

Integrating Clean Energy with Existing Infrastructure: The Role of Mechanical Engineering

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Abstract- The transition to clean energy sources represents a significant but necessary challenge, particularly in integrating them efficiently with existing grid infrastructure. This article underscores the crucial and indispensable role that mechanical engineers play in designing and optimizing clean energy systems, a role that directly impacts the environment we live in. By examining the imperative for grid modernization and the essential role of energy storage solutions, the article sheds light on the critical steps needed to ensure a smooth and effective transition to clean energy. Key questions addressed include: How can aging grid infrastructure be upgraded to handle the variability of renewable energy? What are the most effective energy storage solutions to mitigate power fluctuations? How can distributed energy resources be efficiently integrated into the grid? Ultimately, this work underscores the frontier contribution of mechanical engineers in shaping a sustainable energy future, highlighting their expertise in overcoming the technical hurdles that stand in the way of a cleaner, more efficient energy landscape.

I. INTRODUCTION

Driven by the urgent need to combat climate change and reduce greenhouse gas emissions, the importance of adopting clean energy solutions has never been more pressing. In a significant move towards clean energy, the California government passed a bill in 2018 that mandates a progressive shift in electricity generation for utilities within the state. This legislation requires utilities to source 50% of their electricity from clean energy sources by 2026, aiming to achieve 100% clean energy by 2045 (Source: Michigan State University). The Intergovernmental Panel on Climate Change (IPCC) has warned that we must significantly cut our carbon emissions to limit global warming to 1.5°C above pre-industrial levels, necessitating a rapid shift towards renewable energy sources (IPCC, 2021). In a move towards cleaner energy sources, Tucson Electric Power (TEP) in Arizona U.S.A and Colorado Springs Utilities have outlined plans to transition away from fossil fuels like gas and coal. TEP is particularly ambitious, aiming to source a significant portion of its

power from renewable sources. By 2035, they plan to generate a whopping 70% of their electricity from wind and solar power, representing a major shift in their energy mix and a significant step towards reducing their carbon footprint. As the global energy demand continues to rise, transitioning to renewable energy sources such as solar, wind, and hydropower presents a significant challenge: integrating these technologies into existing infrastructure, a challenge that requires the expertise of mechanical engineers.

The existing energy infrastructure needs more flexibility and capacity to handle renewable energy sources' variable nature seamlessly. This discrepancy poses technical, economic, and logistical challenges, including grid stability, storage capacity, and energy distribution (International Energy Agency, 2020). Renewable energy's potential to provide a reliable and consistent energy supply can be fully realized with a proper, effective integration strategy.

Mechanical engineers lead the charge in the renewable energy revolution by designing, optimizing, and maintaining the systems that seamlessly integrate these sustainable resources into our energy grid. Their expertise is vital in developing advanced materials, efficient energy conversion systems, and comprehensive storage solutions. Mechanical engineers also work on improving the reliability and efficiency of energy systems to ensure that the infrastructure not only supports but also maximizes the efficiency and reliability of clean energy technologies (American Society of Mechanical Engineers, 2021). Their contributions are essential for overcoming the technical barriers associated with integrating renewable energy into our existing grids, making them indispensable in the fight against climate change. Mechanical engineers have significantly improved the efficiency and reliability of wind turbines, contributing to a 50% reduction in the levelized cost of energy (LCOE) for wind power over the past decade, as reported by the International Renewable Energy Agency (IRENA).

II. TECHNICAL CHALLENGES OF GRID INTEGRATION

Integrating renewable energy sources like solar and wind power into the existing power grid presents a unique challenge. Unlike traditional fossil fuels, these sources are inherently variable, meaning their output fluctuates based on environmental conditions. To address this, mechanical engineers are crucial in designing and optimizing advanced control systems and energy storage solutions that ensure a stable and reliable power supply.

Intermittency

One of the primary challenges is intermittency. Solar and wind power generation depends on weather conditions and time of day, leading to periods when these sources generate little to no power. Solar panels, for instance, do not produce electricity at night or during cloudy weather, while wind turbines depend on wind speed, which can be highly variable. This intermittency creates a mismatch between energy supply and demand, requiring sophisticated management and storage solutions to ensure a stable power supply (Lund et al., 2015). To address this, Engineers must design and optimize battery systems to store excess energy generated during periods of high renewable output and release it during low production periods. Lithium-ion, flow, and emerging technologies like solid-state batteries are key focus areas.

