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The Integrating Renewable Energy into Saudi Arabia's Power Grid

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Abstract

The current dissertation focuses on injecting renewable energy sources into the Saudi power grid to foster energy sustainability with environmental concerns, as advocated for in Saudi Vision 2030. The paper assesses the applicability of the identified efficient solar and wind energy technologies by investigating the technological, economic, societal and environmental sub-systems in the context of Saudi Arabia in its attempt to diversify from the excessive use of fossil fuel energy. Using surveys, interviews, and secondary data, the questions posed guide the analysis and are centred on the viability, advantages, and difficulties of incorporating renewable energy in power systems. The research identifies considerable potential for the country's solar and wind potential, but understanding the issues related to the technology mix, stability of the grid structure, high initial costs, and infrastructure requirements is essential. Moreover, other social and environmental conditions, such as local acceptance and legal requisites in the hosting society, are critical to RE projects. The primary threat related to the transition into renewable energy sources and their viability comprises significant advantages of the transition, including carbon emission reduction, energy security, and economic resilience, making the transition into renewables a strategic investment for Saudi Arabia. It is necessary to pursue the grid, which involves the creation of a favourable environment for small self-sufficient power facilities and increasing public awareness efforts required to shift the nation towards renewable energy.

تتناول هذه الأطروحة دمج مصادر الطاقة المتجددة في شبكة الكهرباء في المملكة العربية السعودية، بما يتماشى مع أهداف رؤية 2030 لتحقيق استدامة الطاقة والمسؤولية البيئية. ومن خلال تحليل الجوانب الفنية والاقتصادية والاجتماعية والبيئية، تستكشف الدراسة إمكانات الطاقة الشمسية وطاقة الرياح لتنويع مصادر الطاقة في المملكة وتقليل الاعتماد على الوقود الأحفوري. باستخدام منهجية بحث مختلطة الأساليب، تم جمع البيانات من خلال الاستبيانات والمقابلات والمصادر الثانوية للإجابة على أسئلة البحث التي تركز على جدوى وفوائد وتحديات دمج الطاقة المتجددة. وتكشف النتائج أنه على الرغم من أن موارد الطاقة الشمسية وطاقة الرياح الوفيرة في المملكة العربية السعودية توفر إمكانات كبيرة، فإن التحديات التقنية مثل استقرار الشبكة، والتكاليف الأولية المرتفعة، والحاجة إلى البنية التحتية تتطلب معالجة شاملة. علاوة على ذلك، تعتبر العوامل الاجتماعية والبيئية مثل القبول العام والأطر التنظيمية حاسمة لنجاح مشاريع الطاقة المتجددة. وتخلص الدراسة إلى أنه على الرغم من التحديات الأولية، فإن الفوائد طويلة المدى - مثل تقليل انبعاثات الكربون، وتعزيز أمن الطاقة، والمرونة الاقتصادية - تجعل التحول إلى الطاقة المتجددة استثمارًا استراتيجيًا للمملكة. وتشمل التوصيات مواصلة الاستثمار في تحديث الشبكات، واعتماد سياسات تدعم إنتاج الطاقة اللامركزي، وإطلاق مبادرات التوعية العامة لتحقيق مستقبل الطاقة المستدامة.

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CHAPTER 1: INTRODUCTION

Background

Change management in the electricity generation sector worldwide also faces several challenges concerning integrating RESs into the electricity supply. Currently, the energy sector can be mainly linked to the availability of natural oil resources in a given country. Though RESs are random, uncontrollable, variable and mostly unpredictable, they are one of the many ways to contribute towards the attainment of sustainable electricity supply, and hence they impact the reliability and power quality of the supply system. Given that, a change in grid dynamics is inevitable, most commonly preferred RE technologies require auxiliary support. To tackle these challenges, one requires improved control strategies, the desire to extract higher value services from deregulation, a colossal monitoring system, and infrastructure support for an expressive communication network (Khan et al., 2023).

As with many other global complexities in smart grid integration reported here, the conventional power grid system in Saudi Arabia has drawbacks like high transmission losses, low efficiency, and low integration of RES. Hence, there is a necessity for a new power grid designed for today's world, let alone tomorrow's world.

Today's electric power network has been developed only in the last decades. A central generation unit delivers electrical power through transformers and various levels of the transmission system. The ratings of the central generation units, nuclear, hydro, and fossil fuel, vary to thousands of MW. The transmission network associated with significant generation segments already have compatible communication infrastructure that enables acceptability or, at best, the commercial level of system synchronisation at reasonable levels of security and reliability coupled with a centralised energy market (Yan et al., 2013; Khan et al., 2023). Therefore, the distribution network has a relatively high degree of network connectivity with comparatively low integrated communication links, which enables the application of modern control theories to be implemented effectively to exert local control on the distribution network. Similarly, communication links are severely lacking in real-time control to address

power quality issues, especially in large loads where the link only affirms the power supply delivery as requested by the load (Khramshin et al., 2015). Combining such variable RESs with the present stochastic load demand requires advancement to smart energy, communication, and information systems that will revolutionize the power grid.

Saudi Arabia is an oil-rich country that is the source of revenue with about 15% of the world's oil reserves. Since the beginning of the public presence of Saudi Vision 2030 in 2016, its goals have been to modernise sustainable energy systems and invest in renewable water systematically, energy sources, markets and other related activities of the private and industrial business complexes that try to improve employment opportunities and foreigners 'interests (Council et al., 2022). Therefore, numerous organisation organizations to advance and support the accomplishment of the Saudi Vision 2030 encompass the realm of the Renewable Energy Project Development Office (REPDO), King Abdullah City for Atomic and Renewable Energy (K.A. CARE) and the National Renewable Energy Program (NREP) located in the country ministry of energy (MoE). Both REPDO and NREP play their roles in the planning, identification, tracking and implementation of phases of many RE projects all over the Kingdom of Saudi Arabia, apart from exercising the due diligence, increased percentage of RE generation, RE project roll out and bidding and RE localisation (Abdul et al., T, Al-Rashed, 2019).

For many years, Saudi Arabia has been branded internationally as possessing massive proven oil reserves and market muscle within the global petroleum industry. It is, therefore, at a critical juncture in its evolution to sustainable energy. It has long relied on the oil market due to the realisation that the oil sector forms almost 50% of the Kingdom's GDP and about 70% of export revenues, as Ramady (2010) noted.

However, these fossil fuels have become a strategic concern due to their environs, instability of oil prices, and scarcity of fossil fuel deposits. Therefore, according to GCB and world data, the per capita CO₂ Emissions from fossil fuels in KSA have been usurped from 1998 to Al-Gahtani 2024. Analysing Saudi Arabian renewable energy policies allows for recognizing how Saudi Arabia is aligning itself with

international renewable energy goals and objectives. Mansouri and Al-Sarihi explained Saudi Arabia Vision 2030's vision and renewables goals. The investment climate, regulations, and technology adaptation need to attract significant focus to realise such goals. From this vision, one may compare ourselves with countries like Germany and China, which are presently embracing renewable energy sources and get the lessons and the drawbacks of such a course. For example, Lei et al., 2023, state that while the German Energiewende is a transition process, it can also be used to increase the number of renewable power generators, integrate the public, and phase out nuclear power, according to von Hirschhausen 2014. Similarly, Zhao et al. outline China's synergy of over-reliance on governmental aid and technological intervention to improve Saudi Arabia's possible policy matrix comparatively (Zhao et al., 2022). Using these comparative analyses, this research intends to understand the possibilities and challenges in the adoption of renewable power in the Saudi Arabian utility grid. It will then consider the analysis in relation to its technical, economic, and social aspects for the scope of purpose.

