



**UNIVERSIDAD
DE GRANADA**

**Strategic Optimization of Hybrid
Microgrid Systems for Renewable Energy
Transition:
A Comprehensive Study with Case
Applications in Iraq**

A dissertation submitted to **Granada University**
in fulfillment of the requirements for the degree of
Ph.D. in Engineering

Electrical Engineering (Specialization in Renewable Energy)

By: Kawakib Arar Tahir

Exp. No: 95765

Under the esteemed supervision of:

Prof. Bonifacio Javier Ordóñez García

Prof. Juan José Nieto Muñoz

Escuela de Doctorado de Ciencias, Tecnologías e Ingenierías
Programa de Doctorado en Ingeniería Civil (B23.56.1)

Doctoral Thesis
Granada University, Granada
2025

**Strategic Optimization of Hybrid
Microgrid Systems for Renewable Energy
Transition:
A Comprehensive Study with Case
Applications in Iraq**

A dissertation submitted to **Granada University**
in fulfillment of the requirements for the degree of
Ph.D. in Engineering

Electrical Engineering (Specialization in Renewable Energy)

By: Kawakib Arar Tahir

Exp. No: 95765

Under the esteemed supervision of:

Prof. Bonifacio Javier Ordóñez García

Prof. Juan José Nieto Muñoz

Escuela de Doctorado de Ciencias, Tecnologías e Ingenierías
Programa de Doctorado en Ingeniería Civil (B23.56.1)



**UNIVERSIDAD
DE GRANADA**

Doctoral Thesis

Granada University, Granada
2025

Editor: Universidad de Granada. Tesis Doctorales
Autor: Kawakib Tahir
ISBN: 978-84-1195-973-5
URI: <https://hdl.handle.net/10481/110612>

La presente memoria, titulada "**Strategic Optimization of Hybrid Microgrid Systems for Renewable Energy Transition: A Comprehensive Study with Case Applications in Iraq**", ha sido realizada por **Kawakib Arar Tahir** bajo la dirección de los doctores **Prof. Bonifacio Javier Ordóñez García**, del Departamento de Ingeniería de la Construcción y Proyectos de Ingeniería, y **Prof. Juan José Nieto Muñoz**, del Departamento de Matemática Aplicada, ambos de la Universidad de Granada. El trabajo reúne todos los requisitos de contenido, teóricos y metodológicos para ser admitido a trámite, a su lectura y defensa pública, con el fin de obtener el título de **Doctor en Ingeniería Eléctrica** con especialización en **Energías Renovables**, en el Programa de Doctorado en Ingeniería Civil (B23.56.1) de la Universidad de Granada. Por lo tanto, al firmar este documento, autorizamos la presentación de la referida memoria para su defensa y evaluación.



Granada, a May 19, 2025.

V.B. Director

V.B. Director

Fdo.: Javier Ordóñez García

Fdo.:

La doctoranda

Fdo.: Kawakib Arar Tahir

DECLARATION

This is to certify that the work reported in the present dissertation titled “Strategic Optimization of Hybrid Microgrid Systems for Renewable Energy Transition: A Comprehensive Study with Case Applications in Iraq” is a record of work done by me in the *Escuela de Doctorado de Ciencias, Tecnologías e Ingenierías, Programa de Doctorado en Ingeniería Civil (B23.56.1)*, Granada University, Granada.

The dissertation is a compilation of research papers that were previously published in peer-reviewed journals. Each chapter of the dissertation corresponds to one of these published papers. While these chapters have been directly included in this dissertation, they have been revised and compiled into a comprehensive study that integrates the individual contributions into a cohesive narrative.

No part of this dissertation has been copied from any other source. All research work presented in these papers was conducted by me independently. The work in this dissertation is my original contribution, and wherever external sources or prior work has been referenced, proper citations have been provided.

Signature of the Student

Abstract

Iraq faces a deepening electricity crisis, marked by chronic power shortages, reliance on diesel generators, aging grid infrastructure, and minimal integration of renewable energy. This research establishes a strategic framework for deploying hybrid microgrid systems (HMGSs) as a sustainable solution to Iraq's energy challenges. It focuses on integrating solar photovoltaic (SPV) generation, battery storage, and, where required, diesel backup in both grid-connected and stand-alone configurations, while addressing the technical, economic, regulatory, and data-related constraints that hinder renewable energy adoption. The investigation follows a five-phase methodological structure. The first phase conducts a bibliometric analysis of more than 2,300 peer-reviewed publications, mapping global trends in HMGS research and identifying a post-2016 shift toward multi-objective optimization, artificial intelligence, and distributed energy systems. The second phase introduces a modeling framework that combines mathematical evaluation, investment analysis, and optimization approaches, highlighting the growing role of AI-based tools in balancing cost, reliability, and environmental criteria. The third phase addresses Iraq's specific electricity crisis, which is exacerbated by years of conflict and inadequate infrastructure. In the absence of reliable electricity consumption data, the Rosetta time transformation technique is introduced to adapt Spanish household load profiles to Iraqi conditions, enabling realistic system modeling. Expert feedback gathered through the Delphi method supports a strategic shift from widespread use of neighborhood diesel generators toward renewable energy solutions, particularly solar-based hybrid systems. This phase incorporates both socio-economic and techno-economic evaluation to assess system viability. The results confirm that grid-connected SPV–battery systems are the most practical and sustainable option, offering favorable cost-performance and payback periods as short as 3.14 years. The fourth phase reviews global optimization techniques and software platforms used in HMGS design. It emphasizes the growing use of metaheuristic and AI-driven methods and the critical role of simulation tools in system evaluation and planning. The fifth phase presents a comparative policy and techno-economic analysis of Iraq, Saudi Arabia, and Spain, examining how Iraq can adopt effective regulatory elements from Spain's decentralized energy transition. Simulations using HOMER Pro and Iraq-specific solar data, with an average annual solar radiation of 5.539 kWh per square meter per day, show that the optimal SPV–battery configuration achieves a renewable energy fraction of 65.6 percent, a Levelized Cost of Electricity of 0.1157 dollars per kilowatt-hour, and a Net Present Cost of 30,038 dollars, with no reliance on fuel-based generators. The research is grounded in a series of peer-reviewed publications that collectively contribute to a comprehensive methodology for renewable energy planning in regions with limited infrastructure and unreliable data. Central to this approach is

the Rosetta load transformation method, which addresses the lack of electricity demand data by adapting external load profiles to local conditions. The study also presents a validated modeling framework supported by expert input and aligned with relevant policy strategies. The findings offer a practical, technically robust, and economically feasible pathway for supporting Iraq's transition to a sustainable and reliable energy system.

Resumen en español

Irak se enfrenta a una crisis eléctrica cada vez más profunda, marcada por continuos cortes de energía, la dependencia de generadores diésel, una infraestructura de red obsoleta y una integración mínima de energías renovables. Esta investigación establece un marco estratégico para la implementación de sistemas híbridos de microrredes (HMGS por sus siglas en inglés) como solución sostenible a estos desafíos energéticos de Irak. Se centra en la integración de la generación de energía solar fotovoltaica (SPV), el almacenamiento en baterías y, cuando fuere necesario, el respaldo de generadores, tanto en configuraciones conectadas a la red como en modo aislado, a la vez que aborda las limitaciones técnicas, económicas, regulatorias y de datos que dificultan la adopción de energías renovables.

La investigación sigue una estructura metodológica de cinco fases. La primera fase realiza un análisis bibliométrico de más de 2300 publicaciones revisadas por pares, barriendo las tendencias globales en la investigación sobre HMGS e identificando una transición posterior a 2016 hacia la optimización multiobjetivo, la inteligencia artificial y los sistemas de energía distribuida. La segunda fase introduce un marco de modelado que combina un análisis matemático y económico con enfoques de optimización, destacando el creciente papel de las herramientas basadas en IA para equilibrar los criterios de costo, confiabilidad y ambientales. La tercera fase aborda la crisis eléctrica específica de Irak, agravada por años de conflictos bélicos y consecuentemente unas infraestructuras inadecuadas. Además, ante la carencia absoluta de datos sobre el consumo eléctrico, hemos creado una herramienta de transformación temporal que hemos bautizado como *Rosetta*, y que proporciona datos fiables de consumo de los hogares españoles iraquíes a partir de los disponibles para los respectivos españoles, lo que permite un modelado realista del sistema de consumo iraquí. Simultáneamente, una consulta a expertos recopilada mediante el método Delphi, respalda la necesidad de un cambio estratégico desde el uso generalizado de generadores diésel locales a soluciones de energía renovable, en particular sistemas solares híbridos. Esta fase incorpora una evaluación socioeconómica y tecnoeconómica para evaluar la viabilidad del sistema resultante. Los resultados confirman que los sistemas combinados de SPV+baterías conectados a la red eléctrica, pese a sus abundantes cortes de luz, resultan ser la opción más práctica, eficiente y sostenible, con una relación calidad-precio muy favorable, con plazos de amortización desde tan solo 3,14 años.

La cuarta fase revisa las técnicas de optimización global y las plataformas de software utilizadas en el diseño de HMGS. Hacemos hincapié en el creciente uso de métodos meta-heurísticos e impulsados por IA, así como en el papel fundamental de las herramientas de simulación en la evaluación y planificación del sistema. La quinta fase presenta un análisis comparativo tecnoeconómico y de políticas en Irak, Arabia Saudí y España, examinando como Irak puede adoptar elementos

regulatorios eficaces de la transición energética descentralizada española. Simulaciones realizadas con *HOMER Pro* y datos solares específicos de Irak, con una radiación solar anual promedio de 5,539 kWh por metro cuadrado al día, muestran que la configuración óptima de SPV y baterías alcanza una fracción de energía renovable del 65,6 %, un Coste Nivelado de la Electricidad de 0,1157 dólares por kWh y un Valor Actual de 30.038 dólares, sin depender de generadores diésel. La investigación se basa en una serie de publicaciones revisadas por pares que, en conjunto, contribuyen a una metodología integral para la planificación de energías renovables en regiones con infraestructura limitada y ausencia de datos fiables. Un elemento central de nuestro enfoque es el método de transformación *Rosetta*, que aborda la falta de datos sobre la demanda de electricidad adaptando los perfiles de carga externos a las condiciones locales. El estudio también presenta un marco de modelado respaldado por aportaciones de expertos y alineado con las estrategias políticas actuales. Nuestros resultados ofrecen una vía práctica, técnicamente sólida y económicamente viable para apoyar la transición de Irak hacia un sistema energético sostenible y fiable.

Contents

1	Introduction and Methodology	1
1.1	Introduction	1
1.1.1	Background	2
1.1.2	Problem Statement	2
1.1.3	Hypothesis and Justification	3
1.1.4	Research Objectives	4
1.2	Methodology	4
1.2.1	Research Approach	5
1.2.2	Data Collection	6
1.2.3	Analytical Techniques and Tools	6
1.2.4	Scope and Limitations	7
1.3	Research Variables	7
1.4	Conceptual Framework	8
1.5	Research Contributions	10
	References of Chapter 1	10
2	Scientific mapping of optimization applied to Microgrids integrated with renewable energy systems	13
2.1	Introduction	14
2.1.1	Materials and method	18
2.1.2	SLR of bibliographic records on optimisation applied to MGs integrated with RESs	19
2.2	Bibliometric analysis: Scientific mapping and performance analysis .	20
2.3	Results and discussion	22
2.3.1	SLR of bibliographic records on optimisation applied to MGs integrated with renewable energy systems	22
2.3.2	Bibliometric analysis: Science mapping and performance analysis	25
2.3.3	Strategic diagrams	25
2.3.4	Thematic networks	30
2.3.5	Overlay graph and thematic evolution map	32

2.3.6	Performance analysis	33
2.4	Comparative analysis of case studies of optimisation applied to MGs integrated with RESs	36
2.5	Conclusions	41
	References of Chapter 2	42
3	Exploring Evolution and Trends: A bibliometric Analysis and Scientific Mapping of Multiobjective Optimization Applied to Hybrid Microgrid Systems	56
3.1	Introduction	57
3.2	Methodological Framework	60
3.2.1	First Phase: Mathematical Model of HMGSs	60
3.2.2	Second Phase: Decision-Making Tools and Investment Metrics for HMGSs	65
3.2.3	Third Phase: Bibliometric Analysis and Comparative Case Studies	67
3.3	Findings and Analysis	72
3.3.1	SLR on the Application of MOO for HMGSs	72
3.4	Bibliometric Analysis: Insights from Science Mapping and Performance Metrics	74
3.4.1	Strategic Diagrams	74
3.4.2	Thematic Networks	78
3.4.3	Graphical Overlay and the Evolution of Theme Mapping	79
3.4.4	Evaluation of Performance	81
3.5	Comparative Analysis of MOO in HMGs: Evaluating Techniques and Algorithms for Enhanced Performance and Sustainability	82
3.6	Conclusions	88
	References of Chapter 3	89
4	From diesel reliance to sustainable power in Iraq: Optimized hybrid microgrid solutions	102
4.1	Introduction	103
4.1.1	Energy profile and reliability of electricity in Iraq	108
4.2	Evaluation strategy	112
4.2.1	Socio-economic impact assessment of NDG in Iraq	112
4.3	Delphi method	112
4.3.1	Delphi process	112
4.3.2	Study design	115
4.3.3	Results and discussion	117
4.3.4	Techno-economic evaluations	119
4.4	Optimization and economic analysis	126

4.4.1	Economic baseline data	127
4.4.2	Optimal design of the SPV installation	128
4.5	Feasibility analysis	131
4.5.1	Payback period definition	132
4.5.2	Alternative energy solutions to meet demand without NDG .	133
4.5.3	Performance Evaluation and Analysis of the HMGS	136
4.5.4	Energy Management Systems	137
4.6	Conclusion	139
	References of Chapter 4	140

5 A Systematic Review and Evolutionary Analysis of the Optimization Techniques and Software Tools in Hybrid Microgrid Systems 150

5.1	Introduction	151
5.2	Systematic Review of OTs and STs	153
5.3	Optimization Techniques	154
5.3.1	Classical Techniques	154
5.3.2	Modern Optimization	159
5.4	STs for HMGS Optimization	165
5.5	Evolution of Techniques and Tools (Scopus Analysis)	169
5.6	Systematic Review Framework and Results	171
5.6.1	Problem Formulation	171
5.6.2	Database and Search String Determination	171
5.6.3	Literature Selection (PRISMA Analysis)	172
5.7	Results	175
5.7.1	Yearly Distribution of Documents	176
5.7.2	Top Contributing Countries	178
5.7.3	Top Cited Documents	179
5.7.4	Top Contributing Journals	181
5.7.5	Top Contributing Authors	183
5.8	Conclusions and Insights	184
5.8.1	Overview of Key Findings	184
5.8.2	Trends and Implications	184
5.8.3	Gaps and Opportunities	184
5.8.4	Final Takeaways	185
5.9	Conclusions	186
	References of Chapter 5	186

6 Renewable Energy Policy Assessment in Iraq, Saudi Arabia, and Spain: A Multi-Dimensional Approach Using HOMER 198

6.1	Introduction	198
-----	------------------------	-----

6.1.1	Global Renewable Energy Trends and Electricity Generation Insights	199
6.1.2	Global Electricity Demand	201
6.2	Geographical and Resource Background: A Comparative Overview .	203
6.2.1	Electricity Demand and Reliability	204
6.2.2	Energy Profiles and Policies	205
6.2.3	SPV Potential in Iraq, KSA, and Spain	208
6.3	HMGS Analysis: Iraq Optimization with HOMER	210
6.3.1	Application of HOMER for HMGS Optimization in Iraq . .	211
6.3.2	Input Data	213
6.3.3	Simulation and Optimization	219
6.4	Sensitivity Analysis	229
6.4.1	Capital Cost Impact on Case 3 Configuration	230
6.4.2	Renewable Fraction Sensitivity Analysis	231
6.4.3	Grid Reliability Sensitivity Analysis	233
6.5	Overall Insights	234
	References of Chapter 6	234
7	Conclusion and Recommendations	242
7.1	Conclusion	242
7.2	Recommendations and Suggestions	243

Chapter One

Introduction and Methodology

Introduction

This section introduces the research problem, objectives, and the significance of study.

Methodology

This section explains the research design, data collection, and analysis methods.

Chapter 1

Introduction and Methodology

1.1 Introduction

Energy is essential for social and economic progress, powering industrial growth, technological innovation, and better living standards. As economies around the world continue to grow, the demand for energy, especially in developing countries, is increasing rapidly. However, this growing need presents several challenges, including the depletion of fossil fuel reserves, escalating energy prices, and the environmental consequences of over-reliance on conventional energy sources.

Fossil fuel dependency raises both economic and ecological concerns. According to the International Energy Agency (IEA), fossil fuels still account for more than 80% of the global energy mix [1], and in the absence of major policy reforms, they are projected to remain dominant for the foreseeable future. Volatile oil and gas prices further exacerbate energy security issues, especially in countries with limited domestic production. Simultaneously, rising global temperatures, the increasing frequency of extreme weather events, and expanding carbon footprints underscore the urgent need for cleaner, more sustainable energy solutions [2]. In response to these challenges, the global energy landscape is shifting toward renewable energy sources (RESs), which offer sustainable, low-carbon alternatives to fossil fuels. Technologies such as solar, wind, hydro, and biomass are becoming increasingly viable due to technological advancements and decreasing costs. According to recent IEA reports, solar photovoltaic (SPV) has emerged as the most cost-effective form of electricity generation in many parts of the world. By 2030, RESs are projected to supply the majority of the growth in global electricity demand, significantly reducing dependence on fossil fuels [1, 3]. Iraq, like many developing countries, is experiencing severe energy challenges that hinder both economic recovery and long-term development. Despite its substantial solar and wind resource potential, particularly the more than 3,000 hours of sunshine recorded

annually in many regions, the country's energy sector remains heavily dependent on fossil fuels. This dependence contributes to high carbon emissions, ongoing electricity shortages, and limited access to reliable power across the country. To address these issues, Hybrid Energy Systems (HESs) and more specifically Hybrid Microgrid Systems (HMGS) have emerged as promising solutions. By integrating RESs such as solar and wind with energy storage and, where necessary, conventional generators, HMGS can deliver a reliable, decentralized power supply that is both cost-effective and environmentally sustainable [4, 5]. Microgrids (MGs) offer additional advantages such as increased resilience, modularity, and the ability to operate independently or in conjunction with the national grid, making them suitable for diverse operational contexts, including regions with unstable grid infrastructure. This dissertation focuses on the strategic optimization and deployment of HMGS in Iraq, aiming to explore how these systems can support energy security, rural electrification, and the country's broader energy transition goals. By leveraging Iraq's renewable potential and applying advanced optimization techniques and simulation tools, this research seeks to design economically viable, technically robust HMGS configurations that are scalable and context-specific. The findings will provide valuable insights for policymakers, planners, and engineers working toward a more resilient and sustainable energy future for Iraq.

1.1.1 Background

Iraq has long faced persistent challenges in its energy sector, including outdated infrastructure, limited electricity generation capacity, excessive dependence on fossil fuels. These challenges have been intensified by insufficient investment in modern energy systems, the impact of multiple wars, and rapid population growth. As a result, the national electricity grid frequently fails to meet demand, leading to widespread power outages and unreliable energy access. Although Iraq possesses significant fossil fuel reserves, the inefficiency and centralization of its current energy system have made it increasingly unsustainable. Fluctuating oil prices, aging infrastructure, and high operational losses continue to hamper efforts toward reliable energy provision. At the same time, the country's RESs potential, particularly in solar and wind, remains largely underutilized. This situation highlights the urgent need for innovative, decentralized, and sustainable energy solutions. In this context, HMGSs offer a promising approach to enhancing energy security, improving system performance, and supporting Iraq's long-term development goals.

1.1.2 Problem Statement

Solar energy is considered one of the most promising sources of sustainable power, especially with recent advancements in technology and significant reductions in

system costs. Despite the high potential for solar energy in Iraq, many provinces continue to face unreliable electricity supply. In areas where the power grid is absent or unstable, residents often rely on shared or private diesel generators. These generators provide limited electricity, impose high operational costs, and contribute to environmental degradation. The central research problem is the absence of a cost-effective, reliable, and technically optimized system capable of integrating RESs to address ongoing electricity shortages in Iraq. Solving this problem requires a comprehensive approach that combines local resource assessment, system design, and the application of advanced optimization techniques tailored to the technical and socio-economic context of the country. This study aims to deliver a detailed analysis of HMGS optimization and propose suitable solutions that can enhance the reliability of power supply across Iraq.

1.1.3 Hypothesis and Justification

Frequent and prolonged power outages have become a defining characteristic of the current energy crisis in Iraq. These outages disrupt daily life, strain economic productivity, and severely limit access to essential services. In the absence of reliable grid electricity, many communities resort to costly and polluting diesel generators, which offer only short-term relief and fail to meet long-term sustainability goals. This study is built on the hypothesis that optimized HMGSs, incorporating RESs and battery storage, can provide a technically viable and economically sustainable solution to the electricity reliability issues in Iraq. Through systematic evaluation of system configurations, optimization algorithms, and cost-benefit metrics, the research aims to propose solutions that address power supply challenges at both the technical and policy levels. The investigation is guided by the following research questions:

- What are the most effective strategies for reducing the cost of HMGSs designed for regions affected by frequent power outages?
- Which technical and economic parameters most significantly influence optimal system design and performance?
- What simulation tools and optimization techniques are most suitable for managing energy flow, component sizing, and cost-efficiency in HMGSs?
- How can research findings be effectively disseminated through scientific publications and presentations at international conferences?

The study will focus on system optimization, cost analysis, and energy management, particularly in the context of the evolving energy landscape in Iraq.

1.1.4 Research Objectives

Reliable access to electricity is fundamental for improving quality of life, including healthcare, education, and economic opportunities. HMGSs that integrate RESs with conventional generation offer a promising approach to mitigating power outages and improving energy resilience in Iraq. This study aims to support energy planners and technical stakeholders by identifying cost-effective and sustainable HMGS configurations adapted to local conditions. The main research objectives are:

1. Conduct a technical and economic review of HMGSs as a solution to recurring power outages in Iraq.
2. Analyze the key factors influencing optimal HMGS design, including system reliability, operating cost, and environmental performance.
3. Develop a simulation model and energy management framework for HMGSs under grid-limited or standalone scenarios.
4. Evaluate financial and economic aspects of different HMGS configurations, focusing on cost optimization for grid-tied systems.
5. Assess the availability of weather data, projected power output, and demand profiles to support accurate system modeling.
6. Review and assess multi-objective optimization methods to inform future HMGS design, while applying simulation-based optimization to evaluate feasible system configurations.
7. Recommend technically and economically viable HMGS setups to mitigate electricity shortages and enhance energy resilience.

Achieving these objectives will provide critical insight and practical guidelines for policymakers, engineers, and stakeholders involved in the Iraqi energy transition. Ultimately, this research aims to contribute significantly toward enhancing electricity reliability, economic stability, and environmental sustainability in Iraq.

1.2 Methodology

This research employs a comprehensive methodological approach to optimize HMGSs in Iraq, aiming specifically at addressing persistent power outages. The methodology integrates findings from prior studies and encompasses economic, technical, and socio-economic analyses to propose a reliable, sustainable, and context-specific solution.

1.2.1 Research Approach

A multi-method approach guides this study, structured around the following interrelated strategies:

- **Literature review and scientific mapping:**
A systematic literature review and bibliometric analysis were conducted to identify key trends, methodologies, and optimization frameworks in HMGS research. This approach ensures alignment with global advancements and identifies gaps and emerging trends.
- **Case study analysis (Iraqi context):**
Detailed analysis and evaluation of RES in Iraq, with a primary focus on solar radiation. This analysis informs the context-specific design and optimization of HMGS configurations, explicitly tailored to the technical, economic, and environmental conditions in Iraq.
- **Socio-economic analysis (Delphi method):**
Expert consensus via the Delphi method was used to assess the practicality and socio-economic acceptance of proposed HMGS solutions. This analysis provided valuable insights from local and international experts regarding deployment challenges, feasibility, and potential societal impacts.
- **System design in response to energy challenges in Iraq:**
An applied study was carried out to develop an HMGS tailored to energy conditions in Iraq. The design process incorporated expert feedback and employed the Rosetta method to adapt international load profiles to the Iraqi context. The main focus was on integrating solar photovoltaic (SPV) and battery systems as sustainable alternatives to diesel generators. Technical and economic viability was evaluated across different electricity demand scenarios.
- **Simulation and technical modeling:**
HOMER software was utilized extensively to simulate various HMGS scenarios, enabling precise modeling of system configurations. Through iterative simulations, this study identifies optimal combinations of RESs, conventional backups, and energy storage solutions.
- **Comparative policy assessment:**
The study integrates comparative analyses of energy policy frameworks in Iraq and other international contexts (e.g., Saudi Arabia, Spain), highlighting the role of regulatory environments and policy incentives in promoting effective RESs integration.

This structured approach provides comprehensive insights into the technical, economic, and socio-political dimensions critical to optimizing HMGS deployment in Iraq.

1.2.2 Data Collection

The data employed in this study encompass:

- **Primary data:**
 - Solar radiation assessments and RES evaluations specific to regions in Iraq.
 - Expert opinions and consensus findings obtained through the Delphi method to validate technical and socio-economic assumptions.
- **Secondary data:**
 - Official government reports addressing national energy strategies, infrastructure development, and environmental policies.
 - Academic literature related to HMGS optimization and renewable energy integration frameworks.
 - Real-world case studies and datasets from comparable international contexts to supplement local data limitations.

1.2.3 Analytical Techniques and Tools

This study employs a range of analytical techniques and software tools to support technical, economic, and socio-contextual analysis:

- Bibliometric analysis (SciMAT):
Applied to map thematic evolution and identify research trends related to HMGS optimization and renewable energy system development.
- Systematic literature review (Scopus database):
Conducted to evaluate and classify optimization techniques and software tools used in HMGS studies, identifying dominant methods and research gaps.
- Delphi method:
Utilized to gather expert consensus regarding technical, economic, and social aspects of HMGS deployment, and to validate critical assumptions underlying the system design.

- Rosetta method:
Implemented to adapt international electrical load profiles to Iraqi conditions, enabling accurate simulation and optimization despite the scarcity of local demand data.
- Simulation and energy modeling (HOMER software):
Used to simulate HMGS performance, conduct techno-economic analysis, evaluate system reliability, and optimize configurations under Iraqi conditions.

1.2.4 Scope and Limitations

The scope of this research includes:

- Analysis and design of HMGS configurations tailored specifically to address ongoing electricity shortages in Iraq.
- Focus on performance indicators such as cost, system reliability, renewable penetration, and environmental impact.

The primary limitations considered in this study include:

- Availability and accuracy of local renewable resource and consumption data.
- Financial and economic constraints specific to the Iraqi context.
- Modeling assumptions inherent in simulation-based research methodologies.

1.3 Research Variables

Figure 1.1 presents the model of the core research variables highlighting the relationships between RES (independent), HMGS (mediating system), optimization (mediating mechanism), and system performance (dependent variables).

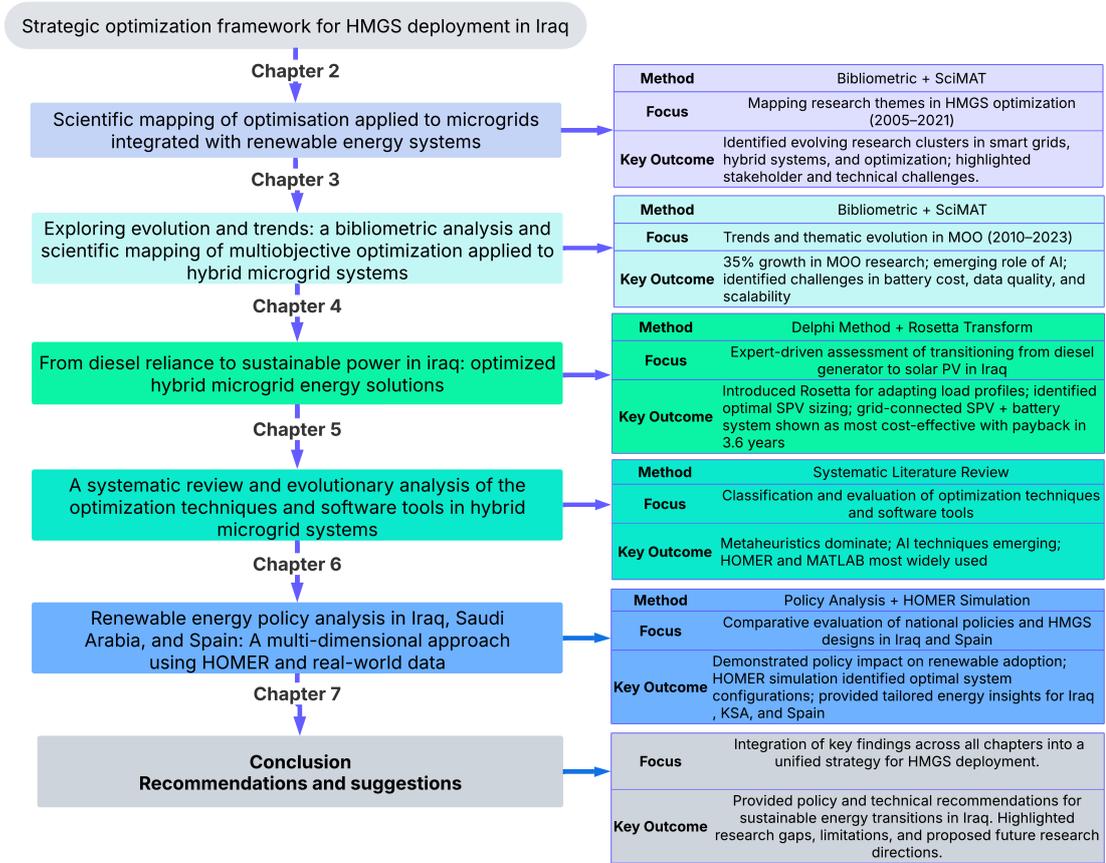


Figure 1.2: Sequential contribution of research investigations to HMGS optimization

Each chapter addresses a specific dimension of HMGS optimization, with a cumulative structure that builds toward a comprehensive strategic framework tailored to Iraq’s energy context. The research begins with a bibliometric mapping of global scientific trends (chapter 2), followed by an in-depth analysis of multi-objective optimization methods and emerging technologies (chapter 3). It then transitions to a case-specific analysis of solar photovoltaic integration in Iraq, using expert consensus and the innovative Rosetta transform to adapt foreign load profiles (chapter 4). This is complemented by a systematic evaluation of optimization techniques and simulation tools relevant to HMGS design (chapter 5). Finally, a comparative policy analysis involving Iraq, Saudi Arabia, and Spain explores the role of regulatory frameworks and national strategies in supporting renewable energy transitions (chapter 6). Collectively, these studies inform the conceptual and practical dimensions of HMGS deployment, providing a layered framework that integrates technical modeling, tool selection, and policy alignment. The structure

reflects not only academic progression but also real-world applicability to scalable, sustainable energy planning in Iraq.

1.5 Research Contributions

This research makes the following key contributions:

- Proposes a techno-economic framework for HMGSs tailored to the Iraqi energy context.
- Introduces a novel use of the Rosetta method to adapt international load profiles.
- Applies the Delphi method to incorporate expert consensus on neighborhood diesel generator (NDG) and SPV feasibility.
- Evaluates multi-objective optimization tools through simulation using HOMER Pro.
- Offers policy-relevant insights by comparing Iraqi energy planning with global best practices.

In addition to these, the study conducts a scientific mapping of the research landscape using the SciMAT tool. This bibliometric analysis traces the evolution and emerging trends in HMGS optimization research, offering a structured understanding of how the field has developed over time and where future research opportunities lie.

References for Chapter 1

- [1] International Energy Agency. Electricity 2025, 2024. Accessed on May 11, 2025.
- [2] International Energy Agency. Implementing a long-term energy policy planning process for azerbaijan: A roadmap – key elements of energy policy planning, 2024. Accessed on May 11, 2025.
- [3] International Energy Agency. Monthly electricity statistics, 2025. Accessed on May 11, 2025.
- [4] K.A. Tahir, J. Nieto, C. Díaz-López, and J. Ordóñez. From diesel reliance to sustainable power in iraq: Optimized hybrid microgrid solutions. *Renewable Energy*, 238:121905, 2025.
- [5] K.A. Tahir, M. Zamorano, and J.O. García. Scientific mapping of optimisation applied to microgrids integrated with renewable energy systems. *International Journal of Electrical Power & Energy Systems*, 145:108698, 2023.

Chapter Two

Scientific Mapping of Optimization Applied to Microgrids Integrated with Renewable Energy Systems

*This chapter is presented as a standalone research paper and forms an integral part of this doctoral dissertation. It has been published in **International Journal of Electrical Power & Energy Systems**, Volume 145, February 2023, 108698. Available at: <https://doi.org/10.1016/j.ijepes.2022.108698>.*

Chapter 2

Scientific mapping of optimization applied to Microgrids integrated with renewable energy systems

This chapter investigates research trends in the optimization of hybrid microgrid systems integrated with renewable energy sources. One of the most essential factors affecting socio-economic growth is energy. In addition to rising fuel prices, climate change has led to an interest in finding alternative sources of energy. Renewable energy sources, especially those based on hybrid systems, are very popular as alternative sources of energy. The integration of hybrid energy systems into the main grid has permitted the use of microgrids that operate in both on- and off-grid modes. The literature has paid a lot of attention to the optimisation of hybrid microgrid systems. To get useful and fair information for future research trends, this study evaluates three major themes (microgrids, renewable energy, and optimisation). Through a comprehensive evaluation of the literature on hybrid microgrid optimisation and a review based on a bibliometric analysis of 2,307 Scopus records, this work employs SciMAT software to assess the state of this research area. Additionally, hidden themes and their evolution in this area were discovered from 2005 to 2021, and strategic diagrams were made to illustrate the thematic development and performance metrics throughout the course of three time periods. The findings show that this scientific subject is constantly evolving, which is supported by the significant increase in research papers, especially in the recent five years. Since 2016, studies have mostly focused on microgrids and multi-objective optimisation. In the first period, studies concentrated on smart grids and optimisation. A trend toward employing these energy systems as an alternative to conventional grids may be seen by the rise in research publications discussing microgrids that are integrated with renewable energy sources. The utilization of microgrids still faces various challenges, the most frequent of which

are stakeholders, technical and financial challenges, and unpredictable renewable energy sources. This report provides a summary of the existing situation and identifies exciting new research opportunities.

2.1 Introduction

A reliable, affordable electricity supply is vital in today’s economies. At the same time, rising oil prices and the desire to combat climate change are reshaping energy systems worldwide. Researchers have investigated alternative fuels and other solutions due to rising oil costs, particularly following the 1973 oil crisis and the 1991 Gulf War, the restricted geographic availability of oil, and the enforcement of harsher government laws on exhaust emissions [95]. To address climate change, renewable energy sources (RESs) are crucial for supplying clean, sustainable energy. In 2020, the world generated 29% of its electricity from renewable sources, an increase of 2% from the year before [44]. In 2020, the amount of renewable electricity generated increased by 7%, with over 60% coming from wind and solar photovoltaic (PV) technologies. The third-largest renewable energy technology after onshore wind and hydropower, PV contributed 3.1% to the world’s electricity production [45].

The graph in Fig.2.1 demonstrates that the cost of wind and solar energy technologies decreased significantly from 2010 to 2020.

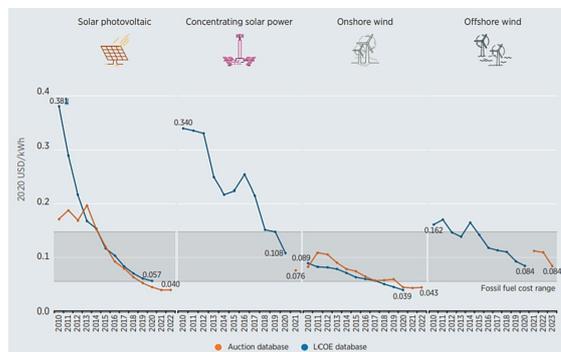


Figure 2.1: Global weighted average and power purchase agreements for solar PV, onshore wind, offshore wind, and CSP, 2010-2023 (source: IRENA Renewable Cost Database)

During this decade, the cost of PV electricity decreased by 85%, that of CSP by 68%, that of onshore wind by 56%, and that of offshore wind by 48% [47]. RESs are an important alternative energy source, but their dependence on environmental variables like solar radiation and wind speed is a problem. As a result, individual

energy sources can't provide a consistent power supply to meet demand because of their unpredictable and irregular nature. However, RESs can be combined to create hybrid systems that are more dependable and environmentally friendly[83]. Hybrid RESs (HRESs) can operate as isolated systems or can be connected to the grid and are made up of either a single source of renewable energy and/ or a single source of conventional energy, or more than one renewable source with or without conventional energy sources[57]. These types of RES are referred to as distributed energy resources (DERs), and the generation is known as distributed generation (DG) [108]. The fundamental components of HRESs are loads, AC/DC converters, and energy sources (including renewable and/ or non-renewable energy sources, as well as energy storage systems), as depicted in Fig.2.2.

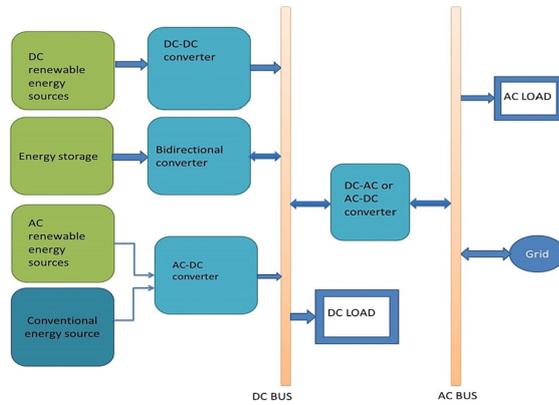


Figure 2.2: Essential elements of a hybrid energy system

Studies show that PV and wind energy combinations are becoming more prevalent because of their complementing natures [117], [32]. The fluctuation of these supplies in reaction to external circumstances is one of the major obstacles that could be overcome by the deployment of energy storage devices. The optimal size of house installations consisting of PV sources and lithium-ion batteries, and the influence of these installations on the main grid, were reviewed in [31] by de Oliveira e Silva and Hendrick. Their findings suggest that 30% of the electrical supply required for self-sufficiency may be supplied by PV alone. More than 40% self-sufficiency necessitates energy storage, which drives up the price of these facilities. To overcome the discrepancy between the electricity produced by PV systems and the demand from home appliances, Schram et al. in [93], focused on the techno-economic aspects of PV-coupled batteries in order to address the mismatch between the electricity generated by PV systems and the demand from household appliances. Sharma et al. [98] addressed the challenge of minimising the MG operation cost, and a cost-based formulation was used to identify the best battery size. A grey wolf optimisation (GWO) scheme was used to tackle

the issue under various constraints. Several studies have proposed optimisation techniques for resolving issues in renewable energy (RE) systems. Recent years have seen an upsurge in research utilizing optimisation approaches to address RES difficulties, notably with regard to solar and wind systems [37], [50]. In an HRES, a diesel power generator may be used as backup due to the unpredictability of RE supplies. The optimisation of a hybrid PV-wind-battery-diesel system, which is typically employed as a stand-alone HRES in subsequent studies, is another thoroughly researched arrangement. In order to establish the optimal design of an HRES system in an unpredictable environment, Monte Carlo simulation and simulation optimisation techniques were examined by Chang and Lin [21]. In [40], Guangqian et al. demonstrated the effectiveness of two metaheuristic algorithms, harmony search and simulated annealing, to obtain the optimum design of a stand-alone HRES. In [69], the effects of safety parameters on the reliability and cost were explored in different HRES scenarios to find the optimum design using Monte Carlo simulation. In [80], Ogunjuyigbe et al. used a genetic algorithm (GA) to implement a tri-objective design for a stand-alone HRES. The goal of this study was to lower the life cycle cost (LCC), carbon dioxide emissions, and dump energy for a typical residential complex. The authors of [87] introduced an optimisation module based on a multi-objective GA, an uncertainty module that created uncertainty scenarios using the Latin hypercube sampling method and Monte Carlo simulation, and a simulation module, which simulated the power system under the actual operating conditions. The integration of HRESs into the utility grid has paved the way for the use of microgrids (MGs). An MG offers a self-contained system made up of distributed energy resources that can operate in an islanded condition after a grid outage [126]. MGs are “electrical distribution systems that contain loads and distributed energy resources (such as distributed generators, storage devices, or controllable loads) that may function in a controlled, coordinated manner whether connected to the main grid or islanded mode” [105]. In order to maximise system reliability and minimise system costs and emissions, the design of a hybrid MG system (HMGS) takes into account a number of variables, such as component size, the mode of operation, the choice of location, and the selection of material. Investors may find RE technology more alluring because of the potential for providing reliable, affordable electricity [8], [13], [103]. The design, optimisation, operation, and control of HMGSs have been the subject of extensive research in recent years [9]. One of the aforementioned objectives, the optimisation of an HMGS, has received a lot of attention in the literature. Fig.2.3 shows a diagram of the procedures needed to describe and design an optimisation problem.



Figure 2.3: Schematic diagram of the required phases to build optimisation problem.

Although single-objective optimisation approaches have been used in the majority of studies, there has been a growing trend in recent publications to apply a multi-objective optimisation strategy. For the study's sites, the authors of [8], [13] suggested a multi-objective particle swarm optimisation (MPSO) scheme to select the optimum configuration of a PV/wind/diesel/battery HMGS and the optimal component sizes for the locations used in the study. In [53], Kharrich et al. employed three multi-objective optimisation methods, namely MOPSO, pareto envelope-based selection algorithm II (PESA II), and strength pareto evolutionary algorithm 2 (SPEA2), to design a PV/wind/diesel/battery HMGS. Dougier et al. [34] suggested an MG design to establish compromises between technological, economic, and environmental goals using a non-weighted multi-objective optimisation process based on a GA called non dominated sorting genetic algorithm II (NSGA-II). The method of analysis and the problem formulation have had an impact on the strategies used for the size optimisation of HMGSs. Due to the wide range of disciplines and approaches involved, it is therefore hard to provide a single entry point to this issue. Furthermore, obtaining useful and unbiased information for future research is challenging due to the narrow focus of this field of study and the quick evolution of its problems. Recent bibliometric analysis research on MGs have focused on topics like optimal battery energy storage systems [120], control strategies [89], and optimal energy storage system [30] algorithms [86]. Despite the fact that there are review articles on HMGs optimisation [37], [52], [96], [30], there are no bibliometric studies on this research topic. There is, thus, a need for comprehensive review to make the integration of these contributions easy and to provide critical perspectives. A bibliometric study offers a macroscopic picture of a sizable body of scientific literature [110] as well as objective standards for judging the work of researchers [78]. In 1969, Alan Pritchard developed the idea of bibliometric analysis. But bibliographic studies have been used since the nineteenth century in some fields of study [81], [88]. The two main approaches used in bibliometric analysis are performance analysis and scientific mapping. These techniques offer a visual representation of the relationships between the important disciplines, fields, particular research articles, and authors [101], and they can be used to study bibliographic material from both an objective and a quantitative perspective [4]. In this paper, the authors use a dual integrated analysis, a systematic literature review (SLR), and a science mapping analysis to examine the present body of

knowledge on optimisation research as applied to HMGSs. The current research will add to existed knowledge by analysing and highlighting trends and pattern in optimisation research, distinguishing research subjects, identifying potential research fields by mapping researcher networks. To accomplish this, the following specific goals were established: (i) a quantitative analysis based on a systematic review of the literature (SLR); (ii) a bibliometric analysis based on performance analysis and science mapping; and (iii) a comparative analysis of case studies of optimisation applied to MGs integrated with RESs.

2.1.1 Materials and method

Using a dual integrated analysis, the study’s objectives were achieved (Fig. 2.4).

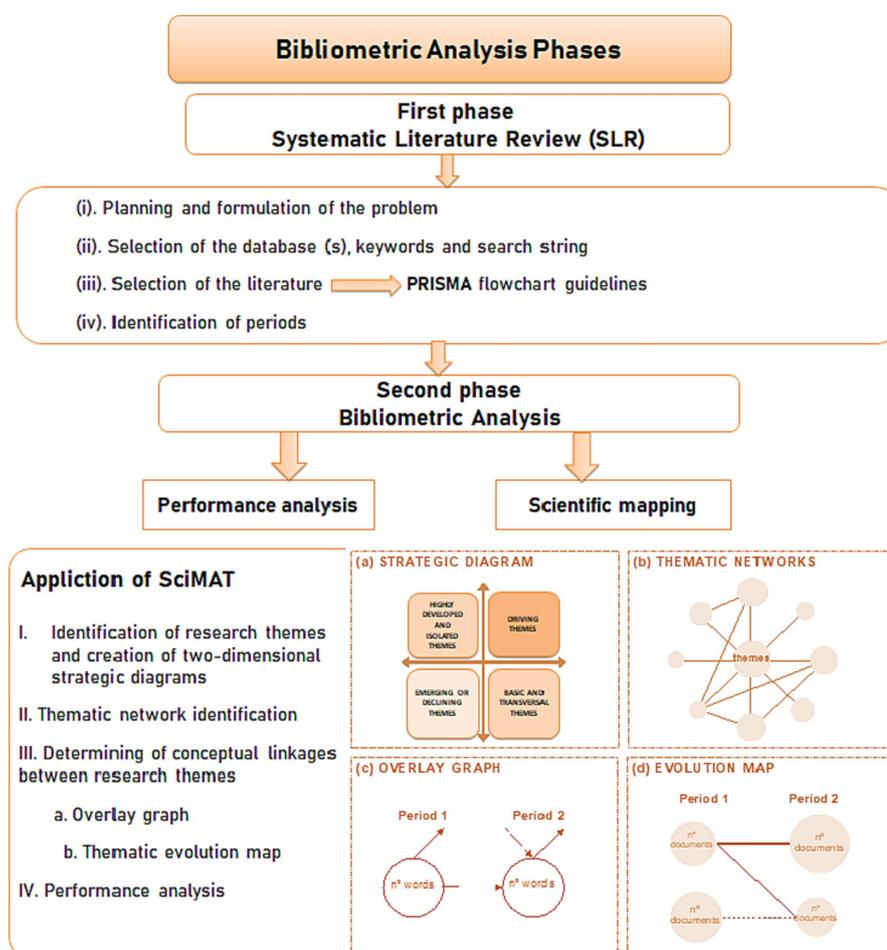


Figure 2.4: Flowchart of bibliometric analysis phases.

The following actions were taken during this analysis: (i) a systematic literature

review (SLR) of bibliographic records of optimisation as applied to MGs integrated with RESs; and (ii) a bibliometrics analysis based on performance analysis and science mapping. The following sections go into further depth about each of these phases.

2.1.2 SLR of bibliographic records on optimisation applied to MGs integrated with RESs

In this part, the authors describe how they searched the pertinent corpus of literature using simple, understandable search options and predetermined selection criteria. A systematic approach known as an SLR adheres to pre-established qualifying criteria while incorporating all relevant evidence [11]. This method reveals the gaps, lessens study bias, and generates reliable data from which judgments can be made [5]. An SLR adheres to a protocol that specifies the search string, approach, exclusion standards, and data extraction techniques [71]. As a result, some authors have utilized SLRs in their studies and the numerous procedures necessary to create a reproducible, scientific, and transparent research process [11], [92], [104], [41], [12], [90]. This paper's SLR is based on the suggestions in [55] (Fig.2.4), which were gathered utilizing the stages below:

- (i) **Planning and formulation of the problem:** In this section, the research questions are chosen in accordance with the objectives, the criteria and procedures used to select the acceptable bibliographic records, the system for rejecting results that are not relevant, and the anticipated outcomes.
- (ii) **Selection of the database(s), keywords and search string:** This stage identifies the bibliographic database(s), keywords, and search term. Determining the keywords and using the right search term are crucial. The list of keywords should be extensive enough to include a variety of studies, yet sufficiently constrained to only identify publications that are pertinent to the subject.
- (iii) **Selection of the literature:** In this stage, The PRISMA (reporting systematic reviews and meta-analysis) flowchart's instructions are followed for choosing the publications that are pertinent to the study's subject [61]. The information required to accomplish the study's objectives is found in papers that are relevant.
- (iv) **Identification of periods:** This decision is relied on several elements, the most crucial of which are the elements and variables of the study, the number of research studies about such topic, and the changes happening in this scope.

2.2 Bibliometric analysis: Scientific mapping and performance analysis

In the second stage, a bibliometric analysis is achieved after applying the SLR in the first stage. It has two combined analysis: it includes a performance analysis and a scientific mapping. The performance analysis evaluates the impact of citations on scientific outputs, whereas the scientific mapping extracts the conceptual and intellectual structure of the research in this area, its evolution, and dynamic aspects. The aim of a bibliometric analysis is to represent the relationships between various specialisations, disciplines, documents, individual authors, and documents. A bibliometric analysis is carried out in this work using the Scientific Mapping Analysis Software Tool (SciMAT v1.1.04). SciMAT relies on a mutual word analysis [16] and the h-index [43]. The h-index, which is based mostly on the number of studies and citations of a given researcher's output, can be used to assess the quality of a publication. Hirsch [70] defined the h-index as follows: "A scientist has index h if h of his or her number of published (N_p) papers have at least h citations each and the other ($N_p - h$) papers have at most $\leq h$ citations each". From pre-processing to presenting the results of the scientific mapping, SciMAT offers methodologies, algorithms, and measurements for each step of a typical scientific mapping workflow [25, 79]. Construction, urban planning, waste management, energy, and information technology are only a few of the fields in which this program has been successfully used [6, 17, 18, 29, 33, 38, 54, 64, 65, 91, 97, 116]. The workflow of this tool is based on the following phases.

I. Identification of research themes and creation of two-dimensional strategic diagrams

The software initially creates an equivalence index [15], before using the single-centre approach [28] to identify the topics that are the most pertinent. A strategic strategy is then created for each phase. The centrality and density concepts [15] provide the foundation for the diagrams. The relationship between the main study issue and related research topics is crucial. According to density, which is used to gauge the topic's level of development, the internal coherence of all relationships among the terms that define a topic is measured [25, 70]. In order to illustrate the four different categories of study topics, the diagrams are divided into four quadrants (Fig.2.4):

- **Driving themes:** These are well-developed and crucial issues in the scientific discipline, located in the upper right quadrant. High density and strong

centrality are characteristics of the themes that are essential to the growth of the study field.

- **Highly developed and isolated themes:** These are topics that are distinct from the other themes but are internally very well developed. They are displayed in the upper left quadrant and are specialized themes in ancillary areas of the research field.
- **Emerging or declining themes:** These are concepts that lack development and relevance and are displayed in the lower-left quadrant. They could gain importance or lose it. This will be decided in the following time frame.
- **Basic and transversal themes:** These themes are major to the research field, but aren't fully formed yet. They can be seen in the lower right-hand corner of the quadrant.

II. Thematic network identification

These are used to supplement the strategic diagrams and examine the links and linkages between the topics and keywords in the strategic diagrams. According to Fig.2.4, each thematic network is given a name that corresponds to the theme's most crucial term. Here, several keywords are linked; the size of the circle is related to the number of documents that correspond to each keyword, and the thickness of the link between two circles is proportional to the equivalence index.

III. Determining conceptual linkages between research themes

The inclusion index [33] pinpoints conceptual relationships between research themes throughout various eras. The firmness of association between themes is also determined. The following two kinds of graphs are utilized (Fig.2.3):

- **Overlay graph:** In the overlay graph, the quantity of words shared between the two periods is indicated by a horizontal arrow. The upper arriving arrow indicates the number of new words in the second period, while the upper outgoing arrow indicates the number of words that vanish in this time.
- **Thematic evolution map:** A thematic evolution map shows that the linked theme and the primary item are connected by solid lines. A dotted line denotes that the themes share non-main item elements. The volume

of each sphere is proportional to the number of published documents, and the thickness of each edge is proportional to the inclusion index.

IV. Performance analysis:

Both quantitative and qualitative standards are used to the proportional contribution of study participants to the overall research field. It's also utilized to state the most productive, notable and high effect subfields utilizing bibliometric indicators, such as, the number of published citations, articles and various kinds of h-index.

2.3 Results and discussion

The outcomes of the steps are described in the previous section and are analysed in Figs. 2.4–2.9 and Tables 2.1–2.5.

2.3.1 SLR of bibliographic records on optimisation applied to MGs integrated with renewable energy systems

This work aims at examining the present state of knowledge on the optimisation of HMGSs. To perform this goal, the following research questions (RQ) were established:

- **RQ1:** What is the present state of research in this scope?
- **RQ2:** What are the key concepts that define the research field?
- **RQ3:** What are the present issues in this field of research?
- **RQ4:** What are the most turning points and pressing concerns in terms of the research subject?
- **RQ5:** What are the most pressing concerns in the field?
- **RQ6:** What are the limitations of existing research?
- **RQ7:** What are the most influential works in this area of research?
- **RQ8:** Who are the most productive authors in the research area?

This inquiry made use of the SCOPUS database. This database contains a large number of high-impact scientific and technological publications written by scholars from all over the world who specialize in various fields. MGs, renewable energy,

and optimisation were the three main areas on which the review was centered. The following keywords were then applied to each topic using an advanced search of SCOPUS.

Finally, an advanced search of SCOPUS was conducted, and the following keywords were assigned to each topic.

The structure of the search was as follows:

“microgrid” AND “renewable energy” OR “hybrid energy”) AND TITLEABS-KEY (“optimization” OR “optimisation” OR “techno economic evaluation”) AND (EXCLUDE (DOCTYPE, “bk”) OR EXCLUDE (DOCTYPE, “ed”) OR EXCLUDE (DOCTYPE, “tb”) OR EXCLUDE (DOCTYPE, “Undefined”) OR EXCLUDE (DOCTYPE, “ch”) AND (EXCLUDE (SUBJAREA, “MEDI”) OR EXCLUDE (SUBJAREA, “BIOC”) OR EXCLUDE (SUBJAREA, “NEUR”) OR EXCLUDE (SUBJAREA, “ARTS”) OR EXCLUDE (SUBJAREA, “IMMU”) OR EXCLUDE (SUBJAREA, “PHAR”)) AND (EXCLUDE (PUBYEAR, 2022)) AND (LIMIT-TO (LANGUAGE, “English”)) AND (EXCLUDE (LANGUAGE, “Chinese”) OR EXCLUDE (LANGUAGE, “Japanese”))

From the Scopus database, 2,667 bibliographic records were retrieved using a procedure based on the PRISMA flowchart. 333 records were removed altogether after the exclusion criteria were applied (only article papers, entire documents connected to the research topic, and materials in English were considered). The title, abstract, and keywords were used to further screen the remaining 2,334 results and a further 25 records were omitted as they did not evoke to the themes of the review. After the final elimination process, 2,307 relevant papers remained for the study (Fig.2.5).

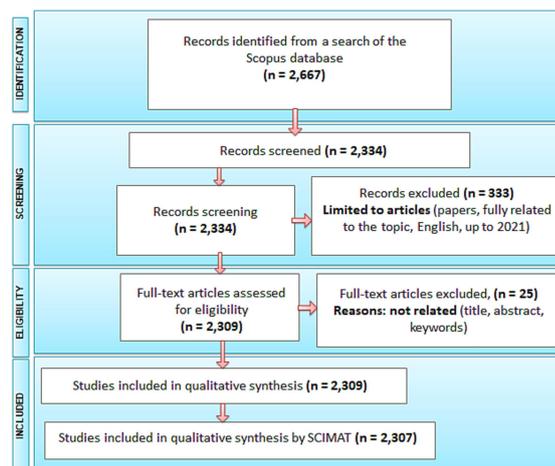


Figure 2.5: PRISMA flowchart.

In order to investigate trends in publication patterns, a time window of 2005-2021 was employed, which was divided into three periods depending on the number of papers selected and the pertinent milestones:

First period (2005-2011): 66 papers. The US Department of Energy (DOE) organized the first workshop around this time to determine potential areas for MG research and development. The price of PV modules dropped dramatically throughout that time period. In 2011, the minimal cost per watt dropped below \$1.

Second period (2012-2015): 290 papers. 2015 saw a number of occasions that promoted the growth of renewable energy, including the approval of the United Nations Development Goals (SDGs) (2015) and the Paris Conference of the Parties. In terms of the SDGs, target 7.2 of goal 7 (affordable and clean energy) [2]. The major goal of the Paris Climate Conference (COP) was to improve the global response to the threat of climate change by keeping global temperature increases well below the limit of 2°C above pre-industrial levels in this century. Generating energy from renewable sources was a critical factor in achieving this aim.

Third period (2016-2021): 1,951 In 2016, the price per watt of solar panels dropped significantly, as shown in Fig.2.1. Over this time, there was also an upsurge in research. The need to combat climate change and prevent growing dependent on fossil fuels, which has become a geostrategic threat, is likely to cause RE output to increase in the next years. Fig. 2.6 depicts the time distribution of the final 2,307 publications.

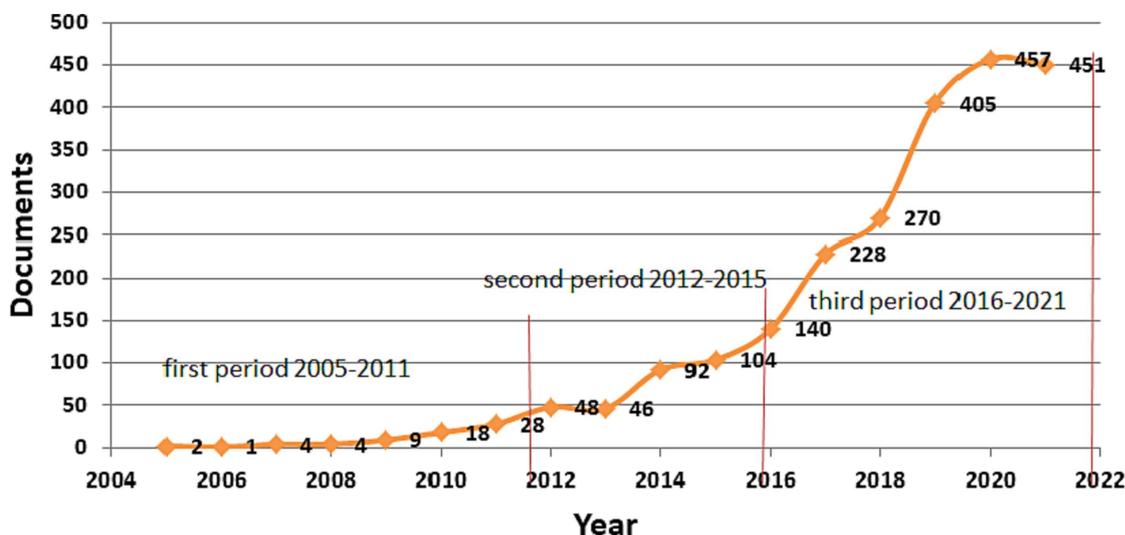


Figure 2.6: Number of documents per year.

The exponential increase in the number of related articles shows that this field is continually growing, and will continue to grow in the coming years. The

number of research articles in which optimisation approaches are applied to solve the challenges of HMGS has risen considerably since 2005, indicating a definite increase in research interest in this area. The number of research articles also rose considerably after 2016, particularly for wind and solar energy systems, coinciding with the adoption of the SDGs, the COP, and DOE workshops. Some of these optimisation methods were based on traditional techniques, and some researchers have successfully tackled multi-objective problems involving RESs.

2.3.2 Bibliometric analysis: Science mapping and performance analysis

The following graphs are analysed and discussed in this section: strategic diagrams (one for each period); critical thematic networks; an overlay graph; and a thematic evolution map. In addition, the evolution of the time horizon for the documents, the number of citations, the most cited authors, and the publications themselves are numerically and qualitatively examined.

2.3.3 Strategic diagrams

Three strategic diagrams were made for the three time periods under consideration (2005-2011, 2012-2015, and 2016-2021) (see Fig. 2.7), where the size of the circle represents the number of papers linked to each research topic that have been published. The performance measurements for each topic and time period are shown in Table 2.1 in terms of the quantity of documents, the h-index, the centrality and density values, and the number of documents. Below is a breakdown of the results for each time period.

- **First period (2005-2011):** Thirteen research themes were identified in the 66 papers selected in this period, according to the strategic diagram shown in Fig. 7a. Four were identified as driving themes (controllers, investment, diesel generators, and optimal control). Three were identified as highly developed and isolated themes (power systems, particle swarm optimisation, and linear programming). Three were identified as emerging or declining themes (storage, energy storage, and distribution networks), and three were identified as basic themes (smart grids, optimisation, and PV). A performance analysis for each theme, as shown in Table 1, added to the information supplied by the diagram, and it can be seen that the themes of smart grids and optimisation had the highest performance measurements. These themes had higher values for the h-index than the others, since they had more than 6,000 citations.

- **Second period (2012-2015):** The strategic diagram in Fig.2.7b shows that nine research themes were found from the 290 papers for this period. Two were considered driving themes (MGs and distributed energy resources), three were considered highly developed and isolated themes (grid-connected modes, electric vehicles, and stochastic models), one was an emerging or declining theme (controllers), and three were basic themes (power generation, distributed energy generation, and energy storage systems). Two themes stood out based on the performance measures (Table 2.1), which were MGs and distributed energy resources. These research topics had higher values for the impact rate and h-index than the others.
- **Third period (2016-2021):** Eleven research themes were observed in the 1,951 publications selected for this period, according to the strategy diagram shown in Fig. 2.7c. Two were identified as driving themes (MGs and fossil fuels), four as highly developed and isolated themes (power markets, distribution systems, virtual power plants (VPPs), and neural networks), one as an emerging or declining theme (controllers), and four as basic themes (wind turbines, multi-objective optimisation, stochastic models, and smart grids). Three themes were highlighted based on the performance measures (Table 2.1): MGs, smart grids, and optimisation. These topics had higher values for the h-index and impact rate than the others.

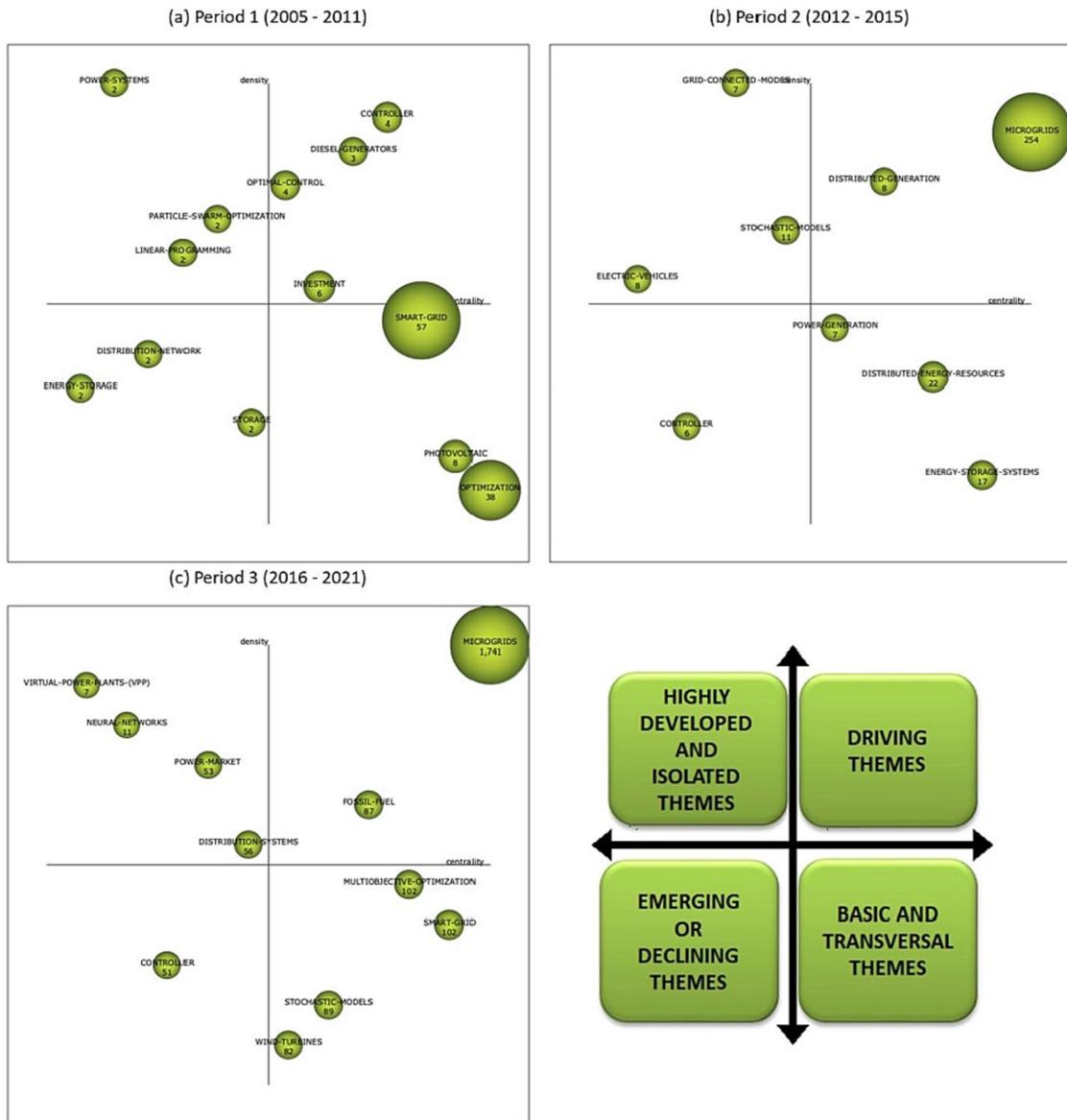


Figure 2.7: Strategic diagrams for (a) period 1; (b) period 2; (c) period 3.

