INTEGRATING LEAN MANAGEMENT PRACTICES FOR ENHANCING SUSTAINABILITY IN SOLAR ENERGY SECTOR

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Abstract

The solar energy sector is swiftly advancing to address increasing energy demands and diminish reliance on fossil fuels. Nonetheless, inefficiencies, resource wastage, and elevated operational expenses persist in obstructing sustainable development. This study seeks to establish a strategy framework for attaining sustainability in Pakistan's solar business by implementing Lean Management practices. Lean approaches, recognized for improving operational efficiency through waste reduction and value maximization, possess significant potential to revolutionize solar project management in the local context. The study also reveals the obstacles that impede the adoption of Lean practices. The study utilizes a mixed-methods approach, commencing with an extensive literature analysis to delineate the conceptual connection between Lean concepts and sustainability features. Primary data were obtained through standardized questionnaires administered to key stakeholders, such as managers, engineers, and sustainability officers inside Pakistan's solar energy companies. The aims were to: (1) investigate stakeholder awareness and views of Lean and sustainability; (2) evaluate the correlation between Lean practices; and (3) utilize these findings to develop a feasible framework for Lean integration. Research demonstrates a robust acknowledgment among professionals on the significance of Lean principles in advancing sustainability within the solar sector. The utilization of methodologies such as Value Stream Mapping (VSM), Just-in-Time (JIT) inventory management, and continuous improvement (Kaizen) demonstrated substantial beneficial associations with diminished project delays, cost reductions, and improved collaboration. The study pointed out the barriers and, in this regard, the suggested framework integrates Lean practices with the operational realities of solar installation in Pakistan, offering a blueprint to enhance productivity, minimize waste, and promote national sustainability objectives. The study underscores the significance of company culture, leadership dedication, and governmental assistance in enabling Lean transformation. Training programs and stakeholder participation are recognized as essential facilitators for successful adoption, in addition to improve performance, promote sustainability, and facilitate the overall shift to clean energy.

Keywords

Lean Management (LM); Solar Energy; Sustainability; Renewable Energy; Waste Reduction; Project Efficiency; Operational Performance; Lean Management Practices (LMP), Lean tools

1. Introduction

The rapid expansion of the solar energy sector necessitates novel approaches to address inefficiencies in construction methods and project implementation. In Pakistan, solar construction projects frequently experience delays, budget overruns, and resource inefficiencies due to dependence on conventional methods. This research advocates for the incorporation of Lean methodologies focused on waste minimization and value enhancement as a remedy for these systemic issues. Through the implementation of lean methods, solar companies can optimize operations and enhance project timeframes. It promotes ongoing enhancement, effective communication, and optimal resource usage. This study examines the influence of Lean methods on improving operational and sustainability results in Pakistan's solar construction industry. The research provides a framework to assist organizations in adopting Lean methodologies for enhanced project delivery and enduring sustainability [1]. This study emphasizes the critical necessity for enhanced efficiency in the solar business and presents Lean methods as a viable option. It analyses how Lean methodologies can optimize project results by reducing waste and refining procedures. The research advocates for a culture of continual improvement through best practices and case insights. Ultimately, it enhances efficiency and sustainability in the growth of renewable energy.

In recent years, escalating environmental and social concerns have necessitated that firms implement more responsible and sustainable operational procedures. This transition has compelled both industry and academia to investigate effective methods for incorporating sustainability into fundamental processes. The worldwide importance of sustainability was prominently highlighted in the 1987 report by the United Nations' World Commission on Environment and Development, entitled "Our Common Future". This seminal statement emphasized the interconnection of society, natural resources, and the environment, promoting long-term planning and systemic transformation to guarantee sustainable development for future generations [2]. Sustainable development is defined as fulfilling existing demands without jeopardizing the capacity of future generations to satisfy their own needs. This notion underscores a balanced strategy that integrates economic development, environmental conservation, and social fairness to guarantee sustainable well-being and resource accessibility for present and future generations [3]. The notion of "lean," initially presented by Toyota Motor Corporation in the 1950s, has undergone considerable evolution in tandem with progress in operations management. This evolution transpired in two

principal phases. The initial phase, extending into the early 1990s, emphasized constant quality enhancement. By the late 1990s, lean methodologies broadened to include quality, cost, and delivery efficiency. The second phase arose in the 2000s, as increasing interest in sustainability began to transform operational goals, redirecting lean's emphasis toward providing more customer value. During this period, researchers increasingly examined the alignment and integration of traditional lean concepts with sustainability aims, acknowledging the potential for synergy between efficiency-driven processes and ecologically and socially responsible practices [4].

The increasing emphasis on sustainability and intensified focus on environmental enhancement have established environmental sustainability as a primary goal in corporate initiatives. This transition highlights the necessity of integrating sustainability initiatives with conventional organizational objectives, including the improvement of profitability and operational efficiency [5]. Green industrialization, seen as a crucial strategy for attaining sustainable development within the industrial sector, fosters expansion without augmenting the use of natural resources. The system prioritizes efficiency and environmental stewardship. Lean management closely adheres to this principle, promoting minimal waste and efficient resource use in production and operational operations [2]. Simultaneously, academic study has progressively investigated the potential correlation between lean adoption and ecologically friendly production results. This junction has led to the emergence of the "lean–green manufacturing" paradigm, which amalgamates lean concepts focused on fulfilling consumer demand with environmentally sustainable methods designed to reduce ecological effect. Despite its increasing significance, lean-green manufacturing is an evolving field, devoid of a broadly accepted definition or organized research methodology. Lean is fundamentally acknowledged as a methodical approach for ongoing process enhancement [4]. The lean methodology emphasizes the identification and eradication of waste while promoting ongoing enhancement. In the context of renewable energy product manufacturing, lean approaches can markedly decrease operational expenses, improve capital efficiency, shorten lead times, and facilitate the industry's continuous growth. By optimizing processes and enhancing value, lean promotes more efficient resource utilization, so bolstering the competitiveness and sustainability of renewable energy industries [6]. Certain experts assert that lean firms can improve their environmental performance, as lean and green techniques possess intrinsic common goals. Both methodologies prioritize the eradication of waste and the enhancement of process efficiency. By addressing analogous inefficiencies, lean approaches might unintentionally advance environmental objectives, harmonizing operational excellence with sustainability results [7]. Non-electricity industries are advancing at a sluggish rate, with energy efficiency enhancements achieving merely 1.5% last year, which is less than half of the 3.2% aim required to fulfill global sustainability objectives. In emerging nations, such as Pakistan, energy costs have escalated significantly due to a global demand for natural gas, with increases soaring up to 1,900%. Notwithstanding these expenses, access to natural gas is constrained, leading to prevalent "brownouts" and energy deficits. Simultaneously, investment in fossil fuel production persists in its expansion, while numerous measures designed to eliminate coal have either stagnated or been overturned, presenting a significant obstacle to the shift to greener energy systems [8].

