

Lean Six Sigma and Sustainability in the Energy Sector: A State of the Art Review

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ABSTRACT - The energy industry is particularly put under pressure to enhance the efficiency of its operations and at the same time maintain high targets in sustainability and decarbonization. Lean Six Sigma (LSS) as a systematic approach to combine waste minimization with variation control has become a promising operating scheme to overcome these issues. The narrative review is a synthesis of the current research on the use of LSS in the energy sector and specifically on its environmental, economic, and social sustainability consequences. The review follows the development of LSS since its beginning with traditional energy operations through the growth of its application in renewable energy systems and utilities, and smart grids. It is always evident that LSS has the potential to bring quantifiable results, such as energy conservation, emission cuts, cost effectiveness, increased asset durability, and worker safety through operational strategies, by integrating sustainability goals into the workplace. One of the current trends that have been pointed out in the literature is the integration of LSS with computer technologies, including Industry 4.0 tools, real-time monitoring, artificial intelligence, and digital twins, which enhance the work on data-driven decision making and scale improvement. Irrespective of these benefits, structural, organisational, and regulatory impediments continue to curtail its implementation even in complicated resource-hindered environments. This review makes LSS a critical interaction point between sustainability and efficiency by defining patterns of application, its effect on sustainability, and implementation issues. It also provides the future research directions to facilitate the shift to resilient, low-carbon energy systems.

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1.0 INTRODUCTION

The global energy sector is increasingly needing to provide secure, affordable and reliable energy while rapidly decarbonising and limiting the impact on the environment [1]. This pressure is also driven by the overlapping demands of climate commitments, fuel and electricity market volatility, energy demand growth, infrastructure modernization needs, and rapid expansion in low-carbon technologies [2]. There have been numerous recent global assessments emphasizing the need to dispel conventional wisdom that energy systems must transition more gradually while ensuring system resilience and economic viability, as well as social acceptability [3, 4]. Within this context, energy organizations have acute pressure to drive operational efficiency not just as a cost-cutting measure but also in support of emissions reduction, resource optimization and long-term sustainability [5].

In that regard, Lean Six Sigma (LSS) has become a systematic, factual approach to operational excellence in complex systems [12]. Combining Lean principles that aim at eradicating waste with the ones of Six Sigma that are concerned with the stability of processes and reduction of variation, LSS provides a methodical way of enhancing efficiency, reliability, and quality [13]. Its effective use in the manufacturing and service sectors has created an increasing interest in its use in the energy sector to overcome operational problems, such as power generation, transmission, distribution, as well as energy utilities [14].

Notably, the current literature and practice are starting to appreciate the fact that operational excellence and sustainability are not two focused and exclusive goals [15]. Efficient, stable and minimized processes on waste will

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directly lead to lower consumption of resources, lower emissions, greater use of assets and greater workforce safety. In this paradigm, Lean Six Sigma acts not as a tool of productivity, but as an operation facilitator of environmental, economic, and social sustainability in the energy systems [16].

Despite the growing literature covering Lean, Six Sigma, and Lean Six Sigma in the energy sector, the available research is disjointed in terms of disclosing the energy subindustries, methodology and sustainability aspects [17]. The majority of the contributions are based on isolated case studies or narrow performance metrics without providing much synthesis of wider sustainability impacts or cross sectoral understanding. As a result, the lack of in-depth knowledge exists as to the contribution of Lean Six Sigma to sustainability outcomes in various energy situations [18].

To address this gap, the present review provides a structured synthesis of Lean Six Sigma applications in the energy sector, with particular emphasis on sustainability-related outcomes and implementation patterns across energy sub-sectors. Specifically, this review pursues three objectives: (1) to map Lean Six Sigma implementation patterns across conventional energy systems, renewable energy systems, and utility or smart-grid environments; (2) to critically analyse the environmental, economic, and social sustainability outcomes reported in the literature; and (3) to identify implementation challenges, research gaps, and future directions for the use of Lean Six Sigma in sustainable energy management. In doing so, the review aims to move beyond descriptive discussion and provide a clearer analytical foundation for both academic research and practical decision-making in the energy sector.

2.0 REVIEW METHODOLOGY

A structured literature review approach was used to identify, screen and synthesize published studies on Lean Six Sigma and sustainability in the energy sector. This review aimed to assess the extent of Lean Six Sigma application in various energy sub-sectors and evaluate the sustainability outputs, barriers of implementation, and future research trends reported in literature.

The main academic databases, including Scopus, Web of Science, Science Direct and Google Scholar were used to carry out the literature search. Keywords on Lean Six Sigma and energy sector like “Lean Six Sigma”, “Lean”, “Six Sigma”, “energy sector”, “power generation”, “renewable energy”, utilities, smart grid, sustainability etc were used to develop search terms. Further backward and forward citation tracking was employed to identify studies missed in the initial database search.

Studies were included when they: (1) All analysed Lean, Six Sigma or Lean Six Sigma within the domain of energy context; (2) reported operational, environmental, economic, social, organisational and/or strategic outcomes; and (3) published in peer-reviewed journals, conference proceedings/theses or recognised scholarly sources in English. Studies were excluded if they only described non-energy sectors, offered generic discussion of the concept without relevance to its energy applications, or provided insufficient detail on implementation context and/or outcomes.

Following, the selected studies were screened by title, abstract and full text followed by a thematic synthesis of the included studies. The extracted data were categorised by energy sub-sector, applied Lean Six Sigma tools or approaches, reported outcomes, barriers to implementation and links to sustainability dimensions. The findings were then comparatively synthesised to highlight emerging themes, differences between sub-sectors and gaps in the existing literature. This systematic approach aids the analytical goals of this overview and enhances transparency in study selection and interpretation.

3.0 CONCEPTUAL FOUNDATIONS

3.1 LEAN SIX SIGMA: PRINCIPLES, METHODOLOGIES, AND TOOLS

The core element of lean thinking is to create value to the end user by systematically searching and eradicating wastage as part of the process [19]. Waste in energy systems can be defined to be more than material losses and involves the production of overproduction, over waiting time, process defects, unnecessary transportation, underutilization of human potential and critically wastage of energy [20]. Lean concepts focus on optimising the process flows, use of resources and value added activities, which makes them specifically applicable to the operations of energy where the inefficiencies directly translate to increased emissions, higher costs and decreased reliability of a system [21].

