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Review

Comprehensive Review of Socio-Economic Costs and Benefits, Policy Frameworks, Market Dynamics, and Environmental Implications of Microgrid Development in the UAE

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Abstract: This research paper presents a comprehensive review of the literature on microgrid development in the UAE, focusing on the socio-economic costs and benefits, policy frameworks, market dynamics, and environmental implications. The analysis encompasses publications from 2011 to 2021, with a particular emphasis on the United Arab Emirates (UAE) and the Gulf Cooperation Council (GCC) countries. A total of 33 papers were identified and classified, revealing gaps in comprehensive valuation models, consideration of environmental and social governance factors, and research informing policy and investment decisions. The findings highlight the significance of microgrid technology in the UAE, its limited adoption and commercialization, and its predominant usage in remote areas and academic testbeds. The paper underscores the UAE's vision for net-zero emissions by 2050 and the potential of microgrids in supporting its realization. Recommendations include the development of a comprehensive valuation framework to drive effective investments in microgrid technology, aligning with the UAE's sustainable energy goals. The study contributes to the understanding of microgrid development in the UAE, offering insights into its socio-economic, policy, market, and environmental dimensions.

Keywords: microgrid development; socio-economic costs; policy frameworks; market dynamics; valuation models

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1. Introduction

Diversification of energy resources and integrating multiple energy resources into the distribution grid comes with several challenges [1]. Due to the variable nature of solar energy and other renewable energies (RE) from day to nighttime and from season to season, a system to manage these variations has to be implemented. The microgrid technology and paradigm is a key enabler for implementing, utilizing, and managing variable energy resources efficiently. Microgrids (MG) are systems of distributed energy resources (DERs) that have enabled facilitating the generation of various renewable energy sources, such as wind and solar power. These systems have elements in which energy storage resources are used to store excess generation and to provide power back to the grid when generation is suboptimal [2]. The control system, which is a key component of the MG, enables it to efficiently manage and operate multiple energy resources with minimum waste, and, therefore, minimum carbon emissions, and with greater resilience [3]. The two-way communication between the MG control system, and the energy storage systems within the MG provides continuous quality power to end users.

The United Arab Emirates (UAE) has been among the first nations in the Middle East to be involved in utilizing renewable energy and combating climate change. Moreover,

the UAE has a vision for 2050—to have net-zero emissions. The level of adoption of technology in the UAE is high, especially technology that increases energy efficiency, grid resiliency, power quality and growth in infrastructure [4]. There is a high potential for effective utilization of MG technology to support the implementation of the UAE 2050 vision. However, in the UAE, microgrids are not as common as in other parts of the world, such as the United States. MGs in the UAE are mostly used for remote areas and islands. They are neither widely applied nor commercialized. Many MGs are designed as a testbed for electrical engineering research at universities in the UAE [5]. A long-term strategy on investing in renewable energy generation is being taken seriously in the UAE. The body of literature discussing microgrids in general in the UAE is limited, let alone the management of microgrids. The MG is yet to be utilized widely in the UAE, as an enabler for renewable energy in particular and grid disaster recovery and resilience in general [6,7].

This paper reviews the literature on microgrids in the UAE related to MG technology in terms of socio-economic costs and benefits, policy, market, and environmental aspects, and valuation models. This article also reviews the potential for long-term optimization of the United Arab Emirates' (UAE) energy future. It assesses the country's energy system using a bottom-up optimization model, which considers all sectors of the economy and the entire energy conversion chain. The model is used to investigate the cost-effective potential for reducing primary energy demand and carbon emissions in the UAE by 2050.

This paper will attempt to answer the following questions by reviewing the research that has been published related to the topic:

1. What are the socio-economic costs and benefits associated with microgrid development in the UAE, specifically in terms of renewable energy integration and grid resiliency?
2. What are the existing policy frameworks and regulations governing microgrid implementation in the UAE, and how do they impact the adoption and commercialization of microgrids?
3. What are the market dynamics and challenges related to the widespread utilization of microgrids in the UAE? How can these challenges be addressed to encourage greater deployment of microgrid technology?
4. What valuation models or frameworks are currently used to assess the effectiveness and economic feasibility of microgrids in the UAE, and how can they be improved to consider environmental, social, and governance (ESG) factors more comprehensively?
5. How does the UAE's vision for net-zero emissions by 2050 align with the potential role of microgrids in achieving this goal? What are the strategies and long-term optimization approaches that can be employed to integrate microgrids effectively into the UAE's energy future?

2. Statistical Analysis of Literature on the Research Topic

This literature review covers research papers starting from the most recent publications and going back over the past 12 years. The main target is research addressing the economic models, socio-economical models, and technical evaluations related to the development and deployment of microgrids and their relationship to policy, investments, market, and socio-economic aspects. This topic has received significant attention in worldwide research due to the improved applications of MGs and an increase in the understanding of their benefits.

2.1. Geographic Analysis of the Review Pool

This work surveys 112 references, review articles, journal articles, books, and conference papers that meet the date span requirement mentioned above. The statistics presented in Table 1 shows distribution of the review pool in terms of the geographic area addressed. At the start, the target of this review was mainly to research work related to the UAE. However, it was found that papers in the literature specifically related to the UAE are quite limited. Therefore, the target geographic area was widened to incorporate all of the Gulf Cooperation Council (GCC) countries, since these countries share a good degree of similarity in economic, social, and environmental challenges.

Table 1. Regional distribution of publications related to microgrids.

Location	Number of Publications
UAE/GCC	33
South Asia (Pakistan, India, Bangladesh, and Nepal)	8
North America	8
Asia and Australia	4
Europe	3
Africa	3
Unspecified others	53

It can be seen from the table that apart from the UAE and the GCC, South Asia (mainly India) and North America are among the most popular regions in terms of research on microgrids. The UAE/GCC were specifically addressed in 33 papers (about 29 percent of the review pool), as shown in Figure 1, which is remarkable given the size of the region's power industry compared to the rest of the world.

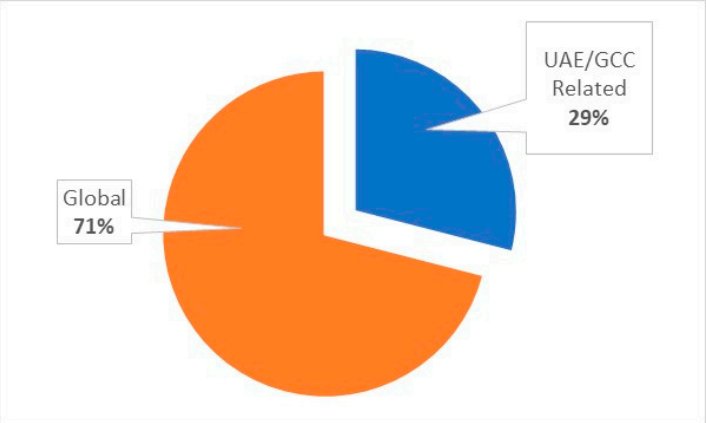

Figure 1. Distribution of articles addressing MG (UAE/GCC vs. global).

This paper will concentrate on the results of the 33 works that address the geographic area of the UAE and GCC. The review will discuss these works in terms of their relevance to the market and investments, optimization and simulations methods, socio-economic cost analysis, types of renewable energy discussed, assessment models, policy, and challenges and opportunities.

2.2. Temporal Analysis of the Review Pool

Figure 2 shows the research interest in the topic of microgrids and its growth over the years in the Middle East (mainly in the UAE and the GCC) compared to the rest of the world. The figure shows that publication rates addressing this topic in the Middle East are on the rise, demonstrating increased interest among researchers. This growth is due to the goals and visions of the countries of the GCC on environmental and social governance (ESG), decarbonization, renewable energy integration, energy infrastructure investments, diversifying energy resources, and sustainability.

