Research Article

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The global dimension of the energy transition

Die globale Dimension der Energiewende

Contributions from PTB's international cooperation
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Abstract: The paper highlights the global dimension of the energy transition and the crucial role of quality infrastructure. With a growing global population and rising energy consumption, the demand for electricity worldwide could almost double by 2050. This requires a fundamental shift from fossil energy systems to more sustainable and environmentally friendly alternatives. The energy transition involves not only technological but also societal transformations that enable the shift to renewable energy sources. A key facilitating and driving factor is quality infrastructure: it encompasses metrology, standardization, accreditation, conformity assessment, and market surveillance, enhancing the quality, safety, and environmental compatibility of products, services, and processes. The projects of the Physikalisch-Technische Bundesanstalt (PTB) International Cooperation contribute significantly to the development of a robust and reliable quality infrastructure that promotes international trust in products and services. Through close cooperation with global partners, internationally recognized cross-sector standards and good measurement and testing practices, for example, are developed to sustain free and fair trade while boosting safety and quality. This collaboration enables partner countries to establish their own national quality infrastructure, thus strengthening their position in global value chains and advancing the global energy transition. These complex interrelations are illustrated by examples from Vietnam and Tunisia.

Keywords: quality infrastructure; international cooperation; photovoltaics; green hydrogen; Vietnam; Tunisia

Kurzfassung: Der Artikel beleuchtet die globale Dimension der Energiewende und die entscheidende Rolle der Qualitätsinfrastruktur. Angesichts der wachsenden Weltbevölkerung und des zunehmenden Energieverbrauchs könnte sich der weltweite Strombedarf bis 2050 nahezu verdoppeln. Dies erfordert einen grundlegenden Wandel von fossilen Energiesystemen hin zu nachhaltigeren, umweltfreundlicheren Alternativen. Die Energiewende umfasst nicht nur technologische, sondern auch gesellschaftliche Veränderungen, die einen Aufschwung von erneuerbaren Energiequellen ermöglichen. Ein zentraler begünstigender und treibender Faktor ist dabei die Qualitätsinfrastruktur: sie umfasst Metrologie, Normung, Akkreditierung, Konformitätsbewertung und Marktüberwachung, und unterstützt die Qualität, Sicherheit und ökologische Verträglichkeit von Produkten, Dienstleistungen und Prozessen. Die Projekte der Internationalen Zusammenarbeit der Physikalisch-Technischen Bundesanstalt (PTB) tragen wesentlich zum Aufbau einer robusten und zuverlässigen Qualitätsinfrastruktur bei, die internationales Vertrauen in Produkte und Dienstleistungen fördert. Durch die enge Kooperation mit globalen Partnern werden z.B. weltweit anerkannte sektorübergreifende Standards oder gute Mess- und Prüfpraktiken entwickelt, um den freien und fairen Handel zu stärken und gleichzeitig Sicherheit und Qualität zu erhöhen. Die Zusammenarbeit ermöglicht es den Partnerländern, eine eigene nationale Qualitätsinfrastruktur zu etablieren, wodurch sie ihre Position innerhalb von globalen Wertschöpfungsketten festigen und die globale Energiewende voranbringen. Diese komplexen Zusammenhänge werden anhand von Beispielen aus Vietnam und Tunesien veranschaulicht.

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1 Quality infrastructure as a cornerstone of the global energy transition

The world's continuous population growth, together with a steady increase in energy consumption, is driving a surge in global electricity demand that is expected to almost double by 2050 [1]. This trend highlights the urgent need to transition from traditional fossil-based energy systems to innovative, future-ready sustainable solutions. Today's predominant model of energy generation entails two fundamental issues: (1) the limited availability and finite resources of fossil fuels and (2) the resulting emissions and their contribution to global climate change. In response to these challenges, new forms of renewable energy generation and innovative models with enhanced efficiency and cross-sectoral approaches have emerged. Collectively, these approaches are often referred to as the *energy transition*. While there is no uniform or universally recognized definition of the term "energy transition", many publications (for example, from the International Energy Agency – IEA and the International Renewable Energy Agency – IRENA), describe key aspects of it in detail [1], [2]. The following summary can serve as a working definition of an energy transition and provide orientation for the context presented in this article.