Six Sigma is a complement to Lean thinking that aims at minimizing variability of processes and attaining the consistency of stable and predictable performance [22]. The Six Sigma philosophy is based on the principles of statistical process control and quality management that strive to enhance capability of the processes by reducing defects and deviation towards the expected performance levels [23]. In systems that operate variably with regard to energy, i.e., the ephemeral nature of operations may cause unproductive factors, equipment wear, and safety problems, Six Sigma offers an information-based paradigm of finding root causes of variability and taking long-term corrective measures [24].

The convergence of Lean and Six Sigma is operationalized with the help of properly developed methodological schemes, mostly DMAIC (Define-Measure-Analyze-Improve-Control) and DMADV (Define-Measure-Analyze-Design-Verify) [25]. The DMAIC is highly utilized to enhance the performance of existing processes through a structured process of diagnosing the gap in the performance and institutionalizing it, but DMADV focuses on designing new processes or redesigning the old processes to meet performance and sustainability specifications. These approaches guarantee systematic problem-solving, evidence-based decision-making, and performance control in the long-term in energy activities [26].

Lean Six Sigma implementation in energy-related situations is facilitated by a variety of analytical and improvement tools. Value Stream Mapping (VSM) often uses visualization of energy, material flows, identification of bottlenecks, and the expression of non-value-adding activities in the chain of complex processes [27]. The Statistical Process Control (SPC) will allow constant observation of the paramount operational factors that allow noting the emergence of deviations and worsening indicators [28]. In safety critical energy systems, failure mode and effects analysis (FMEA) is a proactive method of analyzing risks based on the possible points of failure and ranking actions to control them.

Root-cause analysis methods, including cause-and-effect diagram and 5 Whys, allow in-depth research of the root of the performance problems. Kaizen and other continual-improvement cycles on the other hand encourage small-scale, employee-based improvements. The two tools together serve to instill the culture of discipline and learning in an organization and embed the concept of continual improvement in the daily running of an organization [29].

Lean Six Sigma is particularly useful in sophisticated and capital-intensive energy environments, where resources are expensive, machinery life cycles are lengthy and regulatory requirements are strict [30]. Lean Six Sigma offers a coherent framework that has the capacity to handle the complexity of operations and support the inclination of performance gains with the overall sustainability goals which renders it a viable option in the modern management of energy-system [31].

Across the literature reviewed, however, these tools are not applied consistently across energy sub-sectors. Conventional energy studies are biased towards process stabilisation, maintenance optimisation and reliability improvement, whereas renewable energy studies are more oriented towards variability management, performance consistency and resource-use efficiency. At utilities and smart-grid studies, an increasing number are integrating Lean Six Sigma into their monitoring, analytics and service optimisation functions. So the point is that Lean Six Sigma actually has practical value in energy sector field not only due to its generic methodology but also due to diverse applied methods of different companies and various priorities leading towards operation and sustainability.

3.2 SUSTAINABILITY IN THE ENERGY SECTOR

The triple bottom line approach is the most widespread way of conceptualizing sustainability in the energy sector because it incorporates the environmental, economic, and social perspectives. Therefore, the appropriate sustainability practices should create a balanced equation- both reducing environmental content and at the same time increase the financial gains, as well as ensuring improvement in social welfare. [32].

The energy systems are also concerned about environmental sustainability because they contribute greatly to global emissions of greenhouse gases and consumption of resources [33]. Some of the environmental goals are to become more energy efficient and ensure that there is reduction of losses during the generation process, transmission and distribution, also reduction of carbon dioxide and other emissions, and also reduction in the utilization of natural resources like fuels, water and raw materials. These results are critical to the reduction of the effects of climate change and to the long-term sustainability of the energy supply mechanisms [34].

In order to remain viable financially amidst the increasing competition and the tighter regulations, energy companies need to minimize operational and maintenance costs, make maximum utilization of assets and increase their productivity. Therefore, the sustainability of the economic performance depends on effective, stable, and smoothly managed working processes. [35].

Social sustainability looks at the social and human characteristics of the manner in which we generate and allocate energy. Occupational health and safety is important in energy activities- workers are exposed to unsafe environments and risky operations on a regular basis. The ability of the workforce, as well as continuous training, is also crucial and necessary to handle the sophisticated technologies and complicated systems. More than inside the boundaries of individual organizations, energy systems define communities, and a broad group of stakeholders, affecting the environment, making or breaking jobs and determining access to reliable power. Due to these long-term implications, social responsibility is an essential part of the sustainable energy management [2, 36].

As well as the above triple bottom line view, sustainability can also be seen in terms of the United Nations Sustainable Development Goals (SDGs) that relate to energy. While all 17 SDGs form a general framework for global sustainability, the ones that are most pertinent to this review are those concerning: (i) SDG 7-Affordable and Clean Energy, (ii) SDG 8 - Decent Work and Economic Growth, (iii) SDG 9-Industry, Innovation and Infrastructure, (iv) SDG12 - Responsible Consumption and Production; and (v) SDG 13 - Climate Action. In this sense, Lean Six Sigma can be considered as an operational enabler serving at the same time these goals through enhancing process efficiency, waste and emissions reduction potential, competitive performance of industry along with prospects for safer and more resilient energy systems.

3.3 CONCEPTUAL SYNERGY BETWEEN LEAN SIX SIGMA AND SUSTAINABILITY

The lean waste reduction is a definite and effective path to reduce emissions and eliminate energy wastage in the power system. With a procedural identification and removal of non-value-adding processes including unnecessary energy consumption, slow throughput, unnecessary rework and non-productive downtime, Lean activities reduce the amount of fuel used and decrease the size of greenhouse-gas emissions. Even minute inefficiencies in energy operations can accumulate to huge environmental footprints, certain operational benefits of Lean-based waste reduction thus combine operational benefits and sustainability objectives [37].

Six Sigma supplements this plan by addressing process variability as a major cause of inefficiency, unreliability, and wastage of resources in energy systems. With a wide variation in the operational parameters, it causes unreliability in performance, escalation in maintenance needs, accelerated equipment wear, and safety hazards become more common.

Through the implementation of statistical process control and root-cause analysis, Six Sigma assists organisations to have more consistent and predictable results, which in turn enhances energy efficiency, operational stability and the overall system resilience [38].

