Prifysgol **Wrecsam**
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Advancing Solar Photovoltaic Efficiency: Breakthroughs And Emerging Trends

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Dissertation/Thesis Declaration

Statement 1

I hereby declare that this work has not been accepted in substance for any degree and is not currently being submitted in candidature for any degree.

Signed: Lakhwinder Singh

Date: 16 May 2025

Abstract

The research investigates modern solar photovoltaic (PV) efficiency technology because it works toward sustainable solutions to resolve worldwide energy deficiencies and environmental concerns. Research uses qualitative methods grounded in positivism to evaluate published literature as it analyses current solar PV technological developments. Liquid Canonical analysis through NVivo software groups critical research results into three main categories, which include material innovations and structural methods, and performance advancements.

Research findings demonstrate that transition metal oxides (MoOx, TiOx, AZO) represent suitable substitutes for indium tin oxide in heterojunction technology solar cells because both decrease manufacturing expenses and maintain performance levels. Lead-free perovskite material Cs_2TiBr_6 double perovskite shows advantageous optoelectronic features for safe portable implementations. Deployment of upcoming PV technologies encounters barriers due to energy decay, inconsistent operational behaviour and high expenses of manufacturing products that stall general market acceptance. Existing analysis shows the need to combine novel materials with system development because traditional PV systems continue to face power grid stability and weather adaptability problems. Advancement of bifacial modules and tandem solar cells, and artificial intelligence optimisation systems, represents important solutions for increasing solar power resistance against changing environmental challenges. Research shows that technological learning generates decreased costs and enhanced performance throughout time, which disproves pessimistic energy models worldwide.

MATLAB Simulink provides a robust computational environment for solar photovoltaic system modelling, enabling advanced numerical simulation, performance analysis, and parameter optimisation in engineering field. The platform integrates sophisticated algorithms to explore complex PV technologies, offering precise visualisation and quantitative insights into solar energy conversion processes. Extensive review of solar PV efficiency boosts offers essential knowledge to policymakers and industry participants, alongside academics who develop sustainable energy systems which protect both sustainability and energy security in both established and distributed power systems.

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Chapter 1: Introduction and Background

1.1 Introduction

Solar photovoltaic (PV) technology delivers a critical solution for fulfilling global energy needs and addressing environmental issues. PV materials, cell design, and energy conversion procedure enhanced efficiency, durability and cost-effectiveness in the transition to renewable energy. Despite all these innovations, problems such as stability issues, energy losses, and production costs in PV technology are discussed to make research more detailed. Emerging solar PV technologies are analysed through a comprehensive overview to ensure widespread adoption. Solar photovoltaic (PV) technology has become a vital factor in renewable power generation because of the worldwide push for renewable energy adoption. This analysis investigates novel advances and modern patterns in solar PV efficiency by reviewing developments which will help resolve existing barriers. This research adopts MATLAB for detailed assessment of datasets and simulation work to study innovative advances in materials science, cellular structures and system performance enhancement methodologies. Research demonstrates remarkable development of perovskite-silicon tandem cells, which function together with bifacial modules and AI-driven performance optimisation algorithms to break traditional efficiency limitations. The combination of improved technology with decreasing production expenses creates an advantageous moment for solar energy adoption worldwide. Roles of advancements in solar PV are reviewed in research on long-term sustainability through case studies and qualitative research through secondary data. Policy recommendations and future research directions are also proposed in this research to optimise solar PV deployment and accelerate global renewable energy integration: purposes include detailed breakthroughs, efficiency improvements and emerging trends in solar photovoltaic technology.

1.2 Study background

Solar photovoltaic technology has become essential to the worldwide transition to renewable energy. Ongoing rise in energy demand and increased awareness of environmental concerns raise the need for solar PV techniques to serve as an eco-friendly approach to converting sunlight into electricity. Cell design and energy conversion technologies, efficiency, durability and cost-effectiveness are improved with improvements in PV materials, and PV systems are being adopted more in different regions [1]. Innovations have driven development of solar PV, such as quantum dot technology, perovskite silicon tandem cells, and product optimisation, which massively increase energy output and operational stability.

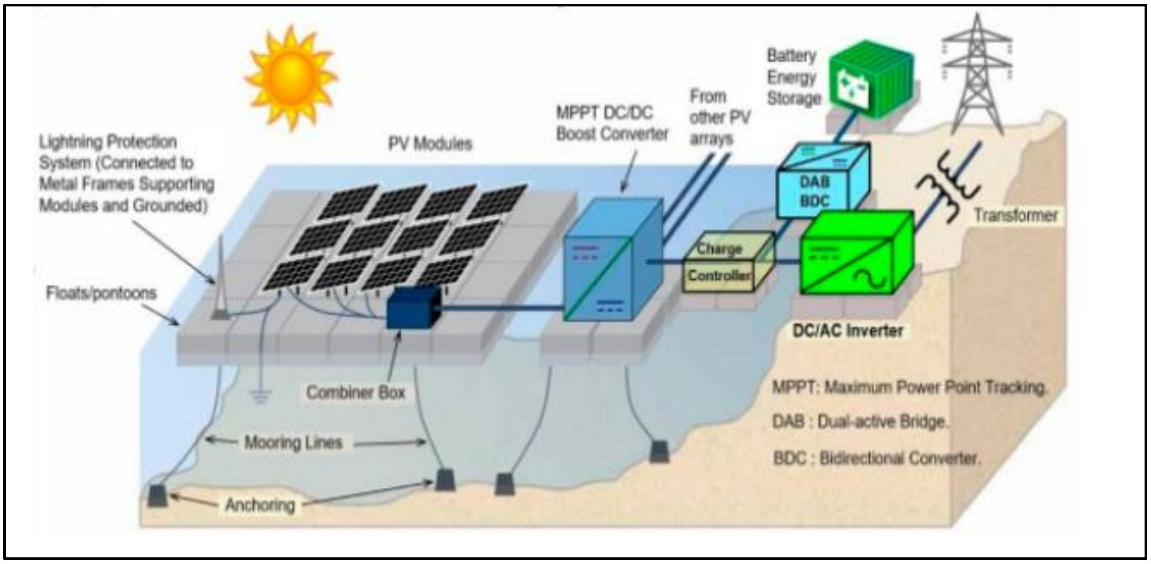

Figure 1.2.1: Architectural representation of Solar PV efficiency [3]

Figure 1.2.1 shows an architectural representation of Solar PV efficiency, which is being used to maximise efficiency in solar PV, such as advanced material compositions, structural improvements, and performance-advancing technologies. The above figure illustrates architectural components of a solar PV system. It shows solar modules collecting sunlight, with electricity flowing through a combiner box to inverters. The system includes battery storage options, controllers, and grid connections. Various elements such as lightning protection, grounding, and maximum power point tracking ensure efficient energy conversion and distribution. All these techniques in PV techniques increased energy conversion rates and increased resilience to different climatic conditions. However, despite such technological breakthroughs, solar PV adoption remains lacking in several aspects, especially in terms of energy losses, production costs and stability issues, which make its large-scale deployment difficult.

Solar PV technology is still an economic concern for global implementation, and this is a critical factor for national budgets in developing countries. Manufacturing costs remain a barrier to first purchase in some areas, as well as the intervention of initial investment. Governments and private enterprises are exploring alternative models such as subsidies, tax incentives, and public-private partnerships to reduce the cost of solar PV and make it accessible [2]. Expanding solar energy infrastructure in developing markets opens up a path towards energy security by decreasing dependence on fossil fuels and helping advance the economy. Solar PV systems help to a great extent in achieving global sustainability in an environmental context by decreasing carbon emissions and dependence on non-renewable energy. Solar PV technology does not produce greenhouse gas emissions such as conventional energy sources, which is a key weapon in fighting climate change. Energy storage solutions are integrated further to increase efficiency of solar PV by exhibiting a consistent power supply in regions where availability of sunlight is not constant [5]. Knowledge of these aspects is necessary to optimise solar PV deployment and accelerate transition to a sustainable energy world.

Industries continue research efforts to improve efficiency along cost-effectiveness of solar photovoltaic (PV) technology [5]. Traditional solar cells made from silicon hold the largest market share, but effectiveness faces two basic limitations, which reduce energy efficiency. Modern research emphasises the development of perovskite solar cells because they combine high performance with low manufacturing expenses. When silicon is combined with perovskite materials in tandem solar cells, the efficiency rate exceeds 30%, which breaks through single-junction technology barriers. Processing approaches that integrate quantum dots with multi-junction approaches drive up energy conversion performance. Bifacial panels, along with transparent solar cells, enable new applications in the solar industry because they enable deployment across both sides of solar modules and through building glass elements such as windows and facades. Combination of nanotechnology with light-trapping mechanisms brings two main benefits: optimised energy loss reduction and increased light absorption effectiveness.

The maximum solar PV efficiency depends on both energy storage systems and integration with electricity grids [7]. At the same time as the need for eco-friendly energy grows, new technologies in light capture and power management have improved the performance of these systems. Models, including the single-diode equivalent circuit, help analyse the behaviour of PV cells precisely and form the base for matching engineering suitability with renewable energy goals.

1.3 Justification for study

Efficiency and technical constraints interfere with the operation of solar photovoltaic (PV) systems, which are increasingly used as a major component of renewable energy adoption worldwide. Adoption of solar PV technology as a sustainable energy solution remains limited because of three main barriers, which include its low energy conversion rates, stability issues and high production expenses. These barriers restrict potential of solar energy to fulfil growing global electricity markets, highlighting demand for continuous research into emerging technological directions and efficiency improvements. Unstable deployment patterns caused by economic barriers and scarce materials make it difficult for solar PV systems to gain acceptance for widespread integration in main electricity grids.

Fast-growing renewable energy markets need technological improvements which can improve solar PV performance while providing low costs and extended service life. Energy policies with incentive structures usually do not fulfil innovation speeds, which produces financial gaps affecting investments in future PV technologies. Further research on perovskite-silicon tandem cells and quantum dot applications, and AI-driven optimisation methods highlights crucial points of durability gaps in real solar power applications.

The extensive growth of solar PV technology into a conventional power source highlights the necessity for detailed investigations about materials and system performance enhancement. Recent emerging technologies maintain superior performance levels under laboratory testing conditions, but face challenges in commercial market implementation and large-scale practical usage. Recognising these issues, systematic review helps to fill the gap between theoretical progress and real-world implementation, which maintains solar PV as a competitive power source. Government entities with corporations agree that better solar PV technology is vital because it aids both renewable energy commitments and fossil fuel independence. In order to guarantee a solid basis, the researchers also use simulation-based verification in MATLAB/Simulink. Applying quantitative modelling ties abstract research to actual PV system use, depending on parameters such as tracking the power point and efficiency. This increases the trustworthiness and usefulness of the study for the renewable energy field.

1.4 Problem statement

Solar photovoltaic (PV) technology has become essential for sustainable power generation as the world requires higher amounts of energy. Technology improvements in solar photovoltaics have failed to overcome efficiency barriers, stability challenges and high production expenses, which limit widespread implementation. Solar PV systems experience problems with energy loss, economic barriers and material degradation, which reduce extended sustainability and expansion capability of contemporary solar technology. Shortage of standardised policies with absent financial incentives acts as a barrier to increasing solar technology installations. Defining revolutionary innovations is a key focus of improving solar PV performance and applying to operational budgetary needs. A MATLAB computational analysis examines long-standing barriers for solar photovoltaic technology in this research study. Current solar PV technology generates efficiency problems while maintaining instability and requiring costly manufacturing, preventing its widespread deployment. While research is progressing, it is still hard to match the use of new PV materials with how the systems behave out in the field. This research uses electrical modelling techniques to study solar cell behaviour under standard conditions for testing. With the simulation, we can learn more about the challenges and how to optimize new PV technologies.

1.5 Review question, aim and objectives

1.5.1 Review questions

- How development of perovskite-silicon tandem cells and quantum dot technology in solar PV materials lead to improved energy conversion efficiency?
- What are the main obstacles to widespread deployment of solar PV technology that involve stability problems and energy efficiency reduction alongside rising manufacturing expenses?
- How scalability and economic feasibility of progressive solar PV technologies diverge according to international marketplace requirements.
- Which Strategic policy initiatives and deployment recommendations accelerate solar PV system distribution for sustainable energy purposes?

1.5.2 Aim

The main aim of this research is to examine breakthroughs, emerging trends, and the impact of solar photovoltaic efficiency improvements for sustainable energy solutions, addressing technological advancements, challenges, and economic feasibility. Develop and validate a solar photovoltaic simulation model that accurately characterises the electrical performance and power output of a 200w PV module under standard test conditions.

1.5.3 Objectives

- To investigate recent advancements in solar PV materials, cell designs, and energy conversion techniques to enhance efficiency and performance
- To analyse challenges such as stability issues, energy losses, and production costs, and identify potential solutions for sustainable solar energy systems
- To explore the scalability and economic feasibility of emerging solar PV technologies through case studies and qualitative research
- To assess policy recommendations and future research directions for optimising solar PV deployment and accelerating the transition to renewable energy
- To conduct a canonical analysis using NVivo to categorise key findings on material developments, structural solutions, and performance improvements in emerging solar PV technologies
- To establish a comprehensive Simulink model that simulates I-V and P-V characteristics of a solar PV module, incorporating key electrical parameters and temperature coefficients for realistic behaviour prediction.
- To analyse and verify maximum power point operation of a PV system through measurement of steady-state voltage, current, and power outputs under controlled irradiance and temperature conditions.

1.6 Research rationale

The main issue regarding solar photovoltaic (PV) technology is its relatively low efficiency and barriers to mass adoption. However, solar PV systems possess a promise as a renewable energy source, but with low energy conversion rates, high production costs, and associated lack of stability. As a result of these limitations, solar energy cannot fully replace ordinary fossil fuels and cannot satisfy increasing global energy demand without harming the environment at present.

Problems in Solar PV technology arise from inefficiency of material properties, manufacturing complexity, and limitations of charge storage. Today, efficiencies for cells have improved, but many technologies remain commercialised because of prohibitively expensive manufacturing methods and durability issues [3]. Another challenge is exterior factors such as geographical limitations to system placement of the system, intermittent access to sunlight, and loss of conversion and storage in integrating solar PV into mainstream energy systems.

Solar PV efficiency identification is in demand because of the critical climate crisis and the global energy transition initiative. Depleting fossil fuel and carbon emissions reserves and international sustainability commitments have improved renewable energy solutions. Decarbonisation is very important for the environment, which can be done by Solar PV. Governments and corporations are required to invest heavily in solar PV as a major component of decarbonisation strategies.

The purpose of this research is to reveal recent progress in solar PV technology and estimate its contribution to efficiency, cost-effectiveness and scalability improvement. An analysis based on feasibility and impact of emerging trends such as material innovation and AI-driven monitoring systems is discussed in this research by exploring cost-effectiveness and scalability improvement. Research investigators utilise the computational environment of MATLAB for an efficient evaluation of solar photovoltaic efficiency development. Data visualisation features in MATLAB help the team detect how various innovations perform and measure their peak operational effectiveness. Experimental data statistics are used in this research to determine technological advancement levels relative to silicon cells while computing stability projection values. The computational methodology delivers verified information about cost-efficiency relations as well as degradation mechanisms and implementation feasibility, which helps solar manufacturers, along with policymakers, to speed up the deployment of solar technology in actual applications. Problems in Solar PV technology arise from inefficiency of material properties, manufacturing complexity, and limitations of charge storage. Today, efficiencies for cells have improved, but many technologies remain commercialised because of prohibitively expensive manufacturing methods and durability issues [3]. Another challenge is exterior factors such as geographical limitations to system placement of the system, intermittent access to sunlight, and loss of conversion and storage in integrating solar PV into mainstream energy systems.

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1.7 Submission structure overview

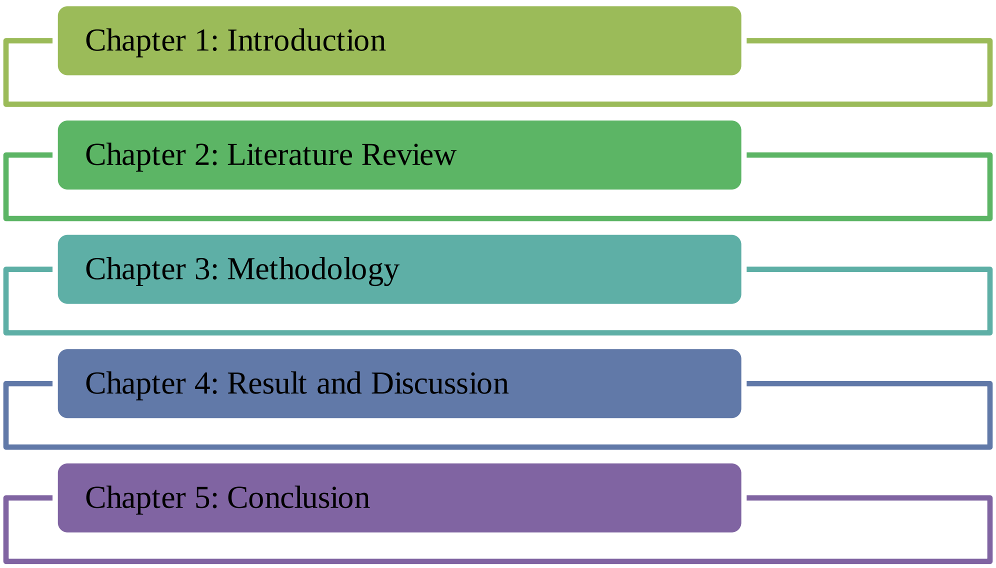


Figure 1.2.2: Research Structure

The dissertation is organized with its five main chapters. The Introduction is the first chapter, following by the Literature Review, then the Methodology, Result and Discussion, and wrapped up with the Conclusion. This method takes us stepwise through the material, from context and theories, to analysis, and finally to our insights.

1.8 Summary

Advancements in solar photovoltaic (PV) technology, with efficiency and growth of trends, are covered in this research. Limitations on efficiency, high costs, and stability issues as big challenges with large-scale adoption of solar in this research. There is a strong need to improve solar PV performance in connection with global energy transition and climate change mitigation to fulfil sustainability goals. Perovskite-silicon tandem cells, quantum dots, and AI-driven optimisation are also highlighted. This research proposes valuable insights into sustainable energy solutions, ensuring long-term environmental sustainability and energy security.

Chapter 2: Literature review

2.1 Introduction

Sunlight transformation into usable electricity through photovoltaic technology stands as a vital process for creating sustainable energy solutions because of climate change. The review analyses breakthrough advances and current trends, and performance developments in solar PV technologies through the synthesis of academic literature, along with industry reports, along official government documentation. The research analysis investigates innovations in materials and structures and optimisation techniques which appeared from 2018 to 2024. The search includes five key terms, which are “solar photovoltaic efficiency”, “perovskite solar cells”, “tandem PV structures”, “quantum dot solar cells”, and “solar PV commercialisation.” There are three main thematic clusters which NVivo software analysed during canonical analysis - these clusters address material developments and structural improvements, and performance advancements, respectively.

