Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
National Metrology Institute

INTERNATIONAL COOPERATION

Quality Infrastructure for Photovoltaic Systems

Assuring safety, quality and sustainability in emerging and developing economies

german cooperation
DEUTSCHE ZUSAMMENARBEIT

On behalf of

Federal Ministry
for Economic Cooperation
and Development

On behalf of the Federal Government of Germany, the Physikalisch-Technische Bundesanstalt promotes the improvement of the framework conditions for economic, social and environmentally friendly action and thus supports the development of quality infrastructure.

PTB's International Cooperation group

The Physikalisch-Technische Bundesanstalt (PTB) is the national metrology institute of Germany. Within the PTB, the International Cooperation group functions as an implementing organization of development cooperation and is commissioned by the Federal Ministry for Economic Cooperation and Development (BMZ) and the European Union. It promotes the improvement of the framework conditions for economic, social and ecological action and as such supports developing and emerging countries in the establishment and utilization of a needs-based and internationally recognized quality infrastructure. A functioning quality infrastructure is indispensable for our daily lives because it enables free, fair and secure trade and forms the foundation for a reliable health system, environmental protection and the expansion of renewable energies. PTB's International Cooperation group advises governments and ministries, promotes quality infrastructure institutions and supports small and medium-sized enterprises.

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Annexes

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Executive Summary

Safety, quality and sustainability challenges constitute barriers to the development of PV energy. This study describes how quality infrastructure (QI)[1], which includes standardization, metrology, testing, certification, inspection and accreditation, can contribute to overcoming these challenges. It compiles the experience gathered in projects implemented by Germany's national institute of metrology (the Physikalisch-Technische Bundesanstalt, PTB) in support of the quality infrastructure required by the PV sector in emerging and developing economies.

1 In this study, we use the term *quality infrastructure* to refer to the system comprising the organizations, policies, relevant legal and regulatory framework, and practices needed to support and enhance safety, quality, and environmental soundness along the PV value chain. *Quality infrastructure services* refers to the actual services offered by quality infrastructure institutions in the same context. *Quality assurance* refers to the measures that *focus on providing confidence that quality requirements will be fulfilled* (ISO 9000). It is part of quality management and includes the use of quality infrastructure services (see the complete definitions in the Glossary in the annex).

The study explains which services of the quality infrastructure are required along the PV value chain and specifies requirements for the further development of global quality infrastructure.

Based on this analysis, the following recommendations have been defined:

- **Support the quality infrastructure alongside with the development of the PV sector:** The development of the PV sector requires the systematic consideration of quality assurance. Different options exist, but quality infrastructure must in all cases be treated as an integral part of PV sector development.

- **Take a holistic approach to the development of quality infrastructure:** The national quality infrastructure represents an interrelated system in which the system's components and its regulatory framework must complement one another. Consequently, they need to be developed together if they are to be coherent and functional.

- **Develop an appropriate policy framework:** The policy and regulatory frameworks are an integral part of the quality infrastructure system and influence both the supply and demand sides of quality infrastructure services. The development of such services should therefore be complemented by appropriate policies and regulations.

- **Foster awareness and information sharing:** It is particularly important to implement effective measures to raise awareness and to inform relevant stakeholders about the benefits of the systematic consideration of quality, safety and sustainability aspects in the PV sector.

- **Develop an appropriate policy framework:** The policy and regulatory frameworks are an integral part of the quality infrastructure system and influence both the supply and demand sides of quality infrastructure services. The development of such services should therefore be complemented by appropriate policies and regulations.

- **Foster awareness and information sharing:** It is particularly important to implement effective measures to raise awareness and to inform relevant stakeholders about the benefits of the systematic consideration of quality, safety and sustainability aspects in the PV sector.

- **Support exchange and cooperation between the national PV sector and the quality infrastructure organizations:** Exchange and cooperation among the stakeholders of the PV sector and the quality infrastructure should be supported to create awareness and foster applied approaches to quality assurance.

- **Base quality assurance approaches on existing international procedures:** The vast experience and previous efforts on quality assurance in the PV sector worldwide have resulted in the development of international standards and best practice procedures. Instead of working on entirely new national approaches, reference should be made to what is already available.

- **Participate in international forums and organizations:** To gain easier access to such international approaches, emerging and developing economies need to engage actively in international forums and organizations.

- **Plan the development of quality infrastructure in accordance with the national PV strategy and the stage of sector development:** PTB's experience shows that two key aspects should be considered by quality infrastructure organizations and policy makers when planning the necessary development: first, the national strategy for the PV sector and the resulting policy focus for the development of quality infrastructure; and second, the stage of development in which the sector finds itself. Based on these key aspects, measures for the development of the required structures and services can be defined. Recommendations are given below for three example scenarios.

Electroluminescence testing and visual inspection of photovoltaic modules

1. Introduction

1.1. Objective

Solar photovoltaic (PV) technologies can reduce the negative impacts associated with energy generation while increasing the reliability of power supply and supporting the achievement of the SDGs. However, safety, quality and sustainability challenges constitute barriers to the development of PV energy. This study describes how quality infrastructure (QI) – which includes standardization, metrology, conformity assessment (testing, certification and inspection), and accreditation – can contribute to overcoming these challenges.

The study compiles the experience gathered in projects implemented by PTB to support the quality infrastructure required by the PV sector in emerging and developing economies. It explains the importance of systematically developing quality infrastructure to improve safety, quality and sustainability, and it identifies gaps in the availability of relevant services. Based on this knowledge, recommendations are made on how to enhance the quality infrastructure to effectively benefit the PV sector in emerging and developing economies and beyond.

The target groups for this publication include policy makers and quality infrastructure institutions in developing and emerging economies as well as other organizations who partner with PTB. This study will likewise benefit PTB itself, in particular those units involved in the implementation of projects having a PV focus.

1.2. Methodology

To explore the main challenges relating to safety, quality and sustainability in the PV sector in emerging and developing economies, and to examine the relevance of quality infrastructure within this context, comprehensive desk research was conducted with an analysis of documents that included existing PTB publications.

The secondary data from this desk research was then complemented with primary data from interviews with PTB staff and further experts in the field of quality infrastructure for PV. The interviews were conducted between June and September 2020. A list of the interviewees is provided in Annex B. Two different guides for semi-structured interviews were prepared. One guide was used for the interviews with the PTB project coordinators and focused on the situation of the PV sector, the available quality infrastructure services in the project country, and on project experience and learnings. The other guide was used for external experts and was broken down into two parts, the first focusing on quality gaps in the PV sector and the second dealing with quality infrastructure services. The questions were adapted to suit each interviewee's background and expertise.

The information from the interviews and the results of the desk research provided the basis for the preparation of case studies on PTB projects that support the quality infrastructure for the PV sector in emerging and developing economies. These cases specify the requirements for quality assurance identified along the PV value chain and provide insights into the effectiveness of the chosen approaches to increase quality and sustainability in different national contexts.

The first part of the study, including the case studies, was reviewed by the respective PTB project coordinators and members of the PTB working group *Energy, Environment, Climate* (part of Group 9.3 International Cooperation) and also by local project staff so that the perspective of the partner countries could be brought in as well.

The consolidated version of sections 1 and 2 formed, together with the case studies, the basis for the preparation of section 3, which provides recommendations for policy makers and quality infrastructure institutions in emerging and developing economies that take account of both the PV sector's development status and of the existing national framework conditions.

1.3. Relevance of the photovoltaic sector for emerging and developing economies

In developing and emerging economies, reliable energy is a cornerstone of further economic and social development. Because energy demand is rapidly increasing, an increase in generation capacity and the expansion of rural electrification are indispensable.[2] Relying on fossil fuels to expand capacity might be a tempting option, given that such fuels are often associated with lower prices. However, this strategy stands in contrast to sustainable development and disregards the numerous negative consequences of non-renewable energy sources, such as dependency on petroleum imports or the social costs of pollution.[3, 4] Therefore, a strategy for expanding electricity generation capacity to foster the economic development of developing and emerging economies should take a holistic approach, considering not only the economic effects but social and environmental aspects as well.

The use of renewable energy avoids the negative consequences of relying on fossil fuels and can thus promote a more reliable and sustainable energy supply.[5] Specific technologies, such as solar PV, also have become an economically better alternative to traditional energy sources. In the context of the Paris Agreement and the Agenda 2030, renewable energy plays a crucial role due to its contribution to the decarbonization of economic development. The expansion of renewable energy capacity has synergy effects on a number of different Sustainable Development Goals (SDGs) adopted by the United Nations (UN), including SDG 7 *(Ensure access to affordable, reliable, sustainable and modern energy for all)*, SDG 8 *(Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all)* and SDG 12 *(Responsible consumption and production)*.[6]

This study considers the three main applications of PV systems:

- **Off-grid applications** without connection to the electricity grid. These are typically used in small-scale projects but can also be integrated with other generation sources to form hybrid systems. This technology is particularly relevant in rural areas of emerging and developing economies, where grid extension is not viable for technical or financial reasons.
- **Distributed generation** involving multiple grid-connected generators. This refers mainly to rooftop PV systems, which (indirectly) contribute to generating the energy needed in the buildings concerned.
- **Utility-scale PV systems,** which are typically ground-mounted and contribute the largest share of overall installed PV capacity. The energy produced here is usually delivered entirely to the grid.[7]

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2 Frame, Tembo and Strachan (2011)

3 Thiam (2010)

4 Schwerhoff and Sy (2017)

5 Schwerhoff and Sy (2017)

6 United Nations (2021)

7 IRENA (2017)

1.4. The value chain of PV power plants

The value chain of PV power plants can be depicted as shown in the figure below:

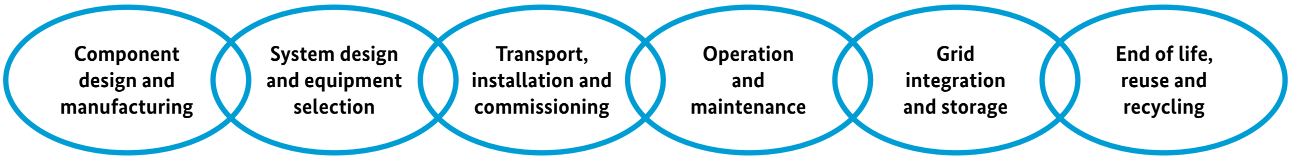


Figure 1: The value chain of photovoltaic power plants[8] (source: the authors)

Each step of the value chain is examined in detail in section 2.2 to identify the opportunities and risks relating to safety, quality and sustainability and to specify which services are required from the quality infrastructure.

1.5. Safety, quality and sustainability challenges in the photovoltaic sector

In many countries, the reputation of PV technology has suffered from negative experiences that occurred when safety, quality and sustainability aspects were not sufficiently addressed. Although PV is often perceived as easily deployable, special expertise is necessary throughout all phases of a PV project to ensure the correct functioning of the system and the long-term success of the project. The required know-how and experience can only be accumulated over time. In countries where PV development is comparatively recent, the sector finds itself at an early stage of the learning curve, and safety, quality and sustainability issues are more common. This is the case for many developing and emerging economies. Nevertheless, many of the challenges described in the following paragraphs are also relevant in industrialized countries and need to be addressed in order to further develop the PV sector.

Safety

PV systems on buildings are associated with a certain risk of fire. Accidental combustion represents a potential danger for people in and near buildings with PV installations.[9]

The fire risk is caused to a large extent by installation faults, which are very common in photovoltaic plants worldwide. A study by TÜV Rheinland found that, throughout the world, installation faults were the cause of more than 50 % of serious defects in photovoltaic plants. Incorrect installation, often due to errors such as improper wiring and grounding, loose screws or incorrectly inserted connectors, can thus have devastating effects on plant safety, performance and financial returns. In several developing and emerging economies, cases of PV rooftop plants catching fire due to faulty installation had a negative impact on the reputation of the entire sector.

Additionally, many emerging and developing economies do not give sufficient consideration to the suitability of buildings for rooftop PV installation. The necessary regulations and national standards are lacking, as is the enforcement of those legal requirements that do exist.

8 Table 1 in section 2.2. gives an overview on the quality infrastructure services required along the PV value chain.

9 Manzini et al. (2015)

Furthermore, health and safety problems among workers in the PV industry during the production, installation and end-of-life stages represent a challenge of growing importance. There is increasing concern about workers' exposure to the hazardous materials processed in the PV industry. During the life cycle of PV systems, there is a risk of potentially toxic materials being released, such as lead, arsenic, strong acids, or dioxins. Exposure can occur through the inhalation of smoke, dust or vapour as well as through ingestion or eye contact. At the same time, there are still information deficits regarding chemical and physical hazards that threaten workers.[10]

A common barrier to effective risk prevention is the lack of joint action by all stakeholders, including manufacturers, researchers, trade unions and government agencies. In many countries, there is a lack of strict and specific regulations. Also, occupational health and safety measures often do not cover the entire life cycle and fail to include the design of PV components and the end-of-life stage.[11]

Quality

To achieve sustainable growth in the PV sector, quality assurance along the entire PV system value chain is essential (see section 1.4 above).

Quality gaps can have substantial impacts on the performance of PV power plants, so assuring product quality is crucial for all components of a solar photovoltaic system. In many emerging and developing economies without substantial in-country production, the capacities for controlling the quality of imported products are lacking and the market is exposed to low-quality imports. Maintaining quality controls is further complicated by the large number of component suppliers in the global market.

PV modules are manufactured in many emerging and developing economies, and some of them also produce PV cells. The application of existing standards as well as the systematic use of testing and certification services during production can increase the efficiency of production, the overall quality of the end product, and the competitiveness of national manufacturers.

For planning and site selection, the availability of reliable solar irradiation data is of utmost importance as it is the basis for determining plant performance.[12] Given the variety of factors that need to be taken into consideration, reliable information is essential to successful plant planning. Moreover, the chosen technology has to be matched to the local climatic conditions, such as dust emissions in deserts or salt mist in coastal areas.

Installation faults, already mentioned in the previous section, also have a severe impact on the quality of the overall PV system. Even if high quality components are used, the performance of a PV power plant will be low if installation is performed by unqualified personnel. In emerging and developing economies, a lack of qualified engineers and skilled labour often represents a barrier to increasing the utilization of PV energy. Specific training for PV projects in educational or training centres is often limited, and many installers are not appropriately prepared for their tasks. A lack of human resources training and development may inhibit industry growth and the adoption of solar PV. According to a study of the Solar Bankability project of the European Union (EU), improper installation has the highest financial impact among the most common issues related to modules and inverters.[13]

During operation and maintenance, the application of appropriate measures and procedures is essential. Especially in the case of PV plants in emerging and developing economies, experience has shown that insufficient attention to quality assurance during this phase leads to a lack of reliable data on how the plants perform in practice, on underperformance, and on system damage.

Finally, quality assurance has a key impact on the end of life, reuse and recycling of PV power plant components. Higher quality components boast longer durability and as such reduce the amount of waste generated. Additionally, appropriate quality management during the component design and manufacturing phases reduces the use of toxic substances and increases the recyclability of components.

10 Bakhiyi, Labrèche and Zayed (2014)

11 Bakhiyi, Labrèche and Zayed (2014)

12 Shahsavari and Akbari (2018)

13 Solar Bankability (2017)

Sustainability

Regarding the overall sustainability of PV projects, environmental, social, political and financial challenges come into play and must be considered in addition to the challenges already described.

Although PV energy has significant advantages over fossil fuels in terms of environmental impact, there are still some concerns that need to be addressed. The most relevant aspect is the additional land use associated with some types of PV systems. While rooftop PV systems do not result in high land-use intensity, larger-scale PV farms require vast areas of about 1 to 2 ha per megawatt peak (MWp) in India and Indonesia, for example.[14] Factors such as the system's energy efficiency and the local solar irradiation influence the land-use intensity of a solar PV plant. High land use is a particularly relevant issue in sensitive environments where the installation of a PV plant has a visual impact or where it competes with traditional land use, e.g., agriculture.[15] However, there are new approaches that address this issue, such as agrivoltaics, which seeks to optimize land use for simultaneous energy and agricultural production.

Another important sustainability issue is the use of water to clean PV modules. This is especially critical in arid zones, where the use of water in PV installations causes additional water stress for both the local ecosystems and the local population.

As more and more systems will reach their end-of-life stage in the foreseeable future, the topics of circularity and recyclability are also becoming increasingly important. PV panels are made from rare or valuable substances, including silver, indium, or tellurium[16], which is why their recycling could prevent the loss of such substances as well as the environmental impacts associated with their extraction. Currently, there are still significant research gaps related both to the inclusion of recycling aspects in the design phase and to the further development and improvement of recycling processes.

14 International Finance Corporation (2015)

15 Shahsavari and Akbari (2018)

16 Redlinger, Eggert and Woodhouse (2015)

Also, the number of old panels up for recycling is still not enough to drive the development of efficient recycling processes, which leads to insufficient access to recycling facilities in many countries.[17] However, initial regulatory steps have been taken since 2014 to address this problem, including the EU's Waste Electrical and Electronic Equipment (WEEE) Directive.

Moreover, an expansion of PV energy cannot be fostered in the long-term without the support of the population. So another challenge is to build awareness about PV technology and to promote social acceptance. The population needs to know about the advantages of PV energy compared to fossil-based power. There is often a lack of consumer awareness regarding the externalities of fossil fuels.[18]

The high upfront investment for PV installations also represents a major barrier to the development of PV projects.[19] Despite the tremendous drop in the amount of capital expenditure required for PV power plants over the past years, these systems still require higher initial investments compared to a number of fossil fuel alternatives. The recurring costs associated with PV are, however, lower.[20] The high upfront investments are particularly problematic when combined with high investment risks, which is the case in many developing economies. Governments are often the main investors in energy infrastructure. If they can only borrow in the market at high costs, the consequence will be an inclination to favour investments that come with lower initial costs. The reasons behind the increased investment risks for PV in developing economies include insufficient quality assurance, unstable political frameworks, and a lack of regulation.

17 Kabir et al (2017)

18 Shahsavari and Akbari (2018)

19 Schwerhoff and Sy (2017)

20 This is, for example, the case for diesel generators used in remote areas in developing economies. These generators require relatively low capital expenditure but have very high operational costs compared to PV.

1.6. Relevance of the quality infrastructure in addressing existing challenges and in supporting the sustainable development of the sector

As illustrated in the previous sections, a more sustainable energy supply is essential for developing and emerging economies, and solar PV constitutes an important technology in this context. The development of a functioning quality infrastructure can help to overcome the challenges discussed above and facilitate the wider use of PV energy. The quality infrastructure system comprises the following elements[21]:

- **Standardization** provides requirements and specifications to ensure that products, processes and services are fit for their purpose. The national standardization body is responsible for standards development, for the adoption and adaptation of international standards, and for awareness raising and the provision of related information.

- **Metrology** is the science of correct and reliable measurements for legal matters, industry and science. The national metrology institute (NMI) defines the primary national standards. Secondary calibration laboratories are often attached to universities, research centres or private companies. They provide calibration services for all kinds of measuring equipment.

- **Testing** allows the characteristics or performance of a product or process to be determined following a specific procedure.

- Furthermore, **inspection** can be used to determine whether a product or process complies with certain requirements and involves the examination of the respective site, equipment or processes by an independent body.

- **Certification** is usually based on testing and inspection and confirms that a product or process complies with a standard or specification.