Three periods were set up for the three main themes that the study aims to assess (MGs, RES, and optimisation), and the results of the three strategic diagrams are in Table 2.1. Table 2.2 shows a comparative study of the findings of the strategic diagrams for the three periods. The articles that received the most citations during the first period [14, 20, 24, 102, 106, 119] dealt with the subject of control, optimal control and optimisation.

Table 2.1: Performance measures for each theme.

Period 1 (2005–2011)	No. of documents	h-index	No. of citations	Centrality	Density
Controller	4	4	437	168.45	128.33
Investment	6	5	160	115.35	70.6
Diesel-generators	3	3	87	124.16	118.75
Smart-grid	57	25	3,458	212.45	62.32
Optimal-control	4	4	362	104.97	113.13
Optimization	38	22	2,870	278.66	18
Photovoltaic	8	6	247	219.47	29.86
Power-systems	2	2	20	22.83	231.25
Particleswarmoptimization	2	2	95	71.13	93.06
Distribution network	2	2	18	32.22	52.78
Linear programming	2	2	95	35.1	83.33
Energy-storage	2	2	26	20.1	45.83
Storage	2	2	94	75.61	37.5
Period 2 (2012–2015)					
Microgrids	254	57	11,066	145.19	51.48
Distributed energy resources	22	14	1,487	35.71	7.67
Energy-storage systems	17	9	471	40.35	5.45
Stochastic-models	11	4	281	12.67	14.38
Power-generation	7	6	684	24.57	8.07
Distributed generation	8	7	547	27.85	30.54
Grid-connected modes	7	4	176	12.47	84
Electric-vehicles	8	6	504	10.2	10.29
Controller	6	4	489	10.82	6.07
Period 3 (2016–2021)					
Microgrids	1,741	73	24,354	131.4	45.83
Controller	51	12	517	9.64	2.81
Smart-grid	102	32	3,094	29.61	2.88
Fossil-fuel	87	23	1,739	26.79	4.15
Power-market	53	14	987	17.69	4.49
Stochastic-models	89	24	1,707	25.27	2.34
Multiobjective optimization	102	21	1,773	28.06	3.05
Wind-turbines	82	23	1,779	21.15	1.93
Distribution systems	56	18	1,156	18.34	3.69
Virtual-power plants (VPP)	7	4	93	5.28	22.59
Neural-networks	11	6	117	7.88	7.52

Reference [14] discusses the use of power electronic converters and their contributions to achieve controllable, reliable, sizeable, and efficient systems, particularly with the use of RES. A bidirectional converter is used as an energy control centre for a DC nanogrid in a presumption sustainable house. Given the volume of citations and the number of documents covering them, the second period saw considerable interest in the issues of MGs and distributed-energy-resources. It should be emphasized that the majority of the highly cited studies [22, 23, 27, 51, 60, 74, 122, 123] covered the optimisation of HMGSs' technical, economic, and environmental aspects. To execute the economic analysis and define optimal operation using the CPLEX solver on the GAME platform, a hybrid PV-WT-battery MG is proposed in ref. [23].

Table 2.2: A comparative study of the findings of the strategic diagrams for the three periods.

Comparative based on	First period (2005–2011)	Second period (2012–2015)	Third period (2016–2021)
1. Research themes and the number of publications	From 66 papers, 13 research themes recognized	In 290 papers, 9 research themes were observed	1,951 papers contained information on 11 research themes. Most articles were published over this time period, demonstrating the significance of the subject and its ongoing progress
2. The highlighted themes	The themes of smart grid and optimisation discussed in a large number of documents	Given the volume of citations and the number of articles addressing MGs and Distributed-energy-resources themes, substantial attention was paid to these areas	The driving themes have been recognized as MG and fossil fuels. The findings reveal a strong bias in the volume of citations and articles addressing MG
3. The emergence of themes (MG, RESs, and Optimisation)	MGs theme does not emerge in this period while the other major themes and its hidden related topic like optimisation (Linear programming, PSO) and hybrid energy (DG, PV, storage, energy-storage) are emphasized	MGs and Distributed-energy-resources have focused as driving themes. It should be noted here that this period was the beginning of the focus on utilizing MGs	The themes (MGs and Multiobjective optimisation) have received high attention since they were one of the results and findings of the DOE workshop in 2011, which suggested the development of multiobjective optimisation and utilizing it as a tool for economic and design analysis of Microgrid [105]
4. High cited documents	The documents with more than 100 citation [14, 20, 24, 102, 106, 119] focused on optimisation, optimal control, and controller	The articles [22, 23, 27, 51, 60, 74, 122, 123] with the most citations examined HMGS' technological, economic, and environmental aspects	In this period, the various aspects of evaluating HMGS, including feasibility, environmental impact, sizing, and technicalities, as well as the usage and development of various optimisation approaches, were discussed.

Stochastic dynamic programming technique was utilized to minimise the cost of PV- WT- DG- battery HMGS in [76]. Using an artificial bee colony (ABC), the optimal PV-WT-biomass-storage HMG size was reported in [100]. For combining demand response management and thermal comfort optimisation in MG integrated with RES and energy storage, a novel control method was developed in [56]. In order to design a hybrid RES microgrid, the optimal type, size, and loca-

tion of DERs were examined in [27]. The Distributed Energy Resources Customer Adoption Model (DER-CAM) was then used to determine the best configuration and location, as well as the financial advantages of deploying these systems. According to the information presented above, optimisation can be applied to every component of HMGs, including the power market [115], energy management for DERs integrated with MG [39], and optimal controller for virtual power plant integrated with MG [1]. The strategy diagram shows new topics that show the study field’s current direction during the previous five years, such as using a neural network to solve an optimisation problem [42, 72, 111] and using multi-objective optimisation as a tool to assess HMGs [53, 107]. It should be noted that the areas of optimisation applied to HMGs have been roughly divided into three categories: generation, control, and distribution.

2.3.4 Thematic networks

In this section, three thematic networks, one for each period, were developed to enable further exploration of the relevant subjects and future trends based on their saliency. Advanced, fundamental, and emerging research are all captured by these networks across time. Fig. 2.8 shows the relationships between the themes (circles), where each circle’s size corresponds to the number of documents and each line’s thickness to the strength of the connection between two nodes. Below is a breakdown of the outcomes for each time period.

In the first period, it was noted that the keyword “smart grids” was closely related to other keywords like “MGs,” “renewable energy,” “energy management,” and “emission control.” These are all interconnected in some way. According to the International Energy Agency (IEA), a smart grid is defined as follows: “A smart grid is an electricity network that uses digital and other advanced technologies to monitor and regulate the transportation of electricity from all sources of generation in order to satisfy the various electricity needs of end users. In order to operate every component of the system as efficiently as possible, smart grids coordinate the needs and capabilities of all generators, grid operators, end users, and electricity market stakeholders,” minimising costs and environmental impacts while maximising system reliability, resilience, and stability [46].

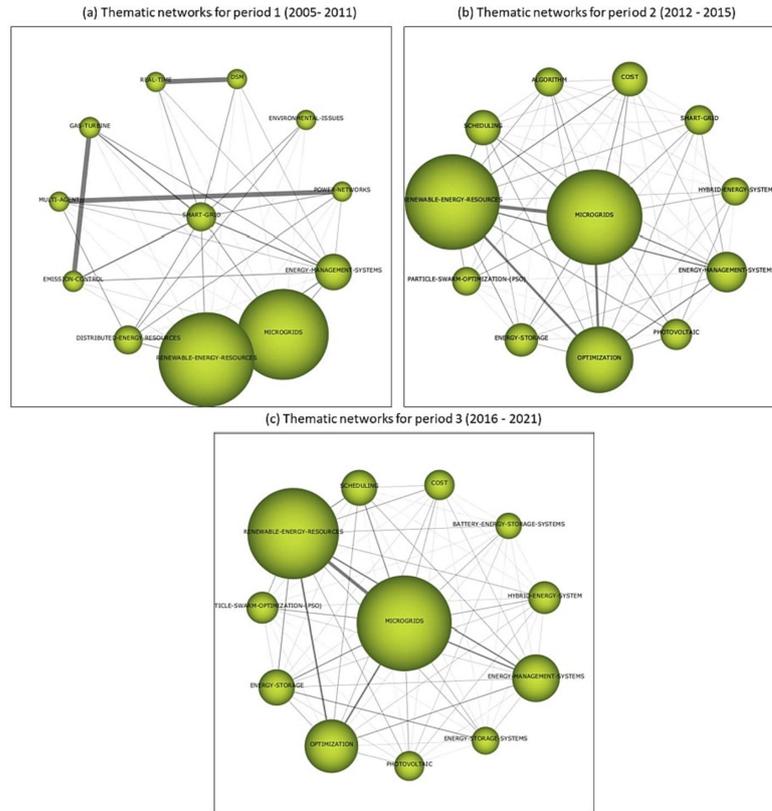


Figure 2.8: Thematic networks for (a) period 1; (b) period 2; (c) period 3.

In order to increase the system's energy efficiency, improve power quality and stability, and give individual end-user locations the option of grid independence, MGs have been cited as a crucial component of a smart grid [105]. Energy management of the MG is essential to enable the most effective use of these resources in a dependable, secure, and coordinated way since the MG is a major component and permits the use of DERs as a source of energy. The theme of MGs emerges as the most significant over these periods based on these networks, as seen in Fig. 2.8b and c, which depict the thematic networks for the second and third periods. Throughout these periods, the theme of MGs is closely related to concepts like RE resources, optimisation, energy management, solar, and energy storage. These are all intimately related to one another and have recently been the focus of many research studies. Based on the aforementioned findings, it is concluded that although the idea and the initial MG tests date back to the 1980 s, these have only recently begun to move from the experimental stage to the commercialisation stage, with pilot projects emerging worldwide [103]. The effectiveness of MG systems has been assessed using a range of performance models, indicators, tools, and optimisation techniques. The significance of the MG system has recently been

recognized in a number of study papers. Most documents over the preceding ten years concentrated on the topics of smart grids, optimisation, and PV, while the top authors were interested in the RE investment aspects. Since 2012, there has been significant interest in resolving the problems with RE through the utilization of optimisation tools, and interest has also concentrated on the development of MGs. In the latest research, the concept of multiobjective optimisation has drawn the most interest from researchers. The most intriguing research fields in relation to renewable and sustainable energy MGs are those using heuristic methods, particularly genetic algorithms, particle swarm optimisation, Pareto-based multiobjective optimisation, and parallel processing.

2.3.5 Overlay graph and thematic evolution map

The number of outgoing and incoming keywords, the number and evolution of keywords for each period, the number and percentage of keywords that were maintained from one period to the next are all shown in Fig. 2.9a. Between the first and last periods, there were 406% more keywords, going from 138 to 699. Of the 138 keywords that appeared in the first period, 75% (104) were maintained in the second period, and 185 words were added, to give a total of 289. In the third period, 263 words (91%) were maintained from the second period and 406 new words were added, giving a total of 699 words. According to these findings, there are a lot of new and transitional keywords, and the number of keywords used in different times has grown. The fact that the research field of MG assessment is growing more thematically diverse and that certain keywords have come back stronger in future periods may be signs that this relatively new research subject is becoming normalizing. Based on an examination of the roots of the topics and their interrelationships, Fig. 2.9b depicts the thematic progression of the research field. When the graph is examined in terms of the number of articles, it is clear that the first period saw the emergence of the theme of smart grids, which had the biggest number of publications. From there, the themes of MGs, distributed energy resources and DG during the second period. The transition from conventional energy grids to smart grids is the result of growing concerns about the effectiveness, reliability, economics, and sustainability of electricity production and distribution [58]. In order to fulfil the rising demand for energy, minimise environmental pollution, and provide social and economic benefits in terms of sustainable development, RE resources are currently being used on a wide scale. The integration of these distributed energy sources into the utility grid paves the way for MGs [126]. The MG, which has both on-grid and off-grid modes of operation, is a novel approach to integrating RESs into a DG system [24].

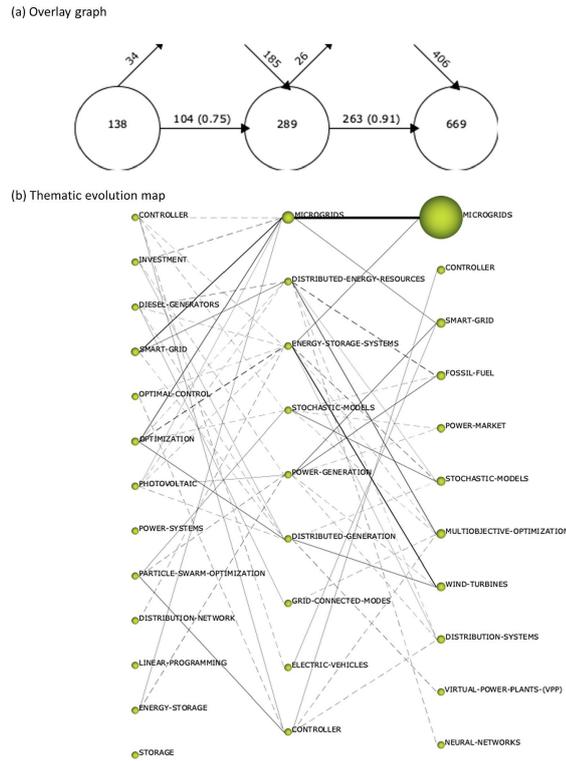


Figure 2.9: (a) Overlay graph and (b) thematic evolution map.

The idea of an MG was developed to enable a self-sufficient system made up of distributed energy resources that could function in off-grid mode throughout a grid outage failure [126]. The most popular topic for papers in the second period, MGs, later became MGs and smart grids in the third period. In order to enhance power quality and reliability, raise system energy efficiency, and provide grid independence for specific end-user sites, MGs were recognized as a crucial part of smart grids. The promotion of the integration of distributed and RE resources is one of the key advantages of MGs. By identifying generation sources that are close to the demand, securing energy supplies for critical loads, maintaining local control over the quality and reliability of power, and promoting consumer involvement in the electricity supply through demand-side management, this can help to reduce peak loads and losses [105].

2.3.6 Performance analysis

951 journals were found in this study, with the majority of them concentrating on energy usage and RE, energy management and operation of MGs, improvement and optimisation of MG technologies, and technical, environmental, and economic

evaluations of MGs. Table 3 displays the top ten research journals that contributed with (581) articles, or 25.18% of the total number of documents analysed, and is sorted by the number of citations.

Table 2.3: Prominent journals contributing to the research field.

Name	No. of articles	No. of citation indexes	No. of citations	Ref.
Applied Energy	87	4791	349	[126]
IEEE Transactions on Smart Grid Energy	58	4489	355	[10]
Energy	63	2451	193	[77]
IEEE Transactions on Sustainable Energy	30	1823	510	[123]
International Journal of Electrical Power and Energy Systems	60	1477	126	[60]
Energy Conversion and Management	26	1406	240	[122]
Energies	127	1336	130	[59]
Renewable Energy	26	1102	209	[84]
IEEE Access	80	898	88	[99]
IET Generation, Transmission and Distribution	24	594	139	[98]

In Table 6.3, the most cited article for each journal is also shown. There is no correlation between the number of research papers published and the number of citations, therefore the journals with the most published research studies are not necessarily the most significant in the area in terms of the number of citations, as shown in Table 6.3. The systematic literature review of this study allowed us to identify 5,135 authors who had published articles on the topic under study. According to the total number of published documents, Table 4 lists authors with more than 10 studies that have been published. Additionally, it contains the number of citations obtained and the h-index (Hirsch index), which gauges an author’s professional caliber based on how frequently their academic works are cited [94].

Table 2.4: Main authors contributing to the research field.

Name	No. of documents	Total citations	h-index	Most cited document	Ref.
Guerrero, J.M.	35	1350	105	Microgrids: Experiences, barriers and success factors	[103]
Wang, J.	35	795	80	Decentralized energy management system for networked microgrids in grid-connected and islanded modes	[114]
Wang, X.	35	500	6	Energy management of multiple microgrids based on a system of systems architecture	[124]
Zhang, Y.	31	820	9	Robust energy management for microgrids with high-penetration renewables	[123]
Liu, Y.	28	525	16	Distributed robust energy management of a multimicrogrid system in the real-time energy market	[63]

Name	No. of documents	Total citations	h-index	Most cited document	Ref.
Xu, Y.	28	739	45	A two-layer energy management system for microgrids with hybrid energy storage considering degradation costs	[48]
Zhang, J.	27	400	45	Short-term photovoltaic solar power forecasting using a hybrid wavelet-PSO-SVM model	[36]
Wang, Y.	27	193	15	Optimal operation of microgrid with multi-energy complementary based on moth flame optimization algorithm	[112]
Li, Z.	26	406	6	A two-stage optimization and control for CCHP microgrid energy management	[67]
Wang, L.	25	640	11	Robust optimization for energy transactions in multi-microgrids under uncertainty	[121]

According to our research, Guerrero, J.M., who published 35 documents on the subject of optimisation of MG integrated with RE resources, had the highest citation count and h-index. Wang, J. and Wang, X had the same number of documents as the first author, and the majority of those documents were published solving optimisation problems based on the economic, technical, and environmental issues related with the use of MGs.

The systematic literature review ended with a study of the most frequently cited documents. 40,950 citations were made to the 2,307 documents that were examined for the review. The 10 publications with the most citations are listed in Table 2.5, totaling 4,243, or 10.36% of all citations. These publications covered a variety of topics, including the development and assessment of MGs, the utilization of RE resources, and the presenting of optimisation techniques for MGs' operational and financial performance.

Table 2.5: Most frequently cited documents.

Title	Author(s)	Year	No. of citations	Ref.
Centralized control for optimizing microgrids operation	Hatziargyriou, N.D., Tsikalakis, A.G.	2008	797	[106]
Robust energy management for microgrids with high-penetration renewables	Zhang, Y., Giannakis, G.B., Gatsis, N.	2013	510	[123]
Future electronic power distribution systems-a contemplative view	Boroyevich, D., Cvetković, I., Dong, D., Burgos, R., Wang, F., Lee, F.	2010	481	[14]
Multiobjective intelligent energy management for a microgrid	Chaouachi, A., Kamel, R.M., Andoulsi, R., Na- gasaka, K.	2013	471	[22]
Optimization in microgrids with hybrid energy systems-A review	Fathima, A.H., Palanisamy, K.	2015	380	[37]
Intelligent frequency control in an AC microgrid: Online PSO-based fuzzy tuning approach	Mitani, Y., Bevrani, H., Habibi, F., Babahajyani, P., Watanabe, M.	2012	355	[10]
Distributed intelligent energy management system for a single-phase high-frequency AC microgrid	Chakraborty, S., Weiss, M.D., Simoes, M.G.	2007	351	[20]
Microgrids energy management systems: A critical review on methods, solutions, and prospects	Zia, M.F., Elbouchikhi, E., Benbouzid, M.	2018	349	[126]
Optimal bidding strategy for microgrids considering renewable energy and building thermal dynamics	Nguyen, D.T., Le, L.B.	2014	276	[75]
Control methods of inverter-interfaced distributed generators in a microgrid system	Liu, W., Chung, I.-Y., Cartes, D.A., Collins Jr., E.G., Moon, S.-I	2010	273	[24]

2.4 Comparative analysis of case studies of optimisation applied to MGs integrated with RESs

An analysis was carried out for the relevant SLR documents and a comparison of case studies on optimisation applied to HMGS. Hybrid energy sources are becoming more and more common in light of the current energy situation and environmental issues. This study addressed the significant advancements in research surrounding the usage of MGs integrated with RESs and the application of optimisation approaches to address issues related to the utilization of these resources. Artificial intelligence (AI) can be utilized to optimise the technical and financial components of these systems, as evidenced by the current trend in HMGSs optimisation. MGs vary greatly depending in terms of their location, components, and the aims of optimisation, which leads to a range of challenges and barriers. Four categories of the most frequent hurdles have been determined: technological, regulatory, financial, and stakeholder constraints [103]. Research on using optimisation approaches to identify the solutions for HMGSs is listed in Table 6; the studies were chosen based on the number of citations. The goal of optimisation, as described by Nguyen and Le in [75], was to strike a balance between maximising the expected

benefits of the MG in the liberalized electricity market and minimising operating costs while taking into account the users' needs for thermal comfort and other system constraints. A compact standalone PV-wind-biomass-battery hybrid system was described by Singh et al. [100], who also created a mathematical model to determine the optimal sizes of this hybrid system's components using an artificial bee colony algorithm (ABC). Their outcomes were contrasted with those of two common software applications, hybrid optimisation model for electric renewable (HOMER) and particle swarm optimization (PSO). The suggested algorithm produced superior outcomes.

Atia and Yamada looked into how load flexibility affected the component sizing of a hybrid system for a residential MG in [7]. In order to simulate varied technological constraints and uncertainty levels, they also took into account alternative operation situations. The stochastic models were created using Matlab software, and mixed integer linear programming (MILP) was employed to optimise the system design. The models were solved utilizing the CPLEX optimisation engine as deterministic problems, which required about 90 min per instance. The crucial topic of frequency management of AC MGs in the presence of disturbances, uncertainties, and load fluctuations was examined by Bevrani et al. in [10]. Adaptive control with two levels, based on a PI controller and a fuzzy system method, was used to control the frequency of the AC MG system. The PSO algorithm was employed to enhance the membership function's parameters because of the membership function's substantial reliance on the fuzzy system. Ramli et al. [84] studied the optimal sizing of a PV/wind/diesel HMGS with battery storage using a multi-objective self-adaptive differential evolution (MOSaDE) algorithm. A multi-objective optimisation approach was then used to analyse the loss of power supply probability (LPSP), the cost of electricity (COE), and the renewable factor (RF) in relation to the HMS cost and reliability, and was tested using three case studies involving different numbers of houses. In [82], Ou and Hong proposed an MG hybrid PV-wind- fuel cell (FC) system-based stand-alone power supply. The performance of the PV generation source was analysed using an improved particle swarm optimization method (PSO) and a general regression neural network (GRNN). The optimal speed that the turbine should have attained to harness the most power from the wind was determined using a highperformance on-line training radial basis function network-sliding mode algorithm (RBFNSM).

Table 2.6: Case studies of optimisation applied to MGs integrated with renewable energy systems.

Hybrid design	Mode of operation	Factors considered for optimisation	Optimisation technique	Merits and demerits of optimisation technique	Ref.
PV, WT, FC, and diesel generators	On-grid	Cost, design	Monte Carlo simulation	Merits: Simulations dealing with stochastic events are a part of the Monte Carlo method -Appropriately addresses uncertainty variables - Any solution chosen is completely independent of any previous decision and its outcomes; Demerits: The process requires complex calculations[26]	[75]
PV, WT, biomass, and battery	Off-grid	Cost, size, reliability,	ABC	Merits: - Simplicity and the flexibility to explore local solutions - Ease of use in the implementation Demerits: - Ineffective for resolving complex problems[118]	[100]
PV, WT, and battery	On- and off-grid	Size	MILP	Merits: - A potent and flexible method for solving difficult problems - Accurate and effective in finding the optimal solution to the linear problem Demerits: - Nonlinear effects cannot be considered, and all time periods must be considered simultaneously[109]	[7]
PV, WT, and battery	Off-grid	Power quality	Fuzzy logic and PSO	Merits: -The most important advantages of PSO is the simplicity of both concept and application level, and its fast convergence rate and ease of use. - Supports multi-objective optimisation problems Demerits: -Difficulties in controlling diversity when used as a multi-objective optimisation[49]	[10]
PV, WT, diesel, and battery	Off-grid	Cost, size, reliability	MOSaDE	Merits: -The good convergence ability -An effective approach to handle multiobjective optimisation problems Demerits: -computational complexity [113]	[84]

Hybrid design	Mode of operation	Factors considered for optimisation	Optimisation technique	Merits and demerits of optimisation technique	Ref.
PV, WT, FC, SVAR, intelligent controller	Off-grid	Max power, control	PSO, GRNN, RBFNSM	Merits: -GRNN's merits include its accuracy and short training process. -The drawbacks of GRNN include its potentially enormous size, which would make it computationally expensive [3], - The merits of RBFNSM are its reliability, speed, and effectiveness. - Effective in solving classification and regression problems - RBFNSM has disadvantages in that the computational time is expensive when dealing with a high number of data points [62]	[82]
PV, WT, diesel, and battery	Off-grid	Emissions, LCC, MRP	GA	Merits: -Easy to understand the concept - Supports multi-objective optimisation problems Demerits: - Time consuming comparing to the PSO - Complicated computations [26]	[125]
PV-thermal/WT, micro-turbine/diesel, electrical and thermal storage	Off-grid	LPSP, COE, RF	E-PSO	Merits: Merits: -EPSO joins together the characteristics of evolutionary algorithms and particle swarm algorithm - EPSO can deal effectively with a diversity of objective functions -Very successful in solving the power system optimisation problem -EPSO has better convergence characteristics than the conventional PSO [73]	[66]
PV	On-grid	Power prediction	Hybrid WTPSO-SVM	Merits: Solves convex and non-convex problems; Demerits: Poor for large data sets, computationally expensive[19]	[36]
PV, WT, PAFC, and battery	On-grid	EOM	GSA	Merits: -Simple implementation -GSA is good at finding the global optimum - Shows good results for non-linear optimisation problems Demerits: -Slow convergence speed and getting stuck in local minima in the last iterations -The GSA operators are complex[85]	[77]

Hybrid design	Mode of operation	Factors considered for optimisation	Optimisation technique	Merits and demerits of optimisation technique	Ref.
Biomass, natural gas generator, and diesel generators	Standalone	Economic evaluation	HOMER	Merits: -Homer is a powerful tool for developing and sizing HRES components by utilizing technoeconomic analysis. - Very thorough results for analysis and assessment. -Provide a realistic, regularly updated library of components Demerits: - If critical values or sizes are missed, HOMER won't attempt to guess them. -Time and detailed input data are required [35]	[74]
PV, WT, pumped storage	Standalone	LPSP, COE, LCC	GA	Merits: -Easy to understand the concept - Supports multi-objective optimisation problems Demerits: - Time consuming comparing to the PSO - Complicated computations [26]	[68]

Key: PV = photovoltaic, WT = wind turbine, ABCA = artificial bee colony algorithm, MILP = mixed integer linear programming, PSO = particle swarm optimisation, MOSaDE = multi-objective self-adaptive differential evolution, GRNN = general regression neural network, RBFNSM = radial basis function network-sliding mode, GA = genetic algorithm, E-PSO = evolutionary particle swarm optimisation, FC = fuel cell, SVAR = static var compensator, LPSP = loss of power supply probability, COE = cost of electricity, RF = renewable factor, LCC = life cycle cost, MRP = maximisation of renewable energy source penetration, WT-PSO-SVM = wavelet transformation, particle swarm optimisation, and support vector machine, PAFC = phosphoric acid fuel cell, EOM = energy and operation management, GSA = gravitational search algorithm, MOGA = multi-objective genetic algorithm, HOMER = hybrid optimisation of multiple energy resources.

An intelligent controller was created that was composed of an RBFNSM and a GRNN for MPPT (maximum power point tracking) control in order to produce a quick and stable response for real power control. A genetic algorithm (GA)-based method was used to solve the sizing optimisation problem with multiple objectives, including minimisation of the LCC, maximisation of RES penetration and minimisation of pollutant emissions. The proposed method was applied to the design and development of a real MG system on Dongfushan Island, Zhejiang Province, China, consisting of wind turbine generators, solar panels, diesel generators and battery storage units [125]. The optimal size and other technical and financial features of a standalone multi-carrier an MG integrated with a PV-thermal/small turbine WT/diesel system were analysed by Lorestani et al. in [66]. The optimisation problem was solved by an evolutionary particle swarm optimisation (E-PSO). The outcomes showed that the suggested arrangement was effective in terms of its financial, energy-efficient, dependable, and environmental qualities. PV power generation is affected by changes in weather and solar radiation, which pose a significant barrier to integrating PV power into the grid. A hybrid prediction model that combined wavelet transformation, particle swarm optimisation, and a sup-

port vector machine (Hybrid WT-PSO-SVM) was proposed by Eseye et al. for short-term (one day ahead) power generation prediction for a real MG-PV system [36]. Niknam et al. [77] reported on the application of a self-adaptive optimisation algorithm based on the gravitational search algorithm (GSA) to identify the optimal energy management of a hybrid PV-WT-PAFCbattery MG in an uncertain environment. Their approach considered uncertainties in load demand, market prices, and the availability of electrical power from wind farms and solar systems [74]. Montuori et al. used HOMER software to carry out an economic evaluation of an MG supplied by a biomass gasification power plant and isolated from the grid, and compared this to alternative generation technologies (diesel generator/gas generator). A techno-economic analysis of a standalone hybrid solar-wind-pumped storage system for an isolated MG was presented by Ma et al. [68]. To find the optimal system configuration, a GA optimisation was used. The results showed that the COE for the system was marginally lower than that of a solar-only system and much lower than that of a wind-only system, owing to the high cost of wind turbines. Pumped storage systems based on renewable energy were found to be able to supply stable and uninterrupted power to remote areas. Table 2.6 shows that extensive research has gone into determining the optimal sizes of HMGS components to ensure that all load requirements are met with a low COE and the highest level of reliability. The optimisation of HMGSs is crucial because it offers a variety of design options and operational scenarios that can help academics and professionals choose the optimal system configuration. Given that the cost of PV has been steadily declining over the past 30 years as a result of technological advancements in the solar panel sector, solar PV is used as one of the sources of the hybrid system in the majority of HMGSs. Due to environmental concerns, fluctuating fossil fuel prices, and the fact that the cost of PV and wind has decreased by 85% and 56%, respectively, over the past 10 years, PV-wind is the most well-known hybrid RE system. This discovery has motivated researchers to carry out numerous investigations in this field.

2.5 Conclusions

This paper has presented a review of research developments related to three themes: microgrids (MGs), renewable energy (RE), and the optimisation of these systems. The systematic literature review was based on a SciMAT bibliometric analysis of the evolution of the selected field of research between 2005 and 2021, using publications available from Scopus. The trends were analysed based on an overview and a more specific analysis of three different phases of the period under review (2005–2011, 2012–2015, and 2016–2021). The analysis revealed that multi-objective optimisation and MGs have been prominent areas of research, par-

ticularly during the last five years. Since 2016, there has also been a notable rise in the number of articles on these subjects that have been published in international journals. Overlapping graphs by period showed significant developments in the number of new and transitional keywords, with an increase of 406% between the first and last periods, indicating that research on each of the topics in the analysed domain is in a state of continuous development. Strategic diagrams were created to analyse the changes in the field of research over the three periods studied, and these indicated an emphasis on developments in the technical and economic evaluation of hybrid microgrid systems (HMGSs). The first period (2005–2011) contained a large number of documents focusing on two topics (smart grids and optimisation). Within this period, the US (DOE) Smart Grid Research and Development Program stated that MGs were basic building blocks for the smart grid. Following the first workshop held by the DOE in August 2011 that brought together experts and practitioners to identify priorities in the field of research and development of MGs, the end of this period is therefore considered to be the beginning of the development that occurs in research that studies the evolution of the MG. The second period (2012–2015) contained the largest number of documents focusing on MGs and the distribution energy resources. The most recent period (2016–2021) indicated interest and a very large increase in the number of studies on MGs and multi-objective optimisation. The use of smart grids rather than traditional grids has attracted research attention due to the increasing interest in the efficiency, reliability, economy, and sustainability of the production and distribution of electricity. This was evident in the strategic plan for each period under study as the subject of smart grids was covered in a significant number of documents with numerous citations. Due to the lower cost and new developments in RESs components, the rise in the number of research studies evaluating these networks, and the significant advancements in algorithms for solving optimisation problems related to these systems, this study has demonstrated that MGs integrated with RESs represent the future of power systems.

References for Chapter 2

- [1] G.M.G.M. Abdolrasol, M.A. Hannan, A. Mohamed, U.A.U. Amiruldin, I.B.Z. Abidin, and M.N. Uddin. An optimal scheduling controller for virtual power plant and microgrid integration using the binary backtracking search algorithm. *IEEE Transactions on Industry Applications*, 54(3):2834–2844, 2018.
- [2] International Energy Agency et al. Sdg indicator metadata, 2021.
- [3] A.J. Al-Mahasneh, S.G. Anavatti, and M.A. Garratt. Review of applications of generalized regression neural networks in identification and control of dynamic systems. *Engineering Applications of Artificial Intelligence*, 2018.
- [4] G. Albort-Morant and D. Ribeiro-Soriano. A bibliometric analysis of international impact of business incubators. *Journal of Business Research*, 69(5):1775–1779, 2016.
- [5] E.M. Antman, J. Lau, B. Kupelnick, F. Mosteller, and T.C. Chalmers. A comparison of results of meta-analyses of randomized control trials and recommendations of clinical experts treatments for myocardial infarction. <http://jama.jamanetwork.com/>, 1992. Accessed: 2025-04-25.
- [6] G. Aparicio, T. Iturralde, and A. Maseda. Conceptual structure and perspectives on entrepreneurship education research: A bibliometric review. *European Research on Management and Business Economics*, 25(3):105–113, 2019.
- [7] R. Atia and N. Yamada. Sizing and analysis of renewable energy and battery systems in residential microgrids. *IEEE Transactions on Smart Grid*, 7(3):1204–1213, 2016.
- [8] M. Azaza and F. Wallin. Multi objective particle swarm optimization of hybrid microgrid system: A case study in sweden. *Energy*, 123:108–118, 2017.

- [9] P. Bajpai and V. Dash. Hybrid renewable energy systems for power generation in stand-alone applications: A review. *Renewable and Sustainable Energy Reviews*, 16(5):2926–2939, 2012.
- [10] H. Bevrani, F. Habibi, P. Babahajyani, M. Watanabe, and Y. Mitani. Intelligent frequency control in an ac microgrid: Online pso-based fuzzy tuning approach. *IEEE Transactions on Smart Grid*, 3(4):1935–1944, 2012.
- [11] H. Bhimani, A.L. Mention, and P.J. Barlatier. Social media and innovation: A systematic literature review and future research directions. *Technological Forecasting and Social Change*, 144:251–269, 2019.
- [12] E. Binali and A. Polater. Managing airports in non-aviation related disasters: A systematic literature review. *International Journal of Disaster Risk Reduction*, 2018.
- [13] H. Borhanazad, S. Mekhilef, V. Gounder Ganapathy, M. Modiri-Delshad, and A. Mirtaheri. Optimization of micro-grid system using mopso. *Renewable Energy*, 71:295–306, 2014.
- [14] D. Boroyevich, I. Cvetković, D. Dong, R. Burgos, F. Wang, and F. Lee. Future electronic power distribution systems - a contemplative view. In *Proceedings of the International Conference on Optimization of Electrical and Electronic Equipment (OPTIM)*, pages 1369–1380, 2010.
- [15] M. Callon, J.P. Courtial, and F. Laville. Co-word analysis as a tool for describing the network of interactions between basic and technological research: The case of polymer chemistry. *Scientometrics*, 22(1):155–205, 1991.
- [16] M. Callon, J.P. Courtial, W.A. Turner, and S. Bauin. From translations to problematic networks: An introduction to co-word analysis. *Social Science Information*, 22(2):191–235, 1983.
- [17] M. Carpio, A. González, M. González, and K. Verichev. Influence of pavements on the urban heat island phenomenon: A scientific evolution analysis. *Energy and Buildings*, 226:110379, 2020.
- [18] L.A. Casado-Aranda, J. Sánchez-Fernández, and M.I. Viedma-del Jesús. Analysis of the scientific production of the effect of covid-19 on the environment: A bibliometric study. *Environmental Research*, 193:110416, 2021.
- [19] J. Cervantes, F. Garcia-Lamont, L. Rodríguez-Mazahua, and A. Lopez. A comprehensive survey on support vector machine classification: Applications, challenges and trends. *Neurocomputing*, 408:189–215, 2020.

- [20] S. Chakraborty, M.D. Weiss, and M.G. Simões. Distributed intelligent energy management system for a single-phase high-frequency ac microgrid. *IEEE Transactions on Industrial Electronics*, 54(1):97–109, 2007.
- [21] K.H. Chang and G. Lin. Optimal design of hybrid renewable energy systems using simulation optimization. *Simulation Modelling Practice and Theory*, 52:40–51, 2015.
- [22] A. Chaouachi, R.M. Kamel, R. Andoulsi, and K. Nagasaka. Multiobjective intelligent energy management for a microgrid. *IEEE Transactions on Industrial Electronics*, 60(4):1688–1699, 2013.
- [23] Y.H. Chen, S.Y. Lu, Y.R. Chang, T.T. Lee, and M.C. Hu. Economic analysis and optimal energy management models for microgrid systems: A case study in taiwan. *Applied Energy*, 103:145–154, 2013.
- [24] I.Y. Chung, W. Liu, D.A. Cartes, E.G. Collins, and S.I. Moon. Control methods of inverter-interfaced distributed generators in a microgrid system. *IEEE Transactions on Industry Applications*, 46(3):1, 2010.
- [25] M.J. Cobo, A.G. López-Herrera, E. Herrera-Viedma, and F. Herrera. An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the fuzzy sets theory field. *Journal of Informetrics*, 5(1):146–166, 2011.
- [26] C.A.C. Coello, G.B. Lamont, and D.A. Van Veldhuizen. *Evolutionary algorithms for solving multi-objective problems*. Springer, 2007.
- [27] S. Conti, R. Nicolosi, S.A. Rizzo, and H.H. Zeineldin. Optimal dispatching of distributed generators and storage systems for mv islanded microgrids. *IEEE Transactions on Power Delivery*, 27(3):1243, 2012.
- [28] S.K.N. Coulter and I. Monarch. Software engineering as seen through its research literature: A study in co-word analysis. https://www.researchgate.net/publication/220433686_Software_Engineering_as_Seen_through_Its_Research_Literature_A_Study_in_Co-Word_Analysis, 2012. Accessed: 2025-04-25.
- [29] T.M. David, P.M. Silva Rocha Rizol, M.A. Guerreiro Machado, and G.P. Buccieri. Future research tendencies for solar energy management using a bibliometric analysis, 2000–2019. *Heliyon*, 6(7):e04452, 2020.
- [30] S.M. Dawoud, X. Lin, and M.I. Okba. Hybrid renewable microgrid optimization techniques: A review. *Renewable and Sustainable Energy Reviews*, 82:2039–2052, February 2018.

- [31] G. de Oliveira e Silva and P. Hendrick. Photovoltaic self-sufficiency of belgian households using lithium-ion batteries, and its impact on the grid. *Applied Energy*, 195:786–799, June 2017.
- [32] M.K. Deshmukh and S.S. Deshmukh. Modeling of hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*, 12(1):235–249, 2008.
- [33] C. Díaz-López, M. Carpio, M. Martín-Morales, and M. Zamorano. Analysis of the scientific evolution of sustainable building assessment methods. *Sustainable Cities and Society*, 49:101610, August 2019.
- [34] N. Dougier, P. Garambois, J. Gomand, and L. Roucoules. Multi-objective non-weighted optimization to explore new efficient design of electrical microgrids. *Applied Energy*, 304:117758, 2021.
- [35] Homer Energy. Optimization of renewable energy efficiency using homer. https://www.researchgate.net/publication/263765594_Optimization_of_Renewable_Energy_Efficiency_using_HOMER, 2014. Accessed: Sep. 02, 2022.
- [36] A.T. Eseye, J. Zhang, and D. Zheng. Short-term photovoltaic solar power forecasting using a hybrid wavelet-pso-svm model based on scada and meteorological information. *Renewable Energy*, 118:357–367, 2018.
- [37] A.H. Fathima and K. Palanisamy. Optimization in microgrids with hybrid energy systems – a review. *Renewable and Sustainable Energy Reviews*, 45:431–446, 2015.
- [38] J.M. Fernández-González, C. Díaz-López, J. Martín-Pascual, and M. Zamorano. Recycling organic fraction of municipal solid waste: Systematic literature review and bibliometric analysis of research trends. *Sustainability*, 12(11):4798, 2020.
- [39] Y. Fu, Z. Zhang, Z. Li, and Y. Mi. Energy management for hybrid ac/dc distribution system with microgrid clusters using non-cooperative game theory and robust optimization. *IEEE Transactions on Smart Grid*, 11(2):1510–1525, 2020.
- [40] D. Guangqian, K. Bekhrad, P. Azarikhah, and A. Maleki. A hybrid algorithm based optimization on modeling of grid independent biodiesel-based hybrid solar/wind systems. *Renewable Energy*, 122:551–560, 2018.
- [41] S. Gupta, P. Rajiah, E.H. Middlebrooks, D. Baruah, B.W. Carter, K.R. Burton, et al. Systematic review of the literature: Best practices. *Academic Radiology*, 25(11):1481–1490, 2018.

- [42] A. Heydari, D. Astiaso Garcia, F. Keynia, F. Bisegna, and L. De Santoli. A novel composite neural network based method for wind and solar power forecasting in microgrids. *Applied Energy*, 251:113353, 2019.
- [43] J.E. Hirsch. An index to quantify an individual’s scientific research output. *Proceedings of the National Academy of Sciences of the United States of America*, 102(46):16569–16572, 2005.
- [44] International Energy Agency. Renewable power-analysis. <https://www.iea.org/reports/renewablepower>, 2022. Accessed: 2022-03-11.
- [45] International Energy Agency. Solar pv-analysis. <https://www.iea.org/reports/solar-pv>, 2022. Accessed: 2022-01-04.
- [46] International Energy Agency (IEA). Smart grids – analysis. <https://www.iea.org/reports/smart-grids>, 2022. Accessed: Mar. 28, 2022.
- [47] IRENA. Renewable power generation costs in 2020, 2020.
- [48] C. Ju, P. Wang, L. Goel, and Y. Xu. A two-layer energy management system for microgrids with hybrid energy storage considering degradation costs. *IEEE Transactions on Smart Grid*, 9(6):6047–6057, 2018.
- [49] M. Juneja and S.K. Nagar. Particle swarm optimization algorithm and its parameters: A review. In *2nd IEEE International Conference on Control, Computing, Communication and Materials (ICCCCM)*, 2016.
- [50] S. Kallio and M. Siroux. Hybrid renewable energy systems based on microgeneration. *Energy Reports*, 8:762–769, 2022.
- [51] H. Kanchev, F. Colas, V. Lazarov, and B. Francois. Emission reduction and economical optimization of an urban microgrid operation including dispatched pv-based active generators. *IEEE Transactions on Sustainable Energy*, 5(4):1397–1405, 2014.
- [52] K.A. Kavadias and P. Triantafyllou. Hybrid renewable energy systems’ optimisation. a review and extended comparison of the most-used software tools. *Energies*, 14(24):8268, 2021.
- [53] M. Kharrich, O.H. Mohammed, N. Alshammari, and M. Akherraz. Multi-objective optimization and the effect of the economic factors on the design of the microgrid hybrid system. *Sustainable Cities and Society*, 65:102646, 2021.

- [54] L.M. Kipper, S. Iepsen, A.J. Dal Forno, R. Frozza, L. Furstenau, J. Agnes, et al. Scientific mapping to identify competencies required by industry 4.0. *Technology in Society*, 64:101454, 2021.
- [55] B. Kitchenham. Guidelines for performing systematic literature reviews in software engineering. <https://www.researchgate.net/publication/302924724>, 2007. Accessed: 2025-04-25.
- [56] C.D. Korkas, S. Baldi, I. Michailidis, and E.B. Kosmatopoulos. Occupancy-based demand response and thermal comfort optimization in microgrids with renewable energy sources and energy storage. *Applied Energy*, 163:93–104, 2016.
- [57] V.D. Lazarov, Z. Zarkov, and I. Bochev. Hybrid power systems with renewable energy sources - types, structures, trends for research and development. Available online: <https://www.researchgate.net/publication/236012467>, 2005. Accessed: 2025-04-25.
- [58] H. Liang, A.K. Tamang, W. Zhuang, and X.S. Shen. Stochastic information management in smart grid. *IEEE Communications Surveys & Tutorials*, 16(3):1746–1770, 2014.
- [59] H. Liang and W. Zhuang. Stochastic modeling and optimization in a microgrid: a survey. *Energies*, 7:2027–2050, 2014.
- [60] G.C. Liao. Solve environmental economic dispatch of smart microgrid containing distributed generation system – using chaotic quantum genetic algorithm. *International Journal of Electrical Power and Energy Systems*, 43(1):779–787, 2012.
- [61] A. Liberati, D.G. Altman, J. Tetzlaff, C. Mulrow, P.C. Gotzsche, J.P.A. Ioannidis, et al. The prisma statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: Explanation and elaboration. *BMJ*, 339:b2700, 2009.
- [62] G.F. Lin and L.H. Chen. A non-linear rainfall-runoff model using radial basis function network. *Journal of Hydrology*, 289(1-4):1–8, 2004.
- [63] Y. Liu, Y. Li, H.B. Gooi, J. Ye, H. Xin, X. Jiang, et al. Distributed robust energy management of a multimicrogrid system in the real-time energy market. *IEEE Transactions on Sustainable Energy*, 10(1):396–406, 2019.
- [64] M. López-Alonso, M. Martín-Morales, M.J. Martínez-Echevarría, F. Agrela, and M. Zamorano. Residual biomasses as aggregates applied in cement-based

- materials. In *Waste and By-Products in Cement-Based Materials*, pages 89–137. Elsevier, 2021.
- [65] J.R. López-Robles, M. Rodríguez-Salvador, N.K. Gamboa-Rosales, S. Ramírez-Rosales, and M.J. Cobo. The last five years of big data research in economics, econometrics and finance: identification and conceptual analysis. *Procedia Computer Science*, 162:729–736, 2019.
- [66] A. Lorestani, G.B. Gharehpetian, and M.H. Nazari. Optimal sizing and techno-economic analysis of energy- and cost-efficient standalone multi-carrier microgrid. *Energy*, 178:751–764, 2019.
- [67] Z. Luo, Z. Wu, Z. Li, H.Y. Cai, B.J. Li, and W. Gu. A two-stage optimization and control for cchp microgrid energy management. *Applied Thermal Engineering*, 125:513–522, 2017.
- [68] T. Ma, H. Yang, L. Lu, and J. Peng. Optimal design of an autonomous solar–wind–pumped storage power supply system. *Applied Energy*, 160:728–736, 2015.
- [69] A. Maheri. A critical evaluation of deterministic methods in size optimisation of reliable and cost effective standalone hybrid renewable energy systems. *Reliability Engineering & System Safety*, 130:159–174, 2014.
- [70] M.D. Martínez-Aires, M.J. Cobo, M. Herrera, and E. Herrera-Viedma. Analyzing the scientific evolution of social work using science mapping. *Research on Social Work Practice*, 25(2):257–277, 2015.
- [71] M.D. Martínez-Aires, M. López-Alonso, and M. Martínez-Rojas. Building information modeling and safety management: A systematic review. *Safety Science*, 101:11–18, January 2018.
- [72] A. Masoumi, S. Ghassem-zadeh, S.H. Hosseini, and B.Z. Ghavidel. Application of neural network and weighted improved pso for uncertainty modeling and optimal allocating of renewable energies along with battery energy storage. *Applied Soft Computing*, 88:105979, 2020.
- [73] V. Miranda and N. Fonseca. Epso-evolutionary particle swarm optimization, a new algorithm with applications in power systems. In *Proceedings of the 2002 IEEE Transmission and Distribution Conference and Exhibition*, 2002.
- [74] L. Montuori, M. Alcazar-Ortega, C. Alvarez-Bel, and A. Domijan. Integration of renewable energy in microgrids coordinated with demand response resources: Economic evaluation of a biomass gasification plant by homer simulator. *Applied Energy*, 132:15–22, 2014.

- [75] D.T. Nguyen and L.B. Le. Optimal bidding strategy for microgrids considering renewable energy and building thermal dynamics. *IEEE Transactions on Smart Grid*, 5(4):1608–1620, 2014.
- [76] T.A. Nguyen and M.L. Crow. Stochastic optimization of renewable-based microgrid operation incorporating battery operating cost. *IEEE Transactions on Power Systems*, 31(3):2289–2296, 2016.
- [77] T. Niknam, F. Golestaneh, and A. Malekpour. Probabilistic energy and operation management of a microgrid containing wind/photovoltaic/fuel cell generation and energy storage devices based on point estimate method and self-adaptive gravitational search algorithm. *Energy*, 43(1):427–437, 2012.
- [78] E.C.M. Noyons. Combining mapping and citation analysis for evaluative bibliometric purposes: A bibliometric study. [https://asistdl.onlinelibrary.wiley.com/doi/abs/10.1002/\(SICI\)1097-4571\(1999\)50:2<115::AID-ASI3>3.0.CO;2-J](https://asistdl.onlinelibrary.wiley.com/doi/abs/10.1002/(SICI)1097-4571(1999)50:2<115::AID-ASI3>3.0.CO;2-J), 1999. Accessed: 2025-04-25.
- [79] M. Oakleaf. Writing information literacy assessment plans: A guide to best practice. *Communications in Information Literacy*, 3(2):4, 2010.
- [80] A.S.O. Ogunjuyigbe, T.R. Ayodele, and O.A. Akinola. Optimal allocation and sizing of pv/wind/split-diesel/battery hybrid energy system for minimizing life cycle cost, carbon emission and dump energy of remote residential building. *Applied Energy*, 171:153–171, 2016.
- [81] F. Osareh. Bibliometrics, citation analysis and co-citation analysis. *Library Review*, 46:149–158, 1996.
- [82] T.C. Ou and C.M. Hong. Dynamic operation and control of microgrid hybrid power systems. *Energy*, 66:314–323, 2014.
- [83] P. Paliwal, N.P. Patidar, and R.K. Nema. Planning of grid integrated distributed generators: A review of technology, objectives and techniques. *Renewable and Sustainable Energy Reviews*, 40:557–570, 2014.
- [84] M.A.M. Ramli, H.R.E.H. Bouchekara, and A.S. Alghamdi. Optimal sizing of pv/wind/diesel hybrid microgrid system using multi-objective self-adaptive differential evolution algorithm. *Renewable Energy*, 121:400–411, 2018.
- [85] S.A. Rather and P.S. Bala. A holistic review on gravitational search algorithm and its hybridization with other optimization algorithms. In *2019 3rd IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT)*, 2019.

- [86] M.S. Reza, N. Rahman, S.B. Wali, M.A. Hannan, P.J. Ker, S.A. Rahman, et al. Optimal algorithms for energy storage systems in microgrid applications: An analytical evaluation towards future directions. *IEEE Access*, 10:10105–10123, 2022.
- [87] J.J. Roberts, A. Marotta Cassula, J.L. Silveira, E. da Costa Bortoni, and A.Z. Mendiburu. Robust multi-objective optimization of a renewable based hybrid power system. *Applied Energy*, 223:52–68, 2018.
- [88] N. Roig-Tierno, T.F. Gonzalez-Cruz, and J. Llopis-Martinez. An overview of qualitative comparative analysis: A bibliometric analysis. *Journal of Innovation & Knowledge*, 2(1):15–23, 2017.
- [89] M.F. Roslan, M.A. Hannan, P.J. Ker, M. Mannan, K.M. Muttaqi, and T.I. Mahlia. Microgrid control methods toward achieving sustainable energy management: A bibliometric analysis for future directions. *Journal of Cleaner Production*, 348:131340, 2022.
- [90] R.W.S. Ruhlandt. The governance of smart cities: A systematic literature review. *Cities*, 81:1–23, 2018.
- [91] M. Santana and M.J. Cobo. What is the future of work? a science mapping analysis. *European Management Journal*, 38(6):846–862, 2020.
- [92] P. Savaget, M. Geissdoerfer, A. Kharrazi, and S. Evans. The theoretical foundations of sociotechnical systems change for sustainability: A systematic literature review. *Journal of Cleaner Production*, 206:878–892, January 2019.
- [93] W.L. Schram, I. Lampropoulos, and W.G.J.H.M. van Sark. Photovoltaic systems coupled with batteries that are optimally sized for household self-consumption: Assessment of peak shaving potential. *Applied Energy*, 223:69–81, August 2018.
- [94] M. Schreiber. Restricting the h-index to a publication and citation time window: A case study of a timed hirsch index. *Journal of Informetrics*, 9(1):150–155, 2015.
- [95] S. Sen, S. Ganguly, A. Das, J. Sen, and S. Dey. Renewable energy scenario in india: Opportunities and challenges. *Journal of African Earth Sciences*, 2015.
- [96] P.H. Shaikh, A. Shaikh, Z.A. Memon, A.A. Lashari, and Z.H. Leghari. Microgrids: A review on optimal hybrid technologies, configurations, and applications. *International Journal of Energy Research*, 45(9):12564–12597, 2021.

- [97] A. Sharifi. Urban sustainability assessment: An overview and bibliometric analysis. *Ecological Indicators*, 121:107102, 2021.
- [98] S. Sharma, S. Bhattacharjee, and A. Bhattacharya. Grey wolf optimisation for optimal sizing of battery energy storage device to minimise operation cost of microgrid. *IET Generation, Transmission & Distribution*, 10(3):625–637, 2016.
- [99] J. Shen, C. Jiang, Y. Liu, and X. Wang. A microgrid energy management system and risk management under an electricity market environment. *IEEE Access*, 4:2349–2356, 2016.
- [100] S. Singh, M. Singh, and S.C. Kaushik. Feasibility study of an islanded microgrid in rural area consisting of pv, wind, biomass and battery energy storage system. *Energy Conversion and Management*, 128:178–190, 2016.
- [101] H. Small. Visualizing science by citation mapping, 1999.
- [102] E. Sortomme and M.A. El-Sharkawi. Optimal power flow for a system of microgrids with controllable loads and battery storage, 2009.
- [103] M. Soshinskaya, W.H.J. Crijns-Graus, J.M. Guerrero, and J.C. Vasquez. Microgrids: Experiences, barriers and success factors. *Renewable and Sustainable Energy Reviews*, 40:659–672, 2014.
- [104] C. Theisen, N. Munaiah, M. Al-Zyoud, J.C. Carver, A. Meneely, and L. Williams. Attack surface definitions: A systematic literature review. *Information and Software Technology*, 104:94–103, December 2018.
- [105] D.T. Ton and M.A. Smith. The u.s. department of energy’s microgrid initiative. *The Electricity Journal*, 25(8):84–94, 2012.
- [106] A.G. Tsikalakis and N.D. Hatziargyriou. Centralized control for optimizing microgrids operation. In *IEEE Power and Energy Society General Meeting*, 2011.
- [107] K. Ullah, G. Hafeez, I. Khan, S. Jan, and N. Javaid. A multi-objective energy optimization in smart grid with high penetration of renewable energy sources. *Applied Energy*, 299:117104, 2021.
- [108] S. Upadhyay and M.P. Sharma. A review on configurations, control and sizing methodologies of hybrid energy systems. *Renewable and Sustainable Energy Reviews*, 38:47–63, 2014.

- [109] L. Urbanucci. Limits and potentials of mixed integer linear programming methods for optimization of polygeneration energy systems. *Energy Procedia*, 148:1199–1205, 2018.
- [110] K. van Nunen, J. Li, G. Reniers, and K. Ponnet. Bibliometric analysis of safety culture research. *Safety Science*, 108:248–258, October 2018.
- [111] T. Wang, X. He, and T. Deng. Neural networks for power management optimal strategy in hybrid microgrid. *Neural Computing and Applications*, 31(7):2045–2054, 2019.
- [112] Y. Wang, F. Li, H. Yu, Y. Wang, C. Qi, J. Yang, et al. Optimal operation of microgrid with multi-energy complementary based on moth flame optimization algorithm. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 42(7):785–806, 2020.
- [113] Y.N. Wang, L.H. Wu, and X.F. Yuan. Multi-objective self-adaptive differential evolution with elitist archive and crowding entropy-based diversity measure. *Soft Computing*, 14(3):193–209, 2010.
- [114] Z. Wang, B. Chen, J. Wang, and J. Kim. Decentralized energy management system for networked microgrids in grid-connected and islanded modes. *IEEE Transactions on Smart Grid*, 7(2):1097–1105, 2016.
- [115] Z. Wang, X. Yu, Y. Mu, H. Jia, Q. Jiang, and X. Wang. Peer-to-peer energy trading strategy for energy balance service provider (ebsp) considering market elasticity in community microgrid. *Applied Energy*, 303:117596, 2021.
- [116] H. Xie, Y. Zhang, and K. Duan. Evolutionary overview of urban expansion based on bibliometric analysis in web of science from 1990 to 2019. *Habitat International*, 95:102100, January 2020.
- [117] H. Yang, L. Lu, and W. Zhou. A novel optimization sizing model for hybrid solar-wind power generation system. *Solar Energy*, 81(1):76–84, 2007.
- [118] D. Yazdani and M.R. Meybodi. A novel artificial bee colony algorithm for global optimization. In *4th International Conference on Computer and Knowledge Engineering (ICCKE)*, pages 443–448, 2014.
- [119] X. Yu, A.M. Khambadkone, H. Wang, and S.T.S. Terence. Control of parallel-connected power converters for low-voltage microgrid—part i: A hybrid control architecture. *IEEE Transactions on Power Electronics*, 25(12):2962–2970, 2010.

- [120] E. Zarate-Perez, E. Rosales-Asensio, A. Gonzalez-Martinez, M. de Simon-Martin, and A. Colmenar-Santos. Battery energy storage performance in microgrids: A scientific mapping perspective. *Energy Reports*, 8:259–268, 2022.
- [121] B. Zhang, Q. Li, L. Wang, and W. Feng. Robust optimization for energy transactions in multi-microgrids under uncertainty. *Applied Energy*, 217:346–360, 2018.
- [122] D. Zhang, N. Shah, and L.G. Papageorgiou. Efficient energy consumption and operation management in a smart building with microgrid. *Energy Conversion and Management*, 74:209–222, October 2013.
- [123] Y. Zhang, N. Gatsis, and G.B. Giannakis. Robust energy management for microgrids with high-penetration renewables. *IEEE Transactions on Sustainable Energy*, 4(4):944–953, 2013.
- [124] B. Zhao, X. Wang, D. Lin, M.M. Calvin, J.C. Morgan, R. Qin, et al. Energy management of multiple microgrids based on a system of systems architecture. *IEEE Transactions on Power Systems*, 33(6):6410–6421, 2018.
- [125] B. Zhao, X. Zhang, P. Li, K. Wang, M. Xue, and C. Wang. Optimal sizing, operating strategy and operational experience of a stand-alone microgrid on dongfushan island. *Applied Energy*, 113:1656–1666, 2014.
- [126] M.F. Zia, E. Elbouchikhi, and M. Benbouzid. Microgrids energy management systems: A critical review on methods, solutions, and prospects. *Applied Energy*, 222:1033–1055, 2018.

Chapter Three

Exploring Evolution and Trends: A Bibliometric Analysis and Scientific Mapping of Multiobjective Optimization Applied to Hybrid Microgrid Systems

*This chapter is presented as a standalone research paper and forms an integral part of this doctoral dissertation. It has been published in **Sustainability**, 2024, **16**(12), 5156.*

Available at: <https://doi.org/10.3390/su16125156>.

Chapter 3

Exploring Evolution and Trends: A bibliometric Analysis and Scientific Mapping of Multiobjective Optimization Applied to Hybrid Microgrid Systems

This chapter presents a bibliometric analysis of hybrid microgrid systems, focusing on renewable energy, microgrids, and multiobjective optimization between 2010 and 2023. Hybrid energy systems (HESs) integrate renewable sources, storage, and optionally conventional energies, offering a sustainable alternative to fossil fuels. Microgrids (MGs) bolster this integration, enhancing energy management, resilience, and reliability across different levels. This study, emphasizing the need for refined optimization methods, investigates three themes: renewable energy, microgrid, and multiobjective optimization (MOO), through a bibliometric analysis of 470 Scopus documents from 2010 to 2023, analyzed using SciMAT v1.1.04 software. It segments the research into two periods, 2010–2019 and 2020–2023, revealing a surge in MOO focus, particularly in the latter period, with a 35% increase in MOO-related research. This indicates a shift toward comprehensive energy ecosystem management that balances environmental, technical, and economic elements. The initial focus on MOO, genetic algorithms, and energy management systems has expanded to include smart grids and electric power systems, with MOO remaining a primary theme in the second period. The increased application of artificial intelligence (AI) in optimizing HMGS within the MOO framework signals a move toward more sustainable, intelligent energy solutions. Despite progress, challenges remain, including high battery costs, the need for reliable MOO data, the intermittency

of renewable energy sources, and HMGS network scalability issues, highlighting directions for future research.

3.1 Introduction

The global energy transition, aimed at achieving significant reductions in carbon emissions across both the energy industry and end-use sectors, necessitates the adoption of renewable energy sources (RESs) such as low-cost solar photovoltaic (SPV), onshore, and offshore wind. To meet the targets set by the International Renewable Energy Agency (IRENA) in the 1.5 °C scenario, a substantial increase in global renewable energy (RE) capacity is essential. This includes expanding the installed renewable electricity generation capacity to more than 11,000 GW [71]. Notably, this transition occurs amidst fluctuations in the energy market, as electricity prices have exhibited heightened volatility, especially during the 2020–2021 pandemic period, compared to preceding years [79]. This highlights the challenges and complexities of achieving renewable energy targets in a volatile energy price environment. According to the International Energy Agency (IEA), renewables are expected to account for 80% of new power capacity additions worldwide by 2030, with SPV alone contributing more than half of this increase. This substantial growth in RE capacity highlights viable strategies for addressing the global climate crisis as well as the fuel crisis in 2022 [38], as depicted in Figure 3.1.

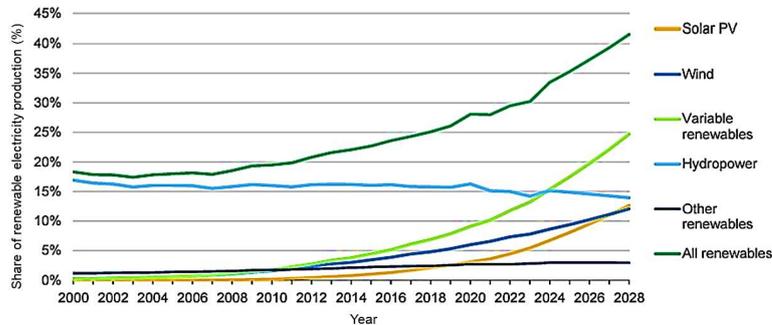


Figure 3.1: Share of renewable electricity production by source from 2000 to 2028 [38].

RESs play a crucial role as environmentally friendly alternatives but face significant challenges, notably the variability in energy production influenced by factors like solar intensity and wind availability. This issue can be addressed by integrating batteries with RESs to create hybrid renewable energy systems (HRESs) [44]. For enhanced reliability, particularly in off-grid installations or when connected to an unreliable grid where consistent power is critical, these systems may

incorporate conventional energy sources such as diesel generators (DGs). This integration broadens their functionality, forming what is known as hybrid energy systems (HESs). Such adaptation allows the systems to maintain power supply continuity and stability, even under variable environmental conditions or grid inconsistencies [67, 68]. To shed more light on these two systems, Table 3.1 provides a comparison between HESs and RESs from different aspects.

Table 3.1: Comparative analysis of RESs vs. HESs across multiple aspects.

Aspect		Renewable Energy Systems (RESs)	Hybrid Energy Systems (HESs)
Reliability		Weather-dependent, can be less reliable.	More consistent power supplies reduce reliance on a single source.
Economic		Higher initial cost, lower long-term operational costs.	More cost-effective long-term due to optimized resource use.
Security		Reduces reliance on imported fuels but is sensitive to environmental changes.	Enhanced security through diversified energy sources.
Environment		Minimal emissions, low environmental impact.	Potentially lower impact through optimized energy mix.
Maintenance requirements	Re-	Regular maintenance needed, varies by technology.	Potentially more complex maintenance due to multiple systems, but can be optimized for efficiency.
Stability		Can be unstable due to reliance on a single energy source.	Generally more stable due to diversified energy sources.
Technological advancement	Ad-	Dependent on specific technology advancements.	Benefits from advancements in multiple technologies.
Geographical suitability	Suit-	Depends on local resource availability.	Better adaptability to various geographical conditions.
Energy Storage and Distribution		Storage solutions are required for inconsistent supply.	More efficient storage and distribution with steady supply.

Economically and technically, HESs provide an optimal solution by ensuring energy supply stability when RESs alone are limited by environmental variability. By integrating multiple energy sources, HESs maintain consistent energy availability [19, 34, 78]. However, it is essential to acknowledge that HESs are not without limitations. Several challenges must be addressed for their successful implementation and widespread adoption. The following are some of these limitations.

1. **Technical Challenges:** HESs face complexities integrating multiple energy sources, ensuring grid stability, and maintaining a consistent energy supply amidst environmental variability [85]. These systems require sophisticated control mechanisms and robust infrastructure to manage diverse energy inputs and outputs effectively.
2. **Economic Feasibility:** High initial investment costs, ongoing operation and maintenance expenses, and funding challenges can pose barriers to the widespread adoption of HESs. A thorough economic analysis is essential for long-term sustainability [54]. This includes assessing the cost-benefit ratio, potential savings over time, and securing adequate funding for implementation.

