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Market Assessment Study of Grid-Connected Solar Inverters Under the Standards & Labeling Program

MAY 2024

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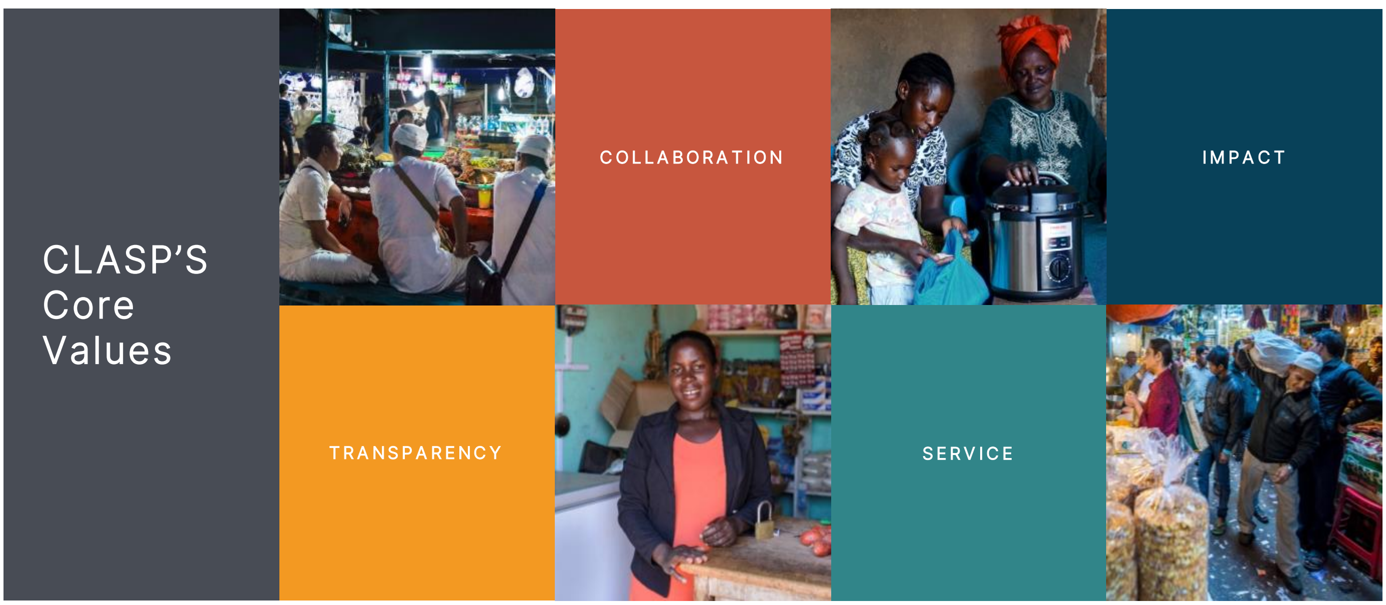
CITATION AND COPYRIGHT

Yatharth Kumar Sharma, PVN Kishore Kumar, PK Mukherjee, Market Assessment Study of Grid-connected Solar Inverters Under the Standards & Labeling Program, CLASP, January 2024

ACKNOWLEDGEMENTS

The authors would like to thank the entire team at the Bureau of Energy Efficiency (BEE) and stakeholders in the Indian commercial beverage cooler industry for their indispensable support in conducting this study.



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ABBREVIATIONS

BEE	Bureau of Energy Efficiency
CAGR	Compound annual growth rate
GW	Gigawatt
IEC	International Electrotechnical Commission
IS	Indian standards
kW	Kilowatt
MEPS	Minimum energy performance standard
MNRE	Ministry of New and Renewable Energy
MPPT	Maximum power point tracking
MW	Megawatt
MWh	Megawatt hours
NISE	National Institute of Solar Energy
PV	Photovoltaic
RE	Renewable energy

Executive Summary

To achieve its ambitious target of ensuring that 50% of its cumulative electric power installed capacity comes from non-fossil-fuel-based sources by 2030, the Government of India has drawn up the Mission 500 GW plan. The policy aims to establish 500 GW of renewable energy (RE) installed capacity by 2030, with 280 GW coming from solar power.[1] To achieve this target, 25 GW of solar capacity must be installed annually for the next 10 years.[2] In line with this target, on 22 January 2023, the prime minister of India announced the Pradhan Mantri Suryodaya Yojna, under which a rooftop solar system will be installed in 1 crore households.