Access to energy from all sources must be the utmost priority for everyone. This must encompass equal access to natural resources and a funding mechanism to mitigate elevated energy prices for the most impacted nations. This study aims to point out the barriers, highlight the benefits and establish a complete framework that facilitates solar energy companies in Pakistan in adopting Lean practices as a strategic approach to attain sustainability. *Figure 1* illustrates the primary aim is to improve the sustainability performance of these companies by assessing the awareness and comprehension of key decision-makers concerning the adoption of Lean methods and seeks to integrate Lean thinking with sustainable growth in Pakistan's solar energy sector.

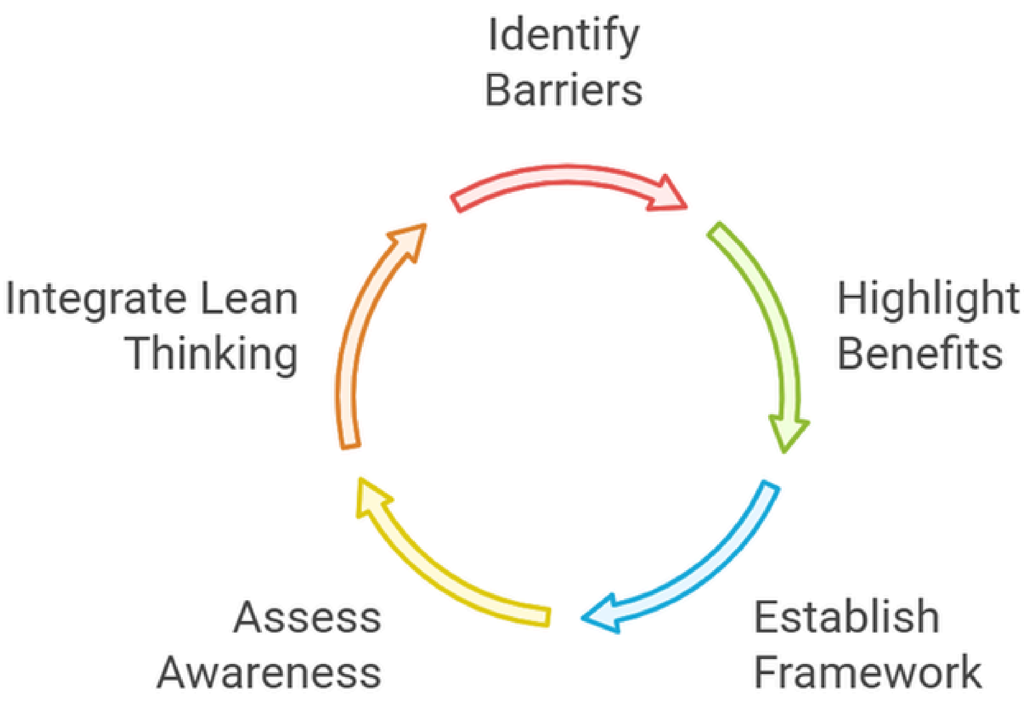

Fig. 1. Cycle of Lean Integration for Sustainability (source: the authors)

2. Literature Review

2.1.Overview of Lean Practices in Construction

Lean Construction (LC) originated in the early 1990s when Koskela proposed a lean production system to tackle construction difficulties using the framework of Transformation, Flow, and Value (TFV). Identifying substantial waste in the construction sector, critical components of lean production, including Just in Time, Total Quality Management, and Kanban, were deemed vital for enhancing construction efficiency [9]. The objective of the LC concept was to optimize workflow, effectively satisfy customer needs, and reduce waste from construction processes and materials. Although LC was initially inspired by lean production, its definition has since expanded and developed in response to the growing interest and adoption of the concept [10]. LC is a new way to manage production that brings together different theories, principles, and techniques in a way that reduces waste, maximizes value, meets customer needs, and smooths out differences in workflow and activities that don't add value in a collaborative, respectful, and people-centred environment [11]. At the heart of these definitions is the fundamental nature of LC as an innovative production management philosophy that directly contests the conventional trade-off among quality, cost, and time [9]. Lean approaches are being used in renewable energy building to improve efficiency and minimize waste. Their integration facilitates prompt delivery, resource optimization, and sustainability across project phases [12]. Lean construction concepts prioritize the delivery of optimal value while minimizing waste, hence enhancing project performance considerably. Their application augments efficiency, diminishes operating expenses, and elevates client happiness. These benefits are especially critical for the solar energy sector, where timely and cost-effective execution is essential [13]. The application of lean principles in engineering and construction has shown great promise for enhancing productivity and reducing environmental impact. According to a thorough analysis, the most important Lean principle is waste reduction. Case studies have shown that by efficiently applying Lean approaches, material waste may be reduced by 15% to 30% [14].

2.2.Application of Lean in Solar Sector

Research on solar photovoltaic (PV) installations indicates that the application of Lean methodologies, such as Value Stream Mapping (VSM) and the Last Planner System, can decrease project length by as much as 25%. These findings underscore Lean's efficacy in enhancing stakeholder cooperation and maximizing resource utilization. These results validate the efficacy of Lean approaches in expediting solar project implementation and enhancing sustainability [12]. Research indicates that the implementation of Lean methodologies in solar photovoltaic (PV) projects, including Value Stream Mapping (VSM), Just-in-Time (JIT), 5S, and the Last Planner System, has resulted in quantifiable enhancements in performance indicators. The implementation of VSM in solar farm development decreased non-value-adding operations by more than 30%, resulting in expedited project delivery [15]. The Last Planner System has demonstrated efficacy in enhancing workflow dependability and minimizing time overruns in solar installation projects [16]. Lean practices have gained traction in Pakistan and other developing countries to mitigate challenges related to material waste, ineffective site management, and coordination failures among stakeholders [4]. With interdisciplinary teams and improved supply chain responsiveness, Lean Construction concepts contributed to the reduction of project delays in solar infrastructure projects. In addition, Lean techniques contribute to sustainable development by reducing the carbon footprint of construction activities and optimizing the use of resources, which is in line with the United Nations' Sustainable Development Goal 7 [17]. Nonetheless, obstacles remain in the use of Lean principles within the solar industry. These factors encompass resistance to change, insufficient formal training, and a poor understanding of Lean advantages among middle management. Successful Lean implementation in renewable energy building projects necessitates robust leadership commitment, process standardization, and a culture of continuous learning [18]. Ultimately, solar companies may help achieve sustainability goals in the areas of both the environment and society by implementing Lean management practices. Solar companies, especially those in developing nations like Pakistan, can speed up the shift to renewable energy sources and overcome operational hurdles with the use of a framework that combines Lean technologies with sustainability indicators.

2.3.Impact on Waste Reduction and Sustainability

A substantial body of work highlights the influence of Lean methods on waste minimization and sustainability in solar construction [12]. By implementing lean approaches, material waste during solar panel installations can be efficiently minimized by as much as 30%. The research contends that Lean does more than just boost efficiency; it also helps bring sustainability objectives into harmony by lessening the impact that solar installations have on the environment [13].