An energy transition is a broad shift in technology and behavior oriented towards replacing one source of energy with another. Apart from a shift towards renewable energy forms, this can imply, for example, shifting from centralized to distributed energy generation, reducing energy consumption via energy-saving measures and increased efficiency, and utilizing overproduction by introducing storage technologies. Additionally, the transformation described includes broader objectives such as reducing greenhouse gas emissions, enhancing energy security, and promoting sustainable development. The International Energy Agency (IEA) has stressed that achieving this transition is crucial for limiting global temperature rise and the negative effects of climate change while also pointing out that its aims are crucial for future energy security [1].

For an energy transition to be successful, it is essential that uniform standards for components and procedures be established across technologies and accompanied by regulatory frameworks conducive to the transformation. As most energy systems, particularly electricity grids, are interconnected (in many cases across countries and even continents), these regulatory and standards frameworks must be harmonized to ensure seamless operation. Furthermore, they must be supported by recognized conformity assessments such as product and plant inspections, system and personnel certifications, material and component testing, and reliable, comparable measurements. The comprehensive system of such services, standards and regulatory frameworks is collectively referred to as *quality infrastructure* (QI). The International Network on Quality Infrastructure (INetQI) defines QI as "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 quality, safety, and environmental soundness of goods, services, and processes" [3]. The key components of QI, according to INetQI, include metrology, standardization, accreditation, conformity assessment, and market surveillance. The simplified interaction of these components around a supplier/buyer relation is shown in Figure 1.

Technical regulation is supported by conformity assessment activities, which are depicted in Figure 1 as certification, testing, metrology and inspection. Standardization establishes common benchmarks and guidelines, ensuring that products and processes meet universally accepted criteria. Standards are voluntary by nature but are generally employed by regulators to avoid regulation in too much detail (considered internationally to be good regulatory practice) and can therefore become mandatory indirectly. Whether in voluntary application between contract partners or in the field of regulation, conformity assessment is key to evaluating compliance. Metrology provides an important foundation for conformity assessment by ensuring accurate, consistent and comparable (traceable) measurements. Accreditation ensures that organizations and bodies performing conformity assessments are qualified and competent to perform their specific tasks. Lastly, market surveillance, which in Figure 1 under technical regulation, ensures that products and services in the marketplace meet regulatory requirements, preventing, for example, non-compliant goods from circulating.

Together, these components form a robust framework that supports safe, efficient, and interoperable systems that are essential for the successful implementation of energy solutions. QI facilitates the international exchange of energy technologies, promotes the scaling up of renewable solutions, and fosters collaboration between countries with different energy needs and resources. Its roles as enabler and

Figure 1: Elements of quality infrastructure (Source: PTB).

facilitator of trustworthiness make QI a cornerstone of the global energy transition.

2 PTB's international cooperation in the context of German development policy

The Physikalisch-Technische Bundesanstalt (PTB) is the national metrology institute of Germany, but its impact extends far beyond national borders. PTB plays a key role in international calibration services, the global harmonization of measurements, and metrological research. What sets PTB apart from other national metrology institutes is its unique international orientation. For more than 60 years, the institute has been involved in technical cooperation projects commissioned by the German Federal Ministry for Economic Cooperation and Development (abbreviated in German as BMZ). In such projects, PTB focuses on the field of quality infrastructure to strengthen the expertise of partner institutions in developing and emerging countries. Besides metrology, depending on the specific context, the cooperation includes other fields of QI such as standardization, accreditation, conformity assessment and occasionally market surveillance. The primary goal of technical cooperation is to facilitate technology transfer and build technical capacities. Depending on the circumstances, PTB's engagement often extends to providing political and strategic advice, conducting systems analyses, raising awareness, and promoting regional cooperation among partner countries.