- Finally, **accreditation** is provided by the national accreditation body or organized by a national focal point for accreditation and consists of the formal recognition of an organization's competency to carry out a specific task. Testing and calibration laboratories as well as certification and inspection bodies can apply for accreditation to prove that they provide reliable services.[22]

The national quality infrastructure is an interrelated system of complementary components. The national policy environment and the relevant public institutions must also be viewed as part of the extended quality infrastructure as they establish the framework for the different services. For example, a ministry may decide to reference a standard in the text of a technical regulation, thus making the voluntary requirements set down in that standard legally binding in order to ensure environmental protection, health, safety and security.

Quality infrastructure services are needed to ensure compliance with buyer requirements, for example the technical requirements defined in tender documents for PV power plants or in buyer specifications for PV components.

The national quality infrastructure should not be developed in an isolated way but rather linked to the international system by establishing the respective relations to the following:

1. The International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) for standardization
2. The International Bureau of Weights and Measures (BIPM) and the International Organization of Legal Metrology (OIML) for metrology and legal metrology
3. The International Accreditation Forum (IAF) and the International Laboratory Accreditation Cooperation (ILAC) for accreditation
4. The respective regional organizations

21 See also the glossary in Annex C.

22 Sanetra and Marbán (2007); Telfser et al (2019)

Only in this way is it possible to ensure international traceability, comparability, and the recognition of local services, and to benefit fully from the national quality infrastructure.[23]

Such systematic quality infrastructure development is needed to address the challenges, described in section 1.5. above, in the PV sector of developing and emerging economies. Specifically, quality infrastructure can make the following contributions to overcoming these challenges:

Safety
The use of quality infrastructure services is required to increase the level of safety in the PV sector. Standards, best practices, and technical regulations define the safety criteria that apply to products and processes, including the installation and operation of PV systems and, where applicable, the handling and processing of toxic substances. Certification and inspection ensure compliance with these criteria. This is essential to protect the safety of workers, nearby communities, and, in the case of rooftop power plants, buildings, by reducing the risk of electric shock and fire, for example.

Quality
Sustainable market growth in the PV industry is only possible if an appropriate level of quality is ensured and investors, policy makers and consumers can trust in the performance of the products and services. Quality assurance aligned with international standards and best practices is relevant for the entire lifecycle of a PV system from the design phase to the end-of-life phase. It leads to enhanced credibility, which reduces the risks for investors, policy makers and consumers. In this way, the implementation of a functioning quality infrastructure can boost both the development and dissemination of new technologies, thereby fostering innovation in the industry.

Sustainability
Developing quality infrastructure services works to build the institutional capacities needed to support the growth of the PV industry in an economically, ecologically and socially sustainable manner. The use of quality infrastructure services can help improve the environmental impacts of materials and products as well as their energy efficiency. Moreover, product compliance with relevant standards and with destination market and consumer requirements boosts the competitiveness of local industry and broadens its access to foreign markets. This promotes the sustainable economic development of the industry. Moreover, a quality-driven sector accelerates investments in PV projects and lowers the cost of capital by bolstering the confidence of and the stability for potential investors. The risks of system underperformance can be reduced, making PV systems a safer investment. This may result in easier access to funds and lower capital costs, as well as in stable returns once the system is in operation. Eventually, it may also lead to reduced electricity costs. Overall, quality infrastructure supports the implementation of the SDGs and can further contribute to improving the environmental and social performance of PV power plants during research and development (R&D), production, design, and operation and maintenance.[24, 25] The following section describes in detail the quality infrastructure services that are relevant at each phase of a PV project.

23 Sanetra and Marbán (2007); Telfser et al. (2019)

24 IRENA (2017)

25 UNIDO (2019)

2. Quality Infrastructure for the Photovoltaic Sector

2.1. Requirements for safety, quality and sustainability as the basis for quality assurance along the PV value chain

The safety, quality and sustainability of PV systems depend largely on the requirements defined on the country or project level and build the basis for quality assurance in the different parts of the PV value chain. Governments and investors have the greatest leverage when it comes to establishing these requirements in the PV sector. Specific criteria need to be included in tenders, contracts, financing schemes and government programmes, and conformity with these criteria needs to be assessed. This means including information about the international and national standards to be applied; indicating which product, process and personnel certifications are required; defining what will be tested or inspected when and how; and specifying if conformity assessment has to be carried out by accredited organizations (testing laboratories and/or certification and inspection bodies). The criteria should take account of the specific local conditions. They may also include the end-of-life management of components, for example by specifying that the module manufacturer must join and adhere to the policies of a recycling initiative.

The definition of appropriate technical requirements is crucial if severe economic and sustainability issues are to be avoided in a PV project. In particular, component selection and design are determinants for the future performance of the PV plant, and wrong choices at these early stages can only be fixed with great difficulty, if at all. The given ownership model and the contractual agreements reached for the system will determine who bears the highest risk. At the same time, they determine who is obliged to define the specific requirements (see case study below).

Example from case studies:

Fostering the application of quality and sustainability criteria in India

In India, PTB implements the project called *Strengthening Quality Infrastructure for the Solar Industry*. As part of this project, PTB is working with the Solar Energy Cooperation of India (SECI) to support the systematic consideration of quality, safety and sustainability criteria in tender processes. The consideration of such criteria is expected to contribute to the sustainability of the Indian PV sector and at the same time lower the risks of investment.

One output of this cooperation was the development of a new tender format with a concise structure broken down into seven topics that provides greater clarity to the bidder. The request for proposal (RfP)[26] sections are applicable to both large-scale and rooftop PV plants. As an annex to the RfP documents, a testing plan for the PV modules is included that contains suggestions for tests tailored to various climate regions in India that go beyond the tests defined by international and national standards. Social and ecological criteria are also included in the restructured tender documents.

The *Eligibility Tool* and the *Bid Ranking Tool* created subsequently serve to classify offers submitted by the bidders according to their level of compliance with the RfP. This greatly simplifies the technical evaluation performed by the organization that published the tender.

26 The RfP informs suppliers that an organization (in this case SECI) is looking to procure supplies and services and specifies the criteria that must be met by the bidders.

2.2. Quality infrastructure services along the PV value chain

The following table provides a non-exhaustive overview of quality infrastructure services required to ensure safety, quality and sustainability along the photovoltaic value chain. A detailed description of related opportunities and risks, required quality infrastructure services, and examples from case studies are provided in sections 2.2.1. to 2.2.6.

QI	Manufacturing	System design and equipment selection	Transport, installation and commissioning	Operation and maintenance	Grid integration and storage	End of life, reuse and recycling
Standardization	Quality management system (QMS) (e.g., ISO 9001) Manufacturing (IEC 62941 for PV modules) Components (IEC 61215 & IEC 61730 PV modules; IEC 62093 BOS etc.) Testing/Measurements (IEC 60904)	System design (IEC 62548, IEC 62124, IEC 60364-7-712) Specific international or national standards on environmental conditions Testing/ Measurements (IEC 60904)	PV system requirements (IEC 62446-1) Transportation testing of PV modules (IEC 62759-1:2015) Reference to relevant standards in national commissioning guidelines	Field testing and monitoring (IEC 62446 parts 2 & 3, IEC 61829 and IEC 61724) Guidelines for operation and maintenance	Grid integration (IEC 61727, IEC 62446-1) Batteries (IEC 60896, IEC 61427) Reference to standards in national grid codes	Current standardization initiatives International standards for recycling and reuse of modules (e.g., after repair) to be defined
Metrology	Calibration and traceability for testing equipment used for PV components. For modules and inverters mainly: ▪ irradiance level and spectral irradiance of the light source ▪ electrical characteristics: current and voltage ▪ temperature Calibration of reference cells and PV modules	Calibration and traceability for testing equipment and monitoring devices for meteorological parameters e.g., irradiance, wind speed, temperature, humidity, conductivity	Calibration and traceability for testing equipment, e.g., force, electric insulation	Calibration and traceability for testing equipment as well as plant and weather monitoring devices required for the monitoring of PV power plants, e.g., current and voltage, irradiance, wind speed and temperature	Calibration and traceability for testing equipment used in quality assurance of storage infrastructure and applied in grid management, e.g., electrical characteristics (current and voltage) for electricity meters and batteries; advanced measurement frameworks for SCADA systems, phasor measurement units, battery characterization	Calibration and traceability for testing equipment used for reuse and recycling
Testing	Testing for R&D, quality assurance during production process, and final products Testing of component samples for market surveillance	Random sample testing of PV modules (for large projects	Testing for transport damage of modules upon arrival Field tests (e.g., performance, infrared and EL imaging)	Field testing on component, string and system level (e.g., performance, infrared and EL imaging)	Batteries	Leaching of hazardous materials from PV waste Purity of recovered material in recycling

Continued on next page

QI	Manufacturing	System design and equipment selection	Transport, installation and commissioning	Operation and maintenance	Grid integration and storage	End of life, reuse and recycling
Certification	Certification of QMS Product certification	Product and QMS certification for equipment selection Personnel certification	Personnel certification Certification of compliance with requirements for transportation Certification of PV power plants after installation	Personnel certification Certification of operation and maintenance contractors	Battery certification Commissioning surveillance as part of the project certification	Certification of sustainability aspects of components (e.g., carbon footprint of modules)
Inspection	–	–	Plant inspection during construction and commissioning	Plant inspection (e.g., to investigate underperformance for warranty claims)	Plant inspection based on grid codes before grid integration	–
Accreditation	For calibration & testing laboratories and for certification bodies	For certification bodies, calibration & testing laboratories	For inspection & certification bodies, calibration & testing laboratories	For inspection & certification bodies, calibration & testing laboratories	For calibration & testing laboratories, certification & inspection bodies	For calibration & testing laboratories and certification bodies

Table 1: Non-exhaustive overview of quality infrastructure services required to ensure safety, quality and sustainability along the photovoltaic value chain (source: the authors)

2.2.1. Manufacturing

Opportunities and risks related to safety, quality and sustainability

The PV manufacturing industry in many countries has matured in recent years and there are now a large number of manufacturers capable of producing quality components. But the industry has also faced an extreme drop in prices for PV modules over the last decades. Manufacturers are thus forced to produce and sell with minimal margins, which in some cases leads to certain trade-offs in quality that reduce the efficiency and lifetime of the final product. The risk of substandard PV modules and other components being used is particularly high when the focus lies on minimizing prices when at the same time quality requirements are too lax and quality control is neglected.

According to a study by PI Berlin (2019) that used 250 audits of more than 120 mainstream module manufacturers worldwide to conduct a benchmark, only 10 % of the audited manufacturers achieved an *excellent* rating, while the majority (45 %) were assessed as *average*, showing a lack of effective quality management measures, and 21 % were rated as *poor*. This shows that quality deficits remain an issue in PV module manufacturing worldwide.[27]

PV module assembly is seen as a promising industry for local economic development and job creation in many developing and emerging economies that are embracing solar PV as a sustainable energy source. Governments are therefore supporting industry development, and protective measures are often put in place to prevent the market from being flooded with lower cost products from abroad. Modules produced in protected local markets often do not fulfil international criteria. The protective measures that foster industry development can thus hinder the development of the sector when substandard PV modules are used in the country and people's experience with the technology is negative.

27 PI Berlin (2019)

Introducing effective quality assurance mechanisms and attaining the demanded levels of quality requires investments by both the government and the PV sector. The experiences of various developing and industrialized economies show that a learning phase is required to develop the appropriate processes and competencies. Both the amount of investment required and the duration of the learning phase increase when basic quality infrastructure services such as standards, testing, calibration and certification are not available in country and need to be purchased abroad. Besides quality, product development and innovation can also be negatively affected by the lack of such services.

Some manufacturers are taking measures to increase the traceability of materials and to move towards more circularity in PV module production, among other things by introducing design-for-recycling approaches. These developments are primarily seen among tier one manufacturers with well-established production lines and large capacities. Most of the industry, however, is not focusing on such aspects, given that the majority of customers make their purchasing decisions based on price and neither consider nor request additional criteria related to sustainability.

For PV inverters, quality and safety also need to be considered starting in the design phase. They have a shorter lifetime than PV modules and represent the PV system component responsible for the highest number of service calls and the highest operating and maintenance costs. [28] It is therefore crucial that all parts of the inverter be durable and do not pose safety hazards, for example due to overheating. Depending on the location of the PV plant, inverters may be exposed to harsh environmental conditions such as heat, humidity, UV rays, dust or frost. These stress factors need to be taken into consideration during the manufacture of inverters. This, however, is often not the case, and the result is the premature failure of inverters.

As concerns the batteries used in PV systems, the efficiency and durability of the final product is determined by the design, the selected materials, and the manufacturing process. For instance, high-capacity, stable materials should be used, with consideration given to both their energy harvesting and storage properties.[29] During the assembly process, temperature and humidity need to be controlled in order to reduce the risk of premature degradation. The size of a battery manufacturing firm is not always an indicator for quality management. Poor quality batteries pose a risk of performance loss as well as a safety risk for PV systems.[30]

Other components such as cables or mounting structures are also decisive for the correct functioning of a PV system. They need to be resistant to solar exposure and other potentially harsh environmental conditions, ideally over the lifetime of the PV system. These components are often produced locally, providing an opportunity for employment and value addition in the country. Failure to meet international standards in this area has led to severe issues in PV power plants in many countries. For example, there are many cases of mounting structures not resisting wind or corrosion and of cable insulation being broken by UV radiation and creating a fire hazard.

Required quality infrastructure services

For manufacturers of PV components, setting up a quality management system according to international **standards** such as ISO 9001 allows them to streamline processes and to ensure the required levels of product quality. An internationally recognized certification of such management systems can enable manufacturers to reach additional customers abroad or to supply goods to local projects with particularly demanding quality requirements. For PV module manufacturing, specific guidance is provided in IEC 62941 *Terrestrial photovoltaic (PV) modules – Quality system for PV module manufacturing*, which presents best practices for product design, manufacturing processes, and the selection and control of materials.

28 Consolidated Electrical Distributors Inc. (2020)

29 Joule (2018)

30 PI Berlin (2019)

Moreover, international product standards are available that define minimum quality and safety criteria for the main PV components. For PV modules, the relevant standards are IEC 61215 *Terrestrial photovoltaic (PV) modules – Design qualification and type approval* and IEC 61730 *Photovoltaic (PV) module safety qualification*. Quality and safety requirements for other components are defined in IEC 62093 *Balance-of-system components for photovoltaic systems – Design qualification natural environments* or more specifically in IEC 62852 for connectors for direct current (DC) applications, in IEC 62790 for junction boxes, in IEC 62109 and in IEC 62894 for power converters and photovoltaic inverters, and in IEC 62930 for cables. Additional requirements regarding testing and measurements for components are provided in IEC 60904 *Photovoltaic devices*. But because these standards and their respective certification (where applicable) are not always considered during component selection – especially if they are not specifically requested in tenders and contracts – quality issues persist.

Metrology assumes an important role in the assurance of manufacturing quality. Metrological services are required for ensuring the traceability and exactitude of the testing and calibration equipment used, thus providing the basis for reliable data and high levels of quality in production. Services include the calibration of the testing equipment itself as well as the calibration of the reference solar cells and PV modules used for internal quality control in the production process and in test laboratories. The manufacturing of PV modules mainly requires metrological services relating to the irradiance level and spectral irradiance of the light source, electrical characteristics (current and voltage) and temperature. [31]

Testing is important for research and development, during the production process, and for the final product. It is a cornerstone of the quality management system, as testing for research and development and in the early stages of production allows manufacturers to track quality and adjust the input material or production process according to the test results. This provides great leverage to improving product quality. The availability of testing services can therefore boost the competitiveness of the local industry. Testing of the final product, in turn, is necessary for product **certification** according to international standards and it can also be relevant for imported products to verify compliance with specifications as part of market surveillance. In this latter case, a selection of tests can be applied to allow a quick assessment of product quality.

Internationally recognized **accreditation** services are required in the manufacturing stage to ensure the technical competence of certification bodies and of calibration and testing laboratories.

Examples from case studies:

Establishing a testing laboratory for PV modules in Indonesia

In Indonesia, the local PV industry comprises various module manufacturers who assemble PV modules. They primarily target the national market, where government tenders favour local content as a measure to support the development of local industry and create jobs. To ensure quality in government-funded PV projects and in the PV sector at large, the Government of Indonesia in 2018 provided funding for a PV module testing laboratory covering all the tests required by IEC 61215.

The PTB project *Strengthening Quality Infrastructure for the Energy Sector* provided consultancy with respect to the preparation of the tender and the establishment of the quality management system for the new testing services. Complementing the activities to support the development of the laboratory, various events were organized for industry and decision makers to raise awareness about the IEC 61215 standard.

Developing testing services for PV modules, inverters and batteries in Senegal

With the aim of increasing the dissemination of quality-tested PV systems in Senegal, the PTB project *Strengthening Quality Infrastructure for Innovative Energy Services* focuses on the development of testing services for PV. Capacity development is concentrated at two partner laboratories: the Center for Renewable Energy Studies and Research *(Centre d'Etudes et de Recherches sur les Energies Renouvelables,* CERER) for the development of testing

31 LNE-CNAM (2012)

services for PV modules; and the Polytechnic Institute *(Ecole Supérieure Polytechnique,* ESP), where testing services for batteries, inverters and controls are being established. The necessary equipment for the two laboratories was procured and technical training provided with the support of the PTB project. Due to travel restrictions because of the Covid-19 pandemic, equipment specifications, installation and procedures were coordinated and carried out virtually. Other important components of the project are the involvement of the private sector (installation and consulting companies), quality awareness raising at all levels, and the networked cooperation of all quality assurance stakeholders.

Developing cell and module calibration services in India

In 2017, the Indian government published an order that requires any manufacturer who manufactures, stores for sale, sells or distributes solar PV systems, devices or components in India to apply to the Bureau of Indian Standards (BIS) for obtaining registration for use of the *standard mark*. Tests for compliance with Indian standards required by the order may only be conducted by laboratories *recognized* by BIS. The accreditation by the National Accreditation Board for Testing and Calibration Laboratories (NABL) is a primary requirement. Additionally, the laboratory must submit a test report to BIS on the basis of which BIS issues a registration certificate for the manufacturer. Against this background, the demand for accreditation and BIS *recognition* of testing laboratories, as well as the demand for reference PV cells and modules that are needed for module testing, have increased considerably in the past years.

As part of the PV project in India, PTB supports several calibration laboratories in India in their efforts to develop services for secondary cell and module calibration. This will facilitate the access of the national industry to the required testing services and help the testing laboratories to save time and money compared to the purchase of the necessary calibration services abroad. This activity is complemented by a collaboration with the accreditation body NABL, the aim being to develop capacities for the accreditation of calibration and testing laboratories. Besides this project, PTB has established a scientific cooperation with the national metrology institute CSIR-NPL (National Physical Laboratory, under the Council of Scientific & Industrial Research) to set up a primary calibration facility for PV reference cells.

2.2.2. System design and equipment selection

Opportunities and risks related to safety, quality and sustainability

In the design phase of a PV project, many factors need to be considered in order to ensure that the PV system is properly designed for the specific site. The required know-how is often lacking in developing and emerging economies, in particular where the development of the PV sector is recent. Consequently, system design and component selection are not always ideal and the potential for increasing efficiency, for example by improving the positioning of components to reduce losses, is not exploited.