The figure shows significant interest in the topic in the Middle East over the years. However, the number of publications specifically addressing the UAE is slightly lower compared to the other GCC countries. Researchers have reported that there is a lack of valuation models and information for policy and decision makers to utilize and start benefiting from such a growing and advancing technology and industry worldwide. The shortage is even more severe when compared to the recently introduced UAE goals and

vision, and the commitment not only by its federal government, but also by big companies, such as the Abu Dhabi National Oil Company (ADNOC) and the Abu Dhabi National Energy Company (TAQA), which have plans to invest USD 660 billion into clean energy and power-related projects.

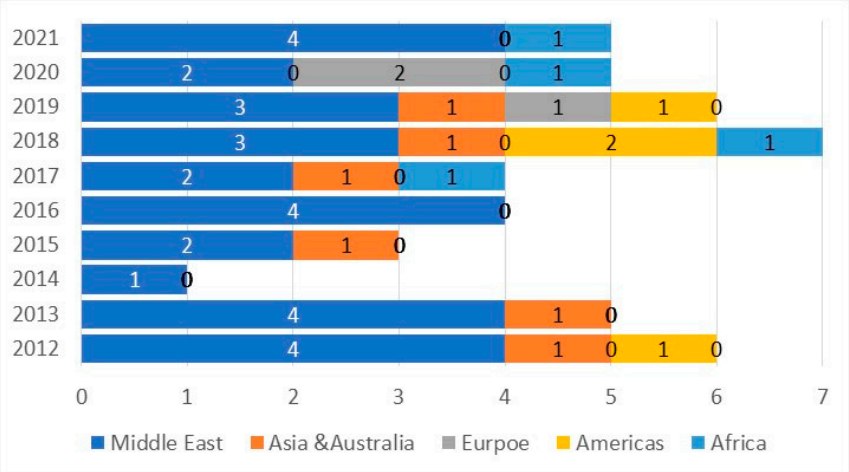

Figure 2. Research interest in topics related to the microgrid.

The data in Table 2 show the number of publications addressing microgrids in the UAE over the past 10 years. The results show that research on this topic has been of the same intensity and volume. The topics are mostly related to renewable energy in relation to microgrids. Governmental reports and other similar references were removed from this data.

Table 2. Temporal analysis of publications related to MG in the UAE.

Year	Number of Publications
Before 2012	4
2012	4
2013	4
2014	1
2015	0
2016	4
2017	3
2018	3
2019	3
2020	3
2021	3

2.3. Distribution of the Research Pool by Topic

The literature on microgrids in the UAE/GCC mostly deals with renewable energy, cost analysis, and carbon emissions. Moreover, opportunities and challenges, general or specific to the three areas mentioned, are also common in the literature. The data in Table 3 show the distribution of interest in research articles addressing the incorporation of clean energy technologies, such as the microgrid, although the emphasis in the body of research is mostly on the technical and economic aspects. The table shows that social aspects of the microgrid are among the least explored, with only two papers discussing social analysis of microgrids up to the date of this research.

Table 3. Topic distribution of publications related to microgrids in the UAE.

Subject Topic	Publication Count
Renewable energy (RE), variable renewable energy (VRE)	13
Cost analysis	12
Challenges and opportunities	9
Carbon emissions and environment	8
MG, smart grid (SG), energy storage system (ESS), distributed energy resources (DER), distributed grid (DG)	7
Solar photovoltaics (PV)	7
MG policy	5
Optimization and simulation integration	5
Research methods	5
Investment	4
Market	3
MG socio-economic valuation	2
MG assessment tool	2

2.4. Summary of the Statistical Analysis of the Literature Pool

Based on statistical analysis, research on the topic of microgrid technology and its applications is on the rise, worldwide and especially in the UAE and the GCC. Moreover, based on the analysis of the increasing numbers as well as the presence of published papers and reports over the past ten years in the UAE, the topic is worth pursuing and in need of more contributions. There are no models considering ESG and social costs along with the monetary feasibility that are specific to the UAE. Microgrids have been utilized in remote islands where they were the only option; however, in terms of converting the distribution grid to multiple microgrids, a feasible and strategically aligned model must be created.

3. Analysis of the Literature Content—Results of Research Methods and Statistical Analysis

The main topics discussed in the literature addressing the UAE are renewable energy, sustainability, carbon emission reduction/combating global warming, the cost of microgrids and renewable energy, policy, socio-economic models, and the research methods used. There is research in the topics related to cost optimization/cost–benefit analysis. Much of the research capitalizes on solar photovoltaics in the UAE. This section discusses the literature on microgrids in the UAE. The country has placed a high priority on lowering its carbon footprint and ensuring sustainable expansions of cities both by public and private developers, making community microgrids a very important type to analyze and study in this context. Moreover, there are economic and social benefits and opportunities available in the community microgrid, with end users being aware of the benefits of renewable energy and the policies supporting clean energy as well as the economic benefits end users reap from a utilized microgrid. It also discusses some existing optimization and simulation carried out on MG technology as a case study in the UAE.

Table 4 shows the distribution of the literature with respect to focus on the business side of microgrids and related topics. On the other hand, researchers do indicate the type of research methods used; however, not all papers specify policy needs, recommendations, measures, and effects.

3.1. Business Considerations

Business considerations are one of the three main analysis points that significantly affect the wider adoption of MG in the UAE, as well as explain its social and economic

benefits. Costs are among the most frequent challenges that have been researched on the MG in the UAE. Moreover, policy, carbon emissions, and market investments are discussed to provide a more comprehensive analysis of the MG business-related issues. Lastly, opportunities and challenges that have been addressed in the literature are analyzed to show an overall comparison.

Table 4. Microgrid consideration by topic.

Topic Considered	Number of Articles
Business aspects of MG	29
Technology aspects of MG	6
Research methods related to MG	4

3.1.1. Energy and Microgrid Policies in the UAE

Energy and MG policies go together when taken into consideration for dealing with today's challenges. Articles discuss different aspects of the policy, be it informing policy makers through research findings or comparing existing policies. Moreover, they discuss policy needs, measures, and effects. The overall result is that energy policy in general and MG policy, in particular, affects how the market and investments prosper in terms of the deployment of RE, and, thus, how MGs work on a larger scale [8]. Since the aim is to diversify its energy mix and reduce dependence on conventional sources, the microgrid was not mentioned literally, although Reference [9], in their study, discussed the development of a long-term energy optimization model for the UAE in order to identify the optimal policy measures which would be required to achieve sustainable development goals. The study found that the UAE has the potential for significant long-term energy savings through changes in policy, technology, and end-use efficiency. The results have implications for both developed and developing countries seeking to achieve greater energy security and sustainability.

When it comes to recommendations on policy, Reference [10] suggested a shift toward decentralized energy systems, incorporating renewable sources, like solar and wind, deregulation, open access to the grid, and financial incentives like feed-in-tariff (FIT).

For policy makers, Reference [11] provided recommendations to policymakers by identifying the opportunities and challenges facing renewable energy adoption. Reference [12] provided insights on how businesses and policymakers can consider the implications of electric vehicles on emissions and energy security. Furthermore, Reference [13] stated that machine learning could help improve the charging part of the MG infrastructure and policies.

