UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG
100 1922 2022

SEF SCHOOL OF
ECONOMICS
AND FINANCE
ISikole Sezomnotho Nezezimali
Sekolo sa Dithuto tsa Moruo
le Tshebediso ya Tjhelete

AN INTEGRATED POWER GENERATION PLAN CONSIDERING CARBON EMISSION CONSTRAINT

A Research Report submitted in partial fulfilment of the Degree of Master of Commerce (Economics/Economic Science) in the School of Economics and Finance,

University of the Witwatersrand

by

Name: Sabrina Koopman

Student No: 2616369

Supervised by: Dr Yuxiang Ye

Word Count: 14 785

Date: 19 August 2024

Table of Contents

List of Figures

List of Tables

Abstract

In the context of South Africa's energy crisis, this research report examines the optimization of South Africa's power generation system, considering coal, onshore wind, and solar PV technologies within a carbon emissions constraint. The primary objective is to minimise costs while addressing the urgent need for sustainable energy solutions in a country heavily reliant on coal-fired power. The methodology comprises two main components: system modelling of solar and wind generation, and a mathematical framework featuring cost minimization as the objective function with a power balance constraint and a carbon emissions constraint as the two key constraints. This approach allows for a comprehensive analysis of potential energy mixes that balance economic and environmental concerns. The study's findings indicate that a more sustainable and balanced energy mix is achievable in South Africa through significant expansion of renewable energy capacities. While this transition requires substantial short-term investment and infrastructure development, it offers long-term benefits including reduced carbon emissions and enhanced energy system resilience. The optimization results suggest that further integration of renewable energy technologies is possible, albeit at a higher cost. The research highlights the increasing cost-effectiveness of renewable energy and emphasises the importance of capitalising on this trend in emerging markets like South Africa. In conclusion, this thesis demonstrates that South Africa can significantly reduce its carbon emissions within the next five years by improving its energy mix through increased integration of renewable energy generation technologies. These insights are crucial for policymakers, industry stakeholders, and researchers in shaping South Africa's future energy landscape and contributing to global climate change mitigation efforts.

1. Introduction

Climate change is one of the most critical environmental challenges of the 21st century (Dietz, et al. 2020; Chikulo 2014). The phenomenon is primarily driven by the increase in greenhouse gas (GHG) emissions, predominantly carbon dioxide, methane, and nitrous oxide, generated from anthropogenic sources such as fossil fuel combustion, industrial processes, deforestation, and intensive agriculture. The adverse effects of climate change were observed more prominently than ever in 2023 as it was the warmest year on record in the last 174 years (World Meteorological Organization, 2024). The effects of climate change are not specific to the country generating the carbon emissions but the whole world as these emissions affect weather patterns, water resources, ecosystems, agricultural stability, and human health. The Intergovernmental Panel on Climate Change (IPCC) has continuously warned against the adverse impacts of climate change on natural and human systems, including rising global temperatures and extreme weather events (IPCC, 2023). Decarbonization is the process of reducing carbon dioxide (CO_2) emissions and it is one of the most important and effective ways to mitigate the effects of climate change. The focus of decarbonization is the energy sector because the sector accounts for the largest share of global GHG emissions (International Energy Agency (IEA), 2024). Decarbonization strategies include a range of approaches, including increasing energy efficiency, encouraging renewable energy investment and integration, implementing carbon pricing mechanisms, and investing in energy storage technologies. Transitioning the energy sector from fossil fuels to low-carbon energy sources is crucial for achieving the targets of the Paris Agreement. The hypothesis for this research paper is that South Africa's energy mix can be improved to include more renewable energy within 5 years and as a result start decreasing carbon emissions sooner than what is stated in the IRP 2019, which plans to only start reducing carbon emissions by 2036 (Department of Mineral Resources and Energy, 2019).

Of the decarbonization strategies mentioned, renewable energy investment and integration have been and will continue to be a central part of decarbonizing the energy sector. Solar, wind, hydro, and biomass offer a sustainable alternative to fossil fuels, not only providing renewable energy but also significantly reducing GHG emissions. The rapid technological advancements and decreasing costs of renewable energy technologies have made them increasingly competitive and accessible, driving their widespread adoption. The IEA tracks clean energy progress for over fifty components including energy systems, electricity, low-emission fuels, and transport. The report found that in 2023 solar photovoltaic (PV), electric vehicles, and lighting were the only 3 components that are fully “on track” with a Net Zero by 2050 scenario, meaning that these technologies are globally advancing at the pace needed to reach the Net Zero target (IEA, 2023). While the current report is not favourable, it is important to recognize the potential for rapid improvement. Notable, the annual growth for solar PV generation in 2022 was 26% (IEA, 2023). This suggests that with appropriate investments during this critical period, considerable progress can be achieved in a relatively short time. Investing in renewable energy not only addresses the challenge of climate change but also offers energy security which is important for an emerging economy such as South Africa.

From an international perspective, in the European region, the largest sources of non-combustible renewable electricity in 2021 were hydro energy at 48% and wind energy at 36% (International Energy Agency, 2021). Solar PV only contributed 14% and this is due to the climate in the Northern Hemisphere. Unlike South Africa and other countries in the Southern Hemisphere, the Northern Hemisphere countries are unable to fully use the longer daylight hours for solar energy generation. Additionally, all 27 member states of the European Union have committed to the Paris Agreement, meaning that they all have net zero emissions targets to reach by 2050. The United States of America (USA) is the world’s second-largest contributor of carbon emissions, second to China (Friedrich, et al., 2023). Both of these countries have made strides in introducing renewable energy into their energy generation mix. The share of renewable energy generation in 2022 in the USA was 21.6% and for such a large country this amounts to 908 TWh in 2022 (International Energy Agency, 2021). China in 2022 generated 2 322 TWh of electricity from renewable energy (International Energy Agency, 2022). However, for both the USA and China, it is important to note that as the 2 largest contributors to carbon emissions in the world, their renewable energy contribution cannot be considered in isolation as these efforts do not offset their substantial carbon emissions. In terms of the world, the share of renewable power generation has grown to 24% in 2021 (International Energy Agency, 2021), this share continues to grow as more countries adopt low-carbon power generation technologies.

In South Africa, the dominant energy generation technology is coal with the generation share dropping below 80% for the first time in 2021 (CSIR, 2023). There has been some progress made in terms of renewable energy integration in the country with a share of 8.4% of the total energy mix in 2022 being generated from renewable energy sources (International Energy Agency, 2022). Building on this global and local context, the research question central to this research report is the optimization of South Africa's generation system using coal, onshore wind, and solar PV within a carbon emissions constraint, with the objective of cost minimization. This question is significant due to the urgent need for sustainable energy solutions that balance economic and environmental concerns, particularly in the context of South Africa's heavy reliance on coal and the global imperative to reduce carbon emissions. To address this question, the study employs optimization techniques to model and analyse the generation system, and its implications for the energy mix and emissions levels. By considering the potential for rapid capacity increases in renewable energy sources, the research seeks to identify pathways to a more sustainable and cost-effective energy system. The findings of this report suggest that a more balanced and sustainable energy mix is achievable in South Africa with a concerted effort to ramp up renewable energy capacities. While this would require significant investment and infrastructure development in the short term, the long-term benefits include reduced carbon emissions and a more resilient energy system. These insights are crucial for policymakers, industry stakeholders, and researchers in shaping the future of South Africa's energy landscape and contributing to global efforts to combat climate change.

2. Background

The South African energy generation landscape is unique in that the country is doubly endowed with abundant coal reserves as well as near-perfect weather conditions for renewable energy generation. Despite this, South Africa remains heavily dependent on coal-fired power stations for electricity generation with more than 70% of the generation coming from coal-fired power stations (Pierce & Le Roux, 2022). The failure to utilize South Africa’s renewable energy potential has contributed to the current energy crisis (Ndenze, 2023) as well as causing South Africa to have the highest per capita greenhouse emissions in Africa (Jain & Jain, 2017). To decrease the country’s carbon emissions and adhere to commitments made by South Africa under the Paris Agreement, the Department of Mineral Resources and Energy (DMRE) released an updated Integrated Resource Plan in 2019 (IRP 2019) (Department of Mineral Resources and Energy, 2019). The IRP 2019 details how the government will increase generation capacity to help sustainably mitigate the crisis via the use of renewable energy while sticking to the milestones laid out in the Paris Agreement. The vulnerabilities of the South African energy system are further accentuated by challenges rooted in economic inequalities, political inefficiencies, and historical legacies of apartheid, all of which undermine the pursuit of sustained energy security.

Eskom's, the state-owned enterprise primarily responsible for South Africa's electricity generation, transmission, and distribution, current generation fleet includes 15 coal-fired power stations contributing 39 824 MW of installed capacity, 2 Hydroelectric power stations with a combined capacity of 600 MW and 1 nuclear power station, Koeberg Nuclear Power Station contributing 1860 MW capacity in 2022 (Pierce & Le Roux, 2022). This fleet has a rapidly declining average Energy Availability Factor (EAF) according to Eskom's System Status Report, the average EAF in 2020 was 61.84%, 58.05% in 2022, and 54.70% in 2023 (Eskom, 2023). The EAF is an important indicator as it represents the percentage of maximum energy generation that a system is capable of supplying over a year. It considers both planned and unplanned outages. A higher EAF indicated a more reliable and productive system, with a lower EAF indicating longer and more frequent outages. As a direct result of a low EAF, South Africa has been implementing load-shedding since 2007 (ESKOM, 2012). Load-shedding refers to the intentional, scheduled interruption of electrical power supply implemented by the national utility, Eskom, to prevent the collapse of the power grid when electricity demand exceeds the system's generation capacity. This is evident in the year-on-year escalation in load-shedding, evidenced by a jump from 2521 GWh in 2021 to 11 529 GWh in 2022 (Pierce & Le Roux, 2022). Moreover, energy analysts have anticipated this upward trend for 2023 with a prediction of a potential upper limit of 16 000 GWh (Creamer, 2023). This number is realistic as for 2023, 332 days out of 365 days, the country had load-shedding. In terms of stages, 2022 was the first year that most of the load-shedding has not been stage 2, it was surpassed by stage 4. At stage 4, power outages are implemented 12 times over four days for 2 hours at a time or 12 times over 8 days for 4 hours at a time (Pierce & Le Roux, 2022). In December 2022, 2667GWh was shed, which is more load-shedding in one month than in 2021.