Spurred by government led RE initiatives, more and more users are embracing solar photovoltaic (PV) technologies. The two main components of solar PV systems are solar modules and solar inverters. A solar module, also called a solar panel, is an assembly of connected solar cells that absorb sunlight to generate electricity. Solar inverters convert direct current (DC) electricity generated from solar modules into alternating current (AC) electricity. Based on the conversion technology employed, solar inverters are categorized into three types: grid-connected, standalone, and hybrid. Grid-connected solar inverters dominate, accounting for nearly 80% of the market, followed by standalone and hybrid solar inverters.

In FY 2022–2023, the market size (sales) for all types of solar inverters was close to 2,520 MW. The solar inverters market is estimated to grow at a compound annual growth rate (CAGR) of 14.4% between 2020 and 2026. To avoid the spread of inefficient solar PV systems in the market, it is essential to ensure the optimal performance of solar PV systems through energy-efficiency guidelines or standards.

To regulate the solar panel market, the Bureau of Energy Efficiency (BEE) launched the Standards & Labeling (S&L) program for solar PV modules in October 2023. The program helps citizens make informed and judicious decisions while purchasing or installing solar panels by mandating that manufacturers publish energy efficiency ratings. To further optimize the efficiency of solar PV systems, the BEE is now planning to launch an S&L program for grid-connected solar PV inverters without storage.

The S&L program for grid-connected solar inverters aims to help Indian customers make informed decisions and contribute to the Government of India's goal of reducing CO_2 emissions. Moreover, the introduction of the endorsement label for grid-connected solar inverters, or a certification of the product's energy efficiency, is expected to result in potential energy savings of 21.1 billion kWh from 2024–2025 to 2033–2034 and a potential reduction in CO_2 emissions by 15.1 million tCO_2.

1. Introduction

The renewable energy (RE) sector is becoming increasingly attractive to both consumers and manufacturers, with the Indian government's increased support for RE and improved economies of scale. One of the key factors driving the Indian solar power market is the growing quantum of investments in RE. In addition, the government is implementing favorable regulations and policies, such as the National Solar Mission, to encourage the adoption of solar energy. On 22 January 2023, the Prime Minister of India announced the Pradhan Mantri Suryodaya Yojna, under which a rooftop solar system is to be installed in 1 crore households.

As per discussions with major manufacturers, in FY 2022–2023, the market size (sales) for all types of solar inverters was close to 2,520 MW. The solar inverters market is also expected to grow at a compound annual growth rate (CAGR) of 14.4% from 2020 to 2026. However, the low conversion efficiency of solar PVs is a key factor that hinders the growth of the solar power market in India. To make solar power systems more efficient and reliable, installing efficient components, including solar panels, inverters, and batteries is vital. It is also essential to ensure that manufacturers produce efficient solar PV systems by establishing energy-efficiency guidelines or standards. The absence of a regulation or performance standard for solar PV systems has led to cost-competitive substandard equipment flooding the market and overshadowing quality solar PV systems. To regulate the solar panel market, the BEE launched the S&L program for solar PV modules in October 2023. To further optimize solar PV systems, the BEE is now planning to launch an S&L program for grid-connected solar PV inverters.

Promoting energy efficiency through an S&L program is cost-effective, as energy savings from such an initiative are generally assured, simple to quantify, and verifiable. Ultimately, the S&L program for grid-connected solar inverters will help Indian customers make informed purchase decisions and contribute to the Government of India's larger goal of reducing CO_2 emissions.