Site selection requires reliable data on solar irradiance. But this information, essential early on for the planning of a PV system, is for many locations not available with a sufficient degree of reliability. Particularly for PV systems in remote areas, satellite data is often used, which has in many cases been found to deviate significantly from the irradiance measured on the ground (see example from the case study below). Also often lacking or neglected is reliable long-term data for other environmental parameters such as wind speed, precipitation, air humidity and salinity, sand abrasion, dust emission, ground water level, and composition of the mounting ground. This leads to risks to the performance and durability of the PV systems since appropriate consideration cannot be given to these environmental parameters in the design phase.

In regions where PV systems are exposed to extreme environmental conditions, components and systems must be designed to achieve higher levels of durability. When components are selected, their suitability to the specific climatic conditions needs to be ensured. Here, the application of basic international standards for component and system design may not be sufficient, as international standards establish criteria for internationally predominant conditions and tend to more prominently reflect the conditions of countries that are well represented in the relevant technical committees of the standardization bodies (mainly IEC). The application of existing standards for specific environmental conditions and the adaptation of international standards to specific extreme environmental conditions can lower the associated risks.

The environmental and social viability of the PV plant also needs to be assessed. Regulations vary by country and in many developing and emerging economies such an assessment is not required by law. Nevertheless, considerations regarding land use and access to land and water are important given the possibility of human rights infringements. The overall sustainability performance of a PV system may be increased through membership in an organization, such as PV Cycle or PVEX, that guarantees the appropriate management of PV modules at the end of their life cycle. Environmental or social certificates based on criteria such as the carbon footprint of modules or fair labour conditions on the manufacturing site contribute to lowering related risks and ensure that negative sustainability impacts can be mitigated or minimized while positive impacts are optimized. However, these criteria are only rarely requested or checked, as price remains the driving factor for component selection. In many developing and emerging economies, components can also be acquired on informal markets, where it is even more challenging to ensure that the purchased products comply with minimum safety, quality and sustainability requirements.

If the planned PV system is supposed to feed the electricity it produces into the grid, the robustness of the existing grid infrastructure and the capacity for integrating electricity from a fluctuating source such as solar PV need to be considered, as this will greatly influence the design of the PV system in terms of sizing and the potential need for additional storage.

Required quality infrastructure services

As mentioned above, international **standards** are the backbone of quality assurance in PV systems. For the selection of components, compliance with international standards ensures that basic quality and safety requirements are fulfilled. Information regarding system design is defined in the standards IEC 62548 *Photovoltaic (PV) arrays – Design requirements,* IEC 62124 *Photovoltaic (PV) stand-alone systems – Design verification,* as well as in IEC 60364-7-712 "*Electrical installations for buildings – Part 7 – Requirements for special installations or locations (Section 712: Solar photovoltaic (PV) power supply systems).* Safety standards are often prescribed by law in the form of technical regulations.

Depending on the climatic conditions, additional standards may be applicable. An example is salt-mist corrosion testing of PV modules according to the IEC 61701 standard, which is relevant for locations close to the sea. There are several initiatives for the adaptation of existing international standards to specific environmental conditions. For example, in India, the development of a standard for the measurement of soiling losses is being discussed in light of the high dust emission levels found there.

Metrological services in this phase are mainly required to provide calibration and traceability for equipment and devices used to test and monitor meteorological parameters. For example, if the solar resource at a certain location is measured over a long period with pyranometers or reference cells, those devices should be regularly calibrated to ensure that the data they provide remains reliable. The services most required are those for the following parameters: irradiance level, wind speed, temperature, humidity, and conductivity.

To facilitate the selection of components that comply with international standards, **certification** is important. It is a clear advantage if a manufacturer can provide a certificate that shows that the components are in line with the requirements of the respective quality and safety standards. If such a certificate is provided by a certification body that has been accredited by an internationally recognized accreditation body, then the certificate will be internationally recognized as well. Experience shows that for PV modules, random sample testing should be provided for in addition to product certification so that the quality of the employed modules can be verified prior to installation and the risk of underperformance reduced. This is especially true for large projects.

Personnel certification is an important service at this stage of the value chain, as it allows the competence of professionals who design PV systems to be verified. In many countries, industry associations take on the task of providing training to the different PV practitioners. An independent certification body should be in charge of certifying their competence. Ideally, this body would also be accredited by an internationally recognized accreditation body according to ISO 17024 *Conformity assessment – General requirements for bodies operating certification of persons*. However, this is not very common.

Example from case studies:

Comparing satellite data with information gathered in weather stations in the GIZ Solmap project in India

At the beginning of the boom of the solar PV sector in India, reliable irradiation data measured on the ground was lacking and developers had to rely on satellite data to identify locations with the best solar radiation and to forecast the solar yield of a planned system. This led to complaints from developers who observed differences between the actual power output and the forecasts based on satellite data.[32] The SolMap project, supported by the *Deutsche Gesellschaft für Internationale Zusammenarbeit* (GIZ) GmbH, helped to close this gap, installing 120 solar radiation measurement stations in the country to form one of the largest national networks worldwide.[33] The project developed a map of solar spots based on reliably monitored data. This map shows the optimum solar radiation intensity and enables developers to accurately pinpoint future project sites. Additionally, the project calculated that if a satellite data prediction exceeds the actual irradiation on the ground by 5 %, financial losses of 20 % of overall revenue can ensue.[34]

32 Solarthermalworld (2012)

33 IKI (2021)

34 Solarthermalworld (2012)

2.2.3. Transport, installation and commissioning

Opportunities and risks related to safety, quality and sustainability

Installation is the phase of the PV project during which most quality and safety issues arise. The installation of PV systems requires specific know-how that is often lacking in developing and emerging economies, especially if the PV sector is in an early stage of development. Even global engineering, procurement and construction (EPC) firms do not always train their local staff sufficiently to make sure that installation is carried out correctly. The result is that PV modules are often damaged during transport or installation, that insufficient attention is paid to electrical safety aspects, or that minor or major workmanship faults (such as loose screws, incorrectly inserted connectors or unstable mounting structures) impede the correct functioning of the system, putting operators and local residents at risk. Such defects may in some cases be immediately apparent, while in other cases a thorough check of the system is required to ensure that it is safe to operate and that the quality requirements have been implemented.

Before the system is taken into operation, inspections performed as part of commissioning procedures are crucial to identifying potential safety and quality issues. Here again, specialized knowledge is indispensable to ensure that the inspection is carried out correctly and that the person in charge can identify non-conformities. In many countries, the inspection performed during commissioning is state regulated, but the commissioning criteria and procedures for PV systems are not standardized. Inspections are often based on electrical or grid connection guidelines intended for other technologies, and these guidelines are simply applied without modification to PV. For instance, the performance ratio – a parameter that allows the determination of PV plant performance depending on the solar irradiance it is exposed to – is not always applied during the commissioning of PV plants, even though it is the most meaningful parameter for determining whether the system is functioning correctly. In some cases, staff members of the EPC itself carry out commissioning, meaning that independent quality and safety assurance may not be guaranteed.

Required quality infrastructure services
International **standards** are available for this phase of the value chain as well. For instance, standard IEC 62446-1 *Photovoltaic (PV) systems – Requirements for testing, documentation, maintenance – Part 1: Grid connected systems – Documentation, commissioning tests and inspection* describes which information and documents need to be prepared during installation. It also defines the testing and inspection requirements for commissioning the system. Additional standards for field tests such as electroluminescence (EL) imaging have also been developed. The IEC 62759-1 standard *Photovoltaic (PV) modules – Transportation testing – Part 1: Transportation and shipping of module package units* defines the testing of the transportation of PV modules. Its application can lead to the use of appropriate packaging. However, these standards are not sufficiently applied. Commissioning procedures have to be defined nationally and with reference to existing international standards. Guidelines for commissioning can facilitate the application of procedures and standards. Specific national requirements or environmental conditions should be considered.

Metrology is important to ensure the accuracy and traceability of testing and measurement devices used during transport, installation and commissioning. Required metrological services include those mentioned for the previous phases (such as irradiance level and spectral irradiance of the light source, current and voltage, and temperature) but also services to provide traceability and calibration for the more specialized testing equipment used during this phase, for example force measurements for transport tests and electric insulation measurements for tests of PV modules and entire plants.

Testing of PV systems or their components may be carried out at different stages of the installation phase. The transportation of PV modules in complete packages can be simulated in a testing laboratory following the methods described in IEC 62759 to check the potential impact of transportation on the modules. The components can then be tested upon arrival at the construction site to identify any transport-related damage. This is particularly relevant for PV modules, which can have microcracks that remain invisible to the naked eye but still negatively affect module performance. EL imaging can be used to identify such cracks. Further tests of the system and the components can be carried out during installation. While these tests are done to ensure the quality and performance of the PV system, the **inspection** during commissioning is aimed at assuring its safety and functionality before it can start operation. Involving inspection bodies that are accredited by internationally recognized accreditation bodies and that perform inspections based on nationally regulated procedures and international standards can substantially increase the safety and reliability of PV power plants.

As mentioned for system design above, personnel **certification** is also crucial for the installation phase. The content of the related training and the certification requirements need to be revised regularly to reflect new developments in the industry. Additionally, the certification of compliance with transportation requirements is important in this phase of the value chain. Once installation is concluded, the PV power plant itself can also be certified.

Accreditation is relevant not only for inspection bodies and organizations that provide personnel certification for installers, but also for the testing and calibration laboratories that provide services during the installation phase.

Example from case studies:

Developing an installation guide in Tunisia
In Tunisia, the PTB project *Strengthening Quality Infrastructure for Photovoltaics* supported the National Agency for Energy Management (*l'Agence Nationale de Maitrise de l'Energie*, ANME) in developing an installation guide for PV systems connected to the low-voltage grid. The guide gives a general introduction to PV systems, covers the procedures for installation, testing and commissioning, and describes common faults and security issues and how to avoid them.

To facilitate the use of the guide, training courses for installers were organized jointly with ANME. The training and the content of the guide can provide the basis for installer certification for the market segment of small and medium-sized PV systems connected to the low-voltage grid. The guide has proven successful and is backed by the Tunisian government. Moreover, it was shared with GIZ and the relevant stakeholders in Morocco and used there as a basis for a similar guide and installer certification scheme.

2.2.4. Operation, maintenance and monitoring

Opportunities and risks related to safety, quality and sustainability

During the operation phase, regular maintenance and continuous monitoring need to be carried out to detect possible defects that may affect the performance or safe functioning of the system and to make sure that the plant offers the best possible operating conditions. Typically, maintenance tasks include cleaning the solar panels (which should be planned in line with local soiling conditions), ensuring that monitoring equipment works correctly, cutting vegetation to avoid shading, and visually checking the system, its components and the monitoring data. When defects arise, the problem needs to be identified and components repaired or replaced. Once again, having competent personnel is crucial.

Many operators, however, lack the specialized PV knowledge required. Procedures for operation and maintenance are not defined for many power plants and the applied guidelines often neglect important aspects. Moreover, monitoring data is not always available, or the data that does exist is not reliable. This may be due to a lack of monitoring equipment, uncalibrated equipment, or inadequate procedures for data storage, transfer and analysis. The less information available on system performance, the more difficult it becomes to efficiently maintain the system, as there is no basis for the planning of maintenance tasks. At the same time, insufficient information on the performance of PV power plants in many countries makes it difficult for sector organizations and policy makers to effectively control and foster the development of the PV sector.

The effectiveness of operation and maintenance largely depends on the ownership model applied. If requirements in this phase are not defined clearly in the relevant contracts, maintenance may be neglected, and many defects left unidentified or unfixed. Persistent issues might lead to reduced performance or even to the complete failure of the PV system.

The challenges relating to operation and maintenance, repair and monitoring are even more pronounced in smaller systems, especially when they are located in remote areas and managed by local communities with little PV-specific technical know-how.

Required quality infrastructure services

The international **standards** relevant to operation and maintenance are the previously mentioned IEC 62446 *Photovoltaic (PV) Systems – Requirements for Testing, Documentation, Maintenance*, and in particular *Part 2: Grid connected systems – Maintenance of PV systems*, and *Part 3: Photovoltaic modules and plants – Outdoor infrared thermography*, which describes one of the main field tests used for maintenance. In addition, IEC 61829 *Photovoltaic (PV) array – On-site measurement of current-voltage characteristics* provides information on field testing. The IEC 61724 standard *Photovoltaic systems performance* gives insights into the monitoring of PV systems, including how to measure and calculate the performance ratio, in its *Part 1: Monitoring*. The standard also provides additional information on different methods in the technical specifications *Part 2: Capacity evaluation method* and *Part 3: Energy evaluation method*. As mentioned above, the bottleneck lies not in the availability but rather in the implementation of the existing standards. The development of guidelines for operation and maintenance can facilitate the application of standards. An example for the development of such guidelines is seen in the current process in India, which was implemented by Solar Power Europe with the support of the Indo-German Energy Forum (IGEF) and the National Solar Energy Federation of India (NSEFI). The KfW Development Bank, PTB, and further stakeholders have contributed to this process.[35]

Metrology services are required mainly to calibrate the testing equipment and sensors used for monitoring the PV system and the weather conditions. These include pyranometers and reference solar cells that are spectrally matched to the installed modules, thermometers and anemometers (wind speed meters), and that must be re-calibrated regularly to generate the reliable data required for the monitoring of plant performance. The primary need for metrology services therefore lies in the areas of current and voltage, irradiance, temperature, and wind speed.

35 SolarPower Europe (2021)

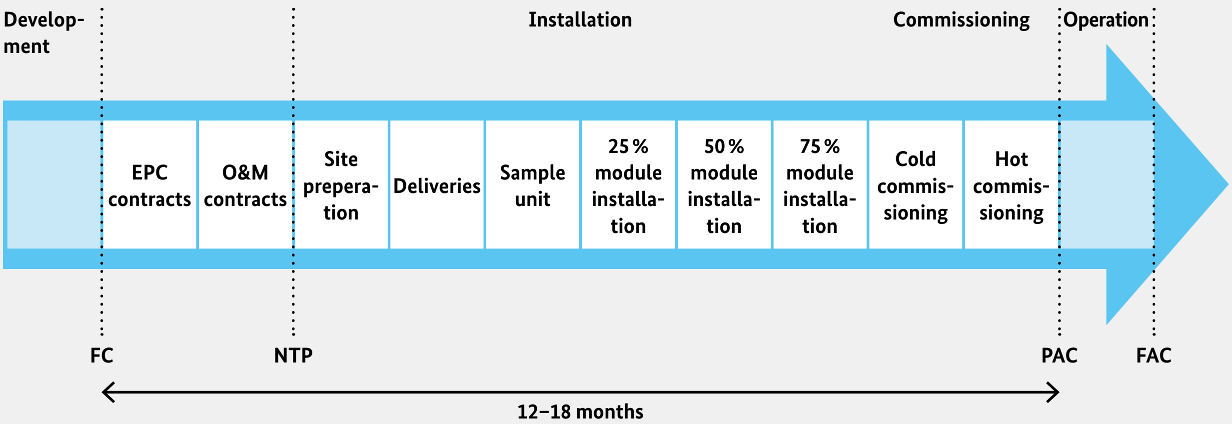
For this phase of the PV value chain, **testing** is relevant for ensuring the reliability of the PV system. Field testing on the component or string level can be carried out to check whether the system is functioning correctly. Different tests such as infrared thermography or electroluminescence imaging are used to identify PV modules with defects when a PV string or system does not demonstrate the expected performance. Additionally, continuous testing of the electrical output parameters is crucial for the monitoring of the PV system's performance. Such information must be combined with weather data to implement a long-term performance test using an actual-versus-expected energy comparison, as defined in the technical specification IEC TS 61724-3.

As mentioned above, personnel **certification** is an important service that provides confidence in the competency of service providers who operate or repair PV systems. Both personnel and organizations in charge of operation and maintenance can be certified.

Accreditation confirms the competency of quality infrastructure institutions, including certification and inspection bodies as well as testing and calibration laboratories. Situations in which the testing of components by an accredited testing provider may be required in combination with a third-party **inspection** include the investigation of system underperformance as part of a warranty claim.

Examples from case studies:

Developing a tool for lenders' technical engineers (LTEs) in India
In the PV project in India, PTB is cooperating with the Indian Renewable Energy Development Agency (IREDA) and other public financial institutions in the development of an assessment tool to support LTEs in the evaluation of a PV project during all its phases. This includes the contracts for the EPC, the construction/installation phase, and the operation and maintenance (O&M) phase after commissioning.



FC: Financial Close
NTP: Notice to Proceed
PAC: Provisional Acceptance Commissioning
FAC: Final Acceptance Commissioning

Figure 2: Overview of phases of a PV project from development to operation (source: PI Berlin)

The tool was developed by PI Berlin on behalf of PTB. To ensure the tool's alignment with the practical requirements of financial institutions and their LTEs, different versions of the tool were discussed with a working group of experts representing a broad range of relevant organizations in India. To support the application of the tool, LTEs were trained virtually and will soon also put the tool into practice at selected PV power plants (pilot phase). Afterwards, a final version will be distributed and may potentially find use in other countries as well.

Developing calibration services for current-voltage (I-V) curve tracers in Mexico
As part of the PTB project on *Strengthening Quality Infrastructure for Renewable Energies and Energy Efficiency* in Mexico, a participatory process to identify and address quality issues in the PV value chain was carried out in 2019. Private sector representatives highlighted the importance of regularly calibrating I-V curve tracers, which are used to check the performance of PV modules or strings as part of the quality control of PV components and installed systems. To respond to this need and to help ensure the reliability of I-V curve measurements, the PTB project supported the National Metrology Institute of Mexico (*Centro Nacional de Metrología*, CENAM) in establishing a calibration service for I-V curve tracers.

Promoting the implementation of standards with an evaluation guide for PV systems in Indonesia
In Indonesia, the PTB PV project is supporting the Ministry of Energy and Mineral Resources in developing a guide for the evaluation of PV systems. It is a step-by-step guide based on the applicable international standards and provides information on using performance ratio data and field testing to assess a PV system and determine its maintenance and repair needs.

2.2.5. Grid integration and storage

Opportunities and risks related to safety, quality and sustainability
To harness their full potential, PV systems are usually connected either to the grid or to a storage system. When more electricity is generated than is needed at a specific moment, this surplus can then either be fed directly into the grid or stored for later use. The electricity can be subsequently utilized by consumers connected to the grid, or, in off-grid systems, taken from storage when power demand exceeds the amount of power currently being generated. It is also possible for a system to feed electricity both into the grid and to a storage system. This allows excess electricity to be stored when the grid is not able to absorb additional electricity from a fluctuating source. At the same time, the stored electricity can be used for grid stabilization, for instance as a backup during demand peaks.

Grid quality can be affected when electricity provision is decentralized. For instance, the load of harmonics may increase, and the voltage may exceed the maximum tolerable at some grid points. When a feed-in system is connected at a grid connection point located far from the transformer, for example, the voltage gradient may be reversed. A loss of grid quality can affect other components in the grid, such as transformers or electric and electronic end user appliances, as it leads to accelerated aging of the equipment. In addition, power outages can occur if the grid is not stable and the demand and supply of electricity not balanced. In the worst case, the transmission lines in a grid segment may experience an overload and shut down. So before electricity from PV systems is fed into the grid, the necessary regulatory framework needs to be developed and the grid codes adapted to ensure that the grid will continue to function adequately even if the quantity of fluctuating feed-in continues to expand.