In addition to that, the success of the deployed policies has been addressed by several authors. Reference [14] discussed the success of the application of the renewable energy policy within the UAE by adopting the Australian 'Solar Town' program. Reference [15] explained the policy's effects on the feasibility of residential rooftop solar photovoltaics in Abu Dhabi. Reference [16] found that the UAE has been making policy innovations in order to transition to sustainable energy. Reference [17] found that UAE's current renewable energy policies are mainly state-managed and focus on mega projects. Success in renewable initiatives and microgrids need innovative policies involving all stakeholders, to ensure genuine engagement. Reference [18] recommend the implementation of a mixed policy of FIT and the quota system for RE electricity generation in order for the UAE to meet its 7% target in 2020.

3.1.2. Carbon Emissions and the Environment, Paris Agreement, COP28, and UAE Vision 2050

One of the many benefits offered by a microgrid is its ability to address climate change by relying more on electric vehicles to reduce emissions caused by fossil fuel vehicles. This is the case since the MG is a key enabler of plug-in electric vehicles. Moreover, greenhouse

gases (GHG) can be tackled by both lowering their emission and capturing already emitted gases from the atmosphere [15]. However, carbon recapturing is slow and expensive with the technologies currently available. Therefore, a reduction in GHG is the more affordable and technologically advanced option. A significant percentage of the UAE's carbon emissions come from the transportation industry. The adoption of MG technology can lead to a reduction in emissions per kWh of electricity generated. The UAE has made an international pledge to lower GHG. However, if the UAE carries on with business as usual, the GHG will reach globally alarming levels. Table 5 shows the increase in carbon emissions over the years due to increased electricity production and the heat associated with gas-fired generation plants [19].

Table 5. Greenhouse gas emissions in the UAE (in million TCO_2e).

Year	Public Electricity and Heat Production	Road Transport	Industrial Manufacturing
2013	69.1	32.8	27.4
2014	68.9	33.2	30.8
2015	73.9	31.5	27.8
2016	76.6	35.1	27.2
2017	77.8	40.7	27.4
2018	77.6	40.8	24.6

Reference [15] has noted that promoting residential rooftop solar photovoltaics in Abu Dhabi could lead to significant reductions in carbon emissions and energy costs. Reference [16] found that there are market and investment opportunities for renewable energy in the UAE as well as challenges to overcome, such as the cost of renewable energy. Reference [14] stated that due to the UAE's geographical and climatic features, the country has an excellent opportunity to capitalize on renewable solar radiation.

There are good developments in terms of policies targeted at emission reductions. The United Arab Emirates was among the first large energy nation to ratify the International Agreement at the United Nations Environment Programme [20,21]. The Abu Dhabi Future Energy Company was established in 2006, and the United Arab Emirates launched itself on a sustainable energy path. The UAE set a strategic goal of achieving a 7 percent renewable energy share of energy production by 2020. However, Reference [18] showed that, except for the UAE, all countries in the GCC had a renewable energy target that was greater than 15 percent at that time.

Since then, the UAE has altered its fuel mix strategy to include renewables and nuclear energy in addition to fossil fuels [15,22]. However, by 2017, 98 percent of the energy was still being produced from fossil-powered stations, with the rest coming from heavy fuel oil and the developing solar energy industry [15]. In 2018, the UAE committed to enhancing its sustainability goals from 24 per cent to 27 percent by 2021. Then, in 2021, federal efforts, such as the UAE Vision 2021 and the Energy Strategy 2050, were announced to lay out a clear roadmap for diversifying the country's economy and federal electricity connections. These strategies committed the country to reducing carbon dioxide emissions by 70 percent, increasing clean energy use by 50 percent, and increasing energy conservation by 40 percent, by the year 2050 [19]. This evolving scenario suggests that the UAE is eager to find an alternative energy source to meet its requirements. The UAE is the first among the GCC countries to embark on a renewable power strategy that includes renewable energy which is sufficient to meet the country's power requirements [23,24].

The current challenges that the UAE faces are old infrastructure and climate change. These challenges demand changes in both the quality and quantity of power supplied, as well as mass technological advances and smart grid technologies [18,19]. The old infrastructure consists of power generation stations that are less efficient and dependent

on fossil fuels. Another issue is the old transmission lines that lack efficiency and are prone to deliver less than the current needs, since their capacity is set to old requirements. Distribution networks in older parts of the cities are outdated and less flexible in adapting smart grid technologies in order to transform existing cities into smart cities. Moreover, there is a need to integrate the growing use of various renewable energy resources, both by individuals and establishments to address the economic, environmental, and sustainability requirements. In line with the UAE's agenda to reduce carbon emissions and promote clean energy, the grid must be able to accommodate these necessary changes and improvements. Deploying sustainable energy technology solutions is a decades-long process.

Reference [25] provides a comprehensive evaluation of options for sustainable energy transition in the UAE, using an integrated energy model, which is a holistic approach that the author suggests for the sustainable energy transition (SET). The study assesses the potential for renewable energy, nuclear power, and carbon capture and storage (CCS) to meet the UAE's future energy demands. Reference [26] assessed the feasibility of transitioning to clean energy in order to reduce carbon emissions by 2050 along with improving the overall efficiency of the grid. Similarly, Reference [9] made an assessment of the country's energy system using a bottom-up optimization model, which considers all sectors of the economy and the entire energy conversion chain. The model is used to investigate the cost-effective potential for reducing primary energy demand and carbon emissions in the UAE by 2050. Reference [27] discussed the potential for integrating PV distributed energy resources into the Dubai smart grid. They highlighted the benefits that this could bring in terms of reducing carbon emissions and improving energy efficiency. Since making the decision to reduce emissions, the UAE has taken the lead in the GCC area in employing renewable energy sources for electricity production [11].

These developments highlight the central role expected for community microgrids in the UAE, since they facilitate RE integration to achieve this commitment. Community MGs allow the embedding of DERs, especially solar thermal and solar PV renewable energies that are available in the UAE. References [28,29] discussed a conceptual design for a smart microgrid in the United Arab Emirates that would include a coordinated power management strategy. The goal of the microgrid is to improve energy efficiency and reduce carbon emissions. They found that the basic design of the smart microgrid showed that the renewable generation microgrid would be reliable and robust, therefore could support UAE Vision 2050. Community microgrids can either be owned by the government or the private sector. An example of such a community microgrid exists in the Al Raha residential community in the Emirate of Abu Dhabi [30]. This community is a fully inhabited 10-year-old development consisting of 1400 villas inhabited by nearly 7000 people. Analyzing the performance of this MG has shown that utilizing multiple RE sources is a more sustainable and cost-effective option for urban communities as compared to traditional grid systems [31]. The study showed that although there may be challenges in implementing such a system, there are many opportunities for cost reduction and environmental benefits.

The results of research carried out in the Emirate of Sharjah suggest that a solar–biomass hybrid system should meet up to 14 percent of the emirate's total annual electrical demand [32]. They analyzed technological pricing, effective energy accessibility, and hybrid renewable energy effectiveness, and determined that such a system would be more efficient, reliable, and environmentally friendly, resulting in reduced emissions.

At the domestic level, several researchers are proposing systems that can propel the country towards meeting its goals and commitments. Researchers have proposed a 4 kWh power supply for the UAE's domestic sector using three distinct photovoltaic technologies [33]. This study has shown that a central PV system produces lower carbon dioxide emissions than an off-grid system. The study by Reference [24] found that the adaptation of a grid-tied photovoltaic (GT-PV) system as a retrofit renewable energy model for single-family houses in UAE could be a viable option for reducing carbon emissions and contributing to the country's goal of becoming carbon neutral by 2050. However, the

study also identified some potential challenges that could impact the adoption of GT-PV systems, including limited space for solar panels and a lack of standardization.

Electric vehicles (EV) are transforming the transportation industry and the smart city concept in terms of lowering carbon emissions and noise, as well as heat pollution [12]. The article's findings suggest that while electric vehicles can help to reduce greenhouse gas emissions and improve energy security, there are still some significant challenges to their wider adoption.