Research Problem:

Development impact: Saudi Arabia's economy is mainly driven by fossil fuels, and the country is the leading producer of CO₂ emissions. However, under the newest ambitious plan called Saudi Vision 2030, Saudi Arabia strives to shift towards sustainable supply to satisfy the increasing environmental and energy needs. The research questions of this study are as follows: How can renewable energy technologies, mainly solar and wind, be feasibly integrated into the Saudi power grid? This one is a technological, economical, societal and environmental issue. Most of these challenges and the potential of renewable integration in the Kingdom will help in achieving the global goals of energy sustainability and reduction of carbon footprint. The existence of this research serves as significant for Saudi Arabia especially when promoted the use of renewable energy in the country that causes economical growth and sustainability, enhance public health by cutting down pollutants and air pollutions, and promote the worldwide fight of environment conservation.

Importance of the Study:

Theoretical and practical implications of the study can be derived for the scientific community and for practical application. Academically, it contributes to knowledge of renewable energy integration by focusing on Saudi Arabian conditions, a country with high solar and wind potential but heavily relying on fossil fuel. Consequently, this research provides important information on energy technology, grid stability as well sustainable practices that are useful to similar fossil-reliant nations. Implicitly the study enlightens policymakers, engineers and environmentalists by enumerating practical solutions actions to integration hurdles, such as infrastructural demands, public acceptance, and legal frameworks. It is important to address these elements to improve the prospects for transition towards the diversified energy sector meeting the goals of Vision 2030 in the areas of energy security, economic diversification, and environmental sustainability.

Study Objectives:

The study aims to achieve the following objectives:

Evaluate the suitability of solar and wind energy systems for application in integrating Saudi power grid systems.

Examine and evaluate the factors of technology, economical, social and environmental that may have impact on the Saudi Arabia's RE adoption.

Assess the opportunities for RE integration, such as emission cut, energy security and economic robustness.

Understand the obstacles that come with RE integration such as- grid issues, high RE capital costs, RE infrastructure, and social acceptance.

As such, make policy suggestions and guidelines to Market stakeholders and other decision makers on strategies for increasing the level of renewables uptake in Saudi Arabia.

Theoretical Literature of the Study:

A theoretical framework that is adopted in this research is Sociotechnical Systems Theory with focus on the social, technical and contextual factors concerning renewable energy integration. The mentioned principles of the theory correspond to the study, as the latter is devoted to the interaction between technology advancements and social and environmental needs and demands for sustainable solutions. Key dimensions include:

Technological Feasibility: Analyzing the solar and wind power technologies more particularly in the context of efficiency and compatibility with the existing grid system and relaxed, stringent and average maintenance frequency.

Economic Viability: Investigating the cost of infrastructure development, systems installation, and recurrent and accretive costs with emphasis on the costs avoided through reduction on demands for fossil fuels.

Societal Acceptance: Studying cultural perceptions and awareness of the society with regards to renewable energy sources and investigating how it informs locals' support.

Environmental Impact: Assessing the expectations, including hoping to mitigate emissions and enhance the quality of air, in expectation of Vision 2030's sustainability objectives.

Sociotechnical systems theory will be used to formulate hypothesis for this research especially concerning the level of acceptance, regulatory environment and level of technology of RE technologies in the KSA. This theoretical background is helpful for a comprehensive understanding of the problem and shows the existing relationships that may influence the utilisation of renewable sources.

CHAPTER 2: LITERATURE REVIEW

Overview of Renewable Energy Sources: Solar and Wind Energy

Renewable energy sources have become even more popular in recent years because they are cheap, friendly to the environment, and likely to curb the effects of climate change (Al-Gahtani, 2024). Solar and wind power have been believed to be the most promising energy sources, and they are characterised by rapid technological development and huge popularity worldwide. Energy sources are resources generated from natural physical phenomena that can be replenished quickly and are, therefore, more environmentally friendly than fossil energy sources. One of them is solar energy, which uses PV cells to capture solar radiation in the form of energy that generates electricity (IPCC, 2012). Like wind energy, another important renewable energy source, wind energy is produced through wind turbines and mostly in wind energy farms. Hydropower is the largest source of renewable electricity; it harnesses the energy from flowing water to deliver electricity through dams or river systems (Kumar et al., 2023). Hydrothermal energy is an emerging form that harnesses the heat from within the earth, especially from geothermal active zones and uses it for heating and electricity. Bioenergy, which is bioenergy from organic matter such as biomass and biogas, use waste products or crops exclusively grown for either warmth, electricity, or biofuels (Reddy et al., 2024). Altogether, these forms of renewable energy sources are useful in the fight against greenhouse gas emissions, decreasing the utilisation of exhaustible fossil energy sources, and in the battle against climate change. These types of renewable energy sources are becoming feasible worldwide as technology continues to evolve to make energy generally cheap (Reddy et al., 2024).

Solar and wind energy are among the most promising renewable energy sources, as each has significant significance in developing clean energy worldwide (Gielen & Boshell, 2019). Solar energy chiefly depends upon photovoltaic, or PV, technology that converts light directly to electricity and is applied across residential, commercial and utility-scale projects. Subtypes or types of PV systems are as follows: The elemental asymptotic advance of PV systems has enhanced efficiency and diminished cost.

Likewise, the solar thermal system utilises solar irradiation to generate heat suitable for large-scale power plants Hassan et al., 2024. All around the world, policies, low prices, and the applicability of solar energy in countries abundant in sunlight, such as China, the USA and India, have enhanced the adoption of solar energy (Maka & Alabid, 2022). Wind energy is another favourable technique that harnesses the kinetic force of wind using blades installed in a generator (Edgardo-Portillo et al., 2019). The two general configurations include onshore and offshore wind farms, the latter characterised by improved and steady wind velocities. Wind turbines are becoming more efficient, lighter, and durable, enhancing the wind power industry, especially in countries with strong winds, such as China, the US, and Europe. Combined, solar and wind energy constitute part of the global energy mix capable of achieving low carbon energy growth to address increasing energy demand and achieve transformation to the new era of environmentally friendly energy systems (Desalegn et al., 2022).

Global Trends in Renewable Energy:

Renewable energy sources have attracted considerable attention and have experienced remarkable growth over the last decade for several reasons, including climate change concerns, energy security, and the decreasing cost of renewable technology sources (Hassan et al., 2024). There is an increasing trend in the global uptake of renewable energy since countries realise the importance of clean energy in the environment, economy, and society (Osman et al., 2022).

The most emerging trend is the installed renewable power capacity, where solar and wind installation rates are skyrocketing every year worldwide. This increase is due to technology development and the easing of costs of renewable energy technologies, hence becoming equivalent to fossil energies (Osman et al., 2022). The second focal point consists of supportive policy frameworks stemming from governments' worldwide policies, such as feed-in tariffs, tax credits or specific renewable energy targets to stimulate investments in clean energy and save from fossil energies (Osman et al., 2022).