To supplement this capacity with further renewable sources, the South African Government in partnership with Eskom conducts purchasing power agreements with Independent Power Producers (IPPs) in an initiative called the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) which started in March 2011 (South African Government

, 2024). The way the program works is that the DMRE announces a new bid window—a specific round of the competitive tendering process with defined parameters for capacity, technology types, and evaluation criteria—specifying the amount of renewable energy capacity it wants to procure and the technologies in which it is interested, inviting independent power producers to submit proposals for renewable energy projects within a specified timeframe. Interested IPPs submit their bids which are then evaluated based on technical feasibility, financial viability, and compliance to bid requirements. As of 2023, a total of 123 projects have been awarded to the private sector, totalling R256 billion in private-sector investment committed to the REIPPPP (South African Government , 2024). Based on the REIPPPP online database, 10 of the 123 projects are under construction, all of these projects were procured from Bid Window 3.5 and 5 (Department of Mineral Resources and Energy, 2024). This accumulates to 2955 MW of new renewable energy capacity. Additionally, 90 projects have reached commercial operation procured from bid windows one to six, meaning they are connected to the grid and generating electricity. The operational projects accumulate to 5935.24 MW of capacity (Department of Mineral Resources and Energy, 2024). Notably, the state capture and widespread corruption between 2013 and 2018 had a significant impact on the REIPPPP which led to no bid windows during this time. The scandal created uncertainty and damaged trust in the procurement process, discouraging potential domestic and international investors and developers.

Eskom and Transnet are both state-owned enterprises (SOE) that are targets of state capture in South Africa (Mathebula & Masiya, 2022). Eskom became the primary target of state capture as it is one of the largest power utilities in the world. The relationship between Eskom and the government is complex as the two are linked through multiple ways, including ownership, policy, regulation, and political pressure. A paper by (Mathebula & Masiya, 2022) examined this relationship and stated that the connection between poor governance and state capture not only has notable consequences for the country but this relationship directly undermines the ability of the SOE to fulfil its constitutional responsibilities. In terms of Eskom, this means that the investment into new generation capacity, specifically using renewable energy sources was not opened to the private sector and in addition, Eskom also did not increase its renewable energy generation capacity during this time. The current generation deficit and heightened load-shedding frequency are the cumulative consequences of several factors including, mismanagement of funds and inadequate maintenance of existing power stations, leading to decreased generation capacity and increased power outages, and insufficient investment in new generation capacity, specifically renewable energy additions, failing to keep up with rising demand.

In addition to Eskom's capacity issues, the power utility is also facing major debt issues with the total debt as of March 2023 being R399 billion which is a 2% increase since March 2022 when it was R389 billion (Eskom, 2023). This high debt weighs heavily on Eskom's financial sustainability, limiting its ability to invest in critical maintenance and new generation capacity. This also causes an increased reliance on the government for debt servicing and funding, which raises concerns about its fiscal burden on the government budget. These concerns became a reality in February 2023 when National Treasury announced a R254 billion debt relief package for Eskom to spread over the next three years (National Treasury, 2023). This includes taking over some of the debt directly and supporting interest payments. The government is also pushing for Eskom to diversify its energy mix and invest in renewable energy sources to reduce Eskom's reliance on expensive and polluting coal.

Despite the current energy crisis, South Africa still boasts some of the world's most advantageous solar and wind resources offering significant potential for renewable energy production. South Africa has high wind speeds of 12 m/s at 100m height at the best sites and 7.5-8 m/s on average which offers very favourable conditions for wind installation (Doorga, et al., 2022). The Western, Northern, and Eastern Cape provinces are especially important with average annual wind speeds of over 4m/s at only 10m above the ground level (Akinbami, et al., 2021). Additionally, in terms of PV, in 2017, South Africa had an average of 2500 hours of sunshine per year and 4.5 to 6.6 kWh/m^2 of radiation level per day (Jain & Jain, 2017). In 2022, another study found that clear sky days occurred on 233 days in the year of the study, resulting in an average daily total GHI of 6.13 kWh/m^2, which means a yearly average of 2 200 kWh/m^2 per year which falls in the medium to high range of yearly GHI for greater potential for solar energy generation (Overen & Meyer, 2022).

Additionally, a study assessed the potential for solar PV extraction on land licensed to the mining industry in the Northern Cape Province. The study included calculating the sum of the areas under investigation which was 2 572 km^2, which is 0.69% of the total land areas in the Northern Cape, with a combined net solar insolation of 12 057 GWh/day (van der Merve & Brent, 2020). The assessed areas varied in size and as a result the net insolation results also varied. However, most mines fell between the 10 to 100 GWh/day category. These numbers cannot be taken in isolation as the biggest factors at play for PV generation are panel efficiency and area factors. The study utilizes a low scenario efficiency value of 12% and a high scenario efficiency value of 22%, respectively (van der Merve & Brent, 2020). Low scenario efficiency (12%) represents a conservative estimate of solar panel performance when calculating potential photovoltaic energy generation from the assessed mine areas. The paper concludes that South Africa's annual electricity consumption exceeds 220 TWh, and their solutions exceed this amount with the low-case producing 369 TWh per annum and the high-case producing 679 TWh per annum (van der Merve & Brent, 2020). This implies that even in the worst-case scenario, utilizing only the identified mines in the Northern Cape for utility-scale PV plants would be sufficient to meet the entire country's electricity demand (van der Merve & Brent, 2020). It is important to note that in both cases either small policy changes or leniency is required for these results to be the reality. While theoretical simulations pave the way for future possibilities, realizing the transformative potential of renewable energy integration hinges on robust policy changes and resolute commitment. Scaling up renewable energy generators within the national energy mix represents a pivotal step towards alleviating the current energy crisis and fostering a sustainable future. Even though, this is a theoretical study the results and policy changes needed for the results to be real are important for policy implications and future generation system design.

This necessitates optimizing the integration of renewable energy generation within South Africa's electricity infrastructure. This holds tremendous potential for realizing a low-carbon and sustainable energy landscape in South Africa. Within a power system, there are different divisions with their own responsibilities, the generation system is responsible for producing the power and this power can come from various sources, the transmission network that carries the power to the load centers, and the distribution system that delivers the power to homes and industries (Zhu, 2015). There are several ways to optimize this process to ensure power is supplied efficiently and reliably. The focus of this research will be the mathematical optimization of the generation system with coal, onshore wind, and utility-scale solar PV power as the energy mix. Cost minimization was the objective. An alternative option is to include a carbon emissions objective to make it a multi-objective optimization problem. However, cost minimization makes the most sense in South Africa's case because of limited financial resources and the debt crisis the country's power utility is currently facing. The constraints to this optimization problem will be a power balance constraint, a power limit constraint, and a carbon emissions constraint. This means for the system to be optimized at a cost minimum, the allocated amount of carbon emissions per year cannot be exceeded and the power balance between supply and demand constantly needs to be met.

When using mathematical optimization techniques, the types of equations and variables will determine the technique used. The classical approach is linear programming (LP), which is widely used for linear objective functions and constraints. It is efficient in optimizing energy dispatch, unit commitment, and power flow calculations. Another well-known mathematical optimization tool used for energy systems optimization is Mixed-Integer Linear Programming (MILP) (He, et al., 2023). MILP can manage a wide range of power system optimization problems that include both continuous and discrete variables. The technique used in this paper will be quadratic programming (QP) which is a specific type of mathematical optimization used to solve problems involving quadratic functions subject to linear constraints (Nocedal & Wright, 2006). In this case, the objective function involves a quadratic function, and the constraints are all linear making QP the ideal choice of technique. The software used for the optimization problem is MATLAB (The MathWorks Inc., 2023). MATLAB provides a powerful Optimization Toolbox that includes a range of solvers for linear, quadratic, integer, and nonlinear optimization problems. This toolbox is also equipped with functions that can manage various constraints and objective functions, making it suitable for energy optimization problems. Additionally, MATLAB is built on advanced numerical algorithms that ensure accurate and efficient solutions to optimization problems. This is crucial for obtaining reliable results in energy systems optimization.

With the chosen QP technique, we will delve into the task of optimizing South Africa's energy mix. With South Africa's current energy crisis, optimizing the energy system by incorporating renewable energy generators and adding a carbon emissions constraint presents a valuable and timely research topic. The contribution of this research will be the optimization of South Africa's generation system using an energy mix of coal, solar, and onshore wind as generators while considering a carbon emissions constraint. South Africa has other sources of electricity generation such as nuclear, centralized solar, pumped storage, and diesel and gas (CSIR, 2023). A study by Nijsse, et al., (2023), recently concluded that solar PV and wind energy would see significant cost reductions in the next few years, with solar PV emerging as the cheapest source of electricity globally by 2027 according to the findings (Nijsse, et al., 2023). The International Energy Agency (IEA) has had comparable results with regards to their research on the costs of utility-scale wind and solar PV (International Energy Agency (IEA), 2023). The reason for the inclusion of coal and not a focus solely on optimizing renewable energy is that South Africa's economy is highly dependent on coal-fired electricity generation and optimizing a system excluding coal would be unrealistic and the results would be inaccurate.

This is an Economic approach to an optimization problem and by addressing the unique characteristics, challenges, and opportunities of the South African energy landscape, this research aims to provide valuable insights into optimal system configuration, operational strategies, and investment decisions. Additionally, this research seeks to contribute to existing knowledge by addressing the economic and environmental aspects of optimizing an energy system that leverages renewable energy in South Africa. Findings of this research could inform policymakers, energy planners, and industry stakeholders in their decision-making process, supporting the development of a sustainable and resilient energy sector. The ultimate output will be an optimal energy mix for the country for the next 5 years. Moreover, the optimization techniques and methodologies employed in this study can serve as a foundation for future research and optimization studies in other regions facing similar challenges and opportunities. The hypothesis for this research paper is that South Africa's energy mix can be improved to include more renewable energy within 5 years and as a result start decreasing carbon emissions sooner than what is stated in the IRP 2019, which plans to only start reducing carbon emissions by 2036 (Department of Mineral Resources and Energy, 2019).

3. Literature Review

This research report proposes an optimization model for a cost-minimised energy generation while simultaneously satisfying multiple constraints. The literature review will include discussions starting with papers that have successfully optimized energy systems with renewable energy integration and ending with case studies from different countries, including South Africa, using these mathematical optimization techniques.

The scope for reviewing the literature will include discussing energy optimization models in the international landscape, the developing country landscape, and then specifically, the South African energy landscape. Looking at these three different landscapes will allow for a comprehensive background and also showcase where South Africa is positioned. Before searching for relevant studies, a criterion was created to narrow down the search. The criteria included four points, studies with high penetration of renewable energy, studies using MILP, QP, or MIQP as their methodology, studies with a cost minimization objective, and studies with a carbon emissions constraint. It was important to consider optimization methods that included power balance constraints as well as a carbon emission constraint to examine how these constraints interact with each other as well as with the objective function. The objective is to identify the most effective optimization model and approaches for managing South Africa's generation mix under carbon and power balance constraints. The methodology will be the most critical part of this research, therefore reviewing the literature on different energy generation optimization problems and deciding on the best fit will be discussed first.