The thematic focus of PTB's projects varies in alignment with the national goals of its partner countries and underlying governmental agreements. The projects encompass diverse sectors including trade and sustainable economic development, health, water and sanitation, environmental monitoring, and energy. The BMZ defines sectoral strategies for Germany's development cooperation policy. In the area of energy, the main guideline is the BMZ Core Area Strategy: *Responsibility for Our Planet – Climate and Energy* [4]. This strategy is closely aligned with United Nations Sustainable Development Goal 7, "Ensure access to affordable, reliable, sustainable and modern energy for all", and its respective targets [5]. The BMZ focuses on two main areas of intervention: "Climate Change Mitigation and Adaptation" and "Renewable Energy and Energy Efficiency", while the strategy's overall objective is stated as "the BMZ advocates meeting the rapidly rising demand for energy in a climate-neutral way while at the same time fully decarbonizing the energy sector by 2050" [6]. While these strategic documents give orientation and provide justification for Germany's engagement in development cooperation, all initiatives and projects must be aligned to the partner countries' policies and strategies. Intergovernmental consultations and negotiations ensure that approaches are not one-sided, while in-depth bilateral discussions precede any concrete cooperation engagement.

The overarching goals and agreements are consequently translated into projects designed to support and strengthen the strategies and objectives of partner countries, in this case in the field of climate and energy. Most countries in the world are working towards achieving a national energy transition to reduce both their dependency on fossil fuels and their CO2 emissions. German development cooperation partner countries can benefit in this field from the support given by PTB and other semi-governmental agencies such as GIZ (Gesellschaft für Internationale Zusammenarbeit) [7], Germany's international technical cooperation agency, and the KfW Development Bank for financial cooperation [8]. The following chapter will provide specific examples from PTB's engagement in two energy-related projects, illustrating how the project objectives are being implemented in practice: the first example is taken from the photovoltaics sector in Vietnam and the second from the introduction of green hydrogen in Tunisia.

3 International partnerships on quality for a sustainable energy future

In today's interconnected world, global challenges require global solutions. Issues such as climate change, energy security, and sustainable development demand collective action. International collaboration plays a pivotal role in addressing these pressing concerns. The energy transition, which involves shifting towards renewable energy and reducing carbon emissions, is one such global challenge that necessitates cross-border cooperation as well as policies and frameworks conducive to a sustainable development [9]. The successful implementation of this transition as described above depends not only on political will, economic potential and technical expertise but also on the establishment of a robust and internationally embedded and recognized national quality infrastructure. There can be no one-size-fits-all approach to international collaboration in QI for energy; instead, the specific context, challenges and opportunities of each partner country must be considered. Partnerships help to foster innovation, promote knowledge transfer, and enable the scaling of renewable energy solutions while respecting local needs, conditions, contexts, and cultures. In addition, reciprocal exchange of experience and perspectives is essential to ensure mutual benefit and helps to develop solutions for global challenges in energy transition.

The power of economies of scale and integrated, universally applicable solutions should, nevertheless, not be underestimated. Global interlinkages through international trade and investment agreements together with a limited number of companies competing worldwide in renewable energy technologies make individual solutions difficult to realize. Therefore, governments actively request that internationally agreed-upon procedures and technologies be adopted, as this is in their best interest. However, it must be conceded that there is also evidence for contrary causality as indicated by Asmelash [10]. Specific challenges in harmonizing international trade law and national regulatory measures and policies that are crucial for the energy transition represent obstacles to international cross-border cooperation, trade and investment. This concerns, among other aspects, divergence in energy subsidy policies, variation of environmental requirements, climate goals and carbon taxing, and barriers created by regulatory measures and standards. The author concludes that "harmonization of standards and technical regulations around international standards helps reduce transaction costs and the risk of lobbying by domestic industries for trade-restrictive national standards and technical regulations" [10].

Moreover, recent studies such as those by Fraunhofer ISI (Institut für System- und Innovationsforschung) [11] and UNIDO (United Nations Industrial Development Organization) [12] highlight the impact of QI on sustainable development. For instance, Fraunhofer ISI presents evidence-based *impact pathways* showing how QI through its pillars supports economic growth, innovation, trade, and environmental goals. The report emphasizes QI's role as an enabler of transformative change, particularly in sectors such as energy and health, and proposes indicators to systematically capture these effects.