3. **Environmental Impacts:** Assessing the environmental footprint of HESs and implementing strategies for mitigation are critical steps toward ensuring their positive impact on the environment [3]. This includes considering the life-cycle emissions, potential land use impacts, and ways to minimize negative environmental effects through innovative design and operation strategies.
4. **Research Scope:** The scope of research on HESs may be limited, potentially overlooking crucial factors like regional variations, scalability issues, and emerging trends.
5. **Social and Policy Implications:** Societal acceptance, public awareness, community engagement, and supportive policies are essential for the successful adoption of HESs. Understanding and addressing these social and policy factors is crucial for the transition to and operation of HESs. Supportive regulatory frameworks, incentives, and educational initiatives can significantly influence the adoption and effectiveness of these systems.

The integration of hybrid systems into the grid necessitates management to maintain operations independently from the main grid as required. This requirement has paved the way for the utilization of microgrids (MGs), which can operate in two modes: connected to the main grid or in an islanded (independent) mode, ensuring coordinated and controlled energy distribution. A microgrid (MG) is a self-sufficient system composed of interconnected loads and distributed energy resources within clearly defined electrical boundaries, acting as a single controllable entity with respect to the grid [81, 96]. This integration, referred to as hybrid microgrid systems (HMGSs), not only reduces costs and grid dependence but also lessens environmental impact [40]. The effective use of HMGSs relies heavily on appropriate sizing, simulation, and optimization software tools, which are crucial for avoiding exorbitant installation costs and ensuring the reliability of the power supply. These tools are instrumental in studying, evaluating, and optimizing resource use, playing a critical role in addressing these challenges. Their application enhances system efficiency and contributes to a more balanced and sustainable energy sector. The optimization of HMGSs has garnered significant attention, as evidenced by a bibliometric study spanning from 2005 to 2021. This study tracked over 2300 scientific papers, revealing a notable increase in publications on this topic. Various artificial intelligence (AI) techniques, tools, and software have been utilized to address challenges associated with HMGS implementation. These approaches have assessed HMGSs from multiple perspectives, including technical, economic, environmental, control, operation, and sizing aspects. Notably, the study identified the adoption of multi-objective optimization (MOO) as the most significant advancement in the field over the last five years [5]. This emphasizes

the pivotal role of MOO in enhancing decision-making processes for HMGS development and implementation, underscoring its necessity for detailed analysis. To comprehensively understand the application of MOO to HMGSs, this study is structured into three phases. The first phase focuses on reviewing mathematical models for prevalent HMGS configurations, laying the theoretical groundwork. The subsequent phase delves into critical economic and reliability metrics to evaluate HMGSs. The study culminates in the third phase, which conducts a bibliometric analysis and comparative case studies to identify research trends and gaps, as illustrated in Figure 3.2.

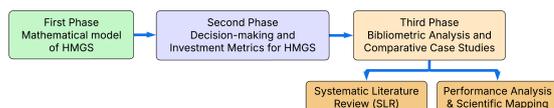


Figure 3.2: The methodological framework of the research on HMGS optimization.

3.2 Methodological Framework

As outlined in Figure 3.2, the study begins with the first phase, which concentrates on the mathematical modeling of HMGSs. This phase is crucial for establishing a solid theoretical foundation, providing the necessary groundwork for subsequent analysis.

3.2.1 First Phase: Mathematical Model of HMGSs

As mentioned earlier, HMGSs are financially beneficial for both current and future electricity supply needs. The most common form of these systems typically integrates SPV, wind, batteries, and DGs [41, 48]. MGs, with their ability to operate both autonomously and in conjunction with the main grid, increase resilience and offer flexibility in power distribution [12]. Figure 3.3 categorizes MG setups by function, demand, and capacity [26], highlighting the range and scalability of MG configurations.

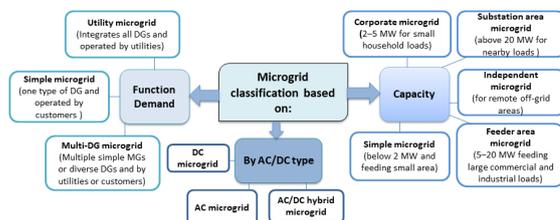


Figure 3.3: Categorization of MGs by demand, type, and capacity.

The subsequent subsections will detail the mathematical models of each component, offering a detailed understanding of their functions within HMGSs.

- SPV System

The SPV system within HMGSs includes the following key elements: SPV panels, an inverter, a charge controller, and a battery storage unit. Detailed discussions of each component will follow.

1. SPV: A solar cell, or photovoltaic (PV) cell, is a device that transforms light into electricity through the photovoltaic effect. The behavior of both an ideal SPV cell and a practical SPV device are typically represented in diagrams, such as those depicted in Figure 3.4.

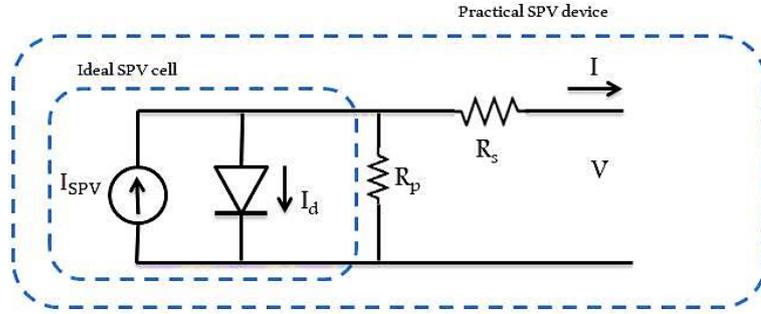


Figure 3.4: Equivalent circuits of an ideal SPV cell and practical SPV device.

The current–voltage relationship of an ideal solar cell is described by a fundamental equation from semiconductor theory, shown as Equation 3.1:

$$I = I_{\text{SPV,cell}} - I_{\text{O,cell}} \left[\exp \left(\frac{qV}{\alpha kT} \right) - 1 \right]. \quad (3.1)$$

Here, $I_{\text{SPV,cell}}$ is the SPV current generated by the cell due to incident light, $I_{\text{O,cell}}$ is the reverse saturation current of the diode, q is the charge of an electron ($1.60217646 \times 10^{-19}$ Coulomb), k is the Boltzmann constant ($1.38064852 \times 10^{-23}$ Joules/Kelvin), T is the absolute temperature (in Kelvin) of the diode junction, and α is the diode ideality factor. Since a practical SPV array has series resistance R_s and parallel resistance R_p , Equation 3.1 does not describe its I – V characteristic. Practical arrays consist of many interconnected SPV cells; this requires the addition of new parameters to the basic equation for accurate monitoring of characteristics in SPV array stations, as demonstrated in

Equation 3.2.

$$I = I_{\text{SPV}} - I_O \left[\exp \left(\frac{V + R_S I}{V_{t\alpha}} \right) - 1 \right] - \left(\frac{V + R_S I}{R_p} \right). \quad (3.2)$$

SPV array datasheets typically provide essential information, including the nominal open-circuit voltage ($V_{\text{oc,n}}$), the nominal short-circuit current ($I_{\text{sc,n}}$), the voltage at the maximum power point (MPP) (V_{mp}), the current at the MPP (I_{mp}), the open-circuit voltage/temperature coefficient (K_V), the short-circuit current/temperature coefficient (K_I), and the maximum experimental peak output power ($P_{\text{max,e}}$).

It is commonly assumed in SPV device modeling that the short-circuit current ($I_{\text{sc,n}}$) is approximately equal to the photovoltaic current (I_{SPV}). This assumption holds because, in practical devices, the series resistance is typically low, and the parallel resistance is high, affecting the overall performance.

The diode saturation current (I_O) is described by Equation (3.3):

$$I_O = \frac{I_{\text{sc,n}} + K_I \Delta T}{\exp \left(\frac{V_{\text{oc,n}} + K_V \Delta T}{\alpha V_t} \right) - 1}. \quad (3.3)$$

The maximum output power $P_{\text{max,m}}$ is calculated to the maximum experimental power $P_{\text{max,e}}$ when $P_{\text{max,m}} = P_{\text{max,e}}$, solving the resulting equation for R_s , as detailed in Equation (3.4).

$$P_{\text{max,m}} = V_{\text{mp}} \left\{ I_{\text{SPV}} - I_O \left[\exp \left(\frac{q(V_{\text{mp}} + R_s I_{\text{mp}})}{\alpha N_s k T} \right) - 1 \right] - \frac{V_{\text{mp}} + R_s I_{\text{mp}}}{R_p} \right\}. \quad (3.4)$$

SPV systems are classified into various configurations based on the application's requirements and the coupling of various power sources. Figure 3.5 depicts various SPV system configurations [80].

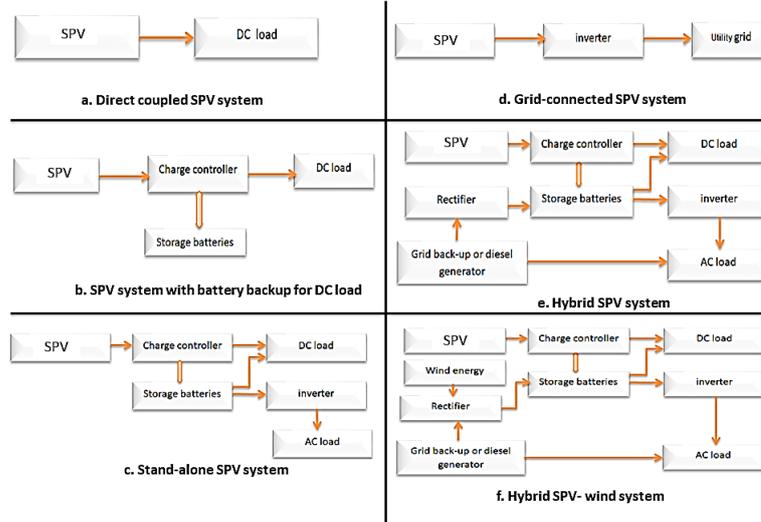


Figure 3.5: Types of SPV Systems.

2. Charge controller: A charge controller, also known as a charge regulator or battery regulator, moderates the flow of electric current to and from the batteries. This control prevents excessive charging and voltage spikes, which can damage the battery, reduce its efficiency, or pose safety concerns. In SPV systems, solar charge controllers adjust the power or DC voltage coming from the solar panels before it is directed to the batteries.
3. Inverter: Various inverter models exist, each tailored to the specific requirements of the load. The selection depends on the load's waveform needs and the inverter's efficiency. The choice is also influenced by whether the inverter is standalone or grid-connected. Inverter failure is a leading cause of malfunctions in SPV systems, presenting opportunities for engineers to improve inverter designs. The efficiency of an inverter (η_{inv}) is typically represented by the ratio of the output power (P_{out}) to the input power (P_{in}), mathematically expressed as:

$$\eta_{inv} = \frac{P_{out}}{P_{in}} < 1 \quad (3.5)$$

indicating that the output power (P_{out}) is always less than (P_{in}) due to inherent system losses. These losses can originate from various sources, such as component resistance, inefficiencies during semiconductor switching, and other imperfections.

4. Battery: A battery bank within HMGSs serves dual purposes: as a power source and for energy storage, balancing power needs over time.

Surplus energy from RESs is stored in the batteries, which then provide energy during low RES output due to adverse weather. Battery size, determined by the autonomy days (N) and the difference between load demand (E_L) and power from RESs (E_G), is calculated using:

$$C_B = N \cdot \frac{(E_L - E_G)}{\eta_B \times \eta_{\text{inv}} \times \text{DOD}} \quad (3.6)$$

where η_B denotes the battery's efficiency and η_{inv} signifies the efficiency of the inverter, with DOD referring to the depth of discharge [7].

- Wind Energy

It is crucial to recognize that the power output from a wind turbine (p) varies continuously due to changes in wind speed (V) and differing operational scenarios. To accurately calculate the average power output over a specific period, it is necessary to account for these fluctuations by integrating the power equation over that duration. Additionally, a wind turbine's power generation is capped by its rated power P_r , which is the maximum power it can generate under optimal wind conditions. The power output from a wind turbine, taking into account the rated wind speed (V_r), the cut-in speed ($V_{\text{cut-in}}$), and the cut-out speed ($V_{\text{cut-out}}$), is determined using the following equation:

$$P(V) = \begin{cases} 0, & \text{if } V < V_{\text{cut-in}} \text{ or } V > V_{\text{cut-out}}, \\ P_r \times \left(\frac{V^3 - V_{\text{cut-in}}^3}{V_r^3 - V_{\text{cut-in}}^3} \right), & \text{if } V_{\text{cut-in}} \leq V \leq V_r, \\ P_r, & \text{if } V_r \leq V \leq V_{\text{cut-out}}. \end{cases} \quad (3.7)$$

This formula becomes particularly relevant in calculating the power generation potential under varying wind speeds, from the point where the turbine starts operating ($V_{\text{cut-in}}$) to the speed beyond which it must stop to avoid damage ($V_{\text{cut-out}}$), including its optimal performance at the rated speed (V_r) [89].

- Diesel Generator (DG)

To accommodate power supply variability from RESs, systems operating off standalone setups or connected to unreliable grids often incorporate batteries to store surplus energy generated during peak times, which is then available for use during low production periods. However, due to limitations such as battery capacity and discharge rates, DGs offer an alternative or supplementary solution to ensure a consistent power supply. The hourly fuel consumption of a DG (G_t) is calculated using the following formula:

$$G_t = \gamma \cdot P_{\text{max}} + \beta \cdot E_t \quad (3.8)$$

where G_t represents hourly fuel consumption, γ (0.24) and β (0.084) are coefficients for converting fuel to electrical energy, P_{\max} is the generator's rated power, and E_t denotes the electrical energy produced during the hour. This equation helps in optimizing fuel usage in response to fluctuating RES outputs, enhancing the system's efficiency [6, 7].

3.2.2 Second Phase: Decision-Making Tools and Investment Metrics for HMGSs

This section outlines the essential metrics for evaluating the economic viability, reliability, sustainability, and investment return of HMGSs. These metrics are pivotal for stakeholders to make informed decisions regarding the implementation and operation of HMGSs.

- Decision-Making Tools (LCOE, LCC, NPC, LPSP, RF)

This section focuses on key decision-making tools that offer stakeholders a comprehensive understanding of the cost, reliability, and sustainability of HMGSs.

1. **Levelized Cost of Energy (LCOE):** This represents the average cost per unit of energy produced by a system throughout its lifecycle, incorporating all lifecycle costs. It is calculated as follows [11]:

$$\text{LCOE} = \frac{\sum_{t=0}^n \frac{C_t}{(1+r)^t}}{\sum_{t=0}^n \frac{E_t}{(1+r)^t}}. \quad (3.9)$$

where C_t is the total cost (capital, operating, maintenance) in year t , E_t is the electricity generated in year t , r is the discount rate, and n is the system's lifetime in years.

2. **Life Cycle Cost (LCC):** Encompasses the total cost of ownership of the HMGS during its lifespan, including installation, operation, maintenance, and decommissioning costs but excluding system depreciation [52]. The LCC is calculated using the equation

$$\text{LCC} = C_{\text{CCA}} + \sum_{t=1}^T \frac{C_{\text{OM},t} + C_{\text{rep},t} - S_t}{(1+I)^t}. \quad (3.10)$$

where C_{CCA} is the initial cost, $C_{\text{OM},t}$ the annual operation and maintenance costs, $C_{\text{rep},t}$ are the replacement costs, S_t the salvage values, T the system's lifetime, and I the interest rate per annum.

3. **Net Present Cost (NPC):** Calculates the present value of all costs and profits associated with the HMGS, offering a net-cost perspective over the system's lifecycle [83]:

$$\text{NPC} = C_{\text{CCA}} + \sum_{t=1}^T \frac{C_{\text{OM},t} + C_{\text{rep},t} - R_t}{(1 + R)^t}. \quad (3.11)$$

where R_t represents annual revenues or savings from operation, distinct from the salvage value S_t .

4. **Loss of Power Supply Probability (LPSP):** Defined as the ratio of the total time the system cannot meet the demanded load to the total observation period (often a year), it indicates the likelihood of power outages. It may be computed using the formula:

$$\text{LPSP} = \frac{\sum \text{Unmet Load Periods}}{\text{Total Observation Period}}. \quad (3.12)$$

5. **Renewable Fraction (RF):** Quantifies the fraction of total energy provided by RESs in the HMGS, a key metric for assessing system sustainability [35]:

$$\text{RF} = \frac{\text{Total Renewable Energy Generated}}{\text{Total Energy Generated}}. \quad (3.13)$$

Here, the *Total Energy Generated* represents the overall energy production of the HMGS, including both renewable and non-renewable sources.

- Investment Metrics (NPV, EPBT, PBP, ROI) Understanding the financial and environmental impacts is crucial for HMGS and RE system projects.

1. **Net Present Value (NPV):** Calculates the profitability of a project by discounting future cash flows to the present.

$$\text{NPV} = \sum_{t=1}^n \frac{R_t}{(1 + i)^t} \quad (3.14)$$

where R_t is net cash inflow–outflow during a single period t , i is the discount rate or the cost of capital, t is time in years, and n is the total number of periods.

2. **Energy Payback Time (EPBT):** Determines how long a renewable energy (RE) system takes to generate energy equal to its energy input over its lifespan. The EPBT formula is:

$$\text{EPBT} = \frac{\text{Total Energy Investment}}{\text{Annual Energy Production}} \quad (3.15)$$

Total Energy Investment refers to the overall quantity of energy used in the system’s development, installation, and operation, while Annual Energy Production is the amount of energy generated annually.

3. **Payback Period (PBP):** Assesses the time it takes for an investment to recoup its value through savings.

$$\text{PBP} = \frac{\text{Cost of Investment}}{\text{Annual Revenue Flow of Savings}} \quad (3.16)$$

4. **Return on Investment (ROI):** Measures profitability from an investor’s perspective.

$$\text{ROI} = \frac{\text{Net Profit}}{\text{Cost of Investment}} \times 100 \quad (3.17)$$

Here, Net Profit is the overall financial benefit from the HMGS after subtracting the initial and operational costs, while Cost of Investment encompasses the total initial cost of setting up the HMGS [23, 32, 63]. This comprehensive exploration provides insights into both the environmental and financial viability of HMGSs. The complexity of designing HMGSs necessitates the use of multi-objective optimization (MOO) to balance cost, reliability, and sustainability effectively. The subsequent section will explore MOO approaches in HMGSs through a bibliometric analysis, shedding light on key trends and influential research in this multidisciplinary area.

3.2.3 Third Phase: Bibliometric Analysis and Comparative Case Studies

This phase begins by delineating MOO from single-objective optimization (SOO). After establishing this fundamental knowledge, the research further explores the intricacies of bibliometric analysis.

Optimization Overview: Optimization tasks can be broadly classified into two categories: those with a single objective and those with multiple objectives. Let us delve into these concepts.

SOO: In basic terms, SOO focuses on optimizing one specific function. Formally, the objective is to either minimize or maximize $f(x)$, subject to constraints $g_i(x) \leq 0$ for $i = 1, \dots, m$ and $h_j(x) = 0$ for $j = 1, \dots, p$, where x is an n -dimensional vector, $x = (x_1, \dots, x_n)$, and belongs to the domain Ω .

MOO: Addresses problems involving multiple objectives, often leading to scenarios where improving one objective adversely affects another, creating a complex balance of trade-offs. Unlike SOO, where the optimal solution is clearly defined,

MOO requires a relative definition of ‘optimal’. A common method in MOO is to seek Pareto optimal solutions, where any improvement in one objective results in a deterioration of another. This makes MOO a challenge, as it is mathematically represented by multiple objectives that cannot all be maximized or minimized simultaneously due to inherent inter-objective constraints.

The general form of MOO is to ‘optimize’ $f_1(x), f_2(x), \dots, f_n(x)$, subject to $g_i(x) \leq 0$ for $i = 1, \dots, m$ and $h_j(x) = 0$ for $j = 1, \dots, p$, where x is an element of Ω .

Here, the term ‘optimize’ is as previously defined; each function $f_n(x)$ represents a unique objective function, where ‘ n ’ denotes the total number of objectives, and Ω signifies the feasible region or solution space, as noted in [18].

Figure 3.6 illustrates the differences between SOO and MOO processes, with a particular emphasis on the selection of a Pareto optimum solution.

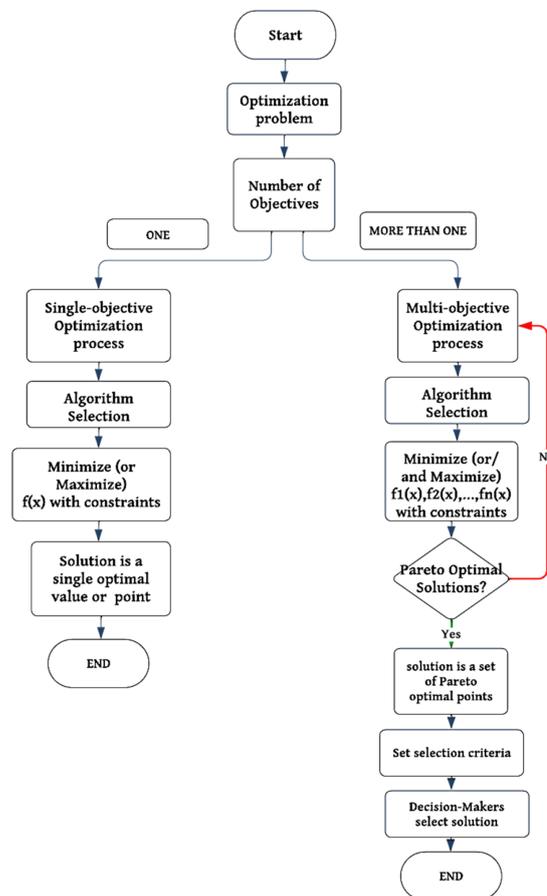


Figure 3.6: Decision flowchart for SOO vs. MOO processes.

The goal of MOO is to optimize solutions across multiple, sometimes con-

flicting, criteria simultaneously. This approach introduces the concept of Pareto optimality, where a solution is considered Pareto optimum if any further improvement in one objective would necessarily worsen at least one other objective [4]. The collection of all such Pareto optimum solutions forms the Pareto front, also known as the Pareto border. Often, no single solution satisfies all objectives optimally, leading decision-makers to rely on this set of Pareto optimum solutions to make choices based on their preferences or other considerations [69]. MOO is particularly crucial in HMGSs, balancing complex and varied objectives such as cost, efficiency, and environmental impact [14, 66, 70]. As such, MOO strategies are instrumental in navigating the trade-offs inherent in decision-making processes, enabling the integration of cost-effectiveness with sustainability.

Bibliometric Analysis

Bibliometric analysis is a popular and effective method for examining large volumes of scientific data. It facilitates the exploration of the evolutionary dynamics of a specific topic and highlights emerging areas [22]. Figure 3.7 illustrates the steps of the bibliometric analysis used in this study, employing a dual analysis approach to achieve its objectives.

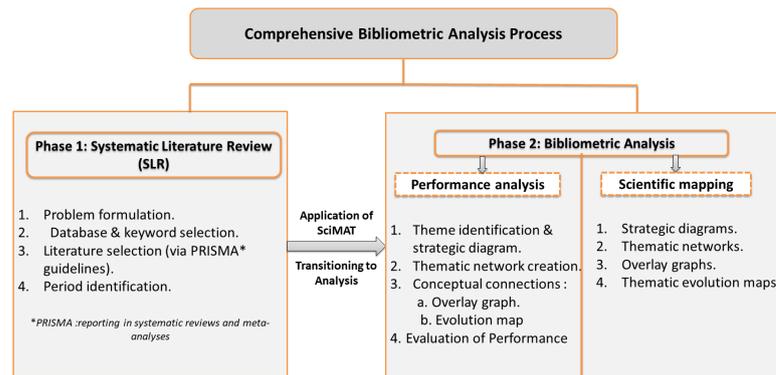


Figure 3.7: Workflow of bibliometric analysis process.

This analysis comprised the following steps: (i) a systematic literature review (SLR) on MOO as applied to MGs integrated with RESs and (ii) a bibliometric analysis focusing on performance analysis and scientific mapping. The subsequent sections briefly describe each of these phases.

First phase: Systematic literature review (SLR):

The literature review structure follows best practices detailed in [22] (see Figure 3.7) and was conducted through the following steps:

1. Problem planning and formulation: This initial step establishes the foundation for the study, involving the framing of research questions, deciding

on relevant literature criteria, methods for filtering unrelated findings, and outlining possible conclusions.

2. Database(s), keywords, and search string determination: A range of databases was chosen, and a set of important terms was identified for searching. Selecting appropriate terms is crucial to encompass varied research while remaining focused on relevant articles.
3. Literature selection: At this stage, adherence to the PRISMA guidelines, which pertain to systematic reviews and meta-analyses, ensures that the selected articles align with the study's direction [49]. Insights from these articles were systematically extracted.
4. Period identification: This step involves considering elements like the topic's depth, existing literature, and its evolution over time.

Second phase: Bibliometric analysis:

Following the SLR, a bibliometric analysis is conducted in the second phase. This combines scientific mapping, describing the conceptual structure and development of the research, with a performance analysis that assesses the impact of citations. The goal is to demonstrate the relationships among authors, documents, and disciplines. The analysis was performed using SciMAT v1.1.04, an open-source tool that involves the following:

1. Theme identification and strategic diagram: Initially, the software sets up the equivalency index. It then employs a specific methodology to identify the most relevant topics. Subsequently, using the concepts of centrality and density, it strategizes for every theme, illustrating how the core research and related subjects are interconnected. Centrality refers to the degree of influence a theme has over others in the network. Themes with high centrality are vital and positioned on the right side of the diagram. Density analyzes the relationships between terms within a theme to determine its development level. Themes with high density are considered well-developed and placed toward the top of the diagram [13, 55]. The diagrams, divided into four sections, as shown in Figure 8, illustrate the various research topic categories.
 - Driving themes: Important and well-understood subjects in the top right, essential for research growth.
 - Highly developed and isolated themes: Topics that stand alone and are well-understood, found in the top left, specialized but separate from the main research.

- Evolving or receding themes: Topics in the bottom left that are not fully developed or currently significant. Their importance may increase or decrease in the future.
- Cross-cutting basic themes: Fundamental subjects important to the research but not yet fully developed, occupying the lower right section of the quadrant.

2. Thematic Network Creation: This explores relationships between keywords and subjects to refine strategic diagrams. Each network depicted in Figure 3.8 is named after its principal keyword. The size of the circles indicates the number of associated papers, while the thickness of the links is determined by the equivalence index.

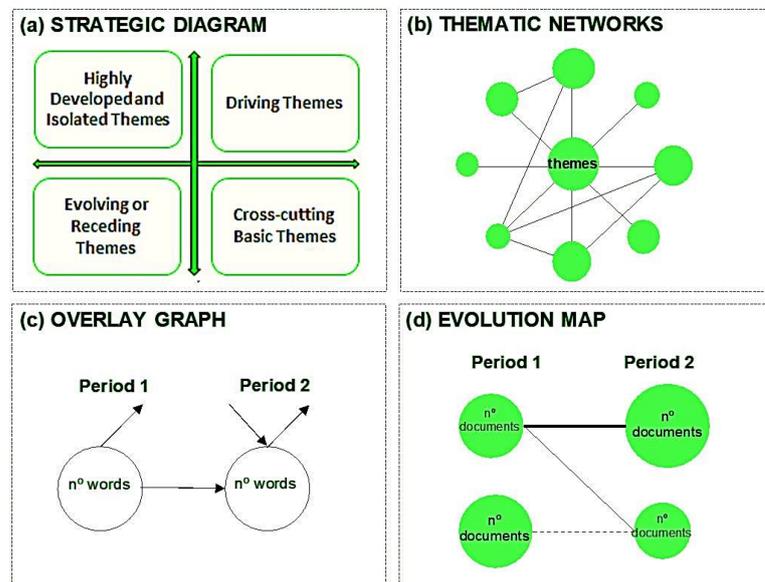


Figure 3.8: Visual representation of research theme analysis and evolution.

3. Conceptual Connections: The inclusion index [20] illustrates how themes are interconnected over time:
- Overlay Graph: Shows prevalent terms alongside keywords that have been added or removed over time.
 - Thematic Evolution Map: Dotted lines represent sub-elements, and solid lines indicate connections to the primary theme. The size of circles and the thickness of lines signify the number of documents and the inclusion index, respectively.

4. Evaluation of Performance: Evaluates research contributions using various metrics. It identifies leading subfields based on indicators such as the number of articles, citation counts, and variations in the h-index.

3.3 Findings and Analysis

The results from the prior sections are detailed and can be viewed in Figure 3.7, Figure 3.8, Figure 9, Figure 10, Figure 11, Figure 12 and Figure 13 as well as Table 2, Table 3, Table 4 and Table 5.

3.3.1 SLR on the Application of MOO for HMGSs

This study aims to explore the current landscape of knowledge concerning the MOO of MGs integrated with RESs, herein referred to as HMGSs. To guide this exploration, the investigation was formulated around the following research questions (RQs):

- RQ1: How is current research evolving in the selected field?
- RQ2: Which core ideas shape this area of study?
- RQ3: Which challenges currently persist in this research domain?
- RQ4: What are the pivotal moments or crucial issues related to the topic?
- RQ5: What topics attract significant focus and discussion?
- RQ6: What gaps or shortcomings can be identified in current studies?
- RQ7: Which publications or studies are considered seminal in this field?
- RQ8: Who are the leading contributors or prolific writers in this sector of research?

This study utilized the SCOPUS database, which houses numerous significant global scientific publications across various fields. The review focused on micro-grids, renewable energy systems, and multi-objective optimization. Keywords relevant to these topics were applied in an advanced SCOPUS search as follows:

TITLE-ABS-KEY (“microgrid” OR “micro grid” OR “micro-grid” OR “micro-grids”) AND (“renewable energy” OR “renewable energy sources” OR “renewable energy systems” OR “hybrid energy” OR “distributed energy resources” OR “hybrid energy systems” OR “hybrid energy sources” OR “hybrid renewable energy system”

OR “hybrid power system”) AND (“multiobjective optimization” OR “multiobjective optimisation” OR “multi objective optimization” OR “multi objective optimisation” OR “multi-objective optimization” OR “multi-objective optimisation” OR “multi-objective programming” OR “multiobjective programming” OR “vector optimization” OR “multicriteria optimization” OR “multiattribute optimization” OR “Pareto optimization”). A systematic literature review (SLR) was conducted following the PRISMA flowchart guidelines depicted in Figure 3.9.

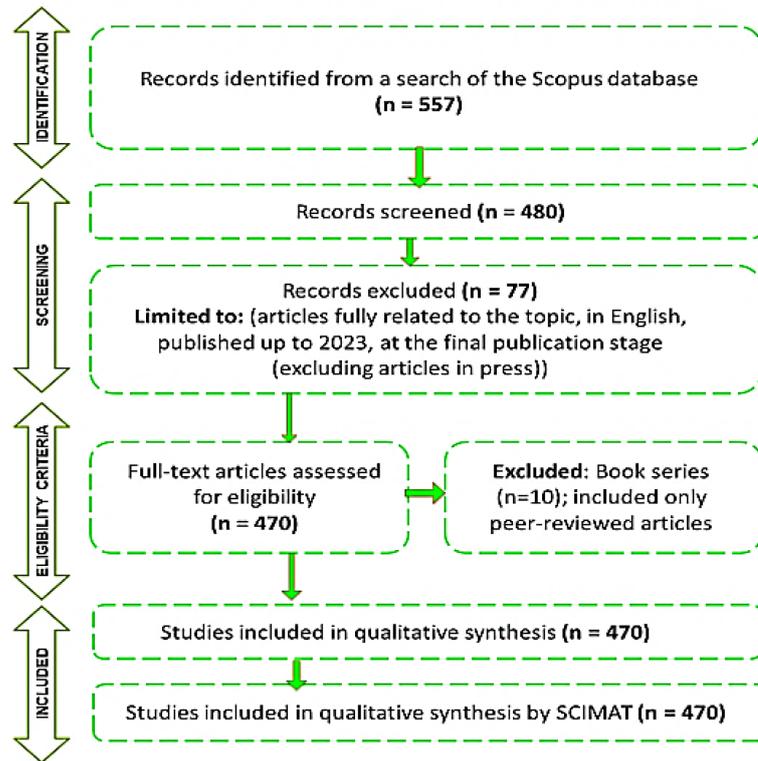


Figure 3.9: PRISMA flow diagram of article selection from the Scopus database.

Initially, 557 bibliographic records were retrieved from the Scopus database. The selection was refined by applying specific exclusion criteria, leading to the removal of 77 records. These criteria included relevance to the research topic, language (with a focus on articles in English), publication date (considering articles published up until 2023), and publication status (excluding articles in press). In the subsequent eligibility phase, book series were excluded due to their format, resulting in the elimination of an additional 10 sources. This refinement process ensured that the final selection comprised articles directly relevant to the research topic. After the final round of eliminations, 470 pertinent papers remained for analysis. To study publication trends from 2010 to 2023, the timeframe was divided

into two periods based on the number of selected papers and relevant milestones. **First period (2010–2019):** 200 articles were recorded. During this period, the US Department of Energy (DOE) held its first workshop on microgrid research areas. SPV module prices saw a significant drop, falling below USD 1 per watt in 2011. The year 2015 was pivotal for RESs, marked by the approval of the United Nations Development Goals (SDGs), specifically target 7.2 of goal 7, and the Paris Climate Conference [84]. The main objective of the Paris Conference was to limit global temperature rises to below 2 °C this century, with RE playing a key role.

Second period (2020–2023): 270 articles were recorded. During this period, research surged, driven by the urgency to address climate change and reduce reliance on fossil fuels. A notable outcome from the DOE Smart Grid R&D Program workshop was the creation of an MG-focused MOO framework using quantitative metrics and dynamic programming, along with the development of specific design tools and a solutions library by 2020 [82]. Figure 3.10 shows the distribution over time of 470 publications, revealing consistent growth in this field.

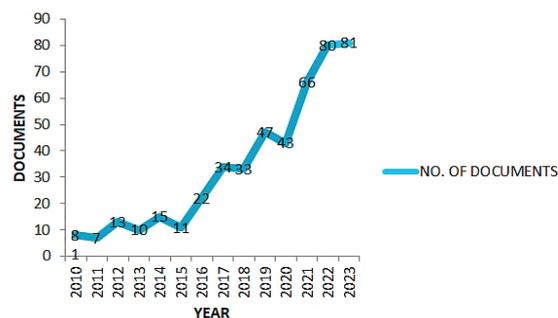


Figure 3.10: Yearly distribution of documents.

3.4 Bibliometric Analysis: Insights from Science Mapping and Performance Metrics

This section examines various graphical analyses, including strategic diagrams for each period, critical thematic networks, an overlay graph, and a thematic evolution map. Additionally, it assesses the timeline progression of documents, citation counts, top-cited authors, and the overall quality and quantity of the publications.

3.4.1 Strategic Diagrams

Figure 3.11 depicts strategic diagrams for the periods 2010–2019 and 2020–2023, respectively, illustrating the popularity of research subjects based on publication volume.

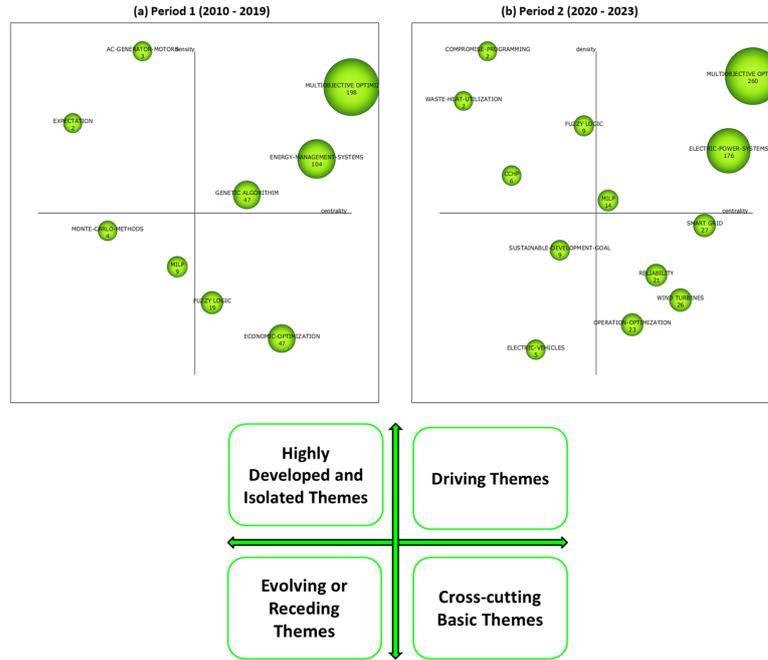


Figure 3.11: Strategic diagrams for ((a) period 1; (b) period 2).

The size of each circle in the diagram indicates the relative volume of publications for each research theme. Table 3.2 summarizes the performance metrics for each theme and period, including the number of documents, h-index, centrality, density, and publication count, providing a quantitative overview of the impact and relevance of each theme within the specified periods. Following is a brief overview of the results for each time period.

First period (2010–2019):

The analysis of 200 selected articles identified 10 research topics, as shown in Figure 3.11's strategic diagram. Three themes—multi-objective optimization, energy management systems, and genetic algorithms—were identified as driving themes, indicating their significance in shaping the field's direction. AC generator motors and expectancy emerged as well-developed yet isolated themes, highlighting areas of focused but separate research. Monte Carlo techniques and MILP were classified as evolving or receding themes, suggesting areas of diminishing focus or emerging interest, while fuzzy logic and economic optimization were identified as foundational yet underdeveloped areas. A comprehensive performance study, as summarized in Table 3.2, alongside the strategic diagram's insights, revealed that MOO and energy management systems exhibited superior performance metrics, notably achieving the highest h-index values with over 16,000 citations.

Table 3.2: Theme-specific performance metrics.

Name of Clusters	Documents Count	h-index	Citations Count	Centrality	Density
Period 1 (2010–2019)					
Multiobjective optimization	198	51	9630	373.74	131.48
AC generator motors	3	3	16	59.44	242.5
Energy-management systems	104	43	7351	226.49	24.94
Genetic algorithm	47	19	2956	126.1	19.49
Economic optimization	47	20	2630	134.23	8.16
Fuzzy logic	19	11	1839	89.02	9.76
MILP	9	7	472	70.22	10.63
Expectation	2	1	13	6.49	44.44
Monte Carlo methods	4	4	177	8.82	16.67
Period 2 (2020–2023)					
Multiobjective optimization	260	30	3347	363.59	135.68
Electric-power systems	176	29	2795	245.16	25.61
MILP	14	9	436	46.55	9.67
Smart grid	27	14	686	65.42	8.09
Fuzzy logic	9	5	193	39.26	47.41
Operation optimization	23	9	324	48.7	4.23
Wind turbines	26	9	381	61.39	4.34
Reliability	21	12	365	54.4	4.84
Sustainable-development goal	9	5	116	24.09	6.92
CCHP	6	4	101	16.65	19.67
Compromise programming	2	1	6	5.73	150
Waste-heat utilization	2	1	5	2.81	77.78
Electric vehicles	5	3	121	17.9	3.45

Second period (2020–2023):

Analyzing 270 papers from this more recent period yielded 13 research themes, as depicted in Figure 3.11b’s strategic diagram. This period saw three driving themes—multi-objective optimization, electric power systems, and MILP—indicating continued or emerging importance. Four themes—fuzzy logic, compromise programming, waste heat utilization, and CCHP—were recognized as developed but isolated, reflecting specialized areas of research with limited cross-theme integration. Sustainable development goals and electric vehicles emerged as evolving or receding themes, pointing to shifting research priorities, while wind turbines, reliability, operation optimization, and smart grids were identified as basic yet foundational themes. Notably, MOO and electric power systems stood out in performance measurements, exhibiting superior h-index and citation impact, as detailed in Table 3.2. It is worth noting that, over the examined periods, the mixed integer linear programming (MILP) theme shifted from ‘evolving or receding’ to a ‘driving’ theme, suggesting an increase in its significance and centrality. Concurrently, fuzzy logic progressed from a ‘basic’ to a ‘developed but isolated’ theme, indicating its specialized growth despite limited connection with broader research themes. These transitions illustrate the dynamic nature of research landscapes, emphasizing the importance of tracking topic evolutions to guide future studies. In the context of evolving research approaches, studies such as [64] have MILP to

optimize energy management and sizing in HMGS, resulting in significant cost savings and improved resource allocation efficiency. Reference [43] applied MILP to simplify the complexity of energy system scenario analysis, thereby enhancing the manageability and strategic planning of MGs. Reference [86] describes an energy management system for MGs that leverages fuzzy logic for efficient energy dispatch and forecasting. This system adapts to variations in RESs and incorporates expert rules, thereby improving reliability and economic returns. During the first period, MOO and genetic algorithms were prominent; ref. [76] showed a multi-objective genetic algorithm (MOGA) optimizing system design for size, cost, and availability using high-resolution insolation data, demonstrating a complete techno-economic analysis. Energy management systems were central in the first period, indicating an increasing emphasis on energy efficiency, with ref. [75] developing an optimal management approach for smart-grid sustainability, cost reduction, and carbon emission minimization while incorporating uncertainties and dynamic conditions over a 24-h cycle. Economic optimization appeared as a basic theme; ref. [29] identifies optimal HMGS capacities for reduced costs and environmental impact, alongside a strategy cutting diesel use by 12%, emphasizing the economic aspect. MILP and fuzzy logic emerged as emerging themes, signaling the start of their path to becoming important methodological tools. Furthermore, the use of Monte Carlo techniques, as noted in [51], indicated the use of probabilistic approaches in system analysis and design, which is critical for dealing with uncertainties in [31]. Moving into the second period, there was a notable shift. MOO remained a significant topic, whereas MILP gained prominence and relevance, becoming a key theme in the research environment. The expanding relevance of electric power systems and smart grids, as shown by an emphasis on renewable-rich HMGSs [45], demonstrates the trend toward integrating intelligent technologies for optimal energy distribution while balancing cost, availability, and area limits. Emerging areas like Sustainable Development Goals, electric vehicles, and wind turbines gained focus, signaling a shift toward sustainable and renewable energy solutions. Since 2022, the movement toward clean energy has increased, as seen by a 55% rise in electric vehicle sales, which have surpassed 10 million [37]. Notably, this includes considering the total cost of ownership for electrifying heavy-duty trucks, a critical aspect of the transportation sector's low-carbon transition [62]. Meanwhile, topics like combined cooling heating and power (CCHP) and waste-heat utilization exhibited a continuous yet concentrated focus on specific energy optimization and recovery techniques, demonstrating a sophisticated approach to RE integration, as evidenced in research sources [46, 58]. This illustrates a substantial push toward different sources of clean energy, where heat pumps have registered an 11% rise in sales, reaching the 15% growth rate required to fully align with the Net Zero Scenario [36]. Finally, the movement in research subjects from basic methodology

to advanced technological applications reflects the field’s growing emphasis on sustainability and intelligent energy solutions. The study underscores the significance of flexibility and innovation in solving complex optimization problems, paving the way for future research to enhance the efficiency and resilience of energy systems. This synthesis not only illustrates the field’s dynamic nature but also highlights the importance of MOO collaboration in advancing the energy transition.

3.4.2 Thematic Networks

To investigate the thematic networks, a key topic was chosen for each period to examine its relationships with other subjects, revealing the underlying themes associated with the main theme. Consequently, ‘MOO’ (see Figure 3.12a) and ‘Electric Power Systems’ (see Figure 3.12b) were selected as the driving themes from the first and second periods, respectively.

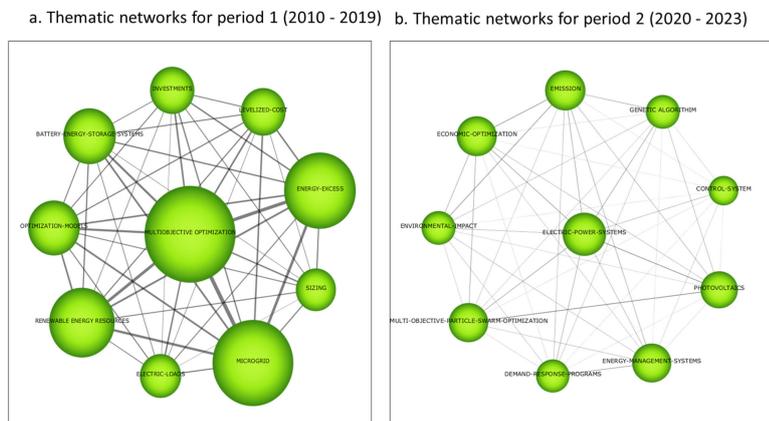


Figure 3.12: Thematic networks for ((a) period 1; (b) period 2).

The analysis in Figure 3.12a underscores the pivotal role of MOO within MGs, emphasizing its strong connections to ‘Microgrid’, ‘Renewable Energy Resources’, and ‘Electric Load’. This highlights how MOO is crucial for balancing objectives such as aligning energy supply with demand, integrating RE smoothly into the grid, and enhancing the efficiency and effectiveness of MG operations. In contrast, Figure 3.12b focuses on the ‘Electric Power Systems’ theme, detailing its complex interactions with key MOO algorithms like ‘Genetic Algorithm’ and ‘Multi-Objective Particle Swarm Optimization’. This underscores the vital role these advanced algorithms play in enhancing the efficiency of electric power systems, particularly in terms of renewable energy integration and demand management. It delves into ‘control systems’, ‘energy management systems’, and ‘demand response programs’, underscoring the importance of these areas in the broader context of

electric power systems optimization. The pronounced use of meta-heuristic methods, especially genetic algorithms, showcases their capability to tackle complex challenges in the energy sector [56]. This dual analysis allows us to compare the evolving focus from MOO's application within MGs to the broader challenges of integrating advanced algorithms for optimizing electric power systems. The visualizations also underscore key operational, financial, and efficiency concerns in both periods, from 'Levelized Cost' and 'Sizing' to 'Emission' and 'Environmental Impact', reflecting the sector's shift towards not only technical and operational efficiency but also environmental and economic sustainability.

3.4.3 Graphical Overlay and the Evolution of Theme Mapping

Figure 3.13 displays two critical aspects of the analysis: Figure 3.13a presents an overlay graph depicting the evolution of keywords over the study periods, while Figure 3.13b illustrates a thematic evolution map that outlines the shifts and relationships within the research themes. Figure 13a illustrates the changing quantity and content of keywords over the years. The number of keywords increased from 726 to 890 from the first to the second period, demonstrating growth rate. Of 726 keywords found in the first period, 27% (196 keywords) were retained in the second period. Additionally, 694 new keywords were added, bringing the total to 890 keywords during the later period. This indicates a significant introduction of new and transitional keywords, as well as overall growth in keyword count over time, suggesting that the field is becoming more thematically diverse. The recurrence of certain phrases in subsequent periods indicates that this emerging subject is increasingly being normalized. The thematic evolution map (Figure 3.13b) emphasizes the evolving nature of the research landscape. The MOO node's prominent placement and size reflect a large concentration of investigations and an extensive range of publications in this field, highlighting its ongoing significance and progress within the HMGS domain. Thematic shifts from 'Energy Management Systems', 'Genetic Algorithm', and 'Economic Optimization' in the first period to 'Electric Power Systems' in the second period indicate a move toward integrating these fundamental concepts into a larger framework of power systems. This demonstrates a growing area in which theoretical models are increasingly being applied to real-world energy systems. The map also shows 'Economic Optimization' branching into themes like 'MILP', 'Operation Optimization', and 'Reliability' in the second period, showing the sector's emphasis on operational efficiency, advanced modeling, and reliability of systems. 'MILP' additionally evolves to 'CCHP', 'Wind Turbine', and 'Smart Grid', indicating its analytical importance in optimizing complex energy systems and incorporating renewable technology.

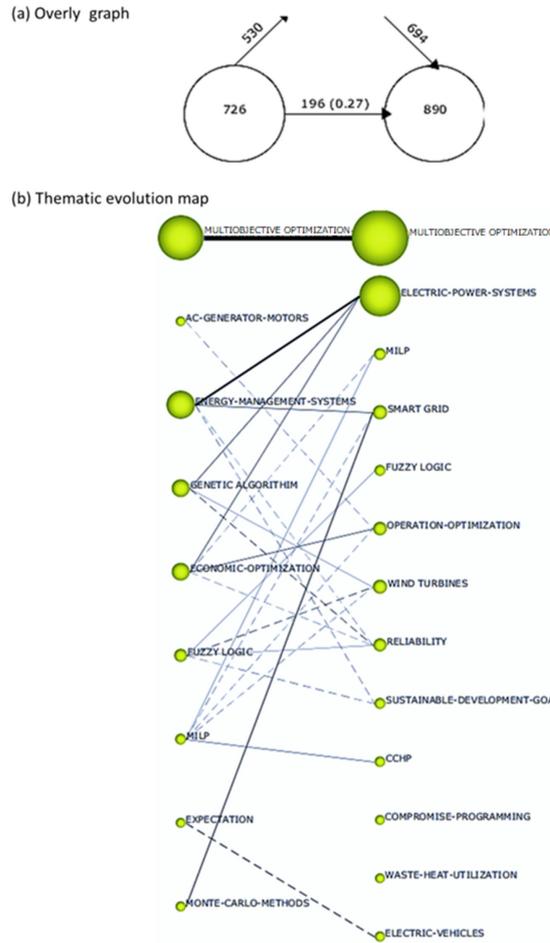


Figure 3.13: (a) Overly graph, (b) Thematic evolution map.

Notably, in the first period, ‘Fuzzy Logic’ connects with itself and progresses to ‘Wind Turbine’, ‘Reliability’, and ‘Sustainable Development Goals’ in the second period, demonstrating its use in mitigating uncertainty in RESs [2], enhancing system dependability, and contributing to sustainability goals. This relevance extends to addressing the complexity of power system outages through innovative strategies like the N-K events scale reduction technique and fuzzy zero-violation clustering for optimizing directional overcurrent relays (DOCRs) [95]. It is worth noting that four topics from the first period migrated to ‘Reliability’ and three others to ‘Electric Power Systems’ in the second phase. This trend reflects a research environment in which power system dependability is becoming more important, driven by the integration of varied energy sources and the need for strong power system infrastructures [24]. Overall, the map depicts a field undergoing significant transformation, with MOO and other modeling techniques being employed to

tackle novel challenges in power systems. The clearly strong thematic connections and the increasing focus of research underscore a sector on the cusp of innovation. This sector is increasingly driven by concerns for sustainability and economic efficiency, spurred by the need to integrate a variety of RESs into reliable and efficient power systems.

3.4.4 Evaluation of Performance

This study analyzed 245 journals. Table 3.3 displays the top 10 journals, which contributed 151 papers, accounting for 32.13% of the total documents evaluated.

Table 3.3: Key journals contributing to the study area.

Name of the Journal	Documents Count	Total Citations	Most Cited Document	Citations Count
Energy	26	2391	[57]	490
Energies	24	264	[91]	29
IEEE Access	22	265	[74]	41
Applied Energy	17	1449	[66]	357
Int. J. Electr. Power Energy Syst.	15	443	[59]	121
Renewable Energy	10	905	[70]	360
Sustain. Cities Soc.	10	386	[53]	121
Energy Convers. Manag.	10	609	[61]	200
J. Clean. Prod.	9	338	[72]	164
IET Renew. Power Gener.	8	271	[28]	96

Additionally, the table displays the most cited document from each journal. These top-cited publications predominantly discuss the development of MGs optimization and management methods, with a focus on the proper integration of RESs. Key concerns highlighted include increasing energy efficiency, ensuring reliability amidst uncertainties (such as fluctuations in wind and SPV), and balancing environmental and economic objectives within MG operations. The SLR conducted for this investigation identified 1369 authors who have contributed to the examined topic, as shown in Table 3.4.

Table 3.4: Key authors in the research area.

Authors' Names	Documents Count	Total Citations	H-Index	Most Cited Document	Citations Count
Yue Wang	8	186	12	[16]	128
Hongdong Wang	8	130	12	[25]	102
Josep M. Guerrero	8	131	13	[74]	41
Tomnoby Senjyu	6	57	9	[33]	33
Meenakshi De	6	57	5	[17]	20
Yuanzheng Li	6	25	3	[47]	12
Yongjun Zhang	6	71	3	[92]	34
Ziqiang Wang	6	101	14	[93]	52
Maria Luisa Di Silvestre	6	445	22	[30]	147
Hesen Liu	6	53	9	[94]	27

The above table lists authors who have published more than five articles, along with their total number of citations and h-index, an indicator assessing an author's

influence and quality based on the frequency with which their research is cited. The articles primarily discuss energy storage management, control techniques, and the optimization of MG operations under uncertainty, with an emphasis on MOO approaches that balance technical, economic, and environmental considerations. The SLR concluded by finding the most-cited papers within the area of the review. Out of the 470 documents analyzed, a total of 12,989 citations were recorded. The top ten most-cited papers, which are detailed in Table 3.5 and account for 3384 citations, or 26% of the total citations observed, largely address the optimization and efficient energy management of MGs employing MOO methods, with an emphasis on the integration of RESs and HESs. Critical topics explored include optimal size, economic dispatch, and the creation of powerful algorithms for boosting the sustainability and reliability of MG operations.

Table 3.5: Top-cited documents in the study.

Authors' Names	Year	Citation Counts	Most-Cited Document
Chaouachi, A., Kamel, R.M., Andoulsi, R., Nagasaka, K.	2013	545	[15]
Niknam, T., Moghaddam, A.A., Seifi, A., Alizadeh Pahlavani, M.R.	2011	490	[57]
Ramli, M.A.M., Bouchekara H.R.E.H., Alghamdi, A.S.	2018	360	[70]
Niknam, T., Azizipanah Abarghoee, R., Narimani, M.R.	2012	357	[66]
Aghajani, G., Ghadimi, N.	2018	347	[1]
Borhanazad, H., Gounder Ganapathy, V., Mekhilef, S., Mirtaheer, A., Modiri-Delshad, M.	2014	342	[10]
Eriksson, E.L.V., Gray, E.	2017	264	[24]
Basu, A.K., Bhattacharya, A., Chowdhury, S., Chowdhury, S.P.	2012	250	[8]
Balog, R.S., Shadmand, M.B.	2014	217	[76]
Abapour, S., Mohammadi-Ivatloo, B., Nazari-Heris, M.	2017	212	[65]

3.5 Comparative Analysis of MOO in HMGs: Evaluating Techniques and Algorithms for Enhanced Performance and Sustainability

Table 6 presents a comprehensive review of the evolution in MOO techniques applied to HMGs from 2010 to 2023, showcasing how these methodologies have addressed changing technological challenges and advancements. The table is organized into two distinct periods, highlighting specific challenges and developments in each era. Studies were meticulously selected for their relevance to the key challenges in HMGs design, their contributions to advancing MOO methodologies, and their impact within the field, as evidenced by their citation metrics.

Table 3.6: Comparative analysis of HMGS optimization techniques.

System Components (Ref.)	Primary Objective	Optimization Technique	Key Findings	Algorithm Performance Comments
First Period (2010–2019)				
SPV, WT, DG, BT [70]	Optimization of component sizing for economic efficiency and system reliability in HMGS	MOSaDE	The study utilizes the MOSaDE algorithm to optimize the sizing of components in an HMGS in Yanbu, Saudi Arabia, focusing on cost-effectiveness and reliability. ‘Sizing’ in this context involves determining the optimal capacity and configuration to achieve economic efficiency while maintaining system performance. The analysis demonstrates the algorithm’s effectiveness in adapting to varied operational scenarios and its impact on reducing the cost of energy (COE). It confirms the practicality and adaptability of the optimization approach, emphasizing its real-world applicability across different settings.	The MOSaDE algorithm has proven highly effective in optimizing HMGS in this study, adeptly handling multiple objectives such as cost, reliability, and integration of renewable energy sources (RESs). Its ability to generate a Pareto front of solutions enhances the versatility of design options, offering a spectrum of optimal solutions tailored to varying priorities. Additionally, the algorithm’s flexibility is underscored by its successful application across different system components, demonstrating its adaptability in real-world settings.
SPV, CCHP, GSHP, BT [88]	Minimizing LCOE, reducing CO ₂ emissions, and alleviating uncertainties	MOCE	The integrated scheduling approach for MGs addresses uncertainties caused by intermittent RESs and random loads. Load shifting is introduced as an effective demand response program for industrial customers. The MOCE algorithm minimizes costs and emissions under worst-case scenarios of uncertainties, with robust sets and budgets of uncertainty capturing these effectively. The strong duality-based model transformation method addresses coupling and nonlinearity in the system’s formulation. Comparative experiments confirm the approach’s superior performance in attenuating disturbances and achieving optimal economic and environmental benefits, outperforming traditional single-objective robust optimization and deterministic MOO approaches.	The MOCE algorithm is selected for its high accuracy and straightforward approach to addressing the proposed formulation. It conceptualizes the optimization problem as an estimation issue, utilizing importance sampling techniques to accurately estimate parameters of probability density functions. Proven highly effective in MOO, this method not only meets all optimization objectives but also delivers a robust solution to the MG scheduling problem under uncertain conditions. This study particularly highlights the algorithm’s capability to efficiently handle complex scenarios, making it a reliable choice for real-world applications.

Continued on next page

Table 3.6 – continued from previous page

System Components (Ref.)	Primary Objective	Optimization Technique	Key Findings	Algorithm Performance Comments
SPV, WT, BT, DG [39]	Minimizing LCOE, reducing CO ₂ emissions, and lowering the LPSP	GA	The author utilizes Pareto front solutions to address a MOO problem, focusing on three critical dimensions: investment costs, emission pollution, and power loss. The optimization process employs a GA, adeptly managing both technical and economic constraints. This method is effective in both grid-connected and standalone HMGS operation modes. The study is particularly noted for its ability to balance the intricate interplay of cost, environmental, and efficiency objectives, presenting a comprehensive and balanced approach to MG planning and resource optimization.	The GA is valued for its effectiveness in solving complex optimization problems. It is particularly suitable for tasks such as DER planning, where both technical and economic constraints are involved. The GA excels in finding optimal solutions within multi-dimensional objective spaces, as demonstrated in this study by its application to the MG across various operational modes.
WT, SPV, BT, MT, FC [2]	Minimize cost and emissions, with and without responsive loads	MOPSO, fuzzy logic	The study utilized MOPSO, complemented by a fuzzy-based mechanism and a non-linear sorting system, to optimize operations, aiming to reduce operating costs and emissions. Including responsive loads notably decreased power generation by WT and SPV during peak hours. Additionally, the implementation of DR programs led to a 24% reduction in operating costs and a 16% decrease in emissions.	In this study, MOPSO proved highly effective in achieving the dual objectives of cost reduction and emission control, demonstrating significant enhancements in both operational efficiency and environmental impact.
WT, SPV, BT, DG [10]	Minimizing LCOE, reducing LPSP, ensuring RES-based supply	MOPSO	The study demonstrated that MOPSO effectively optimized the system configuration and component sizing, focusing on reducing LCOE and LPSP. Results highlighted the effective use of wind and solar energy in various regional contexts, showing notable enhancements in energy reliability and cost efficiency. The sensitivity analysis validated the optimization outcomes, suggesting that the implementation of hybrid systems can significantly improve access to reliable and sustainable energy in remote areas.	MOPSO was successful in optimizing the system for cost-effectiveness and reliability, demonstrating its utility in managing complex energy systems with a focus on renewable resources.

Continued on next page

Table 3.6 – continued from previous page

System Components (Ref.)	Primary Objective	Optimization Technique	Key Findings	Algorithm Performance Comments
WT, SPV, MT, FC, CHP, storage [60]	Minimize total operational cost and emissions in CHP MG	MBFO, fuzzy method	The study introduced an integrated energy management system (IEMS) for a CHP-based MG, employing MBFO and an interactive fuzzy satisfying method to minimize operational costs and emissions. This system efficiently managed total electrical and thermal load demands, effectively balancing economic and environmental criteria.	According to the study results, MBFO, enhanced by the interactive fuzzy satisfying method, successfully balanced the trade-offs between cost and emissions, thereby enhancing the MG's performance efficiency.
MT, DG, DERs [8]	Economic scheduling of DERs in CHP MG	PSO, DE	The study focused on economically deploying DERs in a CHP-based MG, utilizing PSO for optimal sizing and DE for balancing fuel costs and emissions. It assessed various DER combinations, including MTs and DGs, to efficiently distribute electrical and thermal loads. The findings confirmed the effectiveness of these DER mixes in meeting diverse energy demands while maintaining a cost-effective and environmentally friendly balance.	The findings indicated that the integration of PSO and DE was effective for MOO, successfully balancing fuel costs and emissions while promoting economic and efficient MG operations.
SPV, WT, BT, FC, MT [57]	Minimize costs and emissions in RES-based MG	AMPSO, CLS, FSA	This study introduced the AMPSO algorithm to optimize the operations of an MG equipped with RESs and a backup system consisting of MT, FC, and BT. The primary goal was to minimize both operating costs and emissions. SPV and WT were included as part of various distributed generation sources. Enhanced with CLS and FSA, the AMPSO was employed to manage the nonlinear MOO challenge, focusing on balancing power mismatches and optimizing energy storage requirements.	Based on the results, integrating AMPSO with CLS and FSA provided an effective solution for MOO, balancing economic and environmental objectives in MG operations based on RES. AMPSO is adaptable and optimizes quickly but can converge prematurely and requires high computational resources. CLS improves solution diversity and cooperation but is complex to coordinate and scale. FSA effectively explores the solution space and avoids local optima but may be slow to converge and is computationally demanding [27, 50, 87].
GT, SPV [42]	Reduce emissions and fuel use in GT-based MG	MATLAB 'fgoalattain'	The study focused on optimizing an MG that includes GTs and an SPV-based active generator. MOO was implemented to minimize emissions from the GTs and to maximize the use of the non-polluting SPV-based active generator. This optimization led to a 9.17% reduction in equivalent CO ₂ emissions, with the active generator contributing 11% of the total energy to the system.	In this study, the MOO, using the MATLAB function 'fgoalattain', effectively balanced environmental goals with energy management, demonstrating efficiency in reducing emissions and fuel consumption while specifically utilizing SPV systems.

Second Period (2020–2023)

Continued on next page

Table 3.6 – continued from previous page

System Components (Ref.)	Primary Objective	Optimization Technique	Key Findings	Algorithm Performance Comments
SPV, WT, Hydro, Biomass [73]	Minimize annualized cost and reduce grid imports	MOPSO	The article introduces a novel optimization technique for MG production in a Spanish town with inconsistent grid connections. Employing the MOPSO technique, the primary aim is to minimize costs and reduce dependence on the grid. The methodology achieves a practical and feasible solution, demonstrating a 20-year internal rate of return of 8.33%. This is accomplished through a combination of SPV, WT, hydropower, biomass, and turbine-based power production. This approach not only enhances the capacity to meet local energy needs independently but also serves as a model for potentially disconnecting from Spain's national power network.	In this study, the MOPSO algorithm was used to effectively minimize the objective function, achieving a balance between cost and energy imported from the network. The results indicated that higher installed power capacity resulted in reduced energy imports from the network.
SPV, WT, DG, BT [9]	Minimize LCOE, LPSP, and maximize RF	MOSSA	This study proposes an optimization design for a stand-alone MG in Djelfa, Algeria, aimed at serving a remote off-grid community. The system, powered by hybrid sources (SPV, WT, BT, DG), utilizes MOSSA to optimize COE and LPSP. The results demonstrate MOSSA's superiority over algorithms like MODA, MOGA, and MOALO, achieving better RF, COE, and LPSP. The study highlights the use of RESs and suggests future enhancements with diverse renewable sources and advanced AI algorithms.	The application of MOSSA in optimizing a stand-alone MG underscores its effectiveness in managing complex energy systems. By focusing on RE integration and cost-efficient operations, it showcases the potential of advanced algorithms to enhance future MG designs, seamlessly blending sustainability with practicality.