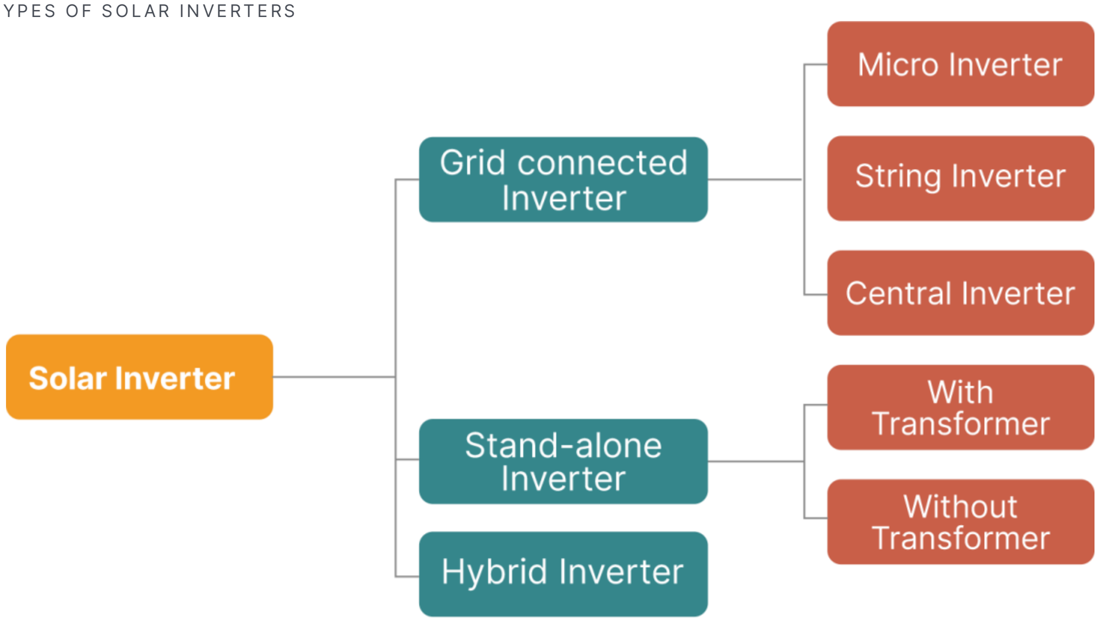
2. Solar Inverter Technologies

A solar or PV inverter converts the variable DC output of a PV solar panel into a utility-frequency AC that can be fed into a commercial electrical grid or used by a local, off-grid electrical network.

2. TYPES OF SOLAR INVERTERS

Solar inverters fall into three categories: grid-connected, off-grid, and hybrid. These inverters are available in different input capacities: 12–48 volt DC. A categorization of inverters based on technology and application is shown in Figure 1.

FIGURE 1: TYPES OF SOLAR INVERTERS



GRID-CONNECTED SOLAR INVERTER: A grid-connected solar inverter feeds the power from a solar PV system into the grid by stepping down the inverter supply voltage to match the grid voltage thus ensuring that the current and voltage are in phase.

A grid-connected solar inverter has an additional safety feature – anti-islanding protection. This allows the inverter to shut down the power supply from the solar PV system whenever the grid supply is interrupted. Anti-islanding is compulsory, because if the electricity flow continues from the solar panels while a lineman works at the site of the fault, there may be an electrical hazard. Grid-connected inverters also send excess electricity to the utility grid via a bi-directional meter.

Grid-connected solar inverters can be further categorized into micro, string, and central inverters.

STANDALONE OR OFF-GRID SOLAR INVERTERS: A standalone or off-grid inverter is also known as a battery inverter. It is designed for remote standalone applications or off-grid power systems with battery backup, where the inverter draws DC power from batteries charged by a PV array and converts it to AC power. Standalone solar inverters are commonly used in areas with limited access to grid power or high rates of interruption.

Standalone solar inverters can be further categorized into those with and without storage.

HYBRID SOLAR INVERTER: A hybrid solar inverter is a combination of grid-connected and standalone solar inverters with battery storage. This single piece of equipment can intelligently manage, and switch between, power from solar panels, batteries, and the utility grid. It allows users to avoid using grid power during peak pricing periods, ultimately reducing their electricity bill.

The salient differences between grid-connected, standalone, and hybrid solar inverters are given in Table 1.

TABLE 1: DIFFERENCES BETWEEN GRID-CONNECTED, STANDALONE, AND HYBRID SOLAR INVERTERS

CHARACTERISTICS	GRID-CONNECTED	STANDALONE OR OFF-GRID	HYBRID
Compatibility	Grid-connected solar power systems	Off-grid solar power systems	Grid-connected and off-grid solar power systems
Energy storage	No solar energy is stored	Solar energy is stored in batteries	Solar energy can be stored in batteries
Power transfer to the grid	Excess power gets transferred to the utility grid	Power is not transferred because it is not connected to a grid	Excess power gets transferred to the utility grid
Anti-islanding feature	Yes	No	Yes
Capacity range[3]	Up to 5 MW	Up to 100 kW	Up to 1 MW

2.1. TYPES OF GRID-CONNECTED SOLAR INVERTERS

Based on the rated capacity (in kW), grid-connected solar inverters are further categorized into three types.

- **MICRO INVERTER** – Micro inverters are installed on the back of each solar panel and convert the DC power generated by a single solar module to AC power. Micro inverters enhance energy harvesting by minimizing shading effects. The upfront costs of micro inverters are high, but they improve system reliability. Micro inverters are best suited for complex solar installations.

- **STRING INVERTER** – String inverters are most common in residential applications. Multiple solar panels in one location are connected to a single inverter. String inverters are cost-effective but susceptible to shading issues. String inverters are best for simple installations.
- **CENTRAL INVERTER** – Central inverters are large devices used in solar power plants to convert the DC produced by solar panels into AC that can be fed into the electrical grid. They are usually installed outdoors and designed to withstand high power. Central inverters are efficient but have large physical footprints.