With focus on renewable energy, findings show that a reliable QI system is essential for the sustainable growth of solar PV markets. QI contributes to ensuring product performance, safety, and reliability, thereby fostering investor confidence and market stability. IRENA's 2017 report, Boosting Solar PV Markets: The Role of Quality Infrastructure [13], provides quantified cost-benefit analyses, highlighting that the benefits of QI services consistently outweigh their costs. The implementation of quality assurance measures such as independent quality testing during the engineering, procurement, and construction phases can improve PV system performance by 2–3 %. This enhancement leads to increased energy generation, reduced degradation rates, and improved energy yield, ultimately boosting revenues for project owners and lowering the levelized cost of electricity over the system's lifetime. Additionally, adopting QI practices reduces the risk of system failures and associated costs. For instance, addressing potential induced degradation through inspections and corrective actions can prevent significant underperformance, safeguarding the financial viability of PV projects. A well-established QI framework also fosters confidence among investors, policymakers, and consumers, making PV systems more attractive and facilitating market expansion [13], [14].

The pivotal role of quality infrastructure in facilitating socio-technical transformations has also been examined in literature such as Knut Blind [15], [16]. He emphasizes that, while regulation initiates change, standardization accelerates the adoption of new technologies, and QI's alignment with global standards is crucial for enabling sustainability and innovation. Furthermore, although traditionally rooted in technical domains, QI is increasingly intersected with broader societal goals. Inclusive development encompassing gender equality, the empowerment of marginalized groups, and the recognition of minority needs has become a central concern in global development agendas. The integration of inclusive principles into QI frameworks offers the opportunity to expand the reach and relevance of technical regulation and innovation. Standards can promote accessibility, gender-sensitive design, and social fairness, while the technical aspects of metrology, testing, inspection and certification systems can support equitable access to technology, markets, and public services.

IRENA's report on a gender perspective for renewable energy is one example from literature emphasizing the need for greater inclusion of women in the renewable energy sector and highlighting their underrepresentation in technical and decision-making roles [17]. Women currently make up 32 % of the workforce in renewable energy, a higher proportion than in traditional energy sectors. However, significant barriers remain, such as cultural norms, lack of gender-sensitive policies, and limited access to training opportunities in technical fields. These challenges are particularly relevant to QI, which plays a critical role in shaping the policies, standards, and practices that drive energy transition and adoption of technology. Thus, QI should not be viewed solely as a technical instrument but as a strategic enabler for more inclusive, participatory, and equitable development processes. These important and complex societal issues merit in-depth exploration to fully understand their implications for sustainable development of the energy transition. However, given the scope and focus of this paper, we concentrate primarily on the technical dimensions of the topic, while acknowledging that a comprehensive analysis would require a broader interdisciplinary perspective. The following chapters give examples of PTB's engagement in support of the energy transition in Vietnam and Tunisia.

3.1 Advancing quality infrastructure for photovoltaics in Vietnam

Vietnam is an emerging economy in Southeast Asia [18] that plays a significant role in the global effort to address climate change and transition towards sustainable energy. With its rapidly growing economy and increasing demand for energy, Vietnam faces important challenges in balancing economic growth with environmental responsibility. A sharp increase in electricity demand from economic sectors and households [19] has contributed to higher greenhouse gas emissions. At the same time, the country is highly vulnerable to climate change, particularly due to its long coastline, mountainous geography, numerous river valleys, and the risks resulting from rising sea levels and extreme weather events.

In response to these conditions, the current government committed itself to green growth by entering a Just Energy Transition Partnership (JETP) with the G7 International Partners Group in December 2022. Historically, Vietnam's energy generation has been roughly divided equally between hydropower, coal, and natural gas. However, since 2017, the country has significantly increased its share of solar and wind energy, reaching initial milestones in its energy transition. Vietnam aims to achieve net-zero emissions by 2050 and phase out coal by the late 2040s [20], [21]. Achieving net-zero emissions will require the same radical measures being pursued by many other countries: accelerating the coal phase-out, expanding renewable energy generation, and improving energy efficiency.