Continued on next page

Table 3.6 – continued from previous page

System Components (Ref.)	Primary Objective	Optimization Technique	Key Findings	Algorithm Performance Comments
MGT, WT, SPV, Bromide Refrigerator, AC, FC, HESS [77]	Minimize generation and pollution treatment costs	BAS-ABC	This study introduces an economically optimized MOO model for a CCHP MG, utilizing an enhanced ABC algorithm with the Beetle Antennae Search Algorithm (BAS-ABC). The model strives to minimize both daily power generation dispatching costs and environmental pollutant treatment costs. An analysis of a grid-connected CCHP MG in Shanghai during summer shows that BAS-ABC achieves faster convergence and lower minimum costs compared to traditional ABC. Additionally, it reveals the inherent conflict between minimizing power generation costs and environmental costs, emphasizing the need for a balanced approach to economic efficiency and environmental sustainability.	The integration of the BAS-ABC algorithm into the CCHP MG model marks an advancement over traditional ABC, particularly in terms of convergence speed and cost-efficiency. However, the study also highlights the inherent trade-offs between economic and environmental objectives, emphasizing their importance for sustainable energy management.
WT, P2G, SOFC/GT, H ₂ , Electrolyzer [21]	Minimize system cost and wind curtailment	MOGA	This research integrates a micro-energy system (MES) with wind power, P2G, H ₂ storage, and a SOFC/GT hybrid. Using a MOO approach with a GA, it focuses on minimizing system costs and wind curtailment rate while managing wind power and load variability. The results demonstrate a low wind curtailment rate of 0.63%, high RE penetration at 90.1%, and an optimized life cycle cost of GBP 2,468,093. The SOFC/GT system operates at maximum electrical efficiency of 67.1%, adhering to safety constraints, and a power management strategy is developed to ensure efficient operation amidst fluctuating demands.	This study demonstrates how MOGA can effectively balance competing goals such as cost-efficiency and RE integration, ensuring an optimized and sustainable MG operation.
SPV, WT, BT [90]	Minimize cost and grid reliance under uncertainty	MOCS, TOPSIS	This study establishes a MOO function for a grid-connected MG, focusing on minimizing the annual comprehensive cost and grid dependency. It utilizes the k-medoids method to handle uncertainties of RESs and load demand. The MOCS algorithm is employed to solve the model, and the TOPSIS method is used to identify the optimal compromise solution.	The combination of the MOCS algorithm and the TOPSIS method in this study presents a robust approach to MG configuration under uncertain conditions. It underscores the importance of addressing multiple objectives and managing uncertainties in RESs to achieve both economic and grid reliability goals.

Abbreviation: ABC: Artificial Bee Colony, AC: Air Conditioner, AMPSO: Adaptive Modified Particle Swarm Optimization, BAS: Beetle Antennae Search Algorithm, BT: Battery, CCHP: Combined Cooling Heating and

Power, CHP: Combined Heat and Power, CLS: Chaotic Local Search, CO₂: Carbon Dioxide, COE: Cost of Energy, DE: Differential Evolution, DERs: Distributed Energy Resources, DG: Diesel Generator, DR: Demand Response, FC: Fuel Cell, FSA: Fuzzy Self Adaptive, GA: Genetic Algorithm, GSHP: Ground Heat Source Pump, GT: Gas Turbine, HESS: Hybrid Energy Storage System, HMGS: Hybrid Microgrid System, IEMS: Intelligent Energy Management System, LCOE: Levelized Cost of Energy, LPSP: Loss of Power Supply Probability, MBFO: Modified Bacterial Foraging Optimization, MGs: Microgrids, MOALO: Multiobjective Ant Lion Optimizer, MOCE: Multiobjective Cross Entropy, MOCS: Multi-Objective Cuckoo Search, MODA: Multiobjective Dragonfly Algorithm, MOGA: Multiobjective Genetic Algorithm, MOO: Multi-objective Optimization, MOPSO: Multi-objective Particle Swarm Optimization, MOSaDE: Multi-objective Self-Adaptive Differential Evolution, MOSSA: Multi-objective Salp Swarm Algorithm, MGT: Micro Gas Turbine, MT: Micro Turbine, P2G: Power-to-Gas, PSO: Particle Swarm Optimization, RE: Renewable Energy, RESs: Renewable Energy Systems, RF: Renewable Factor, SDG: Sustainable Development Goal, SOFC/GT: Solid Oxide Fuel Cell/Gas Turbine, SPV: Solar Photovoltaic, TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution, WT: Wind Turbine.

The research in MG and HMGS optimization significantly evolved from 2010 to 2023. During the earlier period (2010–2019), the focus predominantly centered on managing uncertainties inherent in RESs and load demands, employing algorithms like MOCE, which proved effective in MOO problems. This period utilized a variety of optimization techniques, including GA, MOPSO, MBFO, PSO, and DE, each aimed at balancing economic and environmental objectives, with a common theme of integrating RESs like SPV and WT to minimize operational costs and emissions. The initial adoption of advanced computational algorithms marked an early stage of complexity in MG optimization. Contrastingly, from 2020 to 2023, more sophisticated computational techniques such as MOPSO, TOPSIS, MOSSA, and BAS-ABC were introduced for comprehensive analyses that encompass economic, environmental, and sustainability aspects. There was a notable shift toward sustainability, aligning with the Sustainable Development Goals (SDGs), with studies like ref. [90] employing TOPSIS alongside SDGs goals for a 100% renewable configuration. This period also expanded MG applications to various geographical regions and included novel technologies like power-to-gas (P2G), solid oxide fuel cell/gas Turbine (SOFC/GT) hybrids, and hydrogen storage, continuing to balance economic efficiency with environmental friendliness through algorithms like MOGA and MOCS. The progression from 2010 to 2023 in HMGS optimization research reflects a significant transition from foundational methods to embracing complexity, sustainability, and broader scopes, mirroring the global trend toward sustainable and efficient energy solutions.

3.6 Conclusions

Diversifying energy sources has become essential in addressing global challenges, making the integration of renewable energy into hybrid microgrids (HMGSs) a

crucial and efficient alternative. This study reviews the economic and reliability metrics of HMGSs and further investigates developments in microgrids (MGs), renewable energy (RE), and their multi-objective optimization (MOO). Utilizing SciMAT bibliometric analysis of literature from 2010 to 2023, sourced from Scopus, the study identifies trends through an overview and a detailed analysis of two distinct periods: 2010–2019 and 2020–2023. From 2010 to 2019, 200 research articles were published, which increased by 35% to 270 papers between 2020 and 2023. This surge in publication output underscores the critical role of initiatives like the Department of Energy’s Microgrid Initiative in steering research toward the development of more sophisticated and efficient MG technologies that align with global renewable energy and climate change mitigation goals. Strategic diagrams were employed to assess the evolution of this research topic, indicating a significant shift from the first period’s focus on MOO and energy management systems toward a rising emphasis on advanced, eco-friendly, and intelligent energy management solutions. The second stage highlighted MOO’s strategic importance in balancing competing objectives such as cost, efficiency, and environmental impact, with predominant themes being MOO and electric power systems. This shift mirrors the global movement towards sustainable and efficient energy solutions and broader efforts to integrate renewable energy sources and combat climate change. Analysis of keyword overlap and thematic evolution maps by period demonstrated remarkable progress in developing new and transitional keywords, showcasing the continual evolution of research in this field. Thematic networks and strategic diagrams revealed a marked increase in research activity, particularly in employing artificial intelligence (AI) for optimization, with methods like genetic algorithms, particle swarm optimization, and fuzzy logic gaining prominence. The study also underscored significant challenges addressed by researchers, such as economic sizing, environmental concerns, energy management systems, and investment issues, indicating a shift toward more complex, sustainable, and intelligent energy management systems. Despite recent progress, challenges such as high battery storage costs, data reliability requirements, and managing the intermittency of renewable sources persist. Future research should focus on scalable HMGS designs, cost-effective storage solutions, and improved data analytics for MOO. Leveraging AI to optimize HMGSs will be paramount in addressing energy management challenges. Building on this study’s findings, researchers are encouraged to foster adaptation, collaboration, and innovation, which will significantly contribute to the development of robust, resilient, and sustainable energy systems.

References for Chapter 3

- [1] G. Aghajani and N. Ghadimi. Multi-objective energy management in a micro-grid. *Energy Reports*, 4:218–225, 2018.
- [2] G.R. Aghajani, H.A. Shayanfar, and H. Shayeghi. Presenting a multi-objective generation scheduling model for pricing demand response rate in micro-grid energy management. *Energy Conversion and Management*, 106:308–321, 2015.
- [3] A.A.K. Al-Sahlawi, S.M. Ayob, C.W. Tan, H.M. Ridha, and D.M. Hachim. Optimal design of grid-connected hybrid renewable energy system considering electric vehicle station using improved multi-objective optimization: Techno-economic perspectives. *Sustainability*, 16(2491), 2024.
- [4] H.Y. Alhammadi and J.A. Romagnoli. Process design and operation: Incorporating environmental, profitability, heat integration and controllability considerations. *Comput. Aided Chem. Eng.*, 17:264–305, 2004.
- [5] K. Arar Tahir, M. Zamorano, and J. Ordóñez García. Scientific mapping of optimisation applied to microgrids integrated with renewable energy systems. *International Journal of Electrical Power & Energy Systems*, 145:108698, 2023.
- [6] M. Ashari and C.V. Nayar. An optimum dispatch strategy using set points for a photovoltaic (pv)-diesel-battery hybrid power system. *Solar Energy*, 66:1–9, 1999.
- [7] M. Azaza and F. Wallin. Multi objective particle swarm optimization of hybrid micro-grid system: A case study in sweden. *Energy*, 123:108–118, 2017.
- [8] A.K. Basu, A. Bhattacharya, S. Chowdhury, and S.P. Chowdhury. Planned scheduling for economic power sharing in a chp-based micro-grid. *IEEE Transactions on Power Systems*, 27:30–38, 2012.
- [9] Z. Belboul, B. Toual, A. Kouzou, L. Mokrani, A. Bensalem, R. Kennel, and M. Abdelrahem. Multiobjective optimization of a hybrid

- pv/wind/battery/diesel generator system integrated in microgrid: A case study in djelfa, algeria. *Energies*, 15:3579, 2022.
- [10] H. Borhanazad, S. Mekhilef, V. Gounder Ganapathy, M. Modiri-Delshad, and A. Mirtaheri. Optimization of micro-grid system using mopso. *Renewable Energy*, 71:295–306, 2014.
- [11] M. Bruck and P. Sandborn. Pricing bundled renewable energy credits using a modified lcoe for power purchase agreements. *Renewable Energy*, 170:224–235, 2021.
- [12] A. Cagnano, E. De Tuglie, and P. Mancarella. Microgrids: Overview and guidelines for practical implementations and operation. *Applied Energy*, 258:114039, 2020.
- [13] M. Callon, J.P. Courtial, and F. Laville. Co-word analysis as a tool for describing the network of interactions between basic and technological research: The case of polymer chemistry. *Scientometrics*, 22:155–205, 1991.
- [14] A. Chaouachi, R.M. Kamel, R. Andoulsi, and K. Nagasaka. Multiobjective intelligent energy management for a microgrid. *IEEE Transactions on Industrial Electronics*, 60(4):1688–1699, 2013.
- [15] A. Chaouachi, R.M. Kamel, R. Andoulsi, and K. Nagasaka. Multiobjective intelligent energy management for a microgrid. *IEEE Trans. Ind. Electron.*, 60:1688–1699, 2013.
- [16] R. Das, Y. Wang, G. Putrus, R. Kotter, M. Marzband, B. Herteleer, and J. Warmerdam. Multi-objective techno-economic-environmental optimisation of electric vehicle for energy services. *Applied Energy*, 257:113965, 2020.
- [17] M. De, G. Das, and K.K. Mandal. An effective energy flow management in grid-connected solar–wind-microgrid system incorporating economic and environmental generation scheduling using a meta-dynamic approach-based multiobjective flower pollination algorithm. *Energy Reports*, 7:2711–2726, 2021.
- [18] K. Deb. Multi-objective optimization using evolutionary algorithms: An introduction. In *Multi-objective Evolutionary Optimisation for Product Design and Manufacturing*. Springer, London, UK, 2011.
- [19] M.K. Deshmukh and S.S. Deshmukh. Modeling of hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*, 12:235–249, 2008.

- [20] C. Díaz-López, M. Carpio, M. Martín-Morales, and M. Zamorano. Analysis of the scientific evolution of sustainable building assessment methods. *Sustainable Cities and Society*, 49:101610, August 2019.
- [21] X. Ding, W. Sun, G. P. Harrison, X. Lv, and Y. Weng. Multi-objective optimization for an integrated renewable, power-to-gas and solid oxide fuel cell/gas turbine hybrid system in microgrid. *Energy*, 213:118804, 2020.
- [22] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, and W.M. Lim. How to conduct a bibliometric analysis: An overview and guidelines. *J. Bus. Res.*, 133:285–296, 2021.
- [23] Energy Education. Payback — energy education. <https://energyeducation.ca/encyclopedia/Payback>, 2024. Accessed: 2024-02-19.
- [24] E.L.V. Eriksson and E.M.A. Gray. Optimization and integration of hybrid renewable energy hydrogen fuel cell energy systems—a critical review. *Applied Energy*, 202:348–364, 2017.
- [25] S. Fang, Y. Xu, Z. Li, T. Zhao, and H. Wang. Two-step multi-objective management of hybrid energy storage system in all-electric ship microgrids. *IEEE Transactions on Vehicular Technology*, 68:3361–3373, 2019.
- [26] L. Fusheng, L. Ruisheng, and Z. Fengquan. Microgrid technology and engineering application. In *Microgrid Technology and Engineering Application*, pages 1–198. Elsevier, 2015.
- [27] S. Gao, Y. Yu, Y. Wang, J. Wang, J. Cheng, and M. Zhou. Chaotic local search-based differential evolution algorithms for optimization. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 51:3954–3967, 2021.
- [28] F.S. Gazijahani and J. Salehi. Stochastic multi-objective framework for optimal dynamic planning of interconnected microgrids. *IET Renewable Power Generation*, 11:1749–1759, 2017.
- [29] R. Ghasemi, M. Wosnik, D.L. Foster, and W. Mo. Multi-objective decision-making for an island microgrid in the gulf of maine. *Sustainability*, 15:13900, 2023.
- [30] G. Graditi, M.L. Di Silvestre, R. Gallea, and E.R. Sanseverino. Heuristic-based shiftable loads optimal management in smart micro-grids. *IEEE Transactions on Industrial Informatics*, 11:271–280, 2015.

- [31] H. Haddadian and R. Noroozian. Multi-microgrid-based operation of active distribution networks considering demand response programs. *IEEE Transactions on Sustainable Energy*, 10(4):1804–1812, 2019.
- [32] C.A.S. Hall, J.G. Lambert, and S.B. Balogh. Eroi of different fuels and the implications for society. *Energy Policy*, 64:141–152, 2014.
- [33] A.M. Hemeida, A.S. Omer, A.M. Bahaa-Eldin, S. Alkhalaf, M. Ahmed, T. Senjyu, and G. El-Saady. Multi-objective multi-verse optimization of renewable energy sources-based micro-grid system: Real case. *Ain Shams Engineering Journal*, 13:101543, 2022.
- [34] R. Hemmati and H. Saboori. Emergence of hybrid energy storage systems in renewable energy and transport applications—a review. *Renewable and Sustainable Energy Reviews*, 65:11–23, 2016.
- [35] A. Hiendro, I. Yusuf, F. Trias, P. Wigyantanto, H. Kho, and J. Khwee. Optimum renewable fraction for grid-connected photovoltaic in office building energy systems in indonesia. *International Journal of Power Electronics and Drive Systems*, 9:1866–1874, 2018.
- [36] International Energy Agency. Heat pumps—energy system. <https://www.iea.org/energy-system/buildings/heat-pumps#tracking>, 2023. Accessed on 15 February 2024.
- [37] International Energy Agency. Tracking clean energy progress 2023—analysis. <https://www.iea.org/reports/tracking-clean-energy-progress-2023>, 2023. Accessed on 15 February 2024.
- [38] International Energy Agency. World energy outlook 2023. <https://www.iea.org/terms>, 2023. Accessed on 23 April 2024.
- [39] H. Jahangir, A. Ahmadian, and M.A. Golkar. Multi-objective sizing of grid-connected micro-grid using pareto front solutions. In *Proceedings of the IEEE Innovative Smart Grid Technologies—Asia (ISGT ASIA)*, pages 1–6, Bangkok, Thailand, 2015.
- [40] P. Jha, N. Sharma, V.K. Jadoun, A. Agarwal, and A. Tomar. Optimal scheduling of a microgrid using ai techniques. In *Control Standalone Microgrid*, pages 297–336. Academic Press, Cambridge, MA, USA, 2021.
- [41] A. Kaabeche, M. Belhamel, and R. Ibtouen. Sizing optimization of grid-independent hybrid photovoltaic/wind power generation system. *Energy*, 36:1214–1222, 2011.

- [42] H. Kanchev, D. Lu, B. Francois, and V. Lazarov. Smart monitoring of a microgrid including gas turbines and a dispatched pv-based active generator for energy management and emissions reduction. In *2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*, Gothenburg, Sweden, 2010.
- [43] H. Karimi and S. Jadid. Optimal energy management for multi-microgrid considering demand response programs: A stochastic multi-objective framework. *Energy*, 195:116992, 2020.
- [44] F.A. Khan, N. Pal, and S.H. Saeed. Stand-alone hybrid system of solar photovoltaics/wind energy resources: An eco-friendly sustainable approach. In *Renewable Energy Systems*, pages 687–705. Academic Press, Cambridge, MA, USA, 2021.
- [45] P.V.N.M. Krishna and P.C. Sekhar. Area constrained optimal planning model of renewable-rich hybrid microgrid. *IEEE Access*, 11:70873–70883, 2023.
- [46] Y. Li, J. Huang, Y. Liu, H. Wang, Y. Wang, and X. Ai. A multicriteria optimal operation framework for a data center microgrid considering renewable energy and waste heat recovery: Use of balanced decision making. *IEEE Industry Applications Magazine*, 29(2):23–38, 2023.
- [47] Y. Li, T. Zhao, P. Wang, H.B. Gooi, Z. Ding, K. Li, and W. Yan. Flexible scheduling of microgrid with uncertainties considering expectation and robustness. *IEEE Transactions on Industry Applications*, 54:3009–3018, 2018.
- [48] Y.J. Li, D.W. Yue, H.X. Liu, and Y.F. Liu. Wind-solar complementary power inverter based on intelligent control. In *Proceedings of the 2009 4th IEEE Conference on Industrial Electronics and Applications*, pages 3635–3638, Xi’an, China, 2009.
- [49] A. Liberati, D.G. Altman, J. Tetzlaff, C. Mulrow, P.C. Gøtzsche, J.P.A. Ioannidis, M. Clarke, P.J. Devereaux, J. Kleijnen, and D. Moher. The prisma statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: Explanation and elaboration. *BMJ*, 339:b2700, 2009.
- [50] H. Liu, X. W. Zhang, and L. P. Tu. A modified particle swarm optimization using adaptive strategy. *Expert Systems with Applications*, 152:113353, 2020.
- [51] B. Lokeshgupta and S. Sivasubramani. Optimal operation of a residential microgrid with demand side management. In *Proceedings of the 2019 IEEE*

PES Innovative Smart Grid Technologies Europe (ISGT-Europe), Bucharest, Romania, 2019. IEEE.

- [52] T. Ma, H. Yang, and L. Lu. Study on stand-alone power supply options for an isolated community. *International Journal of Electrical Power & Energy Systems*, 65:1–11, 2015.
- [53] S.A. Mansouri, A. Ahmarinejad, E. Nematbakhsh, M.S. Javadi, A.R. Jordehi, and J.P.S. Catalão. Energy management in microgrids including smart homes: A multi-objective approach. *Sustainable Cities and Society*, 69:102852, 2021.
- [54] J. F. Manwell. Hybrid energy systems. In *Encyclopedia of Energy*, volume 3, pages 215–229. Elsevier Inc., USA, 2004.
- [55] M.D. Martínez-Aires, M.J. Cobo, M. Herrera, and E. Herrera-Viedma. Analyzing the scientific evolution of social work using science mapping. *Research on Social Work Practice*, 25(2):257–277, 2015.
- [56] P. Martínez Fernández, I. Villalba Sanchís, V. Yepes, and R. Insa Franco. A review of modelling and optimisation methods applied to railways energy consumption. *Journal of Cleaner Production*, 222:153–162, 2019.
- [57] A.A. Moghaddam, A. Seifi, T. Niknam, and M.R. Alizadeh Pahlavani. Multi-objective operation management of a renewable mg (micro-grid) with back-up micro-turbine/fuel cell/battery hybrid power source. *Energy*, 36:6490–6507, 2011.
- [58] S. Momen, J. Nikoukar, and M. Gandomkar. Multi-objective optimization of energy consumption in microgrids considering chps and renewables using improved shuffled frog leaping algorithm. *Journal of Electrical Engineering and Technology*, 18:1539–1555, 2023.
- [59] M.H. Moradi, M. Abedini, S.M.R. Tousi, and S.M. Hosseini. Optimal siting and sizing of renewable energy sources and charging stations simultaneously based on differential evolution algorithm. *International Journal of Electrical Power and Energy Systems*, 73:1015–1024, 2015.
- [60] M. Motevasel, A. R. Seifi, and T. Niknam. Multi-objective energy management of chp (combined heat and power)-based micro-grid. *Energy*, 51:123–136, 2013.
- [61] M. Motevasel and A.R. Seifi. Expert energy management of a micro-grid considering wind energy uncertainty. *Energy Conversion and Management*, 83:58–72, 2014.

- [62] Z. Mu, F. Zhao, F. Bai, Z. Liu, and H. Hao. Evaluating fuel cell vs. battery electric trucks: Economic perspectives in alignment with china’s carbon neutrality target. *Sustainability*, 16(6):2427, 2024.
- [63] D.J. Murphy and C.A.S. Hall. Year in review-eroi or energy return on (energy) invested. *Annals of the New York Academy of Sciences*, 1185:102–118, 2010.
- [64] E. Naderi, A. Dejamkhooy, S.J. Seyedshenava, and H. Shayeghi. Milp based optimal design of hybrid microgrid by considering statistical wind estimation and demand response. *Journal of Operation and Automation in Power Engineering*, 10:54–65, 2022.
- [65] M. Nazari-Heris, S. Abapour, and B. Mohammadi-Ivatloo. Optimal economic dispatch of fc-chp based heat and power micro-grids. *Applied Thermal Engineering*, 114:756–769, 2017.
- [66] T. Niknam, R. Azizipanah-Abarghooee, and M.R. Narimani. An efficient scenario-based stochastic programming framework for multi-objective optimal micro-grid operation. *Appl. Energy*, 99:455–470, 2012.
- [67] P. Paliwal, N.P. Patidar, and R.K. Nema. Planning of grid integrated distributed generators: A review of technology, objectives and techniques. *Renewable and Sustainable Energy Reviews*, 40:557–570, 2014.
- [68] J. Paska, P. Biczel, and M. Kłos. Hybrid power systems—an effective way of utilising primary energy sources. *Renewable Energy*, 34:2414–2421, 2009.
- [69] Z.N. Pintarič and Z. Kravanja. Suitable process modelling for proper multi-objective optimization of process flow sheets. *Comput. Aided Chem. Eng.*, 33:1387–1392, 2014.
- [70] M.A.M. Ramli, H.R.E.H. Bouchekara, and A.S. Alghamdi. Optimal sizing of pv/wind/diesel hybrid microgrid system using multi-objective self-adaptive differential evolution algorithm. *Renew. Energy*, 121:400–411, 2018.
- [71] Renewable Energy Agency and Global Renewables Alliance. Global renewables alliance tripling renewable power and doubling energy efficiency by 2030: Crucial steps towards 1.5°C. <https://globalrenewablesalliance.org/>, 2023. Accessed on 14 November 2023.
- [72] A. Rezvani, M. Gandomkar, M. Izadbakhsh, and A. Ahmadi. Environmental/economic scheduling of a micro-grid with renewable energy resources. *Journal of Cleaner Production*, 87:216–226, 2015.

- [73] C. Roldán-Blay, G. Escrivá-Escrivá, C. Roldán-Porta, and D. Dasí-Crespo. Optimal sizing and design of renewable power plants in rural microgrids using multi-objective particle swarm optimization and branch and bound methods. *Energy*, 284:129318, 2023.
- [74] N. Salehi, H. Martinez-Garcia, G. Velasco-Quesada, and J.M. Guerrero. A comprehensive review of control strategies and optimization methods for individual and community microgrids. *IEEE Access*, 10:15935–15955, 2022.
- [75] E.R. Sanseverino, M.L. Di Silvestre, M.G. Ippolito, A. De Paola, and G. Lo Re. An execution, monitoring and replanning approach for optimal energy management in microgrids. *Energy*, 36:3429–3436, 2011.
- [76] M.B. Shadmand and R.S. Balog. Multi-objective optimization and design of photovoltaic-wind hybrid system for community smart dc microgrid. *IEEE Transactions on Smart Grid*, 5:2635–2643, 2014.
- [77] J. N. Shan and R. X. Lu. Multi-objective economic optimization scheduling of cchp micro-grid based on improved bee colony algorithm considering the selection of hybrid energy storage system. *Energy Reports*, 7:326–341, 2021.
- [78] K. Shivarama Krishna and K. Sathish Kumar. A review on hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*, 52:907–916, 2015.
- [79] Z.Z. Stanković, M.N. Rajic, Z. Božić, P. Milosavljević, A. Păcurar, C. Borzan, R. Păcurar, and E. Sabău. The volatility dynamics of prices in the european power markets during the covid-19 pandemic period. *Sustainability*, 16(2426), 2024.
- [80] S. Sumathi, L.A. Kumar, and P. Surekha. *Solar Photovoltaic & Wind Energy Conversion Systems*. Springer, Cham, Switzerland, 2015.
- [81] D.T. Ton and M.A. Smith. The u.s. department of energy’s microgrid initiative. *The Electricity Journal*, 25(8):84–94, 2012.
- [82] D.T. Ton and M.A. Smith. The u.s. department of energy’s microgrid initiative. *The Electricity Journal*, 25(8):84–94, 2012.
- [83] C.T. Tsai, T.M. Beza, E.M. Molla, and C.C. Kuo. Analysis and sizing of mini-grid hybrid renewable energy system for islands. *IEEE Access*, 8:70013–70029, 2020.
- [84] United Nations Statistics Division. Sdg indicators—sdg indicators. <https://unstats.un.org/sdgs/metadata/>, 2024. Accessed on 14 March 2024.

- [85] S. Upadhyay and M.P. Sharma. A review on configurations, control and sizing methodologies of hybrid energy systems. *Renewable and Sustainable Energy Reviews*, 38:47–63, 2014.
- [86] F.J. Vivas, F. Segura, J.M. Andújar, A. Palacio, J.L. Saenz, F. Isorna, and E. López. Multi-objective fuzzy logic-based energy management system for microgrids with battery and hydrogen energy storage system. *Electronics*, 9:1074, 2020.
- [87] J. S. Wang and C. S. G. Lee. Self-adaptive neuro-fuzzy inference systems for classification applications. *IEEE Transactions on Fuzzy Systems*, 10(6):790–802, 2002.
- [88] L. Wang, Q. Li, R. Ding, M. Sun, and G. Wang. Integrated scheduling of energy supply and demand in microgrids under uncertainty: A robust multi-objective optimization approach. *Energy*, 130:1–14, 2017.
- [89] L. Wang and C. Singh. Pso-based multi-criteria optimum design of a grid-connected hybrid power system with multiple renewable sources of energy. In *Proceedings of the 2007 IEEE Swarm Intelligence Symposium*, pages 250–257, Honolulu, HI, USA, 2007.
- [90] J. Wu, Z. Qi, F. Yang, and X. Li. The multi-objective optimal configuration of wind-pv-battery microgrid. In *2020 Chinese Automation Congress (CAC)*, pages 5585–5590, Shanghai, China, 2020.
- [91] X. Wu, W. Cao, D. Wang, and M. Ding. A multi-objective optimization dispatch method for microgrid energy management considering the power loss of converters. *Energies*, 12(11):2160, 2019.
- [92] P. Xie, Z. Cai, P. Liu, X. Li, Y. Zhang, and D. Xu. Microgrid system energy storage capacity optimization considering multiple time scale uncertainty coupling. *IEEE Transactions on Smart Grid*, 10:5234–5245, 2018.
- [93] L. Xiong, P. Li, Z. Wang, and J. Wang. Multi-agent based multi objective renewable energy management for diversified community power consumers. *Applied Energy*, 259:114140, 2020.
- [94] B. Yan, B. Wang, L. Zhu, H. Liu, Y. Liu, X. Ji, and D. Liu. A novel, stable, and economic power sharing scheme for an autonomous microgrid in the energy internet. *Energies*, 8:12741–12764, 2015.
- [95] H.K. Zand, K. Mazlumi, A. Bagheri, and H. Hashemi-Dezaki. Optimal protection scheme for enhancing ac microgrids stability against cascading outages by

utilizing events scale reduction technique and fuzzy zero-violation clustering algorithm. *Sustainability*, 15(20):15550, 2023.

- [96] M.F. Zia, E. Elbouchikhi, and M. Benbouzid. Microgrids energy management systems: A critical review on methods, solutions, and prospects. *Applied Energy*, 222:1033–1055, 2018.

Chapter Four

From diesel reliance to sustainable power in Iraq: Optimized hybrid microgrid solutions

This chapter is presented as a standalone research paper and forms an integral part of this doctoral dissertation. It has been published in Renewable Energy, 238, January 2025, 121905. Available at: <https://doi.org/10.1016/j.renene.2024.121905>.

Chapter 4

From diesel reliance to sustainable power in Iraq: Optimized hybrid microgrid solutions

This chapter investigates Iraq's challenging electricity landscape, exacerbated by the cumulative impacts of four wars, leading to daily power outages. The reliance on neighborhood diesel generators (NDG) as a temporary fix is critically assessed, with a strong expert consensus via the Delphi method advocating for a transition to solar photovoltaic (SPV) panels. The Delphi survey involved 20 experts, with 85% agreeing on the necessity of this transition, and high consensus (90% or higher) achieved on key questions regarding the inadequacy of NDG and the suitability of SPV as a replacement. The scarcity of local load data prompted the adaptation of Spain's load profiles to Iraq using the innovative ROSETTA transform, identifying the optimal number of SPV panels needed for low, base, and high consumption scenarios as 7, 9, and 11 panels, respectively. In a first approach to the viability of such an SPV installation, it is deduced that the minimum prices per kWh should be between \$0.106 and \$0.078, depending on the scenario, for it to be viable, well above the current prices in Iraq. A deeper analysis was then performed to evaluate Hybrid Microgrid Systems (HMGS) integrating SPVs, batteries and gasoline generators, both off-grid and grid-connected, and taking into account NDG-related savings. This analysis evidenced the viability of a grid-connected HMGS, leveraging SPV and battery storage, as the most economically viable solution, achieving payback periods up to 3.6 years in the best case. This research underscores the need for a policy shift towards sustainable energy solutions in Iraq and similar contexts, highlighting the technical and economic advantages of adopting clean, renewable energy systems over traditional NDG, and paving the way for a sustainable energy future.

4.1 Introduction

Energy is an essential determinant in assessing the progress of countries across all aspects. The comparison of statistics on energy consumption across national boundaries highlights this connection.

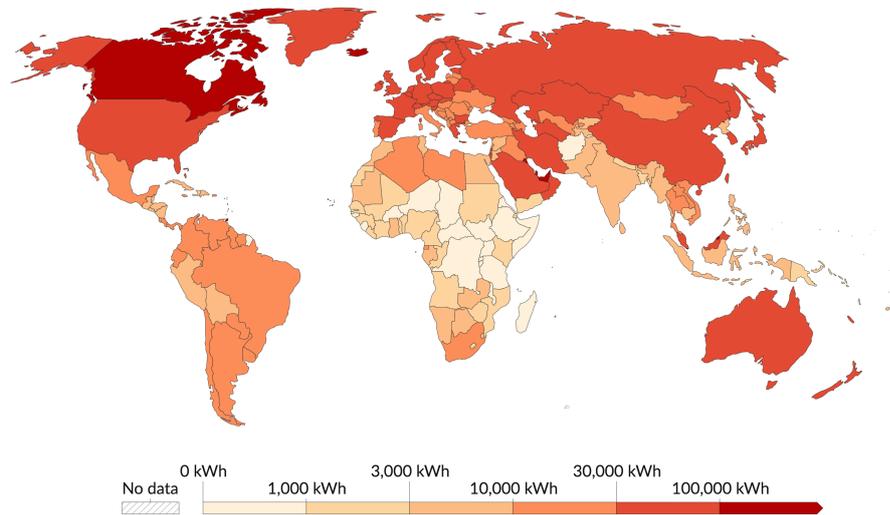


Figure 4.1: Worldwide per capita kWh consumption [1].

For instance, in high-income nations such as Germany, the per capita energy consumption is 40,977 kWh, which is significantly higher compared to the Democratic Republic of the Congo and the Central African Republic, where the corresponding per capita consumption is just 411 kWh and 286 kWh, respectively.

The disparity in energy consumption is clearly illustrated in the map shown in Figure 4.1 [1]. Nevertheless, other factors have contributed to a global transformation in energy generation. These include the ongoing conflict between Russia and Ukraine, rising fuel costs, and the effects of climate change. Nations worldwide are endeavoring to address these challenges by depending on alternative sources to diminish reliance on fossil fuels and transition towards renewable energy sources (RESs) as a more environmentally friendly option. This trend is evident in the International Energy Agency's prediction for 2023-2025, which forecasts that renewable power output will exceed that of all other energy sources. It is expected to rise by more than 9% annually and to account for over one-third of the worldwide electricity mix by 2025, as shown in Figure 4.2 [4].

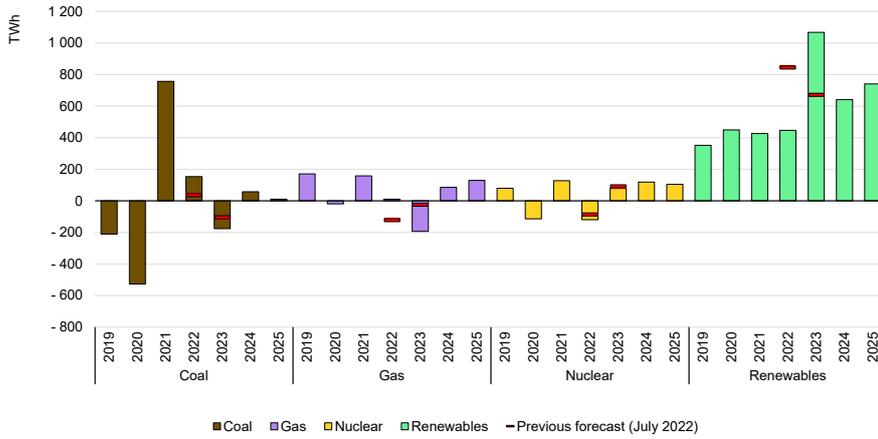


Figure 4.2: Trends of electricity generation in the world 2019-25 [4].

Nomenclature			
BTs	Batteries	NDG	Neighborhood diesel generators
COE	Cost of energy	NPC	Net present cost
DEC	Daily electricity consumption	PBP	Payback period
DG	Diesel generator	Pd	Power demand
GG	Gasoline generator	Pspv	Power of the SPV
HMGS	Hybrid microgrid systems	PVGIS	Photovoltaic Geographical Information System
IRR	Internal rate of return	RES	Renewable energy source
kW, MW, GW	Kilo, Mega, Giga Watts	SPV	Solar photovoltaic
MG	Microgrid	WT	Wind turbine

The graph illustrates a noticeable decline in coal usage, a consistently steady estimate for gas consumption, a modest increase in nuclear energy, and a significant surge in renewables. Projections indicate that the proportion of RESs in the worldwide power generating mix will rise from 29% in 2022 to 35% in 2025. Consequently, CO_2 emissions from worldwide energy production are expected to stabilize by 2025 and will continue to decline in the future [4].

As governments around the globe strive for clean and sustainable power generation methods, emerging nations grapple with shortages in electricity availability. In Iraq, power outages are a frequent occurrence across all governorates, primarily

due to the demand for energy outpacing the growth in generating capacity. This disparity is especially pronounced during the summer months, when the need for cooling surges. Despite the government's significant investments in the electricity system over the past decade, Iraq's power infrastructure has faced continuous challenges since 2003. As a result, residents continue to experience prolonged periods of power outages. The primary reasons leading to the power shortage in Iraq are:

- Over the last four decades, Iraq has experienced three wars, political turmoil, and economic sanctions, all of which have led to substantial damage to its energy infrastructure. The primary factor contributing to this stalemate has been the extensive destruction of Iraq's infrastructure during the 1990-1991 Gulf War. Specifically, the shelling resulted in the loss of 75% of the country's installed capacity of 9,300 MW, leaving just 2,300 MW intact [19], [16].
- Iraq suffers from the highest rate of electrical transmission and distribution losses in the Middle East. This issue stems largely from the damage inflicted during the 1991 Gulf War, compounded by ongoing sabotage and inadequate maintenance [16].
- Iraq faces significant challenges due to climate change, including escalating temperatures and decreased rainfall. These conditions exacerbate droughts, leading to migration from rural to urban areas, thereby placing additional strain on the main electrical grid and causing reliability issues. Furthermore, extreme heat waves diminish the efficiency of power plants, while higher temperatures drive up the demand for electricity. As a result, electricity consumption has been increasing by more than 10% annually [28].
- In Iraq, electricity tariffs start at \$0.0084 per kilowatt-hour (kWh) for monthly consumption up to 1000 kWh [8]. This rate is only a tenth of the average residential electricity price in the Organization for Economic Co-operation and Development (OECD) countries. The significant difference in prices encourages users to concentrate their electricity usage during times when grid-supplied power is available, leading to increased strain on the system and potentially worsening grid malfunctions [16].
- In Iraq, more than 40% of the electricity generated is lost before billing due to inefficiencies. Additionally, inefficient metering, billing, and commercial management systems result in only about half of the invoiced energy being paid for. Consequently, less than 30% of the total power produced contributes to financial revenue. This leads to only about 10% of operational expenses being covered by these payments, perpetuating a cycle of inadequate funding and insufficient economic recovery [28].

- Although the Ministry of Electricity, Law No. 53 of 2017, approved in the Official Gazette “Al-Waqai” 4443 dated 4/17/2017, Article II, the fifth paragraph, which states (support and encouragement of the use of renewable energies in various fields and the localization of its industries) [15]. However, to cope with power outages, citizens often resort to using expensive private or shared neighborhood diesel generators (NDG), which only provide electricity for a few hours daily.
- A significant challenge arises from the presence of over 500,000 informal residences illegally connected to the main electrical grid [56]. According to the Ministry of Planning, approximately 3.3 million people, or 13% of Iraq’s population, live in these informal settlements [2]. Coupled with a population growth rate exceeding one million individuals annually [17], this situation places considerable strain on the national grid, exacerbating reliability issues and further challenging the country’s electricity supply.
- Iraq boasts the world’s fifth-largest crude oil reserves and is the second-largest oil exporter within the OPEC. Its natural gas reserves also rank twelfth globally [27]. Despite these significant resources, Iraq finds itself dependent on gas imports from Iran to fuel its power stations, which are responsible for 57% of its electricity production. This dependence places Iraq in a vulnerable position, particularly if there are delays in gas payments or if demand within Iran exceeds supply. Such a scenario has led to Iran halting gas deliveries to Iraq, as happened during the peak seasonal demand in 2018 [17].

Since 2012, the Iraqi government has invested nearly \$20 billion in the electricity sector. Despite this, and a 13 GW increase in generating capacity, the gap between supply and demand has continued to widen. Of the total 13 GW of added capacity, only 8 GW is ‘effective capacity’; the remainder is lost due to efficiency issues like poor maintenance and fuel quality below specifications. Furthermore, of the 8 GW generated, only 4 GW actually reaches consumers, with the rest lost to technical inefficiencies in the transmission and distribution network [10]. Figure 4.3 highlights the growing gap between demand and available power capacity in Iraq, with the difference between system capacity and demand expected to exceed 90% by 2030.

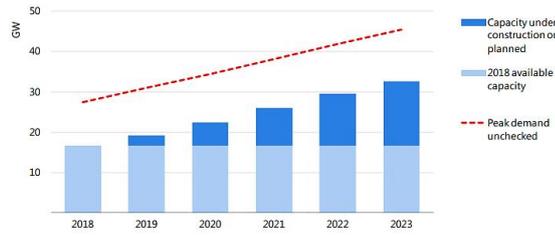


Figure 4.3: Peak electricity demand and supply in Iraq, 2018-2023 [17].

In order to tackle the electrical issue, the Iraqi government resolved to import 1,400 MW of electricity and 28 m³ of natural gas from Iran. Nevertheless, these measures proved inadequate, as evidenced by the continuous, extensive power outages and the substantial expense of importing Iranian gas, which totaled \$6.1 billion [81]. Consequently, Iraq must use its RESs, particularly focusing on solar and wind energy. Benefiting from its location in the global sunbelt, Iraq possesses excellent solar energy resources [17]. Figure 4.4. depicts the expected amount

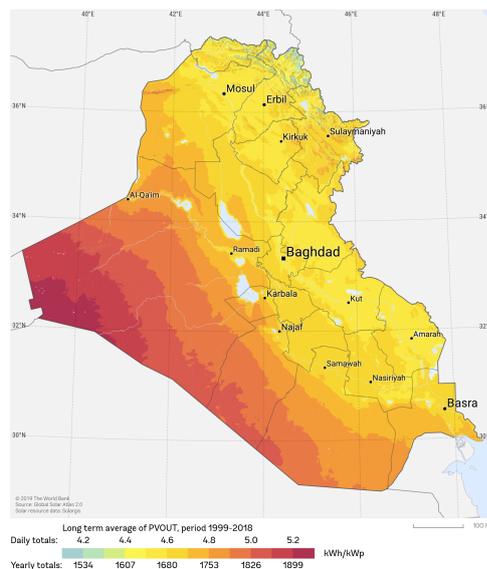


Figure 4.4: Solar resources map in Iraq [13].

of solar photovoltaic (SPV) electricity generated in Iraq between 1999 and 2018 [13], indicating significant potential. Two-thirds of Iraq could significantly benefit from solar energy, especially since the solar radiation duration in the western and southern parts ranges from 2,800 to 3,000 hours per year, with daily horizontal irradiation exceeding 6.5-7 kWh/m². Given the current circumstances, Iraq emerges as an exceptionally favorable location for investing in solar energy, which has the potential to offer a sustainable and lasting solution to the prevailing power deficit

[55].

The utilization of a variety of energy sources and technologies offers advantageous outcomes in comparison to relying solely on one technology. Therefore, the hybrid energy source, which incorporates RESs, battery storage, and optionally conventional energy sources, are identified as the optimal solution in terms of cost, reliability, and sustainability [6]. Microgrid (MG) technology offers economic and reliability benefits by being capable of functioning in both grid-connected and island modes [77]. A Hybrid Microgrid System (HMGS) provides an efficient, dependable, and economical approach to harnessing RESs [36, 49, 53, 61]. HMGS configurations range from a basic 5 kW single-phase setup that can power a single household, to a larger 3-phase system capable of serving as the primary power source for an entire town [45]. Consequently, it is crucial to assess the feasibility of implementing these systems in developing countries, especially those experiencing frequent power disruptions, through a comprehensive evaluation [76]. This research aims to comprehensively analyze the present condition of the energy sector in Iraq and ascertain the issues and dependability of power. The energy profile of Iraq is highlighted in the following subsection.

4.1.1 Energy profile and reliability of electricity in Iraq

The annual statistics report for 2022 from the Iraqi Ministry of Electricity indicates that Iraq has eight thermal stations, 41 gas stations, eighteen diesel stations, and eight hydropower stations. These stations collectively have an electricity production capacity of 14,064 MW. Figure 4.5 illustrates the country's electricity generation profile, with gas turbine generation playing a dominant role, accounting for approximately 57% of the total megawatts generated. In addition, thermal plants utilizing fuel oil, crude oil, and refined gasoline contribute 21% to the overall generation mix. Despite the presence of eight dams, hydropower capacity remains limited, constituting only 2% of the generation. Imported electricity and investment stations together comprise 17% of Iraq's electricity supply, with the remainder being generated by diesel stations [3].

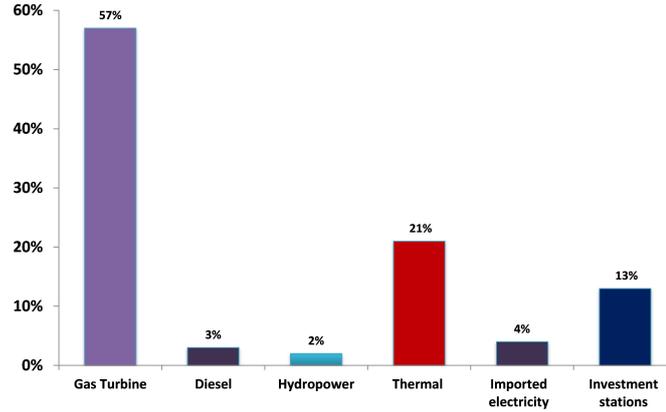


Figure 4.5: Iraq electricity generation profile [3].

Table 4.1 presents a comprehensive overview of the major power plants in Iraq, detailing their respective contributions to the national electricity production rates.

Table 4.1: Electrical power stations in Iraq and their production rates.

Production station	Number of stations	Number of units in service	Total actual production rate (MW)	Participation rate %	The most contributing unit	Production rate (MW)	Contribution (%)
Thermal stations	8	24	3,301	21	Wasit	1,875	57
Gas stations	41	186	9,056	57	Bismayah	3,256	36
Hydropower stations	8	21	303	2	Mosul dam	161	53
Diesel stations	18	238	533	3	Karbala	169	21
Investment stations + imported electricity from Iran+Kurdistan (2,745MW)			2,050 (75%)	13	Rumaila Investment	1,091	53
			403 (15%)	2	(Iran- Khor al-Zubair)	201	28.3
			291 (10%)	2	(Kurdistan- Kirkuk)	143	49
Total	75	469	15,938	100			

In Iraq, the demand for electricity reaches its highest level on extremely hot summer days, when temperatures soar to 45°C. During these times, the peak hourly electricity demand is expected to be 50% higher than the typical demand level [55]. However, on average, the grid supply is available for only about 15 to 17 hours per day. Persistent power outages are a daily occurrence across all governorates, driven largely by a surging demand for energy. This increase in demand, primarily due to the need for cooling during the peak summer months, has exceeded the growth in generating capacity. To address the shortfall in energy supply, over 90% of households in Iraq rely on private generators. These generators, whether individually owned or shared at the community level, play a crucial role in supplementing the public grid [27]. These generators play a crucial role, contributing to fulfilling 20% of the total electricity demand [17].

The average availability of electricity to end-users in Iraq, sourced from the

grid as well as private and shared generators ranges from 11 to 19 hours per day, varying across different regions of the country as illustrated in Figure 4.6.

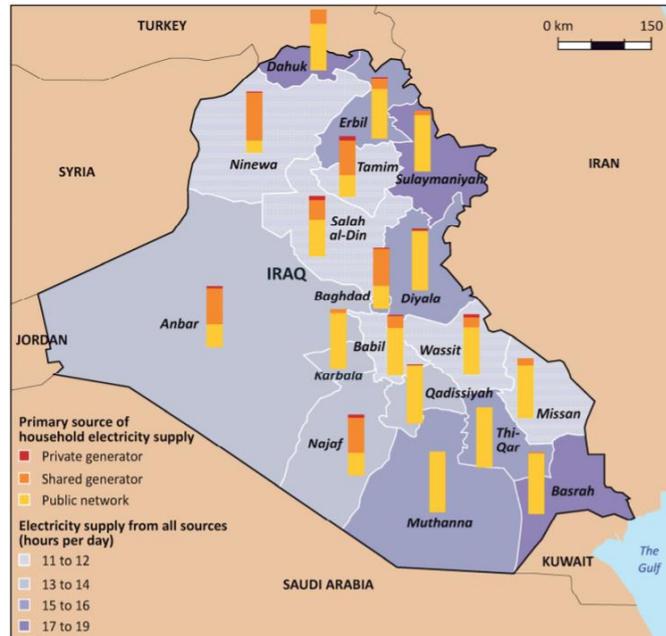


Figure 4.6: Iraq source and reliability of electricity supply by governorate [28].

The financial burden of electricity on Iraqi households is significant, considering the combined costs paid to distribution companies and for the operation of local private generators. The cost for services from neighborhood diesel generators (NDG) is typically around US\$ 8.40 per month for each Ampere, based on an 8-hour daily usage. This equates to approximately \$100 per month for a continuous 6 Ampere power supply throughout the day [19], [56]. For a higher power requirement, such as 15 amperes, NDG services can exceed \$300 per month [17]. Figure 4.8 depicts the specific placement of the NDG and the routing of power cables from the generator to the individual residences in a residential neighborhood. To gain deeper insights into the efficiency of these generators, a Delphi survey was conducted, gathering expert opinions on the utilization of NDG and exploring the potential for their substitution with RESs, particularly SPV.

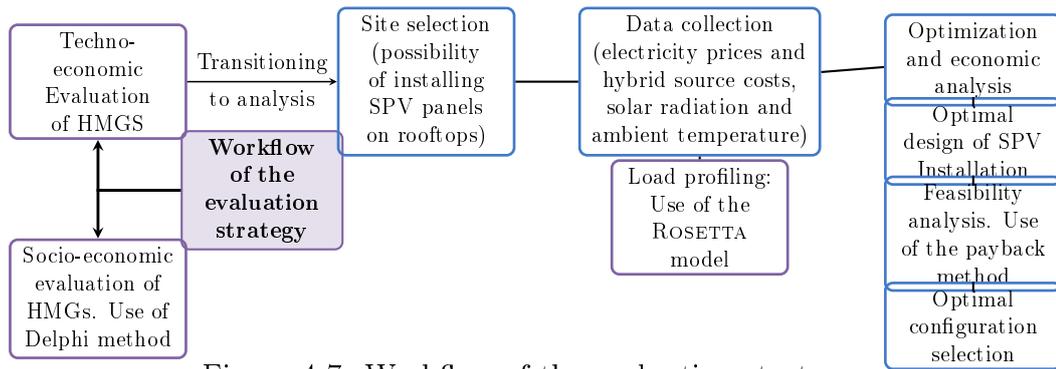


Figure 4.7: Workflow of the evaluation strategy.



Figure 4.8: Installation site and cable routing of a NDG in an Iraqi residential area.

This study aims to address the gap in awareness regarding the limited availability of the national power grid and seeks to tackle the challenge of inadequate energy supply in both standalone and grid-integrated systems across Iraq. Despite the critical need for reliable and sustainable energy solutions, there is a lack of comprehensive studies assessing the feasibility and viability of transitioning from NDG to sustainable energy solutions. This research provides an exhaustive analysis of the technical and economic aspects of HMGS that utilize SPV, Gasoline Generator (GG), and battery systems within a selected governorate. Leveraging the insights from the Delphi survey on the socio-economic impacts of NDG, the research progresses to a techno-economic assessment. This study employs the novel ROSETTA time transformation method to create daily load profiles by adapting Spanish load data to Iraqi conditions. Additionally, a detailed techno-economic analysis is conducted to validate the feasibility and economic viability of implementing the proposed HMGS as an alternative to NDG, focusing primarily on the system's technical capabilities and economic viability.

4.2 Evaluation strategy

To comprehensively address the economic, technical, and social aspects of implementing an SPV-GG-battery HMGS over NDG, this study is divided into two primary analyses: socio-economic and techno-economic evaluations. Figure 4.7 delineates the workflow of the evaluation strategy. The study initiates with a socio-economic analysis employing the Delphi method to critically assess the deployment of HMGS in comparison to NDG. Detailed insights into this evaluative process are elaborated in the subsequent subsection.

4.2.1 Socio-economic impact assessment of NDG in Iraq

The study proposes the employment of the Delphi technique to assess the socio-economic impacts of utilizing NDG. This method is particularly chosen for its distinct advantages in the given context. First, it ensures the transparency and independence of expert opinions, preventing the influence of other participants. Second, it offers a forward-looking view of energy trends in Iraq, which is crucial for long-term planning. Third, it enables a comprehensive analysis of both economic and social implications, grounded in expert insights. Finally, this technique lays the groundwork for a detailed future report on the subject matter. The subsequent subsection will provide a more detailed explanation of the Delphi approach.

4.3 Delphi method

Originating in 1948 during the Cold War, the Delphi technique is a scientific method designed for idea generation or problem solving. It involves structured group communication among experts, particularly effective when information is limited [35]. It uniquely combines individual forecasts into a consensus decision [44]. Widely used in over 2,600 papers from 1975 to 2017 [43], its applications span various fields, including medicine [41, 64, 67, 82], health care [33, 37, 42, 73], education [23, 38, 62], engineering and technology [47, 57, 69, 79], energy and environmental [34, 40, 68, 70], and social sciences [30]. In renewable energy field, it has been employed to explore RES barriers in Pakistan [72] and assess factors affecting RES use in Taiwan's buildings [60].

4.3.1 Delphi process

The study describes the Delphi process as a structured approach divided into three major phases: preparing, conducting and reporting, and results [50]. The 'Overview of the Delphi method: key phases of expert engagement and analysis'

section includes Figure 4.9, which summarizes these phases. This figure illustrates the progression and key activities in each phase.

Phases of the Delphi method for expert consensus		
First phase	Second phase	Third phase
Preparing	Conducting & reporting	Presenting results
Topic selection (questions)	Inviting the experts	Findings
Expert selection	Initial round	Consensus level
Consensus and stop statistical criteria	Controlled feedback & additional rounds	

Figure 4.9: Overview of the Delphi method: key phases of expert engagement and analysis.

First phase: preparing.

Table 4.2: Delphi study questions on Energy Solutions assessment.

N.	Question	Key topic
Q1	The performance of the NDG is satisfying	Performance of NDG
Q2	The supply hours of NDG are sufficient especially in summer	
Q3	Ten hours are considered sufficient for electric supply using NDG	
Q4	It is possible to operate the cooling devices at home by using the NDG	Economic aspects of NDG
Q5	The subscription price is commensurate with the performance of the NDG	
Q6	In terms of location and performance, NDG do not pose environmental damage such as noise, emissions, and waste	Environmental and safety aspects of NDG
Q7	In terms of appearance and safety, the NDG' wiring supply is considered good-looking, does not deform cities, and does not endanger residents	
Q8	Replacing NDG with solar panels is a good solution for power outages	Potential use of SPV
Q9	Iraq's weather in terms of the number of daylight hours and solar radiation is appropriate for the use of solar panels as a source of energy	energy as an alternative in Iraq

1. Defining the topic involves a critical step where the researcher actively defines the survey topic. The relevance and precision of this topic directly influence the quality of the outcomes and the selection of experts. This step also shapes the research questions and the questionnaire used to gather data.
2. Selecting the experts involves the survey team actively choosing experts based on their knowledge of the topic and their willingness to participate in the survey. A well-chosen group of experts ensures higher quality results.
3. Statistical processing; this stage involves defining the statistical methods for analyzing expert responses. Setting up these methods beforehand helps to avoid author bias in data interpretation. The team also establishes stopping conditions at this stage to determine when no further rounds are necessary.

Second phase: Conducting and Reporting. This phase of the Delphi process comprises three stages:

1. **Initial Round:** Introduces participants to the questionnaire. Experts respond in a structured format, and organizers review the responses to assess the need for further rounds.
2. **Collecting Responses and Controlled Feedback:** Organizers analyze the expert responses using a predefined statistical method. This structured feedback minimizes irrelevant content. A summary of expert opinions from the first round informs the decision on whether to proceed to additional rounds [14].
3. **Subsequent Rounds:** Experts receive descriptions and evaluations from previous rounds. They then reconcile these with their initial comments to revise or reaffirm their views. Typically, three rounds are sufficient to capture the panel's perspectives [31, 78].

Third phase: Results. After reaching the necessary number of rounds, organizers process and analyze the data, then actively compile a report to present the findings. The report's depth reflects the analyzed subject and the feedback received. Figure 4.10 illustrates the sequential steps of the Delphi process, as outlined above, in a detailed flowchart.

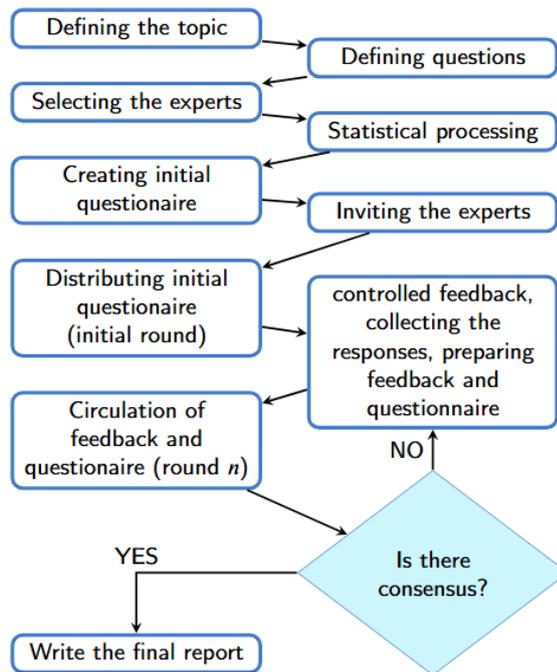


Figure 4.10: Flowchart of the Delphi method process: from topic definition to final report.

4.3.2 Study design

a. Defining the topic. In the preparation phase, how the survey team defines the topic significantly influences the survey's execution. The aim of this survey is to collect expert opinions on the efficacy of NDG and the feasibility of substituting them with solar panels to alleviate electricity shortages. From this research goal, four key questions emerged:

1. Do experts deem NDG a viable solution for power outages?
2. How do experts view the economic viability of NDG?
3. What safety and environmental consequences arise from utilizing these generators?
4. Is there expert consensus on transitioning from NDG to renewable energy, specifically solar power? To address these questions comprehensively, the survey consists of nine structured questions (Table 4.2 provides the rationale behind each question), each with a five-point Likert scale response option (see Figure 4.11 below). The questionnaire was designed to ensure coverage of all critical aspects associated with the use of NDG.

b. Selecting the expert. For the Delphi survey, the team selected experts based on their scientific expertise and knowledge of the topic. Initially, we contacted 30 experts via email to participate. However, 10 experts declined the invitation, leaving 20 respondents. The panel was carefully chosen to ensure diversity, focusing on engineers in energy and electricity, environmental engineering, and economics experts. This alignment ensured that the experts' backgrounds were relevant to the key topics of the questions, providing comprehensive insights into the survey topics. Table 4.3 details the composition of the expert panel.

Table 4.3: Participants' scientific qualifications and experience.

Experience in the field		
3-5 years	5-10 years	15 years
2 (10%)	10 (50%)	8 (40%)
Experts' scientific qualifications		
B.ch	Master	PhD
7 (35%)	9 (45%)	4 (20%)
Total: 20		

c. Statistical processing. The study employs the Likert scale, detailed in Figure 4.11, to analyze survey rounds and determine the expert panel's consensus [14]. This ordinal scale assesses the extent of experts' agreement or disagreement

strongly disagree	disagree	neutral	agree	strongly agree
1	2	3	4	5

Figure 4.11: Likert scale reading.

with specific statements. However, its numerical values, like standard deviations or averages, are not straightforward in meaning. For instance, the gap between 'disagree' and 'strongly disagree' may not be equivalent to that between 'agree' and 'neutral', despite both differences being numerically the same. Earlier points highlight that Likert scale responses are non-quantitative and should not receive numerical treatment.

A clear consensus typically emerges when responses significantly cluster at either high or low extremes. In this study, a straightforward statistical method analyzes this clustering. For questions Q1 to Q7, researchers use the frequency of responses 1 or 2 to estimate the actual proportion of disagreement p_0 and apply

a proportion contrast with the Statistical Package for the Social Sciences (SPSS). This approach is valid because these responses follow a binomial distribution with parameters n (the number of experts) and p_0 . Similarly, for questions Q8 and Q9, the frequency of responses 4 or 5 serves to estimate the agreement proportion. Researchers treat neutral responses (3) as non-consensus, thus strengthening the analysis. The study defines consensus as existing when p_0 is likely 80% or higher and high consensus as exceeding 90%. This determination applies to disagreement for questions Q1 to Q7 and to agreement for Q8 and Q9.

For this contrast of proportions, the study sets a standard level of significance at $\alpha = 5\%$, which allows us to extract the value $z_{0.05} = 1.645$ from the normal distribution and use the following statistical test (according to Moivre's theorem):

$$t_{p_0} = \frac{\hat{p} - p_0}{\sqrt{\frac{p_0(1-p_0)}{n}}}$$

In this analysis, \hat{p} stands for the sample frequency and p_0 , as we said, equals 0.8 to test the consensus and $p_0 = 0.9$ to test the high consensus. The test formula demonstrates easily as shown in Figure 4.12. Two essential phrases, denoting agree-

$H_0 : p_0 \geq 0.8$	test 1:	result: whether it is yes,
consensus	$t_{0.8} \geq 1.645$	consensus is likely true with a 95% of confidence
$H_0 : p_0 \geq 0.9$	test 2:	result: if it is yes, high
high consensus	$t_{0.9} \geq 1.645$	consensus is likely true with a 95% of confidence

Figure 4.12: Consensus interpreting rates ($1.645 = z_{0.05}$).

ment and disagreement among experts, have significantly influenced the opinions of the expert panel. Measuring the level of agreement among panelists involves calculating the percentage of experts who choose either “agree” or “strongly agree” for each response. Similarly, determining the percentage of experts who selected “disagree” or “strongly disagree” establishes the level of disagreement.

4.3.3 Results and discussion

Two essential phrases are carefully selected in the executive summary to show both expert consensus and divergent opinions, providing the groundwork for the Panel of Experts' viewpoints. To assess the degree of agreement, the analysis calculates

the proportion of experts who chose 'agree' or 'strongly agree.' To determine the level of disagreement, it estimates the proportion of those who choose 'disagree' or 'strongly disagree.' Two rounds of questionnaires were handed out during the second phase, 'Conducting and Reporting,' owing to early non-consensus on several aspects. Figure 4.13 illustrates the comparison between the first (a) and second (b) rounds of the questionnaire, highlighting in green color the sample frequencies (\hat{p}) as percentages for selected responses.

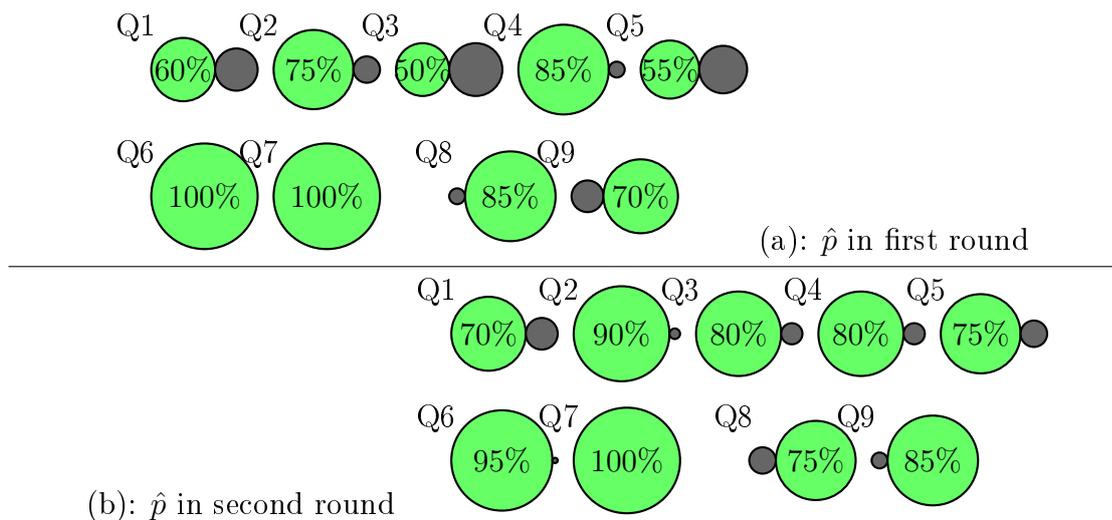


Figure 4.13: Analysis of response frequencies \hat{p} across first and second rounds for questions Q1-Q9.

For questions 1-6, the sample frequency \hat{p} is the percentage of replies marked '1' or '2'. For questions 8 and 9, it is the percentage of replies marked '4' or '5'. These frequencies represent the amount of consensus among the experts, and precise consensus values are later reported in Table 4.4.

Table 4.4: First and second round's consensus result.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
1st round	not consensus	consensus	not consensus	high consensus	not consensus	high consensus	high consensus	high consensus	consensus
2nd round	consensus	high consensus	high consensus	high consensus	consensus	high consensus	high consensus	consensus	high consensus

The third phase, titled "Results", started on August 14, 2022, with the initial Delphi round attracting responses from 20 experts over a 14-day period ending August 28, 2022. This round captured experts' initial reactions to the questionnaire, subsequently analyzed in further rounds. Figure 4.13 (a) displays the first round's sample results, and Table 4.4 reveals the consensus outcomes: agreement consensus on questions eight and nine, high disagreement consensus on questions

four, six, and seven, and only consensus on question two. Questions one, three, and five did not achieve consensus.

The second round began on November 4, 2022, and continued for 12 days until November 16, 2022. All participants agreed to proceed with the survey. Experts received a report summarizing the aggregated findings and comments from the first round. The questionnaire remained unchanged, as it comprehensively covered all necessary aspects. According to Figure 4.13 (b) and Table 4.4, consensus or high consensus emerged on all questions in this round. However, experts modified their opinions on most questions. For instance, several experts were originally hesitant to transition from generators to solar panels because of the high installation costs. One expert proposed government support for the replacement of generators with solar panels, taking into account the current fuel subsidies for NDG. The expert's feedback contributed to increase global consensus levels, as seen by the findings. Following these outcomes, the study progressed to the second stage, focusing on an economic analysis of using SPV panels as an alternative to NDG to address power supply gaps. This stage incorporated data on daily load and hours of interruption during summer, detailed in the study's subsequent section.

