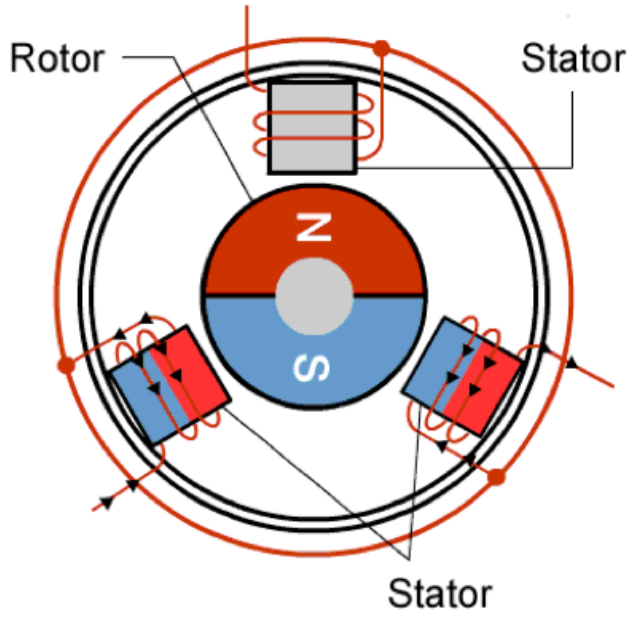


Table 1: Differences in design and performance of PM AC motors vs AC Induction motors [2,3]

Permanent Magnet AC Motors	AC Induction Motors
Use permanent magnet in the rotor	Induces rotor magnetism from the stator
Higher energy efficiency	Eddy current losses
Higher Power Factor[4]	Induction reduces power factor
Smaller size for a given power output	Larger in size
Can achieve full torque at low speeds	Low torque at low speeds
Run cooler	Induction generates some heat
Not easily self-starting	Self-starting achieved with simple circuitry
Require special programming for the Variable Frequency Drive (VFD)[5]	Quite simple to program the VFD
Higher initial cost, lower lifecycle energy costs	Lower initial cost, higher lifecycle energy costs

2. Mishra, Ambarisha & Agarwal, Pramod & Srivastava, S, A Comprehensive Analysis and Implementation of Vector Control of Permanent Magnet Synchronous Motor. Int. Journal of Power and Energy Conversion. 5. 1 - 23 (2014): https://dx.doi.org/10.1504/IJPEC.2014.059982

3.NakuÃ§i, Loreta, and Aida Spahiu, Saving Energy by Replacing IM With BLDC Motor in Fan Application. European Journal of Electrical Engineering and Computer Science 2 (5) (2018): https://doi.org/10.24018/ejece.2018.2.5.27.

4. Power factor is the ratio of real power (that actually drives the load) to apparent power (that flows from the mains into the motor). A high-power factor means most of the power flowing into the motor goes to driving the load, while a low power factor means a significant proportion of the power flowing into the motor is used for other purposes, like generating magnetism in induction motors. Because magnetism is already present in PM motors, their power factor is higher than induction motors.

5. A VFD is electronic equipment that generates voltage at varying frequency to enable an induction motor to run at varying speeds since the speed of such motors is proportional to the frequency of the incoming voltage.

State of Play

PM motors are becoming very popular in many applications due to their high efficiency.[6]

Incremental efficiency improvements are attainable in all motors. For example, through the use of high-quality aluminium and copper, reducing fan losses, increased rotor length, closer machining tolerances, optimised air gap, thinner steel laminations in the stator and more copper in the windings. The switch from an AC or brushed DC motor to a PM motor substantially increases efficiency (Figure 4).

Cost remains an important issue. PM motors on their own cost more than their brushed or induction counterparts. For example, PM motors for electric vehicles cost 18% more than induction motors.[7] The cost increase is primarily due to the higher cost of the rare earth minerals used to make permanent magnets, motor drive controls that enable electronic commutation and the rotor position sensor that gives feedback on the rotor position to the electronics to facilitate commutation.[8] The impact of PM motor cost on the overall appliance cost plays a significant role in their quick adoption. For fans, for instance, PM motor costs contribute up to 36% of the total appliance cost, a substantial fraction of the total for a low-cost consumer appliance.