Germany's development cooperation supports Vietnam in its transition to sustainable, climate-neutral, and inclusive development through policy advice, technology transfer, capacity building, and quality assurance services in solar, wind, biomass, hydrogen, smart grids, and energy efficiency. The focus is partly on ensuring a so-called "just transition", including social measures such as structural adjustments in coal mining regions, vocational training for marginalized groups, and targeted social and labor policies. As Vietnam's energy sector is evolving, the integration of renewable energy requires not only technological advancement but also a robust regulatory framework, industry standards and adequate quality assurance, which is precisely where QI plays a vital role. Vietnam's participation in international projects with PTB funded by the BMZ has been instrumental in strengthening its institutional capacity in areas such as metrology, standardization, accreditation, and conformity assessment [4], [22].

3.1.1 Quality assurance along the PV value chain

The growing importance of green technologies such as photovoltaics and green hydrogen offers useful opportunities for Vietnam to reduce its carbon footprint and promote sustainable energy solutions. As part of this transition, the future of energy generation is increasingly focused on renewable sources, with solar energy playing a leading role in the shift towards an all-electric society. However, despite the potential of photovoltaic (PV) systems, the growth of the sector is still held back by challenges related to quality, safety, and sustainability. Renewable energy technologies must be integrated in a way that is both efficient and sustainable. One way to ensure this is to harmonize national standards with international ones, enabling smoother cross-border trade of energy technologies and energy itself as well as fostering regional cooperation. These and other challenges along the value chain of PV systems – production, installation, use, and end-of-life stages – can be addressed by developing robust QI, a crucial element for ensuring the efficiency and long-term success of PV systems [23].

In countries like Vietnam, the rapid expansion of the PV sector, driven by incentives like feed-in tariffs, has underscored the urgency for improving quality infrastructure. Since the introduction of such tariffs in 2019 and 2020, Vietnam has seen its PV capacity surge by more than 16.6 GW. Yet the swift growth of the sector has outpaced the development of the necessary QI, leaving a gap in quality assurance services that must be filled to prevent future issues. Metrology and competent calibration services are essential to ensure the accuracy and traceability of measuring instruments that influence system design, process control and yield recording. For example, in the system design and equipment selection phase, inaccurate meteorological data such as faulty irradiance measurements can lead to a suboptimal choice of site, flawed design and unreliable performance predictions. During transport, installation, and commissioning, safety hazards often arise, including improper cabling, incorrect grounding, or poorly connected components. These issues increase the risk of malfunction or even fire and pose significant safety threats to both installers and nearby residents. Conformity assessment services such as certifying installers and inspecting PV systems during construction and commissioning play a crucial role in ensuring safety. Finally, for the end of a PV system's life cycle, a lack of recycling-ready designs and inefficient recycling processes can result in the wastage of valuable materials such as silver, indium, and tellurium while contributing to environmental pollution. Developing standards for recycling and reuse along with services that certify the carbon footprint of recycled materials and test the suitability of components for reuse and recycling is critical for addressing these deficiencies and improving the overall sustainability and reliability of the PV sector [23], [24].

A holistic and coordinated approach to QI development is essential to ensure the future success of the PV sector. PTB's bilateral QI project with Vietnam, titled "Promotion of Quality Assurance Services for Sustainable Energy", demonstrates how the simultaneous development of different QI elements such as metrology, conformity assessment, and standardization can support the sector's growth [25]. This approach emphasizes the importance of integrating quality assurance measures from the very beginning, rather than waiting for inefficiencies and accidents to prove their necessity.

3.1.2 Importance of collaboration and international standardization

One key aspect of this strategy is the creation of a supportive policy framework. The success of previous measures in Vietnam such as feed-in tariffs (FiT Phase I) shows that they are crucial to creating incentives for sustainability and the expansion of the sector [26]. However, future policies must prioritize the development of quality infrastructure alongside technological growth. Fostering awareness and facilitating communication between stakeholders is another vital component of quality infrastructure development. Collaboration between government bodies, PV companies, and QI institutions is necessary to create a unified strategy for quality assurance. In Vietnam, this has been facilitated by PTB's project through methodologies like Calidena [27] and collaboration within sectoral groups like the Vietnam Energy Partnership Group (VEPG).

Moreover, it is crucial to base QI development on international best practice. Vietnam's participation in international energy collaboration also involves adapting its energy policies and strategies to align with global standards while addressing local challenges. By engaging with global standardization bodies such as the International Electrotechnical Commission (IEC), Vietnam can ensure that its PV sector adheres to global standards while also adapting those standards to local needs if required. Through this international cooperation, Vietnam can integrate tried-and-tested quality assurance practices into its own regulatory framework. This balancing act ensures that global solutions are available but can be tailored to Vietnam's unique social, economic, and environmental context.