4.3.4 Techno-economic evaluations

Site selection

Wasit Governorate, positioned in central Iraq (Latitude 32.2333, Longitude 46.300), is surrounded by Diyala and Baghdad in the north, Maysan and Dhi Qar in the south, Qadisiyah and Babylonia in the west, and an eastern border with Iran. Spanning 17,731 square kilometers, Wasit comprises 17 sub-districts across six districts. Its population stands at 1,378,723, with a 60% urban and 40% rural demographic split [9]. The region's desert climate, typical of the semi-tropical zone, brings high temperatures and drought in summer, and mild winters. Notably, Wasit recorded the lowest dust fall rate in Iraq at 7 g/m^2 , significantly lower than other governorates ($21\text{-}35 \text{ g/m}^2$) as per of Iraq Environmental Statistics Report [7]. Dust accumulation on SPV panels reduces their efficiency [22], making Wasit an ideal location for installing SPV panels, especially considering the suitable roof areas of local houses for such installations. This technical schematic, Figure 4.14, depicts the rooftop of a typical house in Wasit province, highlighting the possibility for SPV panel installation. The complete plan contains dimensions and divided regions appropriate for the installation of solar panels, allowing for the assessment of how many panels may be place to satisfy the energy demand.

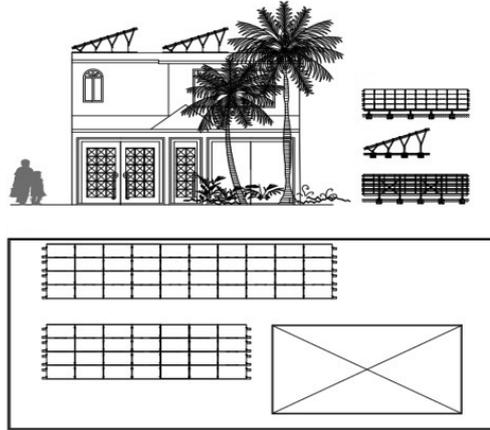


Figure 4.14: Elevation and plan of the SPV system on the roof of a typical building. Just note that there is more than enough space for the installations suggested in Table 4.13 on page 136.

Data collection

a. Electrical load profile: ROSETTA transformation. As mentioned earlier, Iraq lacks smart meters that calculate the accurate consumption of electricity in homes. Then, for estimating the daily electricity consumption (DEC) in Iraq, we present a new method based on the existent similarities in the daily routine between two countries. Actually, we observe that country S (Spain in this study) and country I (Iraq), present the same pattern in the following sense:

- They both present a first time interval $[L - \sigma_L, L + \sigma_L]$ which represent the average time doing housework in the mornings and where the first local maximum point of consumption is achieved;
- They both also have a second time interval around the typical dinnertime $[D - \sigma_D, D + \sigma_D]$, which includes the second (and last) daily local maximum point of consumption. Note that σ_L and σ_D are both related with the duration of this time at home. Roughly speaking, they both have a typical consumption profile as that of Figure 4.15:

Specifically, by utilizing explicit data from ‘Red Eléctrica Española’ [11] and leveraging the unique perspective provided by the fact that the first author has Iraqi heritage, we have estimated the following typical values for these parameters depicted in Table 4.5.

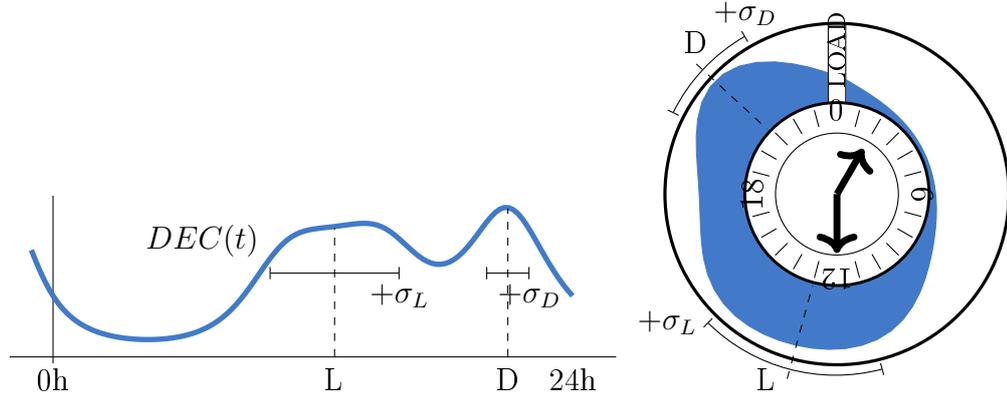


Figure 4.15: Typical winter DEC housing pattern with parameters L , D , σ_L , and σ_D . Represented as a periodic function (above) and as a function on a circle (below).

Table 4.5: Typical values used as ROSETTA parameters.

Parameter	L	D	σ_L	σ_D
Spain	12	21	5	2
Irak	9	19	1.5	3

Our goal consist on first creating a transformation between these two typical patterns, “translating” the typical DEC profile of Spain, with plenty of available data, to that one of Iraq. Secondly, once we have this transformation between typical DEC patterns, by extrapolation of it, we could “generate” Iraq’s data hour by hour all along the year. This is why we call ROSETTA to our transformation, it works as a tool in the same way as the ROSETTA stone do, extrapolating a translation of a small piece (the stone) of an Egyptian text to the whole hieroglyphic text existing everywhere. So, in order to do that, we first create a one-to-one time transformation ϕ on the interval $[0, 24]$ which translates the typical values L , D , σ_L and σ_D presented before and in such a way that $DEC_I(t)$ becomes proportional to $DEC_S(\phi(t))$, where $DEC_S(t)$ and $DEC_I(t)$ are the corresponding (normalized) daily electricity consumption of country S (Spain) and I (Iraq) respectively. Then, for our purposes, it is better to explicitly develop $\phi^{-1}(t')$, it is given by the following piecewise function:

$$\begin{cases} L - \sigma_L + \frac{\sigma_L}{\sigma_{L'}}(t' - L' + \sigma_{L'}), & t' \in I_1, \\ L + \sigma_L + \frac{D - \sigma_D - L - \sigma_L}{D' - \sigma_{D'} - L' - \sigma_{L'}}(t' - L' - \sigma_{L'}), & t' \in I_2, \\ D - \sigma_D + \frac{\sigma_D}{\sigma_{D'}}(t' - D' + \sigma_{D'}), & t' \in I_3, \\ D + \sigma_D + \frac{L - \sigma_L - D - \sigma_D}{L' - \sigma_{L'} - D' - \sigma_{D'}}(t' - D' - \sigma_{D'}), & t' \in I_4, \end{cases}$$

where $I_1 = [L' - \sigma_{L'}, L' + \sigma_{L'}]$, $I_2 = [L' + \sigma_{L'}, D' - \sigma_{D'}]$, $I_3 = [D' - \sigma_{D'}, D' + \sigma_{D'}]$ and $I_4 = [D' + \sigma_{D'}, L' - \sigma_{L'} + 24]$. It transform the intervals $[L' - \sigma_{L'}, L' + \sigma_{L'}]$ and $[D' - \sigma_{D'}, D' + \sigma_{D'}]$ from country S to those of country I, specifically by translating the hours of peak consumption and adjusting the intervals around the inflection points within these periods.

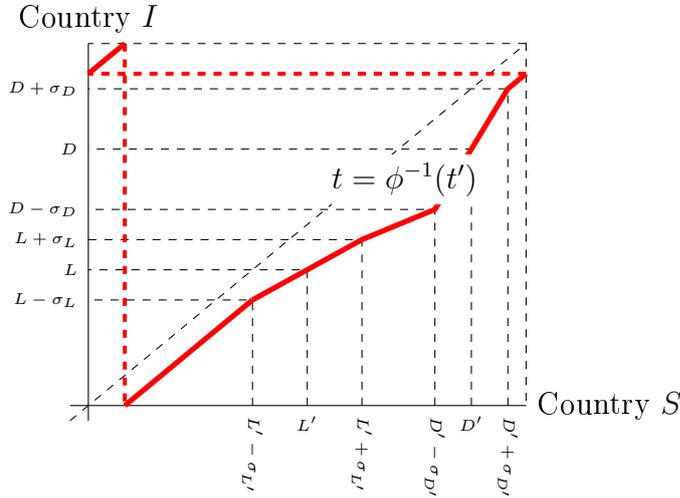


Figure 4.16: ROSETTA transform seen as graph on the torus.

The last line of definition have to be understood in the torus, i.e. time $t' + 24$ is equals to time t' and similarly for the resulting time t . Actually, as shown in Figure 4.16, we can describe it as a kind of graph on the torus.

In order to complete the transformation, two additional factors must be considered: firstly, the local maximum values might differ, as $DEC_I(t)$ is proportional to $DEC_S(\phi(t))$ but not necessarily identical. Secondly, the high-energy consumption in Iraq during summer nights, which deviates from the typical Spanish consumption profile shown in Figure 4.15. To address the first issue, the following adjustment can be made:

$$DEC_I(t) = \frac{r(t)}{r_\phi} DEC_I(\phi(t)),$$

Where the proportionality function $r(t)$ plays the role of adjusting the local maxima (taken as a constant means, as a first approach, that the local maximum values of consumption in both countries are quite similar) and finally the constant r_ϕ is just a normalization scale ratio given by

$$r_\phi = \int_0^{24} r(t) DEC_I(\phi(t)) dt.$$

Due to the lack of better data, we simply set $r(t) \equiv 1$. To accurately represent summer data, a plateau function was incorporated into the nighttime consumption profile for the months from June to September, accounting for the increased energy use during this period. As shown in Figure 4.18, this adjustment is highlighted in purple, illustrating the complete transformation of the DEC profiles.

The final step in the ROSETTA transformation, as depicted in the flowchart in Figure 4.17, involved de-normalizing the profile to ensure it accurately reflects the actual electricity consumption patterns in Iraq. To achieve this, we refer to [56] from the Iraq Energy Institute, which establishes the average household electricity consumption in Iraq across three scenarios: the Low case, the Base case, and the High case, as shown in Table 4.6. The ROSETTA transformation method was adapted from Spain's load profile due to observed similarities in daily routines between Spain and Iraq. However, adjustments were made to account for Iraq's unique consumption patterns, particularly the higher energy usage during summer nights, by introducing a plateau function to the model. While factors such as climatic, economic, and cultural differences may introduce some biases, the transformation includes normalization and scaling adjustments to ensure the generated profiles reflect Iraq's electricity consumption as accurately as possible. Despite these limitations, this method provides a reasonable approximation in the absence of detailed local data.

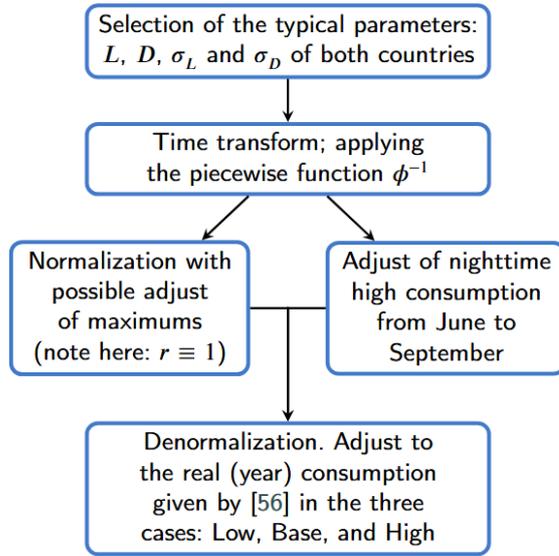


Figure 4.17: Step by step explanation of the ROSETTA transformation process.

Table 4.6: Household electricity consumption scenarios in Iraq: Low, Base, and High Cases (kWh/month) [56].

CASE	LOW	BASIC	HIGH
Winter: Dec. Jan., Feb.	1,071.26	1,428.35	1,856.86
Summer: June, July, Aug.	1,280.53	1,829.33	2,378.12
Total kWh/Year	13,482.93	18,343.14	23,846.10

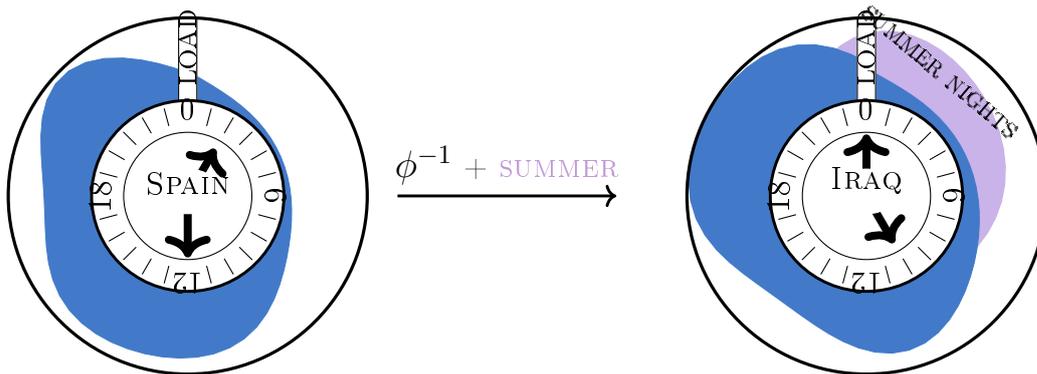


Figure 4.18: ROSETTA transformation from typical (normalized) DEC profiles from Spain to Iraq.

b. Validation of the ROSETTA transformation . The power of the ROSETTA tool lies in its simplicity, allowing the generation of daily load profiles using only four parameters in the simplest case. To validate the ROSETTA time transform, a forecasting experiment was conducted by generating the DEC for Italy in 2023, which is likely to follow a similar pattern to that of Spain. The obtained DEC was then compared with the actual DEC values. For this validation, the following accuracy non-dimensional coefficient was defined:

$$\mathcal{A} := 1 - \frac{\sum_{d=1}^{365} \sum_{h=1}^{24} |Ros_{dh} - Real_{dh}|}{\sum_{d=1}^{365} \sum_{h=1}^{24} Real_{dh}}$$

where Ros_{dh} represents the load predicted by ROSETTA on day d of the year at hour h , and $Real_{dh}$ is the actual load for the same day and hour, obtained from the platform ENTSO-E [5]. For this validation we have chosen the following parameters

Parameter	L	D	σ_L	σ_D
Spain	14	21.2	3.2	4
Italy	12	20	2	3

and also, as in the Iraq case, we put $r \equiv 1$. An accuracy coefficient of $\mathcal{A} = 82.6\%$ was achieved, which is considered sufficient to demonstrate the efficiency of the ROSETTA transformation, especially given that it operates with only four parameters.

c. Solar radiation and ambient temperature. The location considered in the case study is the city of Wasit (Iraq). The geographical coordinates are Latitude 32.2333, Longitude 46.300, and elevation 15 m. The database we used to obtain the solar radiation has been Photovoltaic Geographical Information System (PVGIS) [51], last available year 2022.

d. Electricity prices. In addition to the national network, NDG contribute about 20% of the demand. Then, the electricity prices in Iraq paid by consumers are both the national grid, detailed in Table 4.7, and NDG. The NDG charge around \$300 for 15 amperes to power two air conditioning units, as well as a refrigerator and lights [17]. There are different prices for subscription to NDG, and the price depends on the number of operating hours and the rate of subscription as shown in Table 4.8.

Table 4.7: Electricity prices in Iraq (national grid) [8]

Electricity consumption (kWh)	Value (Iraqi Dinar/kWh)	Value (\$/kWh)
1-1500	10	0.0084
1501-3000	35	0.0293
3001-4000	80	0.0672
>4000	120	0.1008

Table 4.8: Subscription prices to NDG.

Subscription rate	Price/month	Operation	Ref.
15 Amp	\$300	Entire day	[17]
6 Amp	\$100	Entire day	[19], [56]
1 Amp	\$8.4	8 hours/day	[19], [56]

4.4 Optimization and economic analysis

The present state of the electrical network, characterized by frequent power outages, is illustrated in Figure 4.19. These outages are primarily addressed using

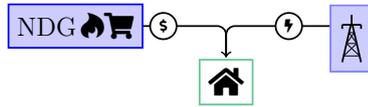


Figure 4.19: Traditional combined grid (with outages) and NDG energy supply to households.

NDG. While NDG offer a temporary solution during power outages, they lead to substantial economic and environmental concerns. Acknowledging these challenges, the study embarks on a comprehensive analysis to assess the technical and economic viability of transitioning from NDG to a more sustainable and reliable alternative. In pursuit of this goal, the development of an HMGS is proposed. The proposed HMGS design, detailed in Figure 4.20, is a composite system incorporating SPV panels, batteries, GG, and potentially other elements.

This approach is designed to enhance the stability and efficiency of the energy supply, notably improving the reliability, performance, and sustainability with respect to the existing network. To meet the outlined objectives, we first compute

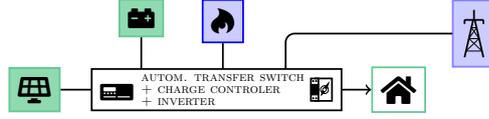


Figure 4.20: Whole configuration of the HMGS studied.

in the following Sections 4.4.1 and 4.4.2 the optimal sizing of the SPV installation, for the three scenarios described in Table 4.6. It will be determined focusing on minimizing the cost of the SPV installation and maximizing simultaneously the saved energy generated by the panels, obtaining as a result a reference price per kWh to be compared with the real prices in Table 4.7.

4.4.1 Economic baseline data

A comprehensive cost-benefit analysis was conducted to assess the financial viability of the proposed HMGS. The initial investment costs were calculated based on actual market prices for solar plants and associated components. Table 4.9 outlines the essential components, including SPV panels, batteries, and a gasoline generator, along with their respective prices. The installation costs for SPV installations range from \$1.73 per watt for a 2300 W installation to \$1.26 per watt for a 6000 W installation (see Figure 4.21). The annual maintenance and operation costs are estimated at \$63 for the SPV installation. If the system includes a generator, an additional investment of \$1300 is required, with a fuel cost of \$0.31 per liter. The cost of batteries is considered to be \$1400 each, which adds essential energy storage capacity to the system. Additional installation expenses, such as brackets and wiring, total \$60.

Table 4.9: HMGS components and initial investment overview.

Component	Description	Capacity	Price in \$	Additional information
SPV panels [12]	460W 24V monocrystalline	0.46 kW	80.71	Cost per Watt detailed in Fig.4.21
Battery	24V, 12A , 90% discharge rate	5.12 kWh	1,400	A total charge capacity of 1,200Ah
Gasoline generator	Operates at 95% efficiency and gasoline consumption of 0.395 Kg/kWh	3.5 kW	1,100	Price of gasoline \$0.31 per liter

The regression analysis in Figure 4.21 illustrates the linear relationship between installation costs and wattage, with an R^2 value of 0.57745, indicating that approximately 57.7% of the variation in installation costs can be explained by wattage. The linear regression equation $p(w) = -0.00014w + 1.98580$ suggests a decreasing trend in installation cost per watt as the wattage increases. The slope coefficient is -0.00014 (95% CI: $[-0.00016, -0.00012]$), and the intercept is

1.98580 (95% CI: [1.95000, 2.02160]). At a higher wattage, the calculated value $p(w) = 1.1458$ represents the cost per watt for that specific wattage level. Section 4.4.2 delves into the methods used to assess the cost-effectiveness of SPV installations, focusing on identifying approaches to minimize the costs associated with generating solar power. This exploration covers a range of cost-influencing factors, including the upfront investment required for solar panels and related equipment, the maintenance costs incurred over the lifespan of the system, and the potential for savings on electricity bills.

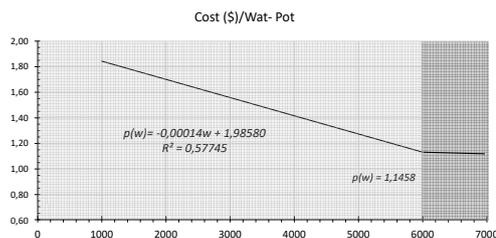


Figure 4.21: Installation cost per Watt.

4.4.2 Optimal design of the SPV installation

In conducting the feasibility study, identifying the most efficient SPV installation capable of supplying energy to the system is essential. The SPV system is designed to meet a portion of the energy requirements during daylight hours by harnessing available solar radiation. The power output of the SPV system is directly derived from solar radiation, utilizing radiation data from the PVGIS database [51], as previously indicated. The output power of the SPV system is mathematically modeled as a function of solar radiation and ambient temperature. This relationship is captured within the following equation:

$$P_{out} = \frac{P_r G}{G_{ref}} \left[1 + K_t (T_{amb} + 0.02256 G - T_{ref}) \right],$$

where P_{out} is the output power of the SPV, P_r is the rated power of the panel at standard test conditions, G is solar irradiance, K_t is a temperature coefficient, T_{amb} is the ambient temperature, T_{ref} is the reference temperature (usually 25°C), and finally G_{ref} is the reference solar irradiance (1000 W/m^2).

In scenarios where the SPV system cannot meet the energy demand, auxiliary sources such as the national electric grid, GG, or batteries are utilized within the HMGS to cover the shortfall. Figure 4.22 depicts the hourly energy needs that must be met, illustrating instances where the output from the SPV system is insufficient. The determination of these demands relies on the ROSETTA model.

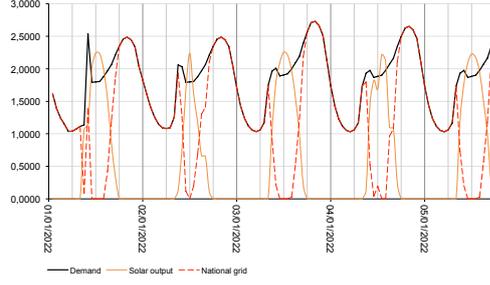


Figure 4.22: Demand and solar contributions curves in kW.

Before calculating the payback period (PBP) for various scenarios, an optimal SPV system configuration was estimated, targeting an internal rate of return (IRR) of $r = 4\%$ over 15 years. This rate is aligned with the financial discount rate recommended by the European Union for cost-benefit analyses, ensuring consistency with standard economic evaluations [39]. The aim is to identify the cost per kilowatt-hour (kWh) necessary to recover the investment in the SPV system, considering this IRR. This cost per kWh is directly influenced by the number of panels, and it will be represented by $p(n)$. In a first step, disregarding the IRR, if $I(n)$ represents the investment for an SPV system with n panels and $E(n)$ is the annual usable energy output from this n panels, the basic equation $I(n) = 15 p(n) E(n)$ must be clearly fulfilled and, it straightforwardly produces

$$p(n) = \frac{I(n)}{15 E(n)}, \quad (\text{for } r = 0).$$

Integrating in a second step the influence of the IRR, $r = 0.04$, the updated formula for $p(n)$ is then given by:

$$p(n) = \frac{I(n)}{S_r E(n)}, \quad \text{where } S_r = \frac{(1+r)^{15} - 1}{r(1+r)^{15}},$$

replacing the constant 15 of the initial formula with S_r to account for the time value of money over a 15-year period at a rate of r . Note that when the value of r approaches zero, the value of S_r converges to 15, effectively reverting to the initial formula. It is important to underscore that throughout the development of this optimization function, the annual energy usage $E(n)$ is assumed to remain constant over the years. This assumption simplifies the projection process. Nevertheless, the formula can be expanded to accommodate variations in this saved energy, if they occur. Expanding $I(n)$, the final formula could be finally given by:

$$p(n) = \frac{r(1+r)^{15}}{(1+r)^{15} - 1} \frac{I_0 + I_{cp}(n)}{E(n)},$$

where I_0 refers to the fix cost of the installation independent of the number n of panels (inverters, wiring...), and $I_{cp}(n)$ indicates the variable cost due to the n panels. This approach has been applied across the three levels of consumption -low, base, and high- described in Table 4.6, and using the ROSETTA transform to compute $E(n)$. The outcomes are illustrated in Figure 4.23, which indicates that

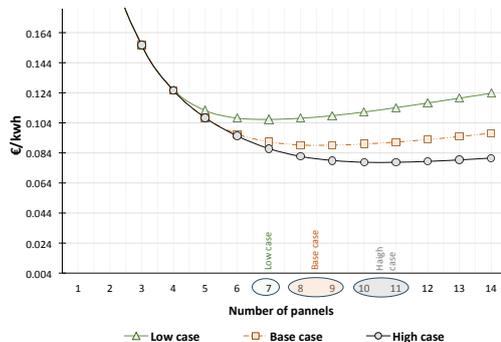


Figure 4.23: Function $p(n)$ for the low, base and high cases.

the optimal number of SPV panels -obviously- varies according to the scenario and are: 7 panels for the low case, 8-9 for the base case, and 10-11 for the high case. The corresponding optimal prices are detailed in Table 4.10.

Table 4.10: Analysis of optimal SPV panels' configuration and corresponding electricity cost.

Electricity Consumption	Low	Basic	High
Number of panels	7	9	11
The optimal $p(n)$ \$/kWh	0.106	0.089	0.078

This table, in agreement with Reference [20], illustrates that SPV installations in Iraq face, *a priori*, economic challenges due to the country's low electricity pricing regime stated in Table 4.7.

This pricing structure makes recouping investments in rooftop solar systems through grid energy savings virtually unfeasible, unlike in European contexts where higher electricity costs have spurred SPV adoption, as seen in Spain [52]. However, factors like grid instability and the reliance on NDG, which present both economic and environmental challenges, add complexity to the feasibility analysis. Further exploration in Sections 3 and 3.1 will delve into scenarios highlighting the SPV systems' capacity for enhancing energy efficiency and economic viability, suggesting that substantial savings can be achieved over time despite initial barriers.

4.5 Feasibility analysis

Optimizing HMGSs is crucial for avoiding exorbitant installation costs and ensuring a reliable power supply [75]. Consequently, several studies have been conducted to evaluate these systems from economic, environmental, and sizing perspectives. The following Table 6.2 presents key technical and economic data for various HMGSs implemented in Iraq and other regions facing similar challenges.

Table 4.11: Comparative analysis of HMGSs in conflict-affected regions

Location	Daily Consumption (kWh/day)	Peak Demand (kW)	Hybrid System Configuration	COE (\$/kWh)	Initial Capital Cost (\$)	NPC (\$)	Ref.
Saudi Arabia (Jubail)/community	11,160-4865-3288	685-463-270	SPV/WT/DG/BTs SPV/WT/BTs (Off- grid)	0.183-0.55	NA	3.9-17 million	[29]
India (Rural)	51.54	11	SPV/WT/DG/BTs (Off-grid)	0.179	63,116	31,439	[58]
Egypt (Marsa-Matruh)/ community	401	NA	SPV/WT/DG/BTs (Off-grid)	0.2262	162,368	351,223	[59]
Iraq (Bagh- dad) /house- hold	46.9	4.4	SPV/BTs (Grid-connected) SPV/DG/BTs (Grid-connected)	0.165	12,940	26,268- 29,713	[25]
Iraq (Erbil, Sakran Village)	33.29	34.34	SPV/Hydro/DG/BTs	0.054	60,740	113,201	[24]
Iran (Shiraz) /non resi- dential community	9911	725	SPV/WT/DG/BTs (Off-grid); SPV/WT/DG/BTs (Grid-connected)	0.093-0.142	2,480,000	NA	[26]
Iran (KhshU Site)	3	0.388	SPV/BTs (Off-grid); SPV/WT/BTs (Off- grid)	0.546-0.620	6,030-6,560	8,173- 9,267	[48]
Saudi Arabia /health care center	23.76	3.38	SPV/DG/BTs (Off- grid)	0.105	6,500	22,275	[21]
Iran/ educa- tional building	9196	79.85	SPV/WT; SPV/WT/DG (Grid- connected)	0.0024-0.0272	74,410-84,437.5	49,022- 224,430	[74]
Malaysia (Sabah Village) 35 household	2138.50	NA	SPV/2DG/BTs (Off- grid); SPV/2DG/BTs (Grid-conn.)	0.151-0.281	NA	2,802,919, 1,500,000	[46]

The table includes information on electricity consumption, peak demand, system design, cost of energy (COE), initial capital investment, and net present cost (NPC). For example, the proposed HMGS for Baghdad, Iraq, includes both SPV/Battery and SPV/diesel generator (DG)/Battery configurations, with peak demands of 4.4 kW. The COE for these configurations is \$0.165/kWh, with an initial capital cost of \$12,940 and an NPC ranging from \$26,268 to \$29,713. Additionally, in Erbil, Iraq, a hybrid system comprising SPV/Hydro/DG/Battery is utilized, with a peak demand of 34.34 kW. From an environmental perspective, these systems demonstrate significant reductions in CO₂ emissions compared to conventional DG. For instance, in Saudi Arabia (Jubail), a 100% renewable system can save approximately 2,800 tons of CO₂ annually, while in India, the optimal system's emissions are around 1.747 tons of CO₂ per year. In Baghdad,

Iraq, emissions were reduced by 8,033 kg/year using an optimized SPV system, although the addition of a 2 kW DG increased emissions to 10,657 kg/year, despite lowering the NPC. In Shiraz, Iran, a non-residential system achieved a CO₂ reduction of up to 791,560 kg per year. Despite these environmental benefits, it's essential to consider the lifecycle impacts of SPV panels and batteries. The majority of SPV panel materials, such as glass, polymers, and aluminum, are non-hazardous; however, elements like silicon, silver, lead, and cadmium require careful handling and disposal to prevent environmental contamination. Furthermore, batteries, particularly lithium-ion types, pose risks such as thermal runaway, leading to fire hazards and the release of toxic substances. Therefore, effective waste management and recycling processes are crucial for minimizing environmental risks associated with SPV systems [54, 66]. The integration of components like SPV panels, wind turbines, DGs, and batteries involves using inverters for DC-AC conversion, energy management systems to optimize power flow, and backup generators to ensure reliability during periods of low renewable energy production. These systems have been carefully sized and configured to meet varying demands while optimizing economic viability. From a comparative perspective, Iraq's COE of \$0.054 to \$0.165/kWh is relatively competitive compared to other regions like Iran and Saudi Arabia, making these systems economically feasible. However, the ongoing instability in the region may influence initial capital costs and NPC. Iraq's high solar potential enhances the viability of SPV-based systems, which might be less effective in regions like India that require a more diverse energy mix. Finally, the success of these systems in Iraq will depend on local acceptance and political stability, factors that have been more favorable in regions like Saudi Arabia and Malaysia.

Table 6.2 provides critical insights into the technical specifications, economic feasibility, and comparative analysis of HMGSs in Iraq and other conflict-affected regions. Building on this comparative data, the viability of the proposed solutions is assessed by calculating the PBP, which represents the duration required to recover the initial investment costs.

4.5.1 Payback period definition

Authors use PBP as an indicator of the profitability of the investment. It refers to the period it takes for an investment to recoup its initial cost. A shorter PBP indicates that the investment is generating a higher return on investment and is therefore more profitable. As usual, the PBP has been calculated, estimating the period n where the net present value (NPV), given by Eq. (4.1), equals the initial cost.

$$NPV_n = \sum_{k=1}^n \frac{R_k}{(1+i)^k}. \quad (4.1)$$

Here, R_k is the cash flow in the year k , and i stand for the interest rate 4% [71]. In literature, researchers have conducted many studies that aim to study economic feasibility analysis using PBP method as listed in Table 4.12.

Table 4.12: Economic analysis of HMGSs using PBP.

HMGs configuration	Location	PBP(years)	Comments	Ref.
SPV	Pakistan	1.84	Economically viable	[61]
	Thailand	2.66		
WT+ storage hydrogen+DG	Arctic villages	< 4	Financially viable	[32]
SPV+ battery	Thailand	6.3	Economical and suitable for rural electrification	[80]
SPV+ battery	Nigeria	1.46	Economical and suitable in developing countries	[18]
SPV+ WT+ battery	Iran	10.53	Technically and economically feasible	[63]
SPV+ WT+ biomass (recycling of sugar cane wastes)	Brazil	3.69	The proposed system is both environmentally and economically feasible	[65]
SPV + battery	Iraq	20-25	When compared to the cost of residential electricity, the system may not be economically viable	[20]

According to the research presented in this Table, HMGS is economically and technically viable, with the exception of reference [20], which deemed it infeasible owing to Iraq’s low national grid costs. The PBP for HMGS investment varies depending on tariffs, capacity, component pricing, and weather, which is crucial for RESs. Given the difficulty of anticipating long-term cash flows, PBP is often used for preliminary evaluations of high-risk projects or during uncertain periods. For the cost-benefit and PBP calculation, based on the price data provided in Section 4.4.1, Table 4.9 (breakdown of the initial investment and maintenance), Table 4.7 (savings in the grid consumption), and Table 4.8 (savings due to the absence of NDG subscription), all relevant costs were considered. The next section will use PBP to examine HMGS’s economic viability under different scenarios, including its potential as an alternative to NDG during power outages.

4.5.2 Alternative energy solutions to meet demand without NDG

Presently, the approach has been to mitigate the power disruptions by using NDG. These generators give rise to a multitude of issues associated with pollution, noise, and so on. Our objective is to guarantee the uninterrupted provision of electricity in residential properties without relying on NDG. To address the issue of power outages and limited solar radiation, it is essential to use a second generation or storage system alongside the SPV system. This will ensure that the energy demand is met consistently, even during periods when the electrical grid is unreliable or when solar radiation is insufficient. We suggest two options: the use of batteries

or a GG. Figure 4.24 presents the various possibilities that were considered while designing the HMGS and conducting the economic feasibility analysis.

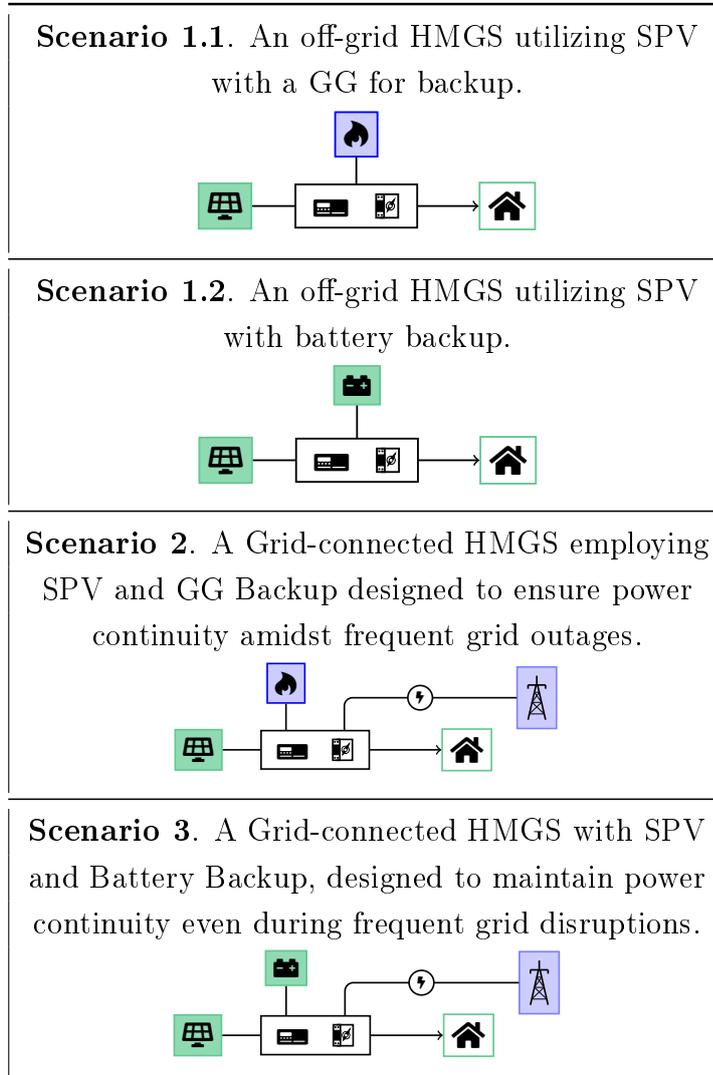


Figure 4.24: HMGS scenarios analyzed.

Scenario 1.1: Off-grid HMGS utilizing SPV and GG backup

It was found that to meet the demand not covered by the SPV system, the GG must operate all day if there are fewer than 5 panels and at least overnight, amounting to approximately 4713 hours per year for the three scenarios (low, high, and base). This operation results in gasoline costs of around \$1500 annually. Additional

concerns include issues with fuel supply, maintenance, noise, and environmental impact, which lead the authors to view this solution unfavorably.

Scenario 1.2: Off-Grid HMGS utilizing SPV and batteries backup

This scenario examines the substitution of GG with battery storage. The large number of SPV panels and batteries required to supply the load (and therefore their very high price) makes this solution impractical for the three cases under study and more broadly. Identifying more affordable storage solutions continues to be a challenge in our shift towards an energy paradigm that minimizes CO₂ emissions and aligns with the United Nations' climate change objectives.

Scenario 2: Grid-connected HMGS utilizing SPV and GG backup

In the model where an HMGS is connected to the grid and supplemented by a GG, random grid outages are estimated at 7 hours per day, equating to an average grid electrical supply capacity of 70.5%. In scenarios where the SPV system fails to generate electricity concurrent with a grid outage, the GG is deployed. It has been determined that the generator must run for approximately 2,535 hours, independently of the case under study, incurring an annual gasoline cost of \$1,455.50. Similar to Scenario 1.1, there are several drawbacks, including fuel supply and generator maintenance, that render this option unfeasible, despite a PBP of only 2.97 years, according to the authors.

Scenario 3: Grid-connected HMGS utilizing SPV and batteries

In the case of an HMGS connected to the grid and supported by batteries, random grid outages totaling 7 hours per day are modeled, resulting in a grid electrical supply capacity of 70.44%. To meet the annual demand outlined in Table 4.6 for three cases, a specialized type of inverter capable of operating in island mode during grid disconnection, along with a bank of 5 lithium batteries as (each with a capacity of 5.12 kWh and a 90% discharge capability, see Table 4.9), is required. This setup provides a total capacity of 29 kWh. Simulations of random outages conclude that the system can cover practically 100% of the annual demand, with an unsatisfied demand not exceeding 4 hours/year. The PBP analysis indicates that this solution is not only viable but also economically beneficial, offering annual savings of up to \$4,216 (in the high case) from the fourth year onward. Table 4.13 summarizes the data used to calculate the PBP for the three cases.

Table 4.13: Feasibility analysis of HMGSs, **Scenario 3**, in the three cases versus different subscriptions of NDG and resulting PBP.

Aspect	Low case		Base case		High case
Num. SPV panels	7		9		11
Num. batteries	3		4		5
NGDs (\$/month)	40	100	100	300	300
PBP (years)	22.37	8.1	8.89	3.14	3.61

The analysis of low, base, and high scenarios shows that HMGSs are feasible, even in the worse case, with a PBP of 22.37 years in the low case with the lower subscription. This feasibility stems from the operating restrictions of this NDG subscription (see Table 4.8), which function only for 8 hours during certain periods of the day. If these operating hours overlap with the availability of the national grid, NDG fail to bridge the electrical gap following an outage, exacerbating power shortages. Furthermore, including air conditioning in the load profile highlights the limitations of NDG, as their delivered power is insufficient for such energy-intensive equipment. This scenario demonstrates the potential of HMGSs to enhance power availability and living standards by providing a continuous and stable energy supply, surpassing the capacity and scheduling limitations of NDG.

4.5.3 Performance Evaluation and Analysis of the HMGS

The performance of the HMGS was analyzed under both low and high load scenarios to evaluate its efficiency, reliability, and capacity utilization. The key metrics for each scenario are summarized in Table 4.14.

Table 4.14: Performance Evaluation of the HMGS under Low and High Load Scenarios

Metric (with formula)	Low-Case Scenario	High-Case Scenario
Total load demand (kWh)	13,482.9	23,846.1
Usable solar energy (kWh)	4,414.7 (32.75% of total load)	7,423.1 (31.13% of total load)
Energy supplied by grid (kWh)	9,068.2 (67.25% of total load)	16,423.0 (68.87% of total load)
Usable battery capacity (kWh)	1.7 (from 2 batteries)	8.5 (from 5 batteries)
System efficiency = $\frac{\text{Total energy supplied}}{\text{Total load demand}}$	100%	100%
Loss of load probability-Grid only = $\frac{\text{Total failure hours}}{\text{Total hours in a year}}$	0.17%	29.17%
Loss of load probability-Hybrid system = $\frac{\text{Total hours of load loss}}{\text{Total hours observed}}$	0%	0%
Capacity factor of PV = $\frac{\text{Usable solar energy}}{\text{Possible annual PV output}}$	81.55%	87.26%
Renewable fraction = $\frac{\text{Total renewable energy generated}}{\text{Total energy generated}}$	32.75%	31.13%

Table 4.14 shows that, in both scenarios, the HMGS (SPV + Grid + Battery)

achieved a system efficiency of 100%, ensuring that the entire load demand was met without any interruptions. The Loss of Load Probability (LOLP) for the grid-only system was 29.17% in both cases, but the integration of SPV and battery storage reduced the LOLP to 0%, demonstrating the system’s reliability. The capacity factor of the SPV system improved from 81.55% in the low case to 87.26% in the high case scenario, indicating efficient utilization of the solar resource as the load increased. Additionally, the Renewable fraction, which represents the percentage of energy supplied by renewable sources, was 32.75% in the low case and 31.13% in the high case, showing that a significant portion of the energy demand was met by solar power. These results confirm the effectiveness of the HMGS in delivering reliable and efficient energy supply across varying load demands, while also emphasizing the contribution of renewable energy to the overall system performance.

4.5.4 Energy Management Systems

The proposed HMGS operates in two modes: off-grid or grid-connected, integrating three energy sources: SPV, GG, and batteries. To ensure a reliable supply to the load while minimizing energy waste, an energy management system control is applied in the four scenarios. In all of them, to maximize the use of the SPV, the first step is to compare the power demand (P_d) with the power of the SPV (P_{spv}).

Standalone mode. The proposed HMGS includes two backup options, as shown in Figures 4.25 and 4.26.

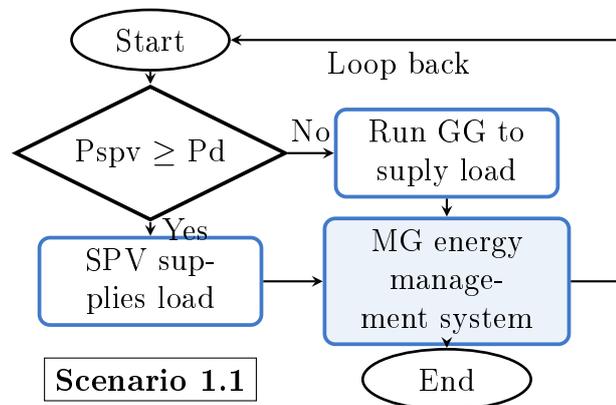


Figure 4.25: HMGS for a standalone system with GG..

- 1.1 During the day, the SPV system supplies electricity if solar radiation is sufficient. Otherwise or when demand exceeds SPV capacity, the GG serves as backup.

- 1.2 When there is adequate solar radiation, the SPV system powers the load during daylight and charges the batteries. When the SPV system fails, batteries provide power to the load.

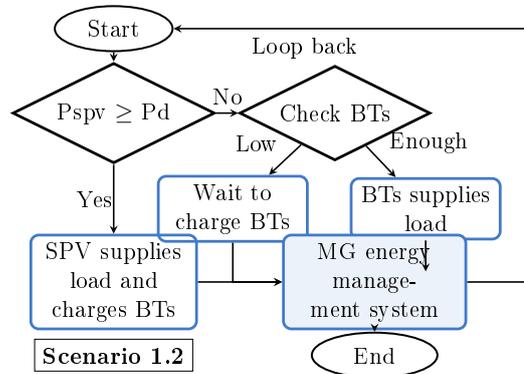


Figure 4.26: HMGS for a standalone system with batteries.

Grid-connected mode. The primary concept behind the second and third scenarios, shown in Figures 4.27 and 4.28 respectively, is to diminish dependence on the national grid and maximize the use of the SPV system.

2. Within a grid-connected setup, the HMGS leverages its SPV component to supply power during daylight. Should solar radiation prove inadequate, the grid will then supply the load if operational. However, should both the grid and the SPV fail, a GG is activated as the backup power source.

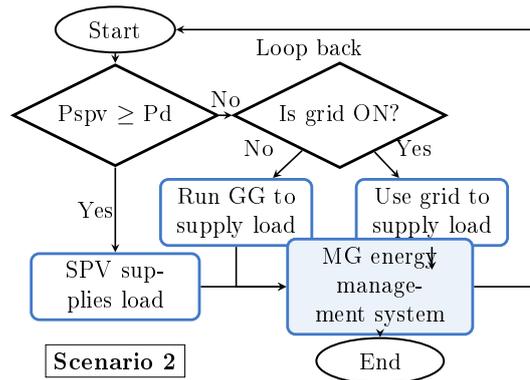


Figure 4.27: Grid-Connected HMGS with GG.

3. In this grid-connected scenario, the HMGS utilizes its SPV component to power the load and charge the batteries during daylight and in case of grid interruptions. If solar radiation is inadequate, the grid, when active, supplies the load and can charge the batteries. Should both the grid and the SPV fail, the batteries act as a backup to power the load.

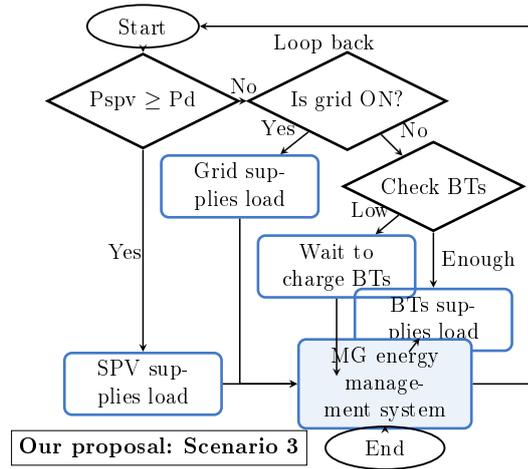


Figure 4.28: Grid-Connected HMGS with batteries.

4.6 Conclusion

In this pivotal study, the complex electricity landscape of Iraq is examined, particularly the impact of four wars on its national infrastructure, which has resulted in daily power outages. The use of neighborhood diesel generators (NDG), although widespread, offers only a poor stopgap for these power disruptions. The study's first phase entailed a socio-economic evaluation using the Delphi method, where experts collectively recognized the necessity to transition from NDG to solar photovoltaic (SPV) panels, underscoring this shift as a solution to the nation's energy woes.

With the aim of providing a reliable energy supply, the research then focused on the innovative application of the ROSETTA model, crucially adapting Spain's load profiles to Iraq's unique circumstances due to the paucity of local data. This adaptation produced three distinct load cases -low, base, and high- laying the foundation for calculating the optimal number of SPV panels required: 7 for the low, 9 for the base, and 11 for the high consumption case, respectively. The investigation moved forward into a detailed optimization process, revealing the optimal cost per kWh for SPV deployment at \$0.106 for the low, \$0.089 for the

base, and \$0.078 for the high scenarios. This analysis proved vital, highlighting the SPV installations' cost-effectiveness and paving the way for a feasibility analysis of Hybrid Microgrid Systems (HMGS). These systems, comprising SPV panels, batteries, and gasoline generators, were analyzed for both on-grid and off-grid installations. The study determined that an HMGS utilizing SPV in conjunction with battery storage was the most feasible on-grid solution, offering not just an answer to power shortages but also financial benefits. The significance of this finding is reflected in the calculated payback periods: 22.4 to 8 years for the low consumption case, 8.9 to 3.14 years for the base case, and 3.6 years for the high case, each demonstrating the economic viability of the proposed system.

The study's conclusions are clear and compelling: despite the infrastructural and financial hurdles, Iraq's adoption of an HMGS supported by SPV and battery storage on the grid is not only technically feasible but also economically advantageous. This research emphasizes the urgency of a strategic shift in energy policies toward embracing clean, renewable energy solutions to replace inadequate temporary measures like NDG. The insights offered here illuminate a pathway for not only Iraq but also potentially other energy-strapped nations to advance toward a sustainable and resilient energy future.

However, further research is needed to address several critical areas:

1. **Regulatory and Policy Framework:** A detailed examination of the regulatory and legal considerations for implementing HMGS in Iraq is necessary. Future studies should focus on identifying the policy changes required to facilitate this transition.
2. **Environmental Impact:** Long-term studies on the environmental impact of widespread SPV and battery adoption are essential, particularly in terms of lifecycle analysis and recycling.
3. **Sensitivity Analysis:** Assessing the impact of variations in key factors like fuel prices and panel costs, and comparing theROSETTA method with other time transformation methods, will enhance the system's robustness.
4. **Social Acceptance:** Research into community engagement and social acceptance of SPV systems will help in understanding the challenges and opportunities in the transition from NDG to renewable energy sources.

References for Chapter 4

- [1] Absolute annual change in primary energy consumption, 2022. <https://ourworldindata.org/grapher/abs-change-energy-consumption>. Accessed Jan. 22, 2024.
- [2] Annual report on electricity production in Iraq. https://mop.gov.iq/en/activities_minister/view/details?id=329. Accessed May 23, 2022.
- [3] Annual statistical report 2022. Available online: <https://moelc.gov.iq/upload/2160481817.pdf>.
- [4] Electricity market report 2023 - analysis - IEA. <https://www.iea.org/reports/electricity-market-report-2023>. Accessed Jan. 22, 2024.
- [5] European network of transmission system operators for electricity. <https://www.entsoe.eu/>. Accessed September 30, 2024.
- [6] Hybrid mini-grids for rural electrification: Lessons learned. www.ruralelec.org. Accessed: May 29, 2022.
- [7] Iraq environmental statistics report: Air pollutants 2019. Available online: <https://shorturl.at/jAMQZ>.
- [8] Ministry of electricity. <https://moelc.gov.iq/>. Accessed May 23, 2023.
- [9] Ministry of planning/central bureau of statistics. Available online: https://cosit.gov.iq/ar/?option=com_content&view=article&layout=edit&id=1214.
- [10] Powering Iraq: Why electricity is key to peace, stability and prosperity. <https://100iraqithoughts.com/2020/07/29/powering-iraq-why-electricity-is-key-to-peace-stability-and-prosperity/>. Accessed Aug. 07, 2021.
- [11] Red Eléctrica Española. <https://www.ree.es/en>. Accessed: Jan. 26, 2024.

- [12] Solar panel reference: Autosolar. <https://autosolar.es/panel-solar-24-voltios/panel-ja-solar-460w-24v-monocristalino-perc>. Accessed: Mar. 05, 2024.
- [13] Solar resource maps and GIS data for 200+ countries. <https://solargis.com/maps-and-gis-data/download/iraq>. Accessed May 29, 2022.
- [14] A group opinion. *The Lancet*, 241(6247):659, 1943. Originally published as Volume 1, Issue 6247.
- [15] Ministry of justice, official gazette “Al-Waqae ’newspaper” 4443. Available online: <https://moj.gov.iq/upload/pdf/4443.pdf>, 2020.
- [16] International Energy Agency. Iraq energy outlook. Technical report, 2012.
- [17] International Energy Agency. Iraq’s energy sector: A roadmap to a brighter future. Technical report, 2019.
- [18] D.O. Akinyele and R.K. Rayudu. Techno-economic and life cycle environmental performance analyses of a solar photovoltaic microgrid system for developing countries. *Energy*, 109:160–179, 2016.
- [19] H. Al-Khafaji. Electricity generation in Iraq problems and solutions. *Al-Bayan Cent. Plan. Stud.*, 2018. Available www.bayancenter.org.
- [20] Ali Al-Wakeel. Local energy systems in Iraq: Neighbourhood diesel generators and solar photovoltaic generation. In *Microgrids and Local Energy Systems*, chapter 6. IntechOpen, Rijeka, 2021.
- [21] A.S. Alsagri et al. Techno-economic evaluation of an off-grid health clinic considering the current and future energy challenges: A rural case study. *Renew. Energy*, 169, 2021.
- [22] F.A.A. Alwesabi et al. Fundamental study on the impacts of water-cooling and accumulated dust on photovoltaic module performance. *Int. J. Power Electron. Drive Syst.*, 13(4):2421–2431, 2022.
- [23] S. Amsler and K. Facer. Contesting anticipatory regimes in education: exploring alternative educational orientations to the future. *Futures*, 94:6–14, 2017.
- [24] A.S. Aziz et al. Optimization and sensitivity analysis of standalone hybrid energy systems for rural electrification: A case study of Iraq. *Renew. Energy*, 138:775–792, Aug 2019.

- [25] A.S. Aziz et al. Feasibility analysis of grid-connected and islanded operation of a solar PV microgrid system: A case study of Iraq. *Energy*, 191:116591, Jan 2020.
- [26] M. Baneshi and F. Hadianfard. Techno-economic feasibility of hybrid diesel/PV/wind/battery electricity generation systems for non-residential large electricity consumers under southern Iran climate conditions. *Energy Convers. Manag.*, 127:233–244, Nov 2016.
- [27] The World Bank. Iraq economic monitor with a special focus on energy subsidy reform, 2018. Available online: <https://goo.su/oBqLmhh>.
- [28] World Bank. Electricity services reconstruction and enhancement project. Technical report, 2019.
- [29] M.A. Baseerand et al. Techno-economic design and evaluation of hybrid energy systems for residential communities: Case study of Jubail industrial city. *J. Clean. Prod.*, 237:117806, 2019.
- [30] D.V.M. Bishop et al. Phase 2 of CATALISE: A multinational and multi-disciplinary Delphi consensus study of problems with language development: Terminology. *J. Child Psychol. Psychiatry*, 58(10):1068–1080, 2017.
- [31] Kenneth W. Brooks. Delphi technique: Expanding applications. *The North Central Association Quarterly*, 53, 1979.
- [32] D. Chade, T. Miklis, and D. Dvorak. Feasibility study of wind-to-hydrogen system for Arctic remote locations - Grimsey island case study. *Renew. Energy*, 76:204–211, 2015.
- [33] I. Cleemput et al. Acceptability and perceived benefits and risks of public and patient involvement in health care policy: A Delphi survey in belgian stakeholders. *Value Heal.*, 18(4):477–483, 2015.
- [34] H.M.G. Coelho, L.C. Lange, and L.M.G. Coelho. Proposal of an environmental performance index to assess solid waste treatment technologies. *Waste Management*, 32(7):1473–1481, 2012.
- [35] N. Dalkey and O. Helmer. An experimental application of the Delphi method to the use of experts. *Manage. Sci.*, 9(3):458–467, 1963.
- [36] S.M. Dawoud, X. Lin, and M.I. Okba. Hybrid renewable microgrid optimization techniques: A review. *Renew. Sustain. Energy Rev.*, 82:2039–2052, 2018.

- [37] E. De Luca et al. A Delphi survey of health education system and interprofessional nurse' role. *Nurse Educ. Today*, 99:104779, 2021.
- [38] R.F. Elmore. Getting to scale with good educational practice. *Harv. Educ. Rev.*, 66(1):1–26, 1996.
- [39] Directorate-General for Regional European Commission and Urban Policy. *Guide to cost-benefit analysis of investment projects – Economic appraisal tool for cohesion policy 2014-2020*. Publications Office, 2015.
- [40] Y. Feng et al. Assessing and prioritizing biogas energy barriers: A sustainable roadmap for energy security. *Renew. Energy*, 223:120053, 2024.
- [41] J. Floege et al. Diagnosis and treatment of patients with focal segmental glomerulosclerosis/steroid-resistant nephrotic syndrome: A Delphi survey. *Kidney Int. Reports*, 2022.
- [42] J. Floege et al. International physicians Delphi survey: Managing patients with IgA nephropathy. *Kidney Int. Reports*, 7(9):2076–2080, 2022.
- [43] A. Flostrand, L. Pitt, and S. Bridson. The Delphi technique in forecasting- A 42-year bibliographic analysis (1975-2017). *Technol. Forecast. Soc. Change*, 150:119773, 2020.
- [44] A.R. Furfeld and R.N. Foster. The Delphi technique: Survey and comment: Essentials for corporate use. *Bus. Horiz.*, 14(3):63–74, 1971.
- [45] J. Giraldez Miner et al. Phase I microgrid cost study: Data collection and analysis of microgrid costs in the United States. Technical report, 10 2018.
- [46] L.M. Halabi and S. Mekhilef. Flexible hybrid renewable energy system design for a typical remote village located in tropical climate. *J. Clean. Prod.*, 177:908–924, Mar 2018.
- [47] M.R. Hallowell. Techniques to minimize bias when using the Delphi method to quantify construction safety and health risks. In *Building a Sustainable Future - Proceedings of the 2009 Construction Research Congress*, pages 1489–1498, 2009.
- [48] M. Haratian et al. A renewable energy solution for stand-alone power generation: A case study of KhshU Site-Iran. *Renew. Energy*, 125:926–935, Sep 2018.

- [49] A.M. Hemeida et al. Multi-objective multi-verse optimization of renewable energy sources-based micro-grid system: Real case. *Ain Shams Eng. J.*, 13(1):101543, 2022.
- [50] C. Hsu and B.A. Sandford. The Delphi technique: Making sense of consensus. *Practical Assessment, Research and Evaluation*, 12:10, 2007.
- [51] T. Huld, R. Müller, and A. Gambardella. A new solar radiation database for estimating PV performance in Europe and Africa. *Solar Energy*, 86(6):1803–1815, 2012.
- [52] IEA. Renewables 2022, 2022. Accessed: Dec. 10, 2022. Available: www.iea.org.
- [53] V. Indragandhi et al. Multi-objective optimization and energy management in renewable based AC/DC microgrid. *Comput. Electr. Eng.*, 70:179–198, 2018.
- [54] IRENA and IEA PVPS. End-of-life management: Solar photovoltaic panels. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf, 2016.
- [55] H. Istepanian. Solar energy in Iraq: From outset to offset. Technical Report IEI181018, Iraq Energy Inst., 2018.
- [56] H. Istepanian. Residential electricity subsidies in Iraq: Exploring options for reform. Technical Report IEI90320, Iraq Energy Inst., 2020.
- [57] B. Ju and S. Pawlowski. Exploring the barriers and challenges of information and communication technology use in distributed research today: A ranking-type Delphi study. In *Proceedings of the ASIST Annual Meeting*, volume 48, 2011.
- [58] F.A. Khan et al. Optimization and sizing of SPV/Wind hybrid renewable energy system: A techno-economic and social perspective. *Energy*, 233:121114, 2021.
- [59] K.M. Kotb et al. Coordinated power management and optimized techno-enviro-economic design of an autonomous hybrid renewable microgrid: A case study in Egypt. *Energ. Convers. Manage.*, 221:113185, Oct 2020.
- [60] S.Y. Liu, Y.H. Perng, and Y.-F. Ho. The effect of renewable energy application on taiwan buildings: What are the challenges and strategies for solar energy exploitation? *Renew. Sustain. Energy Rev.*, 28:92–106, 2013.

- [61] A. Maulik and D. Das. Optimal operation of microgrid using four different optimization techniques. *Sustain. Energy Technol. Assessments*, 21:100–120, 2017.
- [62] J. McGrath and J. Fischetti. The future of compulsory schooling: Participant developed scenarios from a modified Delphi survey. *Futures*, 133:102818, 2021.
- [63] S. Mohseni, A.C. Brent, and D. Burmester. A demand response-centred approach to the long-term equipment capacity planning of grid-independent micro-grids optimized by the moth-flame optimization algorithm. *Energy Conv. Manag.*, 200:112105, 2019.
- [64] F. Monari et al. Iatrogenic late preterm birth: when is it recommended? A Delphi survey promoted by the italian society of perinatal medicine. *Eur. J. Obstet. Gynecol. Reprod. Biol.*, 240:23–28, 2019.
- [65] M.M. Morato et al. Future hybrid local energy generation paradigm for the brazilian sugarcane industry scenario. *Int. J. Elec. Power*, 101:139–150, 2018.
- [66] Author Name. Title of the article. *Journal of Energy Storage*, Volume Number:104790, 2022.
- [67] A. Neubert et al. Defining off-label and unlicensed use of medicines for children: Results of a Delphi survey. *Pharmacol. Res.*, 58(5-6):316–322, 2008.
- [68] H. Puppala et al. Identification and analysis of barriers for harnessing geothermal energy in india. *Renew. Energy*, 186:327–340, 2022.
- [69] A.B. Renzi and S.F. de Freitas. Delphi method to explore future scenario possibilities on technology and HCI. In *Design, User Experience, and Usability: Design Discourse*, pages 644–653, Cham, 2015. Springer International Publishing.
- [70] L.A. Ribeiro et al. Prospects of using microalgae for biofuels production: Results of a Delphi study. *Renew. Energy*, 75:799–804, 2015.
- [71] H. Sadeghi, A. Ijaz, and R.M. Singh. Current status of heat pumps in Norway and analysis of their performance and payback time. *Sustain. Energy Technol. Assess.*, 54:102829, 2022.
- [72] S.A.A. Shah, Y.A. Solangi, and M. Ikram. Analysis of barriers to the adoption of cleaner energy technologies in pakistan using modified Delphi and fuzzy analytical hierarchy process. *J. Clean. Prod.*, 235:1037–1050, 2019.

- [73] A. Sharkey et al. National Delphi survey on anesthesiology resident training in perioperative ultrasound. *J. Cardiothorac. Vasc. Anesth.*, 36(11):4022–4031, 2022.
- [74] H. Taghavifar and Z.S. Zomorodian. Techno-economic viability of on grid micro-hybrid PV/wind/Gen system for an educational building in Iran. *Renew. Sustain. Energy Rev.*, 143, 2021.
- [75] K.A. Tahir, J. Ordóñez, and J. Nieto. Exploring evolution and trends: A bibliometric analysis and scientific mapping of multiobjective optimization applied to hybrid microgrid systems. *Sustainability*, 16(12):5156, 2024.
- [76] K.A. Tahir, M. Zamorano, and J. Ordóñez. Scientific mapping of optimisation applied to microgrids integrated with renewable energy systems. *Int. J. Electr. Power Energy Syst.*, 145, 2023.
- [77] D.T. Ton and M.A. Smith. The U.S. Department of Energy’s Microgrid Initiative. *Electr. J.*, 25(8):84–94, 2012.
- [78] C. J. Torrecilla-Salinas et al. A Delphi-based expert judgment method applied to the validation of a mature agile framework for web development projects. *Inf. Technol. Manag.*, 20(1):9–40, 2019.
- [79] H.Y. Tsai, C.C. Chung, and S.J. Lou. Construction and development of iSTEM learning model. *EURASIA J. Math., Sci Tech. Ed.*, 14(1):15–32, 2018.
- [80] G. Veilleux et al. Techno-economic analysis of microgrid projects for rural electrification: A systematic approach to the redesign of Koh Jik off-grid case study. *Energy Sustain. Dev.*, 54:1–13, 2020.
- [81] S. Watkins. Iraq is on the brink of an energy crisis. <https://oilprice.com/Energy/Energy-General/Iraq-Is-On-The-Brink-Of-An-Energy-Crisis.html>, 2020. Accessed Aug. 07, 2021.
- [82] C.H.L. Wong et al. Prioritizing chinese medicine clinical research questions in cancer palliative care: International delphi survey. *J. Pain Symptom Manage.*, 58(6):1002–1014.e7, 2019.

Chapter Five

A Systematic Review and Evolutionary Analysis of the Optimization Techniques and Software Tools in Hybrid Microgrid Systems

*This chapter is presented as a standalone research paper and forms an integral part of this doctoral dissertation. It has been published in **Energies** , 2025, **18**(7), 1770.*

Available at: <https://doi.org/10.3390/en18071770>.

Chapter 5

A Systematic Review and Evolutionary Analysis of the Optimization Techniques and Software Tools in Hybrid Microgrid Systems

This chapter systematically reviews the optimization techniques (OTs) and software tools (STs) in hybrid microgrid systems (HMGSs) to enhance the efficiency, cost-effectiveness, and energy reliability. An advanced Scopus search was conducted using core keywords related to microgrids, renewable energy systems, and various OTs and STs, which identified 4134 relevant documents on OTs. These were classified into classical (16.87%), metaheuristic (47.12%), and artificial intelligence (AI)-based methods (36.01%), highlighting the dominance of metaheuristics and the growing role of AI-driven approaches in handling uncertainties and real-time decision-making. Additionally, 2667 documents on STs were analyzed, identifying MATLAB/Simulink (65.34%) and HOMER (22.08%) as the most widely used tools for simulation, modeling, and techno-economic analysis. This study identifies key research trends, highlights gaps in the optimization strategies, and emphasizes the need for AI integration, broader adoption of open-source tools, and scalable optimization frameworks. By mapping the evolution and effectiveness of OTs and STs, it provides valuable insights for researchers, policymakers, and industry professionals, supporting the development of sustainable and intelligent HMGS solutions.

5.1 Introduction

Energy is a pivotal element reflecting the social and economic growth of nations and the quality of life of their citizens. As societies grapple with changes in climate patterns and the rising costs of traditional fuels like gas and oil, the challenge of diversifying energy sources and reducing dependence on fossil fuels intensifies. Renewable energy sources (RESs) have emerged as a sought-after solution for electrical energy production due to their environmentally friendly nature compared to conventional methods. This transition toward renewables is further highlighted by reports from the International Energy Agency (IEA), which show a significant uptick in electricity generation using sustainable energy means. According to an IEA report, their central forecast suggests that between 2022 and 2027, the worldwide capacity of RESs will increase by approximately 2400 GW, which is an increase of almost 75%. Two key factors drive this surge in the adoption of RESs. Firstly, the global energy crisis has resulted in the increased costs of fossil fuels and electricity. Secondly, the incursion into Ukraine by Russia has made fossil fuel importers, especially those in Europe, recognize and value the benefits of RESs in enhancing energy security. In response to the energy crisis, China, the European Union (EU), the United States, and India are rapidly implementing existing policies and introducing regulatory and market changes, as well as rolling out new measures faster than previously expected. This has been a significant factor in the growth trajectory shown in Figure 5.1. In this figure, the red bar represents the updated global forecast, while the light blue bars correspond to individual regional forecasts.