PV inverters can support an adequate grid management with services like the provision of reactive power or frequency and load following. As such, PV systems may be able to contribute to grid stabilization, since electronic inverters can reduce grid impedance by balancing the voltage and frequency of the grid. Grid codes and the necessary regulations offer an opportunity for improving the overall electricity system while at the same time smoothly integrating PV. This is particularly true when PV systems are planned and installed where grid codes are insufficiently developed or do not yet exist.

Power storage is particularly important in off-grid PV systems and is often implemented in emerging and developing economies where PV systems are used for the electrification of rural or remote areas that are not connected to the grid. As mentioned in 2.2.4., one major challenge in such settings is the maintenance and repair of PV systems. In many cases, batteries pose problems for the users of such PV systems as they have a shorter lifetime than the other components. Specifically, this can result in electricity being lost and the system not being able to cater to users' needs when the charging capacity decreases with time and the battery is not replaced. An opportunity in this context lies in giving a second life to electric vehicle batteries. When such batteries can no longer be used in vehicles because they have lost the ability to provide or absorb the necessary high currents (e.g., due to increased internal resistance), it is possible to reuse the battery cells in PV storage systems.

Required quality infrastructure services

International **standards** for batteries and secondary use batteries are available (e.g., IEC 60896 *Stationary Lead-Acid Batteries* or IEC 61427 *Secondary cells and batteries for renewable energy storage – General requirements and methods of test*). Also, information regarding grid integration is found in international standards (e.g., IEC 61727 *Photovoltaic (PV) systems – Characteristics of the utility interface* or IEC 62446-1 *Photovoltaic (PV) systems – Requirements for testing, documentation, maintenance – Part 1: Grid connected systems – Documentation, commissioning tests and inspection*). The Institute of Electrical and Electronics Engineers (IEEE) standard 1547 *Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power System Interfaces* provides additional guidance. However, national grid codes are crucial for grid integration and are often not sufficiently developed. Representatives of the national quality infrastructure institutions should be consulted during the development or revision of national grid codes to ensure that relevant aspects of international standards are considered and the necessary metrological, testing, certification, inspection and accreditation services can be developed accordingly.

A wide range of **metrological** services are necessary for grid integration and the storage of electricity generated by PV systems. Measurement devices for the PV system itself as well as for the grid and the storage system need to be regularly calibrated or verified[36] to ensure traceability and measurement accuracy. While basic services such as the verification of electricity meters are also widely available in emerging and developing economies, more sophisticated metrological services still need to be developed. For example, grid impedances can be measured to find out how much electricity can be fed into the grid before a critical limit is reached. This may be necessary for developing or emerging economies if the grid was developed ad hoc and the information available is insufficient to calculate grid impedances. Furthermore, advanced measurement frameworks are required, among other things, to calibrate the supervisory control and data acquisition (SCADA) systems used in PV power plants, to calibrate the phasor measurement units (PMUs) used to manage the grid, and to characterize (used) batteries. For many of the metrological services needed for this stage of the PV value chain, research and development efforts are ongoing internationally, and most emerging and developing economies do not yet offer such services (see 2.3.).[37]

Testing for new and secondary use batteries is important to ensure compliance with the international standards. **Certification** of batteries is also available. For grid-connected systems, tests and an **inspection** of the PV system need to be performed during commissioning (see 2.2.3.) before electricity can be fed into the grid. Commissioning surveillance is also among the certification services offered for PV systems.

Accreditation at this stage of the PV value chain is relevant to ensure the competency of testing and metrological laboratories and certification and inspection bodies.

36 Verification is performed as part of legal metrology. For example, the verification of electricity meters is required by law.

37 EURAMET (2015)

Examples from case studies:

Establishing traceability for phasor measurement units (PMUs) in Brazil
In order to upgrade grid monitoring and increase grid stability – among other things to handle increasing amounts of fluctuating renewable electricity, for example from wind or solar PV being fed into the grid – the Brazilian national grid operator installed PMUs in their lines. These devices allow the operator to measure the magnitude and phase angle of voltage or current and thus identify mismatches between supply and demand or synchronization issues which can cause a loss of power quality or result in power outages.[38] The PTB project in Brazil *Strengthening Quality Infrastructure for Renewable Energies and Energy Efficiency* supported the metrology department of the National Institute for Metrology, Quality and Technology (*Instituto Nacional de Metrologia, Qualidade e Tecnologia*, INMETRO) in establishing traceability for these devices. By regularly calibrating the PMUs, the grid operator can ensure the reliability of the measurement devices and hence of its grid monitoring system.

Revising the grid code to facilitate feeding PV electricity into the Mexican grid
In Mexico, the PTB project provided technical expertise to support the grid integration of renewable energies. Relevant stakeholders, including the National Metrology Institute of Mexico (*Centro Nacional de Metrología*, CENAM), came together to revise the grid code, specifically defining the necessary details regarding parameters for power quality.

38 U.S. Energy Information Administration (2012)

2.2.6. End of life, reuse and recycling

Opportunities and risks related to safety, quality and sustainability
As the use of PV systems for electricity generation increases, so too does the number of PV components used worldwide. Once their useful phase comes to an end, these components need to be managed to ensure the efficient use of resources, prevent toxic waste, and consequently increase the sustainability of PV systems over the entire life cycle. These are aspects that have to be considered early on in the component design process. Improving recyclability and emphasizing the circularity of PV components may result in trade-offs regarding the longevity of the components and their resistance to extreme weather conditions. Such considerations may also increase the price of the components. Official eco-design policies could give industry the necessary impulse to make progress in this area. So far, however, it has been left to private businesses to launch initiatives on eco-design, with limited success as only a few manufacturers are addressing the issue (see section 2.2.1. above).

Such policies are also key in directing the course of end-of-life management for PV components. While some industrialized countries and regions, including the EU, the United States and Japan, have already put forward legislation, a legal framework for end-of-life management is still lacking in many emerging and developing economies. To complement national or regional efforts, the issue could also be addressed on a local level by initiating municipal projects and providing specific guidance to PV practitioners.

Among the components subjected to end-of-life management, PV modules are of principal focus as they are used in greater quantities than inverters or batteries. They also have the longest lifetime of all components. This very longevity explains why end-of-life management has only recently become an important topic in the relatively young PV sector worldwide.

A number of module recovery and recycling initiatives, such as PV Cycle or PVEX, have been in operation for several years now. Their business models, however, have been challenged by falling prices for raw materials such as silicon and for PV modules themselves, as well as by the relatively low quantities of recyclable components, making it difficult to optimize logistics and other cost factors. While low prices remain an issue that make the recovery of materials for reuse economically less attractive, the availability of PV modules for recycling is steadily increasing. This works to improve the cost structure and the financial viability of recycling businesses and has also given rise to local waste management solutions in some countries.

As regards batteries, the recycling of lead-acid batteries is common worldwide, given the value of the lead and the good prices that can be obtained for old batteries and extracted materials. However, if the recycling process is not carried out correctly, lead poses a high risk to human health and the environment, making lead-acid battery recycling one of the most polluting industries on the planet. Lithium-ion batteries, which are increasingly used in storage solutions for PV systems, are more complex and have a lower recycling value, with cobalt and nickel attracting the greatest interest. Currently, only a very low percentage of Li-based batteries are recycled, with figures especially low in developing and emerging economies.[39]

Instead of recycling, the reuse of PV components might be an option in some cases. This represents a great opportunity for increasing the lifetime of the components and reducing waste. However, the quality of second-hand components needs to be ensured to reduce safety risks and avoid damaging the technology's reputation.

Required quality infrastructure services

Quality infrastructure does not yet play an important role in this phase of the PV value chain; both the demand for services from the PV sector and the specific services offered remain very limited. The relevance of quality infrastructure is currently far greater in ensuring the longevity of components and thus postponing this final stage of the value chain (see previous sections). Nevertheless, quality infrastructure has the potential to contribute to an appropriate end-of-life management as well.

When it comes to the reuse of PV modules, minimum quality criteria still need to be defined. **Standardization** could help ensure that safe and functioning modules are available for use, for instance following module repair. International standards have also not yet been developed to govern the recycling of PV components. In Europe, however, Best Available Techniques Reference Documents (BREF) have been issued by the European Integrated Pollution Prevention and Control (IPPC) Bureau as a guide to service providers involved in waste treatment processes. A standard for responsible recycling is also being developed by the EU. In the US, the Sustainability Leadership Standard for PV Modules and PV Inverters, NSF/ANSI 457, also deals with end-of-life management.

Testing is carried out to assess the risk of hazardous materials leaching from PV waste. It is also used to determine the purity of the recovered material in the recycling process. Here, **calibration** services are needed to ensure the accuracy of the measurement equipment used in the recycling process and for testing. Moreover, testing and calibration could become important for the characterization of PV components for reuse, for instance after repairs are carried out, but this is far from being common practice.

Certification that takes account of sustainability aspects, including end-of-life management, is available for PV components. For example, a certification of the carbon footprint of PV modules is available in France and is required for participation in some auctions by the French Energy Regulatory Commission (*Commission de Régulation de l'Energie*, CRE). Once the above-mentioned EU standard on responsible recycling has been developed, the respective certification for recycling facilities will also be available.

39 GIZ (2018)

2.3. Requirements for the further development of global quality infrastructure services

The previous sections have shown that quality infrastructure offers a vast array of services for the PV sector. However, some gaps still persist on a global level. This section provides an overview of aspects that need to be developed further at the international level.

Standardization

One key challenge on the path to international standardization is to define criteria that are sufficient to ensure safety, sustainability and performance but at the same time avert high production and development costs that would hinder the further development of the PV sector, especially in emerging and developing economies.

The International Electrotechnical Commission (IEC) is the most important international player when it comes to standardization in the PV sector. The technical committee IEC TC 82 *Solar Photovoltaic Energy Systems* is one of the most active technical committees of the IEC and has developed many standards for all steps in the PV value chain. Although the TC counts 43 participating countries, emerging and developing economies tend to participate less actively and are less represented. That is why standardization for PV has traditionally been led by the industrialized economies of Europe and North America. The active participation of emerging and developing economies needs to be encouraged so that their specific requirements and conditions can be considered during standards development and revision.

Following the initial development of the PV sector, international standardization has traditionally been divided into two zones: Europe, led by the IEC; and the US, led by Underwriters Laboratories (UL) (e.g., for safety standards) and ASTM International (formerly known as the American Society for Testing and Materials). Due to this division, existing international standards are often not sufficiently harmonized and adherence to the standards of one or the other standardization body becomes a political question coupled with concrete economic interests. For example, US manufacturers of thin film modules may have easier market access if the importing country requires certification to US standards. These differences have decreased in recent years as the IEC and UL foster the harmonization of international PV standards. As a result, US-specific standards like UL 1703 on module safety are being replaced over time with the publication of new UL standards that have been harmonized with the IEC.[40]

Another issue is that due to the time needed for standardization processes, international standards to a certain degree lag behind developments in industry. This is aggravated by the fact that once an international standard is published, it still needs to be adopted into the national standards collection, often undergoing time-consuming translation processes into different languages. In the case of dynamically developing technologies such as PV, this means that standards reflect the status of the industry several years back, and thus need to be regularly updated. Given the often-limited capacities of national technical committees, this forces countries to give priority to the standards that are most relevant to them, leading to further delays in the adoption of other standards.

There is disagreement on the question of whether the most important aspects for quality in PV are covered by the existing standards. While some experts state that the existing collection is sufficient, others highlight the need for defining additional requirements to ensure, for instance, the longevity of PV modules. With IEC TR 63279 *Derisking photovoltaic modules – Sequential and combined accelerated stress testing*, published in August 2020, and IEC TS 63209 ED1 *Extended-stress testing of photovoltaic modules*, this topic is being addressed. The International Photovoltaic Quality Assurance Task Force (PVQAT) is also working on this topic by developing a rating system for PV modules according to their durability under a variety of stresses.[41] Other areas where standards could be further developed include PV plant commissioning, mounting structures, new PV applications such as agrivoltaics, and the end-of-life phase of PV projects.

Currently, international standards on the repair and reuse of PV modules are still not sufficiently developed. PVQAT has established a task group on the reuse, repair and recycling of PV power plants. Following international discussions on standardization in this area, the topic could in future be taken up by the IEC.

40 For example, UL 1703 is being replaced by the UL 61730 standard, which is based on IEC 61730 and includes US national differences.

41 PVQAT (2020)

On the whole, the greatest challenge in the standardization of PV worldwide lies in the actual implementation of standards. Progress here depends largely on the actions of local industry. Where the industry itself is driving the standardization processes, the implementation of standards is usually not an issue. However, in many emerging and developing economies, local industry is not sufficiently involved and sees standards as a burden rather than as instruments of support. Also, standards are not sufficiently referenced in public tenders, government programmes, or contracts. Beyond that, awareness raising and education are needed to foster the voluntary implementation of standards.

In this context, a policy often followed in emerging and developing economies is the definition of quality criteria for the PV sector in technical regulations. As regulations are developed by the responsible ministries and are mandatory, they would appear to be an appropriate way to quickly increase quality in the sector. However, experience shows that the mandatory definition of quality criteria is in most cases neither effective nor efficient. According to the Agreement on Technical Barriers to Trade (TBT) of the World Trade Organization (WTO), technical regulations shall not be created or applied with a view to creating unnecessary obstacles to international trade. To achieve this, technical regulations in the PV sector must be limited to *legitimate objectives*, such as national security, protection of human health or safety, animal or plant life or health, or the environment.[42] Furthermore, technical regulations should be limited to the general requirements. For detailed technical criteria, standards, which can be easily updated to reflect the current requirements, should be referenced.

Metrology

In the area of metrology, establishing traceability for the parameters that are most relevant in the PV sector is a major challenge in most emerging and developing economies. It is a political decision as to which national standards and primary and secondary metrological services should be developed by the national metrology institutes (NMIs) and secondary calibration laboratories in the country and which can be purchased from metrology laboratories abroad. This decision should be informed by assessing the sector's current and potential demand for such services in the country.

Besides these generic aspects, specific metrological services need to be developed further to fulfil the current and future demands of the PV sector, a selection of which are described below:

- One important issue in electric grids with multiple decentralized sources is harmonic oscillation, which can lead to aging effects in the grid. The related measurement standard still needs to be developed.
- Electronic inverters can contribute to stabilizing the grid, an important aspect especially in emerging and developing economies. Traceability for these inverters can currently not be provided in all relevant parameters.
- In general, metrological services for the characterization of batteries need to be further developed. This would include requiring these services to evaluate the recyclability of batteries that were used, for example, in electric vehicles, and are to be reused in energy storage facilities.
- In sector coupling technologies, such as power to gas, improved methods for measuring efficiency have to be developed.
- The increasing use of high-current DC switchgear necessitates the application of new metrological services. Additionally, metrological services required in the operation and maintenance phase need to be further developed in order, for example, to measure the electric insulation capability of modules and PV systems.

Testing

The biggest technical question in PV testing is seen in the relation between testing results and long-term performance. Currently, testing services cannot predict with sufficient certainty how PV power plants will perform in 20 or 25 years. The testing of different parameters, especially those of PV modules, is well defined in the relevant IEC standards. However, it is difficult to predict what the concrete impact of the parameters will be on the performance of PV modules well into the future. In addition, the problems known to occur in PV modules are well covered in the testing methods applied, but it is not clear if all possible issues are covered. In this context, testing laborato-

42 WTO (2021)

ries play an important role in contributing to the continuous improvement of PV components by identifying how products may be improved based on testing results (such as those needed to obtain a certification) and developing testing methods for new issues that may arise.

Another international challenge is to further increase the efficiency of quality assurance provided by module testing. This could be achieved by reducing the number of module samples tested after production, while at the same time strengthening the quality assurance mechanisms (mainly testing and certification) during the manufacturing process of PV cells and modules. Currently, a committee led by ASTM[43] is working on the sampling procedure for PV modules to make sure that the sample is representative for the module type.

For the testing providers, the financial viability of their services is a major issue. The installation of a testing laboratory according to the IEC standards for module testing typically requires an initial investment of approximately 1 to 2 million euros, and high maintenance costs must also be considered. Even in countries with a well-developed PV sector, the testing providers struggle to cover these costs over time. This consideration is especially important for emerging and developing economies that plan to install their own module testing laboratories: If modules are produced nationally, there may be a demand for testing as part of quality control during manufacturing, for product certification, and for R&D. It is important to carefully evaluate whether there is sufficient demand to cover the costs for new module testing laboratories able to perform all the tests required in the IEC standards, or whether the focus should be on a selection of tests that are most in demand.

One area to be further developed is the testing of modules with regard to their environmental impact. Testing for leaching of hazardous materials from a PV module produces a very broad range of results, depending on where and how a sample from a module is taken. In this area, new testing methods must be developed and standardized.

Certification

In the area of certification, one important area requiring further development concerns the certification schemes for PV installers and other service providers. There are several national approaches, but effective and internationally recognized schemes for certifying that service providers have the required competency are currently lacking.

In the area of PV system certification, certification bodies have developed approaches that are specific to their organization. An internationally recognized certification scheme for PV systems does not exist at present. The technical committee of IECRE (IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications) is currently working on a certification scheme for renewable energy systems, but with the focus on wind power.

In this context, the Certification Body (CB) Scheme operated by the IEC System of Conformity Assessment Schemes for Electrotechnical Equipment and Components (IECEE)[44] competes with privately developed certification schemes. IECEE CB is based on a multilateral agreement among participating countries and certification organizations aimed at achieving broader application and mutual recognition and hence reduced costs for the sector, as a product tested and certified in one country is accepted in other countries as well. In practice, many countries do not recognize such certificates and require specific national certifications, among other things to protect their market from more competitive imports.

As current practice shows, another general issue is that certification criteria are not applied with the same rigour in all countries and by all certification bodies. This works to hinder the international recognition of certificates. In this context, the quality assurance mechanisms of certification bodies (including accreditation) must be improved further.

43 ASTM International, formerly known as the American Society for Testing and Materials, is an international standards organization that develops and publishes technical standards for a wide range of materials, products, systems and services.

44 Operated by the IEC System of Conformity Assessment Schemes for Electrotechnical Equipment and Components (IECEE), the IECEE CB Scheme is an international system for mutual acceptance of test reports and certificates dealing with the safety of electrical and electronic components, equipment and products.

Accreditation
The international recognition of accreditation bodies and related mutual recognition schemes are designed to ensure the technical competency of PV testing laboratories and certification and inspection bodies by applying the same recognized criteria and procedures internationally. Important steps to improve the international recognition of quality infrastructure services for PV and ensure that these services are competently delivered therefore include the active participation of accreditation bodies in regional and international accreditation organizations, the organization of peer evaluations, and the establishment of mutual recognition agreements.

The PV sector is a relatively new field for most accreditation bodies in developing and emerging economies. Even where mutual recognition agreements exist, collaboration with experienced accreditation bodies specifically in this sector can help to harmonize the interpretation and application of international standards. Additionally, more capacity development programmes for accreditation assessors and technical experts in the PV sector are needed. Currently, there is a lack of assessors and technical experts with sufficient expertise and experience in PV, especially when accreditation is carried out in the local language. For example, there are only few French-speaking assessors with relevant experience in PV, and waiting times for the accreditation of PV laboratories may be long. The limited pool of local assessors or technical experts in emerging and developing economies may also result in potential conflicts of interest, if, for example, the only assessor or expert available comes from a main competitor.