The systematic approach provides a balanced evidence presentation which integrates academic findings with industrial perspectives to deliver multiple research value points to stakeholders who focus on renewable energy acceleration. In order to obtain data, a high-impact journal analysis, along with authoritative industry publications, has priority status when studying technological breakthroughs and economic feasibility studies and policy frameworks. Canonical analysis using NVivo allows the review to categorise research findings groupings through material development categories while examining structural improvements and performance advancements. The systematic method allows researchers to conduct a comprehensive review of efficiency gains while preserving research integrity through the appropriate selection of sources and balanced presentation of the evidence. By evaluating both technological advancements and implementation challenges, the review provides valuable insights for researchers, industry stakeholders, and policymakers working to accelerate the transition to renewable energy systems through improved solar PV technologies.

2.2 Review of previous research papers

2.2.1 Integration Solutions and Application-Specific Innovations

The integration solutions for solar PV systems focus on handling complicated challenges associated with merging photovoltaic technology into established infrastructure and energy grids. Different solutions exist to handle technical problems, including intermittent voltage stability and power quality, while enhancing total system efficiency. Current integration methods implement sophisticated control systems together with smart inverter devices and energy management solutions to guarantee consistent integration between solar facilities and power infrastructure. Modern standards for grid connection alongside new storage solutions help providers integrate higher amounts of PV generation into existing power systems while managing time-based energy availability gaps.

Solar PV technology development through specific applications produces photovoltaic systems that fulfil the needs of different deployment locations. Scientists create lightweight flexible modules intended for portable needs and specialise photovoltaic cells for low-light interiors and generate custom building-ready form factors. Scientific teams create specific solutions based on particular settings that produce rugged anti-environment designs with space-efficient tandem cell solutions for dense urban applications. The implementation of new materials and manufacturing processes enables the development of applications that used to be impossible, including solar-transparent windows and power-producing wearable clothing. Specialised solutions for solar energy applications extend their distribution from conventional building mounting to new frontiers while accommodating different markets and usage opportunities.

The advancement of solar PV technology happens through two separate avenues that include integration solutions with distinct features from application-specific innovations. Application-specific innovation works on customising PV technology for unique needs by developing specific materials and designs, whereas integration solutions address system problems of solar power connection to current infrastructure. Integration solutions resolve large-scale operational issues, which consist of maintaining grid stability and implementing energy storage solutions, and maintaining regulatory compliance for existing power networks.

Application-specific innovations focus on advanced specialised performance characteristics, which create opportunities to establish altogether new application domains within particular market niches. Fields of materials science need to unite with electrical engineering and systems design to achieve development success. Integration solutions hold standardisation and compatibility to existing systems as a main focus, but application-specific innovations centre around customisation, together with unique performance capabilities. Economic motives vary because integration solutions target utility-scale cost reductions, yet application-specific innovations earn premium rates to achieve specialised performance targets. Advancement of solar PV technology relies more frequently on concurrent development of specialised approaches in application-specific innovations and established integration solutions, since both methods work together to support deployment of innovative applications across different uses.

2.2.2 Policy Frameworks and Market Acceleration Mechanisms

Solar photovoltaic technology promotion in built environments sounds off through government-directed regulations and incentives and purposeful legislative steps. Established frameworks define requirements for both power grid connection and environmental protection market segment rules. Guidelines for solar photovoltaic technologies embrace feed-in tariffs, tax credits and renewable portfolio standards, and carbon pricing mechanisms. Strategic policies maintain a proper alignment between technology advancements for solar PV and customer rights, together with solutions for network interconnection. The way different regions regulate energy matters extensively because it determines both deployment growth and investment movement. Helping nations and international bodies work together to establish standardised rules supports movement of technology across borders, economic benefits, and security of energy resources.

Market acceleration mechanisms function as vital catalytic instruments to speed up diffusion of solar PV technology into the market. Green bonds, revolving loan funds, and risk mitigation products create financial tools to draw private capital investment. Innovation clusters, combined with technology incubators and demonstration projects, enable researchers to develop products that transition from laboratories to market availability. A combination of demand aggregation programs generates excess efficiency, and targeted procurement policies build trust within markets. Public-private partnerships bring together different resources from both sectors to help overcome deployment barriers. New digital trading systems, along with community-owned solar schemes through digital platforms, enable wider market accessibility to novel PV technologies for all groups of society.

The deployment of solar PV requires policy guidelines as well as specific market catalysing instruments which function as separate strategies. Through authority, policy frameworks establish market rules while market acceleration tools directly apply financial instruments to activate market forces.

Government policies function on extended timelines to achieve numerous social goals while solving market breakdowns and giving developers and investors reliable direction. Market acceleration mechanisms demonstrate quick operational capacity by focusing on targeted barriers to mobilise resources, which then enable rapid capitalisation of emerging enterprise opportunities. Specific market segments and applications become a focus for these mechanisms since they present commercial possibilities despite general market barriers.

Both approaches have effectiveness significantly impacted by how well they are coordinated with each other. Policy frameworks enabling conditions which do not specify technologies work hand-in-hand with market acceleration mechanisms to efficiently direct capital alongside expertise toward effective innovations. Commercial acceleration mechanisms verify technology viability, so produce data for policymakers to create better policies.

The partnership between these elements produces positive feedback where reduced investment risks from policies invite additional capital through acceleration mechanisms, making adoption faster and enhancing political backing of enhanced policies. A combination of these approaches in successful deployment scenarios leads to quick and enduring solar PV market expansion as well as domestic manufacturing strength and innovation networks development.

2.2.3 Technological innovations in solar photovoltaic materials and cell design

PV cell materials and design have been advancing technologies through the means of increasing solar energy conversion efficiency. Shafiullah *et al.* (2022) examined the challenges of grid integration of solar PV systems and suggested suitable system-level solutions that include advanced inverter technologies and better forecasting methods, along with the hybrid energy systems. The research does not focus much on cell material innovation, but highlights the necessity for PV systems to utilise intelligent control and storage to stabilise and maintain efficiency in terms of a fluctuating grid. Using extensive system modelling and real-world data examples, the authors demonstrated that even PV modules that are highly efficient will not perform well in their real-world applications unless integration strategies are fully effective. Wang *et al.* (2023) included a thorough technical investigation of kesterite based solar cells and establishes them as a low cost, nontoxic substitute to conventional Si and CdTe technologies. The study investigates material engineering strategies to overcome efficiency bottlenecks in kesterite cells based on bandgap tuning, interface passivation and defect control that takes place at the kesterite absorber. The review also covers qualitative efficiency trends gleaned from many laboratories, finding that kesterite efficiencies have moved closer to 13% in recent times, but remain behind leaders in the mainstream. Authors discuss future commercialisation pathways through advanced deposition techniques and improved device architecture.

Wang *et al.* (2022) research is more on target and more grounded in a material or design innovation in solar cells. It gained legitimacy for the selected theme by being more tangible in lab-based results and concrete engineering jumps. This is more system integration rather than intrinsic cell efficiency, and broader, which substantially contributes to the theme of photovoltaic material innovation.

2.2.4 Emerging trends in solar PV system integration and performance optimisation

Solar photovoltaic (PV) technology is not limited to material improvements but also to integration and performance optimisation strategies due to advances in material improvements. Zhao *et al.* (2022), 2D discussed that materials are highlighted for their evolution beyond the use in improving device efficiency, but also for keeping 2D devices stable and operational for the long term needed for the successful deployment at the system level.

Authors showed a potential for 2D perovskites to make highly stable PV modules compatible for co-incorporation into complex solar energy systems. Owing to their poor performance under real-world environmental conditions, 3d versions of these materials do not have comparable favourable moisture resistance and thermal tolerance compared to their 2D counterparts. It has a direct impact on the parcel and PV system longevity and decrease the service requirements, which is essential for the performance optimization of large scale and distributed solar systems.

Author described the emerging trend of interfacial engineering and reducing non-radiative recombination losses by tailoring the interfaces between 2D perovskite layers and charge transport materials. Moreover, this optimisation improves conversion efficiency and does not affect the energy yield from 0% to 100% of solar radiation in variable outdoor conditions that are vital for grid-connected systems, such as MPPT and smart inverter-based systems.

Zhao *et al.* (2022), implies approaching the integration of flexible and lightweight 2D perovskite modules in Building Integrated Photovoltaics (BIPV). Portable solar systems are also used as an upcoming trend that stresses both form factor adaptability and system efficiency.

Overall, author provides an analysis of material innovation impacts directly on system performance, stating that 2D perovskites are enablers for new ways to integrate PV to gain system performance benefits of enhanced durability, design flexibility, and system compatibility.

2.2.5 Material Innovations in Solar PV Technology

Research into solar photovoltaic materials has experienced significant advancements in its material scientific domain throughout the past multiple years. Current research involves composition design alongside encapsulation technologies to lengthen service durations between months and projected lifetime spans of numerous decades. Perovskite-based materials represent top choices for future solar cells because show outstanding light absorption power together with adjustable bandgap characteristics. Scientific studies on Cs_2TiBr_6 double perovskites assess both environmental benefits through lead-free substitutes without reducing measured efficiency gains. The solar cell industry can obtain economical alternative layers through the implementation of transition metal oxides (TMOS), which include MoOx, TiOx, as well as aluminium-doped zinc oxide (AZO) instead of traditional p-doped, n-doped and indium tin oxide (ITO) layers in heterojunction technology.

The new materials help developers meet it two primary technological goals, which are to maximise energy conversion efficiency and lower hardware production expenses. Computational modelling through density functional theory (DFT) and SCAPS-1D simulations helps identify material properties before physical development by enabling the prediction of optoelectronic characteristics. The well-known technology enables mass-scale production while achieving higher performance rates based on increased volume and enhanced operational efficiency.

2.2.6 Advanced Cell Structures and Manufacturing Techniques

The benchmark analysis by Peterson and Kumar explains how tandem cell architecture functions as the main method to exceed single-junction efficiency boundaries. Advanced manufacturing techniques, including atomic layer deposition and solution processing methods, receive significant attention in Dubey and colleagues' comparative analysis, which quantifies how precision fabrication techniques reduce defect densities that limit cell performance. Work specifically addresses interface engineering between active layers that critically influences charge extraction efficiency. Introduces innovative approaches to light trapping and surface area maximisation through nanostructured surfaces, demonstrating potential performance increases under specific irradiance conditions. The team used comprehensive lifecycle assessments to evaluate energy payback times during manufacturing because resource usage in fabrication links to sustainability metrics independently from manufacturing efficiency. Tandem cell architecture serves as the main approach to surpass single-junction efficiency barriers based on Peterson and Kumar's benchmark evaluation. Such complex solar cell structures unite components with different bandgap properties to collect more solar wavelengths effectively. The implementation of precision manufacturing technologies like atomic layer deposition and solution processing methods succeeds in lowering the regular performance-limiting defects in cells. Active layer interface designs prove essential for optimising the extraction process of electric charges from photovoltaic cells. Current investigations show nano-shaped surfaces boost light-capturing power while improving overall surface area when used under certain irradiance patterns. The sustainability advantages of photovoltaic production show diminishing results when manufacturing techniques demand high temperatures combined with significant energy usage unless renewable power supplies replace non-renewable energy sources. Environmental sustainability metrics should remain at the forefront of technology development because of it connections to production techniques.

The study indicates that manufacturing methods requiring high temperatures, along with large energy consumption, could negatively affect sustainability unless renewable energy becomes the primary power source for the operations. These findings connect production techniques to environmental sustainability goals.

2.2.7 Performance Optimisation and System Integration

The advancement of performance optimisation and system integration forms a key method to improve solar photovoltaic efficiency levels that surpasses material and structural optimisation. Recent findings prove the effectiveness of algorithmic solutions which dynamically modify system parameters according to environmental changes. The implementation of intelligent systems permits the creation of predictive maintenance schedules through analysis of environmental stresses, which results in longer operational durations for installations. Studies measuring the performance benefits of tracking system innovations now cover a wide range of geographical regions as their developments continue. Research creates benefit-cost models to pick the most suitable tracking system complexity by considering both installation location and local sunlight patterns. The identified findings help organisations develop site-specific deployment methods instead of adopting generalised solutions.

The inclusion of solar power into existing power networks becomes a critical issue as solar penetration rates rise throughout power infrastructures. Researchers track down intermittent solutions with added storage systems and stabilisation methods to determine the specific reliability requirements for battery integration. Building-integrated photovoltaics show designers how to create architectural structures that integrate solar gathering functionality into both their construction components and appearance factors, thus creating more deployment opportunities than simple standalone systems. The combination solves usage limitations and raises acceptability standards in tightly populated areas. Several optimisation approaches combine to offer diverse solutions that speed up solar PV adoption according to research requirements about sustainability barriers and scalability issues.

2.3 Theoretical framework

Several academic disciplines combine knowledge to create a full analytical foundation that enables solar photovoltaic efficiency research and development. Researchers use principles from semiconductor physics as well as materials science, systems engineering and technological innovation theory to develop this multidimensional method, which studies efficiency improvement strategies for solar PV development from start to end.

The fundamental framework demonstrates how sustainable energy system transformations from fossil fuel systems occur, utilising combined technological enhancements, policy changes, along economic changes utilising the renewable energy transition theory. The advancement of solar PV efficiency serves as the primary factor allowing solar energy transition because it shapes both cost benefits and maintainable expansion of facilities while improving performance capabilities. The framework displays the process of sustainable energy system transformation, which results from technical advancements, together with policy modifications and economic alterations. The primary role of efficiency improvements allows solar energy transition because produces economic profit ratios and sustainable facility growth. The Technological Innovation Systems (TIS) theory offers standardised research methods to study Photovoltaics technology development from beginning until end alongside its institutional progress involving academic organisations, industry corporations and governmental entities, and network-based.

The preservation of efficiency creates better application returns and greater power ratios from area usage, thus making solar energy more attractive to cities and rural areas. The TIS theory delivers systematic guidelines to researchers who examine PV technology innovation throughout its development phases ,starting from emergence until completion. The TIS theory analyses technological progress through its research institutions, plus firms and governments, followed by supporting and blocking networks and institutions. The research and development of perovskite-based PV technologies and tandem cells successfully integrates market building strategies supported by policy instruments and scientific breakthroughs yet requires sector legitimacy for its implementation.

Rogers' innovation diffusion model serves as a foundation for examining how efficiency improvements translate into market adoption, identifying specific barriers that impede the rapid deployment of high-efficiency technologies. This theoretical lens helps distinguish between technical efficiency as measured in laboratory settings and practical efficiency realized in real-world implementations. Economic frameworks, including levelized cost analysis and technology learning curves, establish methodological approaches for evaluating cost-effectiveness across competing technologies. By synthesizing these theoretical perspectives, the framework establishes analytical coherence for examining the multifaceted nature of solar PV efficiency advancement. This integrated approach provides conceptual tools for evaluating how material innovations, structural designs, and system optimizations collectively drive progress toward sustainable energy solutions.

2.4 Conceptual framework

The conceptual framework for this study outlines the relationship between key technological, economic, and strategic factors and impact on solar photovoltaic (PV) efficiency outcomes. This framework is designed to support a structured analysis of how innovations and industry trends influence the overall performance, scalability, and sustainability of solar PV systems.

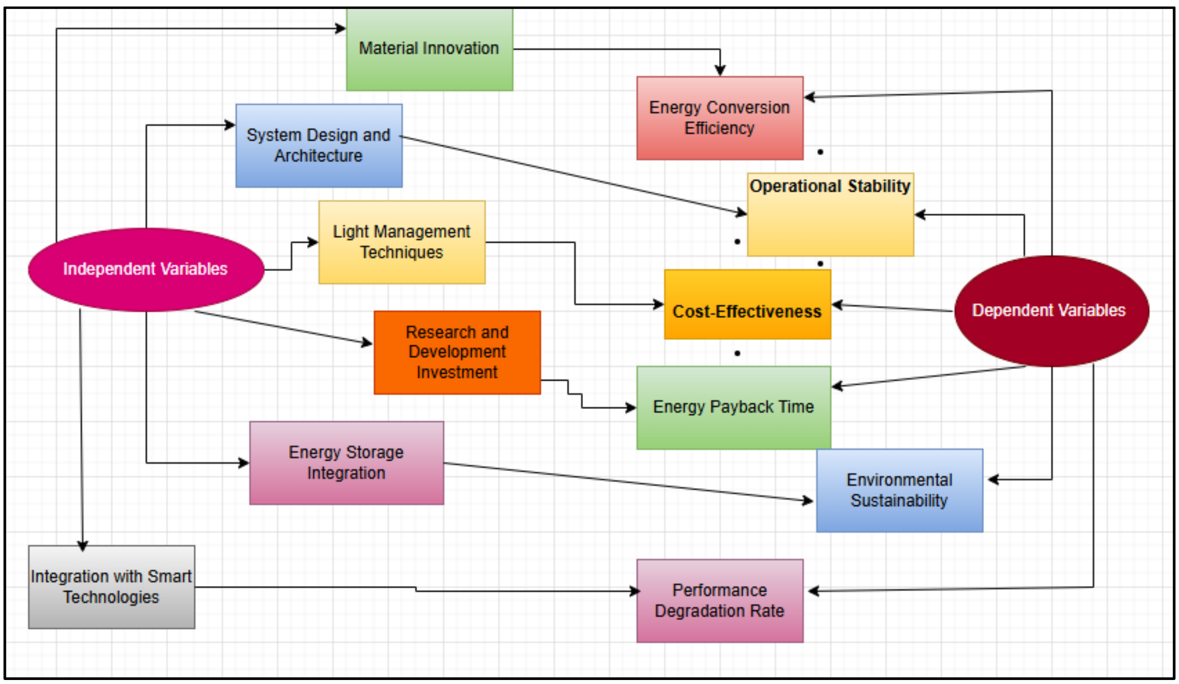


Figure 2.4.1: Conceptual framework

The illustration in the figure establishes how independent variables connect to dependent variables for determining advanced solar photovoltaic (PV) technology effectiveness and performance levels. There are seven organizational groups which categorize independent variables: Material Innovation, System Design and Architecture, Light Management Techniques, Policy and Regulatory Support, Research and Development Investment, Integration with Smart Technologies, and Energy Storage Integration. All these aspects serve essential functions within performance outcome assessment. The conceptual framework depicts the relationships between three main groups of factors, including technological, economic and strategic variables, which shape solar photovoltaic efficiency outcomes. The policies which direct funding for research and development initiatives produce performance results that include lowering costs and market acceptance, combined with environmental sustainability.

The integration process of smart technology delivers three primary benefits related to improved grid connection and enhanced operational flexibility, and reduced system shortfalls. System cost efficiency, together with environmental sustainability and grid flexibility, depends on energy storage integration because it acts as the vital connector between these key outcomes. The five dependent performance variables for output viability and system output stand at Operational Stability, combined with Energy Conversion Efficiency and Cost-Effectiveness and Environmental Sustainability and Performance Degradation Rate. Different innovative features work together to forge a complete overview of PV system performance regarding efficiency and sustainability, plus adaptability. Various performance outcomes, including cost-effectiveness, together with scalability and market adoption rates and environmental sustainability, stem from policy and regulation frameworks and funding for research and development initiatives. Smart Technologies with the power grid achieve three advantages: improved Grid Compatibility alongside enhanced Flexibility and reduced Performance Degradation Rate.