3.1.3. Market and Investment

Market adoption of MGs as an investment in renewable energy resources and infrastructure is increasing globally and in the UAE. It is worth mentioning that government policy can boost the use of renewable energy, which affects the renewable energy market and consequently the MG market. Moreover, renewable energy adoption strategies and projects can cause market stimulation. Globally as well as in the UAE, governments are driving the market with incentives for renewable energy investors at the residential as well as the commercial level.

Another driver for understanding the level of investment needed for the adoption of MGs is the valuation models explaining the benefits of MGs. Reference [9] studied the attempt by the Emirate of Abu Dhabi to increase its share of renewable energy in the total energy mix from 25 percent by 2030 to 50 percent by 2050. The study provides insights into how this can be achieved through microgrid cost optimization. However, the study concluded that better valuation models are needed to help policy makers drive investments in MGs. These models are also relevant in the business context because Abu Dhabi needs to attract investments in renewable energy to meet its ambitious targets.

Reference [15] argued that a robust market design is required for successful outcomes while implementing a renewable energy plan. On the other hand, Reference [33] argued that high incidental solar radiation values, vast capital resources, expanding energy demands, worrying signs of climate change, and a desire to be one of the international leaders in renewable energy know-how all seem to be significant driving forces behind the UAE's willingness to invest in renewable technologies.

Reference [34] discussed the investment required and the potential market opportunities that exist for companies operating in this sector distributed generation and a smart power grid in the UAE. They also [35] provided a comprehensive review of the various aspects of the integration of renewable energy into the energy market. While not directly addressing market and investment, the integration of electric vehicles (EVs) into the power system under the vehicle to grid concept implies considerations for market dynamics and potential investments in EV-related infrastructure. Reference [36] studied the investment potential of renewable energy as an alternative to fossil fuels in the United Arab Emirates. They highlighted that the UAE has one of the highest per capita consumptions of energy and its reliance on imported fossil fuels makes it vulnerable to volatile international markets. As per Reference [18], the most significant barriers include high initial investment costs, lack of technical knowledge and expertise, and low awareness among the public. Another study carried out by Reference [15] highlighted that a well-designed market is necessary for the successful implementation of the UAE's 2050 energy.

Several researchers have investigated the investment potential for renewables in the UAE and concluded that smart microgrids have the potential to create new market opportunities and promote economic growth [16,26,29]. On the other hand, Reference [37] established in their study that one of the challenges for the implementation of smart grid technologies in the GCC region is the significant investment in infrastructure that is required.

3.1.4. Socio-economic Considerations

Policy makers need to account for the social as well as economic costs, which can even be monetized in some conditions [38]. The literature shows that there have been efforts

towards corporate social responsibility (CSR) in Abu Dhabi and the UAE in the field of renewable energy [39]. Although liberalization of the energy industry in the United Arab Emirates is unlikely in the near future, this should not prevent the implementation of a suitable strategy to incentivize small-scale renewable generators to join the industry and ensure a good profit for the company [18].

A number of works highlighted the potential socio-economic benefits of renewable energy, including its ability to create jobs and improve living standards [34,40]. The study by [29] examines the benefits of a smart microgrid in terms of energy and MG policy, carbon emissions and the environment, market and investment, socio-economic factors, and cost analysis. Specifically in the case of the Emirate of Abu Dhabi, the socio-economic context is crucial, as the emirate's renewable energy targets are not only about reducing carbon emissions, but also about creating jobs and boosting the economy [9]. The analysis in their work provides insights on how to ensure that the benefits of renewable energy projects are shared widely across society.

Reference [15] discuss how to maximize the UAE economy's energy productivity and state that safeguarding the interest of its people is the main objective of the research. The analysis revealed that factors, like infrastructure, institutions, and human capacity, play vital roles in energy transitions. Reference [14] discuss the potential for renewable energy policy implementation within the UAE by adopting the Australian 'Solar Town' program. The article discusses the socio-economic benefits that could be achieved through a wider adoption of REs, specifically solar PVs. The literature also provides an in-depth examination of the issues that caused the UAE to tackle the transition from a hydrocarbon-dominated society to a sustainable energy-driven one [17]. The microgrid body of literature based on the UAE is a limited one in which advanced socio-economic valuation models do not exist, such as the social cost–benefit analysis model by [41,42]. Even the updated UAE Energy Strategy emphasizes the importance of grid resiliency and enablers, such as the reliability and security of power supply and resilience of systems, by mentioning the technological tools needed without mentioning the microgrid [7].

3.1.5. Cost Analysis

It was anticipated that peak electricity distribution would be reduced by 15 percent in 2019 when the UAE would be able to generate 25 percent of its electricity through renewables [43]. This should have resulted in significant cost savings, as renewables would provide benefits, such as increased system stability, reduced peak power requirements, improved power supply, and reduced land use. However, the old infrastructure required constant expensive repairs and retrofits, not to mention the expansion that had to be compatible with its old technology and systems.

In the same line, it has been shown that government incentives on the retail cost of electricity are becoming a massive strain on government expenditures, as in [44] and [16]. Accordingly, the government has established incentives for adapting to renewable energies. These incentives lowered the entrance costs for private acquisition of renewable energy [10,19].

Numerous articles have evaluated the cost aspects of transitioning the UAE energy sector towards renewables. The article by Reference [40] discusses renewable energy policy initiatives in the UAE and Pakistan. It highlights the different types of renewable energy being used in these countries and compares the costs of various renewable energy technologies. The most significant barriers include high initial investment costs. The article by [25] discusses the options for transitioning to sustainable energy in the UAE and takes into consideration both the business and technology aspects. It looks at different types of renewable energy and evaluates the costs and benefits of each. They performed a techno-economic assessment of sustainable energy transition and found that under plausible assumptions for fossil fuel costs, the benefits of sustainable energy transition outweigh implementation costs. In general, the country's renewable energy strategies emphasize market stimulation with the intention to increase effectiveness and lower costs [10].

As a result, increasingly reliable and cost-effective renewable energy microgrids are becoming a reality. Such technologies are ideal for areas with inadequate electrical infrastructure. The goal is the development of a cost-effective method for supplying power to locations with inadequate power infrastructure, opening up new business prospects for large-scale deployment [28]. The feasibility of a renewable energy-based microgrids is tested in research testbeds, such as the one in a Al Futaisi island, but such studies are not intended to study microgrids as a country-wide grid modernization tool for the UAE [28]. It has been shown that photovoltaic distributed generation systems (PVDG) have the highest profitability and are strongly recommended for the UAE. Two pilot systems were erected for cost evaluation as energy sources for filtration systems in the Emirate of Abu Dhabi [26]. Additionally, the article by Reference [34] discusses the implementation of distributed generation and a smart power grid in the UAE by 2030. The study found that such an implementation would be beneficial for the UAE in terms of reducing emissions, improving grid reliability, and reducing costs.

In their study, Reference [45] determined that micro-turbines were the most cost-effective technique to minimize the total cost of microgrids. However, Reference [46] investigated the installation of wind and solar power independent microgrids to supply small communities in remote regions in the UAE. Microgrids have been used in remote regions traditionally until the emergence of the new approach to grid modernization that is based on DERs. No published work in the UAE specifically highlights the microgrid as an enabler for grid modernization. They performed a cost-benefit analysis of the installation and determined that solar energy in the UAE provides a more reliable power source. Moreover, it is more efficient and has a lower cost of implementation as compared to wind energy, as in References [33,46].

