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The Role of Metrology in Decarbonization

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Abstract

Climate change poses a substantial risk to ecosystems and global stability. Reducing global CO2 emissions while improving living standards to assure social stability is the critical challenge of our time. Innovation in technology is the most promising approach, enabling electrification, renewable energy production and enhanced energy efficiency (3 E's) to substantially reduce carbon emissions. Industrial metrology can enable innovation cycles and significantly enhance product and manufacturing efficiency. Yet its role in decarbonization remains largely unexamined in scientific literature. This paper addresses this gap by analyzing the role of industrial metrology as an enabler for decarbonization. Innovative approaches and emerging technologies through which metrology contributes to the development of new, more efficient products and production processes that enable decarbonization, are identified. The analysis of 3E Sectors examines the impact of industrial measurement technology on the pursuit of decarbonization, with a particular focus on battery production.

Keywords: Industrial Metrology; Decarbonization; Technological Innovation; Sustainable Manufacturing

1. Introduction

Climate change is projected to cause an economic loss of up to $69 trillion by 2100, with each additional ton of CO2 emitted contributing an estimated 417 US$ in climate damage. [1] With current estimates forecasting that the probability of achieving the 2.0 degrees Celsius target set by the Paris Agreement of 2015 is less than 5%, technological change is inevitable. [2; 3] CO2 emissions have a direct impact on public health, as higher emission levels are correlated with negative effects on individual well-being and increased health risks. [4] Therefore, governments, investors and other stakeholders pressure enterprises to decarbonize their portfolios and processes [5]. In this, wealth loss and slowing development should be avoided if possible. Decarbonization is a challenge that can only be solved globally, with innovation as a core avenue. On the bright side, decarbonization offers cooperative potential, by unlocking several opportunities for innovation, economic growth, and international collaboration. Since the first industrial revolution, the automation of machines and processes, an essential feature of industrial progress, has been inextricably linked to metrology. [6,7] Advances in metrology not only enable automation, but can also drive the development of new and transformative technologies. [6] Modern manufacturing increasingly demands high-quality products, often pushing production technologies to their limits. The inherent stochastic nature of production processes results in defects, making it essential to implement quality control loops with integrated measurement technology to compensate for deviations and minimize production costs. [8] The three E's Electrification, Energy Production, and Energy Efficiency are the key drivers of decarbonization. Their realization depends heavily on advances in technology, based on precision, efficient and sustainable production processes. At the core of this transformation is industrial metrology, which provides the precise data essential for efficient manufacturing and

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accelerated development cycles, supporting today's rapidly evolving technologies. For example, electrification requires new quality assurance methods in battery production, while sustainable energy production demands innovative solutions to enhance the energy supply efficiency. Furthermore, advancing energy-efficient products across sectors like e-mobility, wind energy, solar power, and hydrogen technology is essential for CO_2 reduction. In all these fields, metrology plays a vital role, by providing essential data on product quality, enabling the precision and reliability that are crucial, particularly where tight tolerances are required, for these transformative activities to succeed. [9] In particular, production represents a major lever for facilitating decarbonization. The following sections explore how innovations in metrology may enable sustainable production, with a focus on efficiency improvements, reduced waste, and CO_2 reduction as industries transition toward a decarbonized future. However, assessing the contribution of metrology is inherently complex, as it is closely integrated with manufacturing technology and development processes. A precise quantitative attribution of its impact remains challenging due to these interdependencies. Moreover, improvements in manufacturing technology alone can also contribute to ecological sustainability, as described in [10]. However, this paper specifically examines advancements driven by industrial metrology, analyzing its role as an enabler and its impact on accelerating decarbonization efforts. Key areas of influence, challenges, and advanced measurement technologies driving progress are examined. Insights were further detailed through expert interviews, mapping the use and impact of metrology. The findings outline its current role and emphasize its future potential in advancing sustainability.