The choice of methodology and software depended on the dataset size, the complexity of the optimization problem, the structure of the objective function and constraints, and whether the literature supported the methodology and software. Within the domain of power systems analysis, MILP holds dominance because it can meticulously solve a vast array of problems. Though less prominent due to its limited scope, QP excels in specific use cases where a quadratic objective function accurately represents the problem and linear constraints adequately capture the system's constraint characteristics. Research suggests that power plants' generation costs are considered quadratic rather than linear, which is why the objective function includes a quadratic term, and a quadratic programming (QP) model will be used (Alshamrani, 2023). The constraints to this optimization will be a power balance constraint, power limit constraints, and a carbon emissions constraint, as a result of these linear constraints, the exact methodology we propose is quadratic programming (QP) for this research. In terms of constraints, the power balance constraint is to ensure that electricity supply is always meeting demand. The power limit constraints placed on each technology are to ensure that the optimization does not exceed the physical capabilities and capacities of these technologies. The carbon emissions constraint is to ensure that the new added generation capacity is renewable energy technology, and that coal is limited to the current generation capacity. The integration of renewable energy for system optimization while minimizing costs and meeting the constraints presents a challenge. Theoretical frameworks have successfully demonstrated their feasibility, and practical models are being developed to support the successful transition from fossil fuels to cleaner technologies (Zhao & You 2020; Diéguez, et al. 2021). However, cost minimization is rarely the objective but rather efficiency output maximization and gird stability. These objectives are crucial to any energy system but from an economic standpoint, cost minimization is crucial. Cost minimization in the case of South Africa also makes sense as this approach contributes to optimal resource allocation across the economic system, leading to a state of increased productivity and heightened efficiency.

Within the scope of exploring renewable energy integration research papers, the following papers by Nasiri et al., (2022) and (Nallolla, et al., 2023) are discussed. Both studies highlight the effectiveness of MILP in optimizing renewable energy integration while addressing different facets of the optimization problem—cost minimization and multi-objective trade-offs. Nasiri et al., (2022)'s research emphasize the importance of handling uncertainties and integrating multiple generation sources, while (Nallolla, et al., 2023) extend this by incorporating multiple objectives, including carbon emissions and peak demand reduction. Nasiri et al. (2022) developed a two-stage robust MILP model for unit commitment scheduling in thermal-electrical systems with high solar power integration. This model incorporates high-resolution solar power forecasts and optimizes solar unit operations to minimize total generation costs, demonstrating the effectiveness of MILP in handling uncertainties and scheduling within a high renewable energy penetration context. For total cost results, the hybrid approach consistently achieves the lowest total cost. The study shows that incorporating multiple generation sources can further reduce costs, a strategy relevant for South Africa's diverse renewable energy mix, including onshore wind, solar PV, nuclear, and hydro energy. Similarly, Nallolla et al. (2023) proposed a multi-objective optimization approach for a hybrid AC/DC microgrid with high penetration of wind and solar energy. Their method combines an Evolutionary Algorithm (EA) with MILP to explore diverse solutions and handle discrete decision variables, aiming to minimize costs, carbon emissions, and peak demand. This approach not only reduces operational costs but also significantly lowers carbon emissions compared to conventional coal-fired generation. The results underscore the advantages of integrating renewable energy resources, highlighting how these methods can address the increasing costs of traditional energy sources and ensure system stability and reliability. Both studies emphasize the critical role of MILP in optimizing energy systems with high renewable penetration, though they apply different techniques and objectives to achieve comprehensive optimization. From a South African context, these studies highlight the potential of integrating diverse renewable sources, like wind and solar, to reduce operational costs and emissions, making renewable energy increasingly competitive against traditional coal-fired power. This relevance aligns closely with the current research, which aims to explore and enhance cost-effective strategies for high renewable energy integration in South Africa's energy landscape.

Although less prevalent than MILP, both QP and MIQP showcase valuable applications in research. While locating relevant publications initially posed a challenge, several examples were ultimately identified. Starting with a paper that introduced a QP model to improve linear power system optimization models to consider cost uncertainties (Lopion, et al., 2019). This was achieved by the researchers by incorporating specific investment costs that were tied to the installed capacity of each technology. The paper argues that a QP approach to model investment costs in energy systems optimization models leads to more robust and realistic results compared to the traditional LP. The solution is a better reflection of the current investment behaviour and could also be considered more realistic. The results of the model indicated a broader range and a more resilient allocation of the technologies compared to the linear model. The paper advocates for QP as an alternative to LP in cost minimization problems and is therefore an important study to consider as part of the literature review. While not explicitly focused on energy systems, this principle directly applies to minimizing energy generation costs.

International Case Studies

Building upon these insights, it is important to look at case studies where some of these concepts have been implemented using real-world data. Since this is a growing and dynamic topic, exploring how the literature is implemented practically is an important aspect of building upon current research. An Italian-based case study focused on an industrial plant in the Rome area and proposed a methodology that is based on mixed-integer linear programming to calculate the optimal sizing of a hybrid wind-PV power plant (Lamedica, et al., 2018). The results revealed the practicality of the methodology in identifying the optimal choice, which was combining the needs of the industrial plant with the RES availability and the realizable savings (Lamedica, et al., 2018). This study contributes by demonstrating the successful application of the MILP methodology and how it can determine the optimal sizing of a hybrid wind-PV power plant. This is particularly relevant for industries looking to reduce their carbon footprint and energy costs by leveraging renewable energy sources. While the chosen case study of an industrial plant in Rome differs significantly from the South African energy landscape, it serves as a valuable starting point for further research and adaptation to specific contexts.

Building on the international cases, a study developed a multi-period mixed-integer linear programming (MILP) model to describe the transition from fossil fuels to renewable sources for generating road transport fuels and electricity over the long term (Potrč, et al., 2021). This study was based on the 27 countries in the European Union (EU). The study's objective function was the sustainability net present value (NPV), indicating that the outcomes reflect a balance between environmental, economic, and social considerations. The electricity generation results indicate that wind energy will remain the primary technology for the transition in the initial years, with a greater integration of solar PV expected after 2030. The study's projections include the installation of 550 810 wind turbines and 5 636 km^2 of PV over the next 30 years (Potrč, et al., 2021). Additionally, the results suggest that optimizing larger systems leads to greater economic NPV. For instance, the study revealed that optimizing at the EU level resulted in a 15% higher sustainability NPV compared to optimization at the country level with a substantial 24% increase in economic NPV (Potrč, et al., 2021). Even though the objective function is different, this research is of interest because of the successful use of a MILP model while integrating renewable energy on a continental scale which introduces another set of challenges with regards to collaboration and cost allocation.

Emerging Markets Case Studies

In the context of emerging markets, the following paper introduces a MILP model designed to optimize the design of rural hybrid wind-PV electrification systems in Peru (Ferrer-Martí, et al., 2013). The researchers devised two alternative mathematical formulations utilizing integer variables to determine the location and size of the equipment and the other using binary variables. This approach allowed them to analyse the efficiency of each formulation and select the most effective one. They found that the integer model was the superior model (Ferrer-Martí, et al., 2013).

The hybrid models were applied to two case studies in Peru, demonstrating that the results produced by the new model can lead to substantial cost reductions (Ferrer-Martí, et al., 2013). This is because of the new model's ability to explore and select the optimal combination of microgrids, individual systems, and energy sources that feed each one. The relevance of this paper extends beyond the specific context of Peru as its focus on cost minimization and flexible design choice makes it applicable to larger-scale generation systems in other regions. The incorporation of a power balance constraint ensures that the optimization system can meet energy demand at all times, making it a valuable tool for generation system optimization in emerging markets. By adapting the principles and methodologies from this research, larger countries can develop more efficient and cost-effective rural electrification strategies that leverage the potential of hybrid wind-PV systems. This speaks directly to rural energy security in South Africa and adds to the argument for high renewable energy penetration, not solely for carbon emissions reduction but for sustainable energy security for rural areas.

Additionally, researchers developed a Generation Expansion Planning model tailored for use in developing countries (Afful-Dadzie, et al., 2020). This model helps evaluate and comprehend crucial aspects such as financing, the cost of electricity, and the extent of unmet demand when establishing renewable energy generation objectives (Afful-Dadzie, et al., 2020). This analysis has the potential to offer guidance and support to developing countries concerning the costs and benefits of implementing a target policy for renewable electricity generation (Afful-Dadzie, et al., 2020). The model's design took the shape of a multi-period stochastic MILP, enabling long-term planning and the consideration of uncertainties in parameters like electricity demand and fuel prices. The model's functionality is showcased through a case study focusing on Ghana. The objective function of the model is to minimize costs involved in the provision of electricity over a specific period. The results from the Ghana case study suggest that achieving a 10% renewable energy generation target by 2030, while maintaining unmet demand at a reasonable level, would require the country to allocate a budget of at least 1% of its Gross Domestic Product (GDP) for generation capacity investment (Afful-Dadzie, et al., 2020). This is an important study to consider as Ghana, similar to South Africa, is also heavily reliant on coal-fired power plants as their primary source of electricity generation. Additionally, both Ghana and South Africa have significant renewable energy potential, Ghana in terms of abundant solar and hydropower, and South Africa in terms of solar and wind. Both countries also face transmission infrastructure challenges, with aging and insufficient transmission networks limiting the integration of renewable energy.

A study from China, which similar to South Africa is also a developing country highly dependent on coal-fired power stations, investigates cost-optimal strategies for integrating high levels of renewable energy (wind and PV) into their power system (Li, et al., 2022). The key findings from the study are that there is a trade-off between high renewable energy penetration and costs, higher penetration requires more expensive solutions like energy storage. Furthermore, the findings indicate that with sufficient energy storage technology a maximum renewable energy penetration of 85.8% could be attained by 2050, however, this approach will be more costly compared to the other lower levels of renewable energy penetrating solutions (Li, et al., 2022). The study also finds that optimal solutions differ based on regional resources and needs which is an important consideration for South Africa as there are many different rural and urban areas in the county. The study also focuses on cost minimization and decarbonization which supports the objective and constraint of my research making the results of this study valuable for the literature review. This also further points out that even though the optimization has a cost minimization objective, which does not mean the costs of penetration will be low, the costs will only be optimized accordingly not comparatively.

South African Case Studies

A paper based on the South African landscape from a group of researchers proposed a collaborative MILP optimization approach that minimises power system's operating costs with constraints similar to what will be used for the research for the South African energy system optimization (Mehedi, et al., 2023). The empirical results indicate many results starting with the fact that the model can replicate the inconsistency and overall flexibility of the power system, particularly when variable amounts of renewable energy are generated (Mehedi, et al., 2023). This is an important result because of the intermittent nature of renewable energy generation. Moreover, the model proposes valuable insights into investment decisions by evaluating investment decision by evaluating the installed capacity, utilization, and emission rates of different energy technologies (Mehedi, et al., 2023). This outcome is economically important as cost minimization is the objective function and investment in renewable technology needs to be a viable investment to the government and private sectors. Another study designed a hybrid wind turbine/ photovoltaic/ biomass/ pump-hydro-storage energy system and optimization was based on technical, economic, and environmental parameters to meet the load demand while minimizing costs (Alturki & Awwad, 2021). The results indicate the proposed hybrid system is environmentally and economically practical. This is an important study to investigate as there were many different moving parts and the model still produced useable results.