Sustainable development necessitates the conservation of natural capital, which regulations stipulate must include renewable natural capital [19]. Two distinct principles of sustainable development pertinent to the stewardship of renewable resources. Initially, harvest rates must match regeneration rates, a concept known as sustainable yield. Natural capital should be recognized as possessing regenerative and assimilative capacities, and neglecting to preserve these capacities constitutes capital consumption, which is unsustainable. Natural and artificial capital can be sustained at multiple levels. Secondly, waste emission rates must correspond to the intrinsic absorption capacity of the ecosystems receiving the waste. Natural capital serves as a supplementary source of raw materials and energy alongside artificial capital [20]. Governments formulate long-term visions for sustainable national infrastructure systems, alongside adaptable strategies to illustrate their objectives [21]. Similarly, it was investigated how infrastructure systems serve as the backbone of every society by offering basic services such as water, energy, waste management and natural resources [22]. Consequently, sustainability and environmental consciousness should commence with the selection and use of eco-friendly materials that provide advantageous characteristics compared to traditional construction materials.

2.4. Challenges to Lean Implementation

Considering the benefits, numerous studies have identified challenges such as organizational opposition, inadequate managerial support, and insufficient employee training to the effective application of Lean practices in solar building. [12] [23].

Solar PV technology has advanced dramatically, as can be seen in research by [19], In recent years, it has, however, proven inadequate and necessitates additional investigation. The low conversion efficiency of solar PV technology relative to conventional systems remains the primary technological obstacle in the advancement of solar energy systems. A further limitation is the incapacity of solar facilities to promptly adjust to load demand. This issue is absent in conventional power plants, leading to enhanced efficiency [24]. Multiple studies illustrate various technological challenges in solar energy generation, including the intermittent nature of solar radiation, which hinders the photovoltaic system's capacity to satisfy consumer demand, and discrepancies between standard and real-time conditions that impact performance. When a component malfunctions, the solar photovoltaic system often becomes nonfunctional until the component is substituted [19]. Despite numerous studies endorsing the significance of lean methodologies for enhancing operational flow, challenges persist in its implementation. The primary drawbacks are its inadequacy in addressing variance and the absence of acknowledgment of human factors, alongside the operational emphasis limited to the workplace floor [4]. Numerous issues are indicated by grievances from trade unions and the escalation of employee duties within corporations, without a corresponding increase in compensation. These issues stem from a misconception regarding the mechanism of lean principles are especially pronounced in small and medium enterprises [25]. The issues stem not from lean itself, but from the necessity to comprehend its functionality. The effective deployment of lean is predominantly contingent upon the senior management's comprehension of its operational processes and the appropriate implementation strategies. Also, there is a necessity for a mutual understanding between senior management and employees to collaboratively foster an image of integrated application, with the imperative to cultivate long-term employees and leaders [26].

2.5. Sustainable Solar Energy through Lean Practices

The concept of lean gained prominence through the publication of “The Machine That

Changed the World." The lean idea is characterized by various definitions, since it continues to evolve [27]. The use of lean practices is prevalent method of continuous improvement that has transformed global manufacturing methods, practices, and principles [4]. Also, it centres on a mindset of ongoing performance enhancement through systematic waste elimination on the production floor [4]. A literature review concurred that the primary principles of lean are Value, Value Stream, Flow, Pull, and Perfection, the principles were introduced to tackle the numerous issues that emerged within and among business divisions due to discrepancies in corporate culture and management philosophies [28]. Lean approaches promote sustainability across three interconnected dimensions: environmental, economic, and social. Lean tools, like Value Stream Mapping (VSM) and Just-In-Time (JIT), mitigate material waste and energy consumption by optimizing operations and enhancing workflow efficiency. Ballard and Howell (2003) asserted that the Last Planner System improves planning precision and mitigates delays in construction projects, resulting in more efficient resource utilization and diminished environmental effect [16]. In solar photovoltaic (PV) installations, researchers have documented a 25% decrease in project duration and substantial cost reductions achieved using Lean practices [29], [18]. These enhancements not only diminish greenhouse gas emissions linked to construction but also decrease the lifespan expenses of solar infrastructure.

Economically, Lean management facilitates solar companies in enhancing profit margins by decreasing inventory expenses, augmenting labour productivity, and eliminating rework. Just-In-Time (JIT) and Kanban systems, when utilized in solar component procurement and installation, guarantee the delivery of only essential components at the required time, hence minimizing storage expenses and mitigating damage hazards. Lean principles improve customer happiness and financial performance by closely aligning production with demand, a characteristic especially beneficial in dynamic industries such as solar energy [30]. Socially, Lean fosters employee empowerment by systematic problem-solving, clear communication, and ongoing education. Methods like Kaizen events and Gemba walks promote inclusive decision-making and enhance employee engagement, resulting in increased job satisfaction and diminished occupational risks particularly pertinent on labour-intensive solar installation sites [31].

Numerous academics assert that lean is intrinsically connected to sustainability, as lean facilitates key objectives of sustainability, including cost reduction, emission minimization, economic value creation, and improvement in assessing the work environment [4].

Developing countries have implementation hurdles despite these benefits. Lack of understanding, training, cultural aversion to change, and fragmented supply networks are issues. In Pakistan, Lean is still seen as a production strategy, not a project management philosophy. *Figure 2* illustrates Lean practices to enhance solar energy projects. This strategy focuses on two primary domains: Efficiency Enhancement, utilizing techniques such as Value Stream Mapping (VSM), Just-In-Time (JIT), and the Last Planner System; and Waste Mitigation, emphasizing the reduction of material waste and environmental sustainability. The implementation of lean principles in solar construction seeks to attain substantial sustainability objectives, encompassing emissions reduction, cost minimization, and workforce empowerment. Nonetheless, the implementation encounters significant challenges, including insufficient training, poor leadership support, and technical constraints.

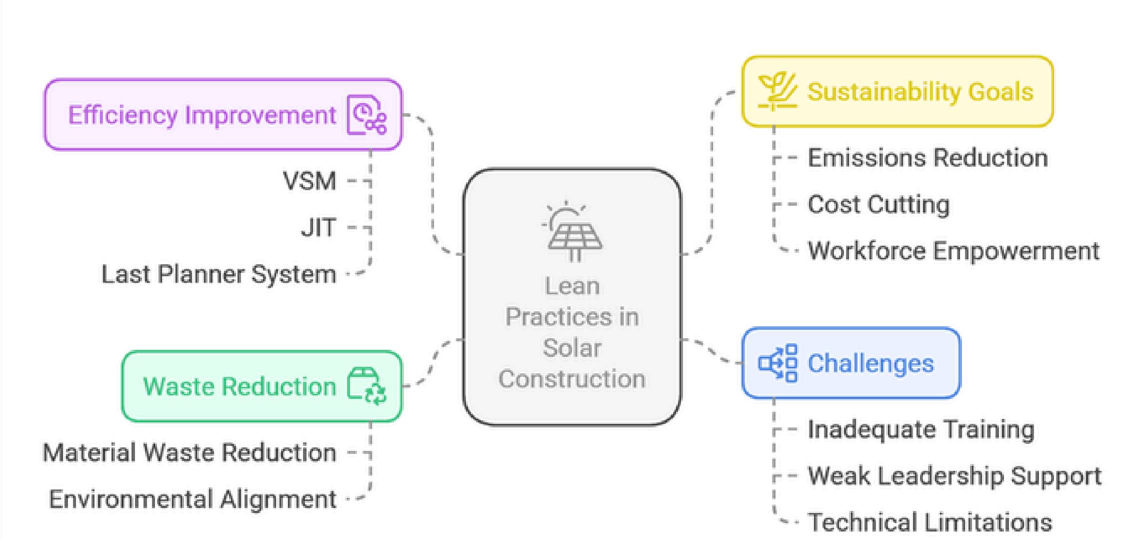

Fig. 2. Lean Practices in Solar Construction (source: the authors)