2. The Role of Metrology in Achieving Decarbonization Across 3E Sectors

Advances in measurement technology are foundational for controlling production processes, enhancing product quality, safety and boosting customer satisfaction, especially in industries undergoing rapid transformation [11]. This is particularly relevant in the rapidly expanding 3E sectors: Electrification, Energy Generation, and Energy Efficiency. Decarbonization, particularly within the electric powertrain sector, is driving substantial shifts in both product and production technologies. The share of electric vehicles in the global car market rose by over 50% from 2021 to 2022 [12]. In China, the installed capacity of power batteries for new energy passenger vehicles increased even by 169.6% to 123.2 GWh in 2021 highlighting the rapid growth and demand in this sector [12]. The introduction of advanced product technologies, such as high-capacity batteries and hairpin motors, necessitates the development of innovative production methods capable of managing increased complexity and higher volumes of standardized components. [12]

The complexities of EV battery production, for example, present challenges that traditional measurement methods, like Statistical Process Control (SPC), can no longer fully address. Modern batteries are complex and varied, demanding advanced and scalable metrology technologies to detect all critical defects essential to their performance [13]. Battery production faces diverse processes, intricate interdependencies, and unknown process interactions, often lacking standards in design and quality assurance [13; 14; 15]. This complexity results in oversized machinery, high rejection rates, and extensive testing before module assembly [9]. In particular, electric vehicle batteries are evaluated based on three key criteria: manufacturing costs, safety and performance. It is therefore essential that they meet stringent quality standards in order to ensure high performance, safety and durability. By 2025, battery costs are projected to decrease from less than 0.048 USD/Wh to under 0.041 USD/Wh by 2035, while specific energy is expected to increase from 200 Wh/kg to over 300 Wh/kg within the same period [12]. To achieve this, reliable and fast measurements are critical at every stage of production. The performance and safety of batteries are significantly influenced by their microstructure, which is formed by the characteristics of the materials used and the manufacturing processes employed. Precise measurements are essential for the analysis of this microstructure, the identification of defects, and the fine-tuning of process parameters as required. In the production of vehicle batteries, approximately 6,800 quality control points are implemented throughout the entire manufacturing process to manage these complexities effectively. [12]

Recent advancements in production metrology have been driven by the demand for greater precision, efficiency, and automation, making metrology an indispensable component in modern manufacturing. The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) into metrology systems offers substantial potential for improving measurement processes by simplifying defect detection and managing complex data. However, challenges such as managing measurement uncertainty, calibration complexities, and data interpretation remain critical for ensuring reliable results. [9]

Together, these developments underscore metrology's role in advancing the sustainability goals of the 3E sectors, offering essential support for quality assurance, production efficiency, and emission reduction efforts as these industries move towards decarbonization. The following subsections explore how metrology addresses specific challenges within these sectors, providing an overview of current technologies and insights into future opportunities for improving quality and reducing emissions.

2.1 Industrial Metrology in Energy Efficiency

Achieving optimal design for high-precision components is a complex challenge, requiring seamless integration of design, manufacturing, testing, and refinement. This process goes beyond finding the best possible design, it also ensures its precise realization and ongoing improvement. For instance, to maximize energy efficiency in aviation, design optimization plays a crucial role in enhancing turbine performance, which directly contributes to reducing CO_2 emissions in aircraft engines. Factors such as the design of airflow and thrust components, the thickness of protective coatings, surface quality, and metallurgy all play a vital role in turbine performance. Through metrology, a Product-Production Co-Design (PPCD) approach can be facilitated, allowing for the optimization of both production and design processes in fast, iterative cycles to achieve optimal energy efficiency. Advanced coordinate measuring machines are essential for the precise inspection and analysis of these complex components. In this way, metrology not only supports improved turbine efficiency but also advances the broader goal of reducing emissions in the aviation industry.