Sustainability goals may be transformed into tangible and measurable results, by incorporating Lean and Six Sigma into the Lean Six Sigma framework. Whereas most sustainability policies and targets remain at the strategic or regulatory tier, Lean Six Sigma can provide tangible methods and tools, e.g. DMAIC, performance measures, and continuous monitoring that can entrench those goals into daily activities. This strategy ensures that efficiency improvements, reduction of emissions and resource utilization become measurable, reactivable and sustainable [39].

From a theoretical perspective, the integration of Lean Six Sigma into sustainable energy management is supported by performance management and systems theory. Lean Six Sigma aligns with the resource-based view by enhancing the efficient use of critical assets, and with continuous improvement theory by fostering organizational learning and adaptability. Moreover, its emphasis on data-driven decision-making and process control supports sustainable systems thinking, making LSS a theoretically robust framework for achieving long-term environmental, economic, and social sustainability in energy systems [40].

Figure 1 summarises the distilled linkage between Lean Six Sigma principles and sustainability outcomes; applicable to energy generation and procurement within an organisational context. On the left side of the framework are the five core Lean Six Sigma inputs, waste elimination, variation reduction, continuous improvement, process control and data-driven decision-making. Such inputs lead to operational mechanisms like energy-efficiency improvement, defect reduction, maintenance optimisation, resource conservation and workflow standardisation. Lean Six Sigma achieves three interrelated dimensions of sustainability, environmental destruction reduction measured through emission and resource loss, economic profitability improvement manifested through cost-time and efficiency betterment coupled with superior asset utilisation, social sustainability derived from safe operations, employee engagement and organisational learning capability.

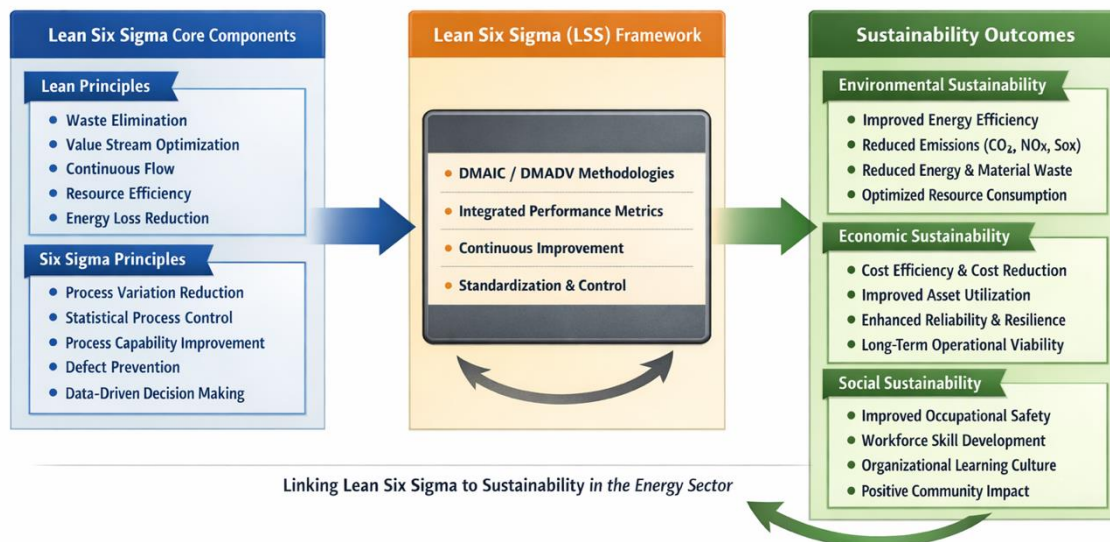


Figure 1. Conceptual linkage between Lean Six Sigma principles and environmental, economic, and social sustainability outcomes in the energy sector.

The diagram thus suggests that Lean Six Sigma should never be regarded as a mere productivity or quality-management tool. Rather, as indicated by the reviewed literature, it serves to act as a pragmatic operational bridge whereby generalized sustainability goals can be framed into evidence-based and tractable process-level improvements within energy systems. Because of this, our interpretation is significant because it enables Lean Six Sigma to be not only for the enhancement of efficiency in general, but a framework within sustainable energy management itself.

4.0 EVOLUTION OF LEAN SIX SIGMA IN THE ENERGY SECTOR

An overview of Lean Six Sigma maturity in the energy context involves four generic phases (see Figure 2), including initial implementation in traditional energy sectors, expansion from efficiency-targeted initiatives to sustainability applications, extension into RE systems and recent links with digital technologies, utilities and smart-grid environments. The topic in this section have followed the sequence to provide a clearer view of how Lean Six Sigma has evolved through time and also across energy sub-sectors.

In the energy sector, Lean and Six Sigma implementation can be dated to the introduction of the two approaches in the traditional energy industries especially thermal power and oil and gas businesses. These industries were some of the earliest to employ formal strategies of process-improvements because of their capital-intensive, complicated operations, and high focus on reliability and safety. Originally, the Lean and the Six Sigma were presented as management and operational instruments to facilitate the process control and promote the operational discipline of large-scale energy plants [40].

In the initial years of adoption, the main attention of the Lean and Six Sigma initiatives was to enhance efficiency, defects, and stabilize the operations. These methodologies were implemented by energy organizations to reduce unplanned failures, optimized fuel consumption, equipment reliability and also the variability in processes. At this point, the improvement of performance was much more economically oriented and the success was measured in economic terms (cost savings, productivity gains, and operational consistency) and not the explicit sustainability results [41].

As time progressed, the sphere of Lean Six Sigma implementation in the energy industry started to increase and go beyond the cost-based improvement toward the more universally focused on sustainability performance goals. Increasing regulatory pressures, environmental consciousness, climate-related responsibilities stimulated energy organizations to associate their efficiency in operations with emission and energy efficiency, and conservation of resources. This move was a significant change in the conceptualization of Lean Six Sigma, which ceased to be seen as an instrument of operational excellence and turned out to be an instrument of supporting the objectives of environmental and economic sustainability [41].