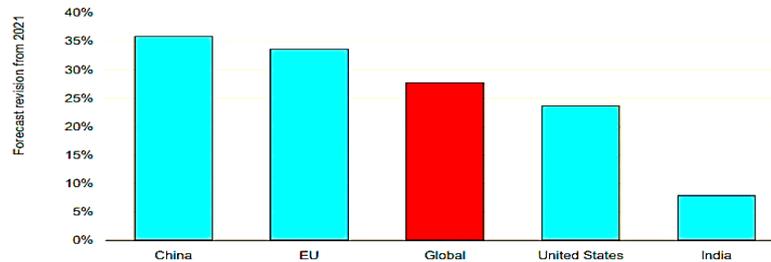


Figure 5.1: Predictions of the expansion of RES capacity between 2021 and 2027 [32].

Since the previous report, RES usage in the EU has seen a 30% increase, with Germany and Spain at the forefront, experiencing boosts of 50% and 60%, respectively [32]. As the need to diversify energy sources and reduce reliance on fossil fuels grows, the significance of RESs continues to increase. However, despite their sustainability, the intermittent nature of RESs such as wind and solar limits their

ability to be used independently. To address this challenge, hybrid energy systems (HESs) combine multiple RESs, often integrating energy storage or conventional sources like diesel generators, to provide a more reliable and stable energy supply [24, 41]. Microgrids (MGs), which can operate both connected to the grid and in isolation, are at the forefront of this innovation, offering flexibility in energy management [88]. The development of hybrid microgrid systems (HMGSs) further enhances this integration by optimizing the balance between renewable and conventional energy sources, achieving cost reductions, increased grid independence, and reduced environmental impact [25, 29, 36, 87]. Within this context, HMGSs provide an advanced solution for energy management by integrating renewable and conventional power sources to reduce costs, enhance grid independence, and minimize environmental impacts. Due to the inherent complexity of HMGSs, advanced optimization techniques (OTs) are essential for achieving high efficiency, cost reduction, and system reliability. Recent advancements in artificial intelligence (AI) and metaheuristics have led to the development of powerful optimization algorithms that effectively address these challenges. Furthermore, specialized software tools (STs) such as HOMER and MATLAB/Simulink provide accurate modeling, simulation, and optimization capabilities, enhancing the practicality and feasibility of HMGSs for various applications.

Area of Study

Despite the rapid development of OTs and specialized STs, existing studies often focus on specific methods or tools without providing a holistic view of their integration in HMGSs. This review aims to fill this gap by analyzing and comparing the effectiveness and trends of various OTs and STs used in HMGSs, using Scopus records to assess their prevalence over time. By reviewing the advancements and adoption trends, and identifying promising approaches, this study provides a comprehensive analysis of OTs and STs, offering actionable insights to improve the efficiency, reliability, and sustainability of HMGSs. Building on suggestions from our earlier investigation [89], the document is organized as illustrated in Figure 5.2, which outlines this study’s workflow and key phases.

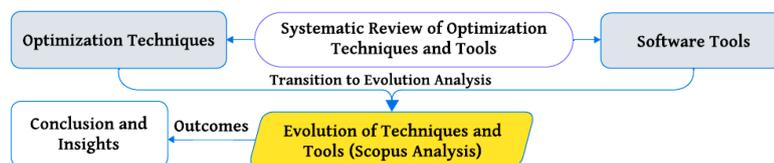


Figure 5.2: Workflow of this study.

The first section presents a systematic review of the OTs and tools, providing an in-depth analysis of various methods and tools employed in HMGSs. This section

achieves our goal of delivering a comprehensive review, highlighting the latest advancements and identifying critical optimization approaches. The second section, Evolution of Techniques and Tools (Scopus analysis), examines the trends in the adoption of these techniques over time, providing a broader perspective on their evolution and impact. Finally, The Conclusion and Insights Section synthesizes the findings and presents valuable outcomes for researchers and practitioners.

5.2 Systematic Review of OTs and STs

Through the optimization process, the optimal value or solution can be identified. Optimization problems may involve one or more objectives, aiming to maximize, minimize, or address both in the case of multi-objective optimization. These problems are prevalent in diverse fields, such as mathematics, engineering, social studies, economics, agriculture, aviation, and RES, among many others [6, 8, 12, 15, 20, 38, 60, 61, 92, 98]. To ensure the most efficient deployment of HMGSs, an optimization procedure is essential. Figure 5.3 highlights the critical OTs and STs utilized to solve problems and evaluate the effectiveness of HMGSs.

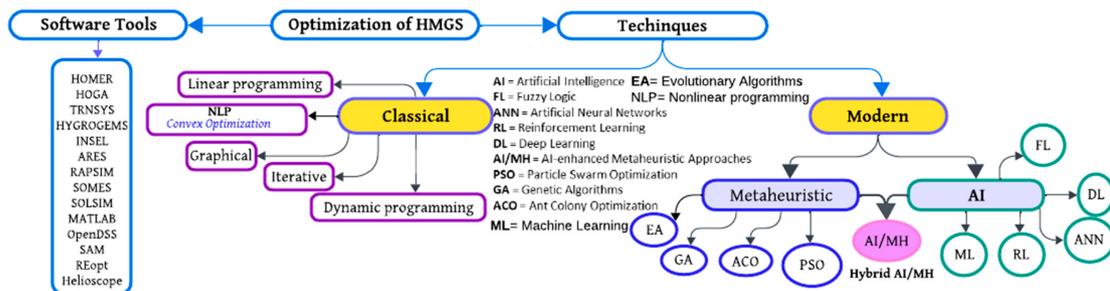


Figure 5.3: Key OTs and STs for HMGSs.

The OTs in HMGS studies are generally classified into the classical, metaheuristic, and AI-based approaches based on the methodologies used in the reviewed studies. These categories are defined as follows:

- **Classical techniques:** This category includes linear programming (LP), non-linear programming (NLP) (with convex optimization as a subset), dynamic programming (DP), iterative methods, and graphical techniques. These methods rely on deterministic optimization models and predefined mathematical formulations to find optimal solutions.
- **Metaheuristic techniques:** These methods use stochastic, population-based, or evolutionary algorithms to explore large solution spaces efficiently. Genetic algorithms (GAs), particle swarm optimization (PSO), and ant colony

optimization (ACO) are among the commonly used techniques in this category.

- **AI-based techniques:** This category includes optimization approaches that incorporate machine learning and neural networks to enhance decision-making and adaptation. Examples include artificial neural networks (ANNs), reinforcement learning (RL), deep learning (DL), and fuzzy logic (FL).

As a distinct subcategory within modern techniques, AI/enhanced metaheuristics (AI/MH) refers to cases where machine learning or AI components are integrated with metaheuristic algorithms to improve performance. Unlike pure metaheuristics, AI/MH techniques use AI-driven learning mechanisms to adapt the search strategies dynamically, increasing the convergence speed and solution quality. This hybrid category differs from standalone AI-based techniques, which operate purely on data-driven learning models, and from traditional metaheuristics, which lack AI-driven adaptation. The following sections provide an in-depth analysis of the OTs and STs most commonly used in HMGSs.

5.3 Optimization Techniques

The stochastic nature of natural resources, nonlinear variation in output power from solar photovoltaic (SPV) and wind turbine (WT), selection of component type and orientations, and economic modeling of energy generation costs in HMGSs all contribute to the complexity of the HMGS optimization problem [19]. This complexity has driven researchers to develop various methods and techniques for optimizing HMGSs, as detailed below.

5.3.1 Classical Techniques

Various OTs are employed to optimize the use of HESs integrated with MGs. This section reviews the research utilizing traditional OT methods, including iterative, graphical, linear, nonlinear, and dynamic programming, to address the optimization challenges in HMGSs. The specific optimization methods used in these studies are described in the paragraph below. Below is a description of the classical optimization techniques applied in HMGSs, and Table 5.1 presents the relevant studies categorized by each technique.

- **Iterative methods** In optimization processes, computer-driven simulations iteratively refine estimations by evaluating various factor combinations, retaining the most effective solutions while reducing the focus on less favorable ones. These methods play a crucial role in HMGSs, particularly in fine-tuning

dispatch strategies and optimizing power flows in hybrid energy storage systems [9]. Their adaptability makes them effective for handling nonlinearity in real-time MG operations, especially in optimizing battery energy storage placement and unbalanced AC/DC power flow modeling [72]. However, iterative approaches can be computationally intensive, requiring proper calibration to prevent slow convergence or local optima trapping. Despite these challenges, they remain widely used due to their flexibility and reliability in solving complex MGs energy management problems.

- **Nonlinear Programming (NLP)** NLP involves optimizing an objective function subject to nonlinear equality and inequality constraints, making it essential for solving real-world HMGS optimization problems with complex, nonlinear variable dependencies [59]. Unlike linear programming (LP), NLP provides greater flexibility, enabling the modeling of the dynamic energy dispatch, demand response programs (DRPs), and RESs integration in HMGSs. However, its challenges include the high computational complexity, sensitivity to initial conditions, and risk of converging to local optima rather than the global best solution [35]. NLP has been applied to optimize cost-efficiency, enhance demand-side management, and improve RES utilization in MG operations [26]. Similarly, stochastic MINLP methods have been used to effectively coordinate fuel-cell-based energy generation and energy storage under RES uncertainty, ensuring reliable MG operation even in the presence of fluctuating energy sources [28]. To address the NLP limitations, convex optimization is widely used to reformulate complex nonlinear problems, ensuring global optimality and computational efficiency. It plays a crucial role in real-time MG energy management, decentralized optimization, and economic dispatch models, guaranteeing scalable and adaptive decision-making [45, 46]. For instance, ref. [76] applies convex optimization in decentralized real-time energy management, optimizing economic dispatch under demand and RES uncertainties. Using Lagrangian dual decomposition, it minimizes the system-wide power costs in both grid-connected and islanded MGs. Similarly, ref. [49] addresses non-convex challenges in hybrid AC/DC MGs, transforming bidirectional converter models into convex formulations to improve the computational efficiency and solution time. Despite its advantages, convex optimization applies only to problems that can be mathematically transformed into convex structures. While researchers work to reformulate real-world problems for better computational efficiency, highly nonlinear or mixed-integer problems remain challenging to solve [45].
- **Linear Programming** Linear programming is a mathematical optimization technique used to determine the optimal solution within defined linear

constraints. It is widely applied in MG energy management, economic dispatch, and resource allocation due to its structured approach, computational efficiency, and ability to handle large datasets [5, 21]. In MG applications, LP is frequently utilized for optimal scheduling of HESs [48], energy storage planning [7], and demand response integration [21]. Its key advantages include reliability, scalability, and guaranteed global optimality for problems with linear relationships. However, LP has limitations—it strictly adheres to a linear framework, which often fails to capture real-world complexities. Additionally, even small modifications can significantly impact the results, and solving large-scale problems can be computationally demanding [14].

- **Dynamic Programming (DP)** Dynamic programming (DP) is an optimization technique that breaks down complex problems into smaller sub-problems, solves each one only once, and stores the solutions for future use. This method is particularly effective for sequential decision-making and is widely applied in MG energy scheduling, storage management, and power flow optimization [75, 95]. DP-based approaches have been successfully used to optimize real-time energy storage management in microgrids, addressing uncertainties in renewable generation while minimizing energy costs [75]. Additionally, adaptive DP methods have been implemented in dynamic energy management systems (DEMSs) for grid-connected and islanded MGs, ensuring efficient dispatch of RESs and storage resources [95]. In the residential sector, DP has been applied for solar energy scheduling, improving cost savings and enhancing electricity efficiency [51]. However, DP requires high computational resources, as it stores intermediate solutions, making it memory-intensive. Additionally, its application is best suited to problems that can be structured into interdependent subproblems, limiting its use in highly dynamic or large-scale real-time decision-making scenarios [13].
- **Graphical Techniques** Graphical optimization is an approach where objective functions and constraints are represented graphically to facilitate optimal decision-making. Graph-based methods are particularly useful for distribution network reconfiguration, energy storage scheduling, and resource allocation in MGs [82]. For instance, graph theory has been successfully applied to optimize MG topologies and distributed generation placement, ensuring radiality constraints and minimizing active power losses [79]. Additionally, graph-based P-Graph has been utilized for multi-period hybrid energy storage planning in MGs, enabling efficient energy dispatch and cost-effective hydrogen battery storage integration [55]. Graph theory is increasingly applied in MG power flow modeling and control, representing voltage/current relationships, energy transfer, and system connectivity. Its expansion has en-

abled alternative power flow methods and improved control strategies. However, graph-based optimization is most effective for structured graph problems. In highly dynamic microgrid scenarios with nonlinear, multi-objective, and stochastic constraints, advanced hybrid techniques may be required [82].

Table 5.1: Classical OTs applied in HMGS studies.

Ref.	System Components	Compo-	Optimization Focus	Key Findings
[17]	SPV, WT, DG, Battery		LCOE, LCOH	Investigated the sizing and economic evaluation of an HMGS SPV-WT-DG-battery system in islanded mode. Results demonstrated reduced life-cycle cost with low LPSP, outperforming HOMER in cost-effectiveness.
[103]	SPV, WT, Battery		Economic, reliability	Developed a multi-objective dispatching model using the MSIO technique, optimizing energy storage utilization. Achieved 4.18% higher economic gains and 82.83% capacity utilization, outperforming PSO and differential evolution.
[35]	SPV, WT, DG		Revenue maximization, cost reduction	Applied a risk-aware mixed-integer nonlinear optimization approach to manage stochastic energy sources. Optimized DG, SPV, and WT operations under market price uncertainties, achieving cost minimization through fuel savings and energy sales. Enhanced energy dispatch and load-generation balance with robust scheduling techniques, including cubic spline interpolation.
[5]	SPV, WT, Battery		Cost reduction, efficiency	Modeled and optimized MG components using MILP, integrating demand response programming for standalone systems. Results demonstrated reduced mismatches, cost savings, and lower battery requirements via load scheduling. Validation performed with HOMER and GAMS using the CPLEX solver.
[64]	SPV, WT, DG, Battery, MT, FC		Cost/emission minimization	Optimized standalone MG energy scheduling using advanced dynamic programming, achieving enhanced efficiency, reduced fuel costs, and decreased emissions. Implemented an optimal energy management system with a constrained single-objective model, minimizing operational and emission costs. Inclusion of battery storage significantly lowered the total costs and emissions, demonstrating system feasibility through simulation.
[50]	SPV, WT, DG, Biogas, H2		LCOE, CO2 reduction	Proposed a method for converting surplus renewable electricity, CO2, and biogas into sustainable hydrogen using a P-Graph graphical optimization approach. Scenarios with 20%, 30%, and 40% demand increments showed annual cost increases of 32%, 27%, and 35%, respectively. Transition to non-renewable electricity began at 20% hydrogen demand, with natural gas usage starting at 40%. Sustainability was enhanced through Pareto frontier and TOPSIS analyses, optimizing the balance between environmental and economic factors.

Abbreviations: SPV = solar photovoltaic, WT = wind turbine, DG = diesel generator, MG = microgrid, HMG = hybrid microgrid, HRES = hybrid renewable energy system, LCOE = levelized cost of electricity, LCOH = levelized cost of hydrogen, MILP = mixed-integer linear programming, CPLEX = commercial optimizer by IBM, HOMER = hybrid optimization model for multiple energy resources, GAMS = general algebraic modeling system, MT = micro-gas turbine, FC = fuel cell.

The table above provides a comparative analysis of the optimization strategies for HMGSs, examining various computational methods, such as iterative processes, NLP, linear programming, and dynamic programming. Each method offers distinct advantages in enhancing the economic, reliability, and environmental outcomes. Iterative methods are often more cost-efficient than traditional models. Meanwhile,

NLP addresses stochastic challenges, offering robust solutions in volatile markets. Linear optimization ensures structured problem-solving but may have limitations in handling complexity. In contrast, dynamic programming excels in decomposing complex issues, albeit at a higher computational cost. Overall, these studies highlight the importance of selecting optimization approaches that align with the specific characteristics, goals, and objectives of HMGSs.

5.3.2 Modern Optimization

Modern OTs in the context of HMGSs include metaheuristic and AI approaches that enhance energy system performance, efficiency, and sustainability by addressing complex challenges in real time or near real time. Metaheuristics are high-level algorithms used to find good solutions for complex problems, especially when exact methods are impractical. Examples include genetic algorithms (GAs), particle swarm optimization (PSO), and ant colony optimization (ACO). These techniques mimic natural processes to explore and exploit solution spaces efficiently. Artificial intelligence (AI) techniques, such as machine learning, reinforcement learning, and deep learning, learn from data to optimize energy systems. AI is adaptive and can improve system performance by predicting behaviors and making real-time decisions. Metaheuristics and AI can be combined to leverage their strengths, creating AI-enhanced metaheuristics that improve the search efficiency and provide more effective solutions for HMGS optimization.

- a. AI in HMGS optimization In the context of HMGSs, AI OTs play a pivotal role in managing fluctuating energy sources and demands. These techniques enable dynamic, adaptive control strategies that enhance the stability, efficiency, and resilience of the grid. The key AI techniques used in HMGS optimization include artificial neural networks, reinforcement learning, and deep learning.
 - Reinforcement learning Dynamically adjusts control strategies to optimize the energy flow within HMGSs. Agents learn by performing actions, observing the outcomes, and adjusting their behavior to maximize a predefined reward. This adaptability makes it powerful for creating control policies that can adjust to varying conditions in real time [26]. The merits include its adaptability and proficiency in handling sequential decision-making. However, this approach often requires extensive data for training and presents challenges in designing an appropriate reward system. Unlike other AI techniques that rely solely on data, reinforcement learning learns directly from interactions within its environment, making it uniquely suited for complex, dynamic systems like HMGSs.

- **Fuzzy logic** Fuzzy logic is a method of reasoning that handles approximate rather than fixed and exact conclusions, making it well suited for dealing with uncertainties and imprecise information in HMGSs. It is advantageous in HMG optimization due to its simplicity, transparency, and effectiveness in handling nonlinear systems under various conditions. Its main merits include the ease of understanding and implementation, as it relies on expert knowledge rather than extensive data for model training. However, a key challenge lies in defining precise membership functions and rules. Compared to data-driven methods like deep learning and artificial neural networks, fuzzy logic is easier to interpret and implement but may lack the depth and adaptability of those techniques.
- **Deep learning** Deep learning, a subset of machine learning, leverages artificial neural networks with multiple layers to effectively recognize patterns and extract features from vast datasets. In HMGS optimization, it excels at forecasting energy consumption and generation, capturing complex nonlinear relationships [28]. Its primary merits include high accuracy in pattern recognition and the ability to handle unstructured data. However, this method requires substantial computational resources and large datasets, and it is often considered a “black box” due to its lack of interpretability. Compared to reinforcement learning and fuzzy logic, deep learning is more data-intensive and is particularly effective for modeling complex patterns.
- **Artificial neural networks** Artificial neural networks are computational systems inspired by the biological neural networks in animal brains. They are highly effective at modeling nonlinear relationships, which is essential for predicting and optimizing energy flows in HMGSs [45, 46]. A major advantage of these networks is their ability to learn from large datasets and generalize across various scenarios, enabling accurate forecasting and optimization in complex systems. However, a notable drawback is their “black box” nature, which can make the decision-making process challenging to interpret. Compared to fuzzy logic, artificial neural networks require more data for training but can model more intricate relationships than fuzzy logic or traditional AI/metaheuristic approaches.
- **AI-enhanced metaheuristic (AI/MH)** AI-enhanced metaheuristic (AI/MH) methods integrate AI techniques, such as learning and adaptation, with metaheuristic algorithms to tackle optimization challenges. In HMGSs, this approach facilitates more effective search strategies for energy management solutions. The key advantages include a balanced exploration

and exploitation of the search space, along with faster convergence to high-quality solutions. However, integrating AI techniques with metaheuristic algorithms can be complex and may increase the risk of overfitting. While AI/MH can often achieve solutions more efficiently than traditional metaheuristics, it requires a more sophisticated design compared to standalone AI methods like deep learning or reinforcement learning. Studies that utilize these techniques are detailed in Table 2, highlighting the applications, objectives, and findings associated with each AI approach in the context of HMGS optimization.

Table 5.2: Comparative analysis of AI algorithm utilization in autonomous MG optimization studies.

Ref.	System Components	Components	Optimization Method	Optimization Focus	Key Findings
[43]	WT, Energy Storage		Reinforcement Learning	Optimize battery scheduling, maximize battery and wind utilization, reduce grid dependence	Applied a 2-step-ahead reinforcement learning algorithm for optimized battery scheduling, addressing wind power uncertainties and mechanical failures to reduce grid reliance. Demonstrated a refined strategy for improved decision-making in MG energy management.
[44]	SPV, WT, Energy Storage, DG, H ₂ , Desalination, heating-cooling		Fuzzy Logic, Gray Prediction	Demand side management	Utilized a multi-agent system with gray prediction for demand management in polygeneration MGs, maintaining effective operation even when demand exceeded design specifications. Optimized within capital constraints, ensuring adaptability for future conditions.
[99]	SPV, Energy Storage, EVs		DRNN-LSTM + PSO	Optimal load dispatch with forecasting integration	Applied the DRNN-LSTM model, outperforming MLP and SVM in forecasting the SPV output and residential load. PSO optimized the load dispatch, achieving an 8.97% daily cost reduction through peak load shifting. Coordinated EV charging contributed to cost savings and stability.
[63]	WT		ANN-based Controller	Fuzzy Voltage stability in wind-fed isolated MG	The ANN-based fuzzy controller effectively maintained voltage stability in variable wind conditions, achieving stable system performance with acceptable THD levels. It successfully managed power distribution between critical and non-critical loads, ensuring near-nominal voltage throughout the system.
[83]	SPV, WT, Energy Storage, DG		BWO	EMS with Demand Response Programs	Used flexible DRP model; BWO optimized scheduling in 3-feeder MG under renewable uncertainty.

Abbreviation: SPV: photovoltaic solar, WT: wind turbine, DG: diesel generator, MG: microgrid, HMG: hybrid microgrid, HRES: hybrid renewable energy system, DRNN-LSTM: deep recurrent neural network with long short-term memory, PSO: particle swarm optimization, EVs: electric vehicles, ES: electric spring, AFC: artificial fuzzy controller, ES-AFC: electric spring-artificial fuzzy controller, ANN: artificial neural network, THD: total harmonic distortion, BWO: black widow optimization, DRPs: demand response programs, EMS: energy management system.

The collection of research spanning references [43, 44, 63, 83, 99] underscores the crucial role of AI-enhanced metaheuristic methods in HMGs optimization. Reinforcement learning and DRNN-LSTM models are notable for their capacity to perform demand-side management and predictive scheduling, leading to improved grid stability and reduced operational costs. The newly developed BWO algorithm exemplifies the efficacy of nature-inspired techniques in the strategic distribution of energy. These studies showcase

how intelligent algorithms can adeptly navigate the complexities of energy management, yielding enhanced technical and economic outcomes. While AI techniques offer advanced capabilities for managing complex, real-time decisions in HMGS optimization, metaheuristic approaches bring a complementary strength through their adaptive, nature-inspired algorithms. These techniques excel in solving multi-objective optimization problems within HMGSs due to their flexibility and robust capacity to navigate vast solution spaces. The following section explores the application of metaheuristic methods in HMGS optimization.

b. Metaheuristic techniques in HMGS optimization

Metaheuristic techniques are algorithmic strategies inspired by natural occurrences and animal behavior that are intended to tackle complicated optimization issues. They use a population-based method, repeatedly improving a collection of options to efficiently identify optimum or near-optimal solutions. These strategies are adaptable, able to solve a broad variety of situations when traditional methods may fail owing to the problem's size or complexity [7]. Here is an overview of the three well-known metaheuristic algorithms, particularly in the context of optimizing an HMGS:

- Particle swarm optimization (PSO): PSO is a metaheuristic that seeks solutions by optimizing particle placements based on natural social behavior. PSO is commonly used to assess HMGSs, as indicated by its inclusion in several research studies. For example, Ref. [14] identifies optimum system topologies and component sizes while considering dependability, cost, and environmental effect, and for enhancing energy management systems in MGs with optimized artificial networks for improved performance and renewable integration, as illustrated in reference [75]. Furthermore, Ref. [95] emphasizes PSO's application in designing and optimizing a smart DC MG's multi-objective function for an HMGS of SPV, WT, and biogas-based IC engine generators, with the goal of maximizing power availability while lowering costs, demonstrating PSO's superior performance in cost reduction and high availability when compared to other algorithms.
- Genetic algorithm (GA): A GA is a metaheuristic inspired by natural selection that use selection, crossover, and mutation to develop solutions toward optimality, which has been widely utilized in various studies to evolve candidate solutions toward optimality. For example, in Ref. [51], the GA improves HMGSs in order to reduce energy production costs while increasing dependability and environmental advantages.

Ref. [14] demonstrates GA's use in designing energy management systems for MGs, with an emphasis on maximizing the profit from energy exchanges and minimizing system complexity for improved smart grid integration. Another application of a GA, as detailed in Ref. [64], is optimizing a hybrid SPV/WT, addressing the loss of load probability (LLP) and system cost by selecting the optimal capacities for the SPV array, wind turbine, and battery, optimizing the SPV array tilt angle, and determining the ideal inverter size, demonstrating the GA's versatility in addressing complex optimization challenges in HMGSs.

- Ant colony optimization (ACO): ACO is a metaheuristic inspired by ant foraging behavior that efficiently solves discrete optimization problems such as routing and scheduling. ACO shows adaptability in HMGS optimization across several studies. Ref. [82] investigates the use of ACO for supervisory control in alternative energy distributed generation MGs, aiming to improve dispatch management while taking environmental and economic factors into account. Ref. [79] uses ACO for maximum power point tracking (MPPT) to enhance power quality in islanded MGs by optimizing HRESs units. Lastly, Ref. [55] applies ACO to an energy management system (EMS) in MGs, concentrating on cost-efficient scheduling and demonstrating significant cost savings over standard EMS and PSO approaches, demonstrating ACO's efficiency in complicated, multi-objective optimization tasks inside HMGSs.

In summary, metaheuristic techniques bring a flexible, adaptive approach to optimizing HMGS by drawing on nature-inspired algorithms to tackle complex, multi-objective challenges. While AI and metaheuristics both play critical roles in HMGS optimization, the need for dedicated STs becomes evident in scaling, simulating, and operationalizing these advanced techniques. The next section explores the STs commonly employed in HMGS optimization, detailing how they assist in system design, simulation, and analysis to achieve cost-effective, reliable, and sustainable energy management solutions.

5.4 STs for HMGS Optimization

The classification of STs for HMGS optimization is based on their primary roles in the design and optimization process [93]. These tools can be categorized into feasibility assessment tools, design and sizing tools, simulation and modeling tools, optimization tools, and comprehensive tools, as illustrated in Figure 5.4.

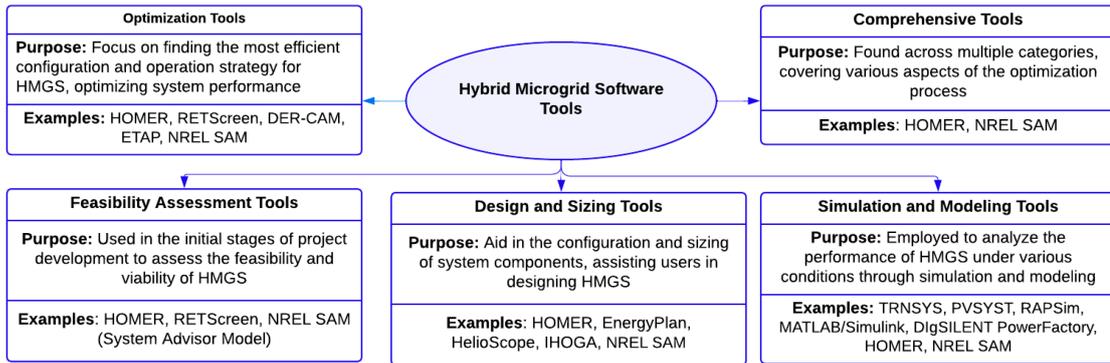


Figure 5.4: Classification of STs for HMGS optimization.

- Feasibility assessment tools: Used in the initial stages to assess the viability and potential of HMGS designs.
- Design and sizing tools: Aid in configuring and sizing system components to ensure they meet design requirements.
- Simulation and modeling tools: Analyze system performance under various conditions and predict behavior during operation.
- Optimization tools: Focus on improving the system's performance by finding the most cost-effective and energy-efficient operational strategies.
- Comprehensive tools: Integrate multiple functions, offering a holistic approach to designing, simulating, and optimizing HMGSs.

Each category serves a distinct purpose in guiding the development and optimization of HMGSs, ensuring that the designs are both technically sound and economically viable. These tools have been applied in various studies, each emphasizing key economic performance metrics:

- Levelized cost of energy (LCOE): Represents the average cost per unit of electricity generated over the system's lifetime, serving as a critical metric for assessing long-term economic viability.

- Net present cost (NPC): Evaluates the total lifetime costs, including installation, maintenance, and operational expenses, providing a comprehensive assessment of the overall costs.
- Net present value (NPV): Assesses the profitability of a system by comparing the present values of the costs and revenues, helping to determine the project's economic feasibility.

These metrics are essential for designing cost-effective and technically sound HMGSs, particularly in isolated or grid-connected systems. Table 5.3 provides a summary of the research studies that utilize these STs, detailing each tool's functionality and primary findings. Table 5.3 presents a diverse range of research studies that have utilized various STs to optimize HMGSs. These studies demonstrate how tools like HOMER, RETScreen, and NREL SAM have been employed for feasibility assessments, system design, and cost optimization. A common theme is the frequent integration of SPV with other energy sources such as WT, biomass, and DGs. Many of the studies prioritize reducing costs, particularly through the optimization of the LCOE, which has become a central performance metric. HOMER stands out as a widely used tool for its comprehensive ability to model, simulate, and optimize HMGSs, particularly in balancing technical performance with economic feasibility. As the table illustrates, the choice of software is crucial, depending on the system's complexity and the desired outcome, whether it is for off-grid or grid-connected configurations.

The description of each software tool listed in Table 5.3 is provided below, highlighting its capabilities, strengths, and limitations as applied in HMGS optimization studies.

1. **HOMER** Hybrid optimization of multiple energy resources (HOMER) was developed in 1993 by the National Renewable Energy Laboratory (NREL) [31]. It is designed to model and simulate various RESs, and it excels in cost analysis and sensitivity analysis, with integration capabilities for typical meteorological year (TMY2) data for weather and solar radiation, or user-provided data [68]. HOMER employs a proprietary simulation-based approach for optimization, using sensitivity analysis and a search algorithm to identify the lowest-cost system configurations across various input variables. It is widely used for the economic and technical assessment of large-scale HESs. Strength: Excellent for optimizing component sizing and conducting thorough cost analyses, with advanced sensitivity analysis capabilities. Weakness: May not capture all the dynamics of complex system behavior without precise, customized input data.
2. **IHOGA** IHOGA, developed by researchers at the University of Zaragoza, Spain, is designed for simulating and optimizing RES-based electric power

Table 5.3: Research studies on HMGS optimization using different software programs.

Ref.	System Components	Optimization Focus	Key Findings	Software Tool
[30]	SPV, WT, Energy Storage, DG	LCOE, LCOH	Assessed HMG for green hydrogen production on a remote island. Scenario analysis revealed 80% RES as most cost-effective.	HOMER
[84]	SPV, WT, Energy Storage, Biomass	Size, LCOE	Proposed SPV-WT-biomass storage system to meet remote area needs. ABC algorithm shortened simulation time vs. HOMER and PSO.	HOMER, ABC, PSO
[2]	SPV, WT, Biomass	Size, LCOE	HMGS for a 50 MW power plant in Pakistan; profitable with national grid integration, ideal for regions with frequent power outages.	HOMER
[1]	SPV, WT, Energy Storage	LCOE	Techno-economic assessment for off-grid HMGSs in the USA, Canada, and Australia; evaluated SPV-WT-battery with hydrogen storage. Minimum COE achieved with integrated SPV-WT battery, electrolyzer, and hydrogen tank, reducing costs to 0.50 USD/kWh compared to non-battery configurations at 0.78 USD/kWh.	HOMER
[81]	SPV, WT, Energy Storage, DG	Cost, size	Assessed thermal energy storage in an islanded HMGS; DG contributed to higher COE.	IHOGA
[104]	SPV, WT, Energy Storage, Biomass	Cost, feasibility	Evaluated HMGSs for tourist regions in Europe, achieving 99% user demand coverage with RES in Gdansk, Poland, and 43% surplus in Agkistro, Greece.	TRNSYS
[97]	SPV, WT, Energy Storage, Biomass, Hydropower	CO2 reduction	Decarbonization study for Sichuan Province: Scenarios showed energy storage significantly reduced operational costs while requiring high investment, demonstrating feasibility for hydropower-rich regions.	EnergyPLAN
[74]	SPV	Modeling and simulation	Demonstrated RAPSIm for optimal DG placement in an MG, considering SPV output variability influenced by solar radiation and time-dependent factors. Showcased the software's capabilities in data output, scenario management, and temporal/weather simulation.	RAPSIm
[66]	SPV	Techno-economic, feasibility	Assessed the viability of a 500 kW SPV MG across 12 sites in Nigeria, including a techno-economic analysis. Findings showed economic feasibility at all sites, with payback periods ranging from 6.3 to 7.4 years based on NPC, internal rate of return, and payback period metrics.	RETScreen
[4]	SPV, Energy Storage	LCOE, feasibility	Evaluated a grid-connected MG with SPV and energy storage, comparing lead-acid (LA) and lithium-ion (LI) batteries. Findings showed that LI batteries are more feasible, with an LCOE of 6.75, compared to 10.6 for LA.	NREL SAM
[85]	SPV, WT, DG	MG protection using communication-assisted digital relays	Proposed a protection scheme using digital relays with communication networks. Demonstrated detection of high-impedance faults in a high-penetration HMGS. Simulated in MATLAB/Simulink's SimPowerSystems toolbox.	MATLAB/Simulink

Abbreviations: SPV: solar photovoltaic, WT: wind turbine, DG: diesel generator, HMGS: hybrid microgrid systems, LCOE: levelized cost of energy, LCOH: levelized cost of hydrogen, HOMER: hybrid optimization of multiple energy resources, CO₂: carbon dioxide, NPC: net present cost, ABC: artificial bee colony, PSO: particle swarm optimization, IHOGA: improved hybrid optimization by genetic algorithms, NPV: net present value, IRR: internal rate of return, TRNSYS: transient system simulation, RAPSIm: renewable alternative power systems simulation, SAM: system advisor model, CST: concentrating solar thermal, FC: fuel cell, LA: lead-acid battery, LI: lithium-ion battery.

systems. It has two versions: IHGO for systems up to 5 MW and MHOGA for larger systems without capacity limits. IHOGA's library includes diverse components like the SPV, WT, batteries, hydropower turbines, and various generators. It calculates the NPC, LCOE, NPV, IRR, and battery lifespan, using genetic algorithms to improve system efficiency and reduce costs over successive iterations [33]. Strength: Effective genetic algorithm for optimizing cost and sizing in HES. Weakness: Computationally intensive; may require fine-tuning for complex systems.

3. **TRNSYS** TRNSYS, developed in 1975 by France, Germany, and the United States, is a transient systems simulation tool used across various energy applications, including biomass, cogeneration, hydrogen fuel cells, wind and SPV systems, high-temperature solar, and geothermal heat pumps. It requires minimal data and computational resources, making it suitable for preliminary assessments [58, 91]. Strength: High-fidelity transient simulation ideal for detailed technical system analysis. Weakness: Economic optimization is not the primary focus and may need additional modules for financial assessment.
4. **EnergyPLAN** EnergyPLAN, developed by Aalborg University's Sustainable Energy Planning Research Group in Denmark in 2000, is a deterministic simulation tool for modeling national energy systems, including power, heating, cooling, industry, and transportation [53]. Strength: Effective for strategic policy scenario analysis. Weakness: Primarily a simulation tool, requiring additional software for detailed optimization.
5. **RAPSim** Developed at Alpen Adria University Klagenfurt, RAPSim is an open-source tool for RES simulation in grid-connected and off-grid MGs. It prioritizes power production estimation for each source before conducting power flow analysis [78]. Strength: Detailed simulation for RES with scenario management. Weakness: Lacks built-in economic and sensitivity analysis; may require additional tools for comprehensive assessments.
6. **RETScreen** Developed by Canada's Ministry of Natural Resources, RETScreen is a publicly available tool for assessing the costs and benefits of RE technologies worldwide. Released in 1998, RETScreen is particularly useful for on-grid feasibility analysis [69]. Strength: Comprehensive feasibility analysis, covering financial viability and risk assessment. Weakness: Limited in optimization capabilities; primarily focused on project feasibility rather than detailed system design.
7. **NREL SAM** The system advisor model (SAM), developed by NREL and Sandia National Laboratories, provides a robust platform for techno-economic

analysis across various RESs, including CST, SPV, WT, fuel cells, biomass, and geothermal. It offers insights into CST technologies and RESs globally, available as a free, versatile tool for technical and financial assessments [67, 70]. Strength: Highly versatile for techno-economic analysis and performance modeling across diverse RESs. Weakness: Broad capabilities may lack the specificity found in dedicated optimization tools.

8. **MATLAB/ Simulink** MATLAB/Simulink, developed by MathWorks, is a high-performance environment for technical computing and simulation, extensively used for modeling, simulating, and analyzing dynamic systems, including MGs [57]. It enables integration with toolboxes like SimPowerSystems for RE applications, grid modeling, and fault detection in MGs [85]. Strength: Flexible and highly customizable, with extensive libraries for RES modeling and advanced fault analysis. Weakness: Requires expertise for custom implementation; computationally intensive for large-scale simulations.

Building on these findings, the next section delves into the evolution of OTs and tools in HMGSs, highlighting the role of advanced AI and metaheuristic methods in achieving efficiency and reliability. This analysis also examines how STs have adapted to support increasingly complex technical and economic objectives in HMGSs, facilitating a balance between performance and cost-effectiveness.

5.5 Evolution of Techniques and Tools (Scopus Analysis)

The exploration of the scientific literature over time enables researchers to track the development and emerging trends within a specific field. This section investigates the evolution of OTs and STs for HMGSs, utilizing Scopus as the primary database. This analysis sheds light on the increasing complexity and advancements in the field, pinpointing key areas where OTs have gained significant traction and addressing insights noted in previous work. Following the established best practices for systematic reviews, as shown in Figure 5.5, this study followed these steps:

1. Problem Planning and Formulation
 - Defined research questions and objectives.
 - Established criteria for selecting relevant literature.
 - Outlined potential conclusions based on the findings.
2. Database, Keywords, and Search String Determination

- Selected Scopus as the primary database.
- Identified relevant keywords to ensure a comprehensive search.
- Developed a focused search string aligned with this study’s objectives.

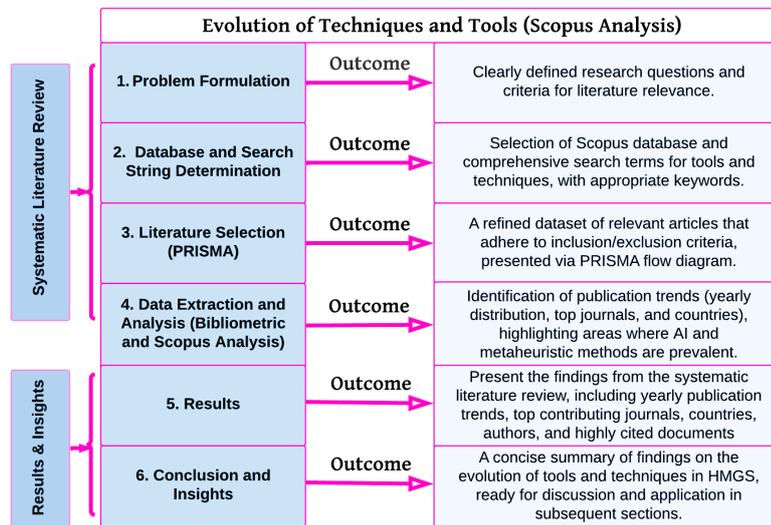


Figure 5.5: Systematic review process for the evolution of OTs and STs in HMGSs.

3. Literature Selection

- Applied the PRISMA methodology to screen and select relevant articles.
- Excluded unrelated studies, books, and non-English publications.

4. Analysis of Results

- Extracted insights from the selected studies.
- Analyzed trends, gaps, and emerging areas of focus in the field.

Figure 5.5 outlines the systematic review process for tracing the evolution of OTs and tools in the HMGS research. With this structured approach, we have gathered a comprehensive dataset of studies that reflect the trajectory and advancements in the field. The following sections present the results of our bibliometric and Scopus analyses, offering insights into the publication trends, leading journals, and geographic contributions in the domain of HMGS OTs and tools. These data reveal patterns and emerging areas of focus that highlight the growing role of AI and metaheuristic methods within HMGS research.

5.6 Systematic Review Framework and Results

This section presents the findings from the systematic review of OTs and STs in HMGSs, following the methodology outlined in Figure 5.5. It encompasses the structured review process (PRISMA) and the results derived from the analysis.

5.6.1 Problem Formulation

This study aims to map the current knowledge landscape surrounding OTs and STs in HMGSs through a systematic, category-specific analysis. By carefully selecting and applying relevant keywords in an advanced Scopus search, this study establishes a focused foundation for analyzing advancements in both techniques and tools, setting the stage for in-depth exploration and evaluation.

5.6.2 Database and Search String Determination

To ensure a comprehensive and targeted search, the keyword selection was based on three key criteria:

1. **Relevance to HMGS optimization:** Keywords were chosen to cover a broad range of OTs and STs commonly applied in HMGSs.
2. **Coverage of classical and modern methods:** The selection includes both classical approaches and widely adopted modern AI-enhanced metaheuristics to reflect proven advancements in optimization.
3. **Scientific and practical significance:** Keywords were derived from highly cited studies and standard industry practices, ensuring alignment with widely recognized methods in HMGS research.

Scopus was chosen for its vast collection of important scientific publications, ensuring thorough and reliable data collection. The search strategy focused on selecting relevant studies based on clear inclusion criteria while maintaining accuracy in identifying impactful research.

a) OTs

For this study, the Scopus database was selected due to its extensive repository of globally significant scientific publications across a wide range of fields. The review focused on core topics in relation to HMGSs, including MGs, renewable energy systems, and various OTs spanning both classical and modern approaches (as illustrated in Figure 5.3). To capture relevant studies, an advanced Scopus search was performed using the following

search string: TITLE-ABS-KEY ((“microgrid” OR “micro grid” OR “micro-grid” OR “microgrids” OR “hybrid microgrid systems” OR “hybrid microgrid system” OR “rural microgrid” OR “urban microgrid”) AND (“renewable energy” OR “renewable energy sources” OR “renewable energy systems” OR “hybrid energy” OR “distributed energy resources” OR “hybrid energy systems” OR “hybrid energy sources” OR “hybrid power system”) AND (“optimization techniques” OR “metaheuristics” OR “genetic algorithm” OR “GA” OR “particle swarm optimization” OR “PSO” OR “ Ant Colony Optimization” OR “ACO” OR “evolutionary algorithms” OR “swarm intelligence” OR “Genetic programming” OR “Differential evolution” OR “Simulated annealing” OR “Tabu search” OR “Harmony search” OR “artificial intelligence” OR “Deep reinforcement learning” OR “fuzzy logic” OR “deep learning” OR “Deep reinforcement learning” OR “Support vector machine” OR “reinforcement learning” OR “machine learning” OR “artificial neural networks” OR “AI-enhanced metaheuristic” OR “linear programming” OR “non linear programming” OR “graphical technique” OR “iterative technique” OR “dynamic programming”)).

b) STs

Similarly, the Scopus database served as the primary source for the literature on STs used in HMGS optimization. This segment of the review targeted topics related to microgrids, renewable energy systems, and specialized STs (as illustrated in Figure 5.3). The advanced Scopus search string applied to capture relevant software-focused studies was as follows: TITLE-ABS-KEY ((“microgrid” OR “micro grid” OR “micro-grid” OR “microgrids” OR “hybrid microgrid systems” OR “rural microgrid” OR “urban microgrid” OR “hybrid microgrid system”) AND (“renewable energy” OR “renewable energy sources” OR “renewable energy systems” OR “hybrid energy” OR “distributed energy resources” OR “hybrid energy systems” OR “hybrid energy sources” OR “hybrid power system”) AND (“HOMER” OR “HOGA” OR “TRNSYS” OR “HYGROGEMS” OR “INSEL” OR “ARES” OR “RAPSIM” OR “SOMES” OR “SOLSIM” OR “MATLAB/Simulink” OR “OpenDSS” OR “System Advisor Model” OR “SAM” OR “REopt” OR “PVSYST” OR “Helioscope” OR “DIgSILENT PowerFactory” OR “PSCAD”)).

5.6.3 Literature Selection (PRISMA Analysis)

The PRISMA flowchart methodology was rigorously followed, as illustrated in Figure 5.6 and Figure 5.7, to systematically refine and select relevant articles for both OTs and STs. This process ensured that the final dataset included only the

most relevant studies aligned with the objectives of this research. The selection process included four key stages:

- Identification—A total of 4696 OT-related and 2950 ST-related records were retrieved from Scopus.
- Screening—Duplicate entries, books, and retracted papers were removed. Additionally, only studies classified as “Final” publications were retained, reducing the count to 4492 OT-related and 2858 ST-related studies.
- Eligibility—Further refinement excluded book series for both OTs and STs. Additionally, trade journal papers were removed only for OTs, while no trade journal exclusions were applied to STs in this step. Finally, English-only publications were retained, resulting in 4134 OT-related and 2667 ST-related studies.
- Inclusion—The final dataset consisted of 4134 OT-related and 2667 ST-related studies used for the qualitative synthesis and analysis.

Note: The document count for the year 2024 includes publications retrieved up to November. Documents published beyond this date were excluded due to the review timeline. To ensure a rigorous selection process, we applied the following inclusion and exclusion criteria:

Inclusion Criteria:

- Studies published in peer-reviewed journals and conference proceedings.
- Research that focuses on OTs and STs applied to HMGSs.
- Articles that include quantitative analysis, simulations, or case studies demonstrating the application of OTs and STs.
- Papers published in English to maintain consistency and accessibility.

Exclusion Criteria:

- Duplicate and irrelevant records removal

Initial filtering removed duplicate entries and irrelevant records, ensuring only unique and relevant studies were considered.

- Exclusion based on document type

Books, book chapters, retracted papers, and undefined document types were excluded.

- Exclusion based on publication stage

Only studies classified as “Final” publications were retained, removing preliminary or non-peer-reviewed works.

- Eligibility assessment and further refinement

Book series were excluded as they do not contribute original, peer-reviewed research. Non-English publications were removed to maintain consistency and avoid translation inaccuracies. The following subsections detail the application of PRISMA for each category.

a) Optimization Techniques

The selection process for OTs was conducted following the PRISMA flowchart guidelines, as depicted in Figure 5.6.

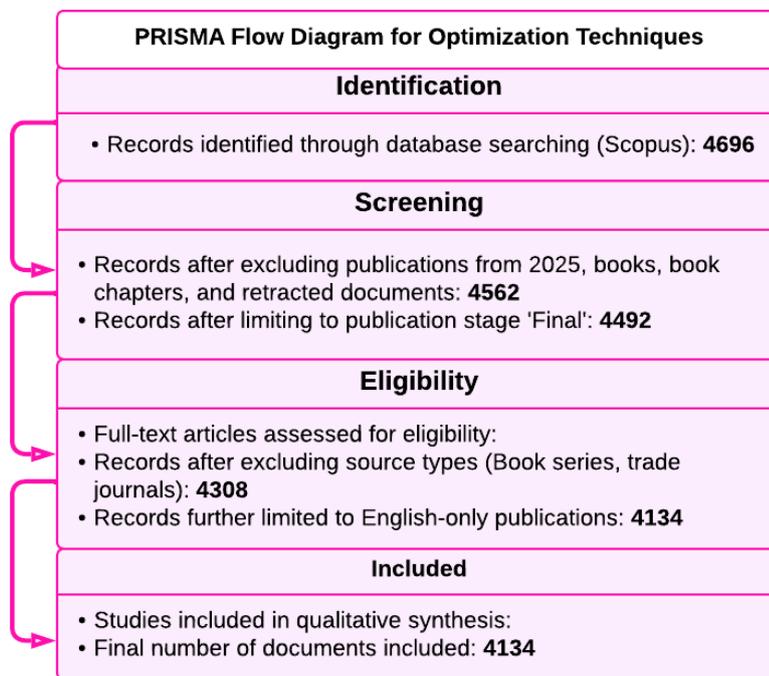


Figure 5.6: PRISMA flow diagram for the OT selection

Initially, 4696 records were retrieved from the Scopus database. Screening excluded publications from 2025, books, book chapters, and retracted documents, narrowing the count to 4562. Limiting the results to “Final” publications further reduced this to 4492. In the eligibility phase, additional exclusions, including book series and trade journals, brought the total to

4308. Finally, limiting the results to English-only publications resulted in 4134 relevant papers for analysis.

b) STs

Following the PRISMA guidelines (Figure 5.7), the selection began with 2945 records from Scopus.

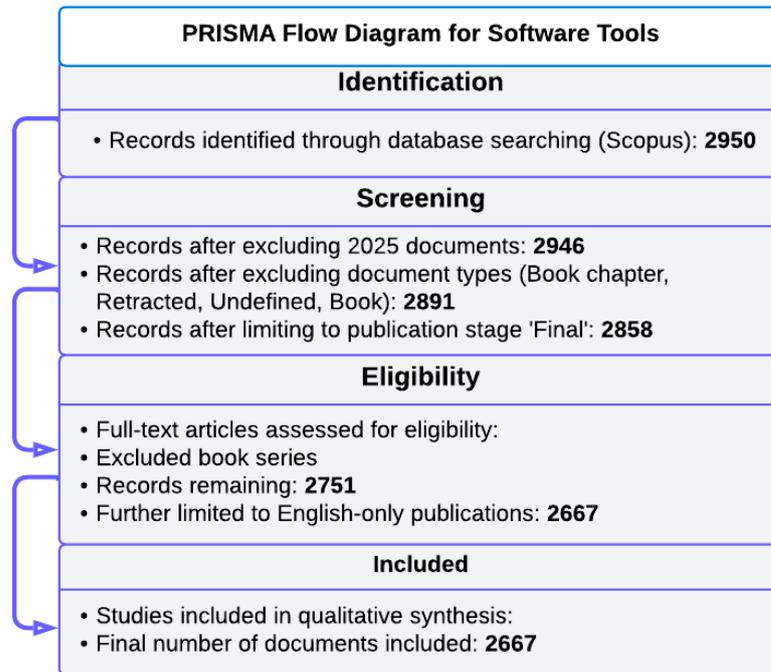


Figure 5.7: PRISMA flow diagram for the ST selection.

Initially, 2950 records were retrieved from Scopus. Screening excluded 2025 publications, books, chapters, retracted documents, and undefined documents, narrowing the count to 2891. Limiting the publication stage to “Final” reduced this to 2858. Further refinement in the eligibility phase excluded book series, bringing the count to 2751. Finally, limiting the results to English-language publications resulted in 2667 relevant papers for analysis.

5.7 Results

This section presents the findings from the systematic literature review, organized into key subsections reflecting the outcomes derived from the analysis. The results

include the yearly publication trends, contributions from top journals, countries, authors, and insights into highly cited documents. These analyses provide an overarching view of the evolution and focus areas within the field of OTs and STs for HMGSs.

5.7.1 Yearly Distribution of Documents

The distribution of documents over the years highlights the growing interest in OTs and STs for HMGSs.

a) OTs

Figure 5.8 illustrates the yearly distribution of documents related to OTs in HMGSs.

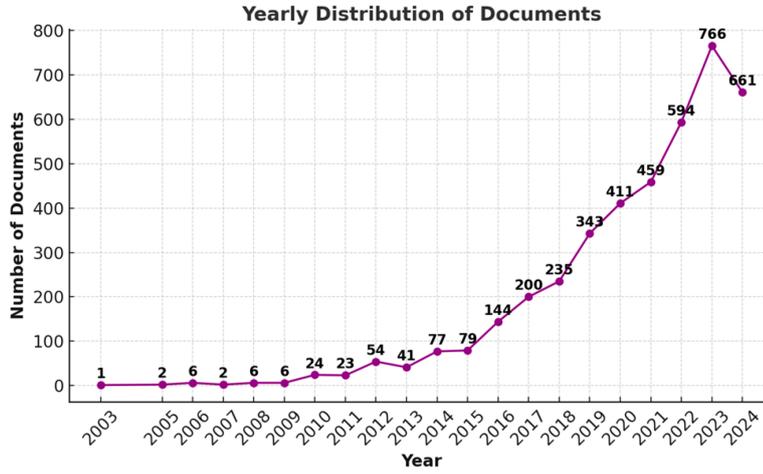


Figure 5.8: Yearly distribution of documents related to OTs in HMGSs (2003–2024).

A noticeable surge in the number of publications is observed, particularly after 2018, reflecting the growing academic and industrial interest in this field. This trend emphasizes the expanding research focus on optimizing HMGSs and the increasing adoption of advanced optimization methods. To gain deeper insights into this collection of documents, our analysis quantified the percentage participation of each category of OT. The participation ratio of each category [P_c] was determined using the following equation:

$$P_c = \frac{N_c}{N_t} \times 100\%. \quad (5.1)$$

P_c Relative research weight (%) of a specific optimization technique category.
 N_c Number of documents in a specific category.
 N_t Total number of documents analyzed.

This measure provides a normalized representation of the research trends, allowing for comparative analysis across different optimization paradigms. The results from our analysis indicate the following distribution:

- **Classical techniques:** $P_c = 16.87\%$ ($N_c = 697$, $N_t = 4134$).
- **Artificial-intelligence-based techniques:** $P_c = 36.01\%$ ($N_c = 1489$, $N_t = 4134$).
- **Metaheuristic techniques:** $P_c = 47.12\%$ ($N_c = 1848$, $N_t = 4134$).

The dominance of metaheuristic methods underscores their adaptability and effectiveness in addressing the complexities inherent in HMGS optimization, such as nonlinearity, uncertainty, and multi-objective constraints. This prevalence highlights a growing reliance on advanced algorithms capable of providing robust and efficient solutions for real-world energy systems.

b) STs

Figure 5.9 illustrates the yearly distribution of documents related to STs in HMGSs, highlighting a notable rise in publications, particularly after 2015.

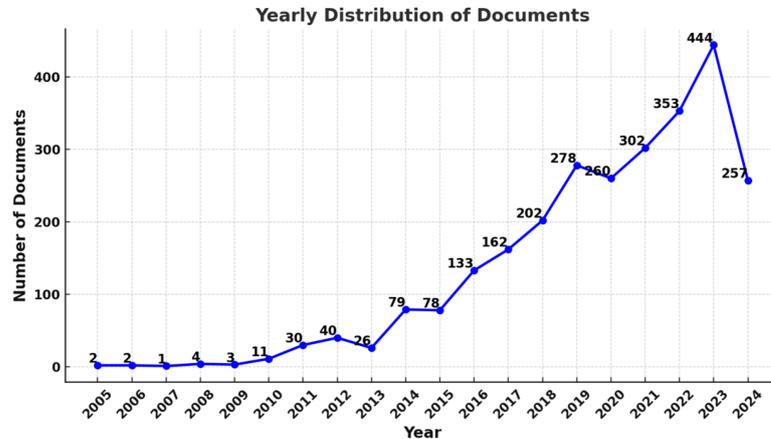


Figure 5.9: Yearly distribution of documents related to STs in HMGSs (2005–2024).

Among the 2667 documents analyzed, the distribution of ST utilization was assessed based on the relative research weight. MATLAB/Simulink exhibited the highest prevalence, appearing in 1743 documents (65.34%), while

HOMER followed with 589 occurrences (22.08%). The participation ratios were derived using Equation 5.1, providing a comparative measure of the research focus across different STs. The dominance of MATLAB/Simulink and HOMER reflects the strong industry and academic preference for commercial tools in HMGS research. As discussed in Table 5.3, commercial software provides validated models, extensive libraries, and industry-standard simulation capabilities, making them reliable choices for HMGS analysis. However, licensing costs can limit accessibility, particularly for researchers in developing regions. In contrast, open-source tools such as OpenDSS and RAPSim remain underrepresented in the dataset despite their potential advantages, including cost efficiency, transparency, and adaptability for specific MG applications. The lower adoption rate of these tools is often attributed to the limited technical support, fewer built-in optimization features, and steeper learning curve compared to commercial alternatives. While MATLAB/Simulink continues to dominate, the increasing demand for cost-effective and customizable MG solutions may drive greater adoption of open-source tools in future research.

5.7.2 Top Contributing Countries

Figure 5.10a,b illustrate the top 10 contributing countries for OTs and STs, respectively.

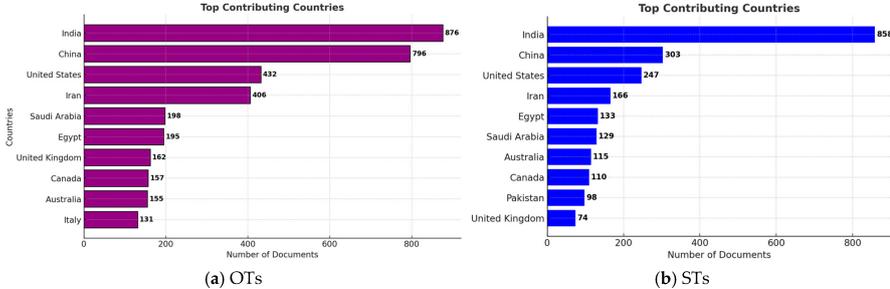


Figure 5.10: Top contributing countries for (a) OTs and (b) STs.

India leads in both categories, followed by China and the United States. Other significant contributors include Iran, Saudi Arabia, and Egypt, along with notable participation from developed countries such as the United Kingdom and Canada. These results emphasize the global interest and collaborative efforts in advancing HMGS research.

5.7.3 Top Cited Documents

a) Top Cited Documents for OTs

The top 10 cited documents listed in Table 5.4 illustrate the diverse methodologies and advanced OTs applied in HMGSs.

Table 5.4: Top 10 highly cited documents for OTs in HMGSs.

Ref.	Authors	Journal	Year	Citations
[22]	Chaouachi, A., Kamel, R.M., Andoulsi, R., Nagasaka, K.	<i>IEEE Transactions on Industrial Electronics</i>	2013	575
[62]	Moghaddam, A.A., Seifi, A., Niknam, T., Alizadeh Pahlavani, M.R.	<i>Energy</i>	2011	540
[16]	Bevrani, H., Habibi, F., Babahajyani, P., Watanabe, M., Mitani, Y.	<i>IEEE Transactions on Smart Grid</i>	2012	519
[3]	Ahmad, T., Zhang, D., Huang, C., Song, Y., Chen, H.	<i>Journal of Cleaner Production</i>	2021	483
[65]	Morais, H., Kádár, P., Faria, P., Vale, Z.A., Khodr, H.M.	<i>Renewable Energy</i>	2010	476
[86]	Suganthi, L., Iniyani, S., Samuel, A.A.	<i>Renewable and Sustainable Energy Reviews</i>	2015	435
[52]	Long, C., Wu, J., Zhou, Y., Jenkins, N.	<i>Applied Energy</i>	2018	422
[77]	Ramli, M.A.M., Boucekara, H.R.E.H., Alghamdi, A.S.	<i>Renewable Energy</i>	2018	421
[21]	Chakraborty, S., Weiss, M.D., Simões, M.G.	<i>IEEE Transactions on Industrial Electronics</i>	2007	403
[18]	Borhanazad, H., Mekhilef, S., Gounder Ganapathy, V., Modiri-Delshad, M., Mirta-heri, A.	<i>Renewable Energy</i>	2014	393

The most cited studies on HMGS optimization demonstrate significant advancements in optimization methodologies, including AI-based approaches, metaheuristics, and mathematical programming techniques. Chaouachi et al. [22] pioneered the integration of AI with linear programming and fuzzy logic for MG energy management, enhancing forecasting accuracy and battery scheduling to minimize operational costs and emissions. Moghaddam et al. (2011) [62] introduced the adaptive modified particle swarm optimization (AMPSSO) algorithm, incorporating chaotic local search (CLS) and fuzzy self-adaptive (FSA) structures to improve the cost and emission minimization in MGs, outperforming traditional evolutionary algorithms. Bevrani et al. (2012) [16] developed an intelligent frequency control approach combining fuzzy logic with PSO, demonstrating superior adaptability in maintaining grid stability under uncertain renewable generation. Ahmad et al. [3]

highlighted AI’s transformative role in the energy sector, emphasizing its applications in smart grid optimization, predictive maintenance, cyberattack prevention, and real-time decision-making, positioning AI as a key enabler of the future digital energy market. Morais et al. (2010) [65] applied MILP for the optimal scheduling of generation units in an isolated DC-MG, proving its effectiveness in economic dispatch and real-time load balancing with rapid convergence. Collectively, these studies illustrate the evolution of advanced OTs, reinforcing their critical role in improving MG efficiency, reliability, and economic performance.

b) Top Cited Documents for STs

STs are indispensable for optimizing HMGSs, offering advanced capabilities in design, modeling, and management. Table 5.5 lists the top 10 highly cited articles in this domain, highlighting diverse applications of STs.

Table 5.5: Top 10 highly cited documents for STs in HMGSs.

Ref.	Authors	Journal	Year	Citations
[85]	Sortomme, E., et al.	<i>IEEE Transactions on Power Delivery</i>	2010	513
[27]	Hafez, O., Bhattacharya, K.	<i>Renewable Energy</i>	2012	489
[84]	Singh, S., et al.	<i>Energy Conversion and Management</i>	2016	383
[5]	Amrollahi, M.H., Bathaee, S.M.T.	<i>Applied Energy</i>	2017	340
[10]	Badal, F.R., et al.	<i>Protection and Control of Modern Power Systems</i>	2019	332
[2]	Ahmad, J., et al.	<i>Energy</i>	2018	282
[1]	Abdin, Z., Mérida, W.	<i>Energy Conversion and Management</i>	2019	268
[73]	Ou, T.-C., Hong, C.-M.	<i>Energy</i>	2014	221
[101]	Yu, X., et al.	<i>IEEE Transactions on Smart Grid</i>	2014	206
[47]	Li, J., et al.	<i>Applied Energy</i>	2017	202

One notable study introduced a communication-assisted digital relay protection scheme using MATLAB/Simulink, ensuring reliable fault detection in MGs with high DG penetration [85]. Another study utilized HOMER to minimize the life-cycle costs and assess the environmental impacts across various MG configurations, showcasing its versatility in HES analysis [27]. HOMER and GAMS software were combined to implement demand response programming, achieving substantial reductions in the battery and inverter requirements and total net present costs [5]. These studies collectively underscore the vital role of STs in enhancing the efficiency and reliability of HMGSs through robust optimization methodologies.

5.7.4 Top Contributing Journals

Figure 5.11a,b highlight the top contributing journals in the fields of OTs and STs for HMGSs, respectively. Both figures underscore the dominance of *Energies* and *IEEE Access* in terms of the document contributions. *Energies* leads the field with 218 documents for OTs and 120 documents for STs, reflecting its significant role in advancing HMGS research. Other key contributors include *Applied Energy*, *Journal of Energy Storage*, and *International Journal of Electrical Power and Energy Systems*, which consistently publish high-impact research.

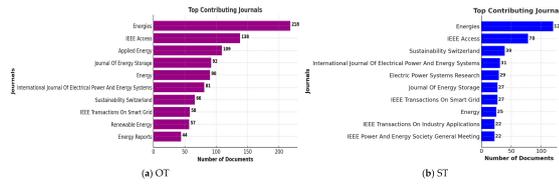


Figure 5.11: Top contributing journals for (a) OTs and (b) STs.

The top ten contributing journals in Table 5.6 showcase cutting-edge OTs driving advancements in HMGSs.

Table 5.6: Top 10 contributing journals for OTs in HMGSs.

Rank	Journal Name	Number of Documents	Highly Cited Article	Citation Count
1	<i>Energies</i>	218	[37]	186
2	<i>IEEE Access</i>	138	[40]	172
3	<i>Applied Energy</i>	109	[52]	422
4	<i>Journal of Energy Storage</i>	92	[54]	244
5	<i>Energy</i>	90	[62]	540
6	<i>International Journal of Electrical Power and Energy Systems</i>	81	[100]	179
7	<i>Sustainability Switzerland</i>	66	[39]	127
8	<i>IEEE Transactions on Smart Grid</i>	58	[16]	519
9	<i>Renewable Energy</i>	57	[65]	476
10	<i>Energy Reports</i>	44	[96]	100

A novel energy management approach using DRL modeled as a Markov decision process (MDP) effectively addresses the challenges of uncertainty in the load demand, RESs variability, and electricity price fluctuations, achieving significant operational cost reductions [37]. To tackle the frequency stability in low-inertia MGs with high renewable penetration, self-adaptive virtual inertia control based on fuzzy logic dynamically adjusts the inertia constants in real-time, delivering an

enhanced transient response and robust system stability [40]. Furthermore, a two-stage aggregated control framework for peer-to-peer (P2P) energy sharing within community MGs leverages constrained nonlinear programming (CNLP) optimization. This method achieves up to 30% cost savings for the community and notable economic benefits for individual prosumers [52]. These studies emphasize the essential role of advanced OTs in addressing critical challenges in HMGS design and operation.