2.2. MAXIMUM POWER POINT TRACKING (MPPT)

The MPPT is an algorithm that is built into the charge controllers used to extract the maximum available power from PV modules under certain conditions. The voltage at which PV modules can produce maximum power is called its maximum power point (or peak power voltage). The MPPT ensures that the solar inverter always works at maximum efficiency. It measures the output of the PV panels and compares it to the battery voltage. Based on this reading, the MPPT determines the maximum power the panel can generate to charge the battery.

Advantages of MPPT solar inverters:

- **OPTIMIZED SOLAR PANEL OUTPUT**: Solar panels have varying operating points based on temperature, shading, and sunlight intensity. The MPPT constantly monitors and adjusts the electrical operating point of panels to ensure that they operate at an optimal point for maximum power generation.
- **INCREASED ENERGY OUTPUT**: By continuously tracking and adjusting the operating point, the MPPT technology enhances the energy output of solar panels. This is particularly crucial for grid-connected systems, where the goal is to maximize the amount of electricity fed into the grid.
- **DYNAMIC ADJUSTMENT**: MPPT algorithms are designed to dynamically adjust the voltage and current in response to changing environmental conditions. This adaptability allows solar panels to operate close to their maximum efficiency in different situations.
- **COMPATIBILITY WITH INVERTER INPUT**: Grid-connected solar inverters are designed to convert the DC power generated by solar panels into AC power for grid injection. The MPPT ensures that the DC input to the inverter is optimized, providing the inverter with the maximum available power for conversion.
- **IMPROVED SYSTEM PERFORMANCE**: Using MPPT technology significantly improves the overall performance of grid-connected solar power systems. It helps achieve a higher energy yield from solar panels, which is essential to meet energy production targets and ensure a better return on investment.

- **PARTIAL SHADING MITIGATION:** The MPPT plays a crucial role in mitigating the impact of partial shading on solar panels. It enables the system to work around shaded areas by adjusting the operating points of unshaded panels to maintain overall system efficiency.
- **INCREASED ENERGY EFFICIENCY:** Grid-connected solar inverters with integrated MPPT controllers increase the overall efficiency of the inverter. This increase in efficiency is significant in grid-tied systems, where the goal is to maximize the power supplied to the grid.

3. Market Assessment

3. RESEARCH METHODOLOGY

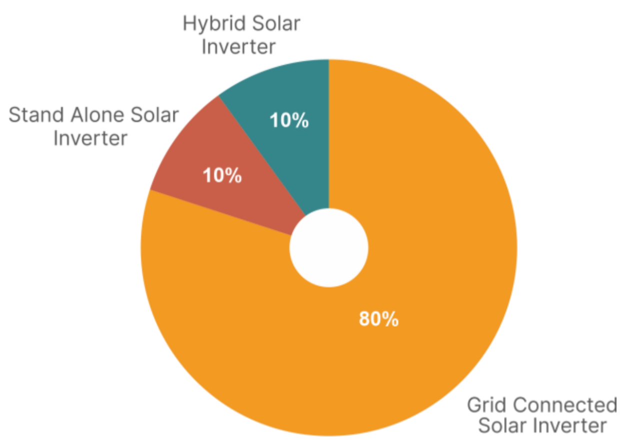
The market assessment yielded a comprehensive understanding of the solar inverters market in India. It includes a detailed preliminary assessment of the product models being marketed by key players, offering insight into the diversity and scope of available offerings. To gather information about the capacity range and efficiency of solar inverters, secondary research was done.

Interactions with major manufacturers and research organizations, such as the National Institute of Solar Energy (NISE), provided an additional layer of expertise. These discussions ultimately increased the overall depth and accuracy of the market assessment.

3.1. PRELIMINARY MARKET ANALYSIS

The discussions with NISE and manufacturers revealed that the market size of solar inverters was 2,520 MW in FY 2022–2023. Grid-connected solar inverters without storage dominated the market (80%), followed by off-grid solar and hybrid inverters, as shown in Figure 2.

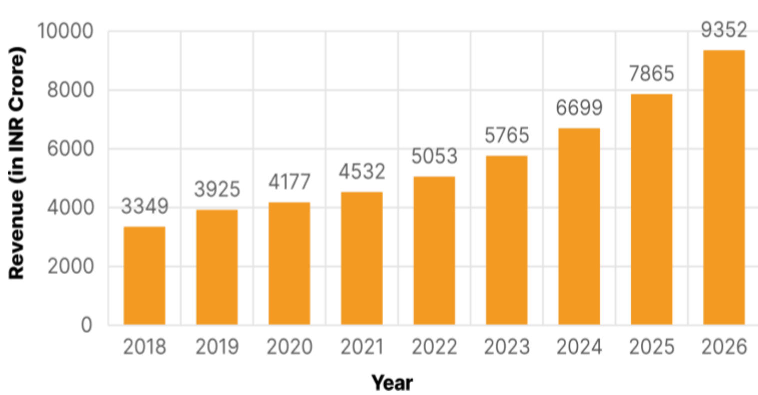
FIGURE 2: MARKET SHARE OF SOLAR INVERTERS



3.2. MARKET FORECAST TILL 2026

Based on the information received from manufacturers, the solar inverters market is expected to reach ₹9,352 INR crore by 2026, with a projected CAGR of 14.4% from 2020 to 2026.