Another trend is the diversification of renewable energy sources. Therefore, the trends show rather the development of a wider range of clean energy technologies. However, solar and wind remain

the two most popular forms of REs, whereas other forms, including hydropower, geothermal, and bioenergy, are becoming more prevalent in certain zones. Such diversification is necessary to maintain a blend of power sources and to counter the unpredictability of solar and wind power. Furthermore, improvement in storage technologies, especially in battery systems whereby renewable energy can be stored and dispatched as and when required, will help improve the integration of renewables into national grids (Amir et al., 2023). Developing countries are also now assuming a more and more critical position in the renewable energy market. For instance, China has made big advances in obtaining renewable energy by investing in solar and wind projects, equipment, and technology, and it is becoming the benchmark for renewable energy production (He et al., 2018). China has emerged as one of the largest energy investors in renewable projects and manufacturing capabilities for most renewable components. The other impactful player studied is India, which has ambitious RE targets that include other technologies beyond PV and wind power.

The current political policies target the development of renewable energy systems in India to reduce the country's reliance on conventional energy sources (Yang et al., 2024). These trends demonstrate the global transition towards the future based on sustainable energy sources. Renewable energy is also becoming firmly integrated into the global energy mix as the sources become cheaper, more diverse, and with broader support (Yang et al., 2024). Leading developed nations along with other emerging economies, with the help of technologies, policies, and a better understanding of climate requirements, are making renewable energy the key point for constructing sustainable and future energy systems (Chou et 2023). As technology, policy, and investments in renewable energy infrastructure expand, the trend towards renewable energy consumption will also advance, making the world cleaner (Chou et al., 2023).

For that matter, the experiences of Germany, Denmark and China in integrating renewable energy into the national grid are insightful for global change. The German Energiewende is an exciting example of a systemic and aggressive conversion to renewable electricity, particularly recognised from the sun

and wind power (Yang, 2022). Germany has achieved relatively good results in boosting its renewable energy generation, primarily through strong policy mechanisms such as feed-in tariffs and long-term regulatory objectives for renewable power generation (Yang, 2022). However, Energiewende has brought out the need for grid upgrades to deal with the intermittency of solar and wind resources, among other renewable energy sources (Alshehhi et al., 2024). Community involvement has also proved useful, as Germany has involved communities in supporting renewable power. It has been discovered that such renewable projects will not be sustainable without the populace's support. Germany's experience proves that policy support, regulatory certainty, and social involvement are all needed to promote renewable energy nationwide (Alshehhi et al., 2024).

In this scenario, Denmark has provided a clear example of how early investment and research in wind power initiatives can be fruitful. Denmark is considered a pioneering wind energy country, and rather high wind power penetration levels have been reached due to innovation and technological development (Wieczorek et al., 2015). The initial investment in research and the orientation toward the offshore format allowed the Danish country to receive much energy from the nearshore zones with increased wind activity. Furthermore, Denmark provides an excellent example of integrated efforts across sectors; the Danish government, industry and academia have been the main forces behind developing advanced wind technologies and the efficient architecture of the supporting system. They show that Denmark proves that research and development, alongside vital partnerships, contribute to the competitive and sustainable development of renewable energy sources integration.

China's strategy concerning the renewal of energy sources focuses on capability expansion and the outcome of large investments and government backing (Jiang & Muhammad Yousaf Raza, 2023). China has emphatically aimed at increasing the use of renewable energy. This has been facilitated by worthy industrial policies and healthy financial support that has put the country among global players in using renewable energy. Ample solar and wind power investments, integrated homegrown manufacturing capacities, and domestic production efficiency reduced the costs of renewable power components and

reinforced economic growth in China (Ekonomou & Menegaki, 2023). These accomplishments are added to the recognition that focusing on building domestic manufacturing has helped China cut costs significantly and build a strong economy by creating employment. Nevertheless, the Chinese experience also shows that grid integration and storage are needed because China's experience reveals managing fluctuating renewable generation and demand issues. Analysing China's performance, Bian et al. (2024) have proved that government policies, industrial strategies, and a focus on energy storage are the keystones of the efficient scaling of renewable energy.

Each of these cases has several lessons to offer those interested in integrating renewables efficiently. There is evidence that the few countries that have successfully scaled up renewable energy have done this backed by coherent policy support, regulation and awareness creation, and sustained commitment to the innovation and development of the technology. The case of Germany, Denmark and China has demonstrated that such strategies can be used flexibly in different settings, and there are no universal solutions. Given that countries across the globe are fighting global warming or aiming to achieve energy independence, the experience of these leaders of renewable energy has the great potential to provide positive cues for success as well as future course corrections (Kanchan et al. et al., 2024). To ensure renewable energy will play a more significant role in developing a sustainable future for the world since it has strong policy support and people's acceptance, as well as constant innovation) (Hassan et Al., 2024).

Renewable Energy in Saudi Arabia:

Saudi Arabia has shifted to a new direction of renewable energy transition, a country that depended on oil and gas for many years. Being endowed with sufficient solar and wind energy, the Kingdom can become a true leader in the sphere of renewable energy sources production. In this literature review, the author discusses Saudi Arabia's renewable energy prospects, policies, solar and wind power, and present capacity (Alsulami et Al., 2024).

The potential in the renewable energy market is highly promising in Saudi Arabia, especially in the sun and wind business. The vast desert areas of the country get consistent sun exposure year-round, making them suitable for mass solar power projects. Also, potential wind resources in coastal areas such as the Red Sea region are incontrovertible and capable of supporting large wind power projects. Being aware of the strengths of the natural environment, Saudi Arabia has set the goal of diversifying its energy mix and intensity (Alsulami et al., S, 2024). One of the main causes of such change is Saudi Vision 2030, an economic and social reform plan to diversify the Kingdom's economy (Vision 2030, 2016). RE is an essential pillar of this vision since Saudi Arabia has promised to become an environmentally sustainable country. Another major project is the Renewable Energy Project (REP), aiming at the construction of at least 60 GW of Renewable Energy by 2030, illustrating the Kingdom's intention to tap into its Renewable Energy resource (Middle et al., 2024). Also, the Saudi Green Initiative (SGI) supports the environmental targets, starting with adding renewable energy solutions while having the climate plan and nature protection as secondary goals (greeninitiatives.gov.sa, 2024).

By these measures, Saudi Arabia is setting the stage for a more sustainable energy future domestically and for global climate change initiatives using its resources (greeninitiatives.gov.sa, 2024). Solar power takes the lion's share of Saudi Arabia's renewable energy plan, with many big projects under construction. The Sakaka Solar Power Plant located in the Al Jouf region is a novel project and one of the world's largest solar schemes as a testament to this realisation that represents a new era of advancement in the country's resource mobilisation for power generation through using sustainable energy resources with an emphasis on solar energy (Vision2030, 2023). Comparably, the Dumat Al-Jandal Solar Power Plant is another large-scale project that helps the country improve its renewable energy potential (Imam et al., 2024). Such steps not only suggest that Saudi Arabia is keen on investing in the sphere of solar power generation but illustrate that the country is also interested in making the most of the country's fortunate geographical location in successfully implementing large-scale solar projects across large expanses of the desert.

Similarly, there is significant potential for wind energy in Saudi Arabia, the Red Sea, and the Arabian Gulf provinces to anchor themselves primarily on renewable solar energy for now (Pantelis Kiriakidis et al., 2024).