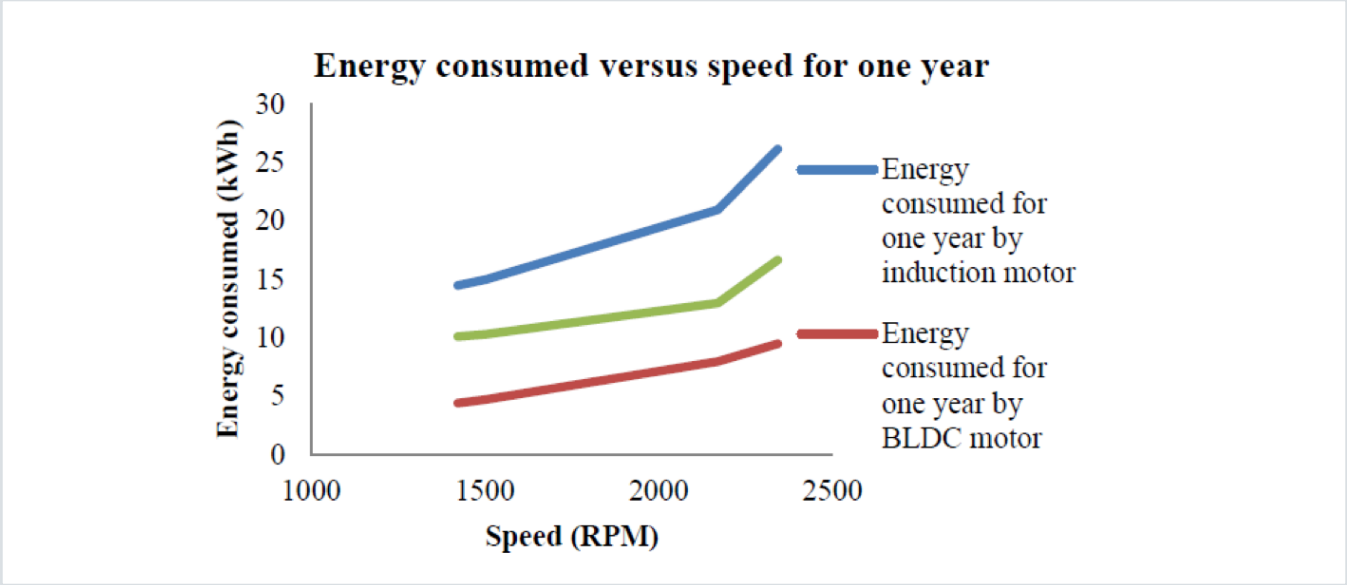
On the other hand, motors contribute less to the overall cost of the system for solar water pumps. Indeed, a more efficient PM motor may lower overall system costs.

Market Insights

PM motors' current and projected market places high value on operating efficiency, variable speed operation for DC PM motors, reliability, low operating internal temperature, low cost and quiet operation, among other features. PM motors already have good traction in white goods such as refrigerators and washing machines, heating, ventilation and air conditioning (HVAC) applications, electric vehicles and industrial applications. PM motor penetration is asymmetric across key appliance categories and markets in off- and weak-grid settings (Table 3, page 6).

PM motors are in many ways superior to conventional AC motors in all parameters that are critical for off- and weak-grid compatibility. The 2017 Low-Energy Inclusive Appliances Technology Summary estimated that PM motors comprised less than 1% of the total market for motors by the end of 2017.[9] However, with the off-grid solar market poised to grow significantly in the coming years, especially in Sub-Saharan Africa and South Asia, appliance manufacturers are expected to switch to PM motor technology for higher-value products. South Asia, India and Pakistan are expected to lead the PM motor-based fan adoption trend, while other countries may have lower volumes. In 2019, the sales of PM motor fans in India and Pakistan were estimated at 0.6 million units (1.15%) and 1 million units (12.1%) in total sales, respectively. Additionally, as of August 2021, 33 of the 37 pumps listed in the VeraSol Product Database (97%) use PM motors, a type of permanent magnet motor.