A recent study conducted in South Africa aimed to optimize the design and dispatch strategies of a resilient renewable energy microgrid intended for a hospital located in the country (Hirwa, et al., 2023). The authors used a MILP programming model for this optimization. This model considered renewable energy sources, combined heat and power, and storage technologies. Additionally, the model aimed to minimise total cost including capital, operational, and utility expenses. The results revealed that the model effectively addressed the reliability challenges, irrespective of the time of occurrence (Hirwa, et al., 2023). This study uses local data, and they are improving reliability which is a major issue for integrating renewable energy into a power system. The PV system size is sensitive to changes in capital and fuel costs, photovoltaic resource availability, and hourly electrical demand. This is an important study to consider because South African data is being used in the South African energy landscape. Although the study is using a microgrid, their objective is cost minimization which aligns with the objective of this study and their results can be used on a larger scale such as the whole country.

4. Methodology and Data

The hypothesis for this research paper is that South Africa’s energy mix can be improved to include more renewable energy and as a result start decreasing carbon emissions sooner than what is stated in the IRP2019. The methodology is broken down into two parts, starting with the system modelling which includes the solar and wind generation. Then there is the mathematical framework which includes the objective function, which is cost minimization, and the two constraints.

4.1 System Modelling

This system includes three equations, the wind and PV generator sets, and the carbon emissions constraint. All three sets are presented and explained below.

4.1 1 Wind Power generation

When setting up the wind power output equation involves knowledge about how wind generation occurs. Kinetic energy is present whenever an object of a certain mass is in motion with a transitional or rotational speed (Tong, 2020). When the air is in motion, the kinetic energy in moving air can be determined as:

$$E_k = \frac{1}{2}\, m\bar{u}^2 \qquad (1)$$

Where the air mass is m and the average wind speed is $\bar{u}$ over a specific period (Tong, 2020). Wind power is obtained by differentiating the kinetic energy in wind with regards to time, i.e.:

$$P_w = \frac{dE_k}{dt} = \frac{1}{2}\, m\bar{u}^2 \qquad (2)$$

However, only a portion of wind power is converted into electrical power. When wind passes through a wind turbine and drives the blades to rotate, the corresponding wind mass flowrate (Tong, 2020) is represented by:

$$m = \rho A\bar{u} \qquad (3)$$

where the air density is ρ and the swept area of the blades is A, then substituting (3) into (2), the available power (Tong, 2020) is expressed as:

$$P_w = \frac{1}{2}\, \rho A\bar{u}^3 \qquad (4)$$

Equation (4) shows that higher wind power is dependent on higher wind speeds, longer length of blades for gaining a larger swept area, and a higher air density. The wind power output is proportional to the cubic power of the mean wind speed, therefore a small variation in wind speed can result in a substantial change in wind power. The average air density at South African wind farms is estimated to be 1.225 kg/m^3. The swept area of the turbine is calculated using the following equation: $A = \pi \times (\frac{D}{2})^2$. D is the rotor diameter and in South Africa, the average rotor diameter is 101m (Jeffreys Bay Wind Farm, 2024). The average wind speeds used in the optimization are from four separate locations in South Africa. The locations were selected based on the Wind Atlas for South Africa (WASA) reports, presentations, and maps (WASA Project Team, 2020). Then the wind speed data based on the locations were gathered from NASA's POWER Project (NASA POWER Project, 2023). The four locations were Napier, Sutherland, Humansdorp, and Noupoort. These locations are located in the Northern, Eastern, and Western Cape provinces of the country. This data is over the period 1 March 2022 to 31 March 2023. These windspeeds were measured at a hub height of 60m but most wind turbines in South Africa are now between 80m and 120m. Since the data was from 60m height, the wind shear power law was used to estimate the wind speeds at 100m, and these values are shown in Figure 1 and used in the optimization.

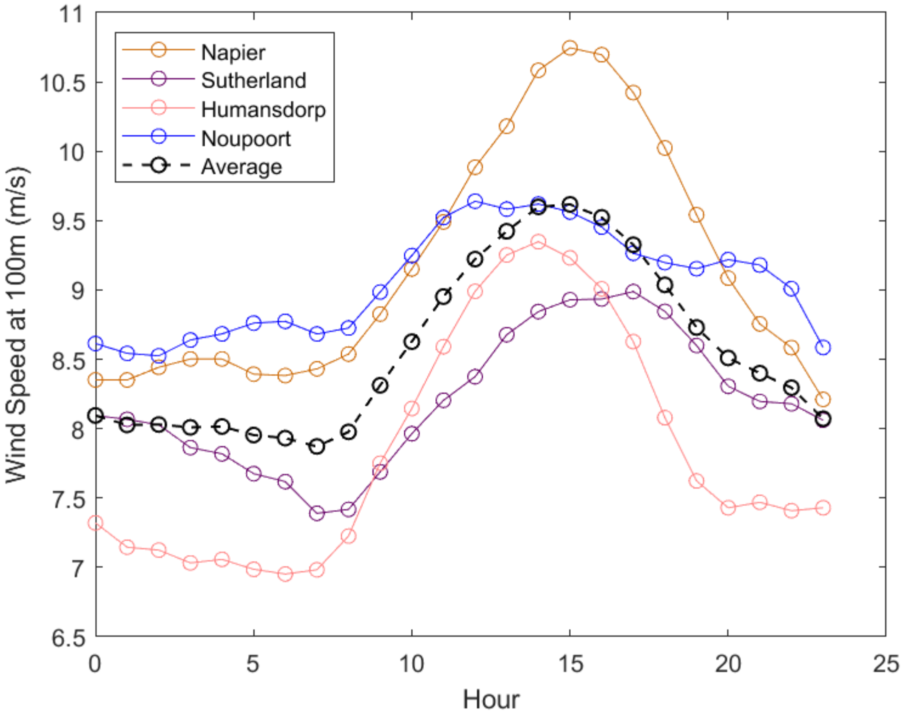

Figure 1: Wind Speeds at 4 locations at 100m.

From the locations, Napier reaches the highest average speeds at 9.2 m/s consistently every day of the year around 15:00. The windspeeds are also consistently greater than 5 m/s which is greater than the usual cut-in speeds of wind turbines in South Africa according to (Rehman, et al., 2022). The lowest wind speed recorded on average was 5.96 m/s in Humansdorp at 06:00.

Now that the wind power output equation and the average wind speeds have been established, the next step is to incorporate cut-in, cut-out, and rated wind speeds. These three parameters are crucial because they define the operational range of a wind turbine and its efficiency within that range. The cut-in speed, v_{cin}, is the minimum wind speed required for the turbine to start generating electricity (Tong, 2020). Below this speed, the wind is not strong enough to overcome the friction and inertia of the turbine blades. By not including the cut-in speed into the equation, the potential power output would be overestimated as the turbine would not generate anything at lower wind speeds. The rated wind speed, v_r, is the speed at which the turbine generates its maximum power output (Tong, 2020). At this point, the blades are capturing the wind energy most efficiently, maximizing electricity production Knowing the rated speed is crucial for estimating the peak generating capacity of the turbine and evaluating its suitability for a specific wind resource. The cut-out speed, v_{cou}, is the maximum wind speed at which the turbine is safely operated (Tong, 2020). When wind speeds exceed this limit, the turbine shuts down automatically to protect itself from damage caused by excessive forces. The rated wind speed, cut-in wind speeds, and cut-out wind speeds were used according to (Pryor, Barthelmie, Bukovsky, & Leung, 2020). Which is an average cut-in speed of 3 m/s and an average cut-out speed of 25m/s, respectively, and they are used like this in the optimization. The average rated wind speed at South African wind turbines is between 13-15m/s and this range was used in the optimization.

Therefore, the total power output of the wind farm is equal to the number of turbines in the wind farm multiplied by the power output of a single turbine. The output of a single turbine is equal to a conditional bracket with three conditions. When the wind speeds are between the cut-in wind speed and the cut-out wind speed, then the following equation applies: $\frac{1}{2}\,\rho A\bar{\mathrm{u}}^3$. If the wind speed falls outside of any of these parameters, the answer will yield a zero as the wind speeds are either too low to meet the minimum or the wind speeds are higher than the maximum which could cause damage to the equipment. The decision variable in this equation is N which is the number of turbines in the find warm and will be determined by the optimization. The total power output (Ju, et al., 2023) can be calculated as follows:

$$P_{wf}^{wd} = \mathrm{N} \times = \begin{cases} \frac{1}{2}\,\rho A\bar{\mathrm{u}}^3, v_{cin} < \bar{\mathrm{u}}^3 < v_r, \\ \frac{1}{2}\,\rho A\bar{\mathrm{u}}^3, v_r < \bar{\mathrm{u}}^3 < v_{cou}, \\ \quad 0, otherwise \end{cases} \tag{5}$$

4.1.2 PV Generation

The equation for PV generation calculates the electrical energy produced by the PV system. This means multiplying the global horizontal irradiance (GHI) by the panel efficiency, and the installed area. The GHI for South Africa is among the top 3 countries in the world with these levels of horizontal irradiance (World Bank Group , 2020) and when calculating utility-scale PV generation, GHI is an indicative parameter for successful generation at a specific location in the Global Horizontal Irradiance (GHI). The GHI refers to the total amount of solar radiation received from above by a horizontal surface on Earth. The range of GHI in clear sky conditions is typically between 100 W/m^2 and 1000 W/m^2. Some locations have been identified by different research and scientific institutions as having the most potential for PV generation in South Africa. For this optimization problem, the 3 locations' GHI data that will be used are Upington, Springbok, and Postmasburg which are all located in the Northern Cape province. Figure 2 shows the GHI for 24 hours of 11 months in 2023 for all 3 locations.

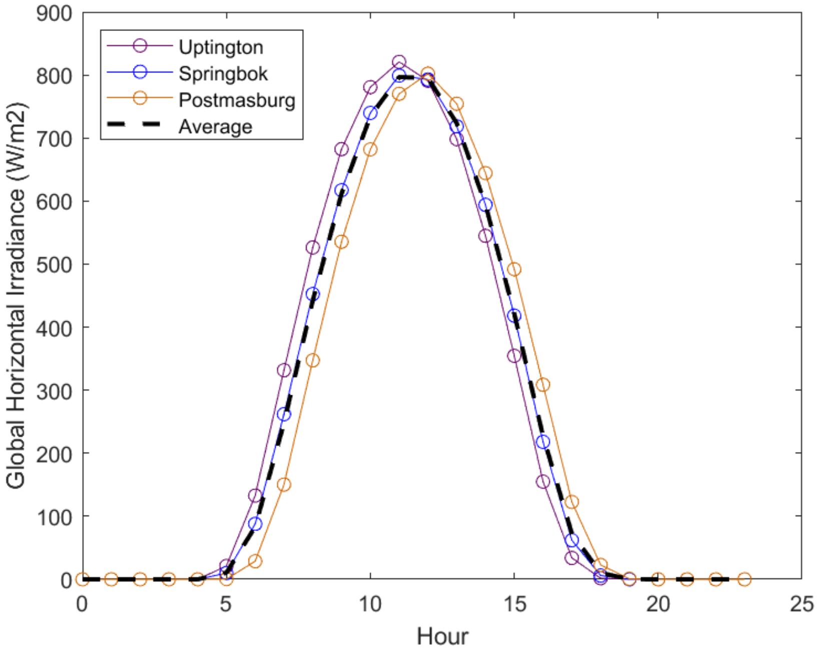

Figure 2: Global Horizontal Irradiance average for the 3 locations.