An illustrative example of practical implementation can be found in the ongoing PTB project, which includes a standardization component focused on the systematic evaluation of PV standards within the national context. The process begins with a comprehensive study in which the PV standards currently applicable at the international level are identified and compared with the standards implemented in the national context of Vietnam. Here, the objective is to evaluate both the extent of global harmonization and any specific national requirements or gaps within the existing standards framework. Jointly with the Vietnamese Technical Committee for Standardization in Renewable Energy, as well as contributions from a wide range of technical experts and sector stakeholders, a set of PV standards not yet available in the national context and/or not yet updated were selected and prioritized based on their relevance. The ongoing activities support the integration and updating of these standards into the Vietnamese national standardization system.

3.1.3 Testing and calibration: the role of solar simulators

Looking ahead, the development of quality infrastructure in countries like Vietnam must be aligned with the national PV strategy and maintain pace with the sector development. PTB's experience in countries throughout the world shows that a deep understanding of national policies and the state of the industry is essential for creating relevant and effective QI systems. A prime example of this can be seen in the rapidly evolving solar energy industry in Vietnam, and PV module production in particular. An essential element for quality assurance is the accurate classification of solar simulators and their calibration against reference modules within manufacturing facilities and testing laboratories. This ensures that PV modules are tested under conditions that closely mimic actual sunlight, leading to reliable performance data.

Solar simulators are specialized devices that replicate sunlight to test and calibrate PV cells and modules under controlled indoor conditions. Their performance is categorized into 4 classes from A+ (the best category) down to C, based on three primary criteria defined in the international standard IEC 60904-9:2020: spectral match, spatial non-uniformity of irradiance, and temporal instability of irradiance [28]. The spectral match assesses how closely the simulator's light spectrum aligns with the standard solar spectrum across specific wavelength intervals. A precise spectral match ensures that PV modules are tested under conditions that accurately reflect real-world sunlight exposure. Spatial non-uniformity of irradiance is a criterion that measures the uniformity of light intensity across the test area. High uniformity is crucial to ensure consistent illumination of the PV module during testing. Temporal instability of irradiance evaluates the stability of the light output over time, encompassing both short-term and long-term fluctuations. Stable light output is essential for obtaining repeatable and accurate measurements of PV modules.

The classification and calibration of solar simulators directly affects the quality of PV modules produced. Every module is tested before leaving the factory. Accurate testing conditions enable a precise assessment of a module's efficiency, ensuring that only high-performing modules reach the market and meet the expected yield. The modules are classified into different yield classes based on the test results. Consequently, trust in the stated performance data of entire PV systems is enhanced, as such data relies on the consistent accuracy of the measurement of individual PV modules.

Among the activities of the joint project is the ongoing capacity building for the classification and calibration of solar simulators. Local institutions' technical capabilities are being enhanced and expanded to ensure that solar testing equipment is accurate and reliable. These improvements contribute to the successful development of the renewable energy sector and foster the quality infrastructure in general.

In conclusion, to fully realize the potential of the PV sector, a comprehensive and systematic quality infrastructure is essential. Ensuring that quality, safety, and sustainability are integrated throughout the entire PV value chain – from design to installation and recycling – will be crucial for the long-term success of solar energy systems. This holistic approach not only strengthens the sector's reliability but also supports global climate commitments. Furthermore, the collaboration between Vietnam and its international partners in energy and quality infrastructure plays a key role in driving a successful energy transition. By leveraging global expertise, aligning with international standards, and addressing national requirements, Vietnam is paving the way for a sustainable energy future that contributes to both regional and global climate goals, making solar power a cornerstone of its future energy system.