They also outlined some of the challenges that need to be overcome in order to make this happen, such as the need for a better understanding of the benefits and the costs of different technologies. According to References [33,47], a central photovoltaic system is the optimum option for the domestic sector in the UAE. Such a system is more cost effective and has a shorter payback period than an off-grid photovoltaic system. Furthermore, the central photovoltaic system produces less carbon dioxide emissions than the off-grid photovoltaic system.

Other possibilities for cost reduction include demand-side management for the generated electricity. This technique has the advantage of reducing overall electricity consumption, including peak demand, thereby making the grid more dependable. However, it has its own challenges, since it depends heavily on the availability of a real-time monitoring system [36]. Along the same lines, [37] have found that proper implementation and use of smart grid technologies, such as smart monitoring, has the potential of saving approximately USD 10 billion in energy costs. In general, Reference [48] found that microgrids have the potential to provide significant benefits in terms of power stability and cost savings.

The GCC region has made significant progress in renewable energy development in recent years [23]. However, a number of challenges still remain. These include the high cost of renewable energy technologies, a lack of skilled personnel, and limited financing options.

3.1.6. Opportunities and Challenges

Reference [39] outlined in their work how the integration of renewable energy provides opportunities in the UAE for energy companies, such as Masdar. Supporting corporate social responsibility aligns with DERs, which brings growth opportunities to energy companies. Accordingly, the research by [34] evaluated numerous types of distributed systems suited for nations, such as the UAE, and produced a comparison of power production vs. consumption in the UAE. Given the UAE's ever-increasing electricity consumption, it becomes an urgent necessity to investigate alternative sources, as the GCC today is keeping pace with the constantly increasing energy consumption. Energy plays an essential role as a generator of both business and residential life, and of rapid industrialization. Saudi Arabia is perhaps the leading user, accounting for nearly half of the overall consumption

in the GCC, followed by the UAE and Kuwait. Residential tariff changes were proposed in 2010 across many European countries, as well as in other countries, like Saudi Arabia and the United Arab Emirates. This shows that various governments recognized that the previous procedures had contributed to unproductive usage—and, thus, unbelievably high consumption levels. The UAE's nuclear capability has witnessed the most progress in the medium- and long term for large-scale generation capacity. The first reactor was completed in 2017 and the remaining three reactors were completed in 2020 [44].This makes MG more relevant to the UAE.

Among the most pressing current needs is dealing with grid weakness. The grid needs be able to withstand the effects of climate change and be more robust during natural disasters, such as typhoons and other extreme weather conditions [49]. Limitations include security, both software and hardware, resilience, and restarting after a major outage, such as during Cyclone Gonu on the eastern coast of the UAE in 2007 [50].

The study by [11] tackled the concerns and challenges associated with RE resource technology in the context of the UAE. The paper also discussed the potential and existing RE resource options for the UAE as well as the prospects for the future of this kind of technology. It is predicted that by utilizing RE technologies properly, and with proper forward planning, these technologies will provide an appropriate solution to the UAE's energy, economic, and environmental challenges. They highlighted that the most significant barrier in the innovation value chain was the technical "Valley of Death" which happens when a breakthrough invention moves from the lab to the market, necessitating switching from government finance to private capital. They concluded that the potential for RE in the UAE is quite strong.

Another issue is the growth in market demand—both in quality and quantity. Quality and reliability demands are particularly significant for businesses and commercial and industrial investors. In today's information age, e-commerce businesses rely heavily on cyber security due to the widespread use of the Internet of Things (IoT) and smart cities. Therefore, power quality and reliability are extremely important. These businesses require interruption-free supply and are sensitive to even the slightest grid vulnerabilities [51].

Reference [27] recommended an alternative to placing limits on the highest PV power production and monthly connection capacity for the elimination of the problem of intermittent uncontrollable distribution. It is by designing interconnection laws to deal with the technological improvements of the contemporary DER system in order to create an environment of opportunity. Among the challenges identified were that regulations are not applied to PV storage. Moreover, the maximum capacity of PV connections in Dubai was limited by grid codes based on total connected loads.

Another opportunity being discussed was that Fujairah had a higher rate of net energy injected and the performance was detected to be much better than the other areas of the UAE. The challenge is the weather conditions of the UAE, which are mostly dusty or really hot and, therefore, are not feasible for such an experiment [36]. The challenges revealed that when analyzing choices, it is common to have conflicting criteria: cost is usually one of the key criteria, and some measure of quality is another frequent factor, which is easily at odds with the cost [16].

Other problems and opportunities associated with the introduction of smart grid technology in the GCC region have been discussed. Several of the opportunities created by smart grids include a need for the governments of the region's countries to privatize power companies, encourage competitive industries rather than monopolies, expand the economy, create jobs, and resolve political tensions. Certain problems, such as a regional power market, the necessity for new legal agreements on purchasing and selling energy, a monopoly in power generation, and massive capital investment, are unavoidable. The benefits of smart grid installation in the GCC area outweigh potential challenges [37].

Another study discusses the attention given to renewable energy in the UAE. The study outlined that despite the implementation of numerous record-breaking RE projects, the country's rentier mindset, the inconsistent nature of biofuels, and geopolitical complications

may prevent it from appearing as a clear frontrunner in the transition. The UAE's difficulty remains a shortage of human resources, since it depends heavily on imported renewable energy technologies and foreign engineers. The UAE has a "window of opportunity" to diversify its energy mix due to falling oil and gas prices, as well as the environmental consequences of over dependence on fossil fuels [17].

3.1.7. Summary of Business Considerations

The surveyed papers showed that in the context of business-related issues around MG technology, research in the UAE is active and continually expanding. For policy, the literature results showed that the UAE has the potential for significant long-term energy savings through changes in policy, suggested a shift toward decentralized energy systems. Authors gave recommendations to policymakers by identifying the opportunities and challenges. It is noted that machine learning could help improve the charging part of the MG infrastructure and policies. Moreover, success can be achieved by applying policy within the UAE that is based on benchmarking other countries. Authors noted that policies are mainly state-managed and focus on mega projects. Involving all stakeholders and small projects as well as a mixed policy of feed-in-tariffs is recommended. Discussions on cost and carbon emission reduction are prevalent in the literature. The UAE's CO_2 emission vision favors GHG reduction, which is cheaper and more sophisticated. MG technology reduces the emissions per kWh of electricity generated. By 2050, rooftop solar photovoltaics in Abu Dhabi might reduce carbon emissions, energy costs, and grid efficiency.

Market and investment opportunities exist for emission reduction since the UAE committed to increasing its sustainability goals from 24% to 27% by 2021. Furthermore, the UAE pledged to cut carbon dioxide emissions by 70% and boost sustainable energy use by 50%. However, renewable energy costs are a problem. Due to demand variations in power quality and quantity, MG is needed. The UAE is well-positioned to use renewable solar energy.

UAE goals can be met with emission reduction solutions. A holistic integrated energy model was created to ensure a sustainable UAE energy transition. A solar–biomass hybrid system could meet 14% of the emirate's yearly electricity demand and reducing emissions. achieving UAE domestic supply goals using three photovoltaic technologies. Integrating PV into a microgrid would be reliable, durable, and increase energy efficiency, decreasing carbon emissions for UAE Vision 2050.

Cost-effective emission reduction was achieved by the Al Raha residential neighborhood microgrid. Grid-tied photovoltaic (GT-PV) and electric vehicles may reduce carbon emissions. For microgrid market investments, implementation of smart grid technologies requires significant investment in infrastructure. The UAE's government has the willingness to invest in renewable technologies. Microgrids have the potential to create new market opportunities and promote economic growth. However, better valuation models are needed to help policy makers drive investments in MGs. Among the most significant barriers are high initial investment costs, lack of technical knowledge and expertise, and low awareness among the public.