The average across all 3 locations for every hour for 24 hours for the 11 months was taken. The data from these locations were sourced from the NASA POWER Project (NASA POWER Project, 2023). PV generation's dependence on sunlight means that from 19:00 to 04:00 there will be no generation taking place. However, between 05:00 and 19:00 the GHI can reach as high as 796.59 W/m^2 which is remarkably close to the upper limit. Within the optimization, the PV generation output is used to constrain the problem to the maximum output available. Alongside GHI, another important aspect of PV generation is panel efficiency. Panel efficiency, η_{PV}, is a coefficient between 0 and 1 reflecting the efficiency with which the PV cell converts solar energy into electrical energy. The higher the panel efficiency, the more power generation for the same amount of sunlight. In South Africa, the average panel efficiency is found to be between 15% and 20% with the highest being 23% (SAPVIA, 2021). The last variable in the equation is the installed area which is a decision variable, and the optimal amount will be decided by the optimization.

Similarly, to wind power generation, understanding the process behind PV generation makes formulating the equations easier and more realistic. The Photovoltaic Cell is a semiconductor device that transforms solar light into electrical energy through a physical phenomenon known as the Photovoltaic Effect (Singh, 2013). The Photovoltaic Effect relies on the unique properties of semiconductors. These materials possess a partially filled valence band and an empty conduction band separated by a finite energy gap, the band gap (Singh, 2013). Photons with energy exceeding the band gap can excite electrons from the valance band to the conduction band, rendering them mobile and able to participate in electrical conduction. Another important concept is recombination losses which is when excited electrons and holes are trapped and the absorbed energy gets released as heat rather than being converted into usable electricity (Singh, 2013). The band gap of a cell determines its sensitivity to different light spectra, directly impacting efficiency under varying conditions. Additionally, temperature plays a key role, as higher temperatures increase recombination losses, reducing efficiency and output. The following equation represents the amount of electrical energy generated by the PV system:

$$PV\ Gen = \eta_{PV} G A_{PV} \tag{6}$$

4.1.3 Carbon Emission Constraint

The carbon emissions constraint will be introduced as an emissions cap on coal-fired generation over the 5 years of the optimization. This means that every year the carbon capacity will decrease by 10% from the previous year’s carbon capacity. The optimization starts in 2026 meaning the baseline for the carbon emissions cap will be the carbon emissions released in 2025 which is predicted to be 260-280 MtCO2e according to the IRP2019. This is the baseline scenario from which the reduction will start. The right-hand side of the equation is the baseline capacity in 2025 times the 24 hours times the 90% which represents the year-on-year reduction.

$$e \times \sum_{t=1}^{24} P_c(5,t) \times 1\ hour \leq 0.9 \times e \times \sum_{1}^{24} P_{c,2024} \times 1\ hour \tag{7}$$

4.2 Mathematical framework

4.2.1 Objective function

The objective function is to minimise the total cost of the system while ensuring adequate electricity supply, with a simultaneous aim to reduce carbon emissions stemming from the power system (Mehedi, et al., 2023). The right-hand side of the objective function equation adds up the total costs from wind, PV, and coal generation. Each of the generation technologies then has their generation cost equations as the cost elements of each technology are different. The target is to minimise the total investment costs of PV, wind, and coal plants from 2026-2030. The total cost minimum is equations (8) and equations (9), (10), and (11) are the breakdown of the different technologies' total cost equations. TC is the total cost variable; this is the minimum amount for all three technologies including their respective operations and maintenance costs. This amount is summed over the 5 years. $TC_{coal}(y)$, $TC_{PV}(y)$ and $TC_{wind}(y)$ are the total cost variables for each technology as indicated by the subscripts. The year indicator is y and represents the year in which the total cost is calculated. OM_{coal}, OM_{PV} and OM_{wind} are the operations and maintenance costs associated with the different technologies. $p_{pv}(y)$ is the capital cost of a 1 MW coal plant in year y, which is assumed to be a fixed amount. $C_{coal}(y)$, $C_{PV}(y)$ and $C_{wind}(y)$ are the capacity variables for each technology and they are decision variables decided by the optimization.

$$\text{Min TC} = \sum_{y=1}^{5}[TC_{wind}(y) * 1.05 + TC_{PV}(y) * 1.05 + TC_{coal}(y) + OM_{coal}] \tag{8}$$

$$TC_{coal}(y) = p_{coal}(y)C_{coal}(y) \tag{9}$$

$$TC_{PV}(y) = p_{pv}(y)C_{PV}(y) + OM_{PV} \tag{10}$$

$$TC_{wind}(y) = \; p_{wind}(y)C_{wind}(y) + \; OM_{wind} \tag{11}$$

Equations (12) and (13) are calculated using the learning curve approach. This is a widely used approach to forecast the cost reduction of new technology as more units of the product is manufactured (Yelle, 1979). C_{t0_PV} and C_{t0_wind} are \$1274/MW and \$876/MW respectively and data is sourced from the International Renewable Energy Agency (IRENA) (IRENA, 2023). Total installed capacity for PV and wind respectively, is represented by q_{t_PV} and q_{t_wind} and this data was sourced from the IRP2019 (Department of Mineral Resources and Energy, 2019). The values are presented in Table 1 from 2026 to 2030.

Table 1: Installed capacities for solar PV and onshore wind for 2026 to 2030 from IRP2019

Year	**Solar PV Capacities (MW)**	**Onshore wind Capacities (MW)**
2026	3985	5042
2027	4985	6642
2028	5985	8242
2029	6985	9842
2030	7985	11442

The wind capacity has a relatively higher increase compared to PV. Additionally, the data for the capacity in 2026 for both technologies, $q_{t0_{wind}}$ and $q_{t0_{PV}}$ are also presented in Table 1. Initially, the learning rate of PV and wind was estimated in 2021 by Grubb, Drummond, Poncia, & Mcdowall, (2021) over the 40 years for PV to be around 20% and 10% for onshore wind. However, IRENA found in 2022 that utility-scale solar PV had a higher estimated learning rate of around 33% (IRENA, 2023) which exceeds the 2021 estimation by (Grubb, Drummond, Poncia, & Mcdowall, 2021). For onshore wind, the estimation is also higher and estimated to be around 20% according to the 2022 IRENA report (IRENA, 2023). The learning rates for PV and onshore wind calculated by IRENA were used in the optimization.

$$p_{PV}(t) = C_{t0\_PV} \left(\frac{q_{t\_PV}}{q_{t0}}\right)^{\frac{\ln(1-LR)}{ln2}} \tag{12}$$

$$p_{wind}(t) = C_{t0\_wind} \left(\frac{q_{t\_wind}}{q_{t0}}\right)^{\frac{\ln(1-LR)}{ln2}} \tag{13}$$

In addition to installation costs, operations, and maintenance costs (O&M) are also required to include a full view into the optimization. The O&M costs for PV and wind are sourced from the National Research Energy Laboratory (NREL) and presented in Table 2. The trend for these costs for both technologies is downward meaning they get cheaper to operate and maintain over time, this is a common feature of renewable energy technologies, as they have much higher installation costs than O&M costs. These costs are imported as fixed annual amounts into the optimization.

Table 2: O&M costs for solar PV and onshore wind in $/MW

	2026	**2027**	**2028**	**2029**	**2030**
Solar PV ($/MW)	20 963	20 705	20 446	20 189	19 932
Onshore wind ($/MW)	29 384	29 020	29 017	28 834	28 650

For coal-fired power station costs, equation (14) will be used to calculate the operations and maintenance costs. This is a quadratic cost equation which is a commonly used equation for power systems optimization problems to represent the variable costs of generating electricity from coal-fired power stations (Wood, et al. 2013; Djurovic, et al. 2012). The coal cost coefficients, a_1, a_2, and a_3, represent different components of cost. The quadratic component represented by a_1 is the variable cost and is related to the efficiency of the plant and the cost of fuel and is a_1 = 2 $/MWh^2 in the optimization. The linear component, represented by a_2, is the variable cost related to variable costs that are directly proportional to the power output, and in the optimization a_2 = $30/MWh. The fixed cost variable, represented by a_3, includes expenses such as salaries and maintenance. This cost is not inclusive of how much power is generated by the power station. This is a large parameter in a South African context as according to Eskom's annual financial statement for 2022, they paid R28 billion in maintenance in 2022 (Eskom, 2022). In optimization, this amount is assumed to be the same for the optimization timeframe, as South Africa's coal-fired power stations and even newer power stations such as Medupi are constantly facing defects and performance issues. Therefore, a_3 = \$1.4 billion as a fixed yearly cost in the optimization.

$$OM_{coal} = \sum_{t=1}^{24} a_1 P_{coal}^2(y,t) + a_2 P_{coal}(y,t) + a_3 \tag{14}$$

4.2.2 Constraints

4.2.2.1 Power Balance Constraint

The power balance equation guarantees that the expanded total generation capacity can meet the load demand of the specified future year (Mehedi, et al., 2023). The left-hand side of the equation is the sum of the generation capacity of coal-fired power stations, PV plants, and wind farms each with a time dimension of 5 years and 24 hours. $P_c(y,t)$, $P_{PV}(\mathrm{y},\mathrm{t})$ and $P_{wind}(y,t)$ are the power output variables, these are also decision variables decided by the optimization. The power balance constraint ensures that the optimization is aware that these 3 power outputs need to equal demand at all times, in every year, y, and at every hour, t.

$$P_c(y,t) + P_{PV}(\mathrm{y},\mathrm{t}) + P_{wind}(y,t) = demand \tag{15}$$

Demand is the next important variable to include in the optimization as generation has to meet demand at all times. The demand forecast data for 2026 to 2030 was used from the IRP2019 data and is presented in Table 3 (Department of Mineral Resources and Energy, 2019). The demand is gradually increasing which is expected from a developing country such as South Africa. To optimize this generation system with a cost minimum objective, the generation capacity of each technology needs to be calculated along with what this generation will cost. The demand is represented as only 83% of the total demand. This is done because the three technologies used in the optimization meet 83% of the total demand and the rest of the generation technologies in South Africa meet the rest of the demand. This discretion is made, as the optimization is not assumed to neglect the rest of the technologies but rather assumes that they stay constant within the 5-year optimization period.