FIGURE 3: SOLAR INVERTERS MARKET FORECAST TILL 2026

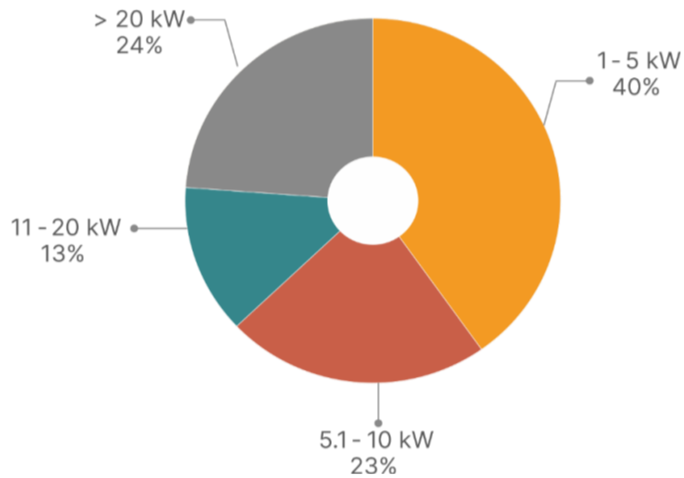


3.3. CAPACITY-WISE MARKET SHARE

A comprehensive preliminary market assessment was done based on information from the Ministry of New and Renewable Energy (MNRE) about solar inverter manufacturers in India. About 450 models from 25 manufacturers were analyzed to understand the capacity range in terms of voltage, rated power, and efficiency.

The analysis revealed that models with a rated output power capacity of 1–10 kW accounted for nearly 63% of the market, as shown in Figure 4.

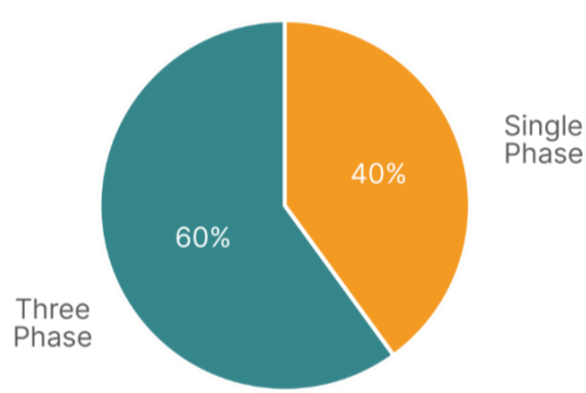
FIGURE 4: MARKET SHARE OF GRID-CONNECTED SOLAR INVERTERS BASED ON RATED OUTPUT POWER



3.5 PHASE-WISE MARKET SHARE

According to the interviewed manufacturers, single-phase solar inverters are more common up to the 5 kW segment, while three-phase solar inverters are more common for higher capacities. Indeed, nearly 60% of the market comprises three-phase solar inverters.

FIGURE 5: MARKET SHARE OF SINGLE- AND THREE-PHASE SOLAR INVERTERS



4. Test Standards and Facilities

4. IEC 61836:2016

This standard has guidelines for measuring the efficiency of the power conditioners used in standalone and utility-interactive PV systems, where the output of the power conditioner is a stable AC voltage of constant frequency or a stable DC voltage. Efficiency is derived from the direct measurement of input and output power.

Efficiency is critical to power conditioners. A standard procedure needs to be established to measure the efficiency of power conditioners and ensure their widespread use in PV systems. This might also help increase the reliability of efficiency claims.

Power conditioner efficiency is affected by the power level, power factor, harmonic content, load non-linearity, and temperature. These parameters are included in the test for this standard explicitly or implicitly. Measurement of no-load loss, load loss, and standby loss are factored in while calculating energy efficiency.

4.1 IS 17980:2022/IEC 62891:2020

The standard specifies a procedure for measuring the efficiency of the MPPT of the inverters used in grid-connected PV systems. Both the static and dynamic MPPT efficiency are considered. Based on the static MPPT efficiency calculated in this standard, and the steady state conversion efficiency determined in IS/IEC 61683, the overall efficiency is defined and calculated. The standard divides the test as such – static MPPT efficiency and overall efficiency.

MPPT EFFICIENCY – MPPT efficiency describes the accuracy of an inverter in setting its operating conditions to match the maximum power point on the characteristic curve of a PV generator. The overall MPPT efficiency is divided into static and dynamic efficiency components.