2.2 Industrial Metrology in Energy Production

Wind turbine production, critical for renewable energy generation, depends on advanced quality control processes to ensure durability and efficiency, as any defects in key components can lead to significant material failures. This challenge is particularly pronounced in the production of large, complex parts such as the main bearing, a core component with a diameter of approximately four meters that must withstand up to 30 years in harsh conditions, including offshore environments. Even slight friction due to minor deviations in the rollers can cause heat and damage, compromising its performance and lifespan. To achieve the necessary reliability, these bearings require micrometer-level precision during both production and measurement to meet the demands of long-term durability. For example, advanced 3D scanning technology enables detailed inspection of such components, assessing parameters like surface consistency and roller alignment to prevent defects that could lead to fatigue fractures or efficiency losses. This level of precision is essential not only for the main bearing but also for other critical turbine components, such as rotor blades, where even slight deviations in aerodynamics can significantly reduce energy output. Manufacturers are therefore compelled to operate within extremely tight tolerances, using metrology systems to ensure that each component meets the standards. Thus metrology is a vital precondition to further scale wind turbine application sustainably, as inadequate measurements and production errors can directly impact turbine durability and thereby the viability of renewable energy investments. [16; 17]

2.3 Industrial Metrology in Electrification

Electrification, particularly through advancements in battery technology and electric motor innovation represents a shift towards more sustainable transportation. The resulting technical innovations enable cleaner, more efficient solutions across a range of industries. Breakthroughs such as increased packing density and optimized air gap sizes between the rotor and stator have significantly enhanced motor efficiency. Metrology ensures precise hairpin positioning and weld quality, both crucial for optimal motor performance. Automated 3D inspection technologies contribute further by providing accurate measurements of these components, which not only enhance motor efficiency but also directly support decarbonization efforts. Special emphasis is placed on battery technology, as it represents the primary cost driver in the electric powertrain [18]. Despite significant advancements in large-scale battery manufacturing, there remains substantial potential for optimization, particularly in areas related to metrology, production efficiency, and quality control. For EV-battery production line with nearly 50 subprocesses, even a minimal failure rate of one in a million in any aspect whether in materials, equipment, or process steps prevents the yield rate from being flawless [12; 17]. Figure 1 shows a simplified representation of the battery production steps. The battery manufacturing process begins with raw material processing. This is followed by electrode production, creating electrodes that are later stacked or wound in the cell assembly stage. During cell assembly, steps such as stacking/winding, pressing, X-ray inspection, welding, and electrolyte injection are performed. An additional X-ray check ensures cell quality before the formation stage, where cells are charged and discharged to activate their electrochemical properties. Cells are then grouped into modules in the module assembly stage, followed by a CT scan to inspect the module's internal structure for any defects. Finally, the modules are assembled into complete battery packs. Quality checks, including X-ray and CT scans, are incorporated throughout the process to ensure safety and functionality. It is not uncommon for diverse defects and faults to occur during the production of batteries. To identify these defects, collect data and enhance future developments, a range of measuring equipment is required. Table 1 lists the most common defects by process step and the