Power Fluctuations

Power fluctuations in renewable energy are another challenge facing integration due to the variable nature of sources like wind and solar, which causes voltage and frequency variations that impact grid stability. Advanced control systems and energy storage technologies are essential to mitigate these fluctuations and maintain stability. Renewable energy, mainly distributed solar and wind, enhances grid resilience by diversifying supply and reducing dependence on centralized fossil fuel plants, but their variability necessitates advanced management solutions. Mechanical engineers address these challenges by developing advanced control systems, optimizing battery and thermal storage, integrating hybrid energy systems, and improving the efficiency of renewable technologies. According to the NREL, wind power capacity factors range from 25% to 50%,

and solar generation can vary by 20% daily; this made necessary advanced grid management to ensure a stable energy supply (Ackermann et al., 2001; U.S. Department of Energy).

Transmission losses

The loss of electrical energy as it travels from power plants to end-users is a significant challenge, particularly with renewable energy generation, often located far from consumption centers. Engineers are required to address this through several methods: using high-voltage transmission lines to reduce current and resistive losses; developing superconductors that eliminate electrical resistance, optimizing grids and implementing innovative grid technologies for better power flow management; deploying distributed generation systems like rooftop solar to reduce transmission distance; designing high-efficiency transformers with materials like amorphous steel to lower core and winding losses; and implementing reactive power compensation techniques such as capacitor banks and static VAR compensators. These strategies collectively enhance the efficiency and reliability of power delivery systems, contributing to a more sustainable energy supply. Upgrading transmission infrastructure and developing more efficient transmission technologies are crucial to minimizing these losses (Jacobson et al., 2015).

Existing grid infrastructure

Integrating renewable energy into the existing grid brings several challenges as these grids are predominantly designed for consistent power generation from fossil fuels and have limitations in accommodating the variable nature of renewable energy. Traditional grids are built to handle predictable energy flows, making integrating intermittent and decentralized renewable sources easier with significant modifications and upgrades. These capacity issues mean that more and better transmission lines, like high-voltage direct current (HVDC) lines, are needed for efficiency. Voltage and frequency stability problems arise from intermittent renewable energy, requiring advanced controls and energy storage solutions. Managing distributed energy resources like rooftop solar is complex but can be addressed with innovative grid technologies and resource management systems. Enhancing grid resilience involves strengthening infrastructure and

developing comprehensive systems to protect against new vulnerabilities. Enhancing grid flexibility, incorporating intelligent grid technologies, and investing in comprehensive energy storage systems are essential to overcoming these limitations and enabling a smooth transition to renewable energy (Blarke & Jenkins, 2013).

III. THE INDISPENSABLE ROLE OF MECHANICAL ENGINEERING IN CLEAN ENERGY INTEGRATION

The successful integration of clean energy sources into existing infrastructure hinges on the expertise of mechanical engineers. These engineers act as the architects of this critical bridge, reconciling the inherent variability of renewable energy sources with the demands of a stable and reliable power grid.

Their contributions extend far beyond simply designing and developing components. Mechanical engineers comprehensively understand thermodynamics, fluid mechanics, and control systems – the cornerstones of clean energy integration.

This expertise allows them to:

Design and Optimize Renewable Energy Conversion Systems

Mechanical engineers are at the forefront of designing and optimizing renewable energy conversion systems to ensure they are compatible with the grid. In wind energy, engineers improve the aerodynamic efficiency of wind turbine blades, develop advanced materials for durability, and optimize turbine designs for various wind conditions. The National Renewable Energy Laboratory (NREL), a US Department of Energy laboratory dedicated to renewable energy and energy efficiency research, is a prime example of how engineers are pushing the boundaries of wind energy in the US. Modern wind turbines, such as the GE Haliade-X 12 MW, can generate substantial power with increased efficiency, thanks to mechanical engineering innovations. The Haliade-X can produce 67 GWh annually, sufficient to power 16,000 European households, demonstrating significant advancements in energy conversion efficiency (GE Renewable Energy).

In solar energy, mechanical engineers focus on enhancing the efficiency of photovoltaic panels and developing concentrated solar power (CSP) systems. They design tracking systems that follow the sun's movement, maximizing energy capture throughout the day. An example is the dual-axis solar trackers, which can increase energy output by up to 40% compared to fixed systems (Solar Power World). Additionally, engineers work on thermal management systems to prevent overheating and ensure optimal performance of solar panels. As of 2020, the global capacity of installed solar PV systems reached 707.5 GW, reflecting the impact of mechanical engineering in scaling solar energy adoption (IRENA, 2020).