Energy Storage Integration operates as an essential connector during PV systems development because it affects all aspects of system cost efficiency and environmental sustainability, and flexibility in dynamic power grids. The output performance and viability of PV systems depend on the five dependent variables, which are Operational Stability, Energy Conversion Efficiency, Cost-Effectiveness, Environmental Sustainability and Performance Degradation Rate. The framework shows that different innovative features together create a comprehensive picture of how PV systems function in terms of efficiency and sustainability, and adaptability.

2.5 Summary

The important technological developments through an analysis of material advancements and system designs and light management approaches, and integration with intelligent technology platforms. The review shows perovskite and tandem solar cells lead as enhanced energy conversion materials, with a bifacial module, and quantum dots improve light absorption together with operational performance.

The supporting documents used in this study combine peer-reviewed journal articles with technical reports and industry publications, together with policy documents. Various research papers confirm how PV systems must integrate storage technologies with artificial intelligence, along with Internet of Things systems to achieve maximum performance and minimise prolonged degradation over time. The review demonstrates contemporary patterns about both the economic efficiency and energy payback durations and market penetration rates while exposing modern constraints in present solar PV implementations. Cross-sectional analysis of solar technology reveals its contemporary state since investigators did not analyse historical data in research. The extensive literature search has developed a solid understanding of solar PV efficiency determination factors, which can help guide ongoing research and development activities.

Chapter 3: Methodology

3.1 Introduction

A comprehensive synthesis of solar power energy is adopted in research, where a systematic approach is followed to evaluate advancements in photovoltaic (PV) efficiency. Strict exclusion and inclusion criteria are used in this research, where mostly peer-reviewed research, industry reports on solar energy and current technical breakthroughs are prioritised while recognising limitations of public data. Ethical considerations such as accuracy in reporting findings, respect for intellectual property, and valuable data interpretation add to research to provide integrity of the review process. This study's objective entails interrogating emerging trends and efficiency-enabling innovations to critically analyse these and provide useful insights into a knowledge base that could lead to more research and technological advancement.

3.2 Review design

3.2.1 Strategy and philosophical standpoint

Research employs a mixed-methods approach, integrating qualitative and quantitative methodologies to comprehensively examine solar photovoltaic (PV) efficiency developments. MATLAB Simulink serves as a critical analytical tool, enabling precise numerical modelling and simulation of PV system performance. By combining scientific literature review, industrial document analysis, and advanced computational modelling, the research leverages both interpretive insights and rigorous numerical validation to explore solar energy conversion technologies and efficiency improvements [13]. Scientific articles, industrial documents and technical evaluations are used in this research to investigate solar energy conversion developments.

Objectivity in knowledge acquisition in a positivist approach requires experimental data supported by measurable quantitative outcomes. Research follows a systematic methodology for identifying efficiency patterns with cause-and-effect relationships and performance trends because solar PV advancements depend on scientific research and technological development principles [8]. Results obtained from the positivist paradigm are based on actual verifiable data, which provides generalizable knowledge about efficiency technologies of perovskite solar cells and tandem constructions and quantum dots. Research technique maintains rigorous standards to establish trustworthy findings in the developing field of solar PV technology [9]. Real-world application strategies are integrated in this research with efficiency developments and scalability metrics to provide findings which benefit both academic and industrial advancements in renewable energy systems.

3.2.2 Review scope

The scope of this review is to investigate solar photovoltaic (PV) efficiency enhancement through technological developments and emerging novel approaches. It assesses PV efficiency evolution through a combination of theoretical approaches, empirical investigations and market progress. Two material advancement sectors, which include perovskite and tandem solar cells, and three system developments, which consist of light-trapping mechanisms and quantum dots combined with bifacial modules [10]. This study considers the importance of linking solar systems with energy storage devices, smart grids and artificial intelligence applications for solar optimisation.

The review scope encompasses a comprehensive investigation of solar photovoltaic technologies, spanning scientific literature, industrial reports, and technical evaluations. MATLAB Simulink facilitates in-depth analysis of complex PV system models, enabling systematic examination of efficiency trends, material innovations, and performance characteristics. The research integrates global perspectives on solar energy conversion, focusing on emerging technologies such as perovskite cells, tandem constructions, and quantum dot solar technologies.

Evaluation of PV efficiency enhancement is analysed in research, where policy development and industrial partnerships are highlighted to showcase innovations in the field. Review investigates both challenges and opportunities regarding high-efficiency PV system adoption through evaluation of cost-effectiveness, scalability and environmental sustainability aspects. Highlighting all these valuable insights, this study developed knowledge about solar energy conversion improvement and its effects on renewable energy systems.

3.2.3 Methodological focus

Solar photovoltaic (PV) efficiency is examined in research advancement by conducting a study of secondary data sources. Information used for this research from published academic findings, industry reports, governmental documents and technical reports of renewable energy organisations. Multiple high-quality and credible secondary sources from diverse sources provide this research project with a solid analytical foundation. MATLAB Simulink plays a pivotal role, enabling advanced numerical modelling and performance simulation of solar cell architectures. The approach systematically explores efficiency improvements by combining theoretical analysis, empirical data collection, and computational modelling.

Secondary data collection provides expedited access to investigate comprehensive technological and market trends in different PV systems [11]. Research design enables evaluation of time-series data to observe how efficiency levels and material advancements, together with policy adjustments, develop throughout time. Analysis of secondary data enables investigation of parallel projects, which improves ability to establish findings that apply to various solar power applications. Research presents a thorough presentation of decisive developments alongside developing patterns that bring important knowledge regarding contemporary solar PV efficiency growth and its position within renewable power systems.

3.2.4 Time horizon

Research on solar energy explores the current state of logical development in solar photovoltaic (PV) efficiency through a cross-sectional time horizon. Analysis follows a particular time horizon where information is collected and evaluates an immediate view of modern solar power achievements with advancing industry patterns and existing technology progress. Investigation utilises a particular time frame to monitor current patterns and frameworks which link variables such as material advancements together with efficiency optimisation procedures and policy creation, as well as market trend adoption.

Review of solar photovoltaic efficiency improvements benefits from a cross-sectional approach because it enables analysis of current developments regarding research activities and industrial change along with regulatory transformations. Modern scaling challenges, as well as roadblocks and opportunities, are identified in time horizon that exists for advancing high-efficiency solar technologies. This method gives important data about present conditions but fails to monitor continuous developments of technology through time. These time frame insights ensure practical significance for relevant renewable energy planning sector and industry representatives. A cross-sectional research approach is chosen because it supports obtaining an extensive analysis of currently accessible data about solar PV efficiency innovations.

Name	Duration	Start	Finish	Predecessors
Proposal & Planning	1 day?	01/02/25 08:00	03/02/25 17:00	
Completing the Research Proposal	1 day	04/02/25 08:00	04/02/25 17:00	1
Introduction	2 days	05/02/25 08:00	06/02/25 17:00	2
Aims and objectives	2 days	07/02/25 08:00	10/02/25 17:00	3
Problem statement	5 days	11/02/25 08:00	17/02/25 17:00	4
Research significance	3 days	18/02/25 08:00	20/02/25 17:00	5
Literature Review	2 days	21/02/25 08:00	24/02/25 17:00	6
Review of previous papers	3 days	25/02/25 08:00	27/02/25 17:00	7
Theoretical frameworks	3 days	28/02/25 08:00	04/03/25 17:00	8
literature gap	2 days	05/03/25 08:00	06/03/25 17:00	9
Research Methodology	2 days	07/03/25 08:00	10/03/25 17:00	10
Selection of Research Approach (Qualitat	2 days	11/03/25 08:00	12/03/25 17:00	11
Establishing the Research Framework	1 day	13/03/25 08:00	13/03/25 17:00	12
Rationale for Utilizing NVivo Software	2 days	14/03/25 08:00	17/03/25 17:00	13
Sampling Strategy & Data Sources	2 days	18/03/25 08:00	19/03/25 17:00	14
Data Collection Methods	2 days	20/03/25 08:00	21/03/25 17:00	15
Data Collection Execution	2 days	24/03/25 08:00	25/03/25 17:00	16
Ethical Considerations	2 days	26/03/25 08:00	27/03/25 17:00	17

Validity and Reliability of Findings	1 day	28/03/25 08:00	28/03/25 17:00	18
Limitations of the Study	1 day	31/03/25 08:00	31/03/25 17:00	19
Data Analysis	3 days	01/04/25 08:00	03/04/25 17:00	20
Preprocessing of the data	2 days	04/04/25 08:00	07/04/25 17:00	21
Categorization and coding in NVivo	3 days	08/04/25 08:00	10/04/25 17:00	22
Thematic Identification	2 days	11/04/25 08:00	14/04/25 17:00	23
Pattern Recognition & Trend Analysis	2 days	15/04/25 08:00	16/04/25 17:00	24
Interpretation of Themes	2 days	17/04/25 08:00	18/04/25 17:00	25
Structuring & Outlining Discussion	2 days	21/04/25 08:00	22/04/25 17:00	26
Discussion	1 day	23/04/25 08:00	23/04/25 17:00	27
Structuring & Outlining Conclusion	1 day	24/04/25 08:00	24/04/25 17:00	28

Figure 3.2.4.1: Time plan

Figure 3.2.4.1 shows a sequential workflow spanning February to April 2025. Project structure reveals dependencies where each task builds upon previous work, with final dissertation document scheduled for completion by May 9th.

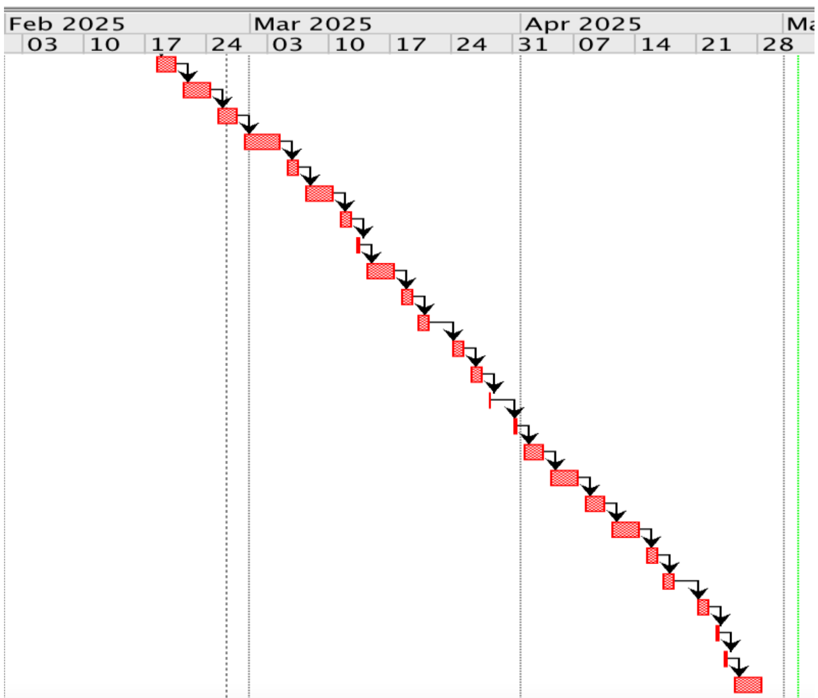


Figure 3.2.4.2: Gantt chart

Figure 3.2.4.2 shows a linear project progression from February through April 2025. Each task transitions smoothly to next with no overlap, indicating sequential rather than parallel execution. Timeline visualisation demonstrates clear task dependencies and shows approximately seven months of continuous research activity with consistent task durations.

3.3 Collection of sources

3.3.1 Search sentence

Development of publications regarding modern solar PV technology is based on search terms that cover "solar photovoltaic efficiency improvements", "emerging solar technologies", "next-generation solar cells", and "renewable energy advancements." Using these specific terms enables to review of a wide range of studies addressing efficiency enhancements along with material developments and new technology integrations in solar power systems [12]. Research also focused on tandem, perovskite solar cells and bifacial modules, along with quantum dot applications and AI-based solar energy optimisation due to changing technological dynamics.

Research incorporates only studies from past five years, which guarantees most modern developments in solar PV efficiency are reviewed. Academic data is obtained primarily from authorised databases comprising Google Scholar, IEEE Xplore, ScienceDirect and additional reputable renewable energy and engineering-focused repositories. The research objective seeks to find studies regarding technological breakthroughs and policy effects as well as market strategies that affect high-efficiency solar photovoltaic systems.

The application of canonical analysis enables to sorting of essential findings for better comprehension of solar PV efficiency enhancement caused by scientific research, together with economic and regulatory elements.

3.3.2 Databases and other sources utilised

Data is gathered for research through analysis of valid academic resources that are available in various academic databases. Google Scholar and IEEE Xplore are used in research, which can help to access comprehensive materials of high quality to obtain primary sources about solar photovoltaic (PV) efficiency improvements [13]. Google Scholar enables users to access extensive academic publications, which cover papers and conference proceedings and provide general insights about technology development, material improvements and efficiency enhancement in solar energy systems. Database maintains comprehensive theoretical and empirical content, which aids PV technology evolution research.

IEEE Xplore is used in this research because it contains specialised research materials about engineering technology and applied sciences. This database delivers important information about modern solar technology developments, with research on perovskite cells and tandem cells in combination with AI solar tracking mechanisms and new photovoltaic module manufacturing practices.

High-impact studies about solar energy efficiency with nanotechnology applications and renewable energy market policies come from peer-reviewed literature found on Web of Science and ScienceDirect. These database sources include government reports from industrial organisations and technical evaluations produced by International Energy Agency (IEA) and National Renewable Energy Laboratory (NREL).

3.3.3 Sampling strategy

Research sampling designs are used to acquire data, which gives a complete and accurate representation of solar photovoltaic (PV) efficiency breakthroughs. Purposive sampling is utilized as a sampling strategy to collect data from strategic cases and sources which fulfil specific research criteria while delivering depth for understanding today's solar energy technological development. This process is focused on gathering sources which suggest detailed information about PV efficiency breakthroughs, material innovations and evolving trends within the solar energy sector.

Solar energy enterprises and solar industry evolution in PV are targeted subjects to lead innovations in solar technology. Selected entities contribute substantially to solar PV system performance enhancement and act proactively to progress solar technology advancement. Organisations and individuals on perovskite solar cells, along with bifacial modules, are examined in research with quantum dots and AI optimisation systems because these innovations represent key elements of research topic.

Secondary data sources such as peer-reviewed academic papers with industry reports, technical assessments and government publications are utilised in research that focuses on trends in solar PV technology. Chosen data represents contemporary information which maintains high credibility alongside close relevance to research fields centred on solar energy technological progress and performance enhancement. Sampling strategy provides a comprehensive understanding of solar PV performance together with its effects on worldwide sustainable energy systems.

Risk	Description	Likelihood	Impact	Mitigation Strategy
Material Degradation	Perovskite and tandem cells are prone to faster degradation under environmental exposure.	High	High	Conduct durability testing and implement protective coatings and encapsulation methods.
Technological Uncertainty	Rapid innovation may render current technologies obsolete quickly.	Medium	High	Adopt flexible design strategies and monitor trends to update research directions.
Data Reliability	Inaccurate or biased secondary data may affect quality of findings.	Medium	Medium	Cross-verify information using multiple credible academic and industrial sources.
Policy and Regulatory Changes	Sudden policy shifts can affect implementation and scaling of new PV technologies.	Medium	High	Monitor policy developments and include flexible recommendations adaptable to change.

Financial Constraints	High costs of R&D and advanced material procurement may limit real-world application.	Medium	Medium	Focus on cost-benefit analysis and explore public-private partnerships for funding.
Integration Challenges	Difficulties may arise when incorporating PV systems with storage or smart grid technologies.	Low	High	Design modular systems and conduct pilot tests for integration reliability.
Environmental Concerns	Waste and chemical usage in new materials may cause ecological risks.	Low	Medium	Emphasise sustainable sourcing, recycling plans, and environmental impact assessments.
Intellectual Property Barriers	Proprietary technologies may limit access to advanced PV innovations.	Low	Medium	Focus on open-source data and collaboration with institutions promoting accessible R&D.

Table 3.3.3.1: Risk assessment matrix

3.3.4 Inclusion and exclusion criteria

Inclusion criteria

The data selection approach of this study features specialised strategies that help to select only top-quality data that pertains to solar photovoltaic (PV) efficiency advancements. Following guidelines are used in research to choose relevant sources which support its academic framework:

- Research includes materials published exclusively from 2019 to 2024 to guarantee selection of contemporary information and solar PV efficiency technological improvements.
- The study includes only materials published in English to ensure factual accuracy and eliminate possible errors related to linguistic differences between articles and studies.
- Study relies exclusively on peer-reviewed articles as well as reputable industry reports and authoritative sources. These measures protect both research credibility and academic standards while guaranteeing reliability as well as validity of data.
- All studies included in this research are required to demonstrate a direct connection to solar photovoltaic technology through advances in material science and new technology developments, and optimisation methods. Research needs to explain how these advancements enhance PV system performance across various markets worldwide.
- The research needs to cover four essential areas that include technological advancement in PV cells, together with material developments of PV cells, alongside artificial intelligence system optimization and solar energy performance improvements.

Exclusion criteria

- Any research from before 2019 is excluded because it fails to display PV technology progress as well as recent efficiency improvements that emerged since then.
- Research papers are excluded that omit solar photovoltaic technology with energy efficiency improvements or related innovations as focus points. Research articles concentrating specifically on unrelated matters, such as general renewable energy without a specific focus on PV systems, cannot be included.
- The research includes only peer-reviewed journals, as well as reputable academic sources and high-quality industry reports. Research excludes any articles which lack peer review or contain non-academic information, along with pieces that fail to meet strong academic standards[11].
- The research excludes findings from studies which do not use a methodological framework, along with insufficient research methods, because only well-established results have to be included.
- Studies which do not establish direct connections between PV efficiency enhancement and technological developments or optimisation methods are excluded from research.

3.4 Analysis tools and techniques

3.4.1 Research tools

Research tools are used on capability to improve systematic capability to evaluate systematically and analyse systematic data. Research tool NVivo assists users in structuring and tagging extensive qualitative data obtained from multiple information sources. Through NVivo, important themes along with trends and patterns across literature can be detected to create more accomplished analysis results. Tool allows for conducting source-based data assessment and data generalisation across multiple information sources for an in-depth look at the subject. NVivo makes it possible to review both theoretical and practical components of data, which helps to present a complete evaluation of study subjects [14]. This tool confirms that research reaches reliable results because it implements cross-checks and verifies the evidence base. The academic framework of study remains stable through NVivo because it ensures all selected sources meet standards of reliability and relevance, together with established quality requirements.