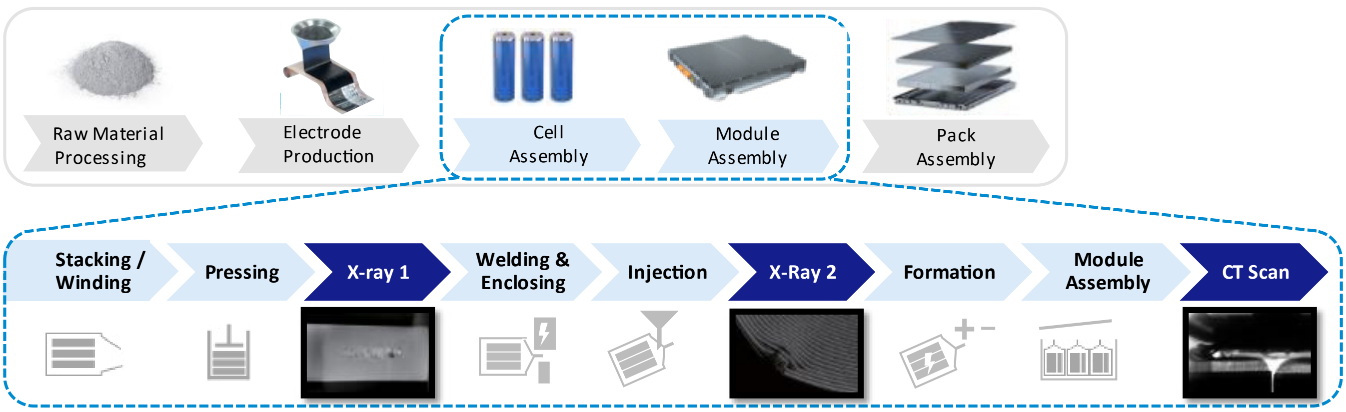

Fig. 1: Battery Production Process

available detection options. In a future TWh-scale market, even small percentage losses will be amplified, ultimately impacting consumer trust and confidence in the enterprise. Although most processes can achieve a 99.9% (3σ) yield rate despite the potential for various defects, the electrode production process still struggles to reach even 99%, presenting a significant challenge for battery manufacturers [12;17].

Table 1. Common Battery production defects [12]

Process	Failure mode	Detection
Stirring	Scratches on coated particles	Off-line sample
	High self-discharge rate of cell	
	Poor slurry stability	
Coating	The dimension of electrode does not meet the requirements	In-line CCD
	Poor thickness consistency	In-line P-ray
Cold pressing	Thin on both sides and thick in the middle	In-line laser thickness measurement
	Broken strip	
	Separator sticking to the roller	
Die-cutting	Dimension and spacing do not meet the assembly requirements	In-line CCD
	Burr out of specification, risk of internal short circuit	Line edge detection
Winding/ lamination	Safety risks such as low capacity and lithium plating	In-line CCD
Hot pressing & shaping	Capacity degradation, increased DCR, JR deformation	
Ultrasonic welding	Void welding, surface cracks	In-line CCD
Laser welding	Particles during void welding/welding	Helium leak detection
Injection and formation	Insufficient electrolyte wetting, lithium plating from electrolyte loss	Off-line sample delivery for laboratory tests
Aging & self-discharge	Drop rate of voltage and capacity	Off-line sample delivery for laboratory tests
Component gluing	Insufficient component bonding strength, compressed cell	In-line visual inspection
Side plate welding	Insufficient sealing performance	
Harness board installation	Improper electrical connection	
High and low voltage connection	Improper electrical connection	
Tighten	Uneven tightening, poor sealing	

To meet cost-reduction goals, it's essential to make advances in key processes and to strengthen quality control systems. For instance, precise metrology tools are essential to monitor and control material utilization rates, which often range between 90-95%, to minimize waste and improve sustainability. [17] Additionally, current overall equipment efficiency (OEE) in battery production varies between 50-85%, indicating the need for improved production processes and faster quality control measures to maximize output and ensure consistent product quality. [17] The complexity of battery manufacturing, along with the high demand for both performance and safety, necessitates new quality assurance strategies. Manufacturing defects such as faulty anode overhangs, material inconsistencies, loose electrical contacts, particle contamination, and inaccurate weld seams can result in critical failures, including battery fires. Advanced measurement technologies, such as scanning electron microscope (SEM), light microscope (LM), and X-Ray and CT tomography are essential for identifying and addressing these risks early in the production process. These technologies enable the precise analysis of electrode thickness, dendrite formation, particle cracking, and other potential defects, ensuring the reliability and performance of batteries in a rapidly expanding market. [19]. Although particle contamination in batteries can never be completely eliminated, early detection is crucial to avoid further waste and inefficiencies. For instance [20] uses X-ray tomography and synchrotron-based analytical techniques to examine multiscale defects in commercial 18650-type lithium-ion batteries reveal potential degradation and failure mechanisms linked to impurity defects. These findings highlight how internal defects can contribute to the overall performance decline and safety risks of batteries, emphasizing the need for advanced diagnostic techniques to detect and mitigate such issues during production. As another example, in the manufacturing process of batteries, wetting and formation alone takes 3 weeks, accounting for around 48% of the entire manufacturing cost [21]. In addition, despite efforts to optimize the conditioning process, the lack of understanding of the different steps still results in 5-10% of the production capacity becoming production waste [21]. Therefore, nondestructive characterization is essential to improve efficiency, reduce costs and scrap rates. Also, for next-generation solid-state batteries, advanced imaging techniques like X-ray and SEM are indispensable. These characterization methods are essential for investigating the complex chemical and physical processes occurring within solid-state batteries. By providing detailed insights into the material structures and behaviors, these techniques offer powerful tools for understanding and addressing the challenges in solid-state battery development, enabling improvements in performance, safety, and longevity. [14;22;23]