Transversal
New PV techniques and applications, such as floating PV power plants, agrivoltaics and bifacial PV modules, are becoming increasingly relevant and will require new quality infrastructure services that have yet to be developed.

More information is needed on the profitability of investments in quality infrastructure services. Obtaining this information requires better power plant monitoring and the execution of pilot studies to evaluate specific profitability scenarios.

3. Supporting Quality Infrastructure According to the Situation of the PV Sector and to National Conditions

Based on the experience gained in projects implemented by PTB in emerging and developing economies in Africa, Latin America and Asia, this section describes the recommendations pertaining to the development of the quality infrastructure required to ensure the safety, quality and sustainability of PV systems. The section starts with general recommendations and moves on to highlight aspects to be considered within specific contexts. It concludes with recommendations for the development of quality infrastructure services.

3.1. General recommendations

General recommendations for the development of the quality infrastructure required by the PV sector can be summarized as follows:

Support the quality infrastructure alongside with the development of the PV sector

The development of the PV sector requires a systematic consideration of quality assurance. Different options exist (see section 3.3. below), but quality infrastructure must in all cases be treated as an integral part of the development of the PV sector. Experience has shown that countries tend to undergo a learning curve: After a boom in the PV sector, awareness for the importance of quality assurance usually increases as cases of underperformance of installed power plants emerge. Countries developing their PV sector today can learn from this experience and integrate the necessary quality infrastructure early on. In this way quality deficiencies and the risk of damaging the reputation of PV technology can be reduced.

Take a holistic approach to the development of quality infrastructure

National quality infrastructure is an interrelated system in which the components and the regulatory framework complement one another. Consequently, they need to be developed together in order to be coherent and functional.

Moreover, national quality infrastructure should not be developed in an isolated way but rather linked to the international system by establishing the respective relations: to ISO and IEC for standardization; to BIPM and OIML for metrology and legal metrology; to IAF and ILAC for accreditation; and to the various regional organizations.

Develop an appropriate policy framework

The policy and regulatory frameworks are an integral part of the quality infrastructure system and influence both the supply of and demand for quality infrastructure services. The development of concrete quality infrastructure services should therefore be complemented by appropriate policies and regulations. Public policies and programmes should include objectives and criteria related to quality in the PV sector and make reference to quality infrastructure services. Furthermore, quality criteria and the relevant standards should be specified in public tenders, contracts and government programmes. At the same time, the inclusion of detailed quality criteria in technical regulations should be avoided. Such mandatory requirements that go beyond safeguarding human health and safety or the environment are not aligned with international best practice and WTO TBT agreements. Moreover, experience shows that mandatory requirements often fail to be implemented due to a lack of enforcement, while an inclusion of quality criteria in tenders, contracts and government programmes leads industry actors to proactively demonstrate that they comply with the requirements.

Foster awareness and information sharing

It is particularly important to implement effective measures to raise awareness and to inform relevant stakeholders about the benefits of the systematic consideration of quality, safety and sustainability aspects in the PV sector. Such measures should include information about existing standards and describe successful approaches in other countries. For example, studies demonstrating the benefits of investing in higher quality compared to the economic risks of underperforming PV plants can contribute significantly to raising awareness among national stakeholders.

Support exchange and cooperation between the national PV sector and the quality infrastructure organizations

The governments of emerging and developing economies should support exchange and cooperation among PV sector and quality infrastructure stakeholders in order to create awareness and foster applied approaches to quality assurance. Improving interaction between these players is crucial because they operate in different areas and normally do not exchange views on a regular basis. Well organized engagement processes among the relevant stakeholders serve to bring related programmes and strategies into alignment, lead to innovative approaches, and create productive relations over the long term, all of which promote quality in the sector.

Define specific priorities depending on the national context

The development of quality infrastructure should be aligned with the concrete needs in the country. These depend on the development status of the quality infrastructure itself, as well as on the current situation and plans for the development of the PV sector (see section 3.2. below). To assess the priorities, current and potential users of quality infrastructure services should be consulted regularly, with consideration given to both the financial viability and the potential impact of services to be developed. It is also advisable to evaluate whether services are already available in neighbouring countries and can thus be easily accessed in the region. If so, there may be no need to develop these services nationally.

Base quality assurance approaches on existing international procedures

The vast experience gained in and the previous efforts put into PV quality assurance worldwide have culminated in the development of international standards and best practice procedures. Instead of working on entirely new national approaches, reference should be made to what is already available. If needed, international standards and best practices can be adapted to a specific country context. Given the global nature of the PV market, international standards and procedures are the best vehicles for fostering global compatibility and effectiveness in an efficient manner.

Participate in international forums and organizations

To gain easier access to such international approaches, emerging and developing economies need to engage actively in international forums and organizations. Moreover, their participation in regional and international quality assurance organizations and networks, such as IEC Technical Committee 82, allows them to contribute their perspective and ensure that the specific requirements and conditions of their countries are reflected in international standards. This is particularly relevant due to the significant development of the PV sector in emerging and developing economies in recent years.

3.2. Aspects to be considered in planning quality infrastructure development

Ensuring safety, quality and sustainability along the PV value chain requires systematic support for the development of the national quality infrastructure. To be effective, policy support and public investments must be focused on the most relevant structures and services and take account of the specific national context and sector requirements.

PTB's experience shows that two key aspects should be considered by quality infrastructure organizations and policy makers when planning the necessary development: first, the national strategy for the PV sector and the resulting policy focus for the development of the national quality infrastructure; and second, the stage of PV sector development.

Policy focus for the development of quality infrastructure

The policy focus for the development of the national quality infrastructure should be based on the national strategy for the development of the PV sector. The related options can be summarized as follows:

- **Market surveillance of imported components:** The development of the PV sector can be based on the importation of the required components. If this option is chosen, quality infrastructure services are needed to support the market surveillance of imported components. As most quality issues occur during installation, a sole policy focus on market surveillance should only be considered as transitional, creating the foundation for more advanced quality assurance systems.

- **Quality assurance of imported components and PV plants:** Economies which do not aim to establish a local manufacturing industry but nevertheless want to promote the national PV sector may take a more comprehensive approach to quality assurance, combining the market surveillance of imported components with quality infrastructure services for PV plants.

- **Quality assurance of imports, national manufacturing, and PV plants:** Economies with a higher degree of industrialization and more ambitious objectives for the development of the national PV sector tend to include the development of PV component manufacturing in their policies. This approach results in higher demands pertaining to the development of the quality infrastructure, such as advanced quality assurance for domestic manufacturing, often also including research and development. But PV plant quality assurance and market surveillance remain relevant and also need to be established if this option is pursued.

Stage of sector development

Besides the policy requirements, the second aspect to be considered when planning the support of the national quality infrastructure is the degree of development of the PV sector. A mature sector built on several years of development requires a broad range of quality infrastructure services and generates the critical volume of demand needed to sustainably offer these services. By contrast, a PV sector at an initial stage of development requires fewer and more basic services. Here, the demand for services is often not sufficient to cover the costs of establishing national quality infrastructure institutions, necessitating – at least for a transition phase – either cooperation with foreign service providers or public funding of both the initial investment for establishing the services and the maintenance costs.

3.3. Guidance on the development of quality infrastructure according to the national context

The definition of the policy focus for quality infrastructure development and the consideration of the stage of PV sector development provide policy makers and quality infrastructure institutions with a clear picture of the relevant national context. Based on these key aspects, measures for the development of the required structures and services can be defined. The figure below describes the possible combinations. In the following section, recommendations are given for the three highlighted example scenarios.

Policy focus for QI development	Stage of sector development: Early	Intermediate	Mature
Manufacturing and PV systems	Not probable as the demand for QI services is too low for the development of advanced services.	Applicable for economies with a focus on supporting the further development of the PV sector towards a mature stage.	**Example scenario 3** Development of an advanced national quality infrastructure for PV, quality assurance along the entire PV value chain.
Imported components and PV systems	Viable with high public investment as the demand for QI services is low.	**Example scenario 2** Development of the national quality infrastructure with focus on market surveillance and quality assurance of PV systems.	Applicable for economies with a mature PV sector but without PV manufacturing.
Market surveillance of imported components	**Example scenario 1** Quality assurance with focus on market surveillance and foreign quality infrastructure services.	Applicable for economies in a transition stage to the inclusion of quality assurance of PV systems.	Not probable as the mature PV sector requires more advanced QI services.

Figure 3: Three example scenarios for the positioning of the national quality infrastructure (source: the authors)

3.3.1. Scenario 1: Quality assurance with focus on market surveillance and foreign quality infrastructure services

For economies with a PV sector in an early development stage and focusing on the quality assurance of imported components, the following recommendations can be defined:

Recommendations on market surveillance

1. Establish effective structures and processes for the market surveillance of imported components based on the review of the product documentation and the recognition of foreign product certificates.

The basis of quality assurance in this scenario consists of effective structures and processes for the market surveillance of imported components. In this context, economies should ensure that the following general requirements for market surveillance[45] are met:

- The legal basis required for market surveillance is defined in national legislation.
- Market surveillance authorities have the necessary power, resources and knowledge to perform their functions.
- Imported PV components are effectively monitored in the national market.
- Marking and documentation requirements defined in legislation are respected.
- Components are designed and manufactured in accordance with international standards.
- Procedures are put in place for following up on complaints.
- The functioning of surveillance activities is reviewed and assessed periodically.

Specifically for PV components, market surveillance in this scenario is based on the review of product documentation and the recognition of foreign product certificates. As the overall demand for quality assurance is low in this scenario, the testing of samples may not be required.

45 Based on the market surveillance requirements for EU countries: *https://ec.europa.eu/growth/single-market/goods/building-blocks/market-surveillance/organization_en*

2. Evaluate the option of establishing a national IECEE Member Body.

The IECEE (IEC System of Conformity Assessment Schemes for Electrical Equipment and Components) provides an international system for the mutual acceptance of certificates and test reports based on the international IEC standards. Economies adhering to this system ensure the international compatibility of their approach to quality assurance and create the basis for the internationally recognized certification of nationally produced components at a later stage of PV sector development.[46]

In this context and considering the policy focus in this scenario, it is recommended to evaluate the option of establishing a national IECEE Member Body whose scope includes the recognition of certificates for PV components.

Recommendations on regulations and public programmes

1. Regulate market surveillance, safety, and environmental criteria.

In this scenario, regulations are required to establish the legal basis for market surveillance (see above). Safety requirements for imported PV components must be regulated with reference to the relevant international standards. These can be complemented by environmental criteria for products. As described above (see section 2.2.6.), this is especially important with regard to the characteristics of PV modules in order to prevent hazardous waste at the end of use, but such regulations are internationally still in an early stage of development.

2. Define safety, quality and sustainability criteria in public programmes.

An effective approach to increasing the safety, quality and sustainability of the PV sector is to have the criteria applicable to imported components defined in public programmes that support the sector's development. Such criteria should be specified with reference to international standards. It is crucial to guarantee that conformity with such criteria can either be assessed by national testing laboratories and certification and inspection bodies, or that procedures exist to recognize certificates of conformity from abroad.

46 IECEE (2019)

Recommendations on services of the quality infrastructure

1. Plan for the quality infrastructure services required in future development stages.
As the demand for quality infrastructure services in this scenario is low, investments in the development of specific services for the PV sector would have relatively low impacts and would not be sustainable in most cases. However, it is recommended to include the development of these services in the initial planning, evaluating whether the national quality infrastructure is compliant with the general requirements for effective quality assurance and with a look ahead to future development stages (see the general recommendations in 3.1. and the description of the scenarios that follow below).

2. Adopt relevant international standards.
In this early stage, the adoption of relevant international standards into the national standards system fosters their recognition on the national level and makes it easier to cite them in national regulations and public programmes. This is particularly true if PV practitioners require a translated version in their local language because of limited proficiency in English or French. If language is not an issue, granting access to the relevant international standards even before they are included in the national standards system may be a helpful first step that the national standards body can undertake to accelerate the dissemination of knowledge about quality requirements in PV.

Recommendations on information, training and awareness

1. Increase information and awareness about the importance of quality infrastructure in the PV sector.
Already in this early stage, activities should be implemented to increase information and awareness about the importance of quality infrastructure for the PV sector. This is key to gaining the needed support from relevant stakeholders for the implementation of the quality assurance mechanisms required to achieve a systematic reduction of related safety, quality and sustainability risks.

2. Implement training programmes on safety, quality and sustainability aspects.
These information and awareness raising activities should be complemented by training programmes covering aspects of safety, quality and sustainability and aimed at people involved in the market surveillance of PV components, the implementation of public programmes, and the planning, installation, operation and maintenance of PV power plants. Such training programmes, which can be combined with personnel certification schemes in future stages (see below), can contribute significantly to the sustainable development of the sector.

3.3.2. Scenario 2: Development of the national quality infrastructure with a focus on market surveillance and quality assurance of PV plants

For economies with a PV sector in an intermediate development stage and a more comprehensive approach to quality assurance that includes both imported components and PV plants, the following recommendations can be defined:

Recommendations on market surveillance

1. Establish effective structures and processes for the market surveillance of imported components, complementing document review with sample testing.
The recommendations given for scenario 1 also apply to this context. As the demand for quality assurance is higher in a more developed PV sector, market surveillance based on the review of product documentation and the recognition of foreign product certificates should be complemented by the testing of product samples according to international standards. These tests can be conducted by accredited testing laboratories in neighbouring countries, as the number of tests required in this scenario will normally not be sufficient to justify developing and maintaining sustainable national testing capacities that comply with international standards.

2. Evaluate the option of establishing a national IECEE Member Body (see scenario 1).

Recommendations on regulations and public programmes

1. Regulate market surveillance, safety, and environmental criteria for imported components and PV power plants.
In addition to the areas to be regulated in scenario 1 as described above, a more comprehensive approach will further include the regulation of PV power plants. Examples of PV rooftop plants catching fire due to faulty installation highlight the relevance of such regulation. The regulation of safety aspects of PV power plants must be accompanied by the establishment of effective control mechanisms, something that requires an authority with the necessary powers, resources and knowledge. Even if such an authority exists, exercising control over smaller PV plants is normally challenging due to the high number of such installations. In this context, it is recommended to focus public control mechanisms on larger sized PV plants (size defined in line with the sector's stage of development). Additionally, the grid codes should be revised to prevent disturbances caused by the feeding of PV electricity into the grid.

2. Define safety requirements for PV installers and implement voluntary quality marks.
The safety, quality and sustainability of smaller PV plants can be fostered effectively by defining requirements and responsibilities for PV installers, and through voluntary approaches such as quality marks for components or ready-made PV systems, which increase transparency in the market.

3. Define safety, quality and sustainability criteria in public programmes (see scenario 1).

Recommendations on services of the quality infrastructure

This scenario requires a systematic development of the quality infrastructure with a clear focus on the services with the highest impact on the safety, quality and sustainability of both imported components and PV plants. Quality infrastructure services that are less needed and have a lower impact on the development of the national PV sector can be accessed via cooperation schemes with foreign quality infrastructure institutions. To define the priorities, opportunities and risks involved, and to determine which quality infrastructure services are most relevant, an examination of the value chain should be performed from market surveillance to end of life, reuse and recycling (see section 2.2. above).

The following recommendations cover the most relevant services identified in PTB projects in emerging and developing economies:

A. Standardization
1. Ensure active participation in relevant international technical committees.

2. Define priorities and adopt relevant international standards in national technical committees.

3. Promote the use of standards in the PV sector by raising awareness and providing guidance and support to PV practitioners.

B. Metrology
1. Develop metrology services (or provide access to services via foreign metrology laboratories) required for PV plant (and component) testing equipment and for plant and weather monitoring.
The following services are especially relevant for the PV sector in this scenario:
- Calibration of pyranometers
- Electrical characteristics: current and voltage
- Wind speed
- Temperature

C. Testing
1. Develop public testing laboratories where required, with particular consideration given to PV power plant field testing.

2. For sample tests of imported PV components, either cooperate with accredited laboratories in neighbouring countries or build up own capacities for those tests most in demand.

3. Support laboratory networks to align demand and supply and to coordinate activities of common interest (e.g., proficiency tests, calibration, standardization, training, marketing, policy advice).

D. Certification
1. Develop and promote certification schemes for personnel (especially engineers and installers), power plants, and operation and maintenance contractors.

2. Define "quality marks" for components of small PV plants and ready-made systems.

E. Inspection

1. Define inspection schemes with reference to international standards for the commissioning of PV power plants.

F. Accreditation

1. Provide access to internationally recognized accreditation services for testing laboratories and certification and inspection bodies by establishing cooperation with foreign accreditation bodies, as demand will in most cases not be sufficient to sustain the specific accreditation services required by the sector nationally.

Recommendations on information, training and awareness

1. Increase information and awareness about the importance of quality infrastructure in the PV sector (see scenario 1).

2. Implement training programmes on safety, quality and sustainability aspects (see scenario 1).

3. Implement online monitoring systems, including the quality assurance of the data generated by these systems, to identify quality challenges and generate awareness about the specific quality infrastructure services required.

Information on how actual performance compares to the planned output of PV power plants is crucial in identifying possible quality gaps. Various initiatives and options exist for the installation of online monitoring systems. To guarantee the quality of the data generated by such systems, the application of appropriate quality assurance mechanisms is essential. For example, pyranometers used in PV plants must be calibrated to ensure that electricity output is compared to accurate solar irradiation data.

Publications that are based on reliable performance data and that identify the reasons for underperformance can significantly help to increase awareness about quality issues in the sector. Furthermore, they can be the basis for the definition of the concrete quality infrastructure services required to overcome the quality issues identified.

3.3.3. Scenario 3: Development of an advanced national quality infrastructure for PV, quality assurance along the entire PV value chain

This scenario applies for economies with a well-developed PV sector covering the value chain from manufacturing to installation to operation and maintenance. This is combined with a policy to develop an advanced national quality infrastructure that is responsive to the high demand that exists in terms of both the variety and volume of services required.

For this scenario, the following recommendations can be defined:

Recommendations on market surveillance

1. Establish effective structures and processes for the market surveillance of imported and nationally manufactured components, complementing document review with sample tests in national testing laboratories.
As the demand for quality assurance is high in this scenario, market surveillance based on the review of product documentation and the recognition of foreign product certificates (as described in scenarios 1 and 2) should be complemented with tests of product samples performed according to international standards. The most highly demanded tests should be performed in national testing laboratories, while specific tests of low demand can be conducted by accredited testing laboratories abroad. In this scenario, both imported components and nationally manufactured components are subject to market surveillance.

2. Evaluate the option of establishing a national IECEE Member Body and a National Certification Body.
Besides the establishment of a national IECEE Member Body (as described for scenarios 1 and 2), the development of a National Certification Body recognized under the same scheme should be considered, as it gives domestic manufacturers access to internationally recognized IEC certificates for their components. The National Certification Body must be approved by the IECEE Member Body and undergo a recognition process by the IEC.

Recommendations on regulations and public programmes

1. Regulate market surveillance, safety, and environmental criteria for components, manufacturing and PV power plants.
In this scenario, regulations must define safety and environmental requirements (such as worker safety and environmental management) for domestic manufacturers, imported components and PV power plants. As explained in scenario 2, this must be accompanied by effective control mechanisms, which in turn requires an authority with the necessary powers, resources and knowledge.