Among the socio-economic benefits of a renewable energy connected microgrid is its ability to create jobs. Masdar Energy Company benefited from corporate social responsibility (CSR) in Abu Dhabi and the UAE in the field of renewable energy, which shows the potential for the same when integrating MG. On the other hand, liberalization of the energy industry in the United Arab Emirates is unlikely in the near future, but this does not prevent the implementation of a suitable strategy to incentivize small-scale renewable generators. Research has shown that factors, like infrastructure, institutions, and human capacity, play vital roles in energy transitions. It demonstrates the socio-economic benefits that could be achieved through a wider adoption of REs, specifically solar PVs. The updated UAE Energy Strategy emphasizes the importance of grid resiliency and enablers, such as the reliability and security of the power supply which supports the socio-economic welfare of users. The

microgrid body of literature based on the UAE is limited, and advanced socio-economic valuation models do not exist, such as the social cost–benefit analysis model by [41,42].

For the cost aspect of the microgrid, the cost of electricity is becoming a massive strain on government expenditures. Under credible fossil fuel cost assumptions, sustainable energy transition benefits outweigh implementation costs. Renewable energy technologies are expensive, skilled workers are scarce, and financing is constrained. The biggest private sector obstacle is hefty initial investment expenses. Private renewable energy purchasing was made cheaper by government subsidies. Photovoltaic distributed generation systems (PVDG) are the most profitable and are recommended for the UAE. Micro-turbines were the most cost-effective way to reduce microgrid costs. For RE, UAE solar energy is more reliable. The implementation is cheaper and more efficient than wind energy. Central photovoltaic systems are best for UAE household use. This technology is cheaper and pays back faster than an off-grid photovoltaic system. Implementing and using smart grid technologies, like smart monitoring, can save USD 10 billion in energy costs. No UAE research highlights microgrids as grid modernizers.

Regarding challenges and opportunities, energy firms can grow by supporting DERs and corporate social responsibility. Businesses need uninterrupted supply and are sensitive to subtle grid risks. RE technology can solve the UAE's energy, economic, and environmental problems if used appropriately and planned earlier. Quality and cost are usually important factors. GCC smart grid installation has more benefits than drawbacks. For intermittent unpredictable distribution, microgrids can replace constraints on PV power generation and monthly connection capacity. It is important to design connectivity laws to address modern DER system technical advances to provide an opportunity environment. In 2010, various European countries, Saudi Arabia, and the UAE suggested residential tariff modifications. The region's governments must privatize power firms, promote competitive businesses over monopolies, grow the economy, and create jobs. New energy purchase and sale agreements are needed to avoid a power producing monopoly and large capital investment. Fujairah had a greater net energy injection rate and better performance than other UAE regions. Due to declining oil and gas costs and the environmental impact of fossil fuel dependence, the UAE can diversify its energy mix. Limitations include software and hardware security, resilience, and restarting after a large outage. Due to IoT and smart city applications, e-commerce enterprises depend on cyber security. Although carbon emission reduction is among the challenges, the research literature lacks a comprehensive model or framework that includes the social cost of carbon emissions in the UAE. Such a model would be an essential contribution, as it could help decision makers set regulations to promote the adoption of the MG paradigm, driving market growth and investment in this area.

3.2. Technology Consideration

An analysis of the literature based on technology considerations is important to highlight the contribution of the MG in terms of technological capabilities, such as the loads and DERs integration, efficient management of power through optimizations, and the breakthroughs in the capabilities of RE generation.

3.2.1. Types of Renewable Energy

Several research articles evaluated different combinations of RE sources with respect to the environmental and economic aspects of the UAE. Reference [46] concluded that when compared to wind energy, solar was the preferred source in the UAE. In another study, Reference [32] evaluated the use of a solar biomass hybrid model to electrify the Emirate of Sharjah. The hybrid model integrates biogas, biomass, biofuels (including ethanol and biodiesel), cogeneration, municipal solid waste, agricultural processing waste, and industrial waste as renewable sources in the microgrid. The work has shown that this hybrid system is not as feasible as solar PVs. Moreover, even though the UAE has enough

sun resources to generate power, the RE supply location is considered a constraint in and of itself.

One scientific study was conducted to evaluate the electricity production performance index and efficiency improvements of an 11kw grid-connected PV power plant in different emirates in the UAE. Compared to other emirates, Fujairah's network ranks the highest for larger net energy delivered to the grid and on arrays of system performance. Raising understanding of renewable power technology has led to an expansion in the adoption and installation of PV systems in the distribution network [36].

3.2.2. Optimization and Integration in Microgrids

Various assessment models of both efficiency and profitability of the MG have been studied in the literature. For example, an article discusses the conceptual architecture of a smart MG testbed for an isolated island in the Emirate of Abu Dhabi. The architecture's contribution is its originality in function and appearance. Reverse osmosis saltwater desalination provides power and water in an integrated utility strategy. The alternating current (AC) equipment is replaced with a high direct current (DC) power distribution network to show potential performance advantages. A synchronized power management plan to analyze, control, and optimize available energy resources was included [28]. Moreover, computational and statistical methods and software simulation were used to build and verify the design idea in [29,32].

Another article addresses numerous smart grid methodologies for the inclusion of DER, such as enhanced functionality of smart inverters, computerized demand response, and scientific and procedural enhancements for DER interconnection to enhance performance and lower its operational costs. This will enable wider implementation of roof-top power systems, resulting in the effectively implemented transformation of traditional power systems [27].

Reference [45] proposed an MG value engineering study for the UAE using genetic as well as ant-bee colony methods. Moreover, global information systems (GIS) data and a multi-criteria decision support method were employed to choose a certain location for RE infrastructure for major projects in solar energy in the UAE. The analytic hierarchy processes (AHP) method was used to determine the weight of the evaluation criteria. This research has identified the most favorable and the least suitable locations in the UAE for installing concentrated solar power (CSP) projects. The study's findings demonstrated that the UAE has multiple hotspots that could be used for CSP initiatives. The suitability maps reveal that the Emirate of Dubai has a higher appropriateness for CSP projects, whereas other hotspot locations for CSP projects have a lower suitability [16].

Another study carried out in Abu Dhabi concludes that Masdar has taken commendable steps towards the integration of sustainable energy technologies in Abu Dhabi and the UAE [39]. Moreover, a study contains fundamental modelling and simulation research on the smart microgrid system in Al Futaisi island, UAE. The hybrid AC-DC microgrid system is created by placing 75 percent of the sources on the AC side and the rest on the DC side. As a result, the project's end product will be useful in constructing an MG system to accomplish the goal of 7 percent RE penetration by 2020 [29]. Additional literature argued that only with the integration of automation and MGs can more RE penetration can be achieved. Another project determined the optimal arrangement to satisfy the needs of Sharjah city. It uses a micropower modelling framework to build a solar–biomass hybrid model to electrify the city. Reference [45] found that microgrids, with a combination of different power sources and optimization techniques, can significantly reduce costs and contribute to the regional power grid.