Hydropower also benefits from mechanical engineering by designing more efficient turbines and generators. Engineers develop technologies like fish-friendly turbines and advanced hydropower systems that can operate efficiently at varying water flow rates, making hydropower more adaptable and sustainable. As of 2020, hydropower contributed approximately 16% of the world's total electricity production, showcasing the vital role of mechanical engineering in renewable energy generation (IHA, 2020).

Developing Energy Storage Solutions

Mechanical engineers contribute significantly by developing and optimizing energy storage solutions, essential to managing surpluses and deficits in renewable energy. Pumped hydro storage, one of the oldest and most widely used forms of energy storage relies on mechanical engineering to design efficient pumps and turbines that can store excess energy by pumping water to higher elevations and releasing it when needed globally; pumped hydro storage accounts for about 95% of all utility-scale energy storage capacity, underscoring its importance (U.S. Department of Energy).

Battery storage technologies like lithium-ion batteries are advancing rapidly due to mechanical engineering efforts. Engineers focus on improving energy density, charge/discharge efficiency, and battery lifespan. Innovations like Tesla's Megapack, a large-scale battery storage solution, illustrate how mechanical engineering advancements enable the integration of substantial renewable energy capacities into the grid. As of 2021, global battery storage capacity was

approximately 17 GW, with significant growth expected in the coming years (Tesla; Wood Mackenzie, 2021).

Designing and Implementing Smart Grid Technologies

Innovative grid technologies are essential for real-time monitoring, control, and optimization of energy flow within the grid. Mechanical engineers design and implement systems integrating sensors, communication networks, and control algorithms to enhance grid resilience and efficiency. These intelligent grids can dynamically balance supply and demand, manage energy storage, and incorporate distributed resources like rooftop solar panels and electric vehicles. An example is the advanced metering infrastructure (AMI) and supervisory control and data acquisition (SCADA) systems that provide real-time data on energy consumption and generation, enabling utilities to optimize energy distribution, reduce losses, and quickly respond to disruptions. The deployment of smart grid technologies is projected to reach a market size of USD 92 billion by 2026, indicating the growing reliance on these systems (U.S. Department of Energy; Markets and Markets, 2021).

Contributing to the Development of New Transmission Line Infrastructure

As renewable energy generation often occurs far from consumption centers, mechanical engineers' role in developing new transmission line infrastructure is essential. They design high-voltage direct current (HVDC) transmission lines that can efficiently transport electricity over long distances with minimal losses. Projects like the Trans West Express Transmission Project in the United States, which aims to deliver wind power from Wyoming to California, demonstrate the importance of advanced transmission technologies. HVDC lines can transmit power over distances exceeding 1,000 kilometers with losses of only around 3%, making them essential for integrating large-scale renewable energy (Trans West Express).

IV. GRID MODERNIZATION AND ENERGY STORAGE

Necessity for Grid Modernization

Modernizing the electrical grid is essential to improving its capacity, flexibility, and resilience to

integrate renewable energy sources. Traditional grids were designed for a one-way flow of electricity from centralized power plants to consumers, which is incompatible with the variable and distributed nature of renewable energy generation. Modernizing the grid involves upgrading infrastructure, incorporating digital technologies, and enhancing grid management practices. This transformation is necessary to accommodate the increasing penetration of renewable energy sources, such as solar and wind, characterized by variability and intermittency.

Advanced grid technologies, such as smart grids, allow for real-time monitoring and control of electricity flows, which helps balance supply and demand more effectively. Intelligent grids integrate sensors, communication networks, and data analytics to provide utilities with comprehensive insights into grid performance, enabling rapid response to fluctuations and outages. According to the International Energy Agency (IEA), global investment in digital grid infrastructure and software is expected to grow significantly, reaching around \$80 billion annually by 2026 (IEA, 2021). This is a significant investment to ensure that grids can handle the dynamic nature of renewable energy and maintain reliability.

Importance of Energy Storage Solutions

Solar and wind power generation depend on weather conditions and time of day, leading to periods of overproduction and underproduction. Energy storage systems can store excess energy generated during periods of high renewable output and release it during periods of low production, thus smoothing out the supply and ensuring a stable and reliable energy supply.

Energy storage systems are also critical for stabilizing grid frequency, managing peak demand periods, and improving overall grid efficiency. By providing ancillary services such as frequency regulation and voltage support, energy storage helps maintain the stability and reliability of the grid. For instance, stored energy can be dispatched during peak demand periods to meet the increased load, reducing the need for expensive and polluting peaker plants. The global energy storage market is expected to grow from 17 GW in 2020 to over 150 GW by 2030, reflecting the

increasing recognition of energy storage's importance in the energy transition (Wood Mackenzie, 2021).