Sustainability goals may be transformed into tangible and measurable results, by incorporating Lean and Six Sigma into the Lean Six Sigma framework. Whereas most sustainability policies and targets remain at the strategic or regulatory tier, Lean Six Sigma can provide tangible methods and tools, e.g. DMAIC, performance measures, and continuous monitoring that can entrench those goals into daily activities. This strategy ensures that efficiency improvements, reduction of emissions and resource utilization become measurable, reactivable and sustainable [42].

The development of digital technologies and intelligent systems of energy has pushed the development of Lean Six Sigma in the energy industry. Leapfrog, Lean Six Sigma applications have been made data intensive and responsive using sensors, real-time monitoring, and high-tech analytics. These developments form the foundation of predictive maintenance, real-time optimization, and continuous performance monitoring, which point to the overwhelming importance of Lean Six Sigma in the operation of the ever-increasing complexity and interdependence of today's energy systems [43].

The majority of its initial applications were in industrialized areas with well established conventional energy infrastructure, but recent research indicates that it is increasingly being used in developing economies and in renewable energy settings. In the course of time, studies and practice have changed the isolated case based applications to more integrated and strategically aligned applications as evidenced by the increase in the awareness of Lean Six Sigma as a major facilitator of sustainable energy system performances [44].

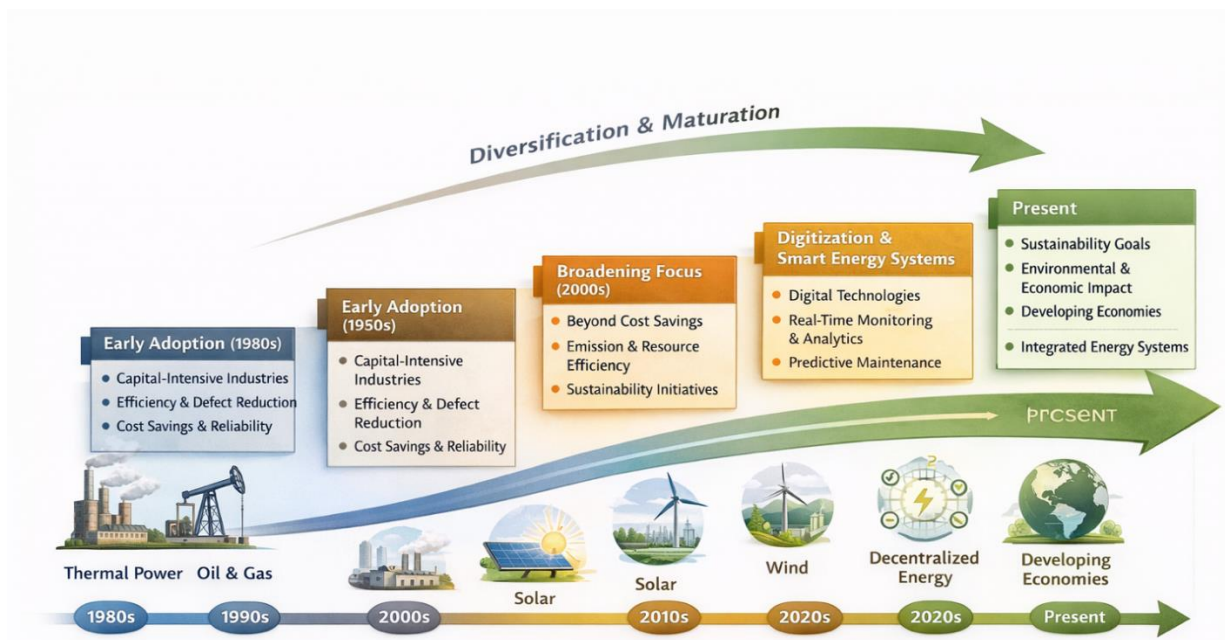


Figure 2. Evolution of Lean Six Sigma applications in the energy sector across time and sub-sectors

The literature reviewed clearly shows an evolution of Lean Six Sigma's role in the energy market. Initial applications were primarily focused on the reliability, efficiency and cost containment of traditional energy operations, while later research increasingly frames Lean Six Sigma as an enabler for sustainability, digitalisation and resilience within systems. However, the literature continues to be heterogenous between sub-sectors, with stronger evidence for conventional operations compared with renewable and smart-energy settings. This uneven development points to the need for a more comparative and evidence-based synthesis across the whole energy landscape.

5.0 LEAN SIX SIGMA APPLICATIONS ACROSS ENERGY SUB-SECTORS

5.1 CONVENTIONAL ENERGY SYSTEMS

Lean Six Sigma has been broadly implemented in the traditional energy systems, especially in the thermal generation of power when operation efficiency and reliability are key performance indicators. Lean Six Sigma techniques have been applied in such environments to simplify process flows, minimize waste of operations, and stabilize complicated generation processes. LSS is organized and data oriented and, therefore, it fits well into large scale power plants that are continuously operated and possess highly interconnected system element [45].

One of the areas of main concern in the implementation of Lean Six Sigma in thermal power generation has been the enhancement of the fuel efficiency and the heat rate performance. The generation of power has seen a notable increase in the efficiency of fuel and heat rate. Lean Six-Sigma (LSS) programs assist in the attainment of a greater degree of uniformity in the combustion and enhancement of energy that is utilized through the detection and eradication of pathways of inefficiency and variation. Emission is also cut as the resultant gains not only reduce the operating costs, but also the emissions increased efficiency in the production of electricity is translated to less greenhouse-gas and pollutant emissions per unit of electricity generated [46].

LSS facilitates prevention and predictive maintenance through tools like statistical process control, failure mode analysis and root cause investigation. These methods minimize unexpected downtimes, increase the life cycle of equipment and enhance the system availability in general, a factor highly valued in capital-intensive energy infrastructure [47].

Lean Six Sigma has been used in the oil and gas operations, where application has been applied in the improvement of safety critical processes. Due to the high-risk environment of upstream and midstream and downstream operations, the LSS tools are applied to determine possible failure points, minimize the variability of the process, and improve the adherence to safety and environmental requirements. Increased consistency in operation and risk control does not only minimise the risk of accidents but also guarantees higher compliance with regulations and better environmental performance [48].

Transmission and distribution networks have also been implemented using lean Six Sigma to deal with technical losses, asset degradation and problem of reliability. LSS helps to make the electricity delivery process more efficient and the grid more effective by improving the asset management practices, optimizing the maintenance schedules, and limiting the system losses. These applications point to the fact that the Lean Six Sigma applications can help the conventional energy become more sustainable and resilient. systems beyond generation facilities [49].