2. Define safety requirements for PV installers and implement voluntary quality marks (see scenario 2).

3. Define safety, quality and sustainability criteria in public programmes (see scenarios 1 and 2).

Recommendations on services of the quality infrastructure

This scenario requires an advanced level of quality infrastructure development in order to satisfy the high demands of a well-developed PV sector.

The services required are summarized above. The following recommendations highlight the most relevant aspects:

A. Standardization
1. Ensure active participation in relevant international technical committees (see scenario 2).

2. Adopt all relevant international standards and define required modifications in national technical committees.

3. Promote the use of standards in the PV sector (see scenario 2).

B. Certification
1. Evaluate the option of establishing a National Certification Body under the IECEE scheme.

2. Develop and promote certification schemes for manufacturing, personnel (especially engineers and installers), power plants, and operation and maintenance systems.

3. Define "quality marks" for components of small PV plants and ready-made systems (see scenario 2).

C. Testing
1. Develop public testing laboratories where required, with particular consideration given to the requirements for research and development, quality assurance during production, and PV power plant field testing.

2. For sample tests required for the market surveillance of imported and locally manufactured components, build up national capacities for those tests most in demand.

3. Support laboratory networks to align demand and supply and to coordinate activities of common interest (e.g., proficiency tests, calibration, standardization, training, marketing, policy advice) (see scenario 2).

D. Inspection
1. Define inspection schemes with reference to international standards for plant inspections during construction, commissioning, grid integration, and operation and maintenance.

E. Metrology
1. Develop the most relevant metrology services required along the entire PV value chain, i.e.:
The following services are especially relevant for the PV sector in this scenario:
- Calibration of pyranometers
- Irradiance level and spectral irradiance of the light source
- Electrical characteristics: current and voltage
- Temperature
- Wind speed
- Humidity
- Conductivity
- Advanced measurement frameworks for SCADA systems, phasor measurement units, battery characterization.

F. Accreditation
1. Develop internationally recognized accreditation services for laboratories and inspection and certification bodies in the PV sector.

2. Develop the capacities of lead evaluators and technical experts for accreditation processes in the sector.

Recommendations on information, training and awareness

1. Increase information and awareness about the importance of quality infrastructure in the PV sector (see scenario 1).

2. Implement training programmes on safety, quality and sustainability aspects (see scenario 1).

3. Implement online monitoring systems, including quality assurance of the data generated.

4. Use the data to identify quality challenges and to generate awareness about the specific quality infrastructure services required.

4. Conclusion

Safety, quality and sustainability challenges constitute barriers to the development of the PV sector. Quality infrastructure services are required along the PV value chain and need to be developed nationally and globally to overcome both persistent and new challenges. The experience gained in projects implemented by PTB shows that it is crucial – especially in developing and emerging economies – to support the national quality infrastructure alongside with the development of the PV sector. By following the recommendations for action in this area, policymakers and quality infrastructure institutions can lay the foundation for the sustainable growth of this sector.

Annex A – Case Studies

Case study – Strengthening Quality Infrastructure for Renewable Energies and Energy Efficiency in Brazil

Situation in the partner country

While renewable energies, and hydropower in particular, have always played an important role in the Brazilian energy mix, the PV sector has been quite slow to develop. For a long time, the technology could not compete on price and as such was not competitive in the bid-based Brazilian energy market. However, the 10-year energy expansion plan from 2017 (*Plano Decenal de Expansão de Energia*, PDEE 2027) indicated a willingness to increase solar PV capacity in the country to a targeted 8.6 GW of installed capacity by 2027.[47] Since then, PV capacity has been rapidly growing and by July 2020 a total of 6 GW had already been installed with a more or less equal share of centralized (48 %) and distributed (52 %) PV systems.[48]

Besides the price, bureaucracy has also had a negative influence on the development of the PV sector. Changing regulations and requirements, especially those affecting the import of PV components, created an uncertain investment climate. Recent efforts to reform the system and lower the bureaucratic hurdles have improved the situation. Import permits for PV components can now be requested online and are granted within five working days at the most. PV modules are also available locally, but the manufacturing industry in this sector remains small.

Quality does not appear to be an important issue in the Brazilian PV sector. For most PV systems, especially when international investors are involved, international know-how and quality assurance services are used. The national quality infrastructure offers only few PV-specific services and there has so far been too little demand to justify expanding the services.

47 *https://www.renewableenergyworld.com/2019/05/31/brazil-plans-to-add-more-solar-to-its-hydrodominated-electricity-generation-mix/*

48 *http://www.absolar.org.br/infografico-absolar.html*

PTB's approach

PTB projects are coordinated by the National Institute for Metrology, Quality and Technology (*Instituto Nacional de Metrologia, Qualidade e Tecnologia*, INMETRO). The first phase of the current project was implemented from 2016 to 2019. The second phase began in 2021 and will run until 2023. This project is working to strengthen the national quality infrastructure by helping to set up new demand-oriented services in line with national energy sector policies. This includes the areas of energy efficiency and renewable energies, where a focus on wind energy and solar PV has been chosen. Specifically, the first phase of the project worked on quality infrastructure for renewable energy generation, grid integration, and public lighting systems. Additionally, the project promoted cooperation among quality infrastructure actors and stakeholders in the energy sector, including the Ministry of Mines and Energy (*Ministério de Minas e Energia*, MME), the Energy Planning Company (*Empresa de Pesquisa Energética*, EPE), national utility companies, the national grid operator (*Operador Nacional do Sistema Eétrico*, ONS) and renewable energy associations.

As the demand for quality assurance services for PV was limited and no major quality issues were reported in the sector, the project activities for energy generation in the first phase were mainly geared towards wind energy. The establishment of a new metrological service that can support the grid integration of electricity from fluctuating energy sources (making it relevant for solar PV as well) is described in the next section.

In the second phase of the project, the establishment of traceability for solar reference cells is envisaged at INMETRO along with new services for the wind industry, such as the calibration of Pitot tubes, and other activities relating to renewable energies and energy efficiency, including the verification of electricity meters and new accreditation services. Moreover, support in modernizing the national labelling program is being provided in this project phase. This will probably also affect the labelling of PV modules and inverters.

INMETRO has designed a strategic plan to develop the institute to become a toolbox for its stakeholders for innovation, digitalization and economic development. The project is supporting the implementation of this plan.

Positive impacts achieved

In order to upgrade grid monitoring and increase grid stability – in part to deal with increasing amounts of fluctuating renewable electricity being fed into the grid, for example from wind or solar PV – the Brazilian national grid operator has taken the decision to install phasor measurement units (PMUs) in their lines. These devices allow the measurement of the magnitude and phase angle of voltage or current and can thus identify mismatches between supply and demand or detect synchronization issues which can cause a loss of power quality or result in power outages.[49] The PTB project supported the metrology department of INMETRO in establishing traceability for these devices. By regularly calibrating the PMUs, the grid operator can ensure the reliability of the measurement devices and hence of its grid monitoring system.

Regarding stakeholder engagement, an important step in fostering exchange and cooperation among quality infrastructure institutions was made by bringing representatives of all designated laboratories for PV modules and inverters and all relevant departments of INMETRO together for a discussion on quality assurance for the PV sector.

Remaining challenges

The Brazilian government is engaged in the modernization of the regulatory framework to foster economic freedom. The aim of this process is to strengthen Brazil's economic and social development, which has suffered greatly under the pandemic. The quality infrastructure will need to accompany this development by offering the newly required services in a timely manner.

Internal lessons learned

It has proven helpful not to focus the first project phase on any one renewable energy technology, as the needs for quality assurance for wind and PV remained unclear during the project appraisal. The flexibility of working on both technologies, and then focusing more on wind, where stronger needs were expressed, allowed the project to achieve a greater impact.

The development of competencies in quality infrastructure institutions takes time, especially when completely new services need to be built up, so expectation management is crucial. Stakeholders involved in the project should be made aware that quality assurance cannot be set up in a matter of a few months or years, but that it is rather a process that is being initiated and/or supported by the project.

Communication with stakeholders is very important and must extend beyond expectation management. It is useful to establish and maintain communication channels and to keep in regular contact. This can only be achieved with a dedicated and proactive project team.

49 *https://www.eia.gov/todayinenergy/detail.php?id=5630*

Case study – Strengthening Quality Infrastructure for Renewable Energies and Energy Efficiency in Mexico – Triangular Cooperation with Cuba and the Dominican Republic[50]

Situation in the partner countries

In **Cuba**, the goal is to cover 24 % of energy production with renewable sources by 2030.

The management of the electricity system is centralized under the national utility *Unión Eléctrica de Cuba* (UNE). UNE is in charge of designing, procuring, installing, operating and maintaining their PV systems in the country. The design, procurement and installation may be outsourced to foreign companies. There is also an automated PV module assembly plant in operation on the island.

When it comes to quality assurance, three laboratories offer services for photovoltaic technologies : the Laboratory for Tropicalization Testing (*Laboratorio de Ensayos de Tropicalización*, LABET); the Center for Solar Energy Research (*Centro de Investigaciones de Energía Solar*, CIES); and the Science and Technology Institute for Materials (*Instituto de Ciencia y Tecnología de Materiales*, IMRE) of the University of Havana.

In the **Dominican Republic**, the renewable energy target for 2030 is 25 %. The market is dominated by private investors, with large international investments dedicated to grid-connected, utility-scale plants while the local private sector plans, builds and operates mainly rooftop systems for residential, commercial and industrial use. Both types of investments are eligible for tax incentives provided by the National Energy Commission (*Comisión Nacional de Energía*, CNE). The Association for Renewable Energy Promotion (*Asociacion para el Fomento de Energías Renovables*, ASOFER) brings together some 90 companies that are active in the sector. However, there is no PV component manufacturing in the Dominican Republic and the country has no testing laboratories available for PV.

In both countries, the level of awareness about quality issues in the PV sector was low before the intervention of the project, and the exchange between quality infrastructure and PV actors was very limited.

PTB's approach

In the framework of PTB's cooperation with Mexico on renewable energies, a triangular cooperation component with Cuba and the Dominican Republic was included in the second project phase (2018 to 2021). The aim of this component was to foster knowledge transfer within the region and establish quality assurance services for the PV sector in Cuba and the Dominican Republic as well. An assessment of potential areas of intervention was carried out in each country. In Cuba, a value chain analysis was carried out with representatives of the quality infrastructure and PV sectors. In the Dominican Republic, the assessment was done in the form of awareness raising and planning workshops.

The following intervention areas were identified in both countries:

- Awareness raising regarding the role of quality infrastructure for PV
- Strengthening of metrology, in particular for the calibration of field-testing equipment
- Certification of installers
- Adoption of the most relevant international standards for PV

Additionally, the project supported the strengthening of testing laboratories for PV in Cuba, while in the Dominican Republic a stronger focus was placed on connecting the private sector with the quality infrastructure institutions.

Positive impacts achieved

The triangular cooperation component worked to raise awareness of quality in the PV sector and of the role of quality infrastructure, both in Cuba and in the Dominican Republic, thus strengthening quality assurance for PV in the region. The (potential) users of quality infrastructure services were included in all phases of the project, from needs assessment and operational planning to awareness raising, capacity building and standardization activities. This permitted the establishment of stronger ties between quality infrastructure providers and users and resulted in an expansion of both the availability and utilization of quality assurance services. In Cuba, considerable progress was attained in the areas of standardization, laboratory and field testing, and the verification of

50 This case study was elaborated in 2021. Please note that all information provided refers to the situation in 2021.

pyranometers. Moreover, increased awareness has led to the increasing inclusion of quality criteria in procurement, installation, and operation and maintenance contracts. In the Dominican Republic, a technical committee for renewable energies was established and a standard for PV system installation is being developed that will provide the basis for installer certification. In the metrology laboratory of the Dominican Institute for Quality (*Instituto Dominicano para la Calidad*, INDOCAL), calibration services are being developed for power quality analyzers and pyranometers.

Remaining challenges
In the few years of implementation, the triangular cooperation component has permitted the initiation of many important processes. However, the level of impact and use of the new services still needs time to develop. For instance, the certification of installers has yet to be rolled out and experience needs to be gained both on the quality infrastructure side and by the installers themselves.

Internal lessons learned
PTB was able to gather initial experience in cooperating with Cuba. Given the economic structure in the country, it was particularly important to communicate the project objectives and implementation modalities in an adequate manner, which included clarifying who should be involved and who will ultimately benefit – directly or indirectly – from the project activities.

In the Dominican Republic, the strong competition in the private sector led the project team to establish individual contacts to private sector representatives first so as to address quality issues more openly. In a second step, the project attempted to bring these representatives together to engage in collective activities.

Case study – Strengthening Quality Infrastructure for the Solar Industry in India

Situation in the partner country

In 2018, India was the third largest electricity producer in the world, and its demand for electricity, according to the International Energy Agency (IEA), is predicted to rise faster than in any other country in the period to 2040[51]. To prevent a strong increase in related CO_2 emissions, a rapid expansion of renewable energy capacities is required. The country has defined very ambitious targets for such development, aiming to achieve 175 GW renewables by 2022 and 450 GW by 2030. In March 2021, according to the Ministry of New and Renewable Energy (MNRE), the installed capacity for renewable energy (excluding big hydropower plants) was 94.4 GW, equal to around 25 % of India's total production capacity[52]. PV shows the fastest increase among the renewable energy technologies, with an additional 7 GW expected to have been installed in 2021. As the achievement of the 450 GW target would require expanding installed renewable energy capacity by around 30 to 40 GW per year, the pace of development in the PV sector will also need to accelerate much faster.

In this context, the Indian government has long focused on the achievement of the quantitative objectives and the required expansion of installed PV capacity. In recent years, however, awareness of the importance of effective quality assurance has increased in the PV sector. It turns out that some of the installed systems have considerable quality deficiencies, and these have led to the non-achievement of expected output. It furthermore became obvious that safety standards had not been met at some plants. These factors together led not only to financial risks but also to safety issues for installers and the local population (e.g., when PV rooftop systems catch fire). Such problems negatively affect the performance of individual projects, the reputation of the PV sector as a whole, and the achievement of national objectives for the development of renewable energy.

51 IEA (2021): India Energy Outlook 2021

52 MNRE (2021): *https://mnre.gov.in/the-ministry/physical-progress*, 15 June 2021

PTB's approach

PTB started its cooperation on quality in the PV sector in India with a two-year identification project in 2012, followed by the first regular bilateral project which ran from 2014 to 2019. Since August 2019, PTB has implemented a follow-up project with the overall objective of improving the quality infrastructure services needed to ensure that PV components and systems are reliable, safe and sustainable.

The project cooperates with the most relevant actors of the Indian quality infrastructure system as well as with further institutions that are important for quality assurance in the PV sector. These include partners in Delhi, Bangalore and Mumbai. The National Institute of Solar Energy (NISE), an autonomous institution of the Ministry of New and Renewable Energy (MNRE), is the major implementation partner, while MNRE itself acts as political partner.

The project focuses on the three fields of activity highlighted in the next section.

Positive impacts achieved

1. Improvement of metrology and testing services by strengthening the technical and institutional capacities of calibration and testing laboratories.

In this first area, the project is working to expand the services offered to the PV industry and to improve the quality of testing and calibration laboratories, especially in the areas of secondary cell calibration and module testing. Key laboratories have been supported by training and consultancy activities, increasing the knowledge of staff, improving procedures, and strengthening the quality management systems. Inter-laboratory comparisons were organized for the testing of inverters and PV modules and for the secondary calibration of cells.

The project also established the groundwork for scientific cooperation between the National Physical Laboratory (CSIR-NPL) and PTB on the establishment of a primary cell calibration laboratory (ongoing since November 2018).

Another important achievement is the establishment of a network of the most relevant public and private PV testing and calibration laboratories in India. It is facilitated and chaired by NISE and meets regularly, both virtually and face-to-face.

Additional support of calibration and testing laboratories is currently being prepared and aims, for example, to improve access to PV proficiency tests and to develop services in the areas of pyranometer calibration.

Finally, a cooperation between the National Accreditation Board for Testing and Calibration Laboratories (NABL) and the United Kingdom Accreditation Service (UKAS) has been established in the framework of the project with the aim of training NABL trainers and assessors and further developing NABL procedures in the field of solar PV.

2. Improvement of quality control mechanisms defined in tender procedures, standards, technical regulations or certification schemes.

In this area, the project has contributed to the development and implementation of improved quality control mechanisms that are relevant for the PV sector and that go beyond testing and calibration. Important activities include collaboration with the Solar Energy Cooperation of India (SECI) on the inclusion of quality and sustainability criteria in tender processes as well as the development of tools for the evaluation of bids for PV projects that are submitted to SECI. Furthermore, the Indian Renewable Energy Development Agency (IREDA) and other public financial institutions have been supported by the development of checklists for the evaluation of PV power plants during different project stages. These lists are primarily addressed to lenders' technical engineers (LTEs) commissioned by financial institutions to evaluate PV plants and to deliver the information needed to make the right financing decisions.

3. Awareness raising activities and development of training formats with regard to the key role of quality infrastructure services.

Since 2014, PTB has contributed significantly to an increased awareness and better availability of information regarding the important role of quality infrastructure for the sustainable development of the Indian PV sector. Different stakeholder engagement formats and informational events have brought the various players together to discuss existing challenges and to define what is required to effectively assure quality and sustainability in the sector. Some of the events were based on two studies commissioned by PTB: *Quality and safety criteria applied in financing photovoltaic projects*[53] and *Pilot Study on Quality Aspects of PV Power Plants in India*[54]. Especially the latter, conducted by PI Berlin on behalf of PTB, contributed substantially to an increased awareness of quality issues in the sector.

Recently, a cooperation with the Confederation of Indian Industry (CII) has been established. The overall goal is two-fold: first, to develop training formats and material for PV module manufacturers who operate their own in-house laboratories; and second, to train CII trainers so that they can themselves conduct regular informational events and training courses for PV module manufacturers in the mid-term.

Remaining challenges

The increasing awareness of key stakeholders concerning the importance of quality infrastructure for the PV sector can be seen as a very positive development. However, concrete policies to support effective quality assurance mechanisms in the sector still need to be defined and implemented. These policies should be based on international standards and best practices, and they should define voluntary incentives. Currently, regulations[55] establish mandatory quality criteria and procedures that, together with the increase of the customs duty on imported PV modules and *domestic content requirements*, may hinder international trade, innovation and investment in the sector.

Moreover, the demand for quality infrastructure services has increased along with rising awareness in the PV sector. At present, this demand cannot be satisfied in all areas by the organizations of the national quality infrastructure, a fact that highlights the relevance of PTB's support in improving the availability of the required quality infrastructure services. Here, it must be considered that not only the demand for basic quality infrastructure services evolves with the development of the PV sector.