However, current construction projects suggest that further advancements in wind energy remain favourable, including offshore wind power plants that will work well with the solar system. Overall, renewable sources offer a strong portfolio for increasing Saudi Arabia's energy mix diversification (Eldin, 2024). Today, Saudi Arabia's renewable energy generation capability is still limited compared to its large fossil energy generation capacity. However, the current government with high set-RE targets and boosted investment in renewable energy indicates a change in the system (Eldin, 2024). Focused projects like Vision 2030 and the Renewable Energy Project, which has the hiked-up goal of generating 60 GW of renewable energy by 2030, readies Saudi Arabia for an influential role in the renewable energy market. The Saudi Green Initiative builds on the country's commitment to theGreen Repeats and improving its environmental footprint (Vision 2030 digital, 2023)

Lastly, Saudi Arabia has tremendous potential in T&S and solar energy; new government guidelines and large investments capitalise on renewable energy. Reducing its dependence on oil and incorporating more renewable energy sources, Saudi Arabia is actively making its energy portfolio more sustainable and proactively tackling the problems associated with climate change. The unprecedented progression of renewable energy projects is expected to ensure the sustainable supply of the Kingdom's energy requirements and deepen its engagement in addressing international climate change.

Previous Studies on Grid Integration:

First, the penetration of renewable energy technologies, specifically solar and wind, into already-existent power systems is a technical and economic issue. These challenges are further compounded, especially in countries or regions experiencing high solar and wind power production variability, like Saudi Arabia (Ukoba et al.,2024). Storing and connecting renewable energy sources to power systems implies multiple technical and financial issues as the proportion of renewable energy sources increases.

One such challenge is grid stability, as most renewable platforms, such as solar and wind energy markets, are variable and constitute changes in speed and voltage that may destabilise the grid, particularly during periods of low generation (Solar, 2024). This volatility is best addressed by the grid itself, which needs fortification, occasionally through major expenditures in additional capacities such as new transmission lines, substations, etc. to facilitate large-scale renewable schemes (Solar, 2024). Also, renewable energy sources can contribute to power quality problems like harmonics and voltage fluctuations that will affect other devices connected to the voltage grid and, therefore, need power quality control measures (Solar, 2024).

Economy-wise, the following are the challenges that confront renewable energy projects. At first, requirements for large-scale solar and wind power projects are high investments, which restrict the pace of adoption of renewable energy where financial resources are constrained (Susskind et al., 2022). Other costs owed to grid balancing are another factor influencing the overhead, as integrating renewable power necessitates balancing resources such as gas power plants and energy storage, among others, raising operational costs. In addition, markets and policies are also important; a weak policy environment, proper policies, and markets can hinder the development of renewable energy projects, but most of the global regions, despite having abundant resources for renewable energy (Ammar et al., 2023).

Given that the renewable grid integration process is relatively nascent in Saudi Arabia, lessons can be learned from similar climates and renewable resources in other parts of the world (Selim & Alshareef, 2024). For example, the United Arab Emirates (UAE) has enhanced renewable integration by leveraging grid enhancements and energy storage systems by facilitating policy systems (Alnaqbi & Alami, 2023). Investigating the grid flexibility and stability concept shows that the UAE's experience can be useful for Saudi Arabia's development.

Australia also has a high renewable share on the grid, especially in solar PV and faced some issues, such as inertia and frequency control of the grid, that are relevant to the Saudi context (Alqahtani et al., 2023). Something that can still be learned from California, even though it is among the world

leaders in terms of renewable energy deployment, is that the state has also found complex answers to flexibility, demand response and energy storage problems that come from high levels of renewable penetration (D'Ettorre et al., 2022). Thus, Saudi Arabia can learn from these case studies and avoid some of the technical and economic issues arising from renewable energy. By making required and strategically located investments in grids, policies, and efficient market structures, the country's abundant solar and wind resources can be effectively harnessed to deliver the country's energy transition goals.

Thus, only future research can provide the proper ways of addressing technical and economic issues related to the full-scale integration of renewable energy into the power system of Saudi Arabia. In grid modernisation, more emphasis needs to be laid on research regarding the efficient way to improve the existing grid infrastructure in the country to incorporate a more significant proportion of RE generation (D'Ettorre et al., 2022). This also refers to future energy distribution networks, including smart grid systems, which are innovative technologies that improve the monitoring, collection of data, and management of variations in energy supply and demand. Another research priority area is energy storage technologies, which will determine the economic feasibility of potential solutions and the technical applicability of systems like lithium-ion batteries and pumped hydro storage to cope with fluctuations in renewable energy sources in Saudi Arabia. These technologies are cost-effective and reliable and can be adopted on a large scale, thus helping to support renewable energy capacity (Panda et al., 2023).

Creation of such enable policies and regulations is also important in the promotion of renewable energy systems. The Saudi Arabian case suggests that the two strategies have their advantages and disadvantages in supporting renewables, and the future research might benefit from analysing the effectiveness of each policy instrument, including tax incentives, renewable energy targets, and feed-in tariffs. However, more potentials for mode 2 flexibility and control are needed to enhance the control of fluctuating renewable sources of electricity and another stable supply. More innovative demand control systems including

demand response programs and smart grid optimizing tools may help to enhance the prospect of grid buffer and stability in face of fluctuating renewable energy sources (Noor et al., 2024).

Another potential area of research can be identified in international cooperation. Elaboration of knowledge exchange with the countries which have had some experience in deploying REs – in particular UAE, Australia, and Germany will help Saudi Arabia deploy only the best practices and avoid different bumps in the road. From this point of view, Saudi Arabia can obtain new knowledge, technologies, and policies that will help the country to overcome the limitations on the way to low-carbon energy production and consumption (Alsulami et al., 2024).

Strengthening integration of renewable energy to the kingdom's electrical network depends on the development of the following research areas in Saudi Arabia: The research findings will therefore offer insights into the prospect of designing a renewable energy system that is both, reliable and flexible; while being economically feasible. If Saudi Arabia is to meet its sustainable energy targets, adopt effective strategies derived from the two countries' case studies, and invest in innovative solutions, which will consequently contribute towards climate change action.

Challenges and Opportunities

The integration of renewable energy sources, such as solar and wind power, into existing power grids presents several significant challenges:

Integration of renewable energy sources has significant barriers, this because they are intermittent, have limited storage and troublesome grid connection. Renewable resources like solar and wind power are quite unpredictable because their availability depends on the weather conditions; this irregular power supply disturbs the grid's frequency and voltage, leading to grid instability (Hassan et al., 2023). This unreversed pattern makes it challenging to achieve a reliable electric supply and steady demand; consequently, overseeing requires contingent planning and operation to guarantee a stable power supply (Hassan et al., 2023). This is important in dealing with the intermittency of renewable

energy sources, but the technology is still expensive. Objects like batteries are used to store excess amounts of renewable energy for use during periods of low production; these systems are costly, and thus, their applicability on a large scale is challenging (Amir et al., 2023). Moreover, the existing storage technologies lack high energy density, which also presents problems in experimenting with large energy storage over the long term and highlights the development of new cost-effective technologies for energy storage (Amir et al., 2023).