Figure 4: Energy Consumed by An Induction and PM Motor-Based Fan Over One Year[10]



Note: The gree line is the energy savings between a PM motor-based fan (red) and an induction motor fan (blue).

6. Irwin, J. David. The Industrial Electronics Handbook. CRC Press, 1997. Page 752.
7. Gudmundsson, Bjarni Freyr & Larsen, Esben, Integration of a Folding Electric Two-wheeler Vehicle for a Future Commuting Transportation. World Electric Vehicle Journal Vol. 5, 276-287 (2012).
8. Toliyat, Hamid A., and Kliman, Gerald B., Handbook Of Electric Motors. CRC Press Page 763 (2004)
9. Efficiency for Access, LEIA Technology Summaries. (2017): https://efficiencyforaccess.org/publications/low-energy-inclusive-appliance-technology-summaries
10. NakuÃ§i, Loreta, and Aida Spahiu, Saving Energy by Replacing IM with BLDC Motor in Fan Application. European Journal of Electrical and Computer Engineering, 31-37 (2018).

Table 3: Off-Grid Appliance Market Trends and PM Motor Penetration (South Asia and Sub-Saharan Africa)

		Estimated overall annual sales[11] (thousands)			Estimated PM motor penetration (%)	
Appliance	**Region**	**2020**	**2025**	**Compound annual growth rate (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%
Solar water pumps	South Asia	86	374	27%	60%	100%
	Sub-Saharan Africa	55	153	18%	60%	100%
Deep freezers[12]	South Asia	1,805	5,592	25%	5%	8%
	Sub-Saharan Africa	5	11.7	19%	NA	NA

11. The estimated sales are inclusive of all types of motors that includes induction motors, PM motors, and others.
12. The represented figures for deep freezers in sub-Saharan Africa are estimated PM motor-based appliance sales and not overall appliance sales.

BOX 1

Photo Credit: Harness Energy

India

Developing a Super-Efficient Fan

In 2019, Harness Energy applied for an Efficiency for Access Research & Development grant to develop a super-efficient rechargeable 12V PM motor pedestal fan. The fan consumes no more than 15 W with a minimum airflow of 50 cubic feet per minute (CFM). It can run on a 30W solar panel or a 2A AC/DC adapter for 9-10 hours. An inbuilt PCB charges the batteries to provide backup power for up to 6 hours. One of Harness Energy's customers indicated that he experienced a reduction of his electricity bills from USD 21 to USD 13 within two months of owning the fan at his furniture shop.[13]

Consumer Impacts

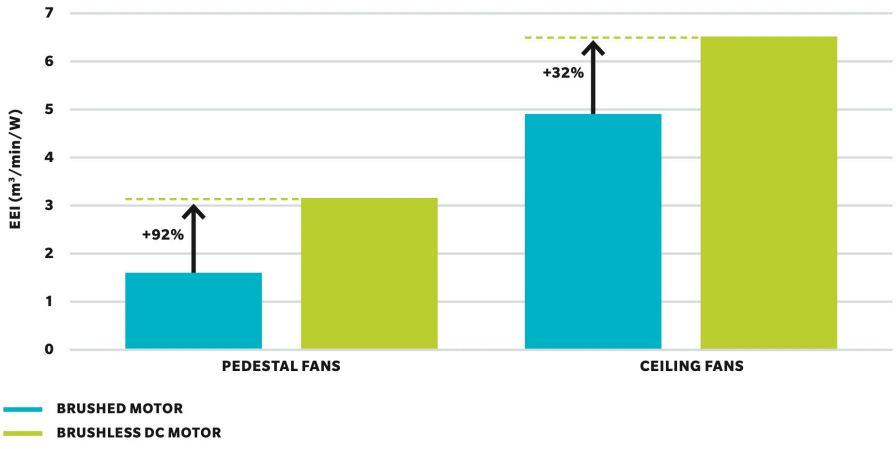
More energy efficient appliances: Using energy-efficient components like PM motors and LEDs in household appliances can reduce household energy costs by 20-41%.[14] This cost reduction is despite the assumption that such efficient appliances have a 20% higher up-front cost.[15]