3.4.2 Research frameworks

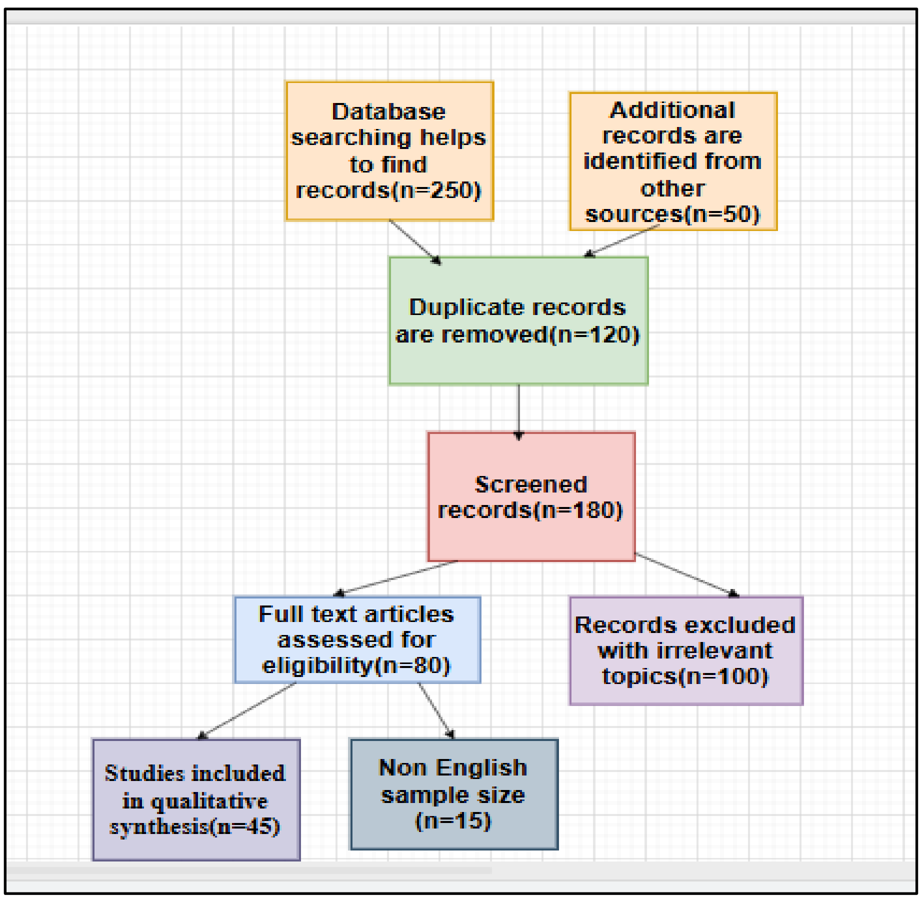


Figure 3.4.2.1: Prisma framework

The image displays a PRISMA flow diagram illustrating the systematic review process. It begins with two orange boxes showing database searching (n=250) and additional records from other sources (n=50). These flow into a green box indicating duplicate records removed (n=120), followed by a pink box showing screened records (n=180). The flow then splits into two paths: one showing records excluded with irrelevant topics (n=100) in a purple box, and another leading to full text articles assessed for eligibility (n=80) in a blue box. The diagram concludes with two final boxes: studies included in qualitative synthesis (n=45) in purple and non-English sample size (n=15) in grey.

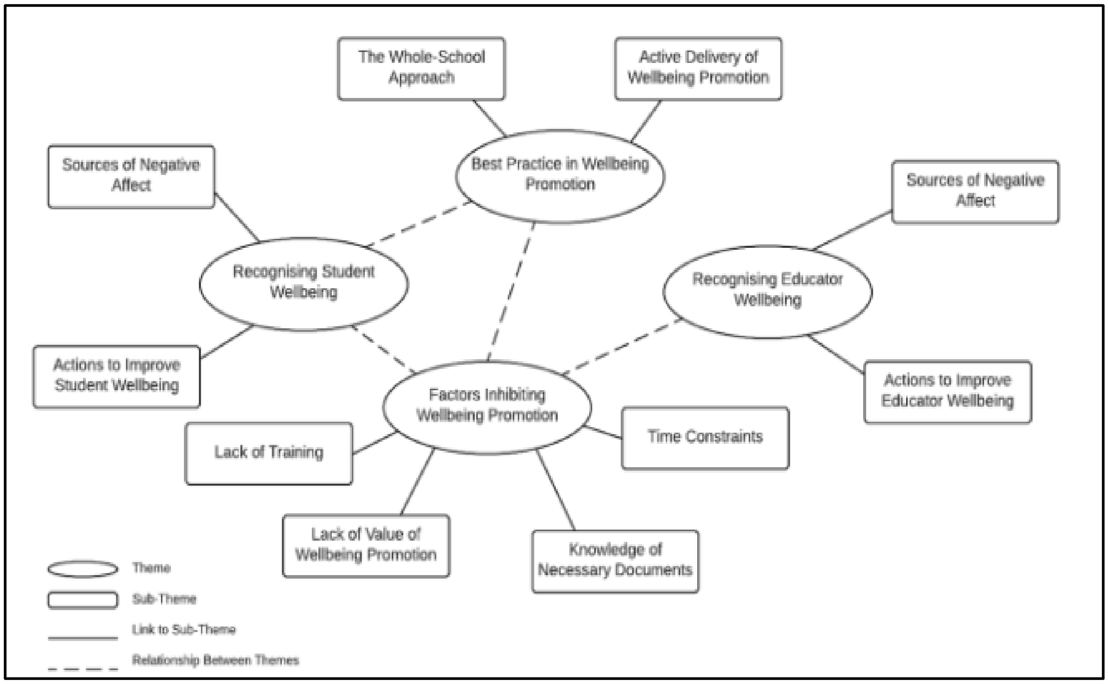


Figure 3.4.2.2: Braun and Clarke's framework [12]

Figure 2.4.2 displays structural elements that influence enhancement of wellbeing, as depicted in Braun and Clarke's graphic. In the same way, methodical factors drive innovation and progress in the area of enhancing solar photovoltaic efficiency. Breakthroughs are result of proactive research and development delivery along with an ongoing understanding of challenges, such as material and environmental constraints. Lack of large-scale adoption strategies, knowledge gaps, and time constraints all hinder faster expansion. However, industry circumvents issues by promoting whole-system approaches, investing in advanced materials such as perovskites, and integrating intelligent tracking systems. Additional strategies to improve solar efficiency include teamwork, updated research data, and continual training in cutting-edge technologies.

3.5 Review limitations

- The research draws its data solely from academic literature, industry reports, and government documents, without including current industry updates.

- The analysis technique involves using a static time window which fails to monitor continuous technological improvements in solar power and market adjustments and regulatory modifications.
- The brief life span of this field reduces practical significance of study results for innovations, including perovskite cells as well as AI-based improvements for solar systems.
- The research design incorporates qualitative assessments that depend on positivist philosophical concepts, which hinders generation of measurable findings dedicated to understanding efficiency rates and scalability potential.
- The study fails to detect new and region-based discoveries, although it analyses several materials and system developments, including tandem perovskite cells and quantum dots.

3.6 Ethical considerations

- The database for information contains only authorised government documents, together with academic research papers and industry reports with established data authenticity.
- The practice requires authors to provide appropriate citations as well as full documentation with respect for copyright laws that prevent plagiarism.
- Proper reference practices allow original writers to obtain credit and support reproduction of copyrighted material according to authorisation requirements and fair use policies.
- The evaluation process of selecting documents should assess their importance while checking reliability and credibility factors to avoid inaccurate interpretation of data.
- The evaluation system treats positive and negative features of solar PV technologies on an equal basis to achieve balanced understanding.
- Data protection ensures freedom from bias and prevents overstatements because it maintains original materials in their authentic state.
- This paper only utilises evidence-based research rather than speculative claims so it excludes any commercially tainted evidence to avoid misleading readers.

3.7 Summary

Secondary sources support qualitative analysis, which studies solar photovoltaic (PV) efficiency improvement methods according to positivist research paradigm. Research findings stem from dependable academic publications and industry reports to establish accurate data about technology progress as well as industrial barriers and market changes. This systematic research method provides detailed knowledge about developing solar PV technology capability and its capacity for renewable energy evolution, and creates space for additional investigation needed for practical PV integration.

Chapter 4: Results and Discussion

4.1 Introduction

Succeeding as integrated materials for traditional and emerging solar photovoltaic (PV) continues to be a point of innovation in renewable energy. Material science in PV technology is analysed in this work with emphasis on evolution of its efficiency, cost reduction, environmental adaptability and implementation challenges. A solar technology design paradigm shift is driven by shift away from conventional silicon-based and ITO-doped layers to properties that next-generation devices possess and have not been previously applied, such as transition metal oxides and lead-free perovskites. Comparing emerging material performance metrics with grid-level integration strategies proves material advancements complement broader system and sustainability goals in both developed and decentralised energy contexts.

4.2 Sample overview

PV technology reflecting on materials-based research to macro level consideration of deployment and grid integration. Issues with voltage instability and energy losses are assessed, as well as system-level analyses of such challenges, replacement of conventional PV materials with alternatives, including MoOx, TiOx, AZO. Application-specific analyses of rooftop and portable PV systems are introduced, where application-specific lightweight and scalable innovation is provided. Focus is ensured, such that analysis of PV efficiency, environmental adaptability, and materials readiness for future is multi-dimensional.

4.3 Findings and discussion

4.3.1 Theme 1: Traditional vs. Emerging solar PV materials

First article provides progress in Photovoltaics, which focuses on cost reduction potential and performance optimization of emerging transition metal oxide (TMO) layers of MoOx, TiOx, and aluminium-doped zinc oxide (AZO). All these alternatives are used for traditional p-doped, n-doped and indium tin oxide (ITO) layers in heterojunction technology (HJT) solar cells. The study presents a bottom-up cost and uncertainty model using Atomic Layer Deposition (ALD) that shows that alternative materials can bring wafer production costs to a level below levels for standard HJT [1]. Although ALD precursors are still a big gap to fill in terms of cost at scale, and indicate that cost-effective efficiency targets are feasible. Results demonstrate increasing competitiveness of advanced materials in exploiting potential of PV efficiency nearing such theoretical limits and reducing cost.

On the other hand, second article is not material-based and provides a perspective of applications of solar PV technologies, mainly with conventional materials, specifically on grid integration challenges [2]. Mechanisms are used to mitigate both intermittency and voltage stability and power quality issues are reviewed from grid operator’s perspective, as well as grid codes and advanced control strategies. The second article is not based on material-specific innovations or performance metrics, but instead limitations of such traditional PV setups. Instead, its ideas are directed towards developing existing solar PV systems more reliably and integrally.

The first article provides deep insight into technical details as well as quantifiable results on next-gen materials, making it a strong contribution to PV efficiency advancement. This represents clear, actionable research directions that use cost modelling, material feasibility analysis, and efficiency benchmarks. Second article is also very relevant for policymakers and operators of PV grids and does not contain empirical lab-based data on materials or cell performance.

4.3.2 Theme 2: Rooftop, Integrated, and portable PV

Rooftop, integrated, and portable photovoltaic (PV) systems have obtained increased importance for sustainable urban development and decentralisation of energy generation. First research on global evolution of PV technologies, with special focus on PV development. Their low material use and flexibility, as well as their adjustability to different surfaces, make these technologies attractive.

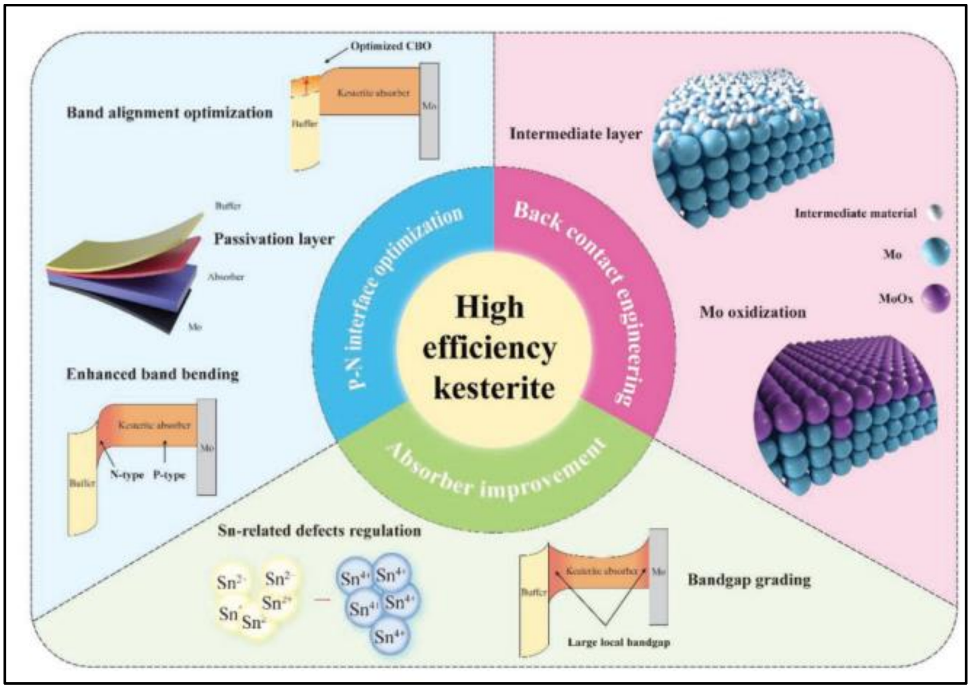


Figure 4.3.2.1: Efficiency improvement strategies of PV [3]

Falling PV module prices and increases in global demand to approximately 10 terawatts by 2030 are said by researchers to drive thin film technology expansion [3]. These lightweight and flexible PV systems are especially appropriate for rooftop, integrated and portable applications as opposed to conventional bulky panels. Results indicate that thin film PV has potential for wide-scale deployment among a wide range of infrastructure types for energy access in urban and remote contexts.

On theoretical approach side, second study serves to examine optoelectronic properties of lead-free Cs_2TiBr_6 double perovskite solar cells using density functional theory (DFT) and SCAPS-1D simulation.

As viable alternatives to existing toxic lead-based cells, these materials are introduced as promising, environmentally safe and possibly efficient. Simulation results demonstrate energy conversion efficiencies and stability to various operational conditions that are promising for such materials to be tailored into lightweight, compact, and portable PV systems [4]. These materials are highly aligned in terms of needs of next-generation integrated solar applications that demand high efficiency without compromise on environmental impact.

Comparison

Ultimately, comparing two studies, first provides a more comprehensive market-oriented view and practical advances in PV deployment, particularly in rooftop and integrated systems. It relies on observed trends and ready-to-use products for large-scale usage. As second paper is mainly theoretical, it provides a deep insight into the potential of future PV cells at material level. First article provides more immediately applicable outcomes with real-world data and market importance.

4.3.3 Theme 3: Energy loss mechanisms for new PV Designs

Energy loss mechanisms for new PV designs are essential for development of next-generation solar technologies, such as efficient and scalable PV designs. First article addresses the critical problem of energy intermittency in solar photovoltaic systems, while candidate solutions for mitigating these losses in terms of materials and storage solutions are explored [6]. Research emphasises recent trends in materials development for enhanced light absorption and conversion efficiency, and therefore decreased energy losses in system and device levels.

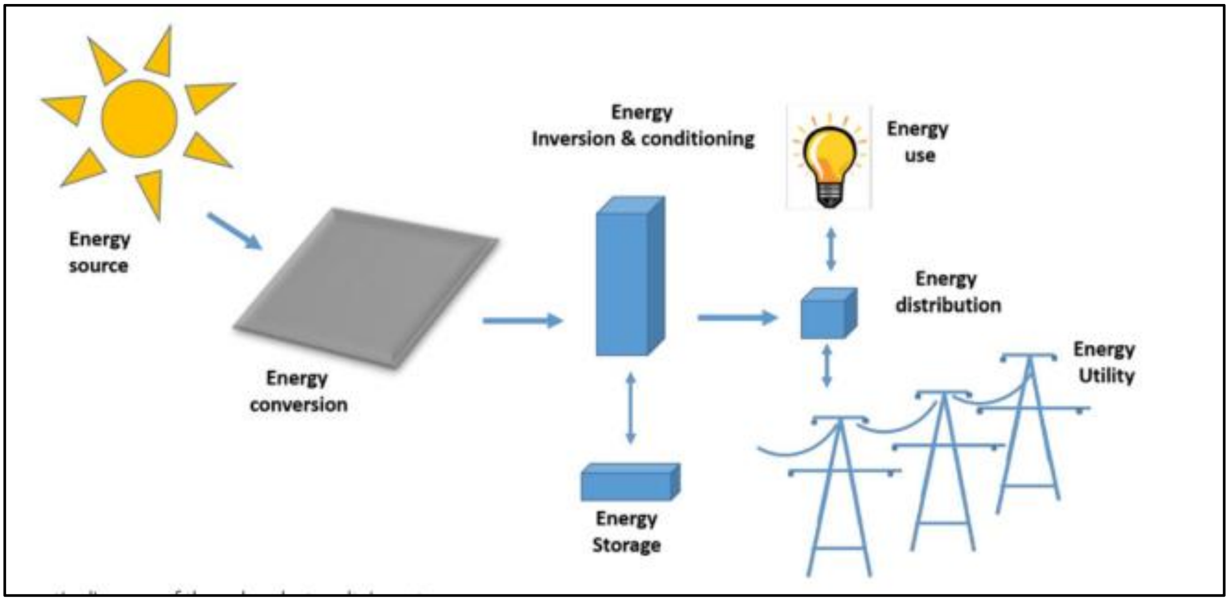


Figure 4.3.3.1: Schematic process of solar photovoltaic systems [7]

Outputs show that improving material properties by tuning bandgap and increasing charge transport can have a major impact on reduction of recombination losses and hence improve overall performance. The overall context of these insights is within domain of hybrid PV-storage systems, which are crucial for sustainable power generation and achievement of grid independence.

Second article explores deeper into how DSSCS can eliminate energy losses in low-light environments such as indoor settings. This review deals in detail with new materials and new design techniques that can be used to improve each component of DSSC, from redox shuttles to hole transport layers and electrode materials. It importantly points out that major energy losses in DSSCS come from interfacial charge recombination, poor photo harvesting, and unfavourable sealing methods [7]. A novel monolithic cell architecture featuring advanced dye and carbon nanotube electrodes can be explored in article to address these issues. Solid state components can be integrated, leading to lower energy losses and thus better device stability at efficient levels under indoor conditions, according to results.

Comparison

Consequently, comparison between two studies shows that the first article is a full description of material science innovations and energy storage strategies to minimize energy losses in conventional PV systems. Second article features a technical and part level analysis of indoor PV performance.

4.3.4 Theme 4: Performance in variable environmental conditions for photovoltaic efficiency

Performance in variable environmental conditions for photovoltaic efficiency has different views about how photovoltaic (PV) technology behaves under global climate and policy environments.

Larger impacts of fossil fuel use and suitability of solar PV technologies from a sustainability and policy perspective are examined in the first article. It presents a correlation between generation of energy-related CO_2 emissions and requirements for solar power. Research stresses PV efficiency across different climatic and environmental conditions, as well as how these influence energy yield and system's viability [15]. Research shows that effects of geographical and atmospheric variation, including temperature variation, dust and cloud variation, are directly equal to PV system performance.