Table 3: South Africa's predicted demand from 2026 to 2030 sourced from the IRP2019

Demand (MWh)	Year
293 379 490	2026
296 424 400	2027
299 284 420	2028
308 363 720	2029
315 059 670	2030

4.2.2.2 Power Limits Constraints

Each technology is constrained to its generation inputs. Equations (16), (17), and (18), represent these constraints per generation technology. Solar PV power output is constrained by panel efficiency, GHI, the initial installed capacity, and the capacity added by the optimization. PV generation cannot occur beyond these limits. Wind power output is constrained by equation (4) which contains, the air density, swept area, and the cubed average wind speeds. Additionally, wind, like PV, is also constrained by the initial installed capacity and the capacity added by the optimization. Wind generation cannot occur beyond these limits. The coal power limit is slightly different as it's an inequality meaning generation can be equal to or less than the initial installed capacity and the capacity added by the optimization. C_{02}, C_{03} and C_{01} are the initial installed capacities in 2026. In the case of PV and wind, new capacities are intended to be added to the initial capacities but in the case of coal, there will be no new capacity added but the intention is for the coal capacity to decrease as new renewable capacity is introduced.

$$P_{PV}(\mathrm{y},\mathrm{t}) = \eta G_t \sum_{i=1}^{y} C_{pv}(i) + C_{02} \tag{16}$$

$$P_{wind}(y,t) = \frac{1}{2}\,\rho A \bar{\mathrm{u}}^3 \sum_{i=1}^{y} C_{wind}(i) + C_{03} \tag{17}$$

$$P_c(y,t) \leq \sum_{i=1}^{y} C_{coal}(i) - C_{01} \tag{18}$$

5. Results and Discussion

The objective of this optimization was to minimise the total cost of an energy mix with a carbon emissions constraint. The period is 5 years from 2026-2030 and the data is used in a South African context. When setting up the optimization problem, the cost minimum objective function was defined as well as all of the constraints laid out in the methodology section. The optimization was solved using the quadratic programming solver in MATLAB. This is a result of the quadratic term in the total cost function and all of the constraints being linear. There were 3 assumptions made concerning the generation energy mix. The first was those assumptions no additional capital costs for coal, as no more coal-fired power stations are being planned to be built in South Africa. The second assumption was that the other technologies in the current energy mix such as nuclear, hydro, gas, pumped storage, and CSP energy would remain their current contribution within the optimization period. Another was the phase-out of coal and not having erratic jumps between the technologies and years, as this would not be realistic.

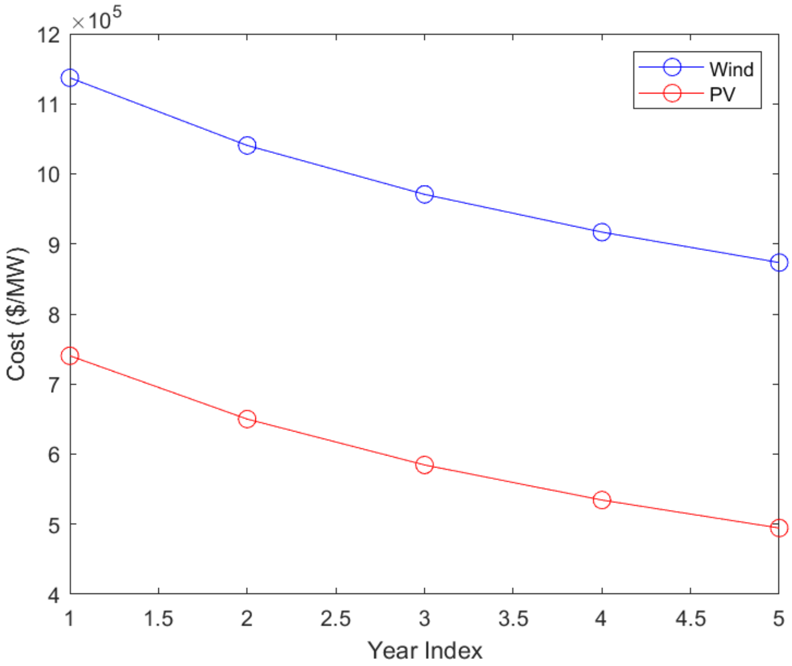

Figure 3: Costs of PV and Wind Generation Technology from 2026 to 2030

The objective of this optimization was cost minimization. The following results are with regards to the cost side of the optimization. Figure 3 shows the installation costs of onshore wind and solar PV. There figures clearly show that the costs of these technologies are decreasing at a rapid rate. This is a result of the technology of renewable energy. The results for the total cost minimum amount were \$35 536 666 520 which is approximately R671 billion. This equates to R134 billion per year over the 5 years. This amount represents the average amount that would need to be spent each year to achieve the minimum total cost for the energy system taking into account the optimization constraints and the cost minimum objective. This result aligns with the findings from the literature by Nasiri et al. (2022), showcasing the effectiveness of different optimization methods in achieving cost minimization while integrating renewable energy sources. With regards to the NDC's estimated investment requirements to achieve South Africa's NDC targets by 2030, a minimum of R99 billion per annum is required and a maximum of R618 per annum is required. This however considers more than the energy sector. Within the energy sector, the NDC estimates a minimum investment requirement of R42 billion per annum and a maximum of R198 billion per annum. The results from this optimization fall on the lower end of the range at R134 billion per annum. This indicates that the optimization results fall within the viable financial range of climate mitigation measures. The assumption underlying this analysis is that achieving the minimum cost for energy generation results in a slower integration of renewable energy sources into the energy mix. This gradual approach may align with budgetary constraints and existing infrastructure capabilities, but it comes with the drawback of delayed progress in mitigating climate risks. On the other hand, a strategy involving maximum annual investment allows for a faster transition to renewable energy, thereby accelerating the reduction of greenhouse gas emissions and contributing more effectively to global climate goals. However, this rapid transition poses challenges, particularly in terms of aligning with the Just Energy Transition (JET) plan.

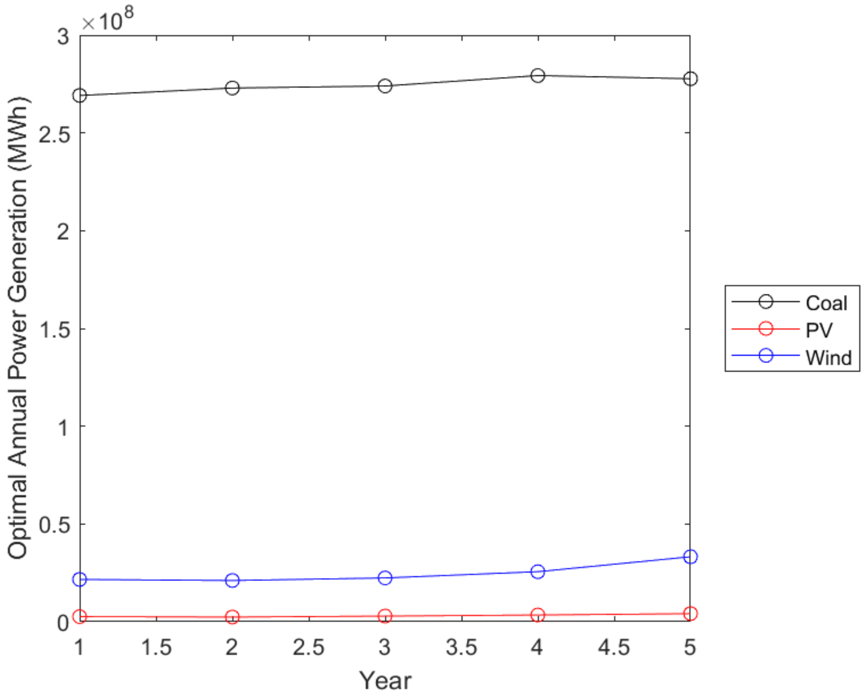

Figure 4: Annual Optimal Power Output for 2026-2030 per Generation Technology

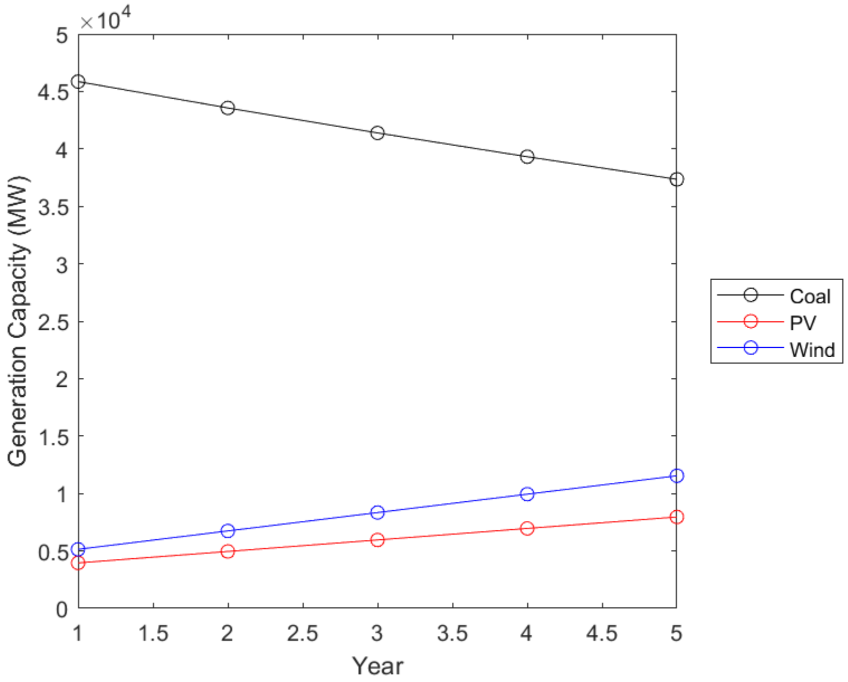

Figure 5: Cumulative Generation Capacities from 2026 to 2030

The optimal energy output per technology and the cumulative capacities over the 5 years are presented in Figure 4 and Figure 5, respectively. In Figure 4, the PV and wind generation increased over the 5 years while coal generation stayed relatively constant until the final year when a sharper decrease was observed. This is an expected result as PV and wind are introduced at 1000 MW and 1600 MW each year. This is a relatively small increase in these renewable energy capacities and the increase is also uniform meaning that if there were to be technological advances, the increase in their generating capacities would reflect that. The forecasted optimal PV output increase annually from 2 610 489 MWh (2.6 GWh) in 2026 to 4 136 755 MWh (4.1 GWh) in 2030. The forecasted optimal wind output increases from 21 631 141 MW (21.6 GWh) in 2026 to 33 236 539 MW (33.2 GWh) in 2030. Therefore, the optimal renewable energy contribution in 2030 in this energy mix would be 37.3 GW. Coal increases from 267 981 666 MW (267 GWh) in 2026 to 279 648 432 MW (279 GWh) in 2030. Figure 5 shows the cumulative capacities over the 5 years. The coal capacities capacity has a decreasing trend over the 5 years, whilst solar PV has an increasing trend. Solar PV increases by 1000 MW capacity per year, making the cumulative capacity at the end of 2030 equal to 7985 MW, and wind increases by 1600 MW each year, making the cumulative capacity at the end of 2030 equal to 11442 MW. Since no more coal-fired generation capacity is expected to be added in South Africa, the maximum coal capacity starts at 45858 MW in 2026 and decreases from there to 37351 MW in 2030.