3. Research Methodology

A mixed-methods strategy was utilized, combining qualitative and quantitative techniques to investigate the research, as previously implemented such as [12] [14]. This method facilitates a thorough comprehension of the problems and efficacy of Lean practices in solar projects through the triangulation of data from experts. To formulate semi-structured questions for surveys and interviews, the Delphi approach was employed in accordance with prior studies such as [32], [33], [34]. Brainstorming sessions were conducted with experts from the solar energy industry, academic scholars, professional peers, and relevant engineering professionals to gather diverse perspectives. A questionnaire was then distributed to 150 targeted stakeholders using purposive sampling techniques, as recommended by [1], resulting in 115 valid responses. Furthermore, comprehensive interviews were carried out with 50 chosen specialists to obtain a more profound understanding of the perceived advantages, current challenges, and the kind of institutional and policy support necessary to improve sustainability in the solar energy sector. Survey data was evaluated with SPSS statistical software as conducted by [12] [35], [36], to find trends, correlations, and patterns associated with Lean implementation in solar development. Participants were thoroughly briefed on the study's goal and scope before their involvement, and their informed consent was secured to guarantee voluntary participation. All data obtained from surveys and interviews were managed with stringent secrecy as shown in *Figure 3*. Personal identifiers were eliminated to preserve anonymity, and the material was utilized exclusively for scholarly and analytical purposes within the scope of this research.

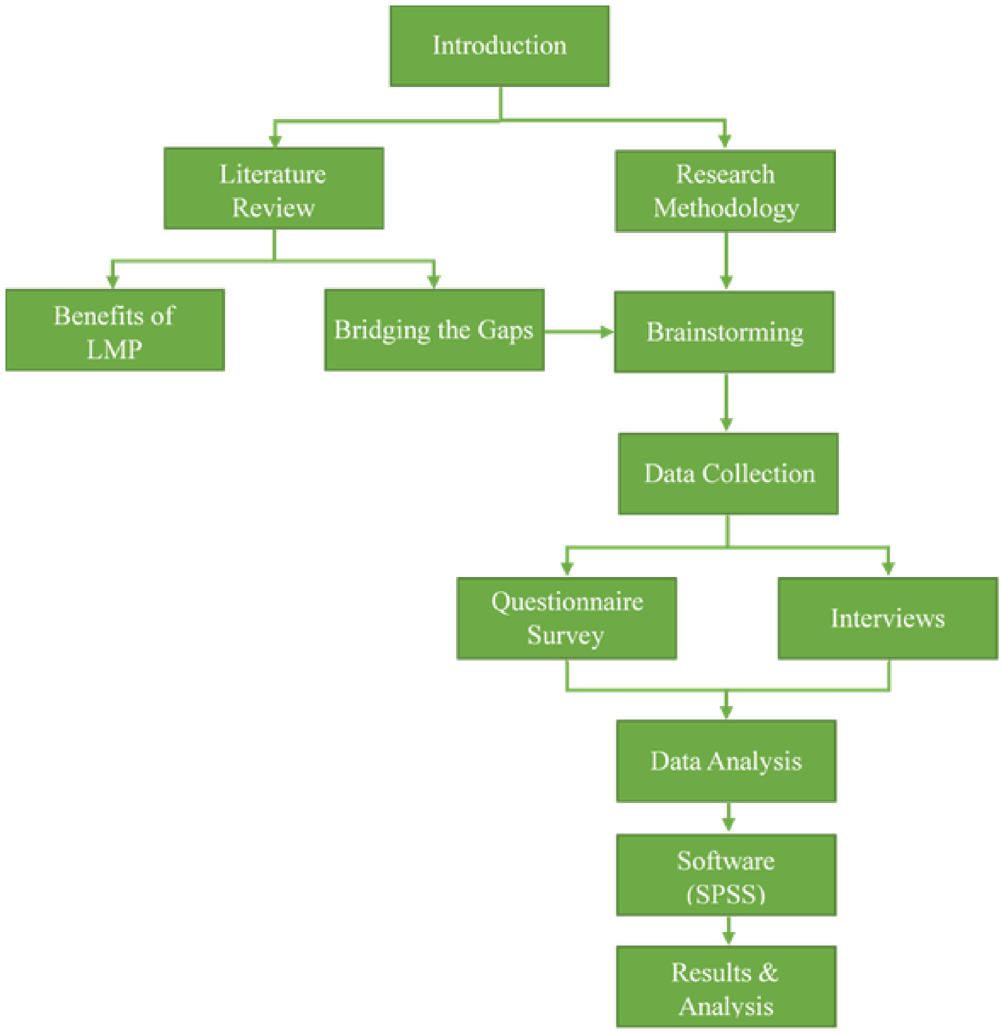

Fig. 3.Flowchart for Research Methodology

4. Results & Analysis

4.1. Respondent's Profile

Figure 4 offers essential information into the professional backgrounds of respondents involved in the study on Lean Management methods and sustainability within the solar energy sector. It underscores the variety in positions, expertise levels, and project types, hence augmenting the validity and representativeness of the research findings. Within the Role in Organization category, the data indicates that Site Engineers constitute the predominant group at 30.5%, highlighting their substantial participation in on-site project execution. Quality/Operations Managers and Design Engineers account for 25.3% and 24.2%, respectively, indicating a significant presence of professionals tasked with maintaining process efficiency and design coherence—both integral to Lean methodologies. Project Managers, responsible for planning and coordination, constitute 20.0%, providing strategic insights into implementation issues and overarching decision-making.

Most respondents (32.6%) indicated having 6–10 years of experience, demonstrating a sophisticated comprehension of the construction sector and operational methodologies. Individuals with fewer than 2 years of experience constitute 27.4%, contributing novel insights, whilst those with 2–5 years and over 10 years of experience are evenly represented at 20.0% each. This broad spectrum facilitates a thorough comprehension of Lean adoption from both novice and experienced experts.