Based on the insights in this chapter, it becomes clear that traditional measurement methods are reaching their limits in supporting the 3E sectors. The rapid development of technologies like high-capacity batteries, advanced electric motors, and optimized turbine components has introduced new requirements of complexity and efficiency requirements that existing quality control methods, such as statistical process control, struggle to meet. These limitations underscore the pressing need for more sophisticated and scalable measurement technologies that can ensure the necessary precision and reliability across each production process step.

3. Innovative Measurement Technologies enabling Product and Production Innovations for Decarbonization

This chapter explores the role of innovative measurement technologies in driving product and production advancements essential for decarbonization. Battery manufacturing, as a cornerstone of the electrification, is a highly resource-intensive process. Even minor improvements in material efficiency, energy use, and waste reduction can substantially impact the sustainability of the industry. As such, this chapter places special emphasis on battery production, where advanced measurement technologies are increasingly crucial for detecting impurities, controlling material usage, and optimizing production quality. Innovations in battery metrology enable the industry to meet growing demand while supporting long-term environmental objectives. One such innovation is the ability to detect multiple types of foreign particles at concentrations below 20 ppm. For instance, copper and aluminum particles larger than 400x400x100 µm and 600x600x600 µm, respectively, can be identified, along with NCM (nickel-cobalt-manganese) fragments and electrode folding issues. Detecting these contaminants early in the production process allows manufacturers to address defects before they escalate, preventing costly waste and ensuring higher quality end products. By incorporating advanced metrology tools into battery production, companies can achieve more sustainable manufacturing practices, reducing energy consumption and material waste while improving the overall reliability and lifespan of their batteries. [17]

Innovative metrology also enables the exploration of long-term effects, allowing for a deeper understanding of how production defects impact battery performance over time and supporting continuous improvement in battery design and durability. Nanoscale 3D X-ray imaging provides therefore a detailed characterization of material structures, resulting in more precise and intuitive defect detection. This technique deepens researchers understanding, enhances the efficiency of research and development, and directly contributes to advancements in battery performance. [17]

Furthermore, 3D and 4D in-situ experiments allow for comprehensive analysis of microstructural changes, offering a clearer visualization of battery aging processes. The use of nanoscale X-ray imaging with synchrotron radiation improves image resolution, enabling a more thorough investigation of degradation mechanisms shown in figure 3. These technological advancements play a crucial role in the development of batteries with enhanced durability and performance. [12;17]