V. POLICY AND REGULATORY FRAMEWORK

Overview of Relevant Policies and Regulations

A complex web of policies and regulations plays a significant role in shaping the integration of clean energy with existing infrastructure. Well-designed and properly implemented, these frameworks can significantly accelerate the transition towards sustainable energy systems. However, poorly structured regulations can hinder progress, creating barriers that delay adoption. Key areas of policy and regulation impacting clean energy integration include:

Renewable Energy Standards (RES) and Portfolio Standards (RPS)

These mandates require that a specific percentage of energy must come from renewable sources. The Renewable Portfolio Standards (RPS) implemented in various states in the U.S. have driven significant investments in renewable energy projects by utilities (U.S. Environmental Protection Agency, 2020). In Iowa, which has one of the most ambitious RPS goals in the country, the RPS is credited with spurring a tenfold increase in wind energy capacity between 2000 and 2017. While Texas reigns supreme in total installed wind power capacity (23,262 MW) and Oklahoma boasts a respectable 7,495 MW, according to the latest U.S. Department of Energy data, Iowa emerges as the true champion of wind energy per capita.

Iowa's wind turbines generate a staggering 2,324 MW per million people, dwarfing Oklahoma's 1,906 MW per million and Texas's 822 MW per million. It translates to a state where wind power has been woven into its energy landscape's fabric. Imagine vast, rolling plains dotted with these clean energy giants, silently harnessing the wind's power to meet its citizens' needs. This impressive feat speaks volumes about Iowa's commitment to renewable energy and its innovative approach to harnessing wind power. It is a testament to the state's forward-thinking leadership and dedication to building a sustainable future.

These RES and RPS are incredibly significant and create a predictable market for renewable energy, encouraging long-term investments and technological advancements.

Incentives and Subsidies

Financial incentives such as tax credits, grants, and subsidies effectively promote renewable energy projects. Notable examples include the Investment Tax Credit (ITC) and Production Tax Credit (PTC) in the U.S., which have been instrumental in reducing the upfront costs associated with renewable energy installations and making them more economically viable for developers and consumers alike (U.S. Department of Energy, 2021).

Grid Access and Interconnection Standards

Regulations that ensure fair and efficient access to the grid for renewable energy producers are essential. These standards govern the connection of renewable energy systems to existing grid infrastructure, addressing technical and administrative barriers that could otherwise prevent renewable energy from being effectively integrated into the grid (North Carolina Clean Energy Technology Center, 2021). Clear interconnection standards help streamline the process and reduce costs associated with grid integration.

Environmental Regulations

Policies to reduce greenhouse gas emissions and other pollutants are integral to promoting clean energy. Regulations such as the Clean Air Act in the U.S. mandate reductions in emissions from power plants, which drives the shift towards cleaner energy sources (International Renewable Energy Agency, 2020). These environmental regulations create a market for emissions reductions, encouraging innovation and investment in renewable energy technologies.

Building Codes and Standards

Requirements for integrating energy-efficient and renewable energy technologies into building designs are becoming increasingly stringent. Standards such as those set by the International Energy Conservation Code (IECC) provide guidelines for energy performance in new and existing buildings, ensuring they are equipped to effectively utilize renewable energy (California Energy Commission, 2020).

Retrofitting existing buildings to enhance their energy performance is vital to these standards.

VI. ROLE OF MECHANICAL ENGINEERS IN POLICY ADVOCACY AND COMPLIANCE

Mechanical engineers, critical frontiers in this integration, are essential in advocating for supportive policies and ensuring compliance with existing regulations. Their technical expertise and practical experience provide valuable insights that can shape effective and realistic policies. Key contributions include:

Technical Expertise

Mechanical engineers offer essential technical input during the drafting of policies and regulations. Their involvement ensures that standards are grounded in current technological capabilities and practical considerations. Engineers might advise on the feasibility of new energy efficiency standards or the technical requirements for integrating renewable energy systems into existing infrastructure (U.S. Environmental Protection Agency, 2020).

Advocacy and Public Engagement

One of the primary roles of mechanical engineers is to promote the benefits of clean energy integration with policymakers, industry stakeholders, and the public. By participating in public consultations and hearings, engineers can represent the interests and perspectives of the engineering community, helping to shape practical and implementable policies (North Carolina Clean Energy Technology Center, 2021). Their advocacy can also help build public support for renewable energy initiatives.