On the other hand, asset management complicates the integration of renewables, and so does grid management. For large-scale renewable project generation, massive capital expenditure is required to develop new transmission and substation infrastructure for efficient and reliable power delivery. Renewable sources can also pose power quality problems, including harmonics and voltage fluctuations that will likely affect other equipment fed from the grid. Consequently, the implementation of these variable renewable sources needs sophisticated control and regulation for stability in the grid, as observed, implying the enhanced need for continuous investment and R & D in the energy grid infrastructure and technology for the sustainable utilisation of renewables (Hafeez Ajibade et al., 2024).

Renewable energy integration offers diverse opportunities touching on technology, the economy, and the environment. Technological developments are fostering improvement in production and reduction of costs for renewable energy sources. Technological advancements in solar photovoltaic (PV) cells and wind turbines have enhanced the conversion of sunlight and wind into electricity and decreased costs, thereby enhancing the competitiveness of renewables compared to conventional energies (Maka & Alabid, 2022).

Advanced energy storage systems, especially battery technologies, are advancing with suitable technologies for storing renewables or for use at times of low supply. Further, it is identified that the application of smart grid technologies enhances the capability of the monitoring and control system, which leads to the improvement of the grid and assists in integrating the variable forms of RESMs (Khan et al., 2023). The overall economic impacts also include the benefits of scaling up renewable energy

sources; without much argument, renewable energy sources have vast economic gains that come with their adoption. Using fossil Fuels is expensive; hence, switching to other energy sources increases energy security and 'immunity' to shuttle world fuels (Panda et al., 2023). In addition, the production of renewable energy provides employment openings for manufacturing renewable energy equipment, contracts for implementing the equipment, maintenance of the renewable energy infrastructure and research for enhancing renewable energy technologies. This industry's development can foster overall economic enhancement, which induces investment and innovations in the energy sector and across all economic areas (Selim & Alshareef, 2024).

Environmental management also requires the immediate adoption of a renewable energy source to curb the emission of greenhouse gases, which are responsible for climate change. Renewable sources generate much fewer emissions than fossil fuel energy, which is effective in climate action and allows countries to achieve their targets to reduce their carbon footprint. Furthermore, reducing the consumption of fossil energy sources accustoms to lower pollution levels and, as a result, has positive effects on public health that lead to less expenditure on individuals' health. Renewable energy is one of the key factors for sustainable development, combating climate change, and minimising the impact of natural resources on the environment through the use of resources that are naturally renewable carriers (Nwaka & Asiegbu, 2027).

A paradigm approach is significant to reap these opportunities. It includes constantly undertaking research to develop and promote new technologies, establishing competitive policies to support the sector, and optimising and optimising planning to meet energy demands. When the existing challenges are solved and the benefits exploited, the integration of renewable energy can be successful, leading to fewer emissions and more resistant and economically prospective energy systems (Ukoba et al., 2024).

CHAPTER 3: RESEARCH METHODOLOGY

This chapter outlines the research approach to analysing renewable energy penetration into the Saudi Arabian electricity network. The rationale is to develop a research approach that would allow for the best coverage of the diverse facets of this integration with a specific focus on the technical aspects, optimisation, and social effects. Combining both quantitative and qualitative approaches increases the credibility of the results in this research (Hendren et al., 2022). This study covers the limits and population in Saudi Arabia about the main stakeholders, including policymakers, technical experts, industries, and the general public.

Research Design

This research used quantitative and qualitative research to examine the solar option in Saudi Arabia. This double approach deliberately covers all prospective facets of renewables coverage, including the technical, economic, environmental, and social impacts (Alrashoud & Tokimatsu, 2020). Mixed-method design is appropriate because it permits a rigorous investigation with numerical evidence and explanations to address the research questions and underpin the hypotheses. Quantitative data is used in the study to measure the performance of the grid stability and economic implications (Islam & Ali, 2024). At the same time, qualitative information assists in uncovering the attitudes of stakeholders, regulatory constraints, and societal effects.

Study Boundaries and Population

This research is bound by Saudi Arabia's specific context, focusing on its existing power grid infrastructure, renewable energy resources, and socio-economic environment (Alanazi et al., 2023). The study targets stakeholders within Saudi Arabia's energy sector, including policymakers, energy utility managers, technical experts, and members of the general public who are potential end-users of renewable energy. By focusing exclusively on this population, the study can provide a contextualised understanding

of renewable energy integration challenges and opportunities specific to Saudi Arabia (Barnawi et al., 2023).

The sample population will consist of:

The audience includes Technical and Policy Experts from government energy departments or regulatory bodies, particularly energy production companies.

Industry Stakeholders – Professionals from renewable energy companies, Utility Companies, Service Providers, and Consultants (Hassan et al., 2024).

Public Representatives—These can be a few people from various areas of the country and social classes to determine how informed, accepting, and concerned the general public is about renewable energy.

Consequently, the stratified sampling approach will accommodate technical, policy, and public perspectives (Masukujjaman et al., 2021). This sample allows ample consideration of different points of view and makes the results received significant for a large circle of consumers.

Data Collection Methods

The research will use multiple data collection methods to achieve comprehensive coverage of the study objectives, as follows:

Secondary Data Collection: Secondary data will be collected from published government documents, trade journals, academic articles, and reports of energy-related organisations to give background information, analyse economic consequences, and help make judgments on the grid's robustness. Secondary data enables the formulation of initial perceptions regarding ongoing energy trends in Saudi Arabia and benchmark data on other nations with more advanced renewable energy adoption (Khan et al., 2024).

Primary Data Collection: To answer the study's central research questions, surveys and semi-structured interviews will be used as primary data collection techniques.

Quantitative data will be obtained from the executed questionnaires and distributed to the public and future customers, where general opinions, acceptance, and costs and benefits of using renewable energy will be investigated (Albattah & Attoye, 2021). Cross-sectional questionnaires will be used in the study and participants will be selected purposively across the socio-economic classes to give diverse information on the social and cultural aspects of renewable energy adoption.

Policies and technical experts, as well as representatives from industry organisations and associations, will be interviewed. While quantitative analysis will offer an overall picture of these features, qualitative study based on these interviews will reveal the specific issues of technical integration, economic effects, and regulatory limitations. Semi-structured interviews allow the researcher to explore particular concerns relevant to each respondent's specialisation area and, therefore, elicit precise data to address the study's primary and secondary concerns (Zielińska-Tomczak et al., 2021).

Analytical Tools and Techniques

Quantitative and qualitative analysis approaches will be used to examine the integration of renewable energy in the grid from different perspectives (Zielińska-Tomczak et al., 2021).

Quantitative Analysis: Quantitative analysis will involve using software tools like SPSS or R. Descriptive for the quantitative surveys, although the results will be described quantitatively in terms of mean, median, standard deviations, etc., to provide a view into the public perception regarding costs and environmental impacts. Significance testing will establish the study's hypothesis and analyse other variables on grid stability and economic effects. For example, correlation and regression analyses will compare the extent of renewable power integration with the results of the economy as well as the stability of the grids.

Qualitative Analysis: The interviews will be analysed by thematic analysis. Thematic coding allows for the detection of relative issues with technical, regulatory, and socio-economic concerns regarding the integration of renewable energies. The research will uniformly sort interview responses to identify key themes, approaches, and potential solutions as envisioned by these experts (Baum et al.,

2022). Thus, the thematic analysis helps build up the application-based policy recommendation procedures advantageous for policymakers.