3.2.3. Summary on Technology Consideration

The types of renewable energy researched in the UAE linked to the MG are mainly solar and wind energy, and to a lesser extent, biogas. However, solar PV is the only primary type that is feasible and applicable on a large scale. Therefore, the research on

technology considerations is limited to experiments on the effectiveness of solar PVs. Mega solar PV projects in which the MG concept of demand-side management and variable energy generation and storage has been discussed and researched over the past few years. Researchers have analyzed and discussed the technology aspect of MGs in the UAE. The main finding is that solar PV should be the only technology considered for wide scale use in the UAE due to its economic feasibility and the abundant availability of solar energy in the UAE. Moreover, solar PV technology is relatively more efficient. For optimization, a synchronized power management plan to analyze, control, and optimize available energy resources was included. Smart grid techniques to include distributed energy resources (DER) include improved smart inverter functionality, computerized demand response, and scientific and procedural improvements for DER connections to improve efficiency and reduce operating costs. Finding the most and least suitable places in the United Arab Emirates for the installation of concentrated solar power (CSP) projects led to the successfully realized transition of traditional power systems. The results showed that there are several hotspots in the UAE that could be utilized for CSP projects. The Emirate of Dubai has a higher appropriateness for CSP projects, according to the suitability maps. More RE penetration can only be attained by integrating automation and MGs. The conclusion is that microgrids can considerably lower costs and support the local power system when they combine a variety of power sources and optimization strategies.

3.3. Research Methods Considerations

The analysis of research methods used in literature related to the MG in UAE can pinpoint the most effective and the different approaches used by researchers. Researchers varied their approach based on the types of data available and the results that they sought. Different assessment tools used provided a wider spectrum of results in the literature.

3.3.1. Assessment Tools/Research Method

The reviewed papers have shown that qualitative analysis was the most used evaluation method. This is due to the nature of the research on the socio-economic models for microgrids. Table 6 shows the distribution of the review pool with respect to the utilized analysis method.

Table 6. Distribution of the literature based on the analysis method.

Analysis Method	Number of Articles
Qualitative	10
Quantitative	2
Mixed	3

The qualitative method was used by [9,12,15–17,29,32,45,51].

Quantitative case studies were used in the works by [34,50], in which meteorological statistical data were used as a secondary source to perform the statistical analysis to evaluate profitability and probability, respectively. Mixed methods were used by [16,26,30].

The qualitative method seems to provide more comprehensive dimensions on microgrids due to its ability to cover the social, economic, environmental, and policy aspects. It is more feasible to use the mixed-methods approach when addressing social issues along with the cost–benefit analysis for investments and when providing a comprehensive model. Table 7 shows that data collection methods varied among reviewed papers. However, a review of the literature/records was the most frequent, followed by case studies, interviews, and secondary data, respectively.

The case study method was used more frequently since MGs differ from one case to another depending on their characteristics. It provides comparisons in terms of social, economic, and environmental impacts. It is better suited for comparing different policies as in the case of [10,14,51]. It is also used to study benefits, such as in [26], or to assess the

suitability of a certain geographic location, such as in [16], or the environmental impact in [12]. Case studies are used for exploring or investigating by [17,30,37]; cost optimization by [9,45]; effectiveness and benchmarking by [48], and comparing performances by [36].

Table 7. Distribution of data collection methods in the literature related to the UAE.

Data Collection Method	Number of Articles
Case study	12
Review	10
Interview	5
Secondary	4
Survey	2
Experimental	2
Observations	1
GIS	1

Interviews are used the most in the research on MG policy and the social, environmental, and economic aspects since it involves experts' opinions. Secondary data are used to support the qualitative research and verify the interviews' results as well as comparing and contrasting. Table 8 shows that the most common design and research method in the literature is the exploratory type, followed by the comparative, descriptive, and comprehensive types.

Table 8. Distribution of the literature with respect to the design and research method.

Design Type/Research Method	Number of Articles
Exploratory	4
Comparative	3
Descriptive	3
Comprehensive review	3
Evaluative	2
Experimental	1
Investigative	1

The exploratory approach studies the challenges, benefits, potential solutions, and technical–economic feasibility of MGs in the UAE, as seen in the works by [27,29,30,32,35,48]. It highlights current policy initiatives and possible incentive mechanisms [40].

The comparative analysis approach is used by [33,36,46] to compare case studies to highlight the differences in costs, benefits, and policy implications relative to different geographical locations. Moreover, it is used to benchmark performance and highlight possible solutions to challenges.

Descriptive and comprehensive methods are mainly used to elaborate on microgrid technology and business considerations, as well as the current state of the art in this area.

3.3.2. Summary of Research Methods Consideration

The qualitative research method is the most frequently used method in the analyzed literature. There are a variety of other research methods used with varying frequency. It seems that the topic is less frequently studied in numbers and using numerical data analysis. However, the quantitative method is used to assess economic feasibility as well as when optimizing using computer simulations. Case studies are used more often when collecting data for comparative and explorative analyses for policy, economic feasibility,

and environmental impacts. Interviews are the most used qualitative method due to the nature of the topic that relate to policy, and socio-economic and environmental factors in which expert opinion is necessary. For a mixed-methods approach in the reviewed topic, it is best to use a combination of case study and interviews with policy makers, small and medium enterprises (SMEs), and market specialists. Based on the literature survey, the most comprehensive method is a mixed method which is a combination of qualitative and quantitative research that assess social and economic factors, respectively.

4. Discussion and Recommendations

This section presents an analysis and discussion of the findings of this review. It will also present some recommendations for future research directions.

4.1. Critical Review

The synthesis of literature on microgrid development in the UAE reveals several key points:

1. Policy recommendations: According to the research, decentralized power systems have the potential to save the UAE a significant amount of money on electricity over the long run. A change in policy toward decentralized systems, international benchmarking, and a hybrid strategy incorporating feed-in-tariffs are among the suggestions. Another way to improve microgrid policies and infrastructure is machine learning.
2. CO_2 emission reduction: Microgrid technology is acknowledged as a practical means of lowering CO_2 emissions, in line with the United Arab Emirates' goal of having net-zero emissions by the year 2050. For Abu Dhabi, rooftop solar PV systems are thought to have a major role in lowering emissions. Although there are market and investment potential due to the UAE's dedication to sustainability goals and initiatives, issues like the cost of renewable energy have to be resolved.
3. Market investments: Significant infrastructure investment is needed in the UAE to implement smart grid technologies. Although the government is prepared to fund renewable energy projects, more accurate microgrid assessment models are required. Significant obstacles include poor public awareness, lack of technical expertise, and high initial investment expenses.
4. Socio-economic benefits: Microgrids have the potential to contribute to corporate social responsibility and create jobs, among other socio-economic benefits. The success of Masdar Energy Company in the renewable energy space shows that microgrid integration can provide comparable advantages. However, the absence of sophisticated socio-economic appraisal models tailored to microgrids in the United Arab Emirates is a considerable issue.
5. Cost considerations: The cost of electricity poses a burden on expenditures by governments, but the benefits of a sustainable energy transition outweigh the associated costs. The high cost of renewable energy technology, a shortage of qualified workers, and the scarcity of funding sources are obstacles. Micro-turbines and photovoltaic distributed generation systems are found to be economical choices.
6. Opportunities and challenges: Encouragement of corporate social responsibility provides growth potential for energy enterprises in line with distributed energy resources. Cost issues and the requirement for new legal agreements on energy trading present challenges. Microgrid technology is considered as an alternative to addressing issues related to intermittent power generation.
7. Technology considerations and optimization: In the UAE, solar energy is the most favored source, whereas hybrid models that combine many renewable sources are deemed less practical. Effective strategies for optimizing microgrid performance include synchronized power management plans and smart grid techniques, such as improved smart inverter capabilities. Achieving greater penetration of renewable energy requires the combination of microgrids and automation.

8. The most popular qualitative method is still conducting interviews, particularly when it comes to policy, socioeconomic, and environmental issues. For a thorough understanding, a mixed-methods approach that combines case studies and interviews with policymakers, SMEs, and market experts is recommended. The literature emphasizes the effectiveness of a mixed-methods approach for evaluating socio-economic factors holistically.
9. Most of the examined literature uses the qualitative research method. Quantitative approaches are used sparingly, mostly for computer simulations and economic feasibility. They are frequently used for exploratory and comparative analysis in case studies.