The top ten contributing journals listed in Table 5.7 illustrate the critical role of advanced STs in modeling, simulating, and optimizing HMGSs.

Table 5.7: Top 10 contributing journals for STs in HMGSs.

Rank	Journal Name	Number of Documents	Highly Cited Article	Citation Count
1	<i>Energies</i>	120	[96]	148
2	<i>IEEE Access</i>	78	[71]	125
3	<i>Sustainability Switzerland</i>	39	[23]	154
4	<i>International Journal of Electrical Power and Energy Systems</i>	31	[11]	130
5	<i>Electric Power Systems Research</i>	29	[80]	81
6	<i>Journal of Energy Storage</i>	27	[56]	59
7	<i>IEEE Transactions on Smart Grid</i>	27	[101]	206
8	<i>Energy</i>	25	[2]	282
9	<i>IEEE Transactions on Industry Applications</i>	22	[102]	142
10	<i>IEEE Power and Energy Society General Meeting</i>	22	[42]	48

MATLAB/Simulink has been effectively used for load frequency control (LFC) in isolated MGs, leveraging multivariable generalized predictive control to stabilize the frequency amidst fluctuating RESs and continuous load disturbances [96]. HOMER Pro has been instrumental in conducting techno-economic feasibility analyses, identifying optimal configurations for HESs by evaluating parameters such as the NPC, COE, and greenhouse gas emissions across various sensitivity scenarios [71]. Additionally, HOMER Pro was employed to assess the viability of hydrogen as a robust energy storage medium in a 100% renewable stand-alone MG, demonstrating its potential to electrify remote communities cost-effectively while reducing carbon footprints [80]. These studies underscore the indispensable role of tools like MATLAB/Simulink and HOMER Pro in advancing HMGS research and achieving sustainable energy solutions.

5.7.5 Top Contributing Authors

This section highlights the most prolific contributors to the HMGS research, categorized into two areas: OTs and STs. Table 5.8 and Table 5.9 summarize the rankings based on the number of publications and key focus areas for each author.

Table 5.8: Top contributing authors in terms of OTs.

Rank	Author	No. of Publications	Key Focus Areas
1	Guerrero, J.M.	35	Distributed control, HMGS optimization, and intelligent energy management.
2	Gharehpetian, G.B.	19	Robust control, fault management, and resilient microgrid operation.
3	Dey, B.	18	Multi-objective optimization, renewable integration, and cost minimization in MGs.
4	Ustun, T.S	15	Cybersecurity, distributed control, and load frequency stability in MGs.
5	Marzband, M.	15	Stochastic optimization, demand response, and energy management in smart MGs.

Table 5.8 identifies the leading authors contributing to the development and application of OTs in HMGSs. These researchers have significantly advanced the field by introducing innovative methodologies to enhance system reliability, efficiency, and cost-effectiveness. Guerrero, J.M., leading the list with 35 publications, has been a pioneer in distributed control and HMGS optimization. Other prominent contributors, such as Gharehpetian, G.B., and Dey, B., focus on fault management and multi-objective optimization, respectively.

Table 5.9: Top contributing authors in terms of STs.

Rank	Author	No. of Publications	Key Focus Areas
1	Guerrero, J.M.	24	Application of HOMER and MATLAB for hybrid systems, renewable integration, and grid stability.
2	Baghaee, H.R.	21	Fault-tolerant distributed control and resilience in islanded MGs.
3	Shahnia, F.	19	Stability analysis, system coupling, and optimization in sustainable MGs.
4	Gharehpetian, G.B.	18	Fault management, robust distributed systems, and islanded MG controls.
5	Ghosh, A.	14	Cooperative energy storage control, harmonic mitigation, and voltage regulation in MGs.

Table 5.9 showcases the authors most active in leveraging STs to design and analyze HMGSs. Their work has facilitated the integration of RESs and improved MG performance. Guerrero, J.M., again ranks first, with 24 publications emphasizing the use of tools like HOMER and MATLAB for HESs. Baghaee, H.R., and Shahnia, F., follow closely, contributing to fault-tolerant systems and sustainable MG configurations.

5.8 Conclusions and Insights

5.8.1 Overview of Key Findings

This study provides a comprehensive evaluation of OTs and STs in the context of HMGSs.

- OTs: Advanced methodologies, such as AI-driven approaches, metaheuristics, and MILP, play a pivotal role in improving energy efficiency, reliability, and sustainability by addressing challenges like resource intermittency, load management, and cost optimization.
- STs: Tools like HOMER, MATLAB, and SAM are indispensable for designing, optimizing, and evaluating HMGS configurations, enabling researchers to analyze complex systems under diverse conditions.

5.8.2 Trends and Implications

The steady rise in research outputs, particularly after 2018, reflects the growing global emphasis on decarbonization and energy resilience, driven by key policy initiatives such as the Paris Agreement (2015) and the United Nations Sustainable Development Goals (SDGs), which have accelerated the adoption of RESs [94]. Additionally, the US Department of Energy (DOE) Smart Grid R&D Program has played a crucial role in advancing optimization strategies [90]. On the technological front, the declining costs of SPV and WT [34], along with the increasing role of OTs and STs, have further fueled research growth. Notably, DOE-led efforts, including the development of specific design tools and a solutions library by 2020, have enhanced the optimization capabilities. The high adoption of metaheuristic techniques, coupled with the integration of AI-based approaches, reflects a paradigm shift toward intelligent energy systems capable of adapting to dynamic conditions and uncertainties. These trends emphasize the critical role of advanced algorithms and modeling platforms in accelerating the transition to cleaner and more efficient energy systems.

5.8.3 Gaps and Opportunities

Despite significant advancements, several critical gaps remain in the optimization of HMGSs:

- Computational complexity and scalability: Many existing OTs struggle with scalability when applied to large-scale MGs. Future research should focus on developing lightweight AI models and hybrid AI–mathematical approaches to enhance real-time performance.

- **Hybrid AI and traditional methods:** The integration of AI with classical optimization techniques lacks standardization, making benchmarking and validation difficult. Developing benchmark datasets and hybrid frameworks is essential for improving model robustness and adoption.
- **Regional disparities:** Research has primarily focused on developed regions, with limited studies addressing cost-optimization strategies for low-resource settings and grid stability in high-penetration renewable systems.
- **Emerging technologies:** The role of blockchain, quantum computing, and the IoT in MG optimization remains largely unexplored. These technologies could enhance decentralized energy trading, security, and predictive maintenance.
- **Cybersecurity and data privacy:** As AI-driven energy management systems become more prevalent, addressing data privacy, security vulnerabilities, and resilience against cyber threats is crucial. Future research should prioritize hybrid optimization frameworks, enhanced AI interpretability, and scalable real-time decision-making models. By fostering interdisciplinary collaboration, the HMGS community can develop more adaptive, secure, and efficient solutions for next-generation energy systems.

5.8.4 Final Takeaways

This work synthesizes critical insights into the HMGS research, providing an invaluable resource for academics, policymakers, and practitioners. It highlights the following:

- The transformative potential of combining advanced OTs with versatile STs.
- The contributions of leading researchers and journals in pushing the boundaries of HMGS innovation.
- The need for continued research into emerging technologies and their integration into energy systems.

By fostering innovation and collaboration, the HMGS community is well positioned to drive a sustainable energy future. This study serves as a roadmap, bridging knowledge gaps and paving the way for impactful advancements in energy systems optimization and management. By leveraging these insights, stakeholders can accelerate the adoption of resilient and sustainable MG solutions, contributing meaningfully to global energy objectives.

5.9 Conclusions

This comprehensive review provided a systematic analysis of the OTs and tools employed in hybrid microgrid systems (HMGSs), offering an in-depth evaluation of the methods and tools used in the field. This study analyzed 4134 documents for OTs and 2667 for STs. An advanced Scopus search was performed using core keywords for both OTs and STs, including microgrids, renewable energy systems, and the relevant tools and techniques from Figure 3, aimed at HMGS design and optimization. The OTs were categorized into classical (16.9%), metaheuristic (48.3%), and AI-based methods (34.8%), demonstrating the dominance of metaheuristics while highlighting the transformative potential of AI-based approaches, particularly in predictive analytics and managing uncertainties. STs like MATLAB and HOMER have established themselves as critical enablers of HMGS design and optimization, facilitating detailed techno-economic assessments and offering scalable solutions for various configurations and geographic conditions. These findings underscore their indispensability in microgrid (MG) planning. The results indicate a significant surge in research activity post-2018, driven by the global transition to renewable energy sources (RESs) and an increasing focus on energy resilience. Analysis of the top-contributing journals, authors, and countries highlights growing collaboration in this field. However, gaps remain in addressing cybersecurity, regional data limitations, and the integration of emerging technologies such as blockchain and the IoT. Future research should focus on addressing these gaps through interdisciplinary approaches and enhancing regional applicability. This study serves as a guiding resource for advancing HMGS innovation. By leveraging the strengths of metaheuristic optimization and robust STs, stakeholders can drive sustainable energy solutions, address global energy challenges, and enhance energy resilience. By fostering innovation and collaboration, HMGS research can accelerate the global shift toward RESs, paving the way for significant advancements in energy systems optimization, resilience, and sustainable management.

References for Chapter 5

- [1] Z. Abdin and W. Mérida. Hybrid energy systems for off-grid power supply and hydrogen production based on renewable energy: A techno-economic analysis. *Energy Conversion and Management*, 196:1068–1079, 2019.
- [2] J. Ahmad, M. Imran, A. Khalid, W. Iqbal, R. Ashraf, S. M. Adnan, F. Ali, S. and S. Khokhar, K. Techno economic analysis of a wind-photovoltaic-biomass hybrid renewable energy system for rural electrification: A case study of kallar kahar. *Energy*, 148:208–234, 2018.
- [3] T. Ahmad, D. Zhang, C. Huang, H. Zhang, N. Dai, Y. Song, H. Chen, T. Ahmad, D. Zhang, C. Huang, and et al. Artificial intelligence in sustainable energy industry: Status quo, challenges and opportunities. *Journal of Cleaner Production*, 289:125834, 2021.
- [4] M. Alam, K. Kumar, and V. Dutta. Analysis of lead-acid and lithium-ion batteries as energy storage technologies for the grid-connected microgrid using dispatch control algorithm. *Studies in Computational Intelligence*, 916:499–515, 2021.
- [5] M.H. Amrollahi and S.M.T. Bathaee. Techno-economic optimization of hybrid photovoltaic/wind generation together with energy storage system in a stand-alone micro-grid subjected to demand response. *Appl. Energy*, 202:66–77, 2017.
- [6] A. Askarzadeh. A novel metaheuristic method for solving constrained engineering optimization problems: Crow search algorithm. *Comput. Struct.*, 169:1–12, 2016.
- [7] R. Atia and N. Yamada. Sizing and analysis of renewable energy and battery systems in residential microgrids. *IEEE Transactions on Smart Grid*, 7(3):1204–1213, 2016.

- [8] Y.M. Atwa, E.F. El-Saadany, M.M.A. Salama, and R. Seethapathy. Optimal renewable resources mix for distribution system energy loss minimization. *IEEE Trans. Power Syst.*, 25:360–370, 2010.
- [9] T. Aziz, N. Al Masood, S.R. Deeba, W. Tushar, and C. Yuen. A methodology to prevent cascading contingencies using bess in a renewable integrated microgrid. *Int. J. Electr. Power Energy Syst.*, 110:737–746, 2019.
- [10] F. R. Badal, P. Das, S. K. Sarker, and S. K. Das. A survey on control issues in renewable energy integration and microgrid. *Protection and Control of Modern Power Systems*, 4:1–27, 2019.
- [11] H. R. Baghaee, M. Mirsalim, G. B. Gharehpetian, and H. A. Talebi. A generalized descriptor-system robust h_{∞} control of autonomous microgrids to improve small and large signal stability considering communication delays and load nonlinearities. *International Journal of Electrical Power & Energy Systems*, 92:63–82, 2017.
- [12] F. Baquero, J.L. Martínez, and R. Cantón. Antibiotics and antibiotic resistance in water environments. *Curr. Opin. Biotechnol.*, 19:260–265, 2008.
- [13] Richard E. Bellman and Stuart E. Dreyfus. *Applied Dynamic Programming*. Princeton University Press, 1957. Available online: <https://books.google.com/> . . . (accessed on 6 November 2023).
- [14] Dimitris Bertsimas and John N. Tsitsiklis. *Introduction to Linear Optimization*. Athena Scientific, Belmont, MA, USA, 1997.
- [15] N. Beume, B. Naujoks, and M. Emmerich. Sms-emoa: Multiobjective selection based on dominated hypervolume. *Eur. J. Oper. Res.*, 181:1653–1669, 2007.
- [16] H. Bevrani, F. Habibi, P. Babahajyani, M. Watanabe, and Y. Mitani. Intelligent frequency control in an ac microgrid: Online pso-based fuzzy tuning approach. *IEEE Transactions on Smart Grid*, 3:1935–1944, 2012.
- [17] F.A. Bhuiyan, A. Yazdani, and S.L. Primak. Optimal sizing approach for islanded microgrids. *IET Renew. Power Gener.*, 9:166–175, 2015.
- [18] H. Borhanazad, S. Mekhilef, V. G. Ganapathy, M. Modiri-Delshad, and A. Mirtaheri. Optimization of micro-grid system using mopso. *Renewable Energy*, 71:295–306, 2014.

- [19] A. Cagnano, E. De Tuglie, F. Marcone, G. Porro, D. Dauphin Rasolomampionona, M. Klos, S. Favuzza, and G. Zizzo. Experimental results on the economic management of a smart microgrid. In *20th IEEE Mediterranean Electrotechnical Conference MELECON 2020—Proceedings*, pages 459–463, Palermo, Italy, 2020.
- [20] G. Calinescu, C. Chekuri, M. Pál, and J. Vondrák. Maximizing a monotone submodular function subject to a matroid constraint. *SIAM J. Comput.*, 40:1740–1766, 2011.
- [21] S. Chakraborty, M.D. Weiss, and M.G. Simões. Distributed intelligent energy management system for a single-phase high-frequency ac microgrid. *IEEE Trans. Ind. Electron.*, 54:97–109, 2007.
- [22] A. Chaouachi, R. M. Kamel, R. Andoulsi, and K. Nagasaka. Multiobjective intelligent energy management for a microgrid. *IEEE Transactions on Industrial Electronics*, 60:688–699, 2012.
- [23] F. Dawood, G. M. Shafiullah, and M. Anda. Stand-alone microgrid with 100% renewable energy: A case study with hybrid solar pv-battery-hydrogen. *Sustainability*, 12:2047, 2020.
- [24] M.K. Deshmukh and S.S. Deshmukh. Modeling of hybrid renewable energy systems. *Renew. Sustain. Energy Rev.*, 12:235–249, 2008.
- [25] A.H. Fathima and K. Palanisamy. Optimization in microgrids with hybrid energy systems—a review. *Renew. Sustain. Energy Rev.*, 45:431–446, 2015.
- [26] S.S. Gharehveran, K. Shirini, S.C. Khavar, S.H. Mousavi, and A. Abdolahi. Deep learning-based demand response for short-term operation of renewable-based microgrids. *J. Supercomput.*, 80:26002–26035, 2024.
- [27] O. Hafez and K. Bhattacharya. Optimal planning and design of a renewable energy based supply system for microgrids. *Renewable Energy*, 45:7–15, 2012.
- [28] T. Hai, M. Aksoy, and A. Rezvani. Optimal energy management and scheduling of a microgrid considering hydrogen storage and pemfc with uncertainties. *Int. J. Hydrogen Energy*, 88:1017–1033, 2024.
- [29] B.S. Hartono, Budiyanto, and R. Setiabudy. Review of microgrid technology. In *Proceedings of the 2013 International Conference on QiR—Quality in Research, in conjunction with ICCS 2013*, pages 127–132, Yogyakarta, Indonesia, 2013.

- [30] T. Hasan, K. Emami, R. Shah, N.M.S. Hassan, V. Belokoskov, and M. Ly. Techno-economic assessment of a hydrogen-based islanded microgrid in north-east. *Energy Reports*, 9:3380–3396, 2023.
- [31] HOMER Energy. HOMER—hybrid renewable and distributed generation system design software. <https://www.homerenergy.com/>, 2023. Accessed: 3 July 2023.
- [32] IEA. Renewables 2022, 2022. Available online: <https://www.iea.org> (accessed on 10 December 2022).
- [33] iHOGA/MHOGA Development Team. ihoga/mhoga—simulation and optimization of stand-alone and grid-connected hybrid renewable systems. <https://ihoga.unizar.es/en/>, 2023. Accessed: 6 July 2023.
- [34] International Renewable Energy Agency (IRENA). Renewable power generation costs in 2020. Technical report, IRENA, Frisco, TX, USA, 2020.
- [35] F. Jabari, M. Zeraati, M. Sheibani, and H. Arasteh. Robust self-scheduling of pvs-wind-diesel power generation units in a standalone microgrid under uncertain electricity prices. *J. Oper. Autom. Power Eng.*, 12:152–162, 2024.
- [36] P. Jha, N. Sharma, V.K. Jadoun, A. Agarwal, and A. Tomar. Optimal scheduling of a microgrid using ai techniques. In *Control Standalone Microgrid*, pages 297–336. Academic Press, Cambridge, MA, USA, 2021.
- [37] Y. Ji, J. Wang, J. Xu, X. Fang, and H. Zhang. Real-time energy management of a microgrid using deep reinforcement learning. *Energies*, 12:2291, 2019.
- [38] R. Jiang, J. Wang, and Y. Guan. Robust unit commitment with wind power and pumped storage hydro. *IEEE Trans. Power Syst.*, 27:800–810, 2012.
- [39] T. Kerdphol, F. S. Rahman, Y. Mitani, K. Hongesombut, and S. Küfeoğlu. Virtual inertia control-based model predictive control for microgrid frequency stabilization considering high renewable energy integration. *Sustainability*, 9:773, 2017.
- [40] T. Kerdphol, M. Watanabe, K. Hongesombut, and Y. Mitani. Self-adaptive virtual inertia control-based fuzzy logic to improve frequency stability of microgrid with high renewable penetration. *IEEE Access*, 7:76071–76083, 2019.
- [41] K.S. Krishna and K.S. Kumar. A review on hybrid renewable energy systems. *Renew. Sustain. Energy Rev.*, 52:907–916, 2015.

- [42] M. Kumar, S. N. Singh, and S. C. Srivastava. Design and control of smart dc microgrid for integration of renewable energy sources. In *Proceedings of the IEEE Power and Energy Society General Meeting*, San Diego, CA, USA, July 2012.
- [43] E. Kuznetsova, Y.-F. Li, C. Ruiz, E. Zio, G. Ault, and K. Bell. Reinforcement learning for microgrid energy management. *Energy*, 59:133–146, 2013.
- [44] G. Kyriakarakos, D.D. Piromalis, A.I. Dounis, K.G. Arvanitis, and G. Papadakis. Intelligent demand side energy management system for autonomous polygeneration microgrids. *Applied Energy*, 103:39–51, 2013.
- [45] M.A. Lasemi, A. Arabkoohsar, A. Hajizadeh, and B. Mohammadi-ivatloo. A comprehensive review on optimization challenges of smart energy hubs under uncertainty factors. *Renew. Sustain. Energy Rev.*, 160:112320, 2022.
- [46] A. Lesage-Landry, H. Wang, I. Shames, P. Mancarella, and J.A. Taylor. On-line convex optimization of multi-energy building-to-grid ancillary services. *IEEE Trans. Control Syst. Technol.*, 28:2416–2431, 2020.
- [47] J. Li, R. Xiong, Q. Yang, F. Liang, M. Zhang, and W. Yuan. Design/test of a hybrid energy storage system for primary frequency control using a dynamic droop method in an isolated microgrid power system. *Applied Energy*, 201:257–269, 2017.
- [48] Y. Li, Z. Yang, G. Li, D. Zhao, and W. Tian. Optimal scheduling of an isolated microgrid with battery storage considering load and renewable generation uncertainties. *IEEE Trans. Ind. Electron.*, 66:1565–1575, 2019.
- [49] Z. Liang, C.Y. Chung, W. Zhang, Q. Wang, W. Lin, and C. Wang. Enabling high-efficiency economic dispatch of hybrid ac/dc networked microgrids: Steady-state convex bi-directional converter models. *IEEE Trans. Smart Grid*, 16:45–61, 2024.
- [50] J.Y. Lim, B.S. How, G. Rhee, S. Hwangbo, and C.K. Yoo. Transitioning of localized renewable energy system towards sustainable hydrogen development planning: P-graph approach. *Applied Energy*, 263:114635, 2020.
- [51] D. Liu, Y. Xu, Q. Wei, and X. Liu. Residential energy scheduling for variable weather solar energy based on adaptive dynamic programming. *IEEE/CAA Journal of Automatica Sinica*, 5:36–46, 2018.
- [52] C. Long, J. Wu, Y. Zhou, and N. Jenkins. Peer-to-peer energy sharing through a two-stage aggregated battery control in a community microgrid. *Applied Energy*, 226:261–276, 2018.

- [53] H. Lund, Z. Thellufsen, J. A. Østergaard, P. P. Sorknæs, R. Skov, I. and V. Mathiesen, B. Energyplan—advanced analysis of smart energy systems. *Smart Energy*, 1:100007, 2021.
- [54] L. Luo, S. S. Abdulkareem, A. Rezvani, M. R. Miveh, S. Samad, N. Aljojo, and M. Pazhooesh. Optimal scheduling of a renewable based microgrid considering photovoltaic system and battery energy storage under uncertainty. *Journal of Energy Storage*, 28:101306, 2020.
- [55] A.X.Y. Mah, W.S. Ho, M.H. Hassim, H. Hashim, G.H.T. Ling, C.S. Ho, and Z.A. Muis. Optimization of photovoltaic-based microgrid with hybrid energy storage: A p-graph approach. *Energy*, 233:121088, 2021.
- [56] M. H. Marzebali, M. Mazidi, and M. Mohiti. An adaptive droop-based control strategy for fuel cell-battery hybrid energy storage system to support primary frequency in stand-alone microgrids. *Journal of Energy Storage*, 27:101127, 2020.
- [57] MathWorks. Simulink—simulation and model-based design—matlab. <https://www.mathworks.com/products/simulink.html>, 2024. Accessed: 24 November 2024.
- [58] D. Mazzeo, N. Matera, C. Cornaro, G. Oliveti, P. Romagnoni, and L. De Santoli. Energyplus, ida ice and trnsys predictive simulation accuracy for building thermal behaviour evaluation by using an experimental campaign in solar test boxes with and without a pcm module. *Energy and Buildings*, 212:109812, 2020.
- [59] A. Merabet, A. Al-Durra, T. El Fouly, and E.F. El-Saadany. Multifunctional energy management system for optimized network of microgrids considering battery degradation and load adjustment. *J. Energy Storage*, 100:113709, 2024.
- [60] H.O. Mete and Z.B. Zabinsky. Stochastic optimization of medical supply location and distribution in disaster management. *Int. J. Prod. Econ.*, 126:76–84, 2010.
- [61] R. Metters. Quantifying the bullwhip effect in supply chains. *J. Oper. Manag.*, 15:89–100, 1997.
- [62] A. A. Moghaddam, A. Seifi, T. Niknam, and M. R. A. Pahlavani. Multi-objective operation management of a renewable mg (micro-grid) with backup micro-turbine/fuel cell/battery hybrid power source. *Energy*, 36:6490–6507, 2011.

- [63] S. Mohanty, S. Pati, Sanjeeb, and K. Kar. Persistent voltage profiling of a wind energy-driven islanded microgrid with novel neuro-fuzzy controlled electric spring. *J. Control. Autom. Electr. Syst.*, 34:609–623, 2023.
- [64] H. Moradi, M. Esfahanian, A. Abtahi, and A. Zilouchian. Optimization and energy management of a standalone hybrid microgrid in the presence of battery storage system. *Energy*, 147:226–238, 2018.
- [65] H. Morais, P. Kádár, P. Faria, Z. A. Vale, and H. M. Khodr. Optimal scheduling of a renewable micro-grid in an isolated load area using mixed-integer linear programming. *Renewable Energy*, 35:151–156, 2010.
- [66] M. Mukhtar, S. Obiora, N. Yimen, Z. Quixin, O. Bamisile, P. Jidele, and I. Irivboje, Y. Effect of inadequate electrification on nigeria’s economic development and environmental sustainability. *Sustainability*, 13:2229, 2021.
- [67] National Renewable Energy Laboratory. Home—system advisor model—sam. <https://sam.nrel.gov/>, 2023. Accessed: 15 July 2023.
- [68] National Renewable Energy Laboratory. NSRDB TMY data set. <https://nsrdb.nrel.gov/data-sets/tmy>, 2023. Accessed: 3 July 2023.
- [69] Natural Resources Canada. Retscreen. <https://natural-resources.canada.ca/maps-tools-and-publications/tools/modelling-tools/retscreen/7465>, 2023. Accessed: 15 July 2023.
- [70] K. Nithyanandam, J. Stekli, and R. Pitchumani. High-temperature latent heat storage for concentrating solar thermal (cst) systems. In *Advances in Concentrating Solar Thermal Research and Technology*, pages 213–246. Woodhead Publishing, Sawston, UK, 2017.
- [71] M. Nurunnabi, N. K. Roy, E. Hossain, and H. R. Pota. Size optimization and sensitivity analysis of hybrid wind/pv micro-grids—a case study for bangladesh. *IEEE Access*, 7:150120–150140, 2019.
- [72] B. Opathella, C.; Venkatesh. Three-phase unbalanced power flow using a -model of controllable ac-dc converters. *IEEE Trans. Power Syst.*, 31:4286–4296, 2016.
- [73] T. C. Ou and C. M. Hong. Dynamic operation and control of microgrid hybrid power systems. *Energy*, 66:314–323, 2014.

- [74] M. Pochacker, T. Khatib, and W. Elmenreich. The microgrid simulation tool RAPSIm: Description and case study. In *Proceedings of the IEEE Innovative Smart Grid Technologies—Asia (ISGT ASIA)*, pages 278–283, Kuala Lumpur, Malaysia, May 2014.
- [75] K. Rahbar, J. Xu, and R. Zhang. Real-time energy storage management for renewable integration in microgrid: An off-line optimization approach. *IEEE Transactions on Smart Grid*, 6:124–134, 2015.
- [76] S. Rahim, N. Javaid, R.D. Khan, N. Nawaz, and M. Iqbal. A convex optimization based decentralized real-time energy management model with the optimal integration of microgrid in smart grid. *J. Clean. Prod.*, 236:117688, 2019.
- [77] M.A.M. Ramli, H.R.E.H. Bouchekara, and A.S. Alghamdi. Optimal sizing of pv/wind/diesel hybrid microgrid system using multi-objective self-adaptive differential evolution algorithm. *Renewable Energy*, 121:400–411, 2018.
- [78] RAPSIm Development Team. Rapsim—microgrid simulator. <https://sourceforge.net/projects/rapsim/>, 2023. Accessed: 15 July 2023.
- [79] S.A. Salimon, I.O. Fajinmi, O.B. Adewuyi, A.K. Pandey, O.W. Adebisi, and H. Kotb. Graph theory-enhanced integrated distribution network re-configuration and distributed generation planning. *Cleaner Engineering and Technology*, 22:100808, 2024.
- [80] L. Shen, Q. Cheng, Y. Cheng, L. Wei, and Y. Wang. Hierarchical control of dc micro-grid for photovoltaic ev charging station based on flywheel and battery energy storage system. *Electric Power Systems Research*, 179:106079, 2020.
- [81] A. Shezan, S. Design and demonstration of an islanded hybrid microgrid for an enormous motel with the appropriate solicitation of superfluous energy by using ihoga and matlab. *International Journal of Energy Research*, 45:5567–5585, 2021.
- [82] J.E. Sierra, A.S.G. Hernández, M.F. Sierra, M. Fernanda, and S. Carillo. Study of graph theory in microgrids. *Webology*, page 19, 2022. Available online: <http://www.webology.org> (accessed on 5 March 2025).
- [83] A.R. Singh, L. Ding, D.K. Raju, R.S. Kumar, and L.P. Raghav. Demand response of grid-connected microgrid based on metaheuristic optimization algorithm. *Energy Sources Part A Recover. Util. Environ. Eff.*, 52:917–928, 2021.

- [84] S. Singh, M. Singh, and C. Kaushik, S. Feasibility study of an islanded microgrid in rural area consisting of pv, wind, biomass and battery energy storage system. *Energy Conversion and Management*, 128:178–190, 2016.
- [85] E. Sortomme, S. S. Venkata, and J. Mitra. Microgrid protection using communication-assisted digital relays. *IEEE Transactions on Power Delivery*, 25:2789–2796, 2009.
- [86] L. Suganthi, S. Iniyar, and A. A. Samuel. Applications of fuzzy logic in renewable energy systems—a review. *Renewable and Sustainable Energy Reviews*, 48:585–607, 2015.
- [87] K.A. Tahir, J. Nieto, C. Díaz-López, and J. Ordóñez. From diesel reliance to sustainable power in iraq: Optimized hybrid microgrid solutions. *Renew. Energy*, 238:121905, 2025.
- [88] K.A. Tahir, J. Ordóñez, and J. Nieto. Exploring evolution and trends: A bibliometric analysis and scientific mapping of multiobjective optimization applied to hybrid microgrid systems. *Sustainability*, 16(12):5156, 2024.
- [89] K.A. Tahir, M. Zamorano, and J.O. García. Scientific mapping of optimisation applied to microgrids integrated with renewable energy systems. *Int. J. Electr. Power Energy Syst.*, 145:108698, 2023.
- [90] D. T. Ton and M. A. Smith. The u.s. department of energy’s microgrid initiative. *The Electricity Journal*, 25:84–94, 2012.
- [91] TRNSYS Development Team. Trnsys 18. <http://sel.me.wisc.edu/trnsys>, 2023. Accessed: 14 July 2023.
- [92] A.G. Tsikalakis and N.D. Hatziargyriou. Centralized control for optimizing microgrids operation. *IEEE Trans. Energy Convers.*, 23:241–248, 2008.
- [93] Dave Turcotte, Michael Ross, and Farah Sheriff. Photovoltaic hybrid system sizing and simulation tools: Status and needs. In *PV Horizon: Workshop on Photovoltaic Hybrid Systems*, Montreal, Canada, September 2001. Available at <https://www.researchgate.net/publication/228496269>.
- [94] United Nations Statistics Division. Sdg indicators—sdg indicators. <https://unstats.un.org/sdgs/metadata/>, 2024. Accessed: 14 March 2024.
- [95] G.K. Venayagamoorthy, R.K. Sharma, P.K. Gautam, and A. Ahmadi. Dynamic energy management system for a smart microgrid. *IEEE Transactions on Neural Networks and Learning Systems*, 27:1643–1656, 2016.

- [96] P. Wang, D. Wang, C. Zhu, Y. Yang, H. M. Abdullah, and M. A. Mohamed. Stochastic management of hybrid ac/dc microgrids considering electric vehicles charging demands. *Energy Reports*, 6:1338–1352, 2020.
- [97] X. Wang, O. Bamisile, S. Chen, X. Xu, S. Luo, Q. Huang, and W. Hu. Decarbonization of china’s electricity systems with hydropower penetration and pumped-hydro storage: Comparing the policies with a techno-economic analysis. *Renewable Energy*, 196:65–83, 2022.
- [98] A.J. Ward, P.J. Hobbs, P.J. Holliman, and D.L. Jones. Optimisation of the anaerobic digestion of agricultural resources. *Bioresour. Technol.*, 99:7928–7940, 2008.
- [99] L. Wen, K. Zhou, S. Yang, and X. Lu. Optimal load dispatch of community microgrid with deep learning based solar power and load forecasting. *Energy*, 171:1053–1065, 2019.
- [100] H. Wu, X. Liu, and M. Ding. Dynamic economic dispatch of a microgrid: Mathematical models and solution algorithm. *International Journal of Electrical Power & Energy Systems*, 63:336–346, 2014.
- [101] X. Yu, X. She, X. Zhou, and A. Q. Huang. Power management for dc microgrid enabled by solid-state transformer. *IEEE Transactions on Smart Grid*, 5:954–965, 2014.
- [102] C. Yuan, M. A. Haj-Ahmed, and M. S. Illindala. Protection strategies for medium-voltage direct-current microgrid at a remote area mine site. *IEEE Transactions on Industrial Applications*, 51:2846–2853, 2015.
- [103] J.-H. Zhu, H. Ren, J. Gu, X. Zhang, and C. Sun. Economic dispatching of wind/photovoltaic/storage considering load supply reliability and maximize capacity utilization. *Electr. Power Energy Syst.*, 147:108874, 2023.
- [104] M. Żołądek, A. Kafetzis, R. Figaj, and K. Panopoulos. Energy-economic assessment of islanded microgrid with wind turbine, photovoltaic field, wood gasifier, battery, and hydrogen energy storage. *Sustainability*, 14:12470, 2022.

Chapter Six

Renewable Energy Policy Assessment in
Iraq, Saudi Arabia, and Spain:
A Multi-Dimensional Approach Using
HOMER

Chapter 6

Renewable Energy Policy Assessment in Iraq, Saudi Arabia, and Spain: A Multi-Dimensional Approach Using HOMER

This chapter explores the techno-economic and environmental performance of hybrid microgrid systems (HMGSs) tailored for the Iraqi context. Using HOMER Pro, both grid-connected and off-grid configurations are analyzed to reflect real-world energy challenges, particularly in areas with unreliable electricity access. The study aligns with Iraq's broader energy policy objectives by identifying cost-effective and sustainable system designs. Realistic technical and financial data are applied to key components such as solar PV, batteries, and generators. The findings reveal important trade-offs between system cost, reliability, and emissions, offering practical insights for future microgrid development.

6.1 Introduction

According to the International Energy Agency's (IEA) most recent assessment, the amount of power from renewable energy sources (RESs) added globally is anticipated to increase by a third during the current year due to strong policy momentum, rising fossil fuel prices, and worries about energy security. The energy issue in Europe is being addressed at the forefront by renewables, which is pushing their expansion there. Over the following two years, new policy initiatives will also contribute significantly to growth in the United States and India. Meanwhile, China is maintaining its dominant position and is anticipated to provide over 55% of all new renewable energy (RE) capacity added globally in 2023 and 2024. By

2024, the combined share of wind turbine (WT) and solar photovoltaic (SPV) in several European nations' annual electricity output will surpass 40%, including Spain, Germany, and Ireland [3]. In response to these global trends, several major markets have established key policies aimed at increasing the use of RESs:

- The European Union's (EU) Council has committed to raising RE targets to 42.5% of total energy consumption by 2030, with aspirations to achieve 45% [2].
- China's 14th Five-Year Plan, published in June 2022, has a target of 33% renewable power production by 2025, up from 30% currently.
- The United States passed the Inflation Reduction Act (IRA) in August 2022, which expands support for RE via tax credits and other measures, and is anticipated to considerably raise investments over the following decade.
- India set ambitious targets at COP26 in 2021, aiming for 500 GW of renewable capacity and a 50% share of renewable power by 2030, with net zero emissions (NZE) by 2070 [31].
- Spain has approved a four-year plan to modernize its electrical infrastructure, aiming for 67% of its power to come from renewables by 2026 [1].
- The Egypt-Kingdom of Saudi Arabia (KSA) energy interconnection project aims to exchange up to 3,000 MW of power, aligning with KSA's goal of 50% power generation from natural gas and renewables by 2030, and Egypt's target of 42% renewables by 2035[24].

Climate change, rising fossil fuel prices, and strict energy policies are driving countries toward renewable energy solutions that are both sustainable and economically viable, supported by declining technology costs. In the following sections, this research will highlight global RE trends and the shifting landscape of electricity generation 6.1.1, followed by an in-depth look at the growing electricity demand, particularly in emerging markets 6.1.2, and its far-reaching implications for energy systems worldwide.

6.1.1 Global Renewable Energy Trends and Electricity Generation Insights

According to the IEA, global renewable power capacity increased by 50% in 2023, reaching 507 GW, driven by policy support in over 130 countries and significant growth in China's SPV and WT capacity. Solar and wind are expected to account

for 96% of new installations over the next five years, with total capacity more than doubling by 2028. Renewables are predicted to overtake coal as the primary source of worldwide power production by early 2025, accounting for 42% of total output by 2028, with WT and SPV playing a considerable role. Although hydropower will remain the most important renewable source, a substantial increase in renewable production is required to fulfill future demand. By 2028, renewables are expected to be the primary energy source in 68 countries, accounting for 17% of worldwide demand, as illustrated in figure 6.1 [22].

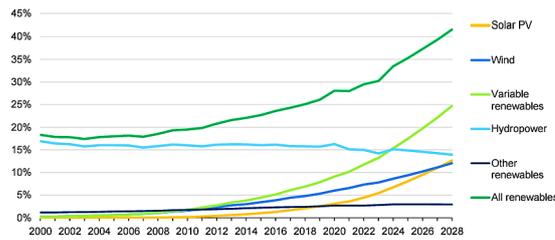


Figure 6.1: share of electricity production by source from 2000-2028 [22]

Furthermore, as shown in Figure 6.2, the rapid expansion of RE is expected to reshape the global power generation mix by 2050, according to three scenarios: STEPS (Stated Policies), APS (Announced Pledges), and NZE.

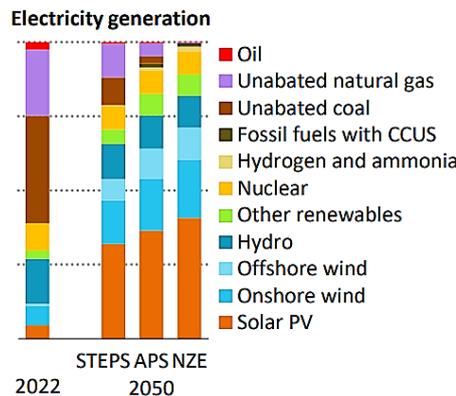


Figure 6.2: Electricity generation mix: 2022 vs. 2050 Scenarios [2]

In all scenarios, reliance on fossil fuels is expected to decline significantly, particularly in the NZE scenario, where SPV and WT will play major roles [2]. On the other hand, in 2022, global investment in SPV grew by 20%, reaching USD 320 billion—three times the investment in fossil fuels. Wind power investment also increased by 20%, totaling USD 185 billion [21]. These trends reflect a strong

global shift toward renewables, with SPV and WT leading the transition as the world moves toward a more sustainable, renewable-powered future. As the global shift to renewables accelerates, rising electricity demand, particularly in emerging markets, presents a key challenge for future energy systems.

6.1.2 Global Electricity Demand

As the world progresses toward universal electricity access, significant strides have been made over the past decade. According to the World Bank, global electricity access rose from 78.4% to 91.4% by 2021 [56]. This progress not only marks a major step toward global electrification but also signals a surge in electricity demand. As shown in Figure 6.3, the IEA projects a significant shift in the geography of global electricity demand growth.

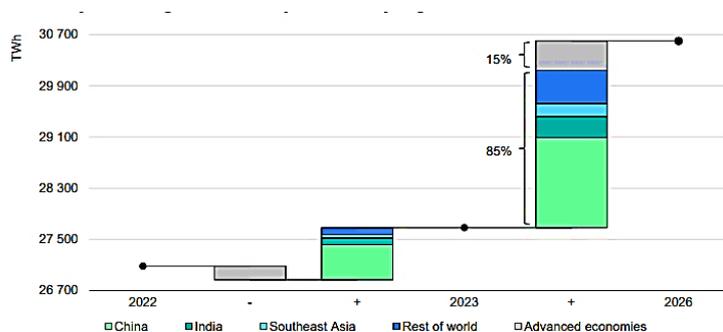


Figure 6.3: Forecasted global electricity demand growth by region (2022-2026) [18].

The graph illustrates that 85% of additional electricity demand through 2026 is expected to come from outside advanced economies, with China, India, and Southeast Asia as the main contributors. Emerging regions show a notable increase by 2023, followed by a dramatic rise in demand by 2026. Advanced economies will account for the remaining 15% of additional global electricity demand. The EU’s electricity demand saw a 6% decline in the industrial sector in 2023, continuing a downward trend influenced by persistently high energy prices earlier in the year, economic slowdown, and excess stock. Although energy prices later dropped from record highs, industrial demand remained weak due to reduced consumer demand, weaker exports, and weather variations. Milder winters and cooler summers further reduced heating and cooling needs. Figure 6.4 illustrates these dynamics, showing the key drivers of change in EU electricity demand from 2021 to 2026 [18].

In summary, global electricity demand saw a modest increase of 2.2% in 2023, slightly lower than 2022’s growth. However, demand is expected to accelerate to

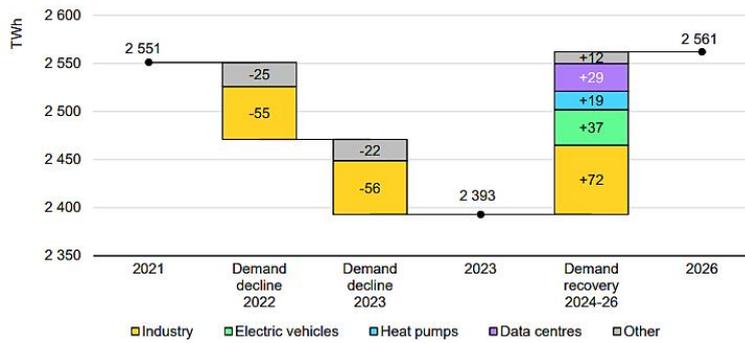


Figure 6.4: Estimated drivers of change in EU electricity demand (2021-2026) [18]

3.4% between 2024 and 2026, primarily driven by burgeoning demand in emerging markets, despite economic pressures and a downturn in advanced economies.

To delve deeper into the RESs transitions of specific countries, this study focuses on KSA, Iraq, and Spain. These countries were selected for their distinct energy profiles and policy approaches. KSA and Iraq, both major oil exporters with significant solar potential, face unique challenges in diversifying their energy sources. In contrast, Spain has emerged as a leader in RE, particularly in the deployment of SPV systems. The goal is to demonstrate how KSA and Iraq can benefit from adopting Spain’s energy policies. The analysis is conducted in two phases, as illustrated in Figure 6.5, evaluating their energy profiles, policies, and potential for transitioning to solar energy.

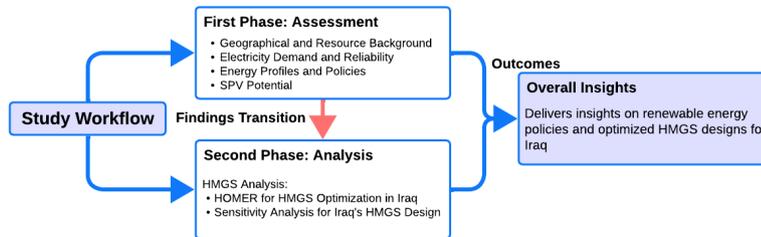


Figure 6.5: Study workflow: assessment and analysis phases

This investigation is based on the recommendations outlined in our previous work [50, 51], which emphasized the need for a detailed examination of the regulatory and policy framework for implementing Hybrid Microgrid Systems (HMGSs) in Iraq. The research aims to identify the necessary policy changes and provide a comparative analysis of Spain’s successful energy policies to facilitate this transition in Iraq and KSA.

First Phase: Assessment

6.2 Geographical and Resource Background: A Comparative Overview

This section provides a comparative overview of the geographical, demographic, and economic aspects of Iraq, KSA, and Spain. Table 6.1 summarizes key data such as total area, population, and natural resources, offering insights into each country’s energy context. These variables are critical for shaping national energy policies and plans, particularly in the realm of RES development. By comparing these aspects, the table highlights how natural resources and demographics influence each country’s approach to energy production, consumption, and sustainability.

Table 6.1: Comparative Overview: Key Country Statistics Influencing Energy Policy

Aspect	Iraq	KSA	Spain	Ref.
Total area (km ²)	434,128.0	2,149,690.0	499,733.2	[54]
Populations (2022)	Total: 44,496.12 Urban: 31,749,763 (71%) Annual growth: 2.2%	Total: 36,408.82 Urban: 30,848.83 (85%) Annual growth: 1.5%	Total: 47,778.34 Urban: 38,845.70 (81%) Annual growth: 1.1%	[55]
Natural resources	Petroleum, natural gas, phosphates, sulfur	Oil, natural gas, iron	Coal, lignite, iron ore, uranium, mercury	[10]
Climate (Summer)	Avg: 35°C - 51°C Peaks up to 47/48°C in northern areas	Avg: 38°C - 55°C Extremely hot and arid	Avg: 18°C - 24°C Warm to hot, coastal areas milder	[15], [16], [17], [11]
Climate (Winter)	Avg: 2°C - 15°C Snowfall in the north	Avg: 17°C - 23°C Cooler in desert areas	Avg: 4°C - 9°C Snow in mountainous regions	[15], [16], [17], [11]
Electric consumption (kWh/capita)	1,244	9,048	5,356	[53]
Access to electricity (% of population)	100%	100%	100%	[56]
Energy Policy Framework	Emerging focus on renewable integration	Vision 2030 for energy diversification	Comprehensive national energy and climate Plan	[34, 52]

The subsections below explain the Electricity Demand and Reliability, as well

as Energy Profiles and Policies for Iraq, KSA, and Spain. This provides a comprehensive understanding of their energy landscapes, covering both their strategies and the demands on their electricity systems.

6.2.1 Electricity Demand and Reliability

In contrast to Spain and KSA, Iraq faces significant reliability issues due to daily power outages. The country’s electric grid has been severely damaged by ongoing wars and conflicts, leading to the collapse of much of its infrastructure. As a result, many citizens rely on neighborhood or private generators to supplement the inconsistent national electricity supply. While these generators provide a temporary solution, they are costly compared to subsidized electricity from the national grid, as discussed in [50]. Figure 6.6 illustrates the electricity consumption across sectors for Iraq, KSA, and Spain. Figure 6.6a shows that Iraq’s electricity consumption is

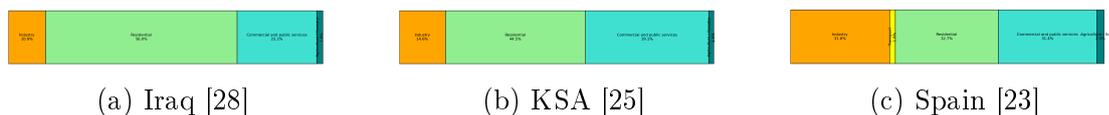


Figure 6.6: Sectoral breakdown of electricity consumption in Iraq, KSA, and Spain (2022).

dominated by the residential sector, which accounts for 56.0% of total consumption, followed by commercial and public services at 23.2%, and industry at 10.9% [28]. The country’s electricity demand is expected to double by 2030, reaching 150 TWh (with an average demand of 17.5 GW). However, Iraq’s infrastructural challenges make it unlikely that this demand will be met without significant investments in the grid and generation capacity [29]. KSA, on the other hand, has seen a steady increase in electricity demand, rising 6% year-over-year from 372 TWh in 2021 to 393 TWh in 2022, with an additional 5% increase expected in 2023. Figure 6.6b illustrates the electricity consumption across sectors, with the residential sector leading consumption in KSA at 44.5%, followed by commercial and public services at 39.1%, and industry at 14.6%. This balanced distribution of electricity use reflects KSA’s diversified energy landscape [25]. However, the growing demand in certain sectors, particularly residential and industrial, is heavily influenced by the country’s Vision 2030 roadmap, which aims to modernize the economy and transition towards a more sustainable energy mix. Spain, in contrast, has a more stable and mature electricity demand profile. In 2023, the country recorded a peak electricity demand of 38,615 MWh in January, reflecting a 2.2% increase compared to the previous winter. However, summer demand in 2023 was 3.1% lower than in 2022, demonstrating Spain’s ability to manage seasonal fluctuations

[46]. The country’s energy policies are enhancing both demand-side efficiency and supply-side diversification through the integration of RESs. The residential sector accounts for 32.7% of total electricity consumption, while industry and commercial services contribute 31.6% and 31.4%, respectively, as shown in Figure 6.6c. Spain’s focus on grid modernization and smart energy management systems ensures the reliability of its electricity supply, even as RESs play an increasingly significant role in the energy mix, as discussed in the section below on Energy Profiles and Policies.

6.2.2 Energy Profiles and Policies

Energy Profiles

The energy profiles of Iraq, KSA, and Spain have evolved significantly over time. Figure 6.7 illustrates the shifts in electricity generation for each country between 2011 and the most recent available data, highlighting the increasing roles of natural gas and RESs. These changes are largely driven by national energy policies that focus on sustainability, diversification, and economic growth.

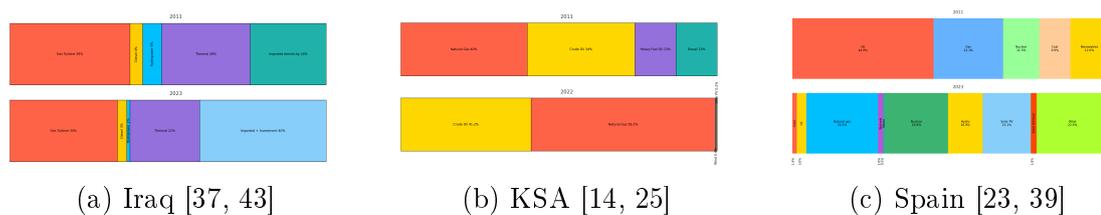


Figure 6.7: Evolution of electricity generation mix in Iraq, KSA, and Spain (2011 vs. most recent data).

Figure 6.7a shows the energy profile of Iraq, which has historically been dominated by natural gas and oil. In 2011, gas turbines accounted for 38% of electricity generation, while thermal power and imported electricity also played significant roles, contributing 28% and 24%, respectively, with diesel and hydropower each contributing 4% and 6% [37]. However, by 2023, there has been a shift in the energy mix. Gas turbines now contribute 34%, while the combined share of imported electricity and investment stations has increased to 40%. The contribution of thermal power has reduced to 22%, while hydropower’s share has decreased to 1%, reflecting the challenges posed by reduced river levels. Diesel continues to play a small role, contributing 3% to the mix. It is evident that Iraq is still heavily reliant on fossil fuels, with limited adoption of RESs[43]. Figure 6.7b illustrates KSA’s energy profile, which in 2011 relied heavily on heavy fuel oil and crude oil (47%) and natural gas (40%) [14]. By 2022, the share of natural gas had increased

to 58.2%, while the share of oil dropped to 41.2%. The KSA’s energy transition is aligned with its Vision 2030, focusing on reducing reliance on oil and expanding the role of gas and RESs. However, despite some progress, renewables remain underdeveloped in the electricity mix, with only a small recorded portion in 2022: 0.2% from SPV and 0.4% from WT [25].

Spain’s energy profile, shown in Figure 6.7c, has shifted significantly towards renewables. In 2011, fossil fuels like oil and natural gas dominated with shares of 44.9% and 22.1%, while renewables contributed just 12% [39]. By 2023, WT and SPV made up 37.6% of electricity generation, with hydropower and solar thermal adding 10.9% and 1.8%. This growth in renewables led to a sharp decline in oil’s share from 44.9% to 3%, and coal also saw a significant drop. According to Red Eléctrica’s data (Figure 6.8), regional contributions played a crucial role in this shift.

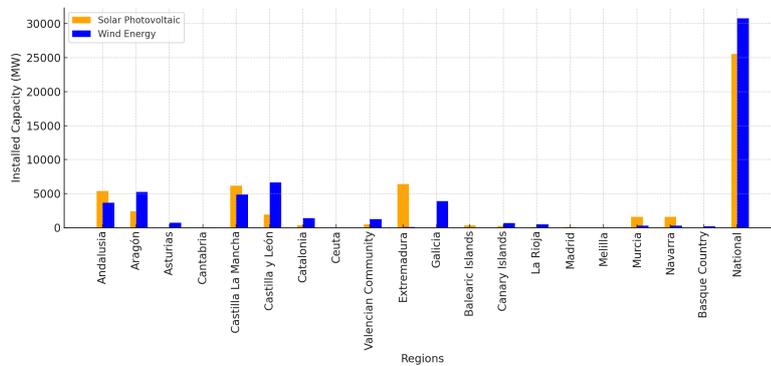


Figure 6.8: Regional breakdown of SPV and WT energy capacity in Spain, 2023 [46].

Andalusia, the third-largest region in installed renewable capacity, reached 11,100 MW, with renewables making up 58.7% of its generation mix. It added 1,170 MW of new SPV capacity, representing 21.1% of Spain’s total SPV capacity. Castilla-La Mancha led the country in new renewable installations, adding 2,121 MW and bringing its total to 12,120 MW (with 83.8% of its mix being renewable), including 6,134 MW of SPV, which accounts for 24.0% of the national total. Castilla and León remained the leader in renewable capacity with 13,046 MW, where wind power dominates, comprising 48.8% of the regional mix. In Aragón, wind power increased by 211 MW, while SPV grew by 551 MW, now representing 20.6% of its generation capacity. Extremadura continues to lead in SPV, reaching 6,410 MW of installed capacity, while Galicia boasts 7,729 MW of RE, representing 70.6% of its total generation capacity. Other notable regions include Catalonia with 31.1% renewables, the Balearic Islands with 45.3% growth in SPV, and the Canary Islands, where renewables now account for 27.3% of installed capacity

[46]. Spain's transition is driven by policies aimed at achieving 100% renewable electricity and climate neutrality by 2050 [23].

Energy Policies

Following the assessment of energy profiles, the energy policies of each country are heavily influenced by their resources and strategic goals:

Iraq: Iraq's energy policy focuses on sustaining oil and gas production while beginning to diversify towards RESs, with the goal of reaching 5% of total capacity from renewables by 2030 [27]. Despite strong potential for solar energy, the country's energy strategy remains largely focused on oil for the time being. However, the Ministry of Electricity Law No. 53 of 2017, approved in the Official Gazette (Al-Waqai 4443 dated 4/17/2017), specifically highlights in Article II, Paragraph 5, the government's commitment to support and encourage the use of RE across various sectors and to localize RE industries within the country [38]. This legal framework represents Iraq's initial steps towards fostering a RE market, though significant challenges remain in scaling up renewable projects.

KSA: As part of Vision 2030, KSA's energy policy focuses on diversifying its economy and transitioning to clean energy. NEOM, a \$500 billion futuristic city, will be fully powered by RE, with an emphasis on green hydrogen and sustainability [42]. SPARK (King Salman Energy Park), launched in 2021, supports clean energy infrastructure and the development of sectors like oil, gas, and renewables [5]. The Exploration Enablement Program (EEP), with a SAR 685 million budget, promotes mineral exploration for critical resources like copper and lithium, aiding the energy transition. Energy efficiency measures in buildings and transport, alongside investments in natural gas and renewables, also play a central role in reducing oil dependency [26, 44].

Spain: Spain is at the forefront of the energy transition, aiming for climate neutrality by 2050 with 100% renewable electricity and 97% RE overall. The policy emphasizes the expansion of solar, WT, and renewable hydrogen, alongside improving energy efficiency and electrification, while driving economic growth, energy security, and innovation [32]. Several key laws underpin this transition to RE:

- Electricity Industry Law 24/2013: Governs Spain's electricity market, ensuring efficient, secure supply while integrating REsources [7].
- Law 8/2011 for Critical Infrastructure Protection: Safeguards essential infrastructure like the electricity grid against threats, ensuring reliable supply during emergencies [20].
- National Energy and Climate Plan (2021-2030): Sets ambitious targets to

reduce greenhouse gas emissions, increase renewable capacity, and improve energy efficiency [30].

- National Climate Change Adaptation Plan: Focuses on addressing risks to energy infrastructure from climate change, such as hydropower shortages and extreme weather [35].
- Royal Decree 43/2021: Strengthens cybersecurity for energy systems, aligning with EU standards to protect against cyberattacks [9].

Royal Decree 244/2019 on Self-Consumption of Electricity has revolutionized RE adoption by [8]:

- Net Metering: Allows consumers to sell surplus electricity to the grid, providing financial incentives.
- Simplified Installation: Eases the process for installing solar systems, particularly for small-scale users.
- Elimination of the "Sun Tax": Removes fees on self-generated solar energy, making solar more accessible.

These laws, along with financial support and regional subsidies, have significantly boosted RE adoption in Spain, enabling consumers to contribute to the national grid. KSA and Iraq, both rich in solar resources, could benefit from adopting similar policies, particularly Spain's Royal Decree 244/2019. The recent global reduction in SPV costs [41] further enhances the opportunity for KSA and Iraq to accelerate their transitions to RE, allowing them to maximize their significant solar potential, as discussed in the following section on SPV potential. By implementing policies that promote renewable technologies, encourage personal energy production for direct use, and facilitate grid integration, these nations can better capitalize on this potential.

6.2.3 SPV Potential in Iraq, KSA, and Spain

Figure 6.9 displays long-term average power production statistics (1999-2018 for Iraq and KSA, 1994-2018 for Spain) and solar energy potential across these countries. The maps use a gradient from yellow to red, with red indicating the highest solar potential [47].

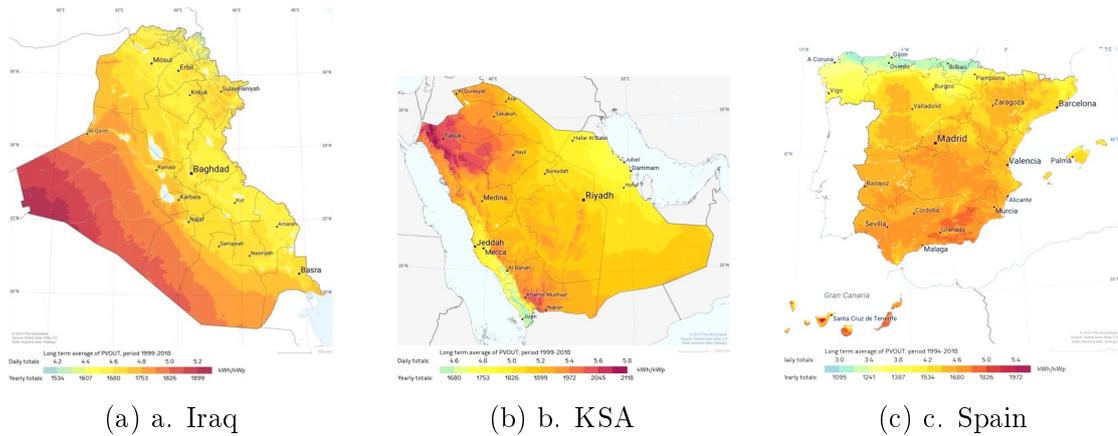


Figure 6.9: SPV power potential in Iraq, KSA, and Spain [47]

The following is an analysis of the solar energy potential in Iraq, KSA, and Spain, as depicted in Figure 6.9:

Iraq: The map in Figure 6.9a highlights Iraq’s strong solar potential, particularly in its western regions. Daily SPV production ranges from 4.2 to 5.2 kWh/kWp, and annual output from 1,534 to 1,899 kWh/kWp. The Global Horizontal Irradiance (GHI) values range from 4.8 to 6 kWh/m² daily, with annual totals between 1,753 and 2,191 kWh/m², indicating significant solar development opportunities.

KSA: As illustrated in Figure 6.9b, KSA’s northwest region demonstrates remarkable solar capacity, with daily SPV production reaching up to 5.8 kWh/kWp and annual totals between 1,680 and 2,118 kWh/kWp. GHI data shows daily values of 5.6 to 6.6 kWh/m², supporting the case for large-scale solar projects.

Spain: The map in Figure 6.9c reveals high solar potential in Spain’s southern regions, especially Andalusia. Daily SPV outputs range from 4.6 to 5.4 kWh/kWp, and yearly totals from 1,680 to 1,972 kWh/kWp. The GHI data correlates with this, showing daily values of 5.4 kWh/m² and annual totals from 1,241 to 1,972 kWh/m². The map confirms that Spain’s southern areas are prime candidates for solar energy development. In all three countries, Iraq’s western areas, KSA’s northwest, and Spain’s southern regions stand out as optimal locations for SPV investments. The maps in Figure 6.9 visually emphasize these prospects, with GHI data reinforcing the solar potential for energy development. Solar energy, known for its abundance and environmental friendliness, has taken the lead among RESs. Figure 6.10 outlines the three primary solar energy capture technologies: SPV, Concentrated Solar Power (CSP), and Solar Heating and Cooling. These technologies highlight the wide range of applications for solar energy, reinforcing its potential as a key driver of RE transitions.

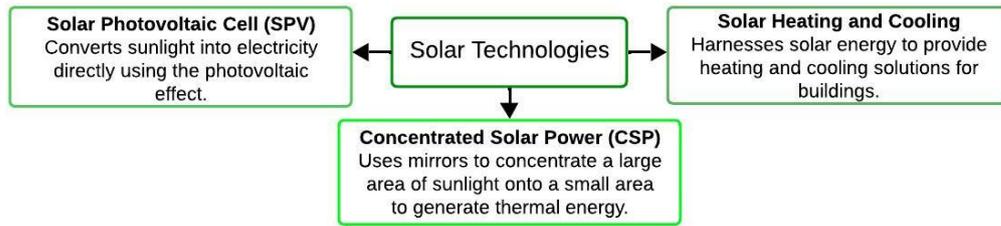


Figure 6.10: Solar energy technologies varieties

With the most rapid expansion in capacity of all RESs in recent years, SPV presently provides 3.6% of worldwide power, ranking third-largest renewable source [21]. Although RESs offer significant environmental and economic benefits, their reliance on weather conditions, such as solar radiation and wind speed, presents challenges, leading to fluctuations in power output. To mitigate this variability, RESs are integrated with storage solutions and/or conventional sources like diesel generators (DG), forming hybrid energy systems (HESs) [13]. These systems maintain power stability, even during RE fluctuations. Additionally, microgrids (MGs), capable of operating independently or alongside the main grid, enhance energy management and resilience. This integration into hybrid microgrid systems (HMGSs) ensures consistent, reliable power under varying conditions [49]. Optimizing HMGSs is vital for reducing installation costs and ensuring a reliable power supply. Effective operation depends on appropriate sizing, simulation, and optimization methods, which are essential for evaluating and maximizing resource use. These approaches play a crucial role in addressing system challenges, improving efficiency, and contributing to a more balanced and sustainable energy sector [51]. Following the assessment phase, the next section transitions to the analysis phase, where HOMER is employed to optimize HMGS configurations in Iraq and analyze real-world energy data from Spain. This phase focuses on addressing energy challenges, evaluating performance, and identifying cost-effective and sustainable solutions.

Second Phase: Analysis

6.3 HMGS Analysis: Iraq Optimization with HOMER

This section examines the optimization of HMGSs in Iraq using HOMER, focusing on addressing the country's unique energy challenges, such as frequent power outages, high demand, and limited renewable infrastructure.

6.3.1 Application of HOMER for HMGS Optimization in Iraq

To contextualize the use of HOMER for HMGS optimization, Table6.2 provides a comparative analysis of HMGSs studied in regions with conditions similar to Iraq. These studies address challenges such as extreme weather, reliability issues, and renewable integration, offering insights that guide this research.

Table 6.2: Case Studies of HMGS Optimization in Comparable Conditions to Iraq

Location	HMGS Configuration	Description	COE (\$/kWh)	Ref.
Northern Nigeria	SPV/DG/BT	Techno-economic assessment of HMGS for a rural health clinic, reducing CO ₂ emissions by 80% (1304 kg/year) compared to DG-only systems.	0.259	[45]
Bangladesh	SPV/DG/BT	Techno-economic analysis of HMGSs to identify cost-effective and environmentally sustainable configurations for different regions of Bangladesh.	0.280 - 0.284	[12]
Case1:Rotterdam, Netherlands Case2:Guwahati, India	Case 1: SPV/WT/BT Case 2: SPV/BT	1: EV charging stations using RES, reducing emissions and energy costs.	Case1: 0.450 Case2: 0.476	[33]
Spain, Mountain	Hydro/HSS/BT	Techno-economic and environmental assessment of a stand-alone energy system for a mountain hut. The optimal configuration (Hydro plant/hydrogen energy storage (HSS)/BT) reduces environmental impacts by 70% compared to diesel-based systems and ensures energy sustainability in remote, sensitive environments.	NA	[40]
Iran (Educational Building)	Case 1: SPV/WT/Grid Case 2: SPV/WT/Grid/DG	1: A techno-economic analysis of HMGSs for an educational building in Iran shows that Case 1 is more cost-effective and environmentally friendly than Case 2. Wind turbines reduce costs, while inflation and fuel prices impact system configuration.	Case 1: 0.0024 Case 2: 0.0272	[48]
Egypt (Qena and Hurghada)	SPV/WT/BT/HES with DSM SPV/WT/BT without DSM	A system with hydrogen energy storage (HES) and demand-side management (DSM) significantly reduces costs and CO ₂ emissions while improving sustainability. Post-DSM systems achieve the lowest NPC and CO ₂ emissions (0.275 kg/year in Qena, 0.0666 kg/year in Hurghada) with higher hydrogen production (953 kg/year in Qena, 850 kg/year in Hurghada).	NA	[57]
Saudi Arabia	SPV-WT-DG-BT SPV-DG-BT	A techno-economic analysis evaluates a standalone HMGS for telecom towers in Saudi Arabia. The proposed system, integrating SPV-BT-DG, significantly reduces costs (LCOE: 0.18/kWh vs. 0.46/kWh in conventional systems) and CO ₂ emissions (by 37,326 kg/year), making it a cost-effective and environmentally sustainable solution.	0.46–0.18	[6]
Lombok Island, Indonesia	System 1: DG/Grid System 2: SPV/BT (Off-grid)	Comparative analysis of resilience-based energy systems for critical hospital loads during outages. System 2 is more environmentally friendly, while System 1 is more cost-effective. Both systems enhance resilience under outage conditions.	System 1: 0.1520 System 2: 0.2151	[4]

The insights from these case studies underscore HOMER’s role in optimizing HMGSs across diverse conditions. By evaluating key factors such as cost-effectiveness, environmental impact, and system resilience, these studies establish a foundation for designing HMGS configurations tailored to Iraq’s specific challenges.