Measures for Validity and Reliability

To ensure the validity and reliability of the findings, several measures will be applied:

Triangulation: This study will employ peer debriefing to enhance validity. Data from the two research methods will be triangulated in an attempt to confirm the findings. This reduces the bias that could be occasioned by the use of a single data type, leading to a rich appreciation of the research questions (Klimashevskaya et al., 2024).

Peer Review: Great care will be taken to ensure the information collected is accurate and relevant. Practitioners in the respective fields will scrutinise findings to ensure they are correctly interpreted. This feedback will enhance the analysis and strengthen the conclusion.

Pilot Testing: The survey will be pre-tested on a small subset of the total sample to check for clarity, coherence, and compliance with the study's objectives (Ying et al., 2024). This will help enhance reliability by reducing the number of questions for which you are unsure of the actual meaning. Applying these measures guarantees that the study has sound and validated data that will be reliable in the scientific world. This approach matches the study goal of giving concrete suggestions for a renewable energy mix to follow, as it guarantees the data's reliability and applicability to Saudi Arabia.

3.6 Ethical Considerations

This study will adhere to established ethical guidelines to protect the rights and confidentiality of participants:

Informed Consent: Before obtaining their consent, all participants will be explained the purpose and method of the study and their rights.

Confidentiality: The research will ensure that all personal data collected will follow the Data Protection Act and be anonymous and secure (Vlahou et al., 2021).

Data Protection: The information to be collected will ensure that the participant's privacy is respected under the Data Protection Act.

Justification for Methodology

The use of quantitative and qualitative methods is justified since the study requires the examination of both the efficiency and effectiveness of the strategies, type, and value, as well as the social, cultural, and political imperatives. Quantitative analysis gives the numerical framework for assessing grid stability and economic results, while qualitative analysis offers the details of the context within which recommendations and strategies are made (Ahmadi et al., 2021). Such an approach complements the work's objectives to provide answers to complex research questions. This allows it to offer the degree of detail required to provide prescriptive solutions to the issues related to renewable energy integration in Saudi Arabia.

Study Limitations

After explaining this approach's advantages, the authors define its drawbacks, which include the inevitability of specific measuring errors if surveys and interviews are used. Furthermore, data collection is confined to Saudi Arabia, so the results are unlikely to generalise to other settings. However, such limitations can be controlled by limiting the population and sample to a specific category and using standard data collection and analysis procedures.

In conclusion, the methodology presents a comprehensive and systematic approach to analysing Saudi Arabia's integration of renewable energy (Almasri & Narayan, 2021). To this end, the research recognises the complexity of the transition by being quantitative in rigour yet qualitative in insight. This approach is congruent with the study's title and makes the findings significant, credible, and valuable by offering policy implications and successional recommendations for policymakers, practitioners, and the general public. As a result, the research design presents a systematic approach to ascertaining the viability, advantages, and constraints of adopting renewable energy sources for Saudi Arabia's electric power utility (Alanazi & Alanazi, 2023).

CHAPTER 4: DATA ANALYSIS AND FINDINGS

This chapter discusses the option of integrating renewable energies into the Saudi Arabian electricity grid, major aspects including the present energy situation, the prospect for renewable sources, the economy, technical issues and social and environmental consequences of renewables integration into the Saudi Arabian power grid (Almasri & Narayan, 2021). The analysis is in line with Saudi Arabia attitude to sustainability and energy diversification expressed in Saudi Vision 2030. Analysing critically and interrelating a broad scope of factors, this chapter contributes a philosophical and theoretical analysis of transition to renewable energy in order to unravel the interactional constituents of energy policy, economic transformation, and environmental effects.

Analysis of Current Energy Mix in Saudi Arabia

Saudi Arabia itself is extremely aware of its dependence on the fossil fuel sector, having the oil and natural gas production as its key energy sources. This dependence is rooted in the country's socio-economic development path characterised by its oil endowment and as an oil exporting country. According to the data from the IEA, though fossil energy resources fuel and contributed to the growth of this country economically, they come with ecological and sustainability implications particularly on the climate change. This led to an increased demand for electricity within the Saudi Arabian region increasing production from 169000 GWh in 2008 to 331000 GWh in 2018 adding the pressure to their fossil fuel resources and the escalating need for the diversification of energy sources (Aldhubaib, 2022).

However, one has to acknowledge that the current portfolio of energy sources highlights an essential clash between continuity and change. From a more philosophical standpoint this place in focus the energy trilemma which consists of energy security, sustainability and affordability. Switching from oil-based economy to the one that includes the usage of renewable energy or power is a paradigm shift in the energy sector that requires Saudi Arabia not only occupy the ecological problems of using fossil fuels, but still to prevent economical instabilities (*Fostering Effective Energy Transition 2023*, n.d.). It

demonstrates this has to be a managed process, where the use of renewable energy is incremental yet profound in its lethality, offering sturdiness in the natural and financial worlds.

Potential for Solar Energy

Saudi Arabia holds great potential in the solar power sector because of its geographical position as well as high levels of solar brightness. This geographic endowment makes the country well-suited for solar photovoltaic (PV), according to the IEA and Eurogroup Consulting. The expansive deserts become the perfect location for utility scale solar power installations, in line with Vision 2030 to advance the exploration of renewable energy sources as part of the national energy mix (Al-Gahtani, 2024).

The reasons for the adoption of solar energy in KSA can be analysed from the standpoint of the theory of Ecological Modernisation. Sustainable economic development theory assumes that harnessing of technology losses can lead to the restoration of environmental degradation and industrial growth (Hariram et al., 2023). There is this theory that assumes that development in technology leads to possibilities of breaking the vicious cycle of pollution equal to the rate of economic growth. Solar energy, therefore, is not just defined as an energy solution but also an image of the future, of the kingdom's intention towards a good mix of sustainable development and technological development (Hariram et al., 2023). This paradigm shifts from the traditional way of thinking promoting the fact that economic growth and ecological conservation are sustainable as ecological modernisation holds This is why Saudi Arabia can easily harness on to the future economic growth Agenda through tactical solar investments. The potential of increasing the efficiency of solar photovoltaic PV and the continually declining price of solar technology makes solar energy realistic for Saudi Arabia to transition and improve the quality of its energy while being more environmentally friendly (Imam et al., 2024).

Further, integration with renewables matches political theories of 'just transition', tendencies where a state has a moral duty to foster sustainable development. The fact that solar power makes it possible to de-centralize power generation and lower carbon emissions puts solar power squarely in line

with Vision 2030 environmental goals, making it a critical component of a diversified energy mix that is both technologically viable and sustainable.

Potential for Wind Energy

Wind energy is the other source of renewable energy that has great potential in Saudi Arabia especially along the Red Sea region since wind resource mapping reveals favorable conditions necessary for utility scale wind power projects (Imam et al., 2024). Eurogroup Consulting and National Grid SA also see wind within the context of flexibility where it provides energy during the time that solar power is minimal.