5.2 RENEWABLE ENERGY SYSTEMS

The operational challenges in renewable energy systems are almost wholly different compared to the traditional energy infrastructure, mainly because the systems are variable and dependent on the environment. The variability of the solar irradiation and wind speed due to weather causes instability in the performance making it hard to plan, maintain and ensure reliability. In this respect, Lean Six Sigma has been studied more and more as a paradigm of handling the complexity of operations, decreasing the variability of the processes, and enhancing the performance of the whole system in the area of renewable energy activities [50].

The main area of Lean Six Sigma implementation in solar energy systems has been on enhancing efficiency in processes of installation, operation and maintenance processes. The lean principles are implemented to simplify the processes, minimize the non-value-adding activities and make better use of the resources and Six Sigma tools are used to identify and manage the performance deviation. Such activities help to achieve a more stable energy production, fewer losses in operation and better use of the solar resources especially in large scale photovoltaic systems [50].

Wind energy systems have equally been embracing Lean Six Sigma oriented methods in improving the reliability and maintenance performance of the system. Considering the mechanical complexity and vulnerability of wind turbines to the adverse environmental factors, LSS tools are implemented to ensure lesser variability in terms of maintenance, enhanced failure prediction, and maintenance scheduling optimization. Lean Six Sigma enables more reliable power production by making turbines more available and minimizes downtime through an organized study of failure modes and operation statistics [51].

Lean six sigma has been used in biomass and bio energy systems to solve the issues associated with feedstock variability, inefficiencies in the process as well as waste generation. LSS programs enhance economic and environmental sustainability by streamlining feedstock processing, conversion and work processes. Reduction of waste and better use of the material not only increase the efficiency of the operations, but also lowers the environmental footprint related to bioenergy generation [52].

5.3 ENERGY UTILITIES AND SMART GRID ENVIRONMENTS

Smart grid environments and energy utilities are a particularly sensitive point of energy generation systems and end users where efficiency, reliability, and quality of services are primary performance metrics. Under these circumstances, Lean Six Sigma has been more extensively used to make grids more efficient and stable in their operations by eliminating process inefficiencies, reducing technical and non-technical losses, and enhancing the coordination of complex utility

processes. Lean six sigma is more stable in grid performance because of its structured and data driven nature in ever-increasingly interconnected and dynamic energy systems [53].

Demand-side management initiatives to enhance customer centric performance and reduce energy consumption patterns have also been implemented using Lean six sigma. As utilities seek to understand the inefficiencies in consumption data and service processes, they use LSS tools to detect the variations in service delivery, minimize variability, and be more responsive to customer needs. By using these applications better demand management can be achieved, improved service reliability and better alignment between the operational performance and customer satisfaction [54].

Another critical domain of utility performance that Lean Six Sigma can bring to is asset optimization in optimizing its lifecycle. The systems operated by the utilities comprise large systems of high value assets that have long operational life cycles and therefore, it is necessary to maintain a proper maintenance and investment planning to undertake the maintenance of the assets [55].

The analysed literature indicates that Lean Six Sigma (LSS) implementations vary across energy sub-sectors with respect to priorities, tools and outcomes. Most of the research in conventional energy focuses on efficiency enhancement, maintenance optimisation, and emissions minimization across large-scale and asset-heavy environments. The field of renewable energy is more tightly linked with issues such as variance management, performance consistency, and operational reliability under time-variable environmental conditions. Within utilities and smart-grid environments, Lean Six Sigma is now being closely associated with service quality, demand side management, loss reduction and data enabled process control. This comparison highlights that Lean Six Sigma does not span a uniform application across the energy sector but instead adapts to the operational and sustainability needs of each individual sub-sector.

Table 1 gives the summary of Lean Six Sigma applications identified across the three energy sub sectors observed and reviewed in this study, including the focus areas, tools applied, operational targets, and reported outcomes.

Table 2 included the cross subsector comparative summary of Lean Six Sigma implementation, highlighting the key variation and similarities in focus areas, tools, outcomes, evidence base, and implementation challenges across conventional energy, renewable energy, and utility/smart grid environments.

Sub-Sector	Focus Area	LSS Tools Used	Operational Target	Reported Outcomes	References
Thermal Power Generation	Fuel efficiency & heat rate optimisation; combustion uniformity	DMAIC, SPC, FMEA, Root Cause Analysis	Reduce fuel consumption; stabilise combustion	Improved heat rate; reduced GHG emissions per unit generated; lower operating cost	[45, 46]
Thermal Power Generation	Predictive & preventive maintenance	SPC, Failure Mode & Effect Analysis (FMEA)	Minimise unplanned downtime; extend equipment life	Reduced breakdown frequency; improved system availability	[47]
Oil & Gas (Upstream / Midstream / Downstream)	Safety-critical process improvement; risk reduction	DMAIC, process mapping, risk matrix	Reduce process variability; improve safety & regulatory compliance	Fewer accidents; improved environmental compliance; reduced variability in high-risk operations	[48]
Transmission & Distribution	Technical loss reduction; asset management	Lean process mapping, SPC	Reduce distribution losses; optimise maintenance schedules	Improved grid efficiency; reduced technical losses; enhanced reliability	[49]
Solar Energy Systems	Installation, O&M process streamlining	Lean principles, Six Sigma variation reduction	Minimise non-value-adding activities; reduce performance deviation	More stable energy output; lower operational losses; better resource utilisation	[50]
Wind Energy Systems	Maintenance reliability & turbine availability	FMEA, SPC, root cause analysis	Reduce maintenance variability; optimise scheduling; predict failures	Higher turbine availability; reduced downtime; more reliable power output	[51]

Biomass / Bioenergy	Feedstock variability & waste reduction	DMAIC, process optimisation	Streamline feedstock processing; reduce waste generation	Improved operational efficiency; lower environmental footprint; reduced material waste	[52]
Energy Utilities & Smart Grid	Grid efficiency; demand-side management	Lean tools, data-driven process control, SPC	Reduce technical & non-technical losses; improve service reliability	Improved grid stability; better demand management; enhanced customer satisfaction	[53, 54]
Energy Utilities & Smart Grid	Asset lifecycle optimisation	LSS integrated with IoT & real-time monitoring	Optimise maintenance planning; reduce capital expenditure	Extended asset life; minimised unnecessary investment; lower total ownership cost	[55]