53 PTB (2016)

54 PTB (2017)

55 For example, the *Solar Photovoltaics, Systems, Devices and Components Goods (Requirements for Compulsory Registration)* order

In the coming years, more and more new quality assurance services will also be required, for example in the following areas:

- Energy storage systems
- New PV technologies, such as floating power plants and bifacial modules
- Online monitoring of PV plant performance
- Quality assurance of PV power plants in the field (including testing and certification)
- Update of standards from the Bureau of Indian Standards (BIS) to new international standards (e.g., IEC 61215:2021)

Selected internal lessons learned

- The involvement of the financial sector, initiated as part of a close cooperation with KfW, has proven to be important in increasing awareness of the relevance of quality infrastructure for the sustainable development of the PV sector as a whole.
- The *Pilot Study on Quality Aspects of PV Power Plants in India* (PI Berlin on behalf of PTB) was an effective way of highlighting existing quality challenges in the sector and has attracted much attention from the relevant stakeholders (also beyond India).
- In addition to providing focused support for sector-specific quality infrastructure services, it is also important to foster the general development of the quality infrastructure system. Doing so may among other things help to address possible inconsistencies within the national quality infrastructure system. For example, one hurdle related to the general structure and regulation of the quality infrastructure is the fact that most BIS standards are of a mandatory nature and can only be tested by laboratories *recognized* by BIS, something that in turn hinders effective and efficient quality assurance. In this context, it is essential to promote overall improvements to the relevant structures and regulations while at the same time supporting specific services (such as the creation of standards required in the PV sector).
- The project has attempted to increasingly involve Indian partners in the organization and coordination of project activities. As the main implementation partner, NISE is already in charge of many activities (also beyond the project). The Indian Institute of Technology in Mumbai (IIT Bombay) was given the role of national coordinator for the consulting programmes on secondary cell and module calibration (organization of training sessions, communication with involved laboratories, etc.). This approach empowers the national partner, enables an effective and sustainable implementation of the activities, and lessens the workload of NISE and PTB.
- A very broad-based steering committee (>10 members) that includes representatives of all key partners is conducive for instilling strong ownership of the project from the Indian partners' side.

Case study – Strengthening Quality Infrastructure for the Energy Sector / for PV in Indonesia

Situation in the partner country

It is a priority of the government of Indonesia to increase rural electrification and at the same time increase the share of renewable energy in the national energy mix. The government target for solar PV energy was ambitiously set at 6.5 GWp of installed capacity by 2025. This can only be achieved by expanding both grid-connected and off-grid PV systems. However, the development of the sector remains slow, with an actual installed capacity in the MW range in 2020, and still relies to a large extent on government funding.

The domestic industry comprises various module manufacturers who assemble PV modules for projects in Indonesia. There are also several engineering, procurement and construction (EPC) companies in Indonesia, some of which are associated with one of the module manufacturers. EPC companies and system operators still have limited experience with PV. Several industry and civil society associations contribute to awareness raising for PV, including quality aspects, and lobby for improved framework conditions for the development of the sector. The national electricity utility (*Perusahaan Listrik Negara*, PLN) is a key player when it comes to PV growth in the country.

Currently, quality issues are common in installed PV systems and locally manufactured components. Additionally, the quality of imported components cannot always be assured. Awareness about quality aspects has been rising in recent years, with the Ministry of Energy and Mineral Resources (*Kementerian Energi dan Sumber Daya Mineral*, ESDM), the National Planning Agency (*Kementerian Perencanaan Pembangunan Nasional*, BAPPENAS) and some local governments taking first initiatives to increase the quality of PV systems by including quality criteria in tenders and by planning and funding the expansion of national quality infrastructure services for the sector, namely the establishment of a testing laboratory for PV modules in 2019. The Technical Committee (TC) for PV has recently been separated from the TC cluster for renewable energies and has developed a roadmap for the adoption of the international standards most relevant to the Indonesian PV sector. However, the implementation of the standards remains limited, as does the use of other quality infrastructure services.

PTB's approach

The project's first phase was implemented from November 2016 to October 2020, with areas of intervention targeted at three levels:

- the enabling environment, where policy and decision makers were made more aware of quality aspects in PV;
- the quality landscape, where the competencies of quality infrastructure institutions were built to expand the service scope for the PV sector;
- the demand side, where (potential) users of quality infrastructure services, including local component manufacturers, EPCs and the national energy provider, were involved in awareness raising measures.

In cooperation with the National Planning Agency (BAPPENAS), a participatory process was carried out in which recurring quality issues in the PV sector were identified and the potential remedies that quality infrastructure could provide defined and prioritized. This assessment activity brought together representatives from government institutions, quality infrastructure organizations and the private sector. It revealed the most important developments needed in the area of quality infrastructure, namely: the expansion of testing and certification services for components; the implementation of standards; the qualification and certification of PV practitioners from system design to installation to operation and maintenance; and the expansion of calibration services. These insights served to guide the further activities of the project and were used as input for the National Medium-Term Development Plan 2020–2024.

A second project phase is being implemented from November 2020 to October 2023. It builds on the achievements of the first phase and continues to support the quality infrastructure institutions in expanding their services for the PV sector, while at the same time raising awareness of quality assurance among decision makers and PV practitioners to foster the use of the available services.

Positive impacts achieved

The participatory process discussed above engaged a variety of stakeholders and was one of the key activities of the project. It provided an opportunity for networking and gave the private sector actors the possibility to have a say in which quality infrastructure services should be given priority in the coming years, thus laying the foundation for a sustainable development of quality infrastructure that is also in line with national demands.

Moreover, the project was able to support the establishment of a testing laboratory for PV modules according to the international standard IEC 61215. The funding for the laboratory was granted by the Indonesian government and the project provided consultancy for the preparation of the tender and the establishment of the quality management system for the new testing services. Complementing the activities at the laboratory, awareness about the standard was raised at various events for industry representatives and decision makers. These included a training session held for PV module manufacturers on the implementation of the standard as preparation for using the testing services for product certification.

The project partners perceive the opportunities for exchange with one another as an important achievement of the project. The meetings of the Project Coordination Committee represent a forum for information exchange and networking among the involved institutions. And a series of PV site assessments brought together representatives from the Ministry of Energy and Mineral Resources and the quality infrastructure institutions to assess quality issues found in existing PV systems. This provided a joint learning experience that allowed the participants to gain a better understanding of the others' tasks and competencies and to learn more about the specifics of the PV technology.

In the second project phase, one initial achievement was to raise awareness of and provide training on performance ratio (PR) monitoring according to the IEC standard. The PR is an important indicator of the correct functioning and quality of a PV system. The testing laboratory therefore installed an automated PR monitoring system for their rooftop PV installation, which can be used for training activities and to disseminate further knowledge on PR in Indonesia.

Remaining challenges

Despite the demand orientation and the awareness raising events pertaining to the international standard IEC 61215 and the newly established testing services, the utilization of quality infrastructure services remains very limited. Some possible reasons and challenges in this context include: the slow development of the PV sector in Indonesia and the resulting small size of the market, creating the need from the industry's perspective to focus more on economics than on quality; a lack of awareness about the benefits of quality assurance services and their potential for cost reduction in the medium and long terms; and the geographical expansion of the country, making it difficult to extend quality infrastructure services to remote areas. Moreover, the Covid-19 pandemic and its economic impacts pose a challenge to the use of quality infrastructure services.

Internal lessons learned

The involvement of a variety of stakeholders in project implementation increases the potential impact of the project while at the same time resulting in a more complex project setting. When regular interaction with stakeholders beyond the institutions of the quality infrastructure is necessary, a local project representative can play an important role in establishing and maintaining relationships with key actors and in this way facilitate smooth project implementation.

The Ministry of Energy possesses great leverage when it comes to quality aspects. Given the ministry's better understanding of quality aspects and quality infrastructure thanks to the cooperation in the project, working with such a key player in the field as political partner may broaden the potential for improving quality in the sector (e.g., through the definition of quality criteria in tenders for PV systems).

The fast-paced digitalization of project management and communication was a positive side-effect of the travel restrictions related to the Covid-19 pandemic. Virtual meetings enabled the project team to discuss issues directly and more regularly with the project partners. Virtual training sessions and technical discussions can be attended by more participants from different institutions and can be more flexibly scheduled. However, these positive developments were only possible thanks to the good relations previously established with the partners and to the support these partners provided.

Case study – Strengthening Quality Infrastructure for Renewable Energies and Energy Efficiency in Mexico[56]

Situation in the partner country

Mexico's PV market is relatively mature and looks back on several decades of experience with this technology, and recent years have seen large increases in installed capacity. By 2019, some 4 GW of PV capacity were in operation, with more than 600 MW generated in distributed systems.

Political support for the technology has varied over the years. A setback came with a new regulation in May 2020 that increased the requirements pertaining to the installation of utility-scale systems. This has affected not only the planning of new PV plants but also impeded recently installed plants from commencing operation. Moreover, rooftop PV is developing only slowly due to a lack of incentives. Nevertheless, government targets for solar energy remain high, with plans envisaging a total of 22 GW installed PV capacity by 2030.

The sector relies mostly on imported components. The domestic manufacturing industry remains small and focuses on the assembly of PV modules. Service providers for the PV sector, on the other hand, are well developed at the local level. Competency has been acquired over the years and most industry actors are aware of the existing quality issues.

While there is a general awareness about quality aspects in the sector, this is not always reflected in the implementation of PV projects. Tenders and contracts often include only few safety and quality requirements, and they do not refer to national or international standards. This is particularly common in connection with smaller distributed systems, where awareness of quality aspects still needs to be raised. For utility-scale PV plants, quality assurance is mainly conducted by international service providers, while the use of services available from the national quality infrastructure remains limited.

The national quality infrastructure offers a variety of services for the PV sector. The Association for Standards and Certification Mexico (*Asociación de Normalización y Certificación A.C.*, ANCE) and the Mexican Electrotechnical Committee have adopted the relevant international standards for PV, and they engage in international standardization efforts in the field. Several testing laboratories have developed competencies for PV and one laboratory for PV modules and inverters has already achieved accreditation of its expanded service scope. Certification of PV modules is offered only by international quality assurance providers in cooperation with their offices and laboratory facilities in the region. The National Metrology Institute of Mexico (Centro Nacional de Metrología, CENAM) offers traceability for a variety of measurement units with relevance for the PV sector. Moreover, personnel certification is available in line with the national competency standards, in particular for the installation of PV systems, their monitoring, and for consultancy for distributed solar PV systems.

PTB's approach

PTB's cooperation with Mexico on renewable energies started in 2013, with an initial project running from 2013 to 2018 and a second project implemented from 2018 to 2021. The projects aimed at supporting quality infrastructure institutions and strengthening the use of quality infrastructure services, thus contributing to the transition to renewable energies in Mexico.

While the first project focused on the expansion of basic quality infrastructure services for renewable energies – specifically solar PV and solar thermal systems – the second project fostered the consolidation and use of existing services and supported the application and improvement of competencies to deal with more complex aspects. Additionally, the Programme for the Development of the National Electrical System (*Programa de Desarrollo del Sistema Eléctrico Nacional*, PRODESEN) as well as different pilot projects were supported. To foster knowledge transfer within the region, a triangular cooperation with Cuba and the Dominican Republic was also a component of the project (see dedicated case study).

A participatory process to identify quality issues in the Mexican PV value chain and define concrete actions to address these issues was carried out in 2019 using the

56 This case study was elaborated in 2021. Please note that all information provided refers to the situation in 2021.

CALIDENA methodology[57]. The initial assessment served as a guide for subsequent project activities, and the actors involved implemented the action plan developed in 2019 until the end of the project.

Positive impacts achieved

The above-mentioned CALIDENA process was an innovative approach in Mexico that fostered exchange between all relevant quality infrastructure institutions and actors of the private sector. The workshops strengthened the network of those stakeholders able to contribute to quality in the PV sector, and the joint implementation of the action plan made it possible to advance quickly on concrete issues and address the demand of the private sector for quality assurance services.

The concrete outcomes of the process included the following: the establishment of a calibration service for I-V curve tracers (used to check the performance of PV modules or strings and important for the quality control of PV components and installed systems); the development of reference solar cells for the measurement of absolute solar irradiation at CENAM; the creation of a board of certified personnel published on the website of the National Association for Solar Energy (*Asociación Nacional de Energía Solar A.C.*, ANES); the development of a diagnostic tool for banks to apply quality criteria to PV projects and thus strengthen the demand for quality assurance services; and the organization of two forums to foster exchange between the quality infrastructure and PV sectors and the Employers Confederation of the Mexican Republic (*Confederación Patronal de la República Mexicana*, COPARMEX), which brings together the most important large Mexican businesses.

The project also provided technical expertise to support the grid integration of renewable energies. An important technical achievement was the construction of a power quality travelling standard at CENAM, which enables an evaluation of the competency of testing laboratories for power quality in electrical grids. Moreover, relevant stakeholders, including the metrology institute CENAM, were brought together to revise the grid code, specifically defining the necessary details regarding power quality parameters.

Remaining challenges

While the project succeeded in expanding testing services for the PV sector, the competencies in several laboratories still need to be strengthened to make sure that testing results are reliable and to prepare additional laboratories for accreditation.

Moreover, awareness about quality issues and the benefits of national quality infrastructure services can be further increased to foster the demand for available services and reduce quality issues in the Mexican PV sector.

As concerns the quality assurance of distributed generation systems, a challenge remains in harmonizing the implementation of existing regulations, given that the requirements they outline are interpreted differently in the different Mexican states. As a first step to tackle this challenge, the project established round tables between key actors from quality infrastructure institutions as well as industry, academia, and contractors.

Internal lessons learned

The involvement of the Ministry of Energy is very important for the leverage of the project activities and for a stronger impact.

Regarding the triangular cooperation, the following lessons learned can be highlighted:

- Extending cooperation to additional countries is an interesting approach that fosters exchange within the region, especially in cases where direct bilateral cooperation with the particular countries would not be possible.
- However, it implies considerable additional effort due to the completely different situations in the countries involved.

57 CALIDENA is a methodology developed by Mesopartner on behalf of PTB that aims at systematically and sustainably supporting the improvement of national quality infrastructure services in line with national demand. At the same time, it works to raise awareness on quality issues and facilitate networking among stakeholders from the selected value chain and support organizations, including quality infrastructure institutions and ministries.

Case study – Strengthening Quality Infrastructure for Innovative Energy Services in Senegal

Situation in the partner country

In Senegal, the development of the PV sector began many years ago, and the technology has been embraced by the government not only for increasing the share of renewable energies, but also for rural electrification, where the aim is to provide electricity to at least 90 % of rural households by 2025. Two dedicated institutions – the National Agency for Renewable Energies (*Agence Nationale pour les Energies Renouvelables*, ANER) and the Senegalese Agency for Rural Electrification (*Agence Sénégalaise d'Electrification Rurale*, ASER) – were created to coordinate and implement activities in their respective areas and to work towards the achievement of the government targets. PV technology also brings opportunities for employment in rural areas, as installation, operation and maintenance are usually carried out by local companies or entrepreneurs. To strengthen competencies in this sector, a training programme for engineers has been launched jointly by five universities in the country.

Senegal relies on imports of specific components for the development of PV capacity, as no modules or inverters are produced locally. However, the quality of imported components – and particularly PV modules – varies greatly, with fake certificates not being rare on the market. Stakeholders in the Senegalese PV sector are generally aware of such quality issues, having had far too frequent negative experiences with the technology. The government wants to address such issues by including safety and efficiency criteria for PV components in public tenders and offering a tax exemption for certified or tested components. At the moment, international certificates are checked for authenticity, while additional testing services to check the compliance of imported components with quality and safety criteria are being put in place.

Quality infrastructure for the PV sector is currently limited. Three laboratories are establishing testing capacities for PV modules, batteries, inverters and controllers. The national standards body (*Association Sénégalaise de Normalisation*, ASN) is part of the mentoring programme of the International Electrotechnical Commission (IEC). It can thus grant access to international standards for PV, and it has initiated their adoption into national standards. Metrological services can be provided for some basic measurements, but there are no plans to establish PV-specific services in light of the very limited demand in the sector so far. The exchange between quality infrastructure organizations and the private sector is still limited, and the demand side is also usually not consulted when it comes to decisions concerning the development of quality infrastructure services.

PTB's approach

The project on quality infrastructure for innovative energy services with a focus on solar PV started in 2018 and is the first bilateral project that PTB is implementing in Senegal. The project was requested by a testing laboratory that wanted to expand its scope of services for the PV sector. This is why the establishment of testing services for PV components is at the core of the project. Two public laboratories are being supported with equipment and capacity development measures to expand their service scope for PV modules, inverters, batteries and controllers.

Another component of the project is the work with electric and electronic installation associations to raise awareness about quality issues and inform the association members about existing quality infrastructure services for PV. Moreover, it is a goal of the project to increase cooperation among different stakeholders, including the relevant ministries and implementing agencies, quality infrastructure institutions, energy suppliers, and associations for consumer protection. To foster cooperation among quality infrastructure institutions and guide the development of quality assurance services, a quality infrastructure strategy is being developed within the framework of the project.

Positive impacts achieved

The establishment of new testing services being at its core, the project was able to make initial achievements in the capacity development area at the two partner laboratories – the Center for Studies and Investigation on Renewable Energies (*Centre d'Etudes et de Recherches sur les Energies Renouvelables*, CERER), which focuses on the development of testing services for PV modules; and the Polytechnic Institute (*Ecole Supérieure Polytechnique*, ESP), where testing services for batteries, inverters and controllers are being set up. The necessary equipment for the two laboratories was procured and technical training was provided. Due to travel restrictions because of the Covid-19 pandemic, equipment specifications, installation and procedures were coordinated and carried out virtually.

Moreover, the project was able to increase the awareness and understanding of quality considerations in PV projects among staff of the Ministry for Petroleum and Energy (*Ministère du Pétrole et des Énergies*, MPE), which acts as the political partner of the project. Milestones with the MPE were the inclusion of quality criteria in tender documents as well as the introduction of a tax exemption for PV components that are aligned with quality requirements. Regulations for the implementation of essential tests are in preparation.

The above-mentioned quality infrastructure strategy process led to the establishment of a *Quality Commission* under the *Consultation Board for Off-Grid Electrification*. The Quality Commission brings together all relevant stakeholders and is an important forum for quality in the sector.

Remaining challenges
The strong focus on capacity development and equipment procurement for the testing laboratories limited the flexibility of the project to attend to specific requests by other stakeholders.

Moreover, getting the private sector involved through collaboration with the industry associations remains challenging. This hampers awareness raising activities among the private sector actors, but even more importantly it makes it difficult to connect the private sector with the quality infrastructure institutions to discuss concrete needs for quality assurance services and to align service development accordingly. A local project consultant is working with the respective stakeholders to discuss possible activities within the framework of the project.

Internal lessons learned
For bilateral projects that go beyond a tight collaboration with metrology or quality infrastructure organizations and also involve other stakeholders, additional budget and time should be calculated to cater for the increased complexity of the project setting. This is particularly true when the procurement of equipment, e.g., for a laboratory, is planned.

During project appraisal, the key quality issues and the potential demand for quality infrastructure services should be assessed very carefully. Based on this assessment, the project can be designed to achieve the necessary impact rather then addressing concrete requests by future project partners that might not be fully aligned with the needs of the sector. In this context, it may be necessary to involve several experts so as to combine a holistic view on quality infrastructure with sector-specific knowledge.

Tight coordination between GIZ, KfW and PTB is helpful in identifying potential synergies and avoiding overlaps or potential conflict.

Case study – Strengthening Quality Infrastructure for Photovoltaics in Tunisia

Situation in the partner country

With a plan to cover 30 % of national energy consumption with renewable energies by 2030, the Tunisian government back in 2015 set the framework for the development of solar power. However, the market has grown at a relatively slow pace. Government projects, often supported by international donor organizations, are the biggest driver when it comes to photovoltaics. Households and local industry remain hesitant, not least because the legal framework for the grid integration of energy produced by privately owned PV systems has not yet been clearly defined.