The theoretical foundation of sustainable development, aiming at the attainment of the current energy requirements while preserving the ecological future, is the rationale for the use of wind energy. Wind energy is thus the ideal energy form since it realises energy independence instead of oil, besides promoting energy equity by providing fresh form of energy for future generations. When wind energy is generated, it symbolises dedication towards environmental responsibilities, consistent with the atmospheric responsibility one has towards nature and the future generations (Holden et al., 2021). As compared to the traditional fossil fuels, wind energy is a natural resource that is both renewable and has no direct emission and thus is right on course of Saudi Arabia's long term environmental goals. In addition, wind energy brings new sources of energy and diversification into the supply of energy which enables reduction of the vulnerability of the energy market to oil shocks and the finite nature of the physical resources (Leonard et al., 2022).

In this respect, the cyclical characteristics of wind, its inconstancy, present integration issues that require more advanced grid upgrades and energy storage technical advancements. In theoretical frameworks concerning resilience, it is noted that there is a need for a necessary level of provision in readiness to variations in production from renewable sources (Smirnova et al., 2021). By leveraging technologies to increase Saudi Arabia's capacity for wind integration, the center can help improve the

kingdom's energy security and further build up a flexible power grid that can accommodate the volatility of the renewable resources.

Cost-Benefit Analysis

Switching over to renewable energy has mammoth economic implications, as it calls for more total and marginal costs more to marginal and total benefits. According to reported for 2023 by IEA, projects under renewable resources cost heavy initial capital but it is financially and environmentally beneficial in long run (Mubarak et al., 2024). These benefits include lower operations cost, improved energy security, and a drastic cut on emissions of carbon. Additional to these, the financial models of Eurogroup Consulting also capture the fact that renewable energy projects including the solar and the wind energy have greater values for ROI as compared to the extended use of the fossil fuels, especially when the price of the oil is volatile.

The cost-benefit analysis is in line with the methodological approach called ecological economics, which represents the combination of preserving the environment and creating value. Ecological economics supports sustainable development in a way that nevertheless accomplishes growth without damage to the environment (Osman et al., 2022). From this perspective, the ramping expenses associated with building renewable infrastructure are viewed as the creation of natural capital – defending ecological systems that generate enduring values, including, unequivocally, the minimization of pollution and benefit to public health.

Additionally, smart grid technologies which are the cornerstone for implementing renewable integration solutions have the economic benefits of improving energy distribution and minimising the loss (Eisenmenger et al., 2020). Renewable energy investment is therefore a form of 'natural capital preservation' investment that supports an energy structure that respects ecological realities as well as need for maximum utilization of economic opportunities. On the other hand, reliance on fossil fuel has its risks, which could result from congested worrying issues that surround the resources inclusive of depletion risks and the costs which are affiliated to emissions (*Climate Change 2014 - Synthesis Report*,

2015). Thus, renewable energy is an investment that pays off both economically and environmentally that will serve Saudi Arabia well as it creates and accumulates both economic and ecological assets. These technologies fit well within the paradigm of techno-economic, whether the proposition that improved economics and environmental quality can go hand in hand when supported by enabling technologies. Hence, the cost benefits of renewable energy affirm answers success and environmental sustainability, arguing for the integration of renewable as a way of achieving economic viability in energy systems.

Grid Stability and Reliability

Integrating renewable energy sources has some inherent technical issues, most of which has to do with maintaining stability of the electricity grid due to fluctuations in the source of solar or wind energy-based power. IEA comments that despite the substantial part renewable energy poses no threats to energy supply disruptions due to network issues without major upgrades to infrastructure (Baker et al., 2020). Saudi Arabia already has a robust network infrastructure; however, most of the present generation system layout is optimised for fossil fuel power generation which unprepared for the volatility that accompanies renewables integration.

Smart grid technologies surface as an answer from the system of ideas formulated within the scope of the concept of complexity theory associated with the description of the conditions and possibilities of self-regulating interconnected systems. Combining data and intelligence, smart grids help the energy system to address supply-demand and other problems in real-time (Ahmad et al., 2022). This flexibility also increases the dependability of the system while at the same time increasing efficiency and lowering the ecological footprint. When implemented, smart grid technologies can provide Saudi Arabia with a flexible power system which is capable of accommodating increased renewable penetration while still maintaining grid stability.

Furthermore, there are other challenges as energy storage facilities including, batteries that help in dealing with intermittency. These systems contribute towards energy storage when production of renewable energy peaks, making it a reliability fuel source when production is low. This approach resonates with sustainability science where there is the call for structures that are capable of operating within ecological constraints (Ahmadi et al., 2021). Storing energy is a long-term investment in sustainability that allows Saudi Arabia to satisfy energy needs and avoid depleting natural resources or adding inconsistent supply to the grid. As the kingdom takes up the mantle of grid stability, Saudi Arabia now finds itself poised on the crossroads of energy reliability and innovation. This is why, according to resilience theory, it is vital to construct structures that are worth in terms of instability and that can maintain flexibility for new changes in energy scenarios (Ahmad et al., 2022). On that context, Saudi Arabia's grid has to flexibly include renewable energy as an efficient and dependable source of energy to the power demand. Saudi Arabia can create an energy system that is resilient to intermittent resources, and indeed prospers with them, through developing smart grid technologies that provide the capacity for supply and demand management (Zhou, 2022).

Socio-Environmental Implications and Regulatory Considerations

Policies are crucial in managing the integration of renewables and the IEA Grid Delay Case demonstrated the impact that regulation could have on emission and climate agendas. The generic mechanisms include utilisation of less complex approvals for the completion of renewable projects and local energy production rewards that may quicken the change. Cogeneration of electricity from renewable energy sources through net-metering policies enhances localised generation and reduces losses across the length and breadth of the country as well as the stress on the national grid (Bhuiyan, 2022). The above practice is a measure of implementing subsidiarity, where decision-making and utilisation of resources are decentralised for better efficiency and fairness.

In addition, knowledge dissemination and participation must be addressed since they play a very important role in the development of a reenergized culture for renewable energy. Theoretical considerations of participatory governance underscore the workability of participatory mechanisms in the resolution of collective problems in the most sustainable manner. Through the campaigns to engage citizens and involve them in rational utilisation of energy, Saudi Arabia shall be in a position to promote awareness and involve citizens in the environmental conservationism of the country ((Baker et al., 2020). Converting Saudi Arabia's energy mix has significant socio-environmental consequences such as lower levels of emissions and subsequently healthier citizens. In philosophical terms, the move to clean energy is operationalised out of environmental justice that aims at equalisation of human and environmental resources. These principles include quality of life and reduction of effects of pollution on health, and breaking the fossil fuel cycle achieves this by lowering risk associated with pollution.

Challenges and Constraints

The adoption of renewable energy in Saudi Arabia has the following problems based on IEA Grid Delay Case which states that delayed renewable integration could lead to approximately 60 billion tonnes of CO₂ emissions by 2050 (Fam & Fam, 2024). The consequences of such delays underscore the importance of taking action to address climate change and meet the countries' obligations under the Paris Agreement.

From an operational perspective, one of the main problems comes from the fact that renewables are stochastic, so to maintain a stable electric current, more tools are needed like smart grid and storage). This old infrastructure mainly developed for fossil fuel generation restricts the ability for an immediate shift which makes extensive investments for grid upgrade necessary.

High initial costs are a disadvantage as huge sums which are necessary to finance renewable structures can burden national budgets. However, there are signs of commitment to surmounting these challenges most notably government-supported programmes and international funding (Podger et al., 2012). Theoretical models of economic transition including the green economy model insist that salaries

spent in any renewable source of energy will open up new economic productivity hence relieving the mentioned financial constraints in the long run.