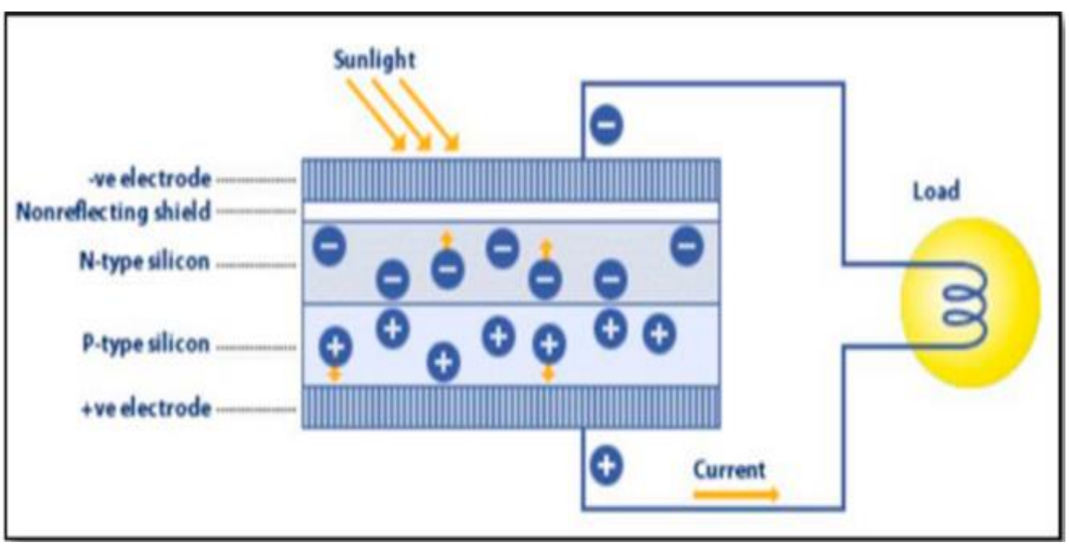


Figure 4.3.4.1: Conversion of PV system [6]

Renewable Energy Laws (REL), legislative bottlenecks and necessity for synergised global strategies compatible with PCR deployment. Results of research provide a robust conceptual framework to link policies, technological advancements, and environmental adaptation as drivers for future PV efficiency improvements.

Second article based on data and innovation-driven work that analyses the extent to which technological learning curves, economies of scale, and other such factors have resulted in a reduction of PV cost and an increase in performance efficiency over time. Results clearly show that the best way to increase resilience under variable environmental conditions is to keep high learning rates through innovations such as bifacial modules, tandem solar cells and advanced manufacturing processes [16]. The article is highly critical of global energy models for assuming an important, but overly limited role for solar PV in meeting climate goals and urges policymakers to reconsider their frameworks in light of true realities of solar PV.

Comparison

First article provides macro analysis that is appropriate for learning about systemic and legislative factors shaping PV efficiency. On other hand, the second article is more technically ambitious, providing practical guidance on how PV tries to escape from environmental performance issues. Second article provides better legitimacy and technical relevance, and thus it is more suitable for PV implementation under dynamic environmental conditions for real life.

4.3.5 Theme 5: Next-Generation PV Materials and Cell Architectures

Photo-voltaic technology progresses through next-generation materials because these exceed silicon-based cell standards. Scientists explore three types of innovative photovoltaic materials, which consist of transition metal oxides (MoOx, TiOx), lead-free perovskites, aluminium-doped zinc oxide (AZO). A focus on these alternative materials exists strongly because they offer better efficiency combined with lower production costs and reduced environmental impact. Materials show excellent optoelectronic behaviour because they achieve optimised band gaps together with enhanced charge transport capabilities. Material development path seeks ecological elements that achieve performance metrics and substitute scarce, expensive, toxic elements such as indium and lead alongside accessible, cost-effective alternative components.

Modern solar technology advancements through new cell designs enable maximum efficiency by creating optimised structural systems. Heterojunction technology (HJT) presents a major improvement through employment of specific stacked layers that minimise recombination failures. Solar cells now incorporate three unique approaches: single-piece monolithic assemblies and double-cell tandems and bimetallic cells, which collect incoming light through front and backside interfaces. Through Atomic Layer Deposition (ALD), engineers agree that nanoscale interfaces can be controlled with high precision, so experts can advance junction designs. Development of cell architecture includes improvements for DSSC components, such as electron transport layers, as well as new electrode configurations. New cell designs solve various conversion and stability issues, adaptation requirements which exist across diverse environmental parameters.

Comparison

PV materials development for future generations and advanced cell design methods operate independently, yet advance solar efficiency through different development processes. The main focus of materials innovation involves fundamental properties for PV energy conversion, such as bandgap optimisation, charge mobility and light absorption coefficients. Cell architecture development focuses on building structured frameworks of materials to bring out its maximum potential at an optimal level.

These development paths connect in a synergistic manner since new materials need suitable architectural approaches to achieve their full potential, or designing optimised cells can trigger specific material requirements. Specialised cell structures become necessary when implementing lead-free perovskites because of its unique optoelectronic characteristics, since monolithic DSSCS need specific materials with matching interface properties.

The fields share identical scalability obstacles, although material development runs into more difficulties when advancing manufacturing and improving environmental resilience. Commercial deployment of cell architectures brings about significantly complicated integration challenges compared to laboratory environments. Improvement of either domain speeds up innovation in the other, creating industrial progress that ultimately accelerates all PV advancement. Better efficiency gains result from research approaches which combine optimised material development with optimal structural implementations, according to scientists.

4.3.6 Theme 6: Efficiency Optimisation Strategies and Performance Metrics

The theme investigates state-of-the-art techniques which aim to increase efficiency of solar photovoltaic energy conversion. This section investigates revolutionary light management approaches along with advanced surface procedures, bandgap transformation methods and interface performance enhancement approaches for lowering energy loss measure. Researchers today dedicate work to development of tandem cell architectures, study of electronic quantum effects and various passivation techniques for recombination elimination. This theme studies new materials used to improve charge carrier transport and collection performance. Implementation of these optimisation strategies leads PV advancements toward theoretical efficiency boundaries at cost-effective and manufacturing-ready conditions.

A thorough examination of fundamental benchmarking procedures, together with standard measurement systems used to assess solar PV technology effectiveness, is conducted in this theme. Beyond conversion efficiency, assessment includes energy yield and performance ratio audits as well as temperature coefficient and degradation rate evaluations, which determine product functionality in real operations. Technical researchers study how to measure spectral response, conducting quantum efficiency computations and optimising filled factors across different environmental situations. This theme conducts research into reliability testing procedures, stability measurements, and accelerated ageing examinations that measure long-term product behaviour. Such metrics act as essential evaluation tools which enable assessment of fresh photovoltaic technologies against laboratory-set industry standards.

Comparison

Solar photovoltaic technology progresses through two parallel yet different approaches, which are Efficiency Optimisation Strategies and Performance Metrics. Evaluation of these solar photovoltaic technology changes through optimisation strategies and performance metrics operates as independent bodies that handle different functions. Control strategies for optimisation work on cellular and modular levels, where focus is on physical functions of optical absorption and charge separation, along with carrier collection processes. Performance metrics deliver comprehensive feedback which considers operational factors exceeding laboratory possibilities.

The evaluative measures for optimisation techniques establish a vital connection with these themes because evaluation methods need to show clear performance results. Evaluation of bandgap engineering methods requires quantum efficiency testing as part of verifying spectral response enhancement. Evolution of performance metrics follows changes in order to match new advantages delivered by advanced optimisation techniques such as bifaciality gain and low-light performance factors. Standardisation and comparability present shared obstacles for two themes despite conceptual and technological differences. The research field is working simultaneously to create optimised optimisation methods as well as to enhance precise economic and implementation performance evaluation metrics. Combination of advancements in technology production, together with quantitative assessment methods, speeds up market implementation of high-efficiency photovoltaic systems.

4.3.7 Theme 7: Economic Viability and Cost Reduction Pathways

The theme explores financial viability factors for emerging photovoltaic technologies within markets that oppose direct competition for energy supply. This evaluation examines fundamental economic indicators, which consist of levelized cost of electricity (LCOE), payback periods and return on investment for advanced PV systems. Evaluation includes market behaviour assessment and risk analysis for investments in new cell designs and materials. Evaluation of economic viability demonstrates how enhanced efficiency levels create commercial opportunities within different power installation settings, including utility facilities and local power generation networks. The research theme offers vital information that enables stakeholders to identify which PV technologies deserve continued development and market release by evaluating financial performance indicators.

The analysis investigates strategic methods for cost reduction in all phases of PV technology, starting from manufacturing and continuing to installation before switching to operation. Research delves into production technique advancements that comprise automated production lines, minimal material utilisation and basic processing strategy optimisation. Study investigates cost-reduction factors of economies of scale, learning effects, and optimised supply chain management. Focus centres on four main objectives: designing substitute materials with lower costs, designing durable solutions for enhanced operational time and developing quick installation solutions. Through specific technological and process innovations, the theme enables solar electricity to become more competitive with traditional energy sources through disruptive cost constructs.

Comparison

PV advancement consists of two connected yet separate elements, which include economic feasibility combined with cost reduction techniques. Evaluation of economic viability bases its assessment on outcome-oriented metrics, market positioning to determine if technology success depends on financial performance compared to alternative options. Process innovations, specific mechanisms, aim to reduce costs while cost reduction pathways remain different from economic viability pathways.

Economic viability strengthens interdependently with cost reduction strategies through its positive effect on profitability and market performance. Analytical methodologies, aside from stakeholder considerations, establish distinct parameters for these two models to follow. Economic viability mainly assists policy creators and strategic decision-makers who assess technology portfolios and serve investors, as well as helps power brokers who evaluate investment opportunities. In contrast, cost reduction pathways function as guidance tools for researchers, manufacturers and supply chain allies, during specific improvement implementations.

Although these analytical approaches recognise efficiency development as value creation, emphasise different aspects of improvement. Economic viability defines the position of efficiency within financial considerations that include risk evaluation and market conditions, and regulatory frameworks. Through Cost reduction pathways, researchers study different methods to obtain efficiency gains by utilising material replacement and industrial modernisation, as well as design advancements. Becoming together enables a complete assessment of commercialisation of solar energy market initiatives through technological advancements.

4.3.8 Theme 8: Environmental Sustainability and Life Cycle Analysis

Environmental sustainability in solar photovoltaic technology encompasses ecological impact and resource efficiency of PV systems throughout its existence. Approach focuses on processing materials that remain non-harmful to the environment throughout its manufacturing cycle and operational phase, as well as its disposal. Sustainable development through this dimension works to decrease carbon emissions while getting rid of dangerous materials such as lead and creating systems that blend smoothly with ecological systems. Environmental sustainability advances through research into split-grid solar technology and other material development, and improved processing efficiency through water reduction. PV technology works toward environmental preservation while supporting world climate objectives in its operations.

The systematic evaluation method of Life Cycle Analysis performs detailed assessments on solar photovoltaic systems environmental impact over its entire lifecycle. The assessment method tracks down energy utilisation while counting resource use and pollutant releases and disposal outputs through the entire product lifecycle, including raw material extraction as well as manufacturing and transportation before built-out and usage phases up to product disposal and final recycling. This method allows scientists to find critical environmental areas and evaluate different photovoltaic systems while finding sustainable design solutions. LCA analytics measure duration of energy repayment, greenhouse gas emissions, and consumption of water and toxicity characteristics. Through complete assessments, environmental consultants provide recommendations for selecting materials and design production methods and end-of-life recycling approaches to reduce environmental impacts.

Comparison

The evaluation of ecological matters in solar photovoltaic developments employs two distinct yet cooperative systems called Environmental Sustainability and Life Cycle Analysis. The framework of environmental sustainability defines guidelines and vision targets for sustainable PV technology, while Life Cycle Analysis quantifies the assessment path for meeting these targets.

Environmental sustainability operates with a comprehensive outlook by applying ecological concepts and fair intergenerational frameworks, yet LCA quantifies effects through separate, defined categories. The sustainability concept develops vision through non-toxic material promotion and renewable material utilisation alongside circular economy principles before LCA transforms these objectives into standardised measurement tools for data-based decision making.

The combination of these methods supports PV research and development through combined effects. Sustainability priorities determine environmental impacts that LCA studies need to prioritise more intensely, along with LCA assessments pointing out urgent sustainability improvement zones. These approaches develop a system which enables technology development while protecting the environment. The scientific community moves toward unifying both perspectives because only advancements in solar technology that meet performance needs while tracking environmental advantages from product birth to death deliver sustainable progress. Practical integration of PV systems helps these systems deliver substantial contributions to sustainable energy developments.

4.3.9 Theme 9: Single-junction vs. multi-junction performance on MATLAB

Recent research on solar energy is focused on the comparative analysis of single-junction vs. multi-junction photovoltaic performance through MATLAB simulations. [39] emphasizes the fact that PV cells can perform beyond 40% efficiency under focused sunlight in multi junction solar cells. Multiple semiconductor layers are used by these cells to absorb a wider range of sunlight to improve energy conversion. It also mentions improvements made to single junction cells, including Passivated Emitter Rear Cell (PERC) cells and bifacial cells, all of which have increased efficiency incrementally. While the research gives a comprehensive range of material and design innovations, there is no comparator simulation data from a single junction and a multi-junction cell using MATLAB. On the other hand, [38] develops PV technology advancements such as tandem and multi-junction cells integration. Author discusses the feasibility and possible increase of efficiencies using the available technologies in different environmental conditions. Consequently, there is a similarity in both specific MATLAB simulation results, which drives comparative analysis between single junction and multi-junction cells.

[39] focuses on a more detail exploration of the theoretical efficiency potentials of multi-junction cells, while[38] mostly concentrates on its broader technological advancement and applications. [38] provides useful additional perspectives for the field, but neither provides concrete MATLAB simulation data for direct comparison in performance. MATLAB-based modelling would help provide detailed simulation analysis for quantifying the performance difference between single junction and multi junction PV technologies under different conditions.

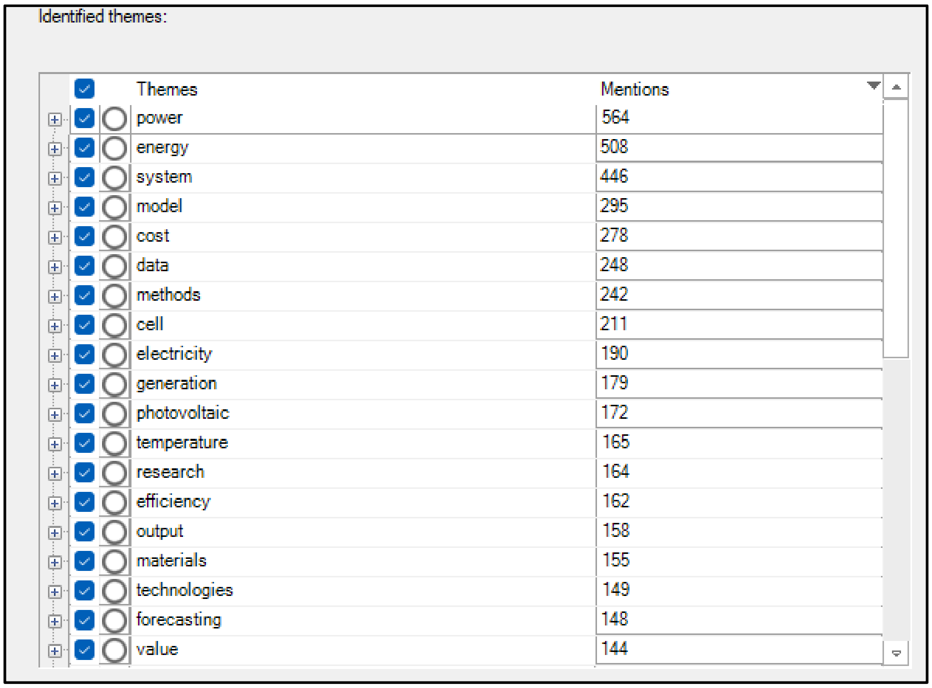
4.3.10 Theme 10: Simulation of bifacial vs. monofacial panels on PV modules

[36] and [37]offers valuable insights into renewable energy optimization 'Simulation of bifacial vs. monofacial panels in PV modules based on MATLAB' are highlighted in the research where the PV system design, simulation, and efficiency are discussed.

The design and sustainability aspects of PV power plants are discussed in depth in the Pharos Engineering Science Journal paper by [36]. Such performance metrics of bifacial vs. monofacial panels are evaluated through MATLAB simulations. In optimal conditions, key findings indicate that bifacial PV modules outperform monofacial modules by an additional 11–13 % energy yield captured on both sides. Analysis of placement and output is thoroughly optimised based on tilt angle, panel height, and albedo effect in the simulation parameters. Materials, lifecycle costs, environmental impact of the materials, and sustainability are also emphasised by the researchers. The work is based on empirical modelling and presents results of pragmatic significance for application in the real world.

Whereas, in their article from the Journal of Advanced Research in Applied Sciences and Engineering Technology, includes both a literature review and MATLAB related to AI-centric optimisation for hybrid solar wind systems. By compiling a comprehensive database that deals with past studies and reviewing optimisation algorithms that are used in hybrid PV-wind energy systems, PSO, GA, and Fuzzy Logic make their contribution. Authors work in a simulation environment that uses MATLAB/Simulink, but they are not primarily concerned with the details of performance simulations of hardware, about their computational modelling strategies and AI techniques. Author also discusses socio-economic and environmental impacts on a less detailed theoretical level. Little original experimentation or results are found in the research, which provides a proper synthesis of existing knowledge.

4.4 Thematic analysis using NVivo



Identified themes:

Themes	Mentions
power	564
energy	508
system	446
model	295
cost	278
data	248
methods	242
cell	211
electricity	190
generation	179
photovoltaic	172
temperature	165
research	164
efficiency	162
output	158
materials	155
technologies	149
forecasting	148
value	144

Figure 4.4.1: Identified themes

The figure displays NVivo-derived themes alongside the number of times each theme was mentioned in Figure 4.4.1. Key aspect “energy” earned the highest number of mentions (508), while “power” had 364 occurrences, and “system” secured 446 mentions in data. Three vital themes which emerge from NVivo analysis are “model”, followed by “cost”, and then “data.” Significant renewable energy ideas, including “methods” (242), “cell” (211), “electricity” (190) and “photovoltaic” (172) become visible through analysis. Interface displays themes through a checklist system that combines each mention count for researchers to view conceptual importance in examined texts. A hierarchical structure shows researchers how to systematically organise themes while counting their appearances.

Name	Codes	References
1. Progress in Photovolta	37	105
10. preprints202102.0345	49	129
11. energies-15-05963-v	58	168
12. s11135-021-01182-y	12	51
13. IJTHM_Volume 4_Issu	64	234
14. sustainability-14-170	41	168
15. energies-15-02790	44	123
16. 1-s2.0-S25424351210	56	180
17. qt2nk1b0k6	12	33
18. International Transact	42	111
19. Song_Air_Pollution_S	52	144
2. Grid_Integration_Chall	161	603
20. Behura_etal_SE_2021_	38	96
21. International Journal	61	186
22. 77324	39	117
23. Jaxa-Rozen-and-Trut	22	45
24. 80694	37	126
25. energies-16-02206-v	36	105

Figure 4.4.2: Coded references

The coded references that served for analysis appear in Table 4.4.2 in Figure 4.4.2. Document "2" contains the maximum number of references according to analysis results. Research includes "2. Grid_Integration_Chall", which contains most references at 603, showing the importance of grid integration to study. Other notable documents include "13. IJTHM_Volume_4_Issu" with 234 references and "1. Progress in Photovoltaic" with 105 references. Each document entry shows its name, its code count, and reference frequency data. The naming pattern combines journal articles with conference papers and research reports, which focus on renewable energy technology with a special emphasis on photovoltaic, solar grid integration problems. Systematic coding processes help researchers identify where key concepts are located in various sources of dataset.