3.2 Enhancing quality infrastructure for green hydrogen in Tunisia

Tunisia, due to its location in North Africa, has excellent climatic conditions and an outstanding potential for renewable energy generation in the form of solar and wind energy [29]. The country, which is still heavily dependent on fossil fuels for energy production, has set for itself the ambitious goal of 45 % carbon intensity reduction by 2030, compared to its 2010 level [30]. Additionally, in 2024, a green hydrogen strategy linked to the national climate and carbon reduction policies was formulated. It comprises Tunisia's vision "to achieve a sustainable, carbon-neutral and inclusive green hydrogen economy by 2050" and to produce more than 8 Mt of renewable hydrogen by that year [31]. Here as well, the geographic location of Tunisia is an important asset regarding access to future hydrogen markets. The country's proximity to Italy and an existing gas pipeline from Algeria to Sicily via Tunisia is a potential export route for the energy carrier produced. This so-called SouthH2 Corridor is among the Projects of Common Interest (PCI) of the European Commission [32].

This promising framework is the setting for the German government to provide support for renewable energies and energy efficiency, as agreed upon with the Tunisian government. Both countries are committed to the objectives of decarbonization and energy transition, and the BMZ is dedicating significant resources to its Tunisian partners in this field [33], [34]. Furthermore, there is the German-Tunisian Energy Partnership led by the German ministry for economic affairs and climate action (abbreviated in German as BMWK), which consists in a political dialogue and high-level cooperation "in the field of energy policy, achieving international climate goals and making climate neutrality a reality by 2045" [35].

PTB is currently implementing a bilateral cooperation project funded by BMZ to support quality infrastructure for the production and use of green hydrogen together with its Tunisian counterparts [36]. The main objective of this cooperation is to create new QI services and improve the available ones required for developing the green hydrogen value chain. The political partner is the Tunisian Ministry of Industry, Mines and Energy (Ministère de l'Industrie, des Mines et de l'Énergie – MIME), which is responsible not only for energy but also for the guidance and coordination of the national quality infrastructure.

Another link to Tunisia has been created through a BMZ financed project by the International Renewable Energy Agency (IRENA) in cooperation with PTB which has produced a publication titled "A Quality Infrastructure Roadmap for Green Hydrogen". This joint work intends "to raise awareness on the importance of quality infrastructure for the green hydrogen value chain and […] to provide recommendations on the development of the related services" [37]. During its development, the roadmap approach was piloted in a Tunisia case study, giving the authors orientation about the suitability and applicability of the approach while providing Tunisia with informative results with the potential to guide further work on QI for green hydrogen [38]. This case study lays the foundation for PTB's engagement with its Tunisian partners in the above-mentioned bilateral project.

A major challenge for the concrete implementation of measures strengthening the national QI for green hydrogen in Tunisia is the many missing parts in the "big puzzle". As the global ramp-up of green hydrogen is much slower than expected [39], it is not clear which investments will take place and which infrastructure elements and services are necessary to support it. However, experience from other countries that have a long history of hydrogen production and utilization (based almost exclusively on fossil fuel technologies) clearly indicates the need for certain basic framework conditions and services to be in place. This includes all fields of QI: standards and regulation, metrology, testing, inspection, certification and the respective accreditation of conformity assessment activities. Based on this and on the findings of IRENA's roadmap publication [37], it is likely that PTB's cooperation project with Tunisia will focus on the following areas: standards development, regulatory frameworks for explosion protection, metrology, and testing services. Support will be provided mainly through consultancy and technical assistance, training, and workshops for sensitization and exchange between stakeholders and interested parties. Cooperation with academic institutions and private sector associations is also envisaged. In the following, three areas of cooperation are described in more detail as examples of the approach and its intended impact.

3.2.1 Standardization

Standards are established by consensus and describe criteria for products, services, and processes. Because standards are an important element to create confidence regarding safety, quality, reliability and compatibility, they are usually the basis for any conformance statement. Given that green hydrogen produced in Tunisia will not only be used nationally but is largely destined for export, the use of international technical standards is indispensable to guarantee the fulfillment of customer requirements and expectations. This is also true for the materials and technologies applied, most of which Tunisia will have to import. It is therefore of key importance that Tunisia adopt existing international standards from the International Standards Organization (ISO) or the International Electrotechnical Commission (IEC) so that they are accessible for Tunisian economic actors as well as for regulators and policy makers. The Tunisian standards institute INNORPI (Institut National de la Normalisation et de la Propriété Industrielle), PTB's partner, can play a role in and influence standard-making at an international level by actively participating in international standards committees. PTB will support INNORPI in this process with advice on the selection of international committees, facilitating participation and providing needed additional expertise from outside of Tunisia.