4.2. Literature Gap Analysis

Based on the preceding analysis of the literature, the following gaps have been identified:

1. There is a lack of policy research on microgrids in the UAE and policies issued by the UAE in the literature.
2. There is very little, if any, research on the enablers of UAE Vision 2050 for net-zero carbon emission. Carbon emission reduction is a leading topic supporting the viability of microgrids; however, not enough specific research is carried out on the benefits of implementing it in the UAE in terms of greenhouse gas reduction.
3. There are case studies on optimization and integration of microgrids and renewable energy; however, there is no single model or framework that comprehensively addresses social, economic, and environmental costs and benefits.
4. Despite the fact that massive opportunities exist in microgrids, the lack of valuation analysis frameworks and models make it difficult for investors and other stakeholders to capitalize on the benefits of microgrids, which are relatively vague and under analyzed.
5. There are no models considering ESG and social costs alongside monetary feasibility that are specific to the UAE.
6. Single microgrids were utilized in remote islands where they were the only option; however, in terms of converting the distribution grid to multiple microgrids, a feasible and strategically aligned model must be created.
7. Although carbon emission reduction is primary among the challenges, a comprehensive model or framework that calculates and includes the social cost is missing in the research literature.
8. The social cost of carbon emissions as well as a case study that is inclusive and tailored to the UAE is missing; therefore, it would be an essential contribution.

4.3. Recommendations on Future Research Directions

It is recommended that researchers continue in the direction of analyzing and testing microgrid policies that have been implemented worldwide and conducting socio-economic analyses to provide a policy supportive of microgrid implementation and market penetration. Microgrids in the UAE lack research in terms of investments, policy, and socio-economic analysis and modeling. Further research on these topics will enrich the literature, help policy makers further evaluate the value streams of microgrid technology, build on opportunities existing in it, and manage challenges, such as the cost and feasibility of long-term investments.

It is recommended that more research is carried out, targeting the viability of MGs in achieving the net-zero carbon target and on implementing it to support the UAE's strategic initiatives, such as UAE Vision 2050 in order to lower carbon emissions.

It is recommended that social costs and benefits of MGs in the UAE be examined carefully to consider all the hidden costs on society that can be saved by MGs. Moreover, ESG should be taken into consideration when valuing microgrids, especially for the UAE.

Additionally, it is highly recommended that a comprehensive framework be established to take into consideration MGs in the UAE, specifically in terms of socio-economic and environmental factors to better represent the value added by MG technology. Along

with established policy, this will drive investments and achieve carbon reduction goals, since its valuation will be more accurate.

It would further enrich the literature and provide clearer and more solid evidence on the socio-economic feasibility of MGs in the UAE by analyzing case studies specifically tailored to the UAE power market, society, and economy. As per the findings of this review paper, it is recommended that a socio-economic study be performed on an MG in the UAE. It will help in understanding the effects of MGs on carbon emissions, economic feasibility, and the UAE's ESG related regulations.

5. Conclusions and Policy Implications

This study provides a comprehensive review of literature on microgrids in the UAE, focusing on their socio-economic, environmental, and policy aspects. The analysis covered publications from 2011 to 2021, with a specific emphasis on microgrid installations in the UAE and the Gulf Cooperation Council (GCC) countries. A total of 33 papers were identified and classified based on their contributions to business and technology considerations, research methods employed, and analysis of policy, investments, and market penetration.

The findings highlight the significance of microgrid technology in the UAE and the GCC, with an observed lack of models/frameworks considering ESG (environmental, social, and governance) factors and socio-economic aspects specific to the UAE. While microgrids are predominantly utilized in remote islands, transitioning the distribution grid into an interconnected network of microgrids requires a comprehensive model.

Regarding business-related aspects, research in the UAE demonstrates a strong and growing focus on microgrid technology. Cost reduction and carbon emission challenges are prevalent topics, but a comprehensive model or framework that accounts for social costs remains absent. Creating a UAE-specific case study and addressing the social cost of carbon emissions are essential for informing decision-making and policy regulation, thus driving effective investments in microgrid technology.

Solar PV and wind energy are the primary renewable sources in the UAE, with solar PV proving economically feasible and readily available. Therefore, further research and implementation of solar PV technology are recommended due to its high viability in the UAE.

The review identified qualitative and quantitative research methods as the most effective for analyzing social aspects and conducting cost–benefit calculations, respectively. The use of mixed methods is optimal for assessing social and economic feasibility, policy analysis, and market evaluation.

Microgrids are less common in the UAE than they are in other countries, such as the US. In the UAE, remote islands and isolated regions are the main uses for microgrids. They are not commercialized or used extensively. Universities in the United Arab Emirates use many microgrids as test beds for electrical engineering research. In the United Arab Emirates, investment in renewable energy generation as a long-term strategy is being considered seriously but not yet for the microgrid. There is not much literature in the UAE on microgrids in general, much less microgrid management and strategy. In the UAE, the microgrid is still not widely used as a tool for grid disaster recovery nor as a tool for enabling renewable energy.

Specifically, for the mentioned research questions, each was answered through the literature analysis. The socio-economic costs and benefits, policy frameworks, market dynamics, and environmental implications of microgrid development in the United Arab Emirates were some of the major issues this research explored. First, it examines the socioeconomic costs and advantages of microgrid development, focusing on issues, like quality enhancement, power resilience, minimizing environmental damages, and economic growth. Second, the study looks at the regulations and policies that currently govern the installation of microgrids in the United Arab Emirates. It finds that there is not a single policy that is specifically focused on microgrids. Thirdly, it explores the market dynamics and obstacles surrounding the widespread use of microgrids in the United

Arab Emirates. It identifies cost as the main barrier and goes over possible solutions. The study also investigates valuation methods for evaluating the economic viability and efficiency of microgrids, emphasizing the lack of a particular model and advocating for a thorough analysis of ESG issues that microgrid can be evaluated on its bases. UAE's vision with respect to CO_2 emissions is totally aligned with benefits provided by the microgrid. Opportunities and challenges are discussed considering the reviewed papers and relating to the UAE's microgrid further adoption.

The discussion lists our nine major findings and eight major gaps. The discussion concludes with an investigation of how the UAE's vision for net-zero emissions by 2050 aligns with the potential role of microgrids. This highlights the critical role that microgrids play in realizing this ambitious goal and suggests long-term optimization strategies and approaches for their successful integration into the UAE's energy future.

For effective policies, the literature on UAE microgrid development promotes hybrid approaches, international benchmarking, and policy adjustments. Microgrids have the potential to lower CO_2 emissions; however, there are still issues with infrastructural gaps and the cost of renewable energy. Although they have socio-economic advantages, there is a problem with the absence of customized appraisal models. To emphasize the need for a mixed-methods approach, cost considerations, potential for energy firms, and technology optimization are addressed.

Significant gaps were identified, including the absence of a comprehensive model/framework that accurately assesses the value of microgrids in the UAE, incorporating ESG factors. Additionally, there is a need for further research to inform policymakers and promote the increased market penetration of microgrids aligned with the UAE's goal of achieving net-zero carbon emissions by 2050. Recommendations are provided for each gap, emphasizing the necessity of designing a comprehensive valuation framework for microgrids in the UAE.

In conclusion, this research highlights the importance of addressing socio-economic, environmental, policy, and market aspects of microgrid development in the UAE. By filling the identified gaps and implementing the recommended actions, stakeholders can effectively harness the potential of microgrids and contribute to the realization of the UAE's sustainable energy vision.

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