A reason for this increase in coal power output could be due to the optimization realizing that there won't be enough renewable energy added to meet demand and therefore due to the power balance constraint is forced to fill that demand with the more expensive but high output coal power. When increasing the capacities by 3000 MW and 4800 MW per year which is quadruple the amount prescribed by the IRP2019, the power output changes to what is presented in Figure 6. Even though this does make for a faster integration of renewable energy, this would cost more and with a cost minimum objective, this increase in renewable energy capacities is not considered for this optimization.

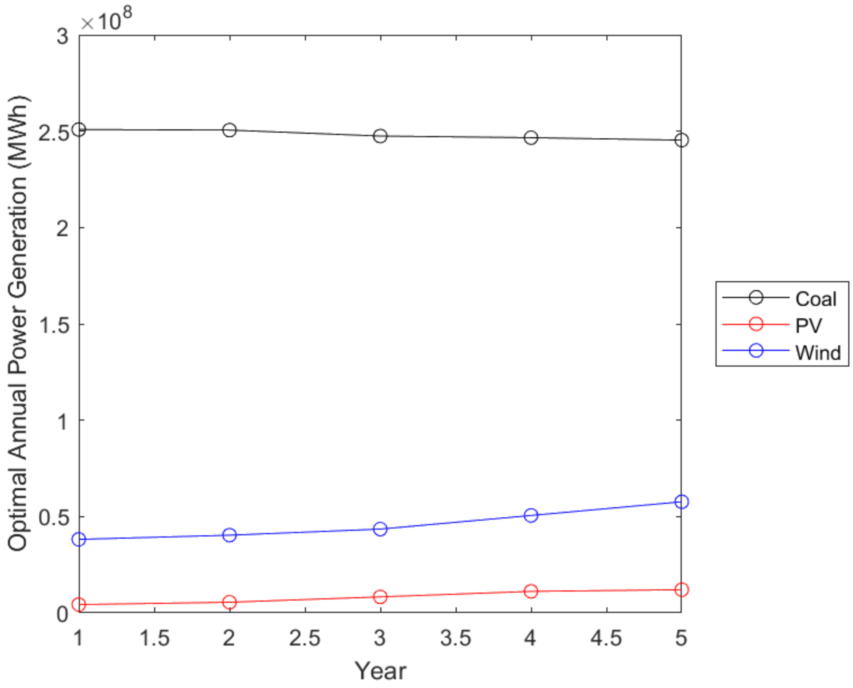

Figure 6: Higher Renewable Output due to Higher Capacities Scenario for 2026 to 2030

Additionally, Figure 7 and Table 4 were created to see the full transition of the energy mix over the 5 years. The energy mix for year 1 which is 2026 is not much different from the current energy mix which is to be expected as the energy system transition over longer periods. The mix only consists of 83% of the electricity generated in the country as this is the current generation by solar PV, onshore wind, and coal-fired power stations. The percentages are as a percentage of 83% not 100% of generation as South Africa uses other generation technologies alongside coal wind and PV, which has been assumed to be constantly generating for the optimization period, e.g., the other 17% of the demand is assumed to be supplied by the other

17% of generation technologies. This is the optimal energy mix produced by the optimization including all of the constraints which included the power balance constraint. This demonstrates that 83% of the demand mainly met by coal-fired generation can be shared by PV, wind, and coal. Wind is increasing as a percentage quicker than PV which can be explained by higher capacity allowance for wind energy in South Africa.

Table 4: Percentage Changes in Optimal Energy Mix from 2026 to 2030

	Generation Technology		
Year	**Wind (%)**	**PV (%)**	**Coal (%)**
2026	7.56	1.17	91.28
2027	6.96	0.84	92.20
2028	6.97	1.04	91.99
2029	8.25	1.16	90.59
2030	9.95	1.37	88.86

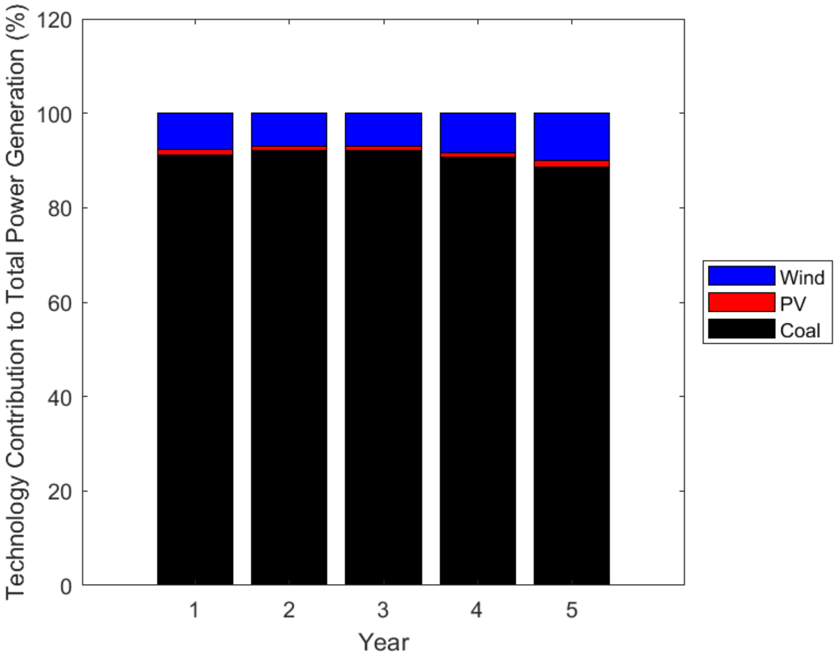

Figure 7: Optimal Energy Mix from 2026 to 2030

The International Energy Agency (IEA) found in 2021 that South Africa generated 391.746 million tonnes of CO2. Additionally, they found that 83% of the total CO2 emissions are from fuel combustion specifically coal, which amounts to 323.8 MtCO2. This will be used as the baseline to measure the carbon emissions generated by the optimal mix. When the IEA did their study South Africa's energy mix consisted of 81% coal, 3.69% onshore wind, and 2.24% of solar PV generation. In comparison to this optimization that uses 83% of the energy mix, it amounts to 97% coal, 4.44% onshore wind, and 2.69% solar PV generation. The country has increased its renewable energy generation since 2021 and the energy mix according to the optimization's 83% assumption, starts in 2026 with 88% coal, 1.42% solar PV, and 10.12% of onshore wind generation in the energy mix. This is already an improvement in the country's commitment to climate change mitigation. When linking this result to the reviewed literature including studies from South Africa and China, it highlights the challenge of balancing carbon emissions constraints with energy system optimization, such as the trade-offs shown in Li et al. (2022) between renewable energy penetration and costs. Your study effectively applies these constraints, demonstrating a reduction in coal dependency and an increase in solar PV and wind capacities over time. The results, which align with the IEA baseline emissions, underscore a significant shift towards cleaner energy and validate the literature's emphasis on integrating carbon constraints into energy system optimization. Based on the baseline emissions in 2021, the emissions factor of 0.95, and the 10% generation reduction constraint placed on coal generation in the optimization, the number of emissions generated between 2026 and 2030 can be calculated. If 97% of the energy mix was coal in 2021, and 323.8 MtCO2 came from that combustion process, then in 2026, 88% of the energy mix that uses coal combustion will generate 293.8 MtCO2. This same calculation is applied for 2027 to 2030 which is shown in Table 5.

Table 5: Annual Carbon Emission from Coal Generation

Year	**Annual Emissions from Coal Generation (million tonnes)**
2026	305.9
2027	308.3
2028	307.9
2029	303.3
2030	297.4

In the context of South Africa's National Determined Contribution (NDC) targets, Table 5 provides crucial insights into the carbon emissions resulting from coal power generation over the 5 years. The emissions were measured against the NDC's target range for South Africa between 2025 to 2030, which was set at 350-420 million tonnes of CO2 annually. This target range is set for the entire economy including transportation and manufacturing, however, this optimization focused solely on emissions from coal combustion. This means that even though in 2026 the annual emissions are predicted to be 305.9 million tonnes this leaves limited room for carbon emissions from other sectors of the economy. The optimization results indicate that the carbon emissions generated by coal generation are not decreasing immediately, only after the 2nd year which is not surprising as coal generation would not decrease immediately. A notable point to make is that for all 5 years, the emissions are below the target range set by the NDC. The emissions are linked to coal generation, meaning the less coal generation is used the less carbon emissions will be generated.