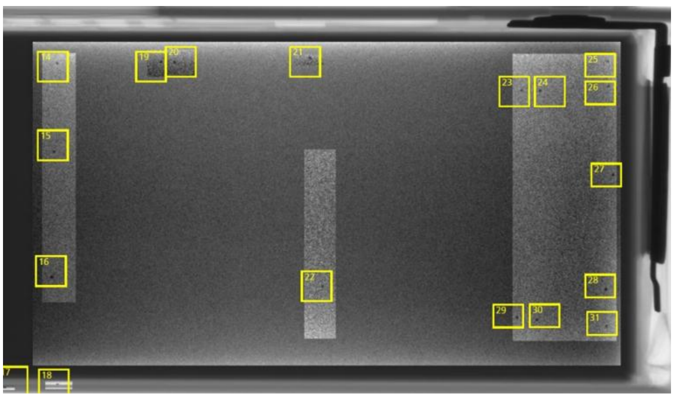

Fig. 2: Inline X-ray quality assurance for foreign particles

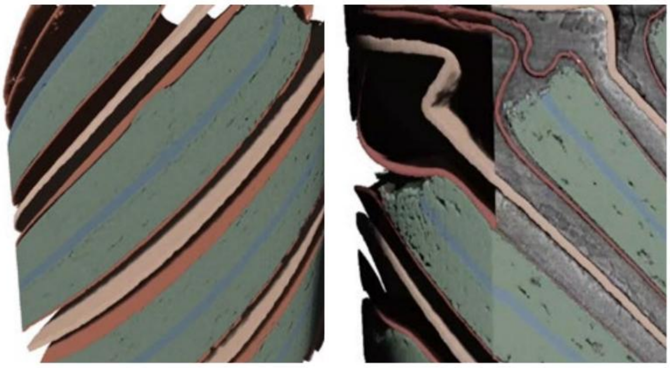

Fig. 3. Observation of the aging of electrode particles

These innovations are essential as the industry moves towards larger-scale production and integration of recycled materials, where precise detection of impurities becomes even more critical to maintaining performance and sustainability standards. The systematic use of industrial metrology in battery production generates large amounts of data that can contribute to economic and ecological sustainability. A leading battery production company has implemented advanced measurement technologies to minimize waste and maximize production efficiency. These include upgrading equipment precision from micron-level to kilometre-level control and establishing over 6,800 quality control points throughout the manufacturing process. Each cell generates an average of more than 10,000 traceability data points and undergoes more than 100 inspection steps before being stored. [12;17]

4 Effects, Quantifying Savings and Future Potential

Chapter 4 shifts the focus to quantifying the concrete effects and savings enabled by innovative measurement technologies. Advanced metrology tools allow for highly precise impurity detection and enhanced production quality control, leading to substantial reductions in waste, energy usage, and emissions in resource-intensive processes. The systematic implementation of particle detection at the PPM level, for example, has already yielded notable improvements in battery manufacturing, setting a benchmark for efficiency and sustainability across the industry. In a studied use case, the core manufacturing qualification rate was increased from 90% to over 99%, significantly enhancing overall production efficiency. Additionally, the process capability index (Cpk) improved from a range of $0.67 \leqslant Cpk < 1.0$ to $1.33 \leqslant Cpk < 1.67$ for critical process steps [17]. As a result, the long-term defect rate in battery module production was reduced by 48%, leading to a substantial reduction in wasted material and energy. Based on [24] it is estimated that around 3.6 kg CO_2-eq per cell can be avoided due to the prevented production of defective products. Moreover, the analysis revealed that early particle detection reduced the defect ratio from 10% to just 1%. This is particularly impactful because more than 50% of the energy consumed in battery production is used during the final performance testing stage. By employing CT-Scan technology to detect defects before this stage, manufacturers can significantly reduce energy consumption and production inefficiencies. Due to the many dynamic influences and uncertainties, the impact of decarbonization can only be quantified in specific aspects. Therefore, this paper focuses on the three main areas of influence and highlights the quantifiable contributions of metrology to decarbonization.

5 Summary and Outlook

This study investigates the role of industrial metrology in decarbonization with a focus on its impact on Electrification, Energy Production, and Energy Efficiency. It examines the use of metrology within these sectors, highlighting its diverse contributions to decarbonization. To provide a comprehensive perspective, the paper addresses key challenges and introduces innovative measurement technologies within the battery production. The direct and indirect impacts of metrology on decarbonization must be evaluated on a case-by-case basis, considering its interdependencies and close integration with manufacturing technology and product development. The battery cell production example presented in this paper demonstrates how metrology can enable contributions to decarbonization. The early identification of particle contamination in battery manufacturing, for instance, has been shown to reduce defect rates from 10% to 1%. Additionally, the core manufacturing qualification rate can be increased from 90% to 99% through systematic use of advanced measurement technologies. These improvements can not only make production more sustainable by reducing waste and defects but also accelerate iteration cycles and enable more targeted root cause analysis. As the use of recycled materials becomes more important, accurate measurement will likely be essential to ensure the quality and performance of products that incorporate recycled materials, making metrology an indispensable tool in future sustainable manufacturing processes.

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