Table 1: Summary of Lean Six Sigma Applications Across Energy Sub-Sectors

Criterion	Conventional Energy	Renewable Energy	Utilities / Smart Grid	Overall Maturity	Ref.
Primary LSS Focus	Efficiency, reliability, cost control, emission reduction	Variability reduction, maintenance reliability, performance consistency	Service quality, loss reduction, demand management, asset optimisation	High - Emerging (Renew/Util)	[40-55]
Dominant LSS Tools	DMAIC, FMEA, SPC, Root Cause Analysis	DMAIC, Lean process mapping, variation analysis	Lean tools, data-driven control, SPC, IoT-enabled monitoring	DMAIC most universal	[40-55]
Environmental Outcomes	Strong - emission reductions, fuel efficiency gains	Moderate - reduced operational losses, lower environmental footprint	Moderate - technical loss reduction, resource efficiency	Moderate - High overall	[56-58]
Economic Outcomes	Strong - cost savings, asset life extension, productivity	Moderate - O&M cost reduction, improved resource utilisation	Moderate-Strong capex reduction, improved service delivery	High overall	[59-60]
Social Outcomes	Moderate - safety improvements in high-risk settings	Low - limited social reporting in literature	Low-Moderate customer satisfaction, workforce engagement	Low overall; least documented	[61-62]
Evidence Base	Strong - multiple published case studies; quantified outcomes	Moderate - growing literature; fewer large-scale studies	Moderate - increasing integration with digital tools	Conventional Renewable Utility	[40-66]
Digital Integration	Moderate - predictive maintenance emerging	Low-Moderate early IoT applications	High - smart grid data, real-time monitoring, AI analytics	Utilities most advanced in digitalisation	[63-66]
Key Implementation Challenge	Organisational resistance; scale complexity	Environmental variability; data scarcity	Regulatory complexity; system interdependency	Common: leadership & data availability	[67-70]

Table 2: Cross-Subsector Comparison Summary of LSS Implementation in the Energy Sector

6.0 SUSTAINABILITY OUTCOMES OF LEAN SIX SIGMA IMPLEMENTATION

The sustainability outcomes uncovered by the literature reviewed suggest that Lean Six Sigma can positively impact the energy sector through various and interconnected avenues. But these outcomes are not evenly distributed in the literature. More environmental and economic outcomes than social outcomes are reported, but more directly reported economic and social outcomes receive very little quantification, which varies greatly across studies. Consequently, the following discussion reports environmental, economic and social or organisational outcomes but also highlights the relative strength of evidence across reviewed studies.

6.1 ENVIRONMENTAL SUSTAINABILITY IMPACTS

Lean Six Sigma can facilitate the sustainability of the environment in the energy sector by the systematic enhancement of energy use and decline. Lean principles assist in the identification and removal of non-value adding processes, and other areas causing inefficiency in the process and allow more efficient transformation, relocation, and utilization of the energy within the system. At the same time, Six Sigma tools contain operational variability, and the variability of energy performance becomes more foreseeable and predictable. Collectively, these advantages reduce technical losses and enhance system efficiency in general, which are major milestones toward the reduction of the environmental footprint of energy operations [56].

Lean Six Sigma leads to optimization of processes which directly reduces emissions within an energy system. Instead of accomplishing compliance only, Lean Six Sigma provides energy organizations with emission-related performance indicators, which are built into ongoing-improvement cycles in order to maintain long-term environmental impact reduction [57].

Not only does Lean Six reduce things like energy consumption and emissions- it also assists in preserving resources and reduction of waste in the whole energy value chain. It also minimizes material usage, by-products and increases efficiency of water, fuel and raw-material utilization by streamlining processes. The advantages are needed particularly in energy resources-consuming operations, where waste minimization saves the environment and reduces expenses at the same time. By so doing, Lean Six reinforces the connection between the objectives of environmental sustainability and the everyday operational activities [58].

6.2 ECONOMIC SUSTAINABILITY IMPACTS

The Lean SixSigma approach, when applied within the energy sector represents, an effective way to reinforce economic sustainability. Lean Six Sigma can reduce operating costs and increase productivity in asset-intensive energy environments by minimising waste, rework, reducing process variance and improving operational consistency. These gains particularly in energy, where minor improvements in efficiency, maintenance performance or process reliability can mean millions of dollars saved at scale are more valuable than ever. [59].

Energy companies deal with high value assets that have a long service life, thus, effective use and maintenance is the only way these organizations are financially sustainable. Lean Six Sigma assists in optimal maintenance planning, decreased equipment downtime, and enhanced decision making during the asset lifecycle. These enhance life of the assets, minimize unnecessary capital investment as well as minimizing total ownership cost [60].

6.3 SOCIAL AND ORGANIZATIONAL SUSTAINABILITY IMPACTS

The Lean Six Sigma will help in social sustainability in the energy industry by aiding in quantifiable occupational health and safety. Safety performance has been a key organizational concern in the energy operations that are associated with hazardous conditions, complicated equipment, and risky operations. Lean Six Sigma can be used to detect unsafe situations, minimize human error, and integrate preventative measures to safety and therefore, this is through systematic risk evaluation, failure data analysis and standard operating procedures. The benefits are not only restricted to reducing accidents but also an increase in regulatory compliance and the well-being of the workforce [61].

Outside the safety results, the Lean Six Sigma facilitates the engagement and development of the workforce by motivating employees to take part in problem-solving and ongoing improvements initiatives. Lean and Six Sigma tools training improves analytical, technical and decision making skills at the organizational levels. The involvement of employees in improvement projects develops a feeling of ownership and responsibility, which enhances motivation of the workforce and leads to more efficient and viable operational performance [62].

Deployment of Lean Six Sigma also helps in the creation of continuous improvement cultures in the energy organizations. Lean Six Sigma changes the behavior of organizations by turning them into entities where data-driven decision-making processes and the performance monitors support the behavior of the organization to become more proactive and preventative in terms of addressing the problem of the organization. This cultural shift is the key to the long-term performance improvement and keeping up with changing technological, regulatory, and market conditions [62].