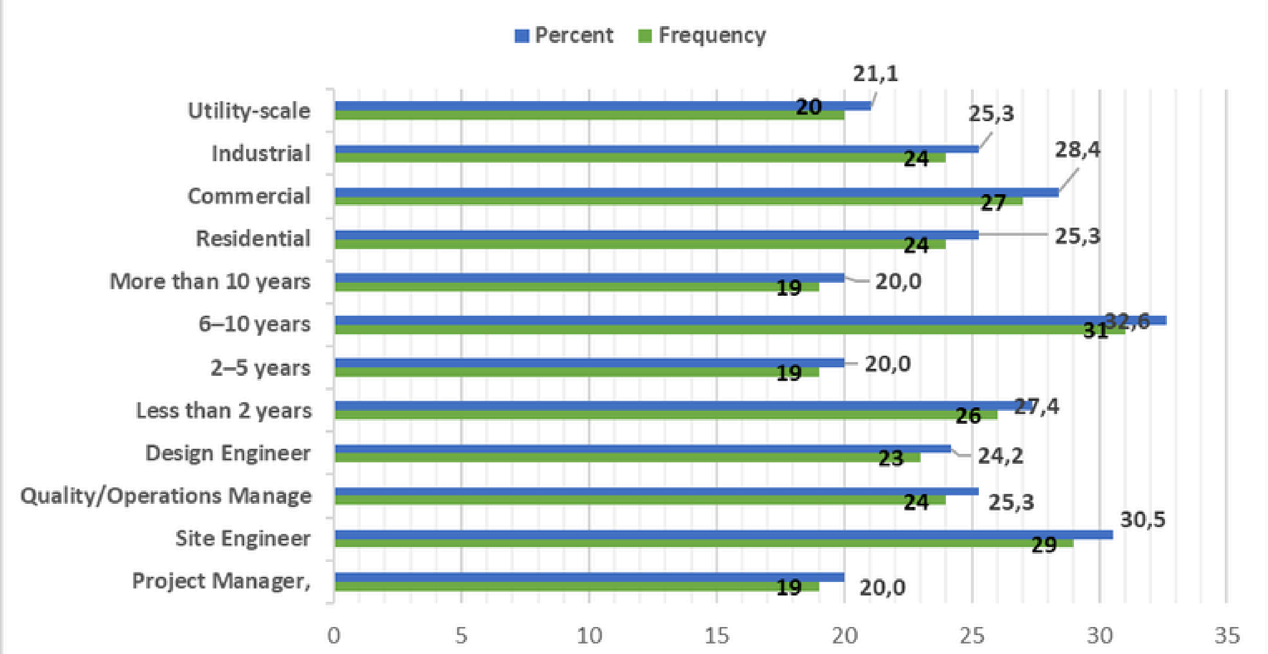

Fig. 4. Respondents Profile

Concerning Types of Projects, Commercial projects constitute 28.4%, closely followed by Residential and Industrial projects, each at 25.3% Utility-scale projects constitute 21.1%, reflecting the involvement of specialists engaged in extensive solar infrastructure development. This distribution across several project types guarantees that the data encompasses a comprehensive perspective on Lean techniques and sustainability initiatives across all scopes and difficulties of solar energy deployment. The table illustrates a comprehensive respondent profile, enhancing the robustness and generalizability of the study findings to diverse solar building situations in developing nations such as Pakistan.

4.2.Benefits & Sustainability Achieved in dimensions by Using Lean Tools

The *Table 1* delineates the contributions of several Lean Management Practices (LMP) to project advantages and sustainability aspects within the solar energy sector.

Value Stream Mapping (VSM) and Just-In-Time (JIT) methodologies provide the most significant influence, particularly in minimizing material waste, enhancing deadlines, and attaining environmental and economic sustainability. 5S demonstrated negligible advantages, with only enhancements in timelines and economic sustainability noted. Kaizen had a moderate impact on all three areas of sustainability. The "All of these" category signifies that employing a mix of LMP strategies substantially aids in attaining all dimensions of sustainability, with 12 responses affirming large advantages. In contrast, individuals not utilizing LMPs or uncertain about their use reported diminished or absent advantages, along with increased occurrences of "none" regarding sustainability outcomes. This underscores the strong association between LMP adoption and improved sustainability in project performance.

Table 1. Benefits and Sustainability Achieved by Adopting LMP

LMP (Tools)	Benefits Achieved							Sustainability Achieved in Dimensions				
	Reduced material waste	Better resource management	Improved project timelines	Reduced costs	Improved team collaboration	Enhanced energy efficiency	None	Environmental	Economic	Social	All of them	None
5S	0	1	5	0	0	0	0	0	6	0	0	0
Kaizen	0	1	1	2	0	0	0	1	1	1	1	0
VSM	5	0	6	1	1	4	0	1	5	5	6	0
JIT	6	1	2	2	0	0	0	8	1	2	0	0
Reducing Rework	1	2	1	0	1	1	0	1	2	1	2	0
All of these	1	5	3	0	3	2	0	0	0	2	12	0
None	1	0	0	7	0	0	14	0	6	4	0	12
Not Sure	0	1	0	9	1	0	4	0	7	4	0	4
Total	**14**	**11**	**18**	**21**	**6**	**7**	**18**	**11**	**28**	**19**	**21**	**16**

A more convenient version of the table is available via the QR code.

The correlation *Table 2* illustrates statistically significant links among the utilization of Lean tools, observed sustainability advantages, and the sustainability aspects affected by Lean practices, derived from a sample size of 95 respondents. The Pearson correlation coefficients indicate positive and relatively strong relationships among all three variables, implying a significant interrelation with Lean adoption in the solar energy sector. The association between "Which Lean tools has your organization utilized?" and "What sustainability benefits have you observed from Lean adoption?" is 0.469, significant at the 0.01 level. This signifies a moderate positive correlation, indicating that firms employing a broader array of Lean technologies are likely to achieve more significant sustainability advantages, including diminished waste, enhanced energy efficiency, and cost reductions.

Table 2. Correlation among LMP, Benefits & Sustainability observed

		Which Lean tools has your organization used?	**What sustainability benefits have you observed through Lean adoption?**	**Which sustainability dimensions are most influenced by Lean practices in your experience?**
Which Lean tools has your organization used?	Pearson Correlation	1	.469**	.377**
	Sig. (2-tailed)		0.000	0.000
	N	95	95	95
What sustainability benefits have you observed through Lean adoption?	Pearson Correlation	.469**	1	.562**
	Sig. (2-tailed)	0.000		0.000
	N	95	95	95
Which sustainability dimensions are most influenced by Lean practices in your experience?	Pearson Correlation	.377**	.562**	1
	Sig. (2-tailed)	0.000	0.000	
	N	95	95	95
**. Correlation is significant at the 0.01 level (2-tailed).				

The association between "Which Lean tools has your organization utilized?" and "Which sustainability dimensions are most impacted by Lean practices?" is 0.377, significant at the 0.01 level. This indicates that with the increased application of Lean technologies, respondents recognize a wider impact on essential sustainability elements (economic, environmental, or social), hence supporting Lean's contribution to comprehensive sustainable development.

The most robust connection identified is 0.562 between sustainability benefits and the sustainability characteristics affected, which is statistically significant. This suggests that an increase in reported sustainability advantages from Lean techniques correlates with a

heightened acknowledgment of its favourable effects across multiple sustainability aspects. These results underscore the efficacy of Lean approaches in improving sustainability in the construction and solar energy industries.