Static MPPT efficiency describes the accuracy with which an inverter can regulate the maximum power point on a given static characteristic curve of a PV generator. Variations in the irradiation intensity and the resulting transition of the inverter to the new operation point are not considered in static MPPT efficiency tests. To evaluate this transient characteristic, a dynamic MPPT efficiency test is used.

OVERALL EFFICIENCY – This is the ratio of the energy delivered by the device being tested at the AC terminals within a defined measuring period to the energy provided theoretically by the PV simulator.

To calculate overall efficiency (η_t), the DC power (P_{DC}) is converted to AC power (P_{AC}) by means of conversion efficiency (η_{conv}). The actual DC power (P_{DC}) of the device being tested is the product of the static MPPT efficiency ($\eta_{MPPTstat}$) and the MPP power provided by the PV simulator ($P_{MPP, PVS}$).

$$P_{AC} = \eta_{conv} \times P_{DC} = \eta_{conv} \times \eta_{MPPTstat} \times P_{MPP,PVS} = \eta_t \times P_{MPP,PVS}$$

The overall efficiency (η_t) can also be considered as

$$\eta_t = \eta_{conv} \times \eta_{MPPTstat} = P_{AC}/P_{MPP,PVS}$$

4.2 IS 16221-2:2015/IEC 62109-2:2011

This standard covers the safety requirements relevant to DC to AC inverter products. It is also used for products that have or perform inverter functions in addition to others, for instance, where the inverter is intended for use in PV power systems. Inverters covered by this standard may be grid-interactive, standalone, or multiple-mode inverters; supplied by single or multiple PV modules in various array configurations; and intended for use in conjunction with batteries or other forms of energy storage.

4.3 IS 16169:2019/IEC 62116:2014

This standard provides a test procedure to evaluate the performance of islanding prevention measures used with utility-interconnected PV systems. It has a guideline for testing the performance of automatic islanding prevention measures installed in or with single- or multi-phase utility-interactive PV inverters connected to the utility grid. The test procedure and criteria described are minimum requirements that allow for repeatability.

4.4 MNRE GUIDELINES FOR SOLAR INVERTERS

The MNRE has established specifications and guidelines for inverters used in rooftop solar PV systems, including efficiency requirements. There are technical specifications for inverters which encompass efficiency standards and compliance with various test codes such as

- IEC 61683/IS 61683:1999 – It has guidelines for measuring the efficiency of power conditioners used in standalone and utility-interactive PV systems.
- IS 16221-2:2015 – It lists the safety requirements of power converters used in PV power systems.
- IS 16169:2019 – It delineates the test procedure for islanding prevention measures in utility-interconnected PV inverters.
- IEC 60068 (Part 2) – It describes the environmental testing procedure for electrotechnical products.

EFFICIENCY THRESHOLDS ACCORDING TO THE MNRE:

- Inverter efficiency (min.): 93% (for 10 kW or above with inbuilt galvanic isolation) and 97% (for 10 kW or above without inbuilt galvanic isolation).
- Inverter efficiency (min.): 90% (for less than 10 kW).
- Specific requirements include total harmonic distortion (THD) less than 3% and a power factor (PF) greater than 0.9 (lag or lead).

4.5 TEST FACILITIES

Ten third-party test facilities in India, as listed in Table 2, have the capability to test the safety and anti-islanding features of solar inverters as per Indian standards and the MNRE guidelines. These test laboratories are also trying to establish test facilities to test solar inverter efficiency as per IEC 62891:2020.