Table 3 shows the structured synthesis of the sustainability outcomes reported in the reviewed literature, categorised according to environmental, economic, and social dimensions, along with an assessment of the strength of evidence for each outcome type.

Sustainability Dimension	Type of Outcome	Reported Benefits	Strength of Evidence	Ref.
Environmental	Energy efficiency improvement	Reduced technical losses; improved energy conversion efficiency; more predictable system performance	High - widely reported across conventional and utility sectors	[56]
Environmental	Emission reduction	Lower GHG and pollutant emissions per unit of electricity generated; integration of emission KPIs into continuous improvement cycles	Moderate-High - frequently reported in thermal/oil & gas; less so in renewables	[57]
Environmental	Resource & waste conservation	Reduced material usage; lower by-products; improved utilisation of water, fuel, and raw materials across the energy value chain	Moderate - reported mainly in conventional energy; limited quantitative data	[58]
Economic	Operating cost reduction	Reduced waste, rework, and process variance; improved operational consistency at scale	High - most consistently quantified outcome across studies	[59]
Economic	Asset lifecycle optimisation	Improved maintenance planning; reduced unplanned downtime; lower total cost of ownership; extended equipment service life	High - well documented in capital-intensive conventional energy settings	[60]
Economic	Productivity & efficiency gains	Higher throughput; better fuel heat-rate ratios; improved output per unit of input	Moderate - reported across sub-sectors but with varying quantification	[59, 60]
Social / Organisational	Occupational health & safety	Identification of unsafe conditions; reduced human error; integration of safety measures through FMEA and standard operating procedures; fewer accidents	Moderate - reported in oil & gas and utilities; limited in renewables	[61]
Social / Organisational	Workforce engagement & development	Employee participation in improvement initiatives; skills development in Lean, Six Sigma, and data analytics; higher sense of ownership	Low-Moderate - qualitative evidence; limited quantitative reporting	[62]

Social / Organisational	Continuous improvement culture	Data-driven decision-making embedded in organisational behaviour; proactive problem-solving culture; enhanced long-term adaptability	Low - generally reported conceptually; least quantified dimension in the literature	[62]
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Table 3: Summary of Sustainability Outcomes Reported in the LSS and Energy Literature

7.0 LEAN SIX SIGMA IN THE CONTEXT OF DIGITAL AND SMART ENERGY SYSTEMS

The development of digital and smart energy systems has greatly widened the horizons of Lean Six Sigma application in the energy industry and made it more effective. Industrial 4.0 technologies are one of the most significant influences in the energy industry, and they increase connectivity and automation as well as the availability of data. These developments enhance the analytical background of the Lean Six Sigma, and it allows organizations to shift to the continuous performance optimization process of data-driven, periodic improvement cycles in complex energy settings [63].

To support the Lean and Six Sigma analysis, the incorporation of the IoT devices, advanced sensors, and real-time data acquisition systems is critical. An ongoing system over control parameters provides an opportunity to identify deviation early, conduct root-cause analysis in real-time, and increase transparency of the processes. [64].

Lean Six Sigma decision-making is also further refined by artificial intelligence and sophisticated analytics that allow making predictions and prescriptions. The machine learning algorithms facilitate failure prediction, performance forecasting, and optimization of energy assets and processes. Together with the statistical rigor of Six Sigma, AI based analytics enable companies to foresee performance concerns, assess the state of improvement opportunities, and apply proactive interventions that can improve the efficiency, reliability, and sustainability results [65].

Digital twins is a new concept of applying Lean Six Sigma along with the optimization and sustainability assessment based on simulations. Digital twins allow exploration of the process improvements, maintenance plans, and operational modifications without interfering with real world operations by developing virtualizations of physical systems of energy. These abilities contribute to the continuous improvement cycles and enable organizations to measure the sustainability effects of decisions in advance [66].

Figure 3 presents an integrated conceptual framework showing how Lean Six Sigma can be strengthened through digital technologies in modern energy systems. The framework links core Lean Six Sigma functions, such as process control, root-cause analysis, and continuous improvement, with enabling digital technologies including IoT, advanced sensors, artificial intelligence, real-time analytics, and digital twins. These digital enablers improve visibility, prediction, responsiveness, and process optimisation, thereby reinforcing both operational performance and sustainability outcomes. The figure is therefore intended to summarise the recurrent themes identified in the reviewed literature rather than to serve as a purely abstract conceptual model.



Figure 3. Integrated conceptual framework linking Lean Six Sigma, digital technologies, and sustainability in energy systems

This integrated perspective is especially important for present day energy systems as digitalisation enhances the quantity and quality of operational data, while Lean Six Sigma provides a structured methodology to turn that data into sustainable progress. Thus, the union of Lean Six Sigma with digital technologies could be an important future path for energy-sector research and implementation.

8.0 CRITICAL SUCCESS FACTORS AND EMERGING BEST PRACTICES

The literature review results demonstrate that Lean Six Sigma implementation success in energy sector not only relies on technical tools, but also on implementing specific organisational, strategic and data-related enabling conditions. Success factors that emerge as recurring across studies, include commitment to sustainability from leadership, alignment to the main sustainability goals of work in progress, capability of the organisation's workforce (culture and operational readiness), availability of robust performance data and institutionalisation for continuous improvement practices. Many of these elements are particularly relevant in the energy space, where implementation generally takes place in heavily regulated, capital-intensive and operationally complex settings.

Strong leadership dedication and planned governance are cited as the enabling factors of the successful Lean Six Sigma implementation in the energy industry. Top management is essential in establishing specific priorities, resource allocation and justification of ongoing improvement programs in complex organizations. When Lean Six Sigma is incorporated into strategic governance systems instead of being considered an independent operational mechanism, the organization is at a better position of upholding the performance enhancements and aligning them to the long term sustainability objectives [67].

Another important key to success of Lean Six Sigma is its alignment with more general sustainability goals. Efforts aimed at improving that explicitly relate process optimization to environmental, economic, and social performance indicators have more chances to create a long-lasting impact. Lean Six Sigma project selection and performance evaluation can help achieve this, by incorporating sustainability goals into the project selection and performance assessment process, so that operational excellence initiatives will effectively reduce the emission level, resource use, and system robustness and position instead of immediate efficiency growth [68].