4.3. Key Challenges & Requirement of Government Support

The *Table 3* displays a cross-tabulation of management support, governmental support requirements, and principal hurdles in executing Lean methods within solar projects.
The data indicates that "Cost of implementation" is the primary issue encountered by firms with highly supportive top management (23 replies), suggesting that even robust leadership is impeded by financial limitations in Lean adoption. In contrast, "Lack of awareness/training" is exclusively linked to businesses without managerial support (19 replies), highlighting the essential function of leadership in fostering knowledge and awareness. Both "Resistance to change" and "Inadequate tools or infrastructure" were only reported by respondents from businesses with moderately supportive management, each with 18 replies. This indicates that partial help may be inadequate to surmount technological and cultural obstacles. Most respondents assert that national awareness campaigns (41) and financial incentives or subsidies (35) are essential, particularly in the absence of internal organizational support. The obligatory incorporation of Lean in contracts was endorsed by proponents claiming insufficient awareness and training, underscoring the necessity for regulatory enforcement to promote adoption. The table demonstrates that effective Lean implementation in solar projects relies on a synergy of robust internal management support and certain external government actions.

Table 3. Cross-tabulation among Challenges, Management Role & Government Support

		Is top management supportive of Lean implementation in your organization?				What level of government support is needed to promote Lean adoption?		
		Very supportive	**Somewhat supportive**	**Neutral**	**Not supportive**	**Mandatory inclusion in contracts**	**Financial incentives or subsidies**	**National awareness programs**
What are the key challenges in implementing Lean practices in solar projects? (Select all that apply)	**Lack of awareness/ training**	0	0	0	19	19	0	0
	Resistance to change	0	18	0	0	0	0	18
	Lack of management support	0	0	17	0	0	17	0
	Inadequate tools or infrastructure	0	18	0	0	0	18	0
	Cost of implementation	23	0	0	0	0	0	23
Total		23	36	17	19	19	35	41

The examination of principal challenges uncovers a multifaceted environment wherein internal organizational constraints and external structural deficiencies coalesce to hinder the successful execution of Lean practices in solar initiatives. Among the most notable obstacles identified, implementation costs (n = 23) arise as a pivotal obstacle, particularly in businesses with strong support from senior management. This paradox indicates that although strategic leadership may advocate for Lean ideals, budgetary limitations frequently impede their implementation. It underscores the necessity for specific financial instruments, such as capital subsidies or tax incentives, to transform managerial purpose into tangible results. A significant challenge is the insufficient awareness and training (n = 19), stated solely by respondents from organizations that are unsupportive of Lean adoption. This pattern suggests that in settings with disengaged leadership, employee familiarity with Lean tools and processes is limited. Consequently, a cascading effect ensues in the absence of leadership understanding, operational teams stay untrained, resulting in stagnation of innovation and process enhancement. The resistance to change (n = 18) and insufficient tools or infrastructure (n = 18), both noted under somewhat supportive leadership, underscore structural inflexibility and technological constraints. These comments indicate that little managerial support is inadequate to dismantle established practices or to facilitate the infrastructural enhancements required for Lean implementation. In these instances, organizational inertia, along with obsolete tools, constrains the adaptability and responsiveness of solar companies, particularly in swiftly changing technology environments.

The absence of management support (n = 17), categorized under neutral leadership, indicates a situation where Lean principles may be conceptually grasped but lack the necessary endorsement or resources for execution. This state impedes progress and results in disjointed or experimental adoption without comprehensive integration. These findings highlight the complex obstacles associated with Lean adoption in the solar business. The text underscores the urgent necessity for a dual-intervention model: one that entails internal organizational transformation, focusing on leadership involvement and capacity enhancement; and the other necessitating external assistance from governmental and industry regulators, encompassing awareness initiatives, obligatory contract stipulations, and infrastructure investment. Neglecting these elements in Lean implementation efforts may result in shallow, fragmented, and ultimately unsustainable outcomes over time. This table provides a detailed analysis of the connections among organizational leadership, governmental support systems, and the primary obstacles faced in the execution of Lean Management Practices (LMP) in the solar energy sector, especially in developing regions like Pakistan. The research indicates a substantial association between the extent of top management support and the characteristics of the issues encountered by firms.

The cost of implementation is a significant barrier (n = 23), mentioned solely by respondents from firms with strong support from senior management for Lean efforts. This observation highlights a conundrum in which the strategic support for Lean concepts is present, while financial limitations impede practical implementation. This underscores the need for supplementary external interventions, such as financial incentives, grants, or subsidies, to translate executive purpose into quantifiable results. In contrast, the absence of awareness and training (n = 19) is exclusively reported by firms with unsupportive leadership, highlighting a systemic disjunction between executive priorities and operational preparedness. In these circumstances, a lack of leadership commitment seems to closely correspond with restricted information diffusion and diminished adoption of Lean approaches throughout the workforce. Challenges such as resistance to change (n = 18) and inadequate tools or infrastructure (n = 18), primarily reported under somewhat supportive leadership, underscore the structural rigidity and operational inertia that can obstruct Lean integration, especially in technologically deficient settings. The obstacle of insufficient management support (n = 17) under neutral leadership exemplifies a condition of organizational ambivalence where Lean may be conceptually recognized but is neither advocated nor sufficiently funded, resulting not disjointed or shallow implementation attempts. Stakeholders predominantly advocate for national awareness programs (n = 41) and financial incentives (n = 35) as essential support mechanisms among external enablers. Furthermore, the compulsory incorporation of Lean clauses in contracts (n = 19) is recommended by individuals facing educational and institutional constraints, indicating that regulatory enforcement could be crucial in normalizing Lean techniques throughout the business. The findings underscore that successful Lean adoption in the solar business requires a dual-pronged strategy. Effective and enduring leadership is essential for fostering organizational transformation and cultural preparedness. External political policies, financial frameworks, and awareness campaigns are crucial to alleviate economic and informational obstacles. In the absence of integrative efforts, Lean projects may become fragmented, diminishing their capacity to improve sustainability and performance in the solar energy sector.

4.4. Suggestions by Experts

Figure 5 examines the perspectives of several stakeholders in Pakistan's solar energy sector concerning the most successful strategies to promote the adoption of Lean Management methods. The analysis utilizes replies from 95 experts classified by their respective roles: Project Managers, Site Engineers, Quality/Operations Managers, and Design

Engineers. Each group was instructed to select desired actions from a list comprising certification and training programs, regulatory policy reforms, inclusion in public tenders/contracts, pilot projects and benchmarking, and a comprehensive plan. The findings provide detailed insights into the perspectives of professionals according to their functional roles. A considerable number of Project Managers highlighted the significance of certification and training programs (n=7) as well as pilot projects and benchmarking (n=6). This indicates a strategy perspective that emphasizes capacity-building and performance assessment systems as essential for Lean implementation. Site Engineers, primarily involved in field execution, equally emphasized training (n=9) and pilot projects (n=7) as essential, showing a practical necessity for experiential learning and demonstrable use of Lean principles.

Fig. 5. Suggestions by Experts

Conversely, Quality/Operations Managers shown a pronounced inclination towards an integrated approach, opting for “All of these” (n=9), indicating that no one measure would suffice independently. Their preference for a multi-faceted strategy emphasizes the necessity for coordinated actions across policy, education, procurement, and implementation sectors. Design Engineers, positioned upstream in the construction lifecycle, expressed a preference for pilot projects (n=6) and contractual inclusion (n=5), indicating a necessity for the procedural integration of Lean principles into formal project frameworks. The cross-functional analysis indicates that although training and pilot projects are universally deemed essential, the significance of institutional support via policy reform and contractual mandates is acknowledged—especially by individuals in quality assurance and design development roles. The findings collectively validate the imperative of a hybrid top-down and bottom-up approach for enhancing Lean Management in Pakistan’s solar construction industry. This includes the formulation of legislative frameworks, capacity-building programs, and the institutionalization of Lean methodologies inside public procurement and project planning systems. This holistic approach would conform to global best practices and enhance the long-term sustainability and competitiveness of Pakistan's renewable energy sector.