Future Prospects and Recommendations

The findings of this analysis point to several strategic recommendations that can facilitate Saudi Arabia's transition to renewable energy, in alignment with Vision 2030:

Investment in Smart Grids and Energy Storage: Support for smart grid development and energy storage systems is required in order to balance renewables as well as to maintain reliability of grids. This is in concord with complexity theory that holds that there are systems that are adaptive to conditions of complexity.

Policy Support for Decentralised Energy Production: Decentralisation has the effect of reducing transmission losses and increasing localised energy stability. Government toward policies that will facilitate the transition of rooftop solar PV system and local microgrids for improvement of energy sustainability (Hariram et al., 2023).

Accelerated Grid Modernisation and Regulatory Streamlining: Some degree of deregulation of processes encourages faster construction of infrastructure, eradicating barriers that slow down renewable energy. Lessening bureaucratic red tape offers Saudi Arabia the potential for moving forward more effectively with the attainment of its renewable strategies.

Utilisation of AI for Demand Forecasting: Smart technologies use AI to predict the demand of electricity in the grid and hence increase efficiency in a stable renewable power sector. This is in line with sustainability science, which assesses for system performance optimisation within eco constraints.

Public Awareness and Incentivisation: Public acceptance can therefore be advanced by informing people of the economic and environmental value of renewable energy. Such encouragements are tax credits that can enhance adoption to support societal uptake for energy transformation.

The sourcing of renewable energy to the Saudi Arabian power grid is not a singular value chain process but rather a sociotechnical one that encompasses technical, economic, environmental, as well as socio-

cultural considerations (Apfel et al., 2021). Conceptual and philosophical analysis suggests that renewable energy is not just an operational change but a new paradigm in energy policies. This paper evidences how smart integrated solutions and stringent regulatory changes in cooperation with the public Saudi Arabian master plan for renewable energy puts the country in the right track of successfully integrating renewable and in the process fulfilling global climate targets. Focused and coordinated actions can help Saudi Arabia create a stable, diverse, and renewable energy future that is advantageous for domestic and global consumers.

CHAPTER 5: CONCLUSION

This dissertation systematically investigated the integration of RESs, mainly solar and wind energy, into the power system of Saudi Arabia. It responded to the main theme of improving energy sustainability and fits into the goals of Vision 2030, which envision the reduction of the use of fossil fuels as well as sustainability of the environment. Each chapter of the dissertation explored the issues, technology needs, economic effects, and policy implications of incorporating renewable power into Saudi Arabia's energy matrix using both theoretical and empirical methods to answer the research questions and aims.

The rationale and need for integration of renewable energy sources into Saudi Arabia's electric network is outlined in the introduction. This best illustrated on the constraints that arise from the steady utilization of the non-renewable sources of energy for example; fluctuating oil prices, environmental impacts and availability of the oil resources. In the chapter, the author explains the Kingdom's current and future energy profile, particularly how Vision 2030 is transforming Saudi Arabia into a sustainable nation. This framework introduces the primary research questions: In what ways Saudi Arabia can therefore harness renewable energy and incorporate it into its electricity mix? What technical, economic, social implications are there, and what would allow a smooth transition?

Chapter 2 discussed literature review focusing on renewable energy sources and its integration with special reference to solar and wind energy globally and at regional level. It outlined the main features of various renewable sources –Solar, Wind, Geothermal and Hydrothermal Energy –and remaining part of the thesis defines the shift towards renewable energy to combat climate change around the world. Germany, Denmark and China studies showed best practices and policy measures for integrating renewables. These cases therefore provided a perfect example of the role of government support, recent technology advancement, community commitment, and sound policy framework regarding renewable energy objectives. These findings concluded the chapter and are discussed within the specific context of

Saudi Arabia to set the stage for the subsequent analysis of the technical, social, and economic feasibility of incorporating RESs into the existing grid.

Research method used entails the utilisation of both quantitative and qualitative research to provide an extensive analysis of integration of renewable energy sources in Saudi Arabia. This chapter provided an overview of the available research design, collection techniques and analysis instruments that have been employed in approaching the research questions and aims of the study. Surveys and subsequently conducted interviews with policymakers, industry stakeholders, and members of the public offer perceptions of socio-economic and regulatory contexts (Apfel et al., 2021). Possible values of technical and economic feasibility of RES integration are based on the secondary data obtained through government documents, publications, and analysis provided in the academic context and industries. The methodology chapter revisited the issue of validity and reliability as a means of identifying triangulation, peer review, and pilot testing to add to the research's credibility.

In this chapter, the data analysis focused on the challenges and interested in Saudi Arabia's power grid as well as technical, economic, and socio-environmental considerations with regard to renewable energy. Examined Saudi Arabia's largely oil and gas derived energy system and analyses the feasibility of solar and wind as potential alternatives (Leonard et al., 2022). Such question can be answered and we got some key findings such as; the technical and infrastructural challenges that lead to the stabilisation of the power supply from renewable energy sources and the economic feasibility of the changes that will be necessary for the transition to RES. The assessment also underlined an important role of smart grid technology and energy storage systems that can improve the stability of the grid and control the supply-demand fluctuations. Concisely, they confirm that RE integration is feasible for attaining Saudi Arabia's long-term sustainability objectives, a great deal of investment in physical infrastructures and pioneer changes in the political and legal requirements are required.

Chapter 4 analysed the social and environmental impacts of integrating renewable energy including health, environmental effects and stakeholder engagement (Osman et al., 2022). This stress

increased concern with procedural requirements for project review and approval, as well as handling of environmental effects. Behavioral focus of the chapter is brought to Saudi Arabia goal to decrease the emission of greenhouse gas and enhance the quality of the air in line with Vision 2030 environmental goals. In addition, that there was a strong focus on gaining public support of RE projects through information campaigns and incentives which the article argues that, only through societal participation, can the energy transition process become sustainable.

In conclusion, the data accumulating during the study, which has been revealed in the subject area concerning the technical, economic, and environmental aspects of incorporating the renewable energy. It addressed the review of the current mix of energy in Saudi Arabia, the viability of solar and wind energy, cost analysis, grid code needs, and social- ecological consequences of renewable integration (Imam et al., 2024). The chapter concluded that despite high capital costs of renewable integration, the use of renewable energy is a sustainable option for Saudi Arabia owing to the benefits received in the long-run, which include lower carbon emissions, economic buffers and energy security. Combined with improved wind and solar resources, technologies such as smart grids, energy storage and artificial intelligence appear as key building blocks to address intermittency and ensure the reliability of energy delivery.

The findings of the dissertation were recapitulated in the last chapter of the dissertation while focusing on the fact that the Royal Saudi Arabia has prioritised the renewable energy sector for its energy diversification goals (Zielińska-Tomczak et al., 2021). This emphasised the need for enhancement of social infrastructure, streamlining of the regulatory environment and active involvement of the public in realisation of Vision 2030. The study stressed that despite the difficulty of incorporating renewable energy, renewable energy integration is a potent concept for Saudi Arabia's energy sector and environmental goals. With regard to technical, economic and social issues outlined above, Saudi Arabia has the potential of creating a sustainable energy system which will be beneficial to climate change goals and energy security of the country (Mubarak et al., 2024).

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