The empowerment of the workforce and the perpetual learning also contribute to the efficiency of Lean Six Sigma in energy systems. Effective implementations will focus on worker participation in the problem solving process, which is reinforced by systematic training in Lean, Six Sigma, and data analytics applications. The empowered employees will find more opportunities to find improvements, maintain gains in operations, and keep pace with changing technological and other regulatory conditions. Constant learning will also contribute to building internal competencies needed to advance and digitally enabled Lean Six Sigma applications [69].

Timely and reliable performance data allows organizations to track the stability of processes, measure initiatives to improve, and be proactive to arising problems. The presence of feedback mechanisms enhances accountability and facilitates the process of learning, which is iterative to ensure that the improvement efforts are responsive to the changing operational and sustainability demands [70].

Table 4 summarises the critical success factors presented across the reviewed literature, outlining their descriptions, relevance to the energy sector, and the relative strength of evidence reported in published studies.

Critical Success Factor	Description	Relevance to Energy Sector	Strength in Literature	Ref.
Leadership Commitment & Governance	Top management sets priorities, allocates resources, and justifies continuous improvement programs within governance structures	Energy organisations are capital-intensive and hierarchical; strategic buy-in is essential to sustain LSS beyond pilot projects	High	[67]
Strategic Alignment with Sustainability Goals	LSS projects explicitly linked to environmental, economic, and social performance indicators rather than isolated efficiency metrics	Ensures operational excellence initiatives contribute to emission reduction, resource optimisation, and long-term system resilience	High	[68]
Workforce Capability & Empowerment	Systematic training in Lean, Six Sigma, and data analytics; employee participation in problem-solving and improvement cycles	In complex, regulated energy environments, skilled and engaged workers maintain gains and adapt to changing operational and regulatory conditions	Moderate-High	[69]
Data Availability & Feedback Mechanisms	Reliable, timely performance data to track process stability, measure improvement, and enable proactive decision-making	Energy systems generate large operational datasets; LSS effectiveness depends on data quality and the presence of structured feedback loops	Moderate-High	[70]

Culture of Continuous Improvement	Institutionalisation of data-driven decision-making; shift from reactive to proactive performance management	Supports long-term performance improvement and adaptability to evolving technological, regulatory, and market conditions in the energy sector	Moderate	[67, 69]
Digital & Technological Readiness	Integration of IoT, AI, predictive analytics, and digital twins to enhance LSS data collection, analysis, and real-time optimisation	Increasing digitisation of energy systems amplifies LSS effectiveness; organisations with mature digital infrastructure benefit most	Emerging	[63-66]

Table 4: Critical Success Factors for Lean Six Sigma Implementation in the Energy Sector

9.0 RESEARCH GAPS AND FUTURE DIRECTIONS

Although the literature demonstrates growing interest in Lean Six Sigma within the energy sector, several important gaps remain. First, there is still limited comparative evidence across conventional energy, renewable energy, and utility or smart-grid contexts. Many studies focus on isolated case applications, making it difficult to draw broader conclusions regarding implementation patterns and transferability across sub-sectors.

Second, the reporting of sustainability outcomes is uneven. Environmental and economic gains are more frequently discussed than social and organisational outcomes, and many studies provide limited quantitative evidence on long-term sustainability impacts. Future research should therefore use more consistent indicators to assess emissions reduction, energy-efficiency gains, cost savings, workforce outcomes, and resilience effects.

Third, the integration of Lean Six Sigma with digital technologies such as artificial intelligence, IoT, predictive analytics, and digital twins remains conceptually promising but empirically underdeveloped. More applied studies are needed to examine how these technologies can strengthen Lean Six Sigma implementation in real operating environments.

Finally, there is a need for more evidence from emerging and developing economies, where energy systems may face different institutional, financial, infrastructural, and regulatory conditions. Future studies should therefore expand the geographical scope of research, apply comparative designs, and develop more robust sustainability-oriented evaluation frameworks for Lean Six Sigma in the energy sector.

10.0 CONCLUSION

This literature review explore Lean Six Sigma role in the energy sector through a structured synthesis of published literature with focus on implementation trends, sustainability impacts and future research directions. Relating to the first goal, the review evidence suggests that Lean Six Sigma has been used across traditional energy systems, renewable energy systems and utility or smart-grid landscape although depth and maturation of application vary across these sub domains. Studies of conventional energy systems are comparably more consolidated, whereas applications of renewables and digitally enabled functionalities are still in their infancy.

Concerning the second goal, it is documented that Lean Six Sigma examine can assist bring about environmental, financial and social sustainability within the power sector. Environmental benefits reported include less waste, Lower emissions and improved Energy efficiency; Economic benefits (for instance cost reduction and asset utilisation) social (safer operations, more engaged workforces) and economic benefits can be seen to live within the scope of IoT as a trend. However, there is variability in evidence strength, and social outcomes are less consistently reported than environmental and financial outcomes.

For the third objective, the review highlights some key implementation challenges and research gaps such as uneven evidence across sub-sectors; a lack of comparative analysis; inconsistent measurement of sustainability outcomes; and the need for stronger empirical research on both digital integration within energy systems and emerging sustainable energy contexts. Such gaps indicate that future efforts would benefit from more systematic comparative designs and by using stronger sustainability metrics.

In summary, Lean Six Sigma must be considered not only as a tool for quality or efficiency, but also and more importantly as an adaptable operational framework that can help in the shift towards flexible, resource-efficient and sustainable energy systems. As energy systems are increasingly digitalised, decentralised and decarbonised, the strategic importance of Lean Six Sigma is probably going to grow even further.

11.0 CONFLICT OF INTEREST

Authors declare that there is no conflict of interests regarding the publication of the paper.

12.0 AUTHORS CONTRIBUTION

The authors confirm contribution to the paper as follows: study conception and design: Sharmelen Subramaniam, Norazlianie Sazali; literature collection and data compilation: Sharmelen Subramaniam, Arigela Satya Veerendra; analysis and interpretation of results: Sharmelen Subramaniam, Norazlianie Sazali, Kumaran Kadirgama; framework development and conceptual modelling: Norazlianie Sazali, Kumaran Kadirgama; draft manuscript preparation:

Sharmelen Subramaniam, Arigela Satya Veerendra; critical revision and technical review: Norazlianie Sazali, Kumaran Kadirgama. All authors reviewed the results and approved the final version of the manuscript.

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