5. Interviews with the Experts

5.1.Understanding and Familiarity with Lean Practices in the Solar Sector

Participants from various positions such as Project Managers, Site Engineers, Quality/Operations Managers, and Design Engineers exhibited differing degrees of knowledge with Lean Management methodologies. Most participants with more than 6 years of experience, especially those engaged in industrial and utility-scale solar projects, demonstrated a robust familiarity with Lean methods like 5S, Kaizen, Value Stream Mapping (VSM), Just-in-Time (JIT), and Reducing Rework (RW). A few of junior professionals (2–5 years of experience) recognized possessing merely a theoretical comprehension, typically acquired throughout their academic education or through minimal practical exposure. All responders acknowledged Lean as a systematic methodology designed to eradicate waste, optimize process flow, and augment project value.

5.2.Observed Benefits from Lean Implementation

Professionals interviewed repeatedly stated that solar construction projects benefited materially from the application of Lean principles. Among the most often mentioned benefits were: (I) Enhanced workflow effectiveness and resource management, especially with the use of VSM and JIT tools. (II) Decrease (25%-30%) in material waste at critical stages of solar panel installation. (III) Improved project schedules; participants reported a 15–20% reduction in the time needed to complete the project. (IV) Improved team coordination, particularly with the Last Planner System and Kaizen. (V) Savings improved inventory control and reduced rework. These advantages were especially noticeable in projects at the utility and industrial scales, when Lean methodologies were used more strictly.

5.3. Sustainability Achieved through Lean Practices

Interviewees firmly linked Lean principles to sustainability outcomes, noting beneficial effects:

5.3.1. Environmental Sustainability: The majority of respondents noted a direct decrease in carbon footprints associated with construction, reduced energy consumption, and material conservation, particularly in areas where Just-in-Time and 5S methodologies were applied.

5.3.2. Economic Sustainability: Almost all participants concurred that Lean enhanced financial performance by reducing costs, preventing rework, and optimizing worker efficiency.

5.3.3. Social Sustainability: Lean methodologies such as Kaizen and Gemba walks were recognized for enhancing worker engagement, job happiness, and safety on solar project sites.

Several professionals indicated that Lean's collaborative and people-centric mindset contributed to improved team morale, a crucial element in maintaining social cohesion at project sites.

5.4. Challenges Faced During Implementation

Participants identified multiple obstacles to the introduction of Lean methodologies in the solar industry:

- The predominant difficulty identified was the absence of formal training and knowledge among field engineers and supervisors.
- Resistance to change, particularly from seasoned personnel familiar with conventional practices, impeded the implementation of Lean.
- Insufficient infrastructure or digital tools to facilitate Lean processes (e.g., VSM software, JIT logistics) were another troublesome.
- The uneven support from top management and the lack of internal policy demands hindered the institutionalization of Lean methods.

In response, several organizations implemented pilot projects or designated Lean champions at the site level to incrementally alter mindsets and evaluate Lean advantages in limited contexts prior to broader implementation.

5.5. Strategies Used to Overcome Challenges on Site

Numerous specialists delineated the proactive strategies they employed to tackle these challenges:

- Workplace training sessions conducted by senior engineers proficient in Lean methodologies.
- Visual management systems and performance dashboards that render Lean adoption quantifiable and transparent.
- Weekly coordination meetings to mitigate miscommunication and encourage a culture of continual improvement.
- Incremental implementation strategies initiating with 5S and progressively including more sophisticated tools such as VSM or JIT.

These localized solutions enhanced stakeholder engagement and enabled teams to develop Lean capabilities organically.

5.6. Suggestions to Top Management and the Government of Pakistan

5.6.1. To Top Management:

- Integrate Lean KPIs into project performance evaluations.
- Allocate resources for Lean-focused training and certifications for personnel.
- Establish Lean policies throughout departments to guarantee consistency and dedication.
- Advocate for success narratives and internal benchmarking to enhance motivation and facilitate adoption.

5.6.2. To the Government of Pakistan:

- Compulsory use of Lean methodologies in public tender papers for solar and infrastructure initiatives.
- Initiate national awareness initiatives cantered on Lean principles for sustainability in construction.
- Offer cash incentives or tax concessions to companies executing certified Lean initiatives.
- Formulate public-private collaborations to initiate Lean implementation frameworks and assess results.

6. Discussion

6.1. Understanding and Familiarity with Lean Practices

The results indicate an increasing but inconsistent comprehension of Lean principles among various jobs in the solar industry. Site engineers and project managers demonstrated moderate to high knowledge with Lean principles, whereas design engineers and younger personnel exhibited confusion or minimal exposure. Interview insights indicated that experience significantly influences awareness; individuals with 6–10 years of field experience demonstrated more familiarity with Lean applications, having observed its effectiveness in reducing delays and optimizing resource management on solar construction sites.

6.2. Perceived Advantages of Lean Implementation

Participants identified numerous advantages associated with Lean adoption, with diminished material waste and enhanced project timeframes being the most mentioned results. Instruments like VSM and JIT facilitated the optimization of procurement and inventory processes, resulting in enhanced operational efficiency. A substantial number of participants recognized the role of Lean methods in improving environmental performance, including energy conservation and diminished carbon footprints.

6.3. Accomplishments in Sustainability

Lean approaches were perceived as positively impacting all three pillars of sustainability. Environmentally, there were reductions in material and energy waste; economically, Lean facilitated cost reduction and enhanced production; and socially, it empowered teams by clarifying responsibilities and improving communication. The implementation of technologies such as Kaizen and the Last Planner System fostered a collaborative culture, resulting in enhanced stakeholder alignment and accountability.

6.4. Obstacles in Execution

Notwithstanding these achievements, numerous companies encountered significant implementation obstacles. Resistance to change, especially among senior management, was a prevalent issue. Numerous companies lacked organized training programs or access to Lean-specific resources. Smaller enterprises were particularly hindered by financial and resource constraints. Adequate assistance from senior management and clear regulations from regulatory authorities were consistently seen as obstacles, highlighting the necessity for leadership commitment and strategic vision. *Figure 6* demonstrates an evolving comprehension of lean principles across various professional areas. It illustrates a continuum from little to comprehensive lean understanding. Junior personnel demonstrate uncertainty and limited familiarity with lean principles, whereas design engineers indicate a moderate comprehension. Site Engineers possess moderate to advanced expertise, while Project Managers display expert-level understanding of lean principles. This visual depiction indicates a clear relationship between professional experience, role responsibility, and the extent of lean knowledge inside an organizational framework.