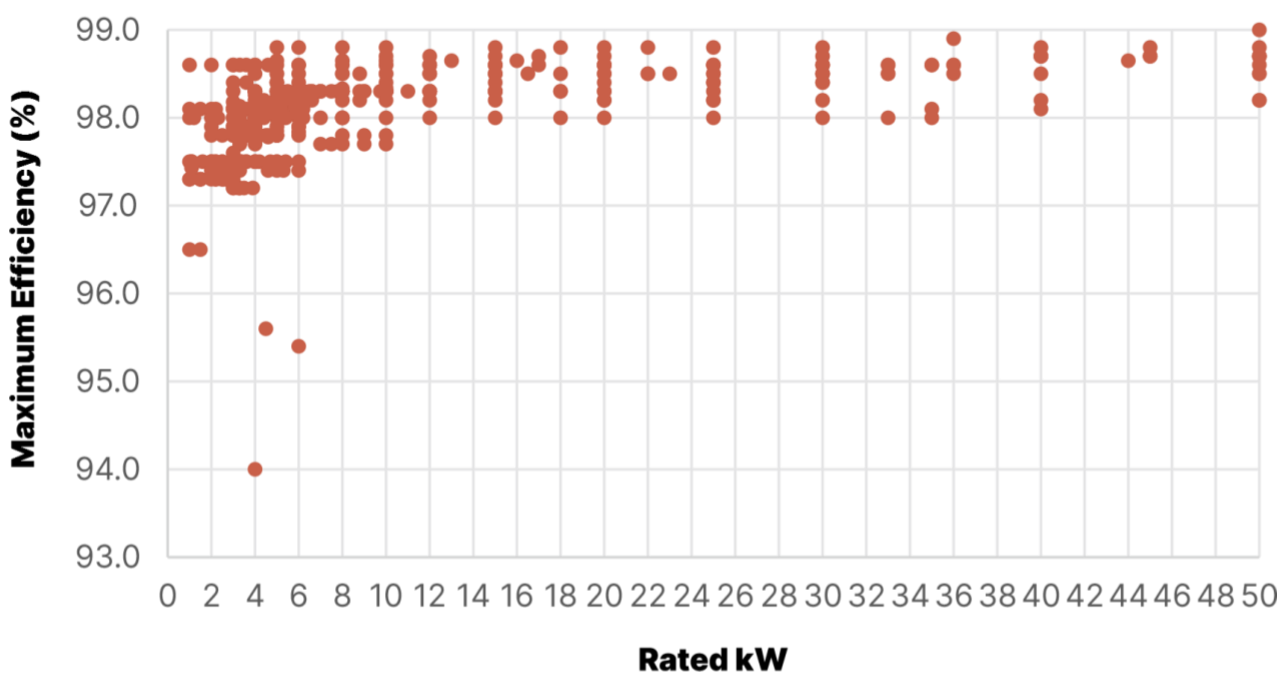
TABLE 2: TEST FACILITIES IN INDIA

S. NO.	LABORATORY NAME	LOCATION
1	Electrical Research and Development Association	Vadodara, Gujarat
2	React Laboratories	Bengaluru, Karnataka
3	URS Products and Testing Pvt. Ltd.	Noida, Uttar Pradesh
4	Nextron International Lab Private Limited	New Delhi, Delhi
5	UL India Private Limited, UL-Jain Fire Laboratory	Ramanagara, Karnataka
6	TUV India Private Limited, Electronics and Electrical Product Testing Laboratory	Bengaluru, Karnataka
7	Vardhamana Testing Laboratory	Greater Noida, Utter Pradesh
8	Bharat Test House Pvt. Ltd.	Sonipat, Haryana
9	Hi Physix Laboratory India Private Limited	Ranjangaon, Maharashtra
10	Central Power Research Institute	Bengaluru, Karnataka

5. Minimum Energy Performance Standard for Grid-connected Solar Inverters

Preliminary market research shows that the maximum efficiency of grid-connected solar inverters is between 94–99%. With an increase in rated capacity, the maximum efficiency also increases. Out of the 450 models reviewed, 445 had a rated efficiency of more than 97%.

FIGURE 6: MAXIMUM EFFICIENCY VS. RATED OUTPUT POWER



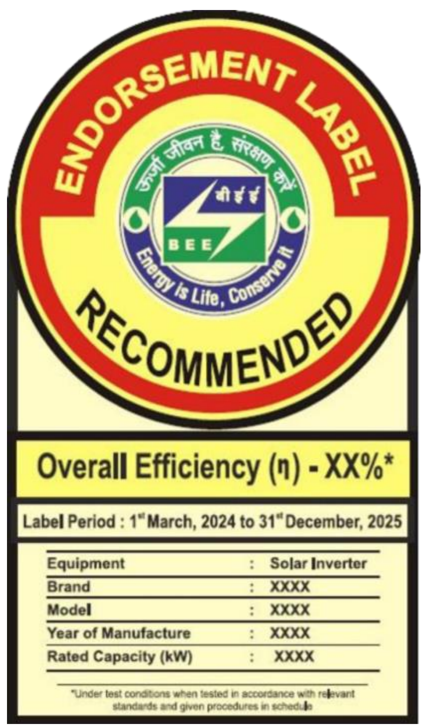
Considering the narrow bandwidth between the efficiency levels, having an endorsement label for grid-connected solar inverters is recommended. To qualify for an endorsement label, the grid-connected solar inverter must meet the minimum overall efficiency requirement mentioned in Table 3.