3.2.2 Explosion protection

PTB has a 75-year history of engagement in explosion protection, encompassing many dangerous substances that include hydrogen. It is a notified body within the European Union legislative framework and a certification body under the IEC System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres (IECEx). With its longstanding experience in the fields of research, testing, consultancy, training and participation in international standardization, PTB has begun to engage with Tunisian partners to support the regulatory framework needed for the safety of products, plants, and processes, as well as the protection of human health in connection with hydrogen along the entire value chain. Tunisia has industrial safety and explosion protection measures in place and, as in many other fields, the country is strongly oriented towards the European Union approaches and guiding ATEX regulations (Atmosphères Explosibles – French for explosive atmospheres). Jointly with the responsible unit from the partner ministry MIME, the project will analyze the existing needs and challenges with respect to production, handling, storage, transport and transformation or utilization of (green) hydrogen. This analysis will direct the actions to follow.

3.2.3 Metrology and testing

As with any other energy carrier, hydrogen needs to be measured for process control, billing and tax requirements, among other purposes. The calibration of flow meters used to quantify gaseous hydrogen volume and mass, and that of its liquid derivatives, is a new area for Tunisia and metrological traceability to a national or international reference must be ensured. Flow meter calibration is of great relevance for the PTB project, which is currently identifying the most appropriate Tunisian counterpart to work with on this topic. There are other fields of metrology that require strengthening (e.g. pressure, temperature, humidity, and chemical composition and purity assessment – for more details consult Krietsch & Wehrhahn [40]) and further investigations will be made by the project partners to prioritize the multiple options.

As the smallest molecule in the universe, hydrogen has properties that make its use unique and more challenging than other gases. Two such properties are its low minimum ignition energy (for reference and further detail consult chemsafe database [41]) and the fact that it is an invisible and odorless gas. The combination of these properties means hydrogen is very hazardous and requires careful handling, entailing strict requirements, including material and leakage testing. These tests apply to any installation (electrolyzers, pipelines, storage tanks, transport vessels etc.) that contains relevant concentrations of hydrogen. Therefore, capacities to carry out such tests are needed in Tunisia for the ramp-up of its hydrogen production. Several governmental technical centers that have been created to support Tunisian industry are engaged in knowledge transfer, consultancy and testing services for their clients grouped by sectors [42]. Among these, PTB together with its counterparts from MIME intends to select a specific field and partner to work with in the project.

4 Conclusion

It has been shown that international cooperation, through capacity building and knowledge transfer, can be an important instrument to support partners in developing and emerging economies in their development of new competencies. Such competencies are needed to promote technological development and innovation with the aim of achieving national and international targets formulated by governments or by multilateral institutions like the United Nations and the International Renewable Energy Agency. The energy transition is a path to a vision of a sustainable energy future. It has become a global challenge that clearly does not stop at national borders. Therefore, it is crucial that all stakeholders follow a common vision and a congruent approach of providing sustainable and clean energy for a better future.

Quality infrastructure has proven to be an important backbone of this transformation by establishing common standards, promoting best practices and providing tools to evaluate conformity and competence. It guarantees safe, efficient and reliable operation while also enabling the seamless integration of renewable energy technologies across borders, fostering international cooperation and ensuring that the benefits of the energy transition are globally shared. This also plays a key role in the world's parallel efforts for climate protection and greenhouse gas reduction.

PTB is actively supporting its partners worldwide in establishing and strengthening national quality infrastructures, as the examples from Vietnam and Tunisia demonstrate. In the field of renewable energy, this is not only to the benefit of partner countries. It is also in Germany's interest that global climate change be halted, to which end renewable energy sources are employed globally for straightforward reasons: the climate is universal, and the planet's resources are limited. Moreover, through innovative technologies and energy carriers like green hydrogen, Germany can potentially benefit in the future from clean imported energy from these countries. Climate protection and energy security are hence being championed not only at home but around the world. Energy transition in Germany cannot be successful without engaging its global dimension.

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