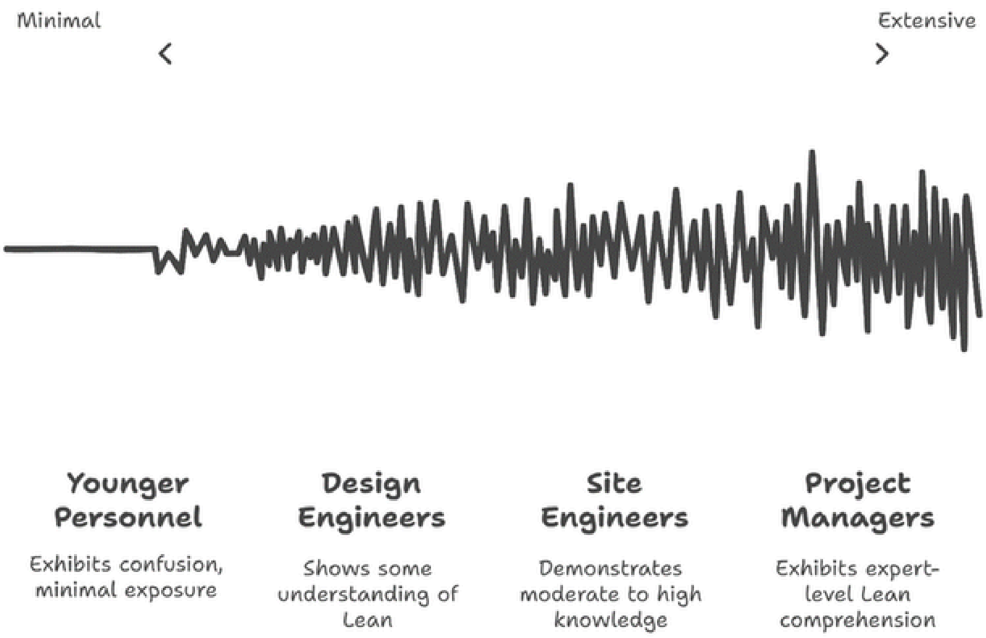

Fig. 6. Lean comprehension varies across roles and experience levels (source: the authors)

7. Conclusion

This study examined the incorporation of Lean Management Practices (LMP) inside Pakistan's solar energy sector to enhance sustainability across environmental, economic, and social aspects. A mixed-methods strategy utilizing a structured questionnaire (n=95) and semi-structured interviews (n=50) was implemented to collect data from professionals such as project managers, engineers, quality managers, and design specialists. The investigation indicated that, although the awareness and utilization of Lean tools like 5S, Kaizen, JIT, and VSM are comparatively low, respondents possess a robust perception of their potential to enhance efficiency, minimize waste, and optimize project timeframes. Statistical findings validated a substantial association between the implementation of Lean techniques and the observed enhancements in sustainability outcomes, namely in minimizing material waste, augmenting energy efficiency, and refining cost control. Notwithstanding the optimistic perspective, many obstacles remain, such as inadequate awareness and training, reluctance to adapt, insufficient managerial backing, and elevated implementation expenses. Respondents with over 6 years of experience demonstrated greater knowledge with Lean principles and were more inclined to have witnessed concrete sustainability benefits. The study indicates that the implementation of Lean methods provides a strategic avenue for Pakistan's solar energy sector to attain its sustainability objectives, contingent upon the enhancement of organizational and policy-level support mechanisms.

8. Recommendation

This research examines the influence of Lean Management Practices (LMP) on enhancing sustainability within Pakistan's solar energy sector through a mixed-methods approach. A total of 95 survey responses and 50 interviews were obtained from various stakeholders, including project managers, engineers, and quality managers. The results indicate that professionals with more than six years of experience possess greater familiarity with and are more inclined to utilize Lean methods such as 5S, Kaizen, JIT, and VSM. These techniques were linked to diminished material waste, optimized project schedules, cost-effectiveness, improved communication, and greater resource use. Participants confirmed that Lean approaches significantly enhance environmental, economic, and social sustainability by reducing emissions, optimizing costs, and promoting team accountability.

Notwithstanding these advantages, significant obstacles such as aversion to change, inadequate managerial support, insufficient training, and elevated implementation costs impede wider adoption, particularly among smaller enterprises. Interviewees underscored the necessity for technical proficiency, leadership involvement, and cultural transformation to facilitate successful Lean adoption. To surmount these obstacles, stakeholders advocated for structured training, pilot initiatives, and active leadership engagement. They urged national organizations such as AEDB and NEPRA to incorporate Lean criteria into public policy and contracting, while advocating for governmental support through incentives and awareness initiatives. These solutions are seen as essential for enhancing solar building efficiency and furthering Pakistan's sustainability objectives.

9. Framework

Following comprehensive research and expert recommendations, the framework is presented in *Table 4* below. This framework aims to deliver a systematic and pragmatic guide for the implementation of Lean Management concepts within Pakistan's solar energy sector. Its objective is to optimize project workflows, reduce waste, and improve overall operational efficiency. The framework integrates Lean tools with sustainability objectives to promote environmental, economic, and social benefits. Ultimately, it directs stakeholders in attaining economical, prompt, and sustainable solar project execution.

Table 4. Suggested Framework to Achieve Sustainability in Solar Energy Sector

Framework	Lean Practice/Tool	Purpose	Implementation Strategy	Expected Sustainability Outcome	Responsible Entity
1. Planning & Design	Value Stream Mapping (VSM)	Identify & eliminate non-value-added steps	Train planning teams to map project flows	Reduced material & time waste	Design Engineers, PMs
2. Site Management	5S (Sort, Set, Shine, etc.)	Improve site organization & productivity	Weekly audits, signage, layout planning	Improved workflow & efficiency	Site Engineers
3. Procurement & Logistics	Just-In-Time (JIT)	Reduce inventory cost & overproduction	Partner with suppliers for scheduled delivery	Cost savings, reduced storage waste	Procurement Managers
4. Execution & Monitoring	Kaizen	Continuous improvement	Weekly meetings for team suggestions	Better collaboration, quality enhancement	Quality/Operations Managers
5. Risk Minimization	Reducing Rework	Avoid repetitive work and material waste	Conduct design clash detection, real-time progress reviews	Reduced delays, improved quality	QA/QC Team, Design Engineers
6. Training & Awareness	Certification Programs	Build lean capabilities	Partner with institutions (e.g., NUST, UET, etc.) for modules	Skilled workforce, cultural transformation	HR, AEDB, Academia
7. Policy & Regulation	Inclusion in Public Contracts	Institutionalize Lean in tenders	Require Lean practices in RFPs for public-funded solar projects	National sustainability alignment	NEPRA, AEDB, Govt Bodies
8. Performance Evaluation	KPIs for Lean Performance	Track Lean effectiveness	Define metrics (e.g., % rework reduced, time saved)	Data-driven decisions, accountability	Top Management, PMs
9. Benchmarking	Pilot Projects	Demonstrate success	Select 2–3 solar pilot projects to showcase lean implementation	Replicable model for industry-wide scaling	Industry Consortiums, AEDB
10. Community & Social	Gemba Walks	Observe real-time challenges on-site	Managers participate in daily field checks	Enhanced team morale, better safety	Supervisors, PMs

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