TABLE 3: MINIMUM ENERGY PERFORMANCE STANDARD (MEPS) FOR GRID-CONNECTED SOLAR INVERTERS

RATED OUTPUT POWER (KW)	MINIMUM OVERALL EFFICIENCY REQUIREMENT (%)
Rated output power <1	92
1≥ rated output power <3	93
3≥ rated output power <5	95
5≥ rated output power <10	96
10≥ rated output power <20	97
Rated output power ≥20	98

The current MEPS is valid from 1 March 2024 to 31 December 2025. There is no negative tolerance in the minimum overall efficiency requirement criterion for obtaining the BEE endorsement label. All tested products must meet the minimum threshold, including manufacturing tolerance and other variations. The sample endorsement label is shown in Figure 7.

FIGURE 7: ENDORSEMENT LABEL FOR GRID-CONNECTED SOLAR INVERTERS



6. Energy Savings and CO_2 Emissions Reduction Potential

6. ASSUMPTIONS

Estimating energy savings requires making a set of assumptions regarding the baseline energy efficiency of grid-connected solar inverters and their capacity-wise market share. Consequently, the following assumptions are made:

1. The assessment period is 2024–2025 (Y1) to 2033–2034 (Y10).
2. The labeling program for grid-connected solar inverters will commence from FY 2024–2025 on a voluntary basis.
3. The program will become mandatory at the start of FY 2027–2028, at which point the MEPS value will be upgraded by 1% for all categories.
4. Daily operating hours of solar inverters is six hours.
5. Annual operating days of solar inverters is 365 days.
6. The life of the grid-connected solar inverter is taken until FY 2033–2034.

6.1 APPROACH

The data obtained from manufacturers indicates that the total market volume of solar inverters based on the rated output power was 2,520 MW in FY 2022–2023. The market share of grid-connected solar inverters was 2,016 MW and is expected to grow at a CAGR of 14.4%. Based on information received from manufacturers, the market volume of solar inverters has been projected till FY 2033–2034. The total volume of solar inverters is sub-divided into six categories (0–1 kW, 1–3 kW, 3–5 kW, 5–10 kW, 10–20 kW, and >20 kW), based on their respective market share.

Secondary research was conducted to find the baseline overall efficiency of grid-connected solar inverters present in the Indian market. The baseline energy efficiency of solar inverter models considered to calculate energy savings is given in Table 4.

TABLE 1: BASELINE OVERALL EFFICIENCY OF GRID-CONNECTED SOLAR INVERTERS

S. NO.	RATED CAPACITY (KW)	BASELINE OVERALL EFFICIENCY OF GRID-CONNECTED SOLAR INVERTERS (%)
1	0–1	91
2	1–3	92
3	3–5	92
4	5–10	92
5	10–20	94
6	>20	96

The baseline rated input power ($P_{Baseline}$) was calculated, based on category-wise rated output power and baseline energy efficiency using this formula:

$$P_{Baseline} = \frac{Rated\ output\ power}{Baseline\ overall\ efficiency\ of\ grid\ connected\ solar\ inverter}$$

The rated input power based on MEPS (P_{MEPS}) was also calculated based on category-wise rated output power and minimum overall efficiency criteria as per the grid-connected solar inverter schedule.

$$P_{MEPS} = \frac{\text{Rated output power}}{\text{Minimum overall efficiency of solar inverter (MEPS)}}$$

The energy savings from BEE's S&L program for grid-connected solar inverters is calculated by subtracting PMEPS from $P_{Baseline}$.

$$\text{Energy savings} = P_{Baseline} - P_{MEPS}$$

The annual energy savings is calculated by multiplying energy savings by daily operating hours, annual operating days in a year, and life of the grid-connected solar inverters.

$$\text{Annual energy savings} = \text{Energy savings} \times \text{Daily operating hours} \times \text{Annual operating days} \times \text{Life of the grid-connected solar Inverter}$$

6.2 ENERGY SAVINGS AND CO_2 EMISSIONS REDUCTION POTENTIAL

TABLE 2: ENERGY SAVINGS AND CO_2 EMISSIONS REDUCTION POTENTIAL

ENERGY SAVINGS DURING ASSESSMENT PERIOD 2024–2025 (Y1) TO 2033–2034 (Y10)		
Total energy savings	Billion kWh	21.1
	MWh	21,052,567

CO_2 EMISSIONS REDUCTION DURING ASSESSMENT PERIOD 2024–2025 (Y1) TO 2033–2034 (Y10)		
Grid emissions factor	tCO_2/MWh	0.715
Total energy savings	MWh	21,052,567
Total CO_2 emissions reduction	tCO_2	15,052,585
	Million tCO_2	15.1

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Endnotes

[1] Ministry of New and Renewable Energy, "India is Marching Ahead in the Renewable Energy Sector," *PIB Mumbai*, July 30, 2023, https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1944075.

[2] There is a long road to 2030 for India's import-heavy solar power sector. "Home," Mongabay, accessed May 9, 2024, mongabay.com.

[3] National Institute of Solar Energy.