Compliance and Implementation

Mechanical engineers ensure that projects adhere to relevant regulations and standards. They conduct assessments and audits to verify compliance with environmental and safety regulations, ensuring that projects meet legal requirements and operate safely and efficiently (International Renewable Energy Agency, 2020). This compliance work is crucial for maintaining public trust and ensuring the long-term sustainability of renewable energy projects.

Research and Development

It is crucial to research to inform policy decisions and demonstrate the feasibility of new technologies. Mechanical engineers often collaborate with academic and research institutions to develop innovative solutions that can be scaled up for commercial use. This research helps to ensure that policies are based on the latest scientific and technological advancements, making them more effective and forward-looking (U.S. Department of Energy, 2021).

VII. GLOBAL CASE STUDIES OF POLICY IMPACT

Germany's Renewable Energy Act (EEG)

The Renewable Energy Act (EEG) has been instrumental in promoting the adoption of renewable energy in Germany. The Act's feed-in tariffs and guaranteed grid access for renewable energy producers have led to significant solar and wind energy investments. Mechanical engineers have been involved in designing and implementing the necessary infrastructure to support this transition, and this shows the importance of technical expertise in policy success (German Federal Ministry for Economic Affairs and Energy, 2020).

California's Building Energy Efficiency Standards (Title 24)

California's Title 24 standards have driven the widespread adoption of energy-efficient technologies in buildings. Mechanical engineers are integral to designing HVAC systems and other building components that comply with these stringent standards. Supportive policies that encourage energy efficiency and sustainability in building design have facilitated the integration of renewable energy systems such as solar panels (California Energy Commission, 2020).

China's Renewable Energy Law

China's Renewable Energy Law provides a comprehensive legal framework to promote renewable energy development, including targets, subsidies, and mandatory grid connection policies. Mechanical engineers contribute significantly to designing and constructing large-scale renewable energy projects such as wind farms and solar power plants. This legal framework has enabled China to become a global

leader in renewable energy production, demonstrating the profound impact that well-designed policies can have when combined with engineering expertise (National Development and Reform Commission, China, 2020).

VIII. FUTURE POLICY DIRECTIONS

Integrated Energy Policies

Developing holistic policies integrating renewable energy with existing infrastructure is crucial for sustainable progress. Integrated energy policies should encourage cross-sector collaboration and systems thinking, ensuring that various energy sources and technologies work together seamlessly. Such policies should also promote the development of smart grids and advanced energy management systems that can optimize the use of renewable energy across different sectors (International Renewable Energy Agency, 2020).

Support for Emerging Technologies

Providing incentives and support for emerging clean energy technologies, such as advanced energy storage solutions and smart grids, is essential. Regulatory frameworks must adapt to technological advancements and ensure that innovations can be quickly and effectively integrated into the existing energy infrastructure. This support can include grants, subsidies, and tax incentives to reduce the financial barriers to adopting new technologies (U.S. Department of Energy, 2021).

Resilience and Adaptation

Developing policies that enhance the resilience of energy infrastructure to climate change and other external threats is vital. These policies should promote adaptive measures to ensure the sustainability and reliability of integrated systems. For example, infrastructure design and construction standards could incorporate resilience criteria, ensuring that renewable energy systems can withstand extreme weather events and other climate-related challenges (California Energy Commission, 2020).

Global Cooperation

Encouraging international collaboration on clean energy policies and technology transfer is essential for accelerating global progress. Sharing best practices

and successful policy frameworks across borders can help countries learn from each other's experiences and implement effective strategies. International cooperation can also facilitate the development of global standards and regulations, promoting consistency and interoperability in clean energy technologies (German Federal Ministry for Economic Affairs and Energy, 2020).

CONCLUSION

Integrating clean energy sources into existing infrastructure is vital for combating climate change and ensuring a sustainable energy future, but this transition is not without its challenges. Technical obstacles such as grid integration, energy storage, and grid modernization must be addressed to realize the potential of renewable energy sources fully.

Mechanical engineers are instrumental in designing and optimizing clean energy systems like wind turbines, solar panels, and energy storage technologies. Their expertise is essential for ensuring their efficiency, reliability, and compatibility with the grid.

Ongoing research and development efforts are focused on advancing renewable energy technologies and grid modernization strategies. These efforts aim to improve the performance and cost-effectiveness of clean energy systems, making them more competitive with traditional fossil fuels. Advancements in innovative grid technologies and energy storage solutions are paving the way for a more flexible and resilient energy infrastructure, and mechanical engineers are shaping a future where clean energy is the norm, not the exception.

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