The Ministry of Industry, Energy and Mines (*Ministère de l'Industrie, des Mines et de l'Énergie*, MIME) and the National Agency for Energy Management (*Agence Nationale pour la Maitrise de l'Énergie*, ANME) are aware that assuring quality along the PV value chain is crucial for the success of the technology and for achieving the government targets. Quality issues in PV systems are common, especially when it comes to small and medium-sized PV systems. This is mainly due to the use of low-quality PV modules and the faulty installation of such systems. Moreover, PV system users often lack awareness of quality and quality assurance.

The necessary quality infrastructure institutions exist in Tunisia, and they have a clear mandate to also provide quality assurance services for the PV sector. Key international standards have already been adopted into national standards and, with the support of the PTB project, it was possible to establish testing services (see below). However, the exchange between quality infrastructure organizations and the private sector to determine concrete needs and priorities for quality assurance and to raise awareness about existing services is still rather limited.

PTB's approach

In its first phase from 2016 to 2019, the project focused on quality assurance for both PV components and systems with the aim of increasing user confidence in PV technology. To do so, the project provided support to two laboratories in setting up testing services for PV modules. The Technical Center for Mechanical and Electric Industries (*Centre Technique des Industries Mécaniques et Électriques*, CETIME) and the Technical Center for Construction Materials, Ceramics and Glass (*Centre Technique des Matériaux de Construction, de la Céramique et du Verre*, CTMCCV) received the necessary equipment and capacity building assistance to develop new tests and incorporate them into the quality management system. On the PV system side, efforts were concentrated on installers, for whom a guide, training courses and a certification scheme were developed in cooperation with ANME and GIZ (see below). Moreover, standardization for PV was supported (in particular with the adoption of an international standard on PV inverters) and awareness raising activities on quality aspects were implemented.

The second project phase, which is being implemented from 2020 to 2023, builds on the achievements of the first phase. It takes a holistic perspective on quality gaps along the PV value chain as well as on quality infrastructure, broadening the activities beyond testing, standardization and certification to also cover metrological and inspection aspects. The focus lies on fostering the use of quality infrastructure services.

Positive impacts achieved

One of the highlights is the project support given to ANME in developing an installation guide for PV systems connected to the low-voltage grid. The guide gives a general introduction to PV systems and covers the procedures for installation, testing, commissioning and maintenance, and describes common faults and security issues and how to avoid them. To facilitate the use of the guide, training for installers was organized jointly with ANME. The training and content of the guide can provide the basis for installer certification for the market segment of small and medium-sized PV systems connected to the low-voltage grid. The guide has proven successful and is backed by the Tunisian government. Moreover, it was shared with GIZ and the relevant stakeholders in Morocco and used there as a basis for a label for installers (Taqa Pro).

The newly available PV module testing services offered for both locally manufactured and imported components can also be highlighted as one of the project's major achievements. Now, services for PV modules as well as for inverters and batteries are available locally. However, the use of these services remains limited (see below).

Remaining challenges

Although the project has successfully supported the Tunisian partner laboratories in setting up testing services for PV modules, demand for such services remains low. The possibility of conducting mandatory import controls on PV modules is being discussed as a means of assuring quality in the PV sector and making use of the new testing services. Such mandatory import controls, however, represent technical barriers to trade that are not in line with the multilateral agreements on trade under the World Trade Organization (WTO). The second project phase thus continues to work on this issue and to provide consultancy on implementing effective quality assurance for PV components in line with international good practice, including, for example, the random sample testing of imports.

Internal lessons learned

It is important to evaluate the actual need for testing services before taking the decision to equip a laboratory and set up new services. In this way, an estimation of the demand for and financial viability of the laboratory can be made.

A holistic approach to quality infrastructure can be helpful, even if the project is focused on a specific sector or where one quality infrastructure pillar is identified as particularly important. Experts with knowledge about the entire quality infrastructure system should therefore be consulted for such projects and provide advice on the potential for overall quality infrastructure improvement.

Many personnel changes on both the PTB and the partner sides result in a loss of information and may slow down or hinder project implementation. A smooth hand-over process within PTB, the thorough onboarding of new counterparts in the partner institutions, and the sharing of as much information as possible should therefore be facilitated whenever possible.

Annex B – List of Interview Partners

PTB head of section, project coordinators, local project representatives, and intermittent short-term experts who contributed to the case studies and study review.

Country / PTB Project	Name
Brazil	Lieselotte Seehausen
India	Elena Ammel
India	Niels Ferdinand
India	Saurabh Kumar
Indonesia	Patrick Dolle
Indonesia	Christian Kramer
Indonesia	Katharina Telfser
Indonesia	Sandra Imelda
Mexico, Cuba, Dominican Republic	Wolfgang Schmid
Mexico, Cuba, Dominican Republic	Caroline Jansen
Mexico, Cuba, Dominican Republic	Mahdha Flores
Mexico, Cuba, Dominican Republic	Haygas Kalustian
Latin America and the Caribbean	Ulf Seiler
Senegal	Carola Heider
Tunisia	Petra Hagemann
Tunisia	Franziska Schindler
Tunisia	Gerhard Kleiss
Tunisia	Gudrun Becker
Morocco	Iris Nadolny
Morocco	Amina Baha

Experts for quality infrastructure and PV interviewed for this publication.

Organization	Name
TÜV Rheinland	Jörg Althaus
DKE VDE	Arno Bergmann
IRENA	Francisco Boshell
PV Cycle	Jan Clyncke
KfW	Daniel Etschmann
NREL	Garvin Heath
PTB	Dr. Ingo Kröger
Sunconnect	Jennifer Mendoza
PI Berlin	Romain Pénidon
IRENA	Alessandra Salgado
PTB	Dr. Clemens Sanetra
PTB	Florian Schilling
PI Berlin	Asier Ukar
IRENA	Stephanie Weckend
PTB	Dr. Stefan Winter

Annex C – Glossary

Accreditation	Formal recognition that an organization is competent to perform specific tasks. For example, testing and calibration laboratories and certification or inspection bodies are accredited for specific services.
Calibration laboratory	Laboratory that measures against a superior standard. The national metrology institute (NMI) defines the primary national standards. Secondary calibration laboratories are often attached to universities, research centres or private companies. They provide calibration services for all kinds of measuring equipment.
Compliance	Conforming to a rule, such as a specification, written down in standards or technical regulations.
Conformity	Compliance of a product, service, process, system, individual or body with the requirements specified.
Conformity assessment	Any activity whose objective is to determine, directly or indirectly, whether the requirements specified for a product, process, system, individual or body are met. Conformity assessment includes activities such as: sampling, testing, inspection or certification; as well as the accreditation of conformity assessment bodies.
Inspection	Assessment of the design of a product, the product, a process or facilities and determination of its conformity with specific requirements or, on the basis of professional judgement, with general requirements. Inspection of a process may include inspection of people, facilities, technology and methodology.
Metrology	The science of measurement. A distinction is made between scientific, legal and industrial metrology.
National quality system	Group of organizations responsible for the quality infrastructure of a country. It usually includes metrology, standards and accreditation bodies.
Nonconformity	Deviation from a specification, a standard or technical regulation. Nonconformities are known as a defect and classified as critical, major or minor.
Proficiency testing	Use of interlaboratory comparisons to determine the individual performance of laboratories in carrying out specific tests or measurements.
Quality	Degree to which a group of inherent characteristics meets requirements. It is demonstrated by customer satisfaction.
Quality assurance	Measures that *focus on providing confidence that quality requirements will be fulfilled* (ISO 9000). It is part of quality management and includes the use of quality infrastructure services.
Quality infrastructure	The system comprising the organizations (public and private) together with the policies, relevant legal and regulatory framework, and practices needed to support and enhance the safety, quality and environmental soundness of goods, services and processes.

Standards	Voluntary agreements made by stakeholders on a product, a service or a process. Formal international standards are developed using the core WTO TBT principles of transparency, openness, impartiality and consensus, effectiveness and relevance, coherence, and addressing the concerns of developing economies. Private standards are elaborated by private or non-governmental organizations (*standards setters*). Standards are prepared by all interested parties. The consensus-based process is facilitated by a national, regional or international standards body. Compliance with standards is voluntary; they can, however, be referenced in legislation and private contracts.
Technical barriers to trade	Bi- and multilateral agreements attempt to facilitate trade and eliminate technical barriers to it. Exceptions are only tolerated when they involve the legitimate interests of states.
Technical committee	Representatives of interested stakeholder groups (e.g., business sector, academia and consumers) that develop standards. This committee is guided by the national standards body, which has an advisory and facilitating role.
Technical regulations	Act issued by the competent authority which establishes the characteristics of a product or service or related products and includes applicable administrative dispositions, the observance of which is mandatory or imperative.
Testing	Determination of one or more characteristics of an object evaluated for conformity according to a procedure.
Testing and analysis laboratory	Laboratory that performs tests and analysis to generate objective data on the quality of a product or a process.
Third party	Individual or organization recognised as independent from the interested parties. The interested parties are usually the supplier (first party) or the customer (second party).
Traceability	Ability to trace or leave records of movements and processes gone through by a specific product, mainly those intended for human consumption. The concept is also applicable to the logistics management of warehouses, inventories and production processes of any product, etc. In metrology, a traceability chain is an unbroken chain of comparisons, each with their stated uncertainties. This ensures that a measurement result or the value of a standard is related to references at the higher levels, ending at the primary physical standard. In chemistry and biology, traceability is often obtained by using certified reference materials (CRM).
Value chain	Complete range of activities carried out by companies taking the product from its creation to its end use and beyond. This process includes materials, production and distribution and it usually involves a number of companies and supporting institutions.

References

All internet sources were accessed between May 2020 and June 2021.

Bakhiyi, B., Labrèche, F., Zayed, J. (2014). 'The photovoltaic industry on the path to a sustainable future– Environmental and occupational health issues'. Environment International. 73. p.224-234.

Consolidated Electrical Distributors Inc. (2020). Inverter Reliability Testing: How do they do it? [Online] Retrieved from: *https://www.cedgreentech.com/article/inverter-reliability-testing-how-do-they-do-it-0*.

EURAMET (2015). Metrology for Smart Electrical Grids. [Online] Retrieved from: *https://www.euramet.org/research-innovation/search-research-projects/details/project/metrology-for-smart-electrical-grids/*.

Frame, D., Tembo, K., Strachan, S. (2011). 'A community-based approach for sustainable off-grid PV systems in developing countries'. IEEE Power and Energy Society General Meeting. p. 1–7.

GIZ (2018). End-of-Life Management of Batteries in the Off-Grid Solar Sector: How to deal with hazardous battery waste from solar power projects in developing countries? [Online] Retrieved from: *https://www.giz.de/de/downloads/giz2018-en-waste-solar-guide.pdf*.

IECEE (2019). IECEE PV certification. The sure way to safety, quality and performance.

IKI (2021). Solar Mapping and Monitoring (SolMap). [Online] Retrieved from: *https://www.international-climate-initiative.com/en/details/project/solar-mapping-and-monitoring-solmap-10_I_142-146*.

International Finance Corporation (2015). Utility-Scale Solar Photovoltaic Power Plants: A project developer's guide. [Online] Retrieved from: *https://www.ifc.org/wps/wcm/connect/a1b3dbd3-983e-4ee3-a67b-cdc29ef900cb/IFC+Solar+Report_Web+_08+05.pdf?MOD=AJPERES&CVID=kZePDPG*.

IRENA (2017). Boosting Solar PV Markets: The Role of Quality Infrastructure. [Online] Retrieved from: *https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Sep/IRENA_Solar_PV_Markets_Report_2017.pdf*.

ISO (2015) ISO 9000:2015 Quality Management Systems – Fundamentals and Vocabulary. Retrieved from 'Preview': *https://www.iso.org/standard/45481.html*

Joule (2018). Solar Charging Batteries: Advances, Challenges, and Opportunities. [Online] Retrieved from: *https://www.cell.com/joule/pdf/S2542-4351(18)30143-0.pdf*

Kabir, E., Kumar, P., Kumar, S., Adelodun, A., Kim, K. (2017). 'Solar Energy: Potential and Future Prospects'. Sustainable Energy Reviews. 82.

LNE-CNAM (2012). Solar Metrology: Photovoltaic Module Performance Measurements. Unpublished.

Manzini, G., Gramazio, P., Guastella, S., Liciotti, C., Baffoni, G.L. (2015). 'The Fire Risk in Photovoltaic Installations – Test Protocols for Fire Behavior of PV Modules'. Energy Procedia. 82. p. 752–758.

PI Berlin (2020). Project Report. Quality Control Procedures for EPC Tendering, Construction and Operation of PV Projects in India. Unpublished.

PI Berlin (2019). PI Berlin introduces deep dive quality assessment for lithium-ion battery production. [Online] Retrieved from: *https://www.pi-berlin.com/battery-diligence/*

PTB (2016). Quality and safety criteria applied in financing photovoltaic projects. [Online] Retrieved from: *https://www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_9/9.3_internationale_zusammenarbeit/datasheet/PTB_Q5_Study_Financing_Photovoltaic_EN.pdf*

PTB (2017). Pilot Study on Quality Aspects of PV Power Plants in India. [Online] Retrieved from: *https://energypedia.info/images/0/09/Pilot_Study_on_Quality_Aspects_of_PV_Power_Plants_in_India.pdf*

PVQAT (2020). About the International PV Quality Assurance Task Force. [Online] Retrieved from: *https://www.pvqat.org/about/*

Redlinger, M., Eggert, R., Woodhouse, M. (2015). 'Evaluating the availability of gallium, indium, and tellurium from recycled photovoltaic modules'. Solar Energy Materials and Solar Cells. 138. p. 1–4.

Sanetra, C., Marbán, R.M. (2007). The Answer to the Global Quality Challenge: A National Quality Infrastructure. [Online] Retrieved from: *https://www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_9/9.3_internationale_zusammenarbeit/publikationen/102_National_QI/PTB_Q5_National_QI_EN.pdf*

Schwerhoff, G., Sy, M. (2017). 'Financing renewable energy in Africa – Key challenge of the sustainable development goals'. Renewable and Sustainable Energy Reviews. 75. p. 393–401.

Shahsavari, A., Akbari, M. (2018). 'Potential of solar energy in developing countries for reducing energy-related emissions'. Renewable and Sustainable Energy Reviews. 90. p. 275–291.

Solar Bankability (2017). Financial Modelling of Technical Risks in PV Projects. [Online] Retrieved from: *http://www.solarbankability.org/fileadmin/sites/www/files/documents/D4.2_Report_on_Financial_Modelling_of_PV_Risks_SB-Final_160930.pdf.*

SolarPower Europe (2021). Solar O&M Best Practices Mark Checklist (Indian edition). [Online] Retrieved from: *https://solarbestpractices.com/documentation/*.

Solarthermalworld (2012). India's First Reliable Solar Map Coming Soon. [Online] Retrieved from: *https://www.solarthermalworld.org/news/indias-first-reliable-solar-map-coming-soon.*

Telfser, K., Dolle, P., Ferdinand, N., Imelda, S., Sanetra, C., Walsh, T. (2019). Priorities for Quality Infrastructure Development for Photovoltaics in Indonesia. [Online] Retrieved from: *https://www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_9/9.3_internationale_zusammenarbeit/publikationen/PTB_9.3_study_photovoltaics_Indonesia_EN.pdf*.

Thiam, D.R. (2010). ‘Renewable decentralized in developing countries: Appraisal from microgrids project in Senegal’. Renewable Energy. 35. p. 1615–1623.

UNIDO (2019). Quality Infrastructure for Sustainable Development. [Online] Retrieved from: *https://tii.unido.org/sites/default/files/publications/QI%20and%20Sustainable%20Development_2019.PDF.*

United Nations (2021). Leveraging energy action for advancing the Sustainable Development Goals. [Online] Retrieved from: *https://sdgs.un.org/sites/default/files/2021-06/2021-SDG7%20POLICY%20BRIEFS.pdf.*

U.S. Energy Information Administration (2012). New technology can improve electric power system efficiency and reliability. [Online] Retrieved from: *https://www.eia.gov/todayinenergy/detail.php?id=5630.*

World Trade Organization (2021): Agreement on Technical Barriers to Trade. [Online] Retrieved from: *https://www.wto.org/english/docs_e/legal_e/17-tbt_e.htm.*

Abbreviations and Acronyms

ANME	National Agency for Energy Management (Tunisia)
ASTM	American Society for Testing and Materials
BGR	Federal Institute for Geosciences and Natural Resources (Germany)
BIPM	International Bureau of Weights and Measures
BIS	Bureau of Indian Standards
BREF	Best Available Techniques Reference Documents
CENAM	National Metrology Institute of Mexico
CERER	Center for Studies and Investigation on Renewable Energies (Senegal)
CRE	Energy Regulatory Commission (France)
CSIR-NPL	National Physical Laboratory, under the Council of Scientific & Industrial Research
DC	Direct current
EL	Electroluminescence
EPC	Engineering, Procurement and Construction
ESP	Polytechnic Institute (Senegal)
IAF	International Accreditation Forum
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
IGEF	Indo-German Energy Forum
ILAC	International Laboratory Accreditation Cooperation
INMETRO	National Institute for Metrology, Quality and Technology (Brazil)
IPPC	Integrated Pollution Prevention and Control
I-V	Current-voltage
IREDA	Indian Renewable Energy Development Agency
ISO	International Organization for Standardization
LTE	Lenders' technical engineer
MNRE	Ministry of New and Renewable Energy (India)
MW	Megawatt
MWp	Megawatt peak
NMI	National Metrology Institute
NPL	National Physical Laboratory (India)
NSEFI	National Solar Energy Federation of India
OIML	International Organization of Legal Metrology
O&M	Operation & maintenance
PMU	Phasor measurement units
PT	Proficiency testing
PTB	Germany's national metrology institute
PV	Photovoltaic
PVEX	Company name
PVQAT	International Photovoltaic Quality Assurance Task Force
QI	Quality infrastructure

RfP	Request for proposal
R&D	Research and development
SECI	Solar Energy Cooperation of India Limited
SCADA	Supervisory control and data acquisition
SDGs	Sustainable Development Goals
TBT	Technical barriers to trade
T&D	Transmission and distribution
UL	Underwriters Laboratories
UN	United Nations
WEEE	Waste Electrical and Electronic Equipment

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Niels Ferdinand is founder and director of Ferdinand Consultants. With over 20 years of experience in the consulting field, Niels has empowered numerous organizations on five continents to create positive sustainability impact. As an international consultant for PTB, the World Bank and IFC, he guides the strategies and activities of projects focused on quality infrastructure in developing economies. For more than eight years, Niels has accompanied PTB quality infrastructure projects in the photovoltaic sectors of India, Indonesia and Vietnam.

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Ferdinand Consultants is an international sustainability consultancy, fostering sustainable impact with a team that combines international experience and local knowledge. For over 20 years, the team of Ferdinand Consultants has been advising national governments, international organizations, development agencies and NGOs on how to foster quality infrastructure in developing economies. The company's unique expertise and international field experience are applied in numerous projects supporting quality, safety and sustainability in the renewable energy sector.

Notes

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