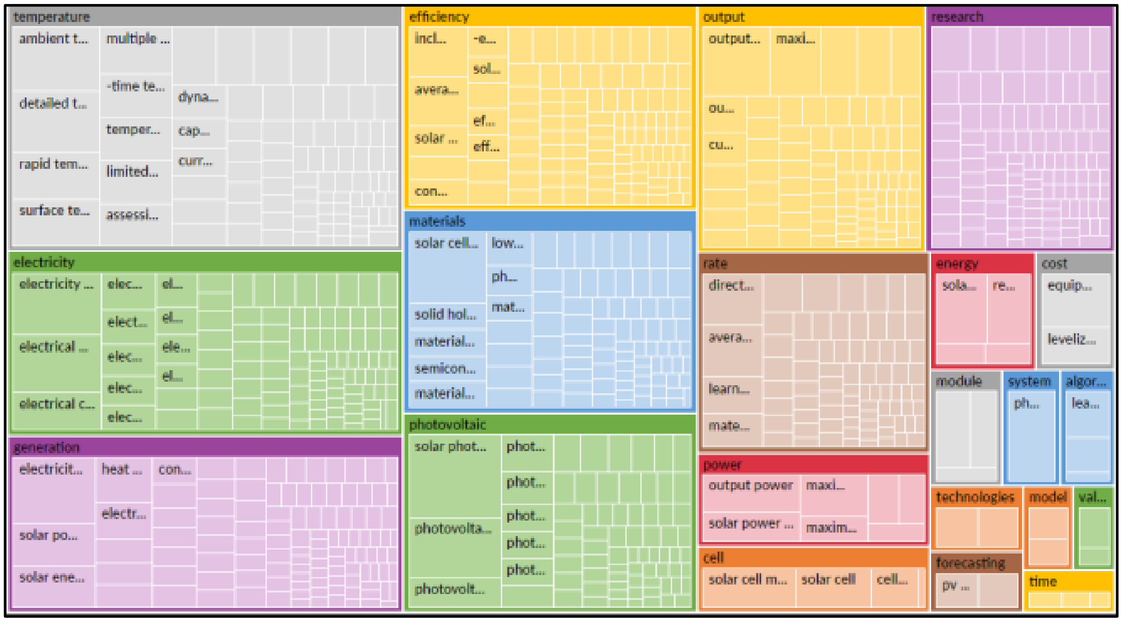


Figure 4.4.3: Number of coded references

Figure 4.4.3 displays a treemap which shows coded references according to their categories and subcategories. Colour-coded rectangular areas display different themes where the areas' sizes correspond to reference frequency. Numerous rectangular elements in yellow, green and purple sections take over visualisation since these categories receive the most references. Visual presentation utilises treemaps to display both hierarchical nature and size-based dependencies between categories and subcategories of concepts. Solar-related concepts occur frequently across multiple coloured sections, which indicates their significance in the examined analysis. Such visual displays let researchers detect prevalent themes together with their related patterns, in addition to showing a detailed overview of coding structures used for qualitative analysis work.

Codes	Number of coding references	Aggregate number of coding references
Codes	44	44
Codes	32	32
Codes	32	32
Codes	32	32
Codes	32	32
Codes	31	31
Codes	31	31
Codes	31	31
Codes	29	29
Codes	29	29
Codes	27	27
Codes	26	26
Codes	26	26
Codes	25	25
Codes	25	25
Codes	23	23
Codes	22	22

Figure 4.4.4: Aggregate number of coded references

The overall reference counts according to frequency distribution in Figure 4.4.4. The most popular code occurs 44 times throughout the text, and multiple codes appear 32 times in total. Table presents frequencies starting from 44 down to 22 citations in descending order. Parallel values between Number of coding references and aggregate number of coding references show unique codes instead of group classifications. Using this view enables researchers to locate dominant codes based on frequency counts, thus revealing the most common study concepts without displaying code names and concentrating only on numerical frequencies.

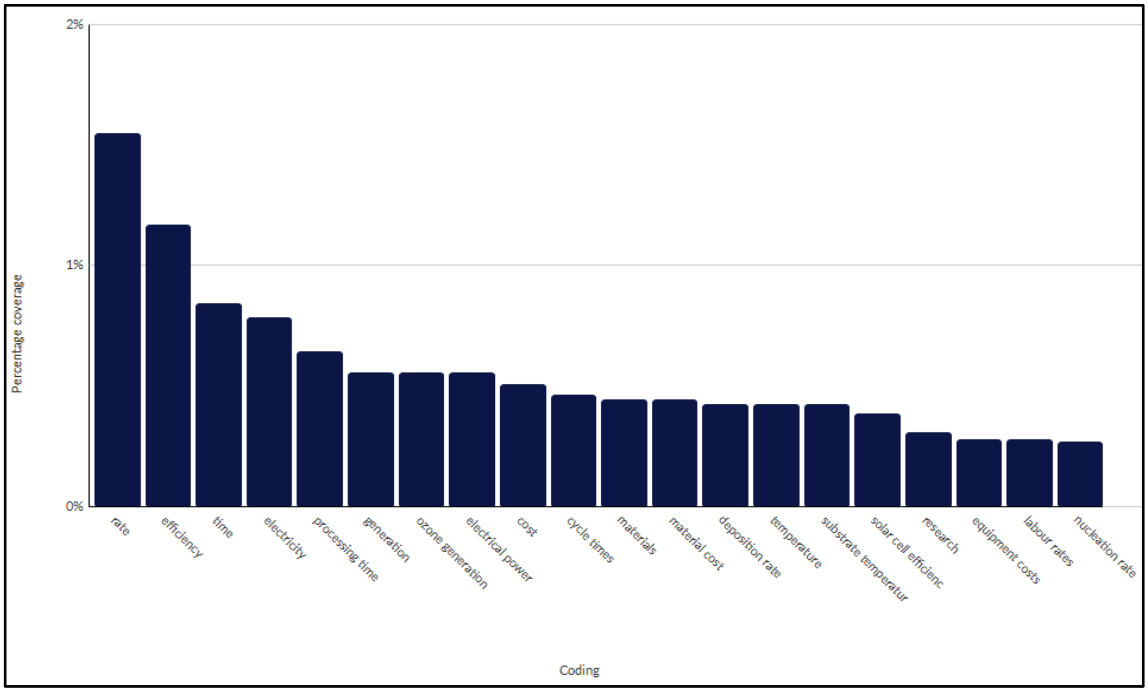


Figure 4.3.5: Bar chart of energy resources

The mentioned energy resources in the analysed texts appear as bar chart visualisations in figure 4.4.5. Numerical data of frequency appear on the y-axis, and coded energy categories appear on the x-axis. Data points start at their highest position in the left section of the chart and then descend toward the right as the values decrease. Visualises relative importance of various energy resources through its data, even though certain labels are unreadable in the image. Visual depiction allows researchers to quickly identify which energy resources appear most frequently alongside their relative positions in studied documents.

Word	Length	Count	Weighted Percentage (%)
solar	5	4274	1.05
sol	3	362	0.09
soiling	7	208	0.05
soft	4	87	0.02
society	7	91	0.02
social	6	125	0.03
smart	5	88	0.02
small	5	136	0.03
sky	3	87	0.02
size	4	230	0.06
site	4	60	0.01
single	6	197	0.05

Figure 4.3.6: Word frequency criteria

This table in figure 4.4.6 shows word frequency analysis criteria using “s” words. Analysis reveals “Solar” stands as the main term with 4,274 occurrences, which represents 1.05% of the weighted percentage. Dataset contains “sql” at 362 occurrences, while “scaling” appears 208 times and “size” appears 230 times. Table demonstrates detailed information about word length, along with frequency and weighted percentage distribution in the corpus. Analysed documents concentrate their vocabulary on specialised jargon which pertains to solar energy investigation. Substantial gap between “solar” and other words shows its essential role in research topics. Such frequency analysis allows researchers to locate essential words which enable them to determine significant domains for deeper thematic exploration.

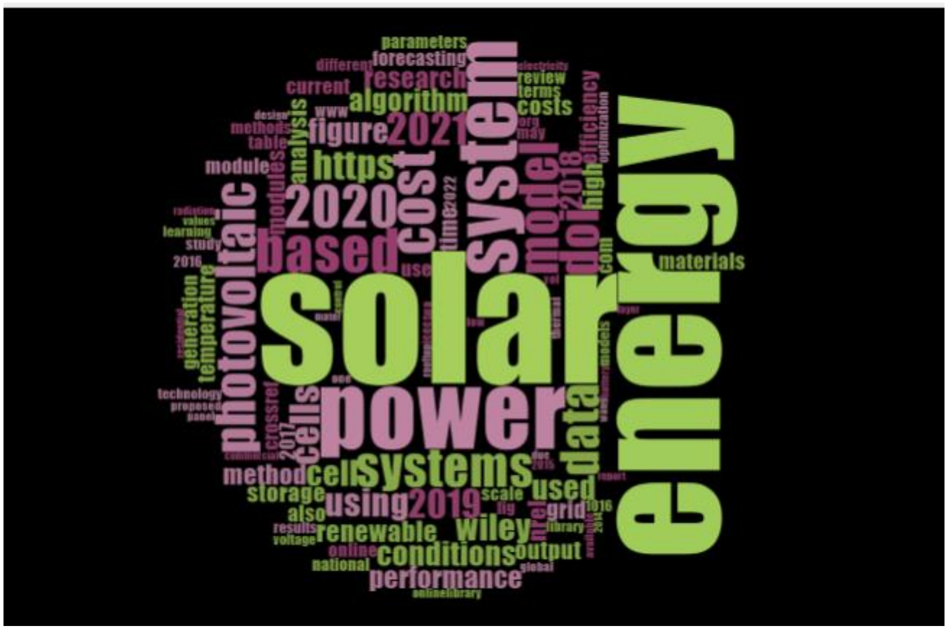


Figure 4.4.7: Word cloud

The analysed documents demonstrate word frequency through figure 4.4.7, which applies text size directly to word occurrence. Visual presents “Solar” and “energy” as the largest words to reflect the critical role in analysis. Main terms of study are “power” “, systems” and “materials”, among others. Most frequent terms receive green colour treatment in this scheme, while secondary terms receive purple colouring to establish better visual separation. Circular organisation of cloud visualises frequent terms in its centre, with terms decreasing in size toward its outer edges. Through this visual representation, researchers can immediately see the main terminology and conceptual ideas of the research dataset because it shows central thematic content, which centres around solar energy systems.

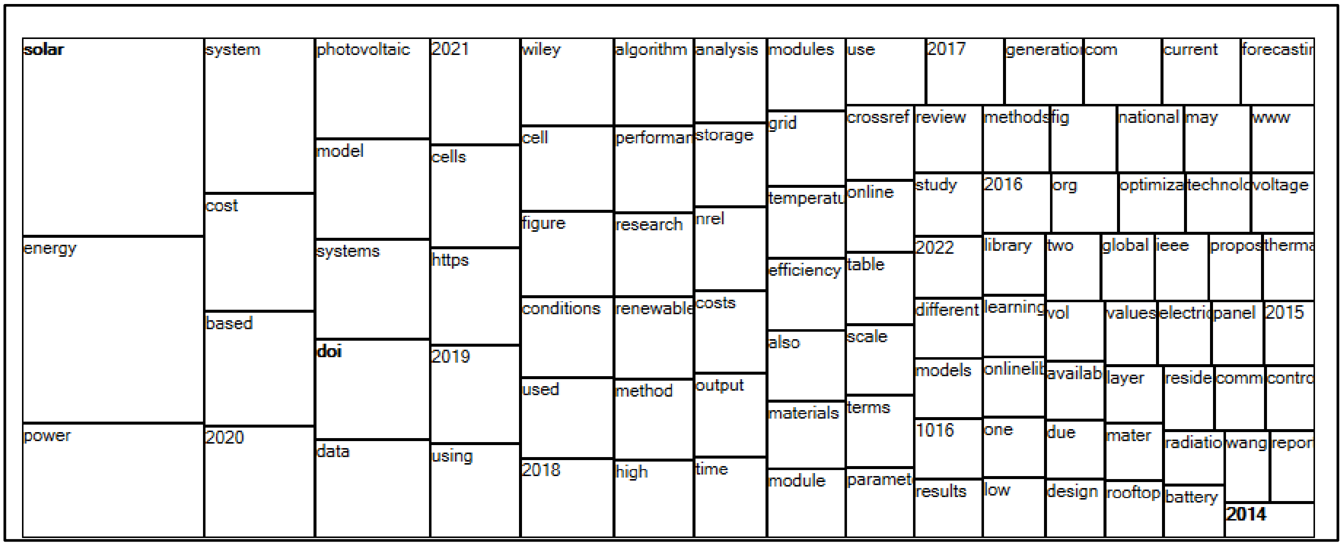


Figure 4.4.8: Tree map

The tree map visualisation arranges hierarchical data through multiple nested rectangles, which vary in dimensions. Different categories from qualitative analysis appear as cells and follow relationships outlined by the coding framework. Visualisation displays period from 2014 to 2021 and multiple themes which cover efficiency, modules, renewable energy and forecasting. Dimensions of rectangular segments in visualisation represent how often or how important each database element appears in the total data. Visual representation offers researchers direct data awareness about structural arrangements and illustrates main topics through large boxes while displaying organisational flows through box placement.

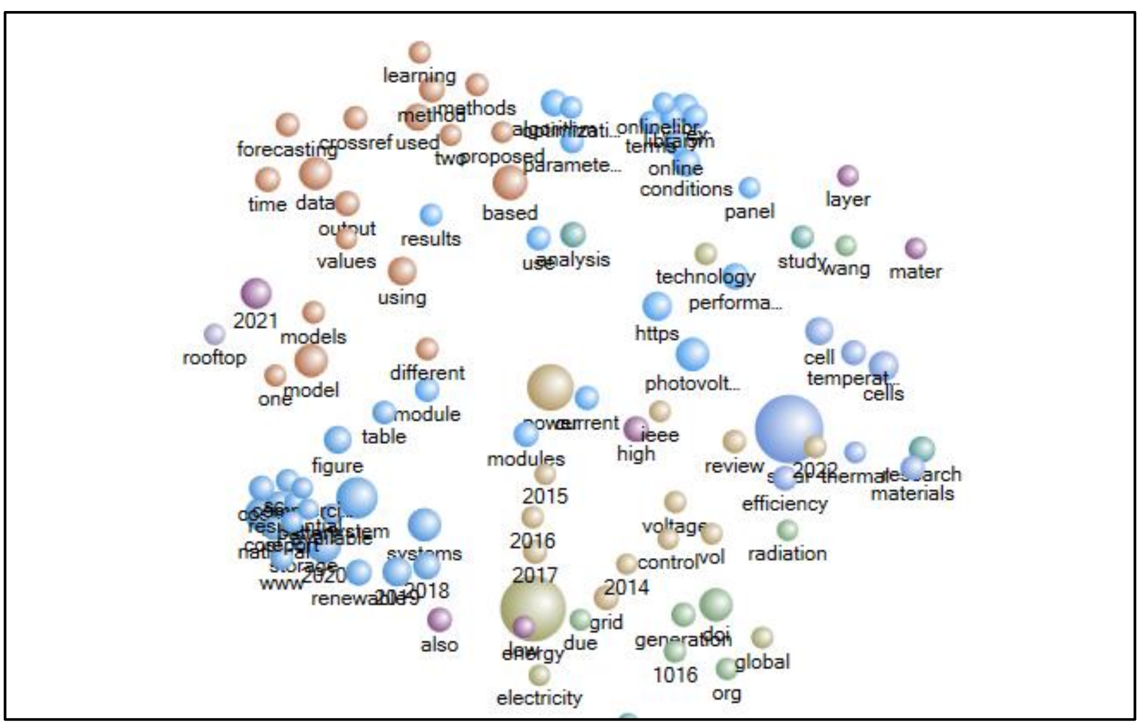


Figure 4.4.9: 2D cluster map

2D cluster maps illustrate textual data through a spatial design showing related concepts as clustered bubbles arranged near each other. Visualisation shows “photovoltaic” “efficiency” and “solar” along with 2014 to 2021 to present bubbles with size variations representing relevance in renewable energy research. Different concept groups function through colour-based distinction. A visual map depicts relationships between terms, so “module”, “efficiency”, and “technology” stand in the central area because these words demonstrate important connections among concepts. This method enables analysts to uncover patterns between concepts which cannot be deduced from textual information independently.

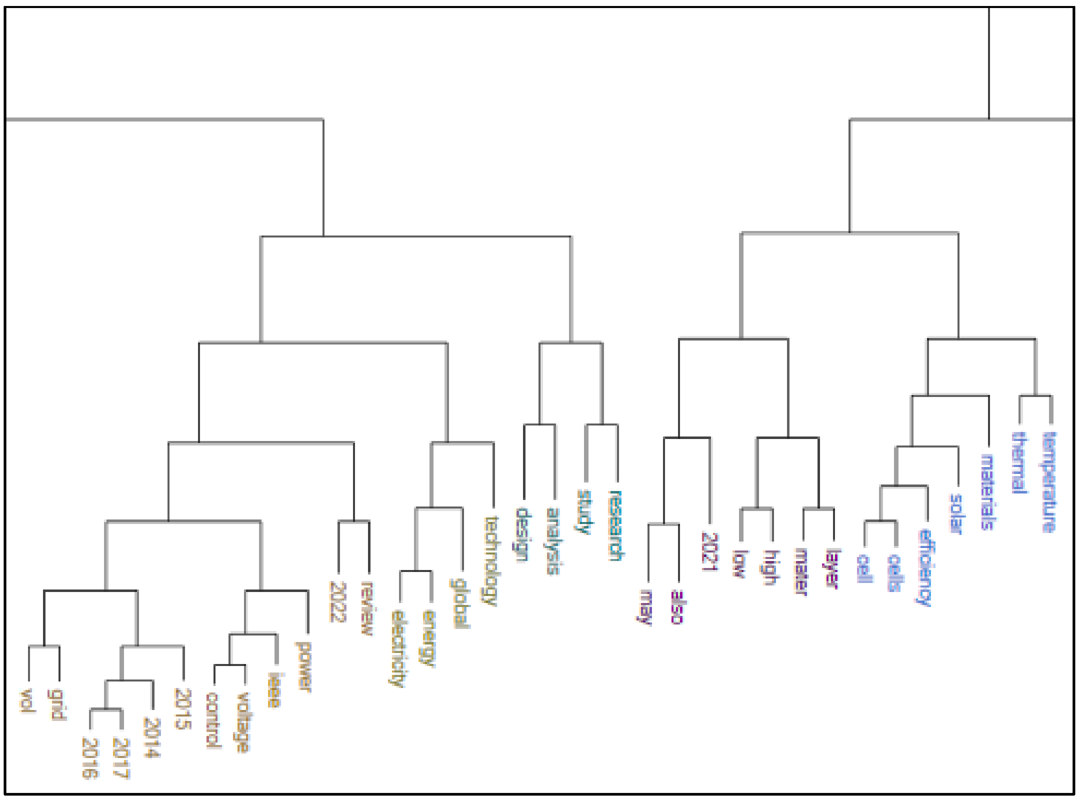


Figure 4.4.10: Dendrogram

The uses a tree-like structure to display data element clustering; while moving from left to right, it illustrates how individual items combine into larger clusters using similarity measurements. Every branch of this graphical structure signifies an entity cluster, while branch length reflects a measure of similarity between clusters. Terminal nodes display specific data points or codes through text that features colour coding. This data visualisation presents a combination of general organisational schemes and detailed analysis for the qualitative dataset structure. Analytical approach of dendrograms enables researchers to detect organic patterns in their data, as well as validate their coding systems and discover relationships between emerging themes when analysing qualitative interview text and related materials.