The flowchart in Figure 6.11 illustrates the general process for optimizing HMGS using HOMER. It outlines the key steps involved, including gathering

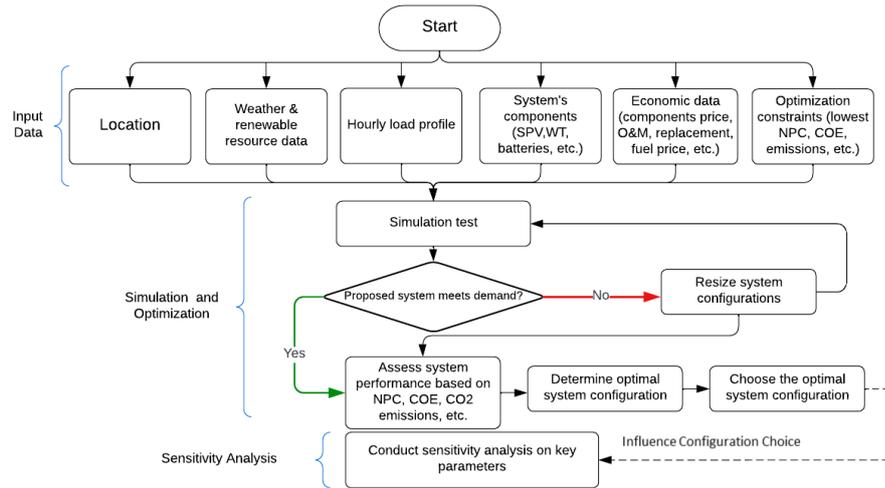


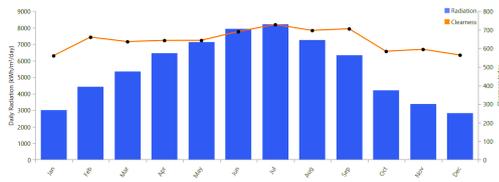
Figure 6.11: Workflow of HOMER simulation and optimization

input data, running system simulations, and performing both optimization and sensitivity analysis. The process begins with data gathering, as follows:

6.3.2 Input Data

The accuracy of input data is crucial for ensuring reliable simulation results. This study carefully selected data to represent realistic conditions for the Iraq case study, specifically focusing on Anbar (33° 4.6' N, 41° 34.0' E), a region with significant solar energy potential [19].

- a. Site Selection and Weather Resource Data: Weather resource data, including solar Global Horizontal Irradiance (GHI) and temperature (shown in Figure 6.12), was obtained from the latest PVGIS (2023) database to ensure high accuracy.



(a) Monthly Average Solar GHI for Anbar [19]



(b) Monthly Average Temperature for Anbar [19]

Figure 6.12: Monthly average solar GHI and temperature data for Anbar, Iraq (PVGIS, 2023).

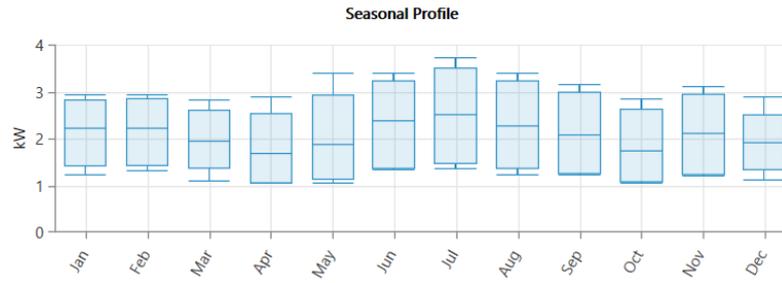
Anbar’s solar resource analysis in HOMER Pro software revealed:

- Annual Average Solar Radiation: 5.539 kWh/m²/day.
- Monthly Peaks: June and July exceed 8 kWh/m²/day, while December records the lowest at 2.8 kWh/m²/day.
- High Clearness Index: Optimal conditions for solar energy generation.
- Annual Average Temperature: 25.13°C, with monthly peaks in July and August exceeding 37°C and the lowest temperatures in January at 10.8°C.

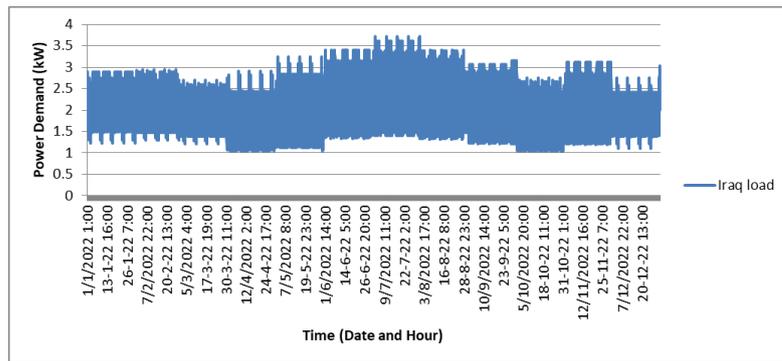
This data underscores Anbar’s potential as a prime location for solar energy applications, leveraging its abundant solar radiation and suitable climatic conditions.

- b. Load Profile: In this study, the load profile of a typical Iraqi household was utilized for the selected site. This profile was derived from our previous study, where the Rosetta time transformation method was applied to approximate realistic energy consumption patterns [49].

Figure 6.13a shows the seasonal load profile, highlighting monthly variations, while Figure 6.13 presents the yearly load profile, illustrating the hourly electricity demand across the entire year. In both figures, summer months (June–August) show increased demand due to cooling requirements. The average daily consumption is 50.24 kWh/day with a peak demand of 3.71 kW, and the load factor of 0.56 indicates moderate variability in demand.



(a) Seasonal electricity demand profile of a typical Iraqi household



(b) Yearly electricity demand profile of a typical Iraqi household

Figure 6.13: Seasonal and yearly load profiles of a typical Iraqi household.

c. Grid Availability and Outage Data: Grid availability across various provinces in Iraq during August 2020 was analyzed, as shown in Figure 6.14. The data, derived from daily reports provided by the Iraqi Ministry of Electricity [36], demonstrate significant regional disparities in grid performance.

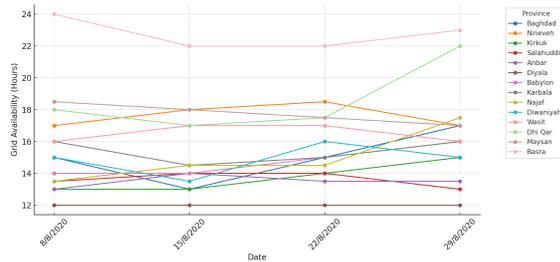


Figure 6.14: Grid availability analysis by province in Iraq during August 2020

Provinces such as Basra and Dhi Qar experienced high grid availability, consistently providing electricity for up to 22–24 hours per day. In contrast,

other provinces such as Diyala, Baghdad, and Anbar saw fluctuations in their grid availability, typically ranging between 12 and 18 hours. This variability is indicative of the inconsistent electricity supply across Iraq during this period, underscoring the need for sustainable solutions to address regional electricity demands. In this study, the grid availability, as well as the frequency and duration of power outages in Anbar Province, were carefully analyzed. The grid outages were simulated using data derived from historical grid disruptions, which are common in certain regions, and integrated into the HOMER Pro model. Figure 6.15 illustrates the typical daily grid outages for Anbar Province, where the black areas represent periods of power failures throughout the year.

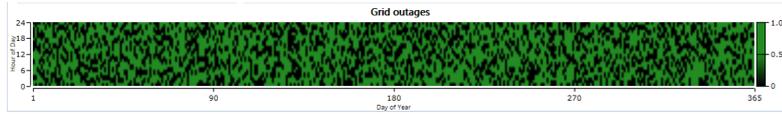


Figure 6.15: Grid outages simulation for Anbar province.

These outages were represented as random events that occur during the year-long simulation. The grid outage parameters for Anbar were defined by a mean outage frequency of 1,800 occurrences per year, with an average repair time of 2 hours for each outage. Additionally, to account for the natural fluctuations in restoration time, the repair time variability was set at 5%. The outages were generated by selecting random time steps throughout the year, with the duration of each outage determined using a normal distribution based on the specified mean repair time and its variability. These outage occurrences, along with their respective durations, play a critical role in accurately modeling the real-life challenges related to grid stability in Anbar. Electricity tariffs in Iraq are determined by the Ministry of Electricity, following an increasing block pricing structure where the cost per kWh rises with higher monthly consumption levels, as shown in Table 6.3.

Table 6.3: Electricity prices in Iraq (national grid) [36]

Electricity consumption (kWh)	Value (Iraqi Dinar/kWh)	Value (\$/kWh)
1-1500	10	0.0084
1501-3000	35	0.0293
3001-4000	80	0.0672
>4000	120	0.1008

Currently, Iraq does not have a net metering system, feed-in tariffs, or smart meters to track electricity consumption and sales in real-time. However, to make this study more comprehensive, a hypothetical sellback scenario has been introduced, where excess electricity—if a mechanism existed to return it to the grid—is sold back at 50% of the grid purchase price. The assumed electricity rates used in the HOMER simulation are illustrated in Figure 6.16, which visualizes how electricity prices vary throughout the day and across different seasons.

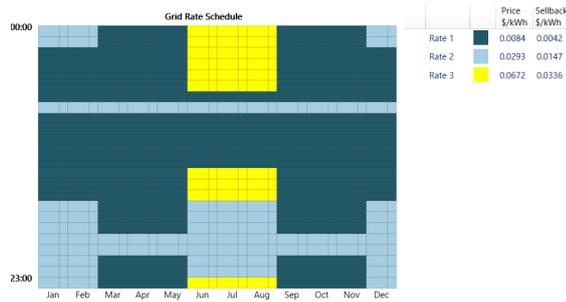


Figure 6.16: Monthly variation of daily grid electricity rates.

Higher electricity prices occur during peak demand periods, particularly in the summer months (June–August), when cooling demand significantly increases residential electricity consumption.

- d. System Components: Figure 6.17 presents the schematic diagram of the HMGS considered in this study, modeled in HOMER Pro.

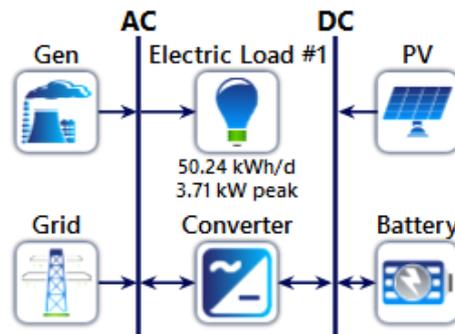


Figure 6.17: HMGS configuration in HOMER.

The system comprises five primary components—the Grid, Generator (Gen), PV, Battery, and Converter—all interconnected to supply an electric load

of 50.24 kWh/day with a peak demand of 3.71 kW. In this configuration, the Generator (Gen) is a gasoline generator, providing backup power when the grid is unavailable or insufficient. Moreover, the system was simulated in both on-grid and off-grid modes to evaluate its performance and cost-effectiveness under varying grid connectivity conditions. The HOMER Pro software simulates various dispatch strategies to determine the optimal way to balance supply and demand while minimizing costs and ensuring reliability.

- e. Economic data: To support the economic analysis, detailed cost data were compiled for each major system component; the following section outlines the cost assumptions for the HMGS components.

- **SPV Component Costs and Assumptions:** The cost of SPV components (including the converter, installation, wiring, and panels) was derived from our previous work [49], using the regression function shown in Figure 6.18.

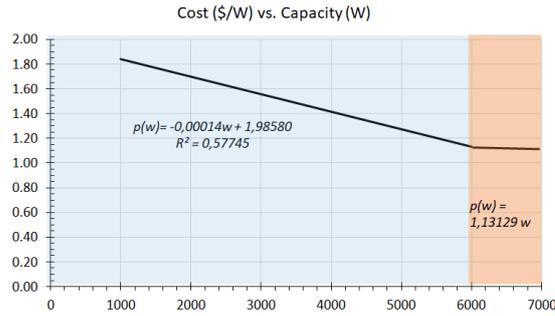


Figure 6.18: Variation of installation cost per Watt with SPV capacity.

The black line represents a linear regression ($p(w) = -0.00014w + 1.98580$, $R^2 = 0.57745$), and the orange-shaded region from 6000 W to 7000 W illustrates extrapolation. At 7000 W, the model estimates a cost of approximately \$1.13 per W.) From this analysis, the total cost per kilowatt of PV capacity is \$1,145/kW, which includes \$600/kW for panels, wiring, and meters. The replacement cost is set at \$600/kW, with O&M of \$10/year and a 25-year system lifetime. For the inverter, the capital cost is \$500, the replacement cost is \$500, O&M is \$20/year, the lifetime is 15 years, and the efficiency is 95%. Finally, HOMER's built-in optimizer is employed to determine the optimal SPV capacity, accounting for both capital and ongoing expenses to achieve realistic economic modeling of the SPV system.

- **Gasoline Generator:** The system employs a gasoline generator operating at 95% efficiency with a rated capacity of 3.5 kW and an initial capital cost of \$1,100. It consumes gasoline at a rate of 0.395 Kg/kWh, with the fuel priced at \$0.31 per liter. In addition, the replacement cost is set at \$1,100, its lifetime is 15,000 hours, and the operation and maintenance (O&M) cost is \$0.05 per hour. These specifications and cost assumptions are based on our previous study [49].
 - **Battery (Trojan SAGM 12 205):** A sealed AGM battery with a nominal voltage of 12 V and a nominal capacity of 205 Ah (maximum capacity 219 Ah). Modeled in HOMER using the kinetic battery model, it has an initial state of charge (SOC) of 100% and a minimum SOC of 20%. The battery's lifetime throughput is 2,285.10 kWh. Capital and replacement costs are \$538 and \$500, respectively, while O&M costs are \$ 8/year, based on our previous study. This configuration ensures reliable deep-cycle performance for the HMGS, and the battery is allowed to charge from the grid at a different rate whenever the grid is available.
- f. **Optimization Constraints:** In HOMER Pro, several optimization constraints were applied to ensure both system reliability and a significant share of renewable energy:
- **Maximum Annual Capacity Shortage:** Set to 1%, meaning the system must supply at least 99% of the total annual load.
 - **Minimum Renewable Fraction:** Fixed at 50%, requiring that at least half of the system's total energy production come from renewable sources.
 - **Operating Reserve Requirements:**
 - (a) 10% of the load in the current time step to account for sudden demand increases.
 - (b) An additional 5% of the annual peak load for broader reliability.
 - (c) 30% of solar output to cover variability in SPV generation.

These constraints guide the optimization process by ensuring sufficient reserve capacity to handle fluctuations in load and renewable output, while also enforcing a target level of renewable penetration.

6.3.3 Simulation and Optimization

A total of 2,807 potential configurations were simulated by HOMER Pro, of which 1,190 were identified as feasible solutions. However, 709 solutions were discarded due to capacity shortage constraints, while 1,054 solutions failed to meet the minimum renewable fraction requirement. Table 6.4 presents the optimization results

for both on-grid and off-grid system configurations, highlighting key economic and technical indicators such as NPC, LCOE, renewable fraction, battery autonomy, and fuel consumption. These results illustrate the economic and operational trade-offs between system configurations and underscore the importance of appropriate sizing and component selection for HMGSs.

Table 6.4: Key Optimization Results for Hybrid Microgrid Configurations

Architecture	PV Capacity (kW)	Battery Units (Numb.)	NPC (\$)	LCOE (\$/kWh)	Renewable Fraction (%)	Dispatch Strategy	Energy Sold (kWh/yr)
Grid-connected							
SPV-Gen-Battery-Grid	6.88	4	26,305	0.0967	50.0	LF	2,390
SPV-Gen-Grid	8.94	0	27,953	0.0893	50.0	CC	5,516
SPV-Battery-Grid	8.82	12	30,039	0.1160	65.6	LF	1,581
Off-grid							
SPV-Gen-Battery	7.08	7	47,816	0.1990	55.4	LF	0
SPV-Battery (Off-grid)	13.90	23	57,606	0.2410	100.0	CC	0

The following subsections discuss each configuration in detail, based on the extensive analysis provided by HOMER Pro, considering economic, environmental, and technical perspectives.

1. Case 1: SPV-Gen-Battery-Grid (6.88 kW PV, 4 Batteries, Grid-Connected, Load Following)

Economic Analysis This configuration achieves the lowest NPC of \$26,305 and a competitive LCOE of \$0.0967/kWh, making it an economically viable solution. The total initial capital cost is \$8,446, with the gasoline generator contributing the largest share at \$11,419, primarily due to fuel expenses and maintenance, followed by battery storage at \$6,337, the SPV at \$4,257, the converter at \$880, and grid connection costs of \$1,929. Operating costs are significantly influenced by fuel expenses amounting to \$8,507 over the system lifetime, highlighting the system’s dependence on the gasoline generator despite a substantial share of RE integration.

Energy Production and Consumption

The system achieves a total annual electricity production of 23,201 kWh/year, with contributions as follows:

- **SPV System:** 12,838 kWh/year (55%)
- **Grid Purchases:** 6,871 kWh/year (29%)
- **Gasoline Generator:** 3,491 kWh/year (15%)

Despite the SPV share exceeding 50%, the effective renewable fraction remains at 50% because part of the SPV generation is either lost as excess electricity (1,654 kWh/year) or sold to the grid (2,390 kWh/year). The renewable fraction only considers the portion of RE that directly meets the load, not total generation. The SPV system operates consistently throughout the year, though slightly lower in winter months due to seasonal variations, as illustrated in Figure 6.19.

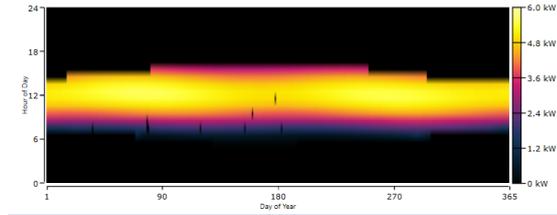


Figure 6.19: SPV power output.

Battery Performance

The system includes four Trojan SAGM 12 205 batteries, providing a nominal capacity of 10.5 kWh, with a usable capacity of 8.41 kWh and an autonomy of 4.01 hours. The battery's lifetime throughput is 9,140 kWh. The state of charge (SOC) analysis indicates effective cycling, ensuring reliable backup power during periods of low solar generation.

Generator Fuel Consumption & Utilization The generator operates for 1,483 hours per year with 764 start cycles annually, reflecting moderate utilization. It has a mean electrical output of 2.35 kW and a capacity factor of 11.4%. Over the system's lifetime, the generator consumes a total of 2,091 liters of fuel per year, with an average daily consumption of 5.73 liters, as shown in figure 6.20.

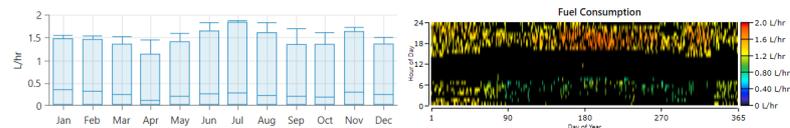


Figure 6.20: Monthly generator fuel consumption and operational heatmap

As illustrated in Figure 6.20, generator fuel consumption is highest during the summer months (June–August), coinciding with peak cooling demands. The heatmap further demonstrates that generator operation is primarily concentrated during nighttime hours when SPV production is minimal.

Dispatch Strategy: Load Following (LF) The system employs a Load Following (LF) dispatch strategy, ensuring that:

- The generator only runs when SPV and battery storage are insufficient, reducing unnecessary fuel use.
- Battery charging is prioritized for immediate demand, extending battery life.
- Grid interaction is optimized, importing energy when required and selling excess production, as depicted in Figure 6.21.

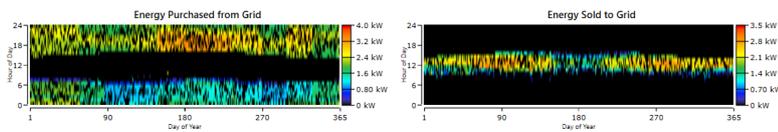


Figure 6.21: Grid interaction: energy purchased and sold over a year

The left panel of Figure 6.21 illustrates the energy purchased from the grid, while the right panel shows the energy sold, highlighting how the Load Following strategy balances supply and demand.

This strategy minimizes fuel costs while maximizing RE utilization, making it suitable for HMGS with grid access.

Environmental Impact While this system significantly integrates RE, generator reliance results in moderate emissions:

- CO₂: 7,653 kg/year
- CO: 34.2 kg/year
- SO₂: 13.3 kg/year
- NO_x: 38.1 kg/year

These emissions, while lower than fully gasoline-dependent systems, emphasize the need for further improvements in renewable penetration to minimize fuel consumption and environmental impact.

Final Considerations While this system balances economic feasibility and operational efficiency, its high fuel consumption makes it suboptimal for long-term sustainability. Increasing SPV capacity or optimizing battery storage could reduce grid dependence and generator reliance. Additionally, at the end of the system's lifetime (year 25), a salvage value of \$386 is accounted for, slightly reducing the final net cost.

2. Case 2: SPV–Gen–Grid (8.94 kW SPV, 3.50 kW Generator, Grid-Connected, Cycle Charging (CC))

Economic Analysis

This configuration incurs a slightly higher NPC of \$27,953 compared to Case 1, with an LCOE of \$0.0893/kWh, which is lower due to a reduced dependency on the gasoline generator and a higher share of grid-supplied electricity, which is typically more cost-effective. The total capital cost is \$7,709, with the main cost contributors being the gasoline generator (\$18,073), the SPV (\$5,495), and the grid connection charges (\$1,636). Fuel expenses amount to \$13,319 over the system lifetime, making it a significant operational cost.

Energy Production & Consumption

The system generates a total of 28,615 kWh/year, with SPV contributing 16,692 kWh/year (58.3%), the gasoline generator 5,121 kWh/year (17.9%), and grid purchases 6,802 kWh/year (23.8%). While SPV has a higher share than in Case 1, grid purchases remain substantial. The system exports 5,516 kWh/year to the grid, yet excess energy amounts to 4,136 kWh/year, suggesting that battery integration could enhance energy utilization.

Generator Performance & Fuel Consumption

The generator operates 2,618 hours per year, significantly more than in Case 1, leading to higher fuel consumption of 3,274 liters per year (8.97 L/day). The increased reliance on the generator despite higher PV capacity raises operational costs and emissions, reducing overall system efficiency.

Dispatch Strategy: Cycle Charging (CC) In Case 2, the system follows the HOMER Cycle Charging (CC) strategy, where the gasoline generator operates when required, prioritizing supplying the load while utilizing any excess generation to feed into the grid. Unlike a battery-supported system, this configuration lacks energy storage, leading to a higher reliance on the generator and more frequent grid interactions. As a result, the generator operates for 2,618 hours per year, producing 5,121 kWh/year, with a significant fuel consumption of 3,274 liters annually. While this approach ensures stable power availability, it leads to higher operational costs and increased emissions (8,361 kg of CO₂ per year), making it less optimal compared to battery-integrated solutions.

Environmental Impact Higher gasoline generator usage results in increased emissions compared to Case 1, with CO₂ emissions reaching 8,361 kg/year, alongside 53.5 kg of CO, 5.18 kg of SO₂, and 52 kg of NO_x. While this configuration reduces emissions compared to fully generator-dependent systems, it remains suboptimal due to excessive reliance on fossil fuel combustion.

Final Considerations While this configuration benefits from lower LCOE and increased SPV generation, its heavy reliance on the gasoline generator makes it less optimal than a battery-integrated system. The inefficiencies in energy utilization and high operational costs due to fuel consumption indicate that a hybrid system with batteries would be more cost-effective and environmentally friendly.

3. Case 3: SPV–Battery–Grid, Load Following (LF) (Optimal Configuration)

Economic Analysis

This configuration incurs an NPC of \$30,038 with an LCOE of \$0.1157/kWh. The total initial capital cost is \$12,764, primarily driven by the battery bank investment. The major cost contributors include battery storage at \$20,200, followed by the SPV at \$5,495, grid connection at \$1,970, and the system converter at \$778. Despite the high upfront cost, this system offers long-term savings by eliminating generator fuel expenses and maximizing RE utilization.

Energy Production & Renewable Penetration The system generates a total of 23,277 kWh/year, with the SPV system contributing 16,472 kWh/year, representing 70.8% of the total generation—the highest share among all cases. Figure 6.22 illustrates the SPV power output distribution throughout the year. The color gradient represents power output intensity, with peak solar generation occurring during midday. Seasonal variations are also evident, with slightly reduced output in winter months due to lower solar irradiance.

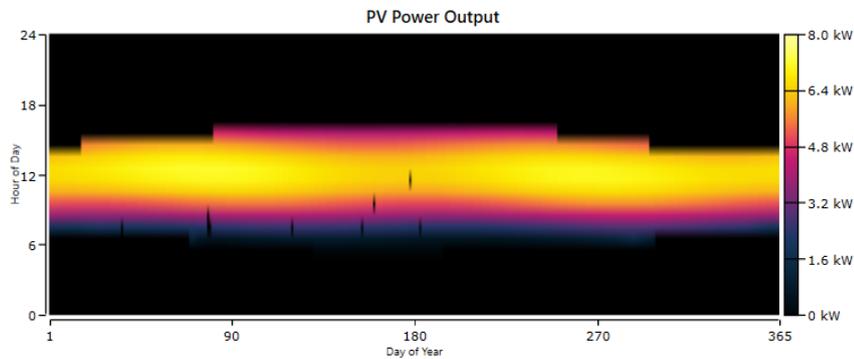


Figure 6.22: SPV power output throughout the year, showing daily and seasonal variations.

However, grid purchases still account for 6,805 kWh/year (29.2%), indicating a notable dependence on external energy sources. The renewable fraction

reaches 65.6%, marking a significant improvement over Case 1 (50%) and Case 2 (50%). Additionally, 1,581 kWh/year is exported back to the grid, while excess energy amounts to 1,937 kWh/year, suggesting that further optimization of storage or load management could enhance renewable energy utilization. Figure 6.23 illustrates the instantaneous renewable output divided by the load.

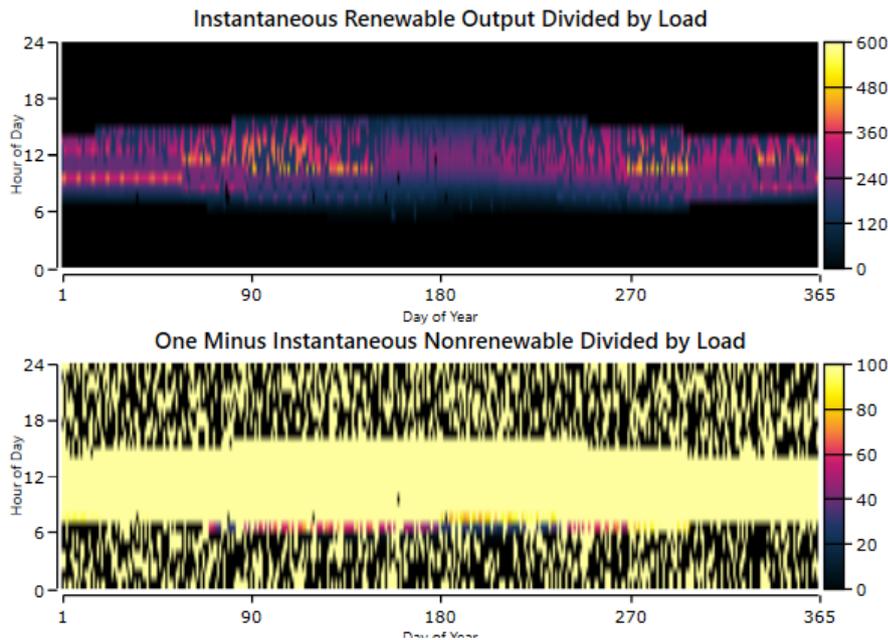


Figure 6.23: Instantaneous renewable output divided by load and nonrenewable contribution throughout the year.

The upper section of the figure demonstrates how RE contributes to meeting demand throughout the year, while the lower section highlights periods when non-renewable sources, such as the grid, compensate for energy deficits. The variation in renewable contribution suggests that although the system achieves a high penetration of renewables, there are still periods when reliance on the grid is necessary.

Battery Performance

The system integrates a battery storage capacity of 31.5 kWh with a usable nominal capacity of 25.2 kWh. The battery autonomy is 12 hours, ensuring adequate energy storage to support the load during periods of low solar generation. The system achieves a total battery lifetime throughput of 27,421 kWh, with an expected lifespan of approximately 5.02 years.

Figure 6.24 illustrates the battery (State of Charge (SOC)) distribution throughout the year. The histogram (top) represents the frequency of different SOC levels, indicating that the battery frequently operates at high SOC values, maximizing energy storage utilization. The heatmap (bottom) provides a temporal view of SOC variations, revealing seasonal trends and periods of deep discharge.

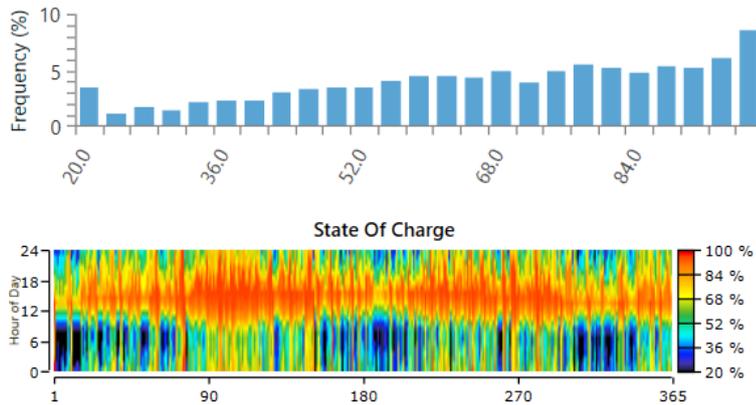


Figure 6.24: State of Charge (SOC) distribution for Case 3, showing SOC frequency (top) and seasonal variations (bottom).

Despite the system's high renewable penetration, some instances of low SOC are observed (blue regions in the heatmap), suggesting increased energy demand or prolonged cloudy periods. However, the battery remains sufficiently charged for most of the year, ensuring stable system operation and reducing reliance on grid electricity.

Dispatch Strategy: Load Following (LF) In Case 3, the system employs the Load Following (LF) dispatch strategy, which prioritizes meeting the immediate load demand while minimizing unnecessary energy production. This strategy is particularly effective for battery-supported systems, ensuring efficient energy use and reducing grid reliance.

- **Battery Utilization:** The system charges the battery bank when surplus solar energy is available and discharges it during periods of low SPV generation, such as nighttime or cloudy days. Additionally, when necessary, the battery can also be charged from the grid to ensure continuous power availability and reduce reliance on expensive peak-hour grid electricity.
- **Grid Interaction:** Instead of storing excess SPV production beyond battery capacity, surplus energy is exported to the grid, with 1,581

kWh/year sold back, generating financial benefits.

- **Minimized Fuel Dependency:** Since this system eliminates the gasoline generator, it completely avoids fuel-related costs and emissions, relying entirely on SPV and grid electricity.

By following this optimized strategy, the system enhances RE integration, reduces operational costs, and improves grid efficiency, making it the most sustainable option among all cases.

Environmental Impact

Among all evaluated configurations, Case 3 achieves the lowest environmental footprint. The complete elimination of a fuel-based generator results in a significant reduction in greenhouse gas emissions. The total annual CO₂ emissions are limited to 3,302 kg/year, which is notably lower than Case 1 (7,653 kg/year) and Case 2 (8,361 kg/year). Other emissions include 14.3 kg/year of SO₂ and 7.0 kg/year of NO_x, primarily associated with grid electricity, as no on-site combustion occurs. This outcome highlights the environmental advantages of relying on SPV energy and battery storage while minimizing dependence on fossil fuels. The system aligns well with sustainability goals, making it the cleanest option among the five evaluated cases.

Final Considerations

Case 3 represents the most optimal configuration among the evaluated scenarios, balancing economic feasibility, RES integration, and environmental sustainability. Despite having a higher initial capital investment of \$12,764 and an NPC of \$30,038, the system achieves a 65.6% renewable fraction, significantly reducing reliance on grid electricity. Additionally, the absence of a fuel-based generator completely eliminates operational fuel costs and emissions, making this configuration the cleanest among all cases.

Battery storage plays a crucial role in ensuring energy availability and flexibility, allowing surplus SPV generation to be stored and utilized during periods of low solar availability. While 1,937 kWh/year of excess energy remains underutilized, this presents an opportunity for further optimization through improved storage management or dynamic load shifting. Overall, this configuration demonstrates a highly efficient and sustainable energy system, effectively integrating SPV generation, battery storage, and grid interaction to achieve a reliable and environmentally responsible solution.

4. Off-Grid Mode: Case 4 & Case 5

- Case 4: SPV–Battery–Generator (Hybrid Off-Grid System): This system integrates 7.08 kW of SPV, a 3.50 kW gasoline generator, 7 strings of Trojan SAGM 12 205 batteries, and a 3.89 kW system converter. It operates under HOMER Load Following mode, prioritizing solar energy but relying on the generator when necessary.
- Case 5: SPV–Battery (Fully Renewable Off-Grid System): This system eliminates the dependency on fossil fuels by using 13.9 kW of SPV, 23 strings of Trojan SAGM 12 205 batteries, and a 5.15 kW system converter. It operates under HOMER Cycle Charging mode, storing excess SPV energy for later use.

Economic Analysis

Both systems require a significant investment, but their cost structures differ:

Case 4 incurs an NPC of \$47,815 and an LCOE of \$0.1987/kWh. The gasoline generator and fuel costs contribute heavily, adding operational expenses over time. Case 5, being fully renewable, has a higher NPC of \$57,606 and an LCOE of \$0.2412/kWh, mainly due to battery investment and replacements. Despite eliminating fuel costs, the higher initial capital requirement and battery degradation increase costs over the system lifetime.

Energy Production & Renewable Penetration

- Case 4 generates 21,389 kWh/year, with 61.8% from SPV and 38.2% from the gasoline generator, achieving a renewable fraction of 55.4%.
- Case 5 produces 25,993 kWh/year, entirely from SPV, achieving a 100% renewable fraction. However, excess electricity reaches 4,749 kWh/year, suggesting room for storage or load adjustments.

Battery & Fuel Utilization

- Case 4 uses a smaller battery bank, requiring 4,938 L of fuel annually, with the generator running for 3,563 hours per year. The reliance on fuel increases operational costs and emissions.
- Case 5 eliminates fossil fuels by significantly expanding battery storage to 23 strings, enabling 23.1 hours of system autonomy. However, storage losses reach 2,127 kWh/year, and battery degradation remains a concern.

Environmental Impact

- Case 4 emits 11,384 kg of CO₂ annually, alongside NO_x and SO₂ emissions due to generator use.

- Case 5 is completely emissions-free, making it the most sustainable option but with a higher financial burden.

Key Takeaways & Applicability

- Case 4 balances solar and generator use, making it more cost-effective than a fully renewable system but still dependent on fuel.
- Case 5 achieves 100% renewable operation but comes at a higher cost due to battery reliance, with challenges in energy storage optimization.
- The choice between the two depends on whether reducing emissions or lowering costs is the priority.
- **Applicability:** These off-grid systems are particularly suitable for remote agricultural areas where grid access is unavailable or unreliable. Case 5, being fully renewable, could provide sustainable power for irrigation systems, farm operations, and rural electrification without relying on fuel supply chains. Case 4 may be a more practical alternative where solar alone cannot fully meet demand, ensuring energy availability in critical operations.

6.4 Sensitivity Analysis

To comprehensively assess the robustness and adaptability of the optimal configuration (Case 3: SPV–Battery–Grid, Load Following), three targeted sensitivity analyses were conducted. These included:

- **Capital Cost Sensitivity:** Evaluated the impact of investment uncertainty by varying the total capital cost by $\pm 10\%$ from the baseline, examining effects on system sizing, cost-effectiveness, and renewable integration.
- **Renewable Fraction (RF) Sensitivity:** Investigated how varying RF constraints from 60% to 80% influenced system architecture, energy flows, emissions, and financial metrics.
- **Grid Reliability Sensitivity:** Simulated realistic weak-grid conditions by adjusting outage frequency, repair time, and variability, assessing the system’s resilience and autonomy under intermittent grid supply.

Each scenario isolates the influence of a key design or operational parameter, enabling a detailed understanding of trade-offs between economic performance, environmental outcomes, and technical feasibility. This multi-layered analysis provides a more complete foundation for guiding investment, policy, and design decisions in HMGSs.

6.4.1 Capital Cost Impact on Case 3 Configuration

Table 6.5 presents the techno-economic and environmental performance of Case 3 under baseline, 10% capital cost reduction (0.90 multiplier), and 10% capital cost increment (1.10 multiplier) scenarios.

Table 6.5: Effect of Capital Cost Variation on Case 3 Configuration

Parameter	0.90 Multiplier	Baseline (1.00)	1.10 Multiplier
Dispatch Strategy	Load Following	Load Following	Cycle Charging
NPC (\$)	28,822	30,038	31,107
LCOE (\$/kWh)	0.1110	0.1157	0.1102
Capital Cost (CAPEX, \$)	11,548	12,764	11,810
Operating Cost (OPEX, \$/year)	1,316	1,316	1,470
Renewable Fraction (%)	65.6	65.6	50.0
Grid Purchases (kWh/year)	6,805	6,805	10,752
Grid Sales (kWh/year)	1,576	1,581	3,264
CO ₂ Emissions (kg/year)	3,305	3,302	4,732

To further support the insights from Table 6.5, Figure 6.25 presents a graphical comparison of the system’s performance under different capital cost scenarios.

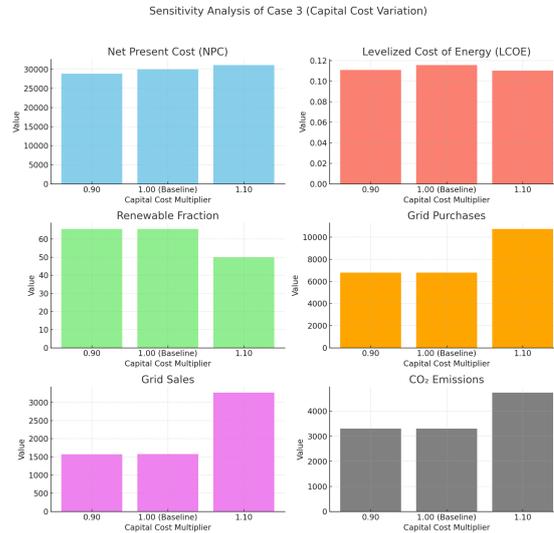


Figure 6.25: Effect of capital cost variation on key performance indicators for Case 3, including NPC, LCOE, RF, grid interaction, and CO₂ emissions.

Capital Cost Reduction (Multiplier = 0.90):

Reducing capital costs by 10% preserved the original system architecture and Load Following dispatch strategy, reflecting high system resilience. The SPV (8.83 kW) and battery storage sizing (31.5 kWh total capacity) remained unchanged. Economic performance improved slightly, with NPC decreasing from \$30,038 to \$28,822, and the LCOE improved from \$0.1157/kWh to \$0.1110/kWh due to lower upfront investment. Renewable Fraction (RF) remained stable at 65.6%, and CO₂ emissions showed negligible variation (3,305 kg/year versus baseline 3,302 kg/year). Grid interaction (grid purchases of 6,805 kWh/year and grid sales of 1,576 kWh/year) also remained consistent, indicating negligible operational impacts.

Capital Cost Increase (Multiplier = 1.10):

Conversely, a 10% capital cost increase led to notable adjustments in system architecture and operational strategy. The system shifted to the Cycle Charging dispatch strategy, significantly reducing SPV size to 7.95 kW and decreasing battery storage to 9 units, substantially lowering capital expenditure to \$11,810 despite the higher capital cost multiplier. This architectural modification drastically decreased RF to 50%, increased annual grid purchases by 58% (from 6,805 kWh/year to 10,752 kWh/year), and notably raised annual CO₂ emissions by approximately 43% (from 3,302 kg/year to 4,732 kg/year). Interestingly, the LCOE slightly improved to \$0.1102/kWh, attributed primarily to reduced investment in renewable infrastructure and increased reliance on less capital.

6.4.2 Renewable Fraction Sensitivity Analysis

To further evaluate the adaptability and inherent trade-offs of the optimal configuration (Case 3: SPV–Battery–Grid, Load Following), a sensitivity analysis was systematically conducted by varying the RF constraints from 60% to 80%, while holding all other economic and technical parameters constant. This detailed assessment highlights essential trends concerning economic feasibility, renewable energy integration efficiency, and environmental impacts, as summarized in Table 6.6.

Table 6.6: Effect of Renewable Fraction Constraint on System Performance (Case 3)

Renewable Fraction (%)	PV Capacity (kW)	Battery Storage (Units)	NPC (\$)	LCOE (\$/kWh)	CAPEX (\$)	CO ₂ Emissions (kg/year)	Grid Sales (kWh/year)
60	8.82	12	30,038	0.1157	12,764	3,302	1,581
70	12.5	11	31,801	0.1077	14,584	1,540	4,313
80	28.0	11	41,282	0.0940	24,620	-5,413	15,242

At an RF of 60%, the system closely mirrors the baseline configuration, main-

taining an SPV capacity of 8.82 kW and battery storage of 12 units (31.5 kWh total). Economic indicators, including Net Present Cost (NPC = \$30,038) and Levelized Cost of Electricity (LCOE = \$0.1157/kWh), show minimal variation compared to the baseline, underscoring the system's robustness at slightly reduced renewable penetration. Annual CO₂ emissions remain low (3,302 kg/year), indicating sustained environmental performance even at this modest RF.

Increasing the RF constraint to 70% necessitates moderate scaling of the system's renewable generation and storage capacities. Specifically, the SPV capacity rises noticeably to 12.5 kW, while the battery count slightly reduces to 11 units (28.9 kWh total capacity), optimizing system storage relative to increased renewable generation. Although this scaling moderately raises the NPC to \$31,801, it significantly improves the LCOE to \$0.1077/kWh, primarily due to enhanced renewable generation and energy trading capabilities. Environmental benefits are pronounced, as CO₂ emissions decline dramatically to 1,540 kg/year—less than half the emissions observed at 60% RF. Increased renewable generation further translates into higher grid energy exports (4,313 kWh/year), contributing to both economic returns and grid sustainability.

At an elevated RF of 80%, substantial expansions of SPV capacity (28.0 kW) and system converter (12.9 kW) are required, resulting in a substantial rise in initial capital expenditure (CAPEX = \$24,620) and total NPC (\$41,282). Despite higher upfront investment, significant economies of scale and extensive renewable energy production notably reduce the LCOE to \$0.0940/kWh, achieving the most cost-effective electricity production among all tested scenarios. Remarkably, the configuration attains net-negative CO₂ emissions (-5,413 kg/year), indicating that the renewable energy exported to the grid substantially offsets emissions from conventional grid generation. The significant surplus electricity (23,268 kWh/year), represented by high grid sales (15,242 kWh/year), emphasizes opportunities for further optimization through advanced storage solutions, strategic load management, or participation in energy markets.

This sensitivity analysis explicitly reveals critical trade-offs inherent in varying renewable penetration levels. Elevated RF targets (70–80%) substantially enhance environmental sustainability and reduce per-unit energy costs but require higher initial capital investments. These findings underscore the importance of aligning renewable energy targets with economic considerations and strategic project goals. For policy-oriented initiatives prioritizing environmental impact mitigation, configurations with RF values exceeding 70% offer compelling benefits. Conversely, projects constrained by budget considerations might prefer configurations in the 60–65% RF range, effectively balancing upfront costs with notable sustainability gains.

6.4.3 Grid Reliability Sensitivity Analysis

To explore how variations in grid behavior affect system performance, a sensitivity analysis was conducted by modifying the baseline grid reliability parameters. While the baseline scenario assumed a highly intermittent grid with very frequent short-duration outages (1,800 events per year), the updated case reflects a different form of instability—characterized by fewer outages (300 per year), but with longer durations (4 hours) and greater variability in repair time (10%). Such conditions align with transitional grid systems in regions improving infrastructure reliability but still facing challenges in outage response and duration. Table 6.7 summarizes the revised reliability assumptions.

Table 6.7: Final Settings for Grid Reliability Sensitivity Analysis

Parameter	Original	Updated	Meaning
Mean Outage Frequency (1/yr)	1800	300	Represents approximately one outage per day, simulating a weak or unreliable grid
Mean Repair Time (h)	2	4	Each outage lasts on average 4 hours—typical of rural or under-served areas
Repair Time Variability (%)	5%	10%	Introduces stochastic delays in outage recovery to mimic field variability

Under these revised conditions, the system reconfigured itself with a slightly downsized SPV capacity of 6.35 kW and 7 battery units, reflecting a shift toward greater grid dependence due to unreliable availability. The techno-economic outcomes and operational parameters are detailed below:

- **Economic Performance:** The NPC was significantly reduced to \$16,775, with an impressively low LCOE of \$0.0612/kWh—almost half the LCOE of the original optimal case. This reduction stems from a leaner system design with reduced capital outlay (CAPEX = \$8,636).
- **Energy Mix:** The system produced 22,154 kWh/year, with SPV contributing 53.5% (11,855 kWh/year) and grid purchases making up 46.5% (10,299 kWh/year). Despite grid unreliability, a renewable fraction of 50.7% was maintained.
- **Grid Interaction:** 2,682 kWh/year of energy was exported to the grid. However, the high grid dependency raised vulnerability to outages, demons-

trated by a minor unmet load of 134 kWh/year and a 1.09% capacity shortage.

- **Environmental Impact:** Annual CO₂ emissions rose to 4,814 kg/year (compared to 3,302 kg/year in the base case), along with higher SO₂ (20.9 kg per year) and NO_x (10.2 kg/year) emissions—directly correlating to increased grid electricity usage.

These findings emphasize that while weaker grid scenarios may drive systems toward grid dependency to minimize capital cost, this shift can compromise environmental performance and system autonomy. From a policy perspective, integrating battery support and localized generation remains critical in regions with poor grid reliability. Moreover, the elevated emissions and unmet load highlight the necessity of balancing economic viability with reliability and sustainability goals in weak-grid regions.

6.5 Overall Insights

This study provided a comprehensive assessment of renewable energy policies and technical feasibility across Iraq, Saudi Arabia, and Spain. By combining policy analysis with real-world data and simulation results using HOMER Pro, the research identified practical pathways for improving energy systems, especially in contexts with unreliable electricity access like Iraq. The results highlight that hybrid microgrid systems, when optimized with a strong share of solar energy and storage, can significantly improve reliability while reducing costs and emissions. Among the various configurations studied, systems that integrate solar panels, battery storage, and limited grid reliance achieved the best balance between affordability and sustainability. Sensitivity analysis showed that even small changes in capital cost, renewable energy targets, or grid stability can strongly influence the system design, environmental impact, and economic performance. This underlines the importance of flexible and responsive planning when designing future energy systems. From a policy perspective, Iraq and Saudi Arabia can benefit from adopting regulatory frameworks similar to those implemented in Spain, especially those that support self-consumption, smart grid integration, and incentives for solar adoption. Spain's experience shows that strong policy support combined with regional planning can accelerate the renewable energy transition while maintaining grid stability. Overall, the findings demonstrate that with the right combination of policies, data-driven design, and modern energy modeling tools, countries with different starting points can move toward cleaner, more resilient power systems.

References for Chapter 6

- [1] Z. Abdin and W. Mérida. Hybrid energy systems for off-grid power supply and hydrogen production based on renewable energy: A techno-economic analysis. *Energy Conversion and Management*, 196:1068–1079, Sep 2019.
- [2] International Energy Agency. Government energy spending tracker–analysis-*iea*. <https://www.iea.org/reports/government-energy-spending-tracker-2024-02-16>.
- [3] International Energy Agency. Renewable power on course to shatter more records as countries around the world speed up deployment-*news-*iea**. <https://www.iea.org/news/renewable-power-on-course-to-shatter-more-records-as-countries-around-the-world-speed-up-deployment>. 2023-08-29.
- [4] Majid Ali, Juan C. Vasquez, Josep M. Guerrero, Yajuan Guan, Saeed Golestan, Jorge De La Cruz, Mohsin Ali Koondhar, and Baseem Khan. A comparison of grid-connected local hospital loads with typical backup systems and renewable energy system based ad hoc microgrids for enhancing the resilience of the system. *Energies*, 16(4):1918, February 2023.
- [5] Saudi Aramco. Saudi aramco’s spark to usher in a new era of growth for saudi arabia. <https://www.aramco.com/en/news-media/news/2018/spark-new-era-of-growth-for-saudi-arabia>, 2018.
- [6] Furqan Asghar, M. Imtiaz Hussain, Fahad Abdullah Alshahrani, Muhammad Imran Akhtar, Waseem Amjad, Muhammad Shahzad, Syed Nabeel Husnain, and Gwi Hyun Lee. Technoeconomic analysis of standalone hybrid renewable energy systems for telecommunication sector under different climatic conditions in saudi arabia. *Energy Reports*, 11:4067–4084, June 2024.
- [7] Boletín Oficial del Estado. Ley 24/2013, de 26 de diciembre, del sector eléctrico. <https://www.boe.es/buscar/pdf/2013/BOE-A-2013-13645-consolidado.pdf>, 2013.

- [8] Boletín Oficial del Estado. Real decreto 244/2019, de 5 de abril, por el que se regulan las condiciones administrativas, técnicas y económicas del autoconsumo de energía eléctrica, 2019. Accessed: 13-Oct-2024.
- [9] Boletín Oficial del Estado. Real decreto 43/2021, de 26 de enero, por el que se aprueban medidas para la adaptación de las actividades industriales al cambio climático, 2021. Accessed: 13-Oct-2024.
- [10] Central Intelligence Agency. The world factbook. <https://www.cia.gov/the-world-factbook/>, 2024. Accessed on 25 February 2024.
- [11] Climates to Travel. World climate guide - climates to travel. <https://www.climatestotravel.com/>, 2024. Accessed on 24 February 2024.
- [12] Barun K. Das, Majed A. Alotaibi, Pronob Das, M.S. Islam, Sajal K. Das, and Md Alamgir Hossain. Feasibility and techno-economic analysis of stand-alone and grid-connected pv/wind/diesel/batt hybrid energy system: A case study. *Energy Strategy Reviews*, 37:100673, September 2021.
- [13] M.K. Deshmukh and S.S. Deshmukh. Modeling of hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*, 12:235–249, 2008.
- [14] Electricity & Cogeneration Regulatory Authority. *Annual Statistical Booklet for Electricity and Seawater Desalination Industries*. Electricity & Cogeneration Regulatory Authority, 2016.
- [15] Encyclopedia Britannica. Iraq - desert, arid, hot | britannica. <https://www.britannica.com/place/Iraq/Climate>, 2024. Accessed on 13 February 2024.
- [16] Encyclopedia Britannica. Saudi arabia - desert, arid, climate. <https://www.britannica.com/place/Saudi-Arabia/Climate>, 2024. Accessed on 13 February 2024.
- [17] Encyclopedia Britannica. Spain - mediterranean, arid, temperate. <https://www.britannica.com/place/Spain/Climate>, 2024. Accessed on 13 February 2024.
- [18] International Energy Agency. Electricity 2024 - Analysis and forecast to 2026. www.iea.org, 2024.
- [19] Joint Research Centre (JRC) European Commission. Photovoltaic geographical information system (pvgis). https://re.jrc.ec.europa.eu/pvg_tools/en/#MR, 2023. Accessed: 2024-11-04.

- [20] European Union Agency for Cybersecurity (ENISA). National cyber security strategies: Practical guide on development and execution. <https://resilience.enisa.europa.eu/enisas-ncss-project/CIIPApproachesNCSS.pdf>, 2016.
- [21] IEA. Renewables - Energy System - IEA. <https://www.iea.org/energy-system/renewables>. 2024-02-26.
- [22] IEA. Tracking clean energy progress 2023 – analysis - iea. <https://www.iea.org/reports/tracking-clean-energy-progress-2023>. 2024-02-15.
- [23] International Energy Agency. Spain: Electricity. <https://www.iea.org/countries/spain/electricity>, 2023.
- [24] International Energy Agency. Egypt-saudi electricity interconnection project – policies - iea. <https://www.iea.org/policies/14291-egypt-saudi-electricity-interconnection-project>, 2024. Accessed on 16 February 2024.
- [25] International Energy Agency. Electricity in saudi arabia. <https://www.iea.org/countries/saudi-arabia/electricity>, 2024. Accessed: 2024-10-13.
- [26] International Energy Agency. Exploration enablement program. <https://www.iea.org/policies/20089-exploration-enablement-program?s=1>, 2024.
- [27] International Energy Agency. Iraq - countries & regions. <https://www.iea.org/countries/iraq>, 2024.
- [28] International Energy Agency. Iraq - electricity, 2024. Accessed: 22-Oct-2024.
- [29] International Energy Agency. Iraq energy outlook, 2024. Accessed: 22-Oct-2024.
- [30] International Energy Agency. National energy and climate plan 2021-2030, 2024.
- [31] International Energy Agency. Policy database – data & statistics - iea. <https://www.iea.org/policies?sector%5B%5D=Electricity+and+heat+generation§or%5B%5D=Electricity+distribution§or%5B%5D=Electricity+transmission>, 2024. Accessed on 16 February 2024.

- [32] International Energy Agency. Spain - countries & regions. <https://www.iea.org/countries/spain>, 2024.
- [33] M.M. Jaganath, Saheli Ray, and N.B. Dev Choudhury. Eco-friendly microgrid carport charging station for electric vehicles (evs). *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, 5:100196, September 2023.
- [34] Middle East Institute. Iraq needs renewables, but they won't solve its power problems without broader reforms. <https://www.mei.edu/publications/iraq-needs-renewables-they-wont-solve-its-power-problems-without-broader-reforms>, 2024. Accessed on 25 February 2024.
- [35] Ministerio para la Transición Ecológica y el Reto Demográfico. Plan nacional de adaptación al cambio climático 2021-2030, 2021.
- [36] Ministry of Electricity. Ministry of electricity. <https://moelc.gov.iq/>, 2023. Accessed on 23 May 2023.
- [37] Ministry of Electricity Iraq. Electricity report 2011. <https://moelc.gov.iq/upload/3117176176.pdf>, 2011.
- [38] Ministry of Justice. Official gazette “al-waqae’ newspaper” 4443. <https://moj.gov.iq/upload/pdf/4443.pdf>, 2020. Accessed on 25 February 2024.
- [39] Tourism MITyC, Ministry of Industry, Trade (Minetur), and State Secretary of Energy. La energía en españa. <http://www.minetur.gob.es/energia/es-ES/Paginas/index.aspx>, 2011. Available online.
- [40] Mitja Mori, Manuel Gutiérrez, and Pedro Casero. Micro-grid design and life-cycle assessment of a mountain hut’s stand-alone energy system with hydrogen used for seasonal storage. *International Journal of Hydrogen Energy*, 46(57):29706–29723, August 2021.
- [41] National Renewable Energy Laboratory (NREL). Solar installed system cost analysis, 2023. Accessed: 14-Oct-2024.
- [42] NEOM. Neom - made to change. <https://www.neom.com/en-us>, 2024.
- [43] Ministry of Electricity Iraq. 2023 electricity report. https://storage.moelc.gov.iq/2024/10/14/2024_10_14_12102232142_3592046521806608.pdf, 2023. Accessed: 22-Oct-2024.
- [44] Ministry of Industry and Kingdom of Saudi Arabia Mineral Resources. Exploration enablement program. <https://taadeen.sa/exploration-enablement-program>, 2024.

- [45] J. O. Oladigbolu, Y. A. Al-Turki, and L. Olatomiwa. Comparative study and sensitivity analysis of a standalone hybrid energy system for electrification of rural healthcare facility in nigeria. *Alexandria Engineering Journal*, 60(6):5547–5565, December 2021.
- [46] Red Eléctrica de España. Installed capacity of the spanish electricity system, 2023. Accessed: 14-Oct-2024.
- [47] Solargis. Free maps and gis data / overview. <https://solargis.com/maps-and-gis-data/overview>, 2024. Accessed on 14 February 2024.
- [48] H. Taghavifar and Z. S. Zomorodian. Techno-economic viability of on grid micro-hybrid pv/wind/gen system for an educational building in iran. *Renewable and Sustainable Energy Reviews*, 143:110877, 2021.
- [49] K.A. Tahir, J. Ordó nez, and J. Nieto. Exploring evolution and trends: a bibliometric analysis and scientific mapping of multiobjective optimization applied to hybrid microgrid systems. *Sustainability*, 16:5156, 2024.
- [50] K.A. Tahir, J. Nieto, C. Díaz-López, and J. Ordó nez. From diesel reliance to sustainable power in iraq: Optimized hybrid microgrid solutions. *Renewable Energy*, 2024.
- [51] K.A. Tahir, M. Zamorano, and J.O. García. Scientific mapping of optimisation applied to microgrids integrated with renewable energy systems. *International Journal of Electrical Power & Energy Systems*, 145:108698, 2023.
- [52] Vision 2030 Saudi Arabia. Environment & nature. <https://www.vision2030.gov.sa/en/progress/environment-nature/>, 2024. Accessed on 25 February 2024.
- [53] World Bank. Electric power consumption (kwh per capita). <https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC>, 2024. Accessed on 13 February 2024.
- [54] World Bank. Land area (sq. km) | data. <https://data.worldbank.org/indicator/AG.LND.TOTL.K2>, 2024. Accessed on 13 February 2024.
- [55] World Bank. Population, total | data. <https://data.worldbank.org/indicator/SP.POP.TOTL>, 2024. Accessed on 13 February 2024.
- [56] worldbank. Access to electricity (<https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS>). 2024-04-01.

- [57] Abdel-Raheem Youssef, Reem Abdelkareem, Hossam H. H. Mousa, and Mohamed A. Ismeil. Economic and technical evaluation of hydrogen storage in hybrid renewable systems with demand-side management: Upper egypt case study. *IEEE Access*, 12:120250–120272, 2024.

Chapter Seven

Conclusion and Recommendations

This chapter presents the final conclusions of the research and provides recommendations and future research directions.

Chapter 7

Conclusion and Recommendations

7.1 Conclusion

Globally, the transition to renewable energy has gained momentum in response to environmental concerns, increasing energy demand, and the need for secure and resilient power systems. Hybrid microgrid systems, particularly those integrating solar photovoltaic (SPV) technologies and battery storage, have emerged as a flexible and sustainable solution. However, their deployment remains limited in many developing countries, including Iraq. The electricity sector in Iraq continues to face serious challenges due to prolonged conflict, deteriorating infrastructure, and heavy reliance on diesel generators. This research addressed these issues through a five-phase investigation into the potential of hybrid microgrid systems (HMGSs) to support a more reliable, affordable, and sustainable energy future. These systems must be carefully evaluated using optimization approaches to avoid excessive costs and ensure efficient, context-appropriate designs. To that end, a comprehensive study was conducted to analyze emerging trends in HMGS research. The findings revealed a notable increase in global publications and the growing use of advanced techniques and tools for system design and evaluation, reflecting a broader international shift toward renewable technologies. In Iraq, accurate evaluation of HMGS performance is hindered by the lack of reliable electricity demand data. To address this challenge, the study developed and introduced the Rosetta time transformation technique, which enables the generation of synthetic load profiles by adapting external data to local conditions. A socio-economic analysis was also conducted using the Delphi method to gather expert opinions on transitioning from diesel generators to SPV-based systems. This expert feedback confirmed both the urgency and feasibility of that transition. Building on this consensus, the techno-economic performance of HMGS configurations was assessed using Rosetta-based demand modeling and payback period analysis. Several demand scenarios were

evaluated, producing Levelized Cost of Electricity (LCOE) values ranging from \$0.106 to \$0.078 per kilowatt-hour. The analysis confirmed the viability of grid-connected SPV–battery systems as the most economically favorable option. In the best-case scenario, these systems achieved payback periods as short as 3.6 years, with renewable energy fractions ranging from 31.13 percent to 32.75 percent. The research also underscores the urgent need for policy reform to support the adoption of sustainable energy solutions in Iraq and comparable regions. Through a two-phase analysis, energy policies in Spain, Iraq, and Saudi Arabia were assessed. Spain’s success in promoting renewable energy adoption was identified as a transferable model that could be adapted to reduce fossil fuel dependence and address chronic energy shortages in Iraq and KSA. To evaluate practical implementation, a techno-economic simulation was conducted using HOMER Pro software, focusing on the high solar potential of Iraq’s Anbar region. Among various system configurations, the optimal solution was a grid-connected SPV–battery system that achieved a 65.6 percent renewable fraction, eliminated the need for generators, and delivered electricity at an LCOE of \$0.1157/kWh with a Net Present Cost (NPC) of \$30,038. This system proved to be the cleanest and most cost-effective. The study also evaluated off-grid scenarios for remote areas. One hybrid system (SPV–battery–generator) prioritized solar energy with generator support when needed, while the fully renewable option used a larger SPV array and battery storage to eliminate fossil fuel dependency entirely. These findings highlight the technical feasibility and environmental benefits of increased SPV integration in both grid-connected and off-grid applications. This study offers a structured and adaptable methodology for renewable energy planning in regions with limited data availability and infrastructure. While the results are promising, future work should focus on pilot project implementation, real-time demand monitoring, and deeper engagement with stakeholders in both regulatory and consumer sectors. Overall, the research provides a practical, technically grounded roadmap for advancing Iraq’s transition toward a cleaner, more resilient, and sustainable electricity system.

7.2 Recommendations and Suggestions

1. Adopt Grid-Connected SPV–Battery Systems as a National Strategy

The study demonstrated that grid-connected SPV–battery systems are economically and environmentally viable alternatives to diesel generators, with short payback periods and high renewable energy fractions. These systems should be prioritized within Iraq’s national energy planning framework, particularly in urban and peri-urban areas with grid instability.

2. Leverage the Rosetta Time Transformation for Demand Modeling

The novel Rosetta technique developed in this research offers a reliable method for generating synthetic electricity demand profiles in the absence of local consumption data. Energy planners, researchers, and utility stakeholders in Iraq and similar contexts are encouraged to adopt this method in feasibility studies and planning models.

3. Implement Policy Reforms Based on International Best Practices

Spain's renewable energy policies, including net metering, consumer-side incentives, and clear microgrid legislation, offer a strong model. Iraq should adapt similar mechanisms to reduce fossil fuel reliance and encourage investment in decentralized renewable systems.

4. Encourage Off-Grid Deployment in Remote and Underserved Areas

The study's off-grid scenario analysis confirmed that both hybrid and fully renewable SPV-battery systems can serve as reliable energy solutions in remote regions. Targeted government support and international development funding should be directed toward these areas.

5. Expand the Use of Advanced Simulation Tools in National Planning

Software such as HOMER Pro, combined with localized economic data and expert input, should be institutionalized as part of Iraq's national energy planning toolkit to evaluate various HMGS configurations under realistic scenarios.

6. Enhance Financial Accessibility for End Users

Despite strong economic performance, initial capital costs remain a barrier. Introducing low-interest loans, subsidies, and tax exemptions can increase household and small-business adoption of SPV-based systems.

7. Invest in Technical Training and Workforce Development

Developing programs that build technical and institutional capacity is essential to support the installation, operation, and scaling of HMGSs. Universities, technical institutes, and private-sector partners should collaborate to provide targeted training in system design, control, and optimization.

8. Promote Pilot Projects for Policy-Technology Alignment

Small-scale, physical installations of HMGSs in selected sites are necessary to test performance beyond simulation environments, validate modeling results, and build public trust. Demonstration projects should be deployed in

diverse settings to assess technical reliability, user acceptance, and long-term scalability.

9. Improve National Energy Data Infrastructure

Establishing a centralized, open-access platform for energy demand, system performance, and cost data will significantly improve the accuracy of planning and modeling, while also supporting research and transparency.

10. Strengthen Regional Collaboration in Renewable Energy

Iraq should pursue bilateral and regional cooperation with countries that have advanced renewable programs. Sharing expertise, financing models, and policy experiences can accelerate the national energy transition.