VeraSol compared the recent pedestal and ceiling fans models with PM motors and brushed motors and found substantial efficiency improvements in follow-up testing. The average Energy Efficiency Index (EEI) of fans with PM motors was greater than brushed motor fans by 92% for pedestal fans and 32% for ceiling fans (Figure 5). One PM motor fan was over 200% more efficient than the average brushed motor fan.[16]

Cost savings: in off- and weak-grid settings, PM motor-based technology in domestic and productive use appliances can catapult more consumers to higher tiers of energy access. Energy-efficient appliances require smaller (and often less expensive) energy systems to power these appliances, allowing for more disposable income for consumers. In Pakistan, a case study revealed an increased uptake of PM motor-based pedestal fans owing to their superior efficiency.[17]

Increased appliance life span: their robust, compact and dust-tight nature gears PM motors towards long life and maintenance-free operations. Under its flagship product line Sun King, Greenlight Planet released a 16-inch fan that incorporates a PM motor. This motor ensures a lifespan of at least five years and makes it less susceptible to defects.[18]

Figure 5: Average Energy Efficiency Index (EEI)[19] by Fan and Motor Type



13. Efficiency for Access, LEIA Technology Summaries. (2017): https://efficiencyforaccess.org/publications/low-energy-inclusive-appliance-technology-summaries
14. Efficiency for Access, Market Opportunity for Permanent Magnet Motors in Off- and Weak-grid Appliances. (2021)
15. Id.
16. Efficiency for Access, 2021 Appliance Data Trends. (2021): https://efficiencyforaccess.org/publications/2021-appliance-data-trends
17. Efficiency for Access, Solar Powered Fans Can Help Support Sustainable Futures. (2021): https://efficiencyforaccess.org/publications/solar-powered-fans-can-help-support-sustainable-futures
18. Efficiency for Access, State of the Off-Grid Appliance Market Report. (2019): https://efficiencyforaccess.org/publications/2019-state-of-the-off-grid-appliance-market-report.
19. Efficiency for Access, 2021 Appliance Data Trends. (2021).

BOX 2


Photo Credit: Agsol

East Africa

Solar Milling Made Possible by Efficient Motors

Agsol, an agro-processing appliance manufacturer based in Kenya, developed a PM motor solar mill for off-grid markets in Tanzania, Kenya and Uganda. This pilot tested the mill's market viability in meeting demand, creating a profitable business and providing the requisite technology.

Agsol's efficient solar-powered mill offers a cleaner and cost-effective solution to rural communities than diesel and electric powered mills, which have a higher operational cost, are difficult to operate and contribute to environmental pollution. According to Agsol, this solution is only possible using energy-efficient PM motors.

Current Successes and Remaining Challenges

Successes to date include:

Sensorless designs: The rotor position sensor helps determine the commutation sequence. Physical sensors, like the hall effect sensor, have hitherto been embedded in the motor, which adds to the complexity and cost of the motor. Developments in sensorless technology, the most common of which uses a back EMF generated in the instantaneously non-conducting stator winding during the commutation sequence and measurable externally to the motor, reduce costs and complexity. This technology also reduces motor weight and size and increases reliability. It also enables the use of a standard variable frequency drive (VFD) that does not need position feedback.

Minimised torque ripples: Physical asymmetries in construction, imprecise timing, imperfect current waveforms, phase delays, friction, and the magnetic hysteresis in the motors often exacerbate torque ripples. Ripple reduction techniques are making motor rotations smoother. Also, better stator designs and controls, such as LC filters and the field of control reduce ripples.

Integration of motor and drive: It is now possible to integrate control electronics into smaller motors due to the reducing size of electronic components and lower temperatures inside the motors by using better permanent magnets.[20] This integration reduces costs and improves compactness and reliability.