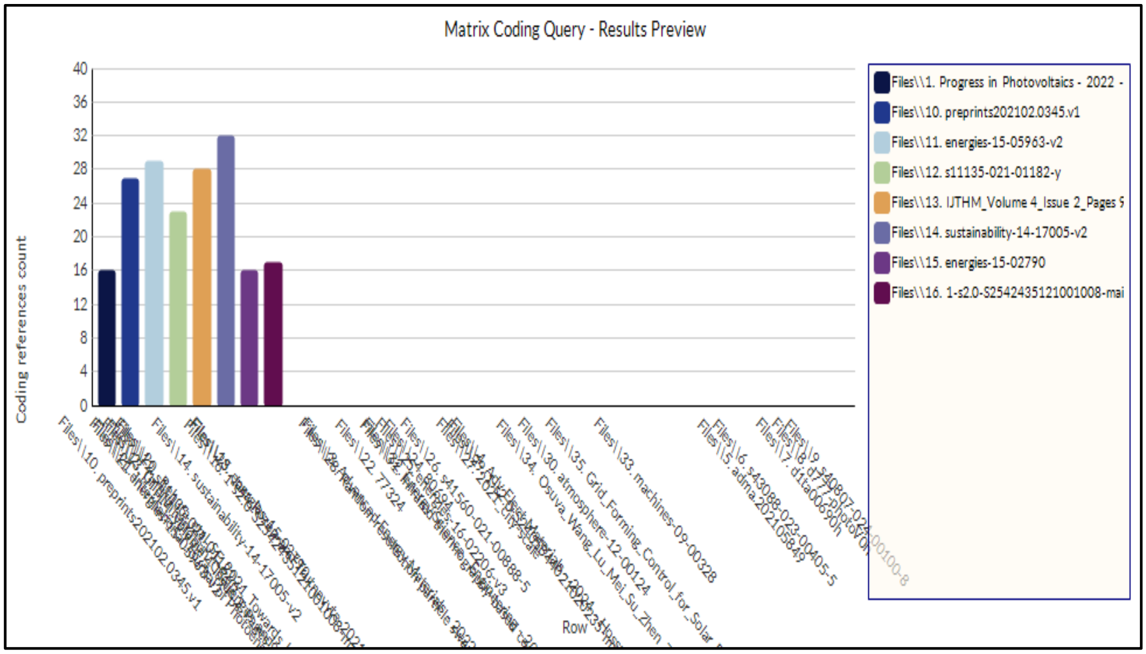


Figure 4.4.11: Matrix coding of "and" query

The matrix coding chart presents "and" query outcomes through code frequency graphs that depict co-occurrence counts among different categories. Frequency data appears on the vertical scale of the chart, yet different coding categories appear across the horizontal segment. Visual legend provides colour codes to distinguish separate code groups shown in bars. Visualisation presents quantitative insights about concept overlap in qualitative material data, with a focus on theme clustering patterns. Vertical lengths of bars illustrate the extent of conceptual relationship strength. By analysing generated output, researchers can better understand coded data patterns, which build theoretical linkages between different themes related to their research domain.

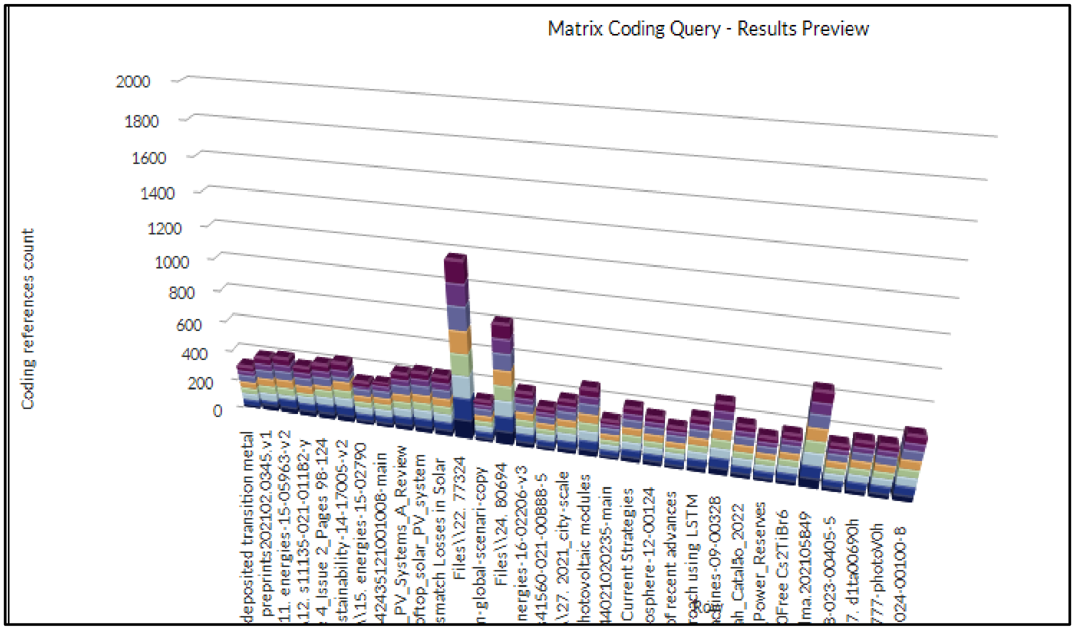


Figure 4.4.12: Matrix coding of "or" query

A 3d column chart shows frequencies of codes in "or" query matrix coding display appearance separately or jointly throughout the entire dataset. Code count scale extends from zero to 2000 on the vertical axis, while code categories appear horizontally across the display with slanted labels. Different source files and code groups build multi-coloured columns to present specific categories. A visualisation system facilitates researchers to study multiple themes at once and find major conceptual elements present within the dataset. "or" query does aggregate occurrences when any single selected code exists in documents, thus delivering a complete picture of themed distributions throughout the whole document set.

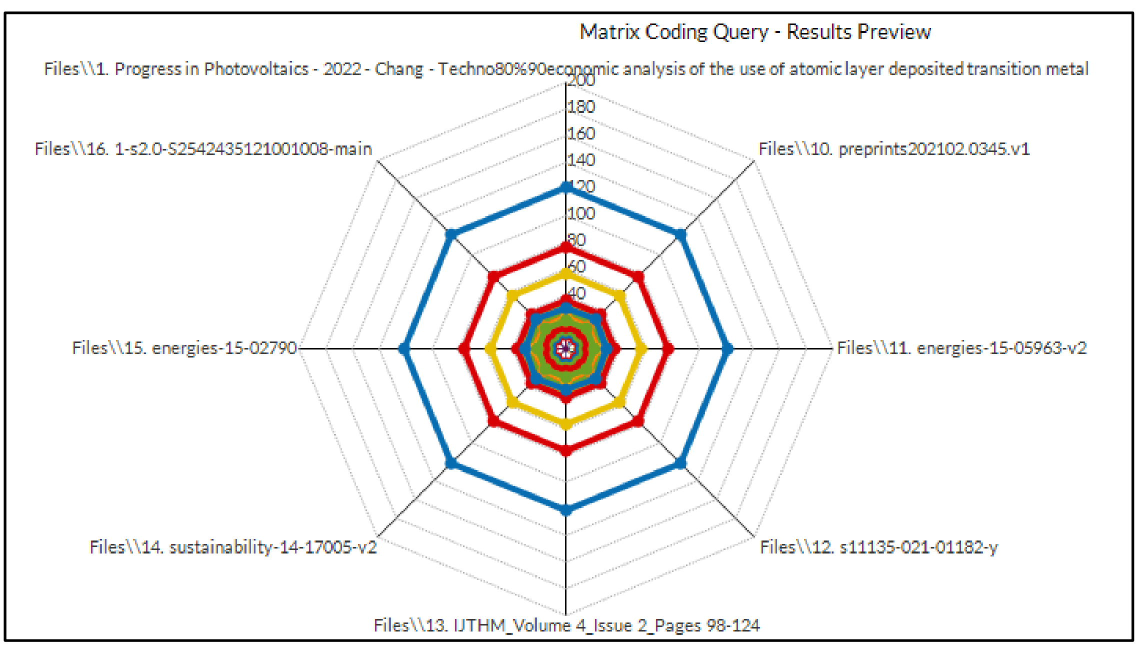


Figure 4.4.13: Radar chart

A radar chart presents multidimensional patterns of coding within different files contained in a dataset through visual comparison. A different file corresponds to each coloured line, which creates distinct polygons to show relative coding frequency and coverage of radial categories around the centre. A radar chart has concentric circles, which provide consistent measurement intervals starting from 0 up to 160. Physical locations of file identifiers appear at both axis extremes and include document references for photovoltaics research and energy studies, and sustainability reports. The visual system helps researchers detect key files that significantly impact certain topics while allowing them to spot similar or different conceptual patterns between several documents at once.

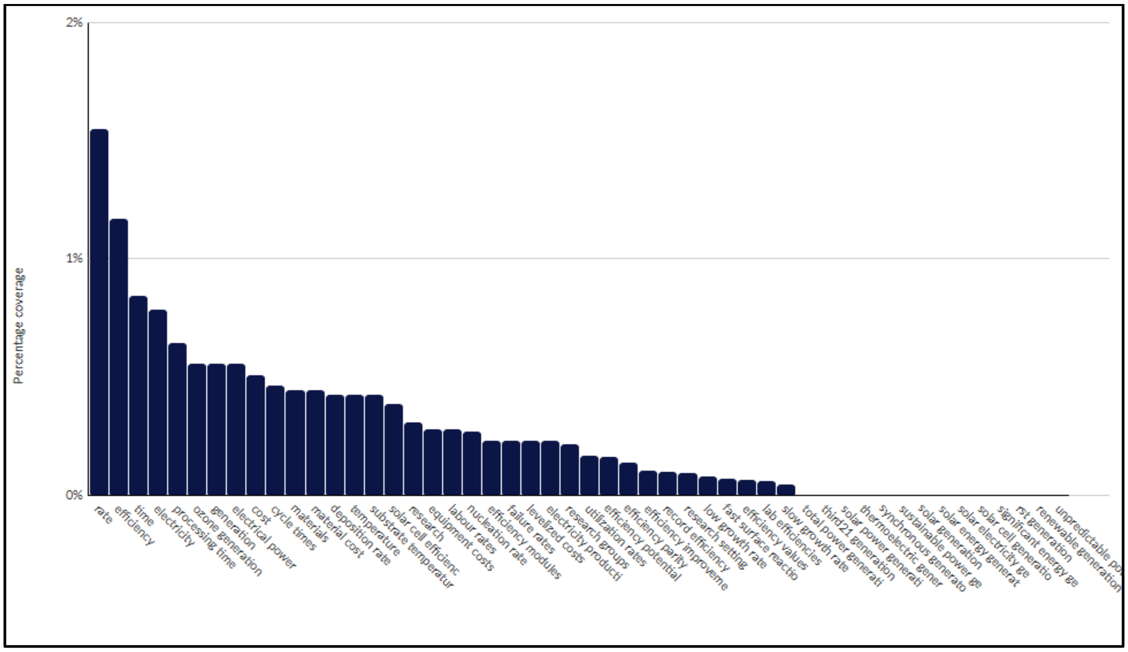


Figure 4.4.14: Percentage coverage

A descending bar graph displays a percentage coverage chart, which shows how major codes affect composition of the analysis dataset. The analysis tool displays percentage coverage on vertical scale and accounts for multiple code categories, which decline from left to right on horizontal axis. Code proportions appear through dark blue bars that decline in height. Most of the observed concepts start with a dominant theme, which then shifts to many rarer concepts based on the graph's declination pattern. A visible representation helps analysts make better analytical decisions because it shows which themes dominate qualitative data to help derive evidence-based conclusions about thematic importance.

4.5 Simulation using MATLAB

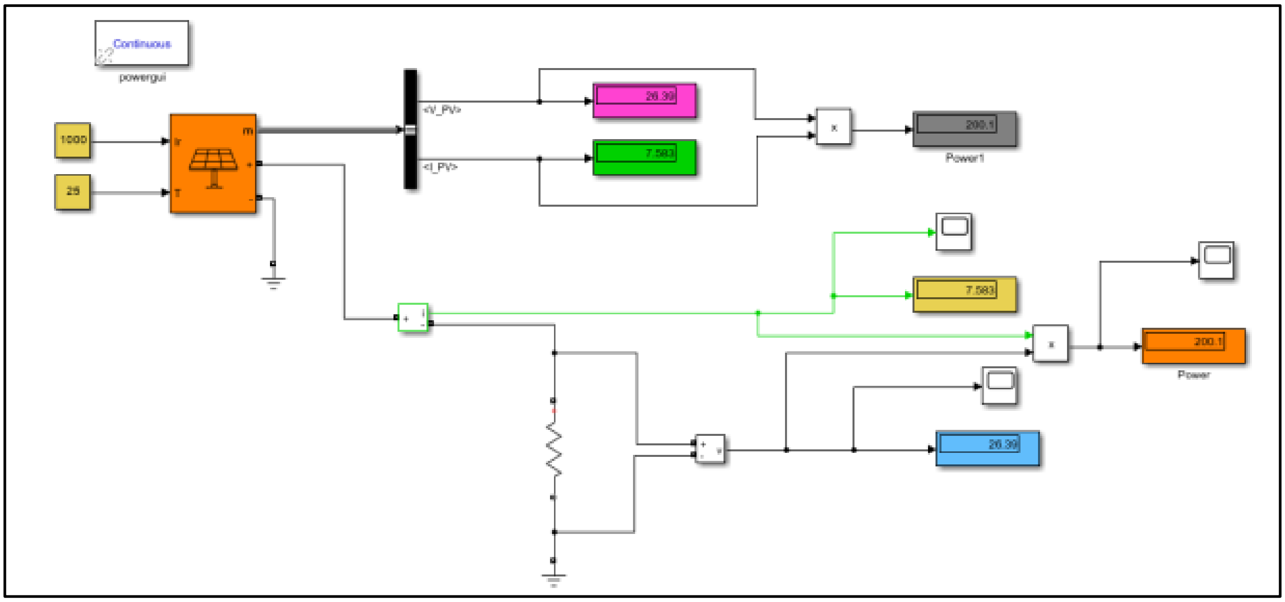


Figure 4.5.1: Solar PV simulated model

This figure shows a comprehensive Simulink model for photovoltaic simulation. The model features a 200w PV array connected to a resistive load via measurement components. Input parameters of 1000 W/m² irradiance and 25°C temperature feed into the PV array block. Current and voltage measurement blocks capture electrical performance data, which is displayed through scope blocks for visualisation and analysis. Bus selector components extract relevant parameters from the PV model for further processing. The model enables investigation of PV behaviour under controlled conditions and validation of theoretical performance characteristics.

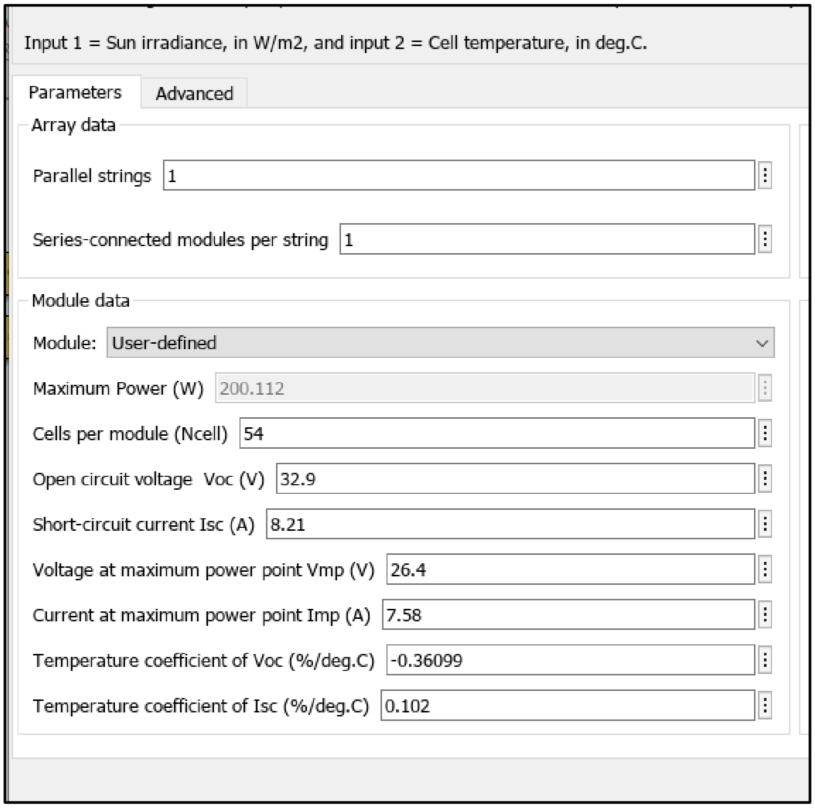


Figure 4.5.2: Module parameters

The figure displays configuration dialog for PV modules showing essential electrical parameters. The module is rated at 200.112W maximum power and consists of 54 solar cells. Key specifications include 32.9V open circuit voltage (Voc), 8.21A short circuit current (Isc), and maximum power point values of 26.4V (Vm) and 7.58A (Im). Temperature coefficients (beta_Voc_pc at -0.36099% and alpha_Isc_pc at 0.102%) characterize the module's thermal response. These parameters form the foundation of a model's electrical behaviour under various operating conditions.