Field of Control (FOC) is one of the methods used in variable speed drives to control the torque of three-phase AC electric motors by controlling the current. FOC allows for smoother operations due to reduced torque ripples and accurate motor control at low and high speeds.

Developments in permanent magnets: Materials such as neodymium and samarium derivatives are high-performing, producing strong and durable magnetism. However, they require rare earth materials for their manufacture, which are currently very expensive. Ferrite materials are cheaper but produce less strong magnets whose magnetism also wanes with time. Extensive research is ongoing to determine the optimal magnets that achieve a good trade-off between cost and performance.

20. Xia, Chang-liang, Permanent Magnet Brushless DC Motor Drives and Controls. John Wiley & Sons. Page 15 (2012).

Remaining challenges include:

High upfront costs: PM motors are more expensive than induction/brushed DC motors because they are more complicated to manufacture. Initiatives like standardisation of appliance architecture, manufacturing processes, quality, and reliability mitigate the high upfront cost and poor access to finance, which are barriers for most off-grid customers.

Inadequate consumer awareness: Efficiency ratings, federal regulations, and subsidies can better address the hurdles of lower consumer awareness levels. Several global initiatives under Efficiency for Access, such as Global LEAP and VeraSol, maintain databases of high-quality, energy-efficient appliances and run campaigns to increase consumer awareness regarding energy-efficient technologies.

Nascent B2C supply chains for PM motors in key off-grid markets: The penetration PM motor-based off-grid appliances is very low in major markets such as Sub-Saharan Africa. This unavailability of motors discourages local start-up manufacturers from investing in and developing PM motor-based appliances. In our 2017 LEIA Technology Summary, we highlighted the need for additional research on the supply chain and the market state to understand the opportunities and address barriers to bridging the gap between OEMs and local manufacturers.[21]

Volatile magnet market prices: Supply constraints around the availability of rare materials such as dysprosium and neodymium lead to fluctuating prices of PM motors. This fluctuation impacts the quantity and quality of PM motors in the global market. In many cases, the end consumer bears the burden of the higher price of the motors.

21. Efficiency for Access, Low Energy Inclusive Technology Summaries. (Washington, DC: 2017), https://efficiencyforaccess.org/publications/low-energy-inclusive-appliance-technology-summaries.

Photo Credit: Aggrico

RECOMMENDATIONS AND PATHWAY TO SCALE

Lower upfront costs

Increased stakeholder support from governments, manufacturers and industry bodies is essential to streamline and drive the sales and distribution of PM motor-based appliances. The efforts needed include: introducing fiscal incentives and subsidies, the availability of consumer financing options (at retail and programmatic levels), and incorporating demand aggregation models in off- and weak-grid markets.

Improve consumer awareness

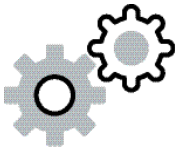
Low consumer knowledge on the energy-efficiency benefits of PM motor-based appliances is a barrier to increased penetration. Governments and industry bodies can play a crucial role in improving the levels of customer awareness through targeted campaigns on the benefits of energy-efficient technologies.

Manufacture locally

In key off-grid markets, original equipment manufacturers (OEMs) and governments can develop a strong local manufacturing base for PM motors to bridge the supply chain gap for sourcing motors and motor accessories. Additionally, this will help stabilise the fluctuating prices for PM motors.

Strengthen standards and labelling programs

Standards and labelling programs help to promote high-quality, high-performance products that deliver expected services to users. Improved user experiences may boost PM motor adoption.



Standardise designs and manufacturing processes

Currently, most OEMs manufacture their own PM motors for their products. Standardised designs will enable specialist motor manufacturers to emerge and operate at scale, as can already be seen in the induction motor industry. At the same time, the standardisation of controls can help address the compatibility and interoperability issues associated with most off-grid appliances.

Increase consumer confidence and experience

Delivering quality post-sales services at a more affordable cost by OEMs and distributors can be crucial in providing value for money to end consumers and boosting the general satisfaction from PM motor-based appliances.

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Photo Credit: Simusolar

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