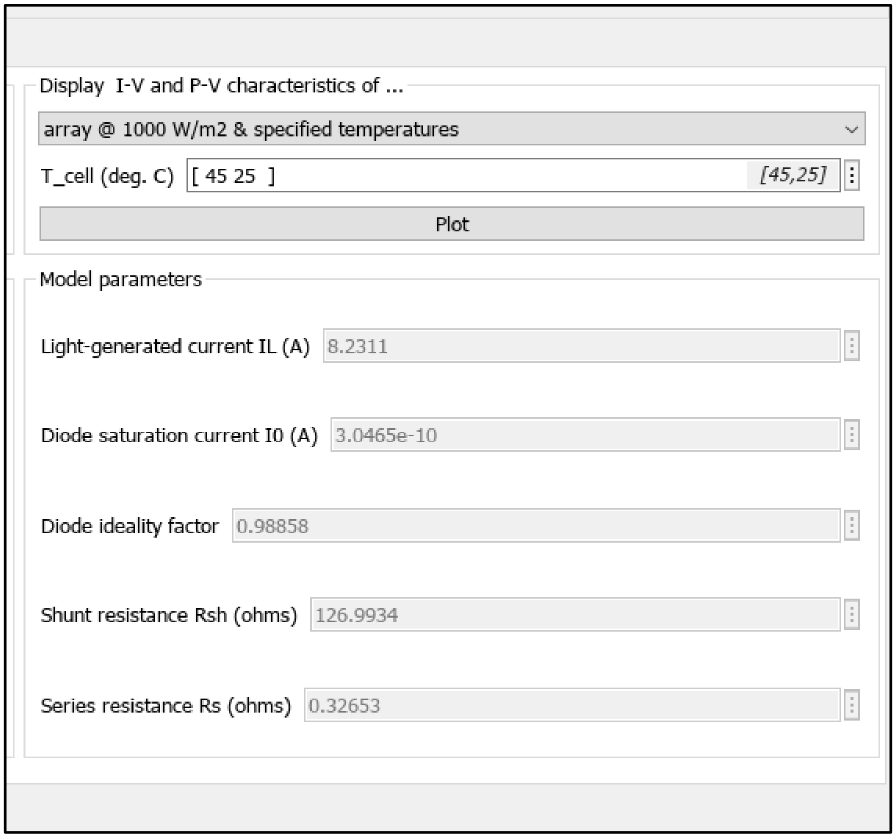


Figure 4.5.3: P-V characteristics parameters

The figures shows the parameter configuration window for the PV model's power-voltage characteristics. It includes detailed electrical parameters that define a single-diode equivalent circuit model: light-generated current (IL), saturation current (I0), diode ideality factor (nI), series resistance (Rs), and shunt resistance (Rsh). These parameters govern the shape of the P-V curve and determine how the module responds to changing environmental conditions. values enable accurate mathematical modelling of non-linear relationship between power output and terminal voltage.

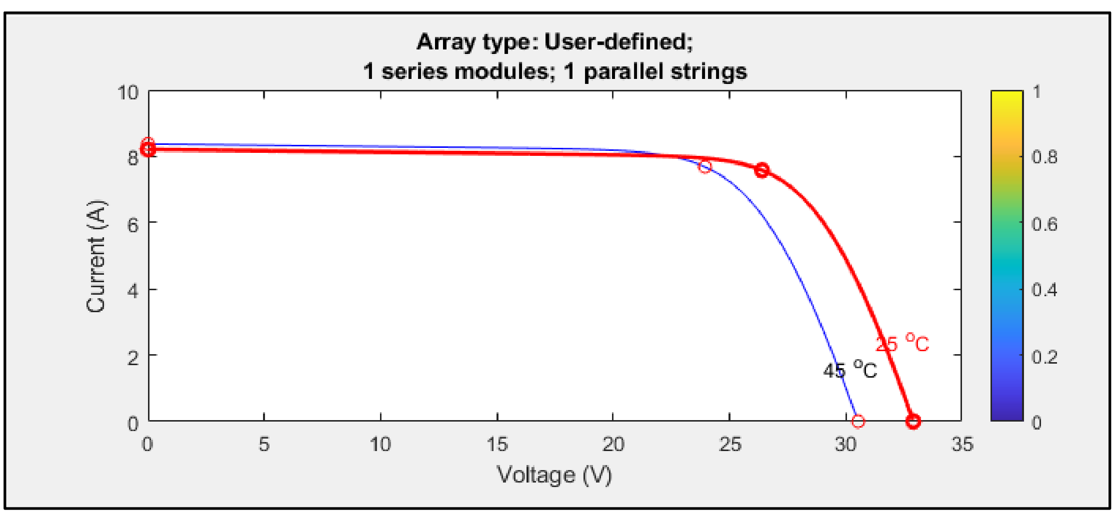


Figure 4.5.4: Current vs voltage

Figure 4 shows the I-V characteristic curve and displays fundamental electrical behaviour of PV module. Non-linear curve begins at short-circuit current (8.21A) when voltage equals zero and gradually decreases to zero current at open-circuit voltage (32.9V). The "knee" of curve indicates maximum power point region. This curve represents performance under standard test conditions (1000 W/m², 25°C) and illustrates the module's current-supplying capability across its operating voltage range. It has been observed that curve shape reveals diode-like behaviour of PV cell.

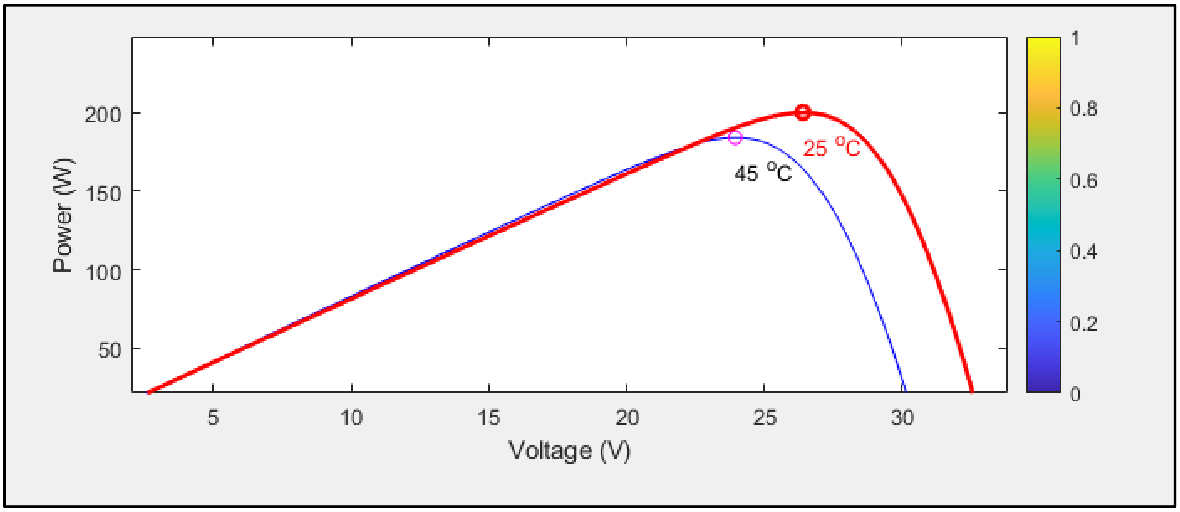


Figure 4.5.5: power vs voltage

Figure 5 shows P-V characteristic curve illustrates relationship between output power and terminal voltage. Starting at zero (at V = 0), power increases with voltage until it reaches its maximum power (approximately 200W) at around 26.4V, then decreases to zero at the open-circuit voltage. The bell-shaped curve clearly identifies the maximum power point (MPP), which is critical for optimal energy extraction. The curve's shape depends on solar irradiance, cell temperature, and internal resistance parameters.

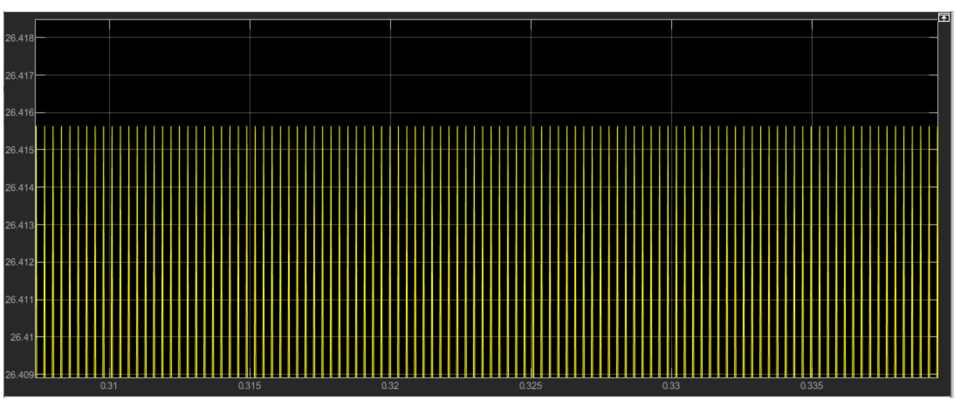


Figure 4.5 6: Measurement of power

Figure 6 shows real-time power measurement from the simulation. Steady value of approximately 200W indicates system has reached stable operation at its maximum power capacity. This confirms model is accurately reproducing specified power output under the given environmental conditions (1000 W/m², 25°C). Horizontal time axis shows simulation duration, while flat line indicates consistent power generation without fluctuations, validating the steady-state operation of PV system under constant input conditions.

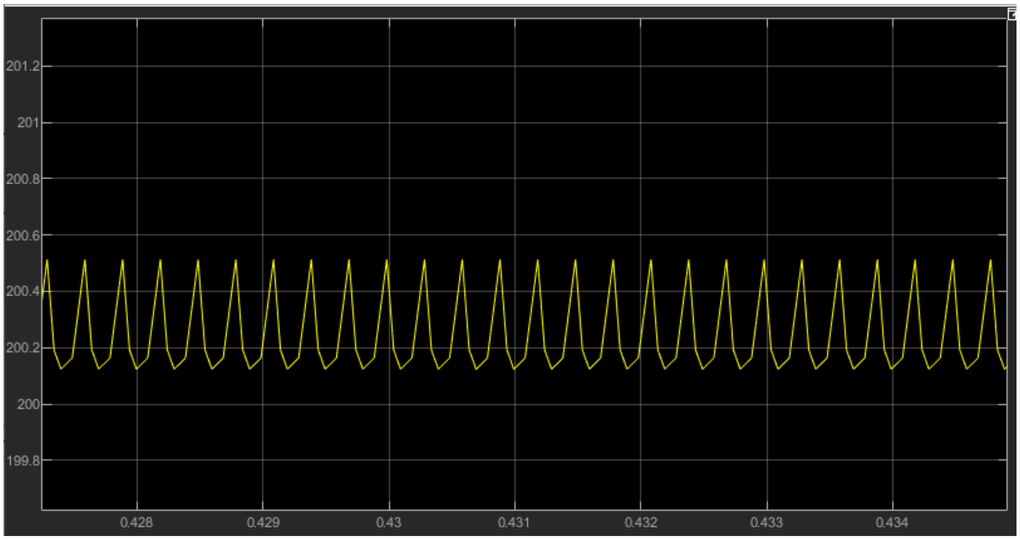


Figure 4.5.7: Measurement of current

Figure 7 shows simulated current output of PV module over time. Steady current value of approximately 7.58A corresponds exactly to specified current at maximum power point (Im). Stable horizontal line indicates the system has reached equilibrium under constant simulation conditions. This current measurement, when combined with the voltage measurement of about 26.4V, confirms that module is operating precisely at its maximum power point, validating proper load matching and optimal energy transfer from PV module.

4.6 Discussion

Analysing performances of emerging PV materials in relation indicates strong potential in improvement of efficiency and reducing manufacturing cost. Transition metal oxides provide feasible alternatives to traditional conductive layers for heterojunction solar cells. Simulation-based studies on lead-free perovskites showcase their environmental safety and suitability for portable and integrated systems. PV system-level research shows that current technologies have shortcomings for grid stability and environmental variation. Resilience under dynamic conditions is addressed through technological learning, new manufacturing methods, such as tandem or bifacial cells. Sustainable solar energy deployment depends on material innovation as well as system enhancements to be aligned. PV simulation presents an idealized PV model, limited by its steady-state assumptions. While providing precise electrical characterisations, it overlooks real-world complexities like partial shading, dynamic environmental changes, and long-term degradation. The single-diode model, though mathematically elegant, oversimplifies non-linear behaviours and thermal interdependencies crucial for comprehensive performance prediction.

4.7 Summary

All analysis of PV process corroborates the fact that emerging PV materials such as TMOS and lead-free perovskites are enormously promising to efficiency and environmental safety. At the same time, evolution in grid control and factory practice creates the possibility of PV under real-world conditions. The traditional silicon-based system is about to be replaced by more advanced material compositions, which respond to the increasing demand for decentralised high-performance solar systems. In order to realise photovoltaic technology's full potential, there is a need to bridge material innovation with a system integration strategy. The simulation models a 200w solar PV system using Simulink, detailing electrical characteristics through single-diode equivalent circuit analysis. It captures key performance metrics including maximum power point, current-voltage relationships, and power output under standard test conditions. The model provides a comprehensive theoretical framework for understanding photovoltaic system behaviour.

Chapter 5: Conclusion

5.1 Introduction

The investigative study integrates key findings on improving PV solar energy efficiency and proposes strategic development routes for upcoming periods. Analysis of material developments coupled with system integration initiatives and policy structures enables solar technology to reach new performance limits and wider market adoption. Chapter unifies an analysis of recent efficiency breakthroughs achieved with perovskites and transition metal oxides, which also explains its solutions to implementation barriers for stability and scalability and environmental concerns. This section explains how breakthroughs in technology and economic sustainability establish market penetration levels, along with methods that smart technology integration provides operational enhancements. The final portion presents applicable guidance for scientists, market specialists, and governmental representatives to drive sustainable energy change through advanced solar PV technologies, along with proposals for additional research areas to address remaining installation challenges.

5.2 Study summary

The development of solar photovoltaic (PV) efficiency continues to progress rapidly, according to research, which examines both theoretical innovation and practical applications. Advancements in material science through perovskite and tandem solar cells technology represent a critical development that advances pursuit of high-efficiency solar energy systems at reduced costs. These materials deliver improved energy transformation rates and slowly address problems linked to stability, as well as scalability and environmental concerns. Light management technologies that use quantum dots together with bifacial modules and anti-reflective coatings have demonstrated substantial progress in enhancing sunlight absorption while reducing energy losses. Techniques directly lead to enhanced PV system responsiveness and efficiency under changing lighting patterns. Better architecture and structural flexibility have led to improved operational performance and durability of photovoltaic systems.

Real-time monitoring and fault detection functions through integration of AI and IoT smart technologies have become more apparent since their implementation in solar power systems. Such technologies remain essential for enhancing power grid connection and maximizing practical use of solar power generation systems. Steady development of energy storage systems allows for a reliable and uninterrupted renewable energy supply when solar radiation reduces. This study developed and validated a comprehensive solar PV simulation model using MATLAB/Simulink to characterize electrical performance of a 200W photovoltaic module. The model incorporated accurate module parameters including open circuit voltage, short circuit current, and temperature coefficients. Analysis of current-voltage and power-voltage relationships was conducted under standard test conditions of 1000 W/m² irradiance and 25°C temperature. Research successfully demonstrated the module's operation at its maximum power point with precise measurement of voltage, current, and power outputs.

5.3 Findings summary

Research on solar photovoltaic (PV) efficiency progression takes place in a vibrant technological domain that advances rapidly because of policy support and global sustainability needs along with innovative initiatives. Qualitative secondary data analysis shows that PV efficiency improvements primarily result from developments in perovskite and tandem solar cells, enhancing energy conversion rates and prospects for market scale-up. New materials surpass traditional silicon cells in efficiency ratings yet require further improvement of durability throughout time and resistance to external conditions. The effectiveness of solar absorption and energy reduction needs system design improvements in addition to light management systems which include quantum dots and bifacial modules and light-trapping approaches. Combination of these systems and smart technologies, and anti-reflective coatings results in improved system performance and better environmental response ability. Harnessed integration of smart technology components such as AI and IoT supports operational control enhancements and predictive maintenance functions, and grid integration requirements. Solar energy storage systems must be integrated into photovoltaic systems to ensure reliability since sunlight conditions often vary.

The simulation results revealed several key findings about the 200W PV module's performance characteristics. The I-V curve confirmed the non-linear relationship between current and voltage, starting at 8.21A short-circuit current and extending to 32.9V open-circuit voltage. P-V curve distinctly identified the maximum power point at approximately 26.4V and 7.58A, yielding 200W of power. Steady-state measurements validated theoretical expectations, with the module operating precisely at its rated maximum power under specified conditions. The simulation also demonstrated the importance of accurate parameter configuration, including series resistance (0.32653 Ω) and shunt resistance (126.9934 Ω), in achieving realistic modelling outcomes that can inform practical system design.

5.4 Recommendations

The direction of future work extends the primary goal, which involves technological innovation to enhance solar photovoltaic (PV) efficiency. Future research studies environmental resilience and manufacturing methods alongside degradation processes to ensure proper implementation of these cells in multiple climates.

The research analyses system-level upgrades through bifacial modules and light-trapping structures, and quantum dot applications to determine impact on energy intake as well as reduced energy wastage. Real-world tests can assess these units while they operate together with AI-based monitoring systems to use IoT-driven predictive analytics for dynamic optimization. Based on this study, implementing maximum power point tracking (MPPT) algorithms to model and optimize energy harvesting under varying environmental conditions has been recommended. System designers should carefully match load resistance to PV characteristics to ensure operation at or near maximum power point. Parameter sensitivity analysis should be conducted during system design to understand how manufacturing tolerances affect overall performance. Model parameters should be regularly calibrated against physical measurements to maintain simulation accuracy.

5.5 Suggestions for future research

Further research is needed to develop stability improvement methods for perovskite-based solar cells through studies of protective coatings and material modifications which enhance operational reliability beyond existing constraints. Advanced processing techniques need assessment to determine how to cut manufacturing energy costs without affecting accuracy of fabrication procedures and supporting sustainability improvements. Strategic investigations regarding bifacial module optimisation under different installation situations, together with predictive maintenance systems, hold enormous promise to optimise system performance.

Future research should extend this simulation to include dynamic environmental conditions such as varying irradiance levels, temperature fluctuations, and partial shading scenarios to represent real-world operating conditions better. Integration of advanced MPPT algorithms and grid-connection inverter models would enhance practical applicability. Incorporating aging and degradation effects would enable lifetime performance prediction. Development of hardware-in-the-loop validation methodologies could bridge simulation-reality gaps, while machine learning approaches could optimize parameter extraction from limited measurement data, improving model accuracy for diverse PV technologies.

5.6 Summary

The evolution of solar photovoltaic efficiency stands as a fundamental process for achieving sustainable energy due to its synergy between fundamental scientific developments and real-world startup methods. The material science discovery of perovskite tandem structures with transition metal oxides has made it possible to surpass traditional efficiency caps and simultaneously lower production costs. Laboratory achievements alone do not guarantee deployment success because understanding that stability maintenance is crucial, together with scalability and grid integration features, is crucial. Through combination of smart technologies and optimised system designs, and energy storage solutions, system performance becomes better in multiple environmental conditions. Reliable policy support coupled with market enhancement systems function as crucial elements for transferring technical capabilities into broad-based commercial utilisation. Research developed and validated a solar PV simulation model that accurately characterises electrical performance of a 200W module. The model correctly predicted I-V and P-V characteristics, confirming maximum power operation at 26.4V and 7.58A. This simulation framework provides a valuable tool for designing, optimising, and predicting the performance of PV systems.

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