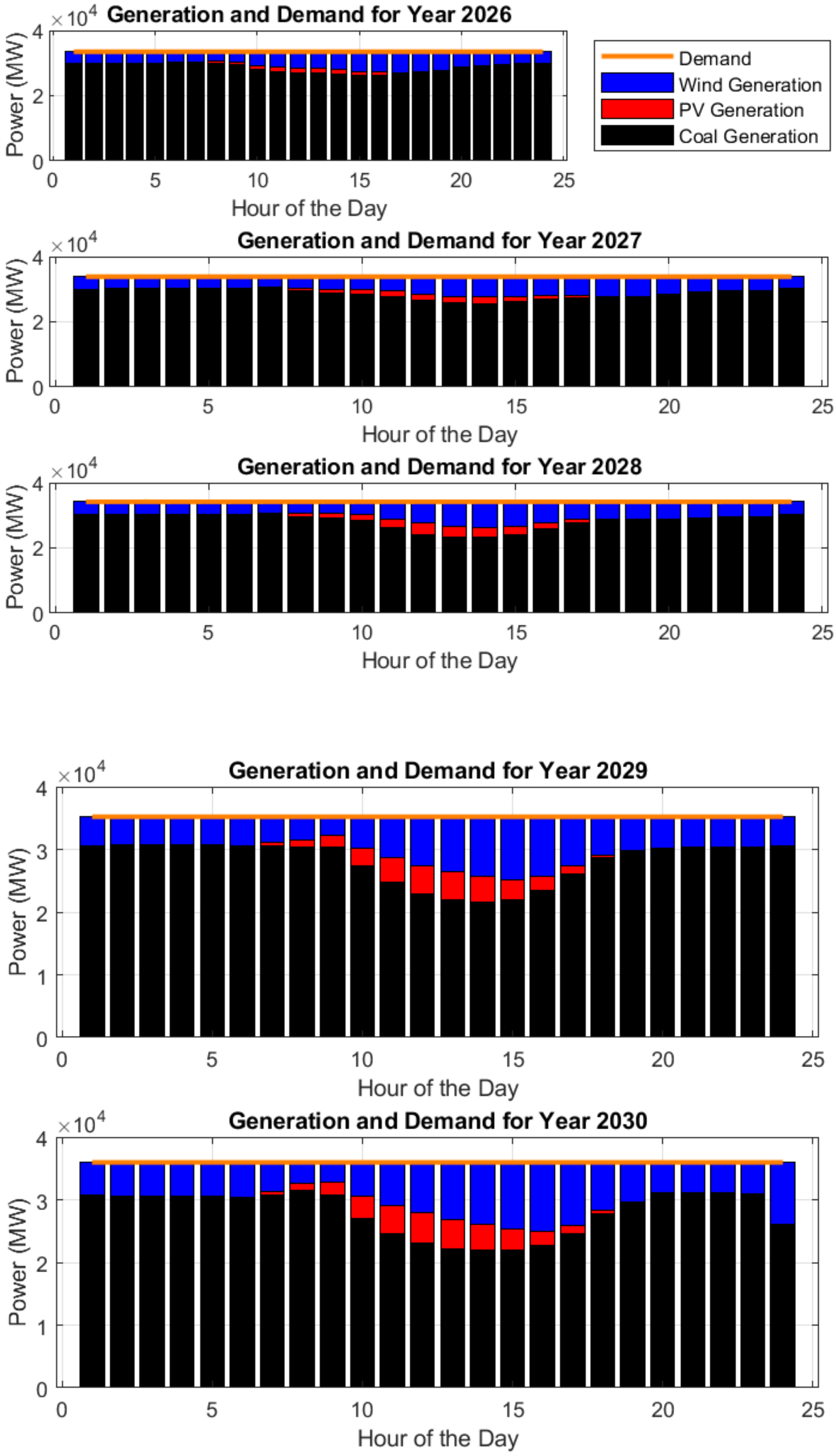

Figure 8: Hourly generation on a typical day from 2026 to 2030.

Figure 8 provides a detailed visualization of the hourly electricity generation on a typical day for a year in the optimization. In 2026, coal remains the predominant source of electricity generation, but notably, wind is generating power for the same number of hours as coal. This suggests an initial shift towards a more diversified energy mix. By 2027 and 2028, the contribution of wind and PV to the energy mix will become more pronounced, indicating a transition away from coal that aligns with South Africa's goals for reducing carbon emissions, supporting the Just Energy Transition (JET) plan, and increasing the share of renewable energy. By 2030, the figure shows a substantial increase of solar PV and wind to the energy mix compared to 2026. Over the 5 years, demand is being met by more renewable energy and less coal-fired generation which is what is observed with the blue and red areas increasing between 2026 and 2030. It is important to note that PV generation is dependent on sunlight and therefore only happens during the day. Energy storage technologies, such as batteries can store excess solar energy generated during the day for use during periods of low sunlight or high demand, thereby enhancing the reliability and flexibility of the energy system; however, this process was not considered in this optimization. Wind energy is favoured compared to solar PV as is being integrated at a faster pace into the energy mix. There are several potential reasons for this preference. Firstly, the capacity increase for wind energy is higher compared to solar PV as prescribed by the IRP 2019. This could be because when the IRP 2019 was written, wind energy was cheaper compared to solar PV, however, that is not the case anymore. Secondly, the capacity factor for wind energy is higher than for solar PV, meaning that the actual power output from the power plant compared to its maximum potential output is higher for wind energy.

6. Limitations and Future Research

This study primarily offers an analysis of South Africa's energy generation system focusing on cost minimization. The results of the analysis were generated using an optimization model. The generation technologies included coal-fired power stations, onshore wind energy, and solar PV generation. There are several limitations to this study that can be used by future researchers to present a more enhanced model.

One critical aspect that the current model does not address is the transmission and distribution network which is an important part of the energy system. In the South African context, the existing transmission infrastructure is old and poses a significant challenge to the large-scale integration of renewable energy sources. Future studies could incorporate transmission constraints which will more accurately reflect the logistical realities of renewable energy deployment after generation. Additionally, the scope of the optimization is limited to five years. Energy system transformations, particularly those involving infrastructure development such as renewable energy integration, typically unfold over longer periods. In addition, policy implementation and the effects of those policies also need to be analysed over a period longer than five years. Extending the analysis to a 10 or 20-year timeframe would allow for a more nuanced understanding of long-term trends, including technological advancements and the impact of energy policies.

A limitation of this research is that is not a direct focus on the Just Energy Transition (JET) plan. The JET plan is crucial for ensuring that South Africa’s transition to a low-carbon economy is socially inclusive and equitable. The current model does not consider the socio-economic implications of a rapid shift to renewable energy, such as job losses in coal-dependent regions and the need for reskilling workers. Future research should integrate JET considerations to ensure that the energy transition supports broader social goals and minimizes negative impacts on vulnerable communities.

The study's focus on a narrow subset of energy sources is another limitation. South Africa's energy mix is diverse, with contributions from various sources beyond coal, wind, and solar PV. Incorporating a broader range of energy technologies into the optimization model would provide a more comprehensive view of the energy landscape, facilitating a deeper understanding of the interactions between different energy sources and their collective impact on costs and efficiency. Moreover, the optimization objective in this study is centred on minimizing total costs without differentiating between technologies. Future research could benefit from a more granular approach, optimizing costs for each technology individually. This would offer insights into the most economically viable options for reducing carbon emissions and guide more targeted investment strategies.

While this study provides a foundational analysis of South Africa's energy system, future research should address these limitations to offer a more complete perspective. Expanding the scope of the model to include transmission constraints, a longer time horizon, a broader range of energy sources, and a more detailed cost optimization approach will enhance its relevance and applicability to policy decision-making and strategic planning in the energy sector.

7. Conclusion

In conclusion, the findings from this research report are that the South African energy mix can be significantly improved by integrating more renewable energy generation technologies, leading to a reduction in carbon emissions over the next 5 years. The optimization results reveal that while achieving a better energy mix is possible within the constraints of current costs, there is potential for even greater progress at higher investment levels. Renewable energy technologies are becoming increasingly more cost-effective, making it essential for emerging markets such as South Africa to capitalize on this trend to secure both environmental and economic benefits.

A key policy implication of this research report is the need for targeted investment in renewable energy infrastructure. Linking carbon emissions directly to coal-fired energy generation highlights the importance of addressing the environmental impact at its source. Phasing out coal in favour of cleaner energy sources is not only essential for meeting South Africa’s targets under the Paris Agreement but also for positioning the country as a leader in the global energy transition. This research underscores the urgency of implementing policies that encourage rapid integration of renewables while managing the social and economic impacts.

Eskom's and by extension, the South African Government’s commitment to reducing absolute emissions through the adoption of low-carbon technologies is a positive development. However, the policy focus should now shift to ensuring the timely and effective implementation of these projects. This includes creating a conducive policy environment that supports renewable energy investment, addresses the socio-economic challenges of transitioning away from coal, and enhances the resilience of the energy infrastructure.

References

Adeyeye, K., Ijumba, N. & Colton, J., 2021. A Preliminary Feasibility Study on Wind Resource and Assessment of a Novel Low Speed Wind Turbine for Application in Africa. *Energy Engineering,* pp. 997-1015.

Afful-Dadzie, A. et al., 2020. Renewable electricity generation target setting in developing countries: Modeling, policy, and analysis. *Energy for Sustainable Development,* Volume 59, pp. 83-96.

Akinbami, O. M., Oke, S. R. & Bodunrin, M. O., 2021. The state of renewable energy development in South Africa: An overview. *Alexandria Engineering Journal,* 60(6), pp. 5077-5093.

Alshamrani, A. M., 2023. A mixed-integer quasi-convex optimization model for joint transmission network and wind power investment problem. *Electric Power Systems Research,* Volume 217, p. 109092.

Alturki, F. A. & Awwad, E. M., 2021. Sizing and Cost Minimization of Standalone Hybrid WT/PV/Biomass/Pump-Hydro Storage-Based Energy Systems. *Machine Learning and Big Data Analytics in Energy Infrastructure,* 14(2).

Alvarez, E. G., Marcovecchio, M. G. & Aguirre, P. A., 2020. Optimization of the integration among traditional fossil fuels, clean energies, renewable sources, and energy storages: An MILP model for the coupled electric power, hydraulic, and natural gas systems. *Computers & Industrial Engineering,* Volume 139, p. 106141.

Andrychowicz, M., 2021. The Impact of Energy Storage along with the Allocation of RES on the Reduction of Energy Costs Using MILP. *Application of Management Tools in the Energy Sector,* 14(13).

Benalcazar, P. & Kamiński, J., 2021. Chapter 14 - Optimizing CHP operational planning for participating in day-ahead power markets: The case of a coal-fired CHP system with thermal energy storage. *Mathematical Modelling of Contemporary Electricity Markets,* pp. 237-258.

Creamer, T., 2023. *Graphics confirm 2023 as loadshedding's annus horribilis,* Johannesburg: Engineering News.

CSIR, 2023. *Statistics of utility-scale power generation in South Africa,* Pretoria: CSIR.

Dalala, Z. et al., 2022. Increased renewable energy penetration in national electrical grids constraints and solutions. *Energy,* Volume 146, p. 123361.

Department of Mineral Resources and Energy, 2019. *Integrated Resource Plan (IRP2019),* Pretoria: The Department of Energy.

Department of Mineral Resources and Energy, 2019. *Integrated Resource Plan 2019,* Pretoria: Department of Mineral Resources and Energy.

Department of Mineral Resources and Energy, 2024. *IPP Projects.* [Online]
Available at: https://www.ipp-projects.co.za/ProjectDatabase
[Accessed 7 March 2024].

Diéguez, M. S. et al., 2021. Modelling of decarbonisation transition in national integrated energy system with hourly operational resolution. *Advances in Applied Energy,* Volume 3, p. 100043.

Djurovic, M. Z., Milacic, A. & Krsulja, M., 2012. *A simplified model of quadratic cost function for thermal generators. In Proceedings of the 23rd International DAAAM Symposium.* Zadar, s.n.

Doorga, J. R., Hall, J. W. & Eyre, N., 2022. Geospatial multi-criteria analysis for identifying optimum wind and solar sites in Africa: Towards effective power sector decarbonization. *Renewable and Sustainable Energy Reviews,* Volume 158, p. 112107.

ESKOM, 2012. *Our Recent Past.* [Online]
Available at: https://www.eskom.co.za/heritage/history-in-decades/eskom-2003-2012/#:~:text=His%20low%2Dkey%20approach%20came,the%20integrity%20of%20the%20grid.
[Accessed July 2024].

Eskom, 2022. *Annual Financial Statements 2022,* Johannesburg: Eskom.

Eskom, 2023. *2022/23 Financial Year Results.* [Online]
Available at: https://www.eskom.co.za/eskom-releases-its-results-for-the-2022-23-financial-year/#:~:text=Eskom's%20net%20debt%20was%20up,at%20the%20end%20March%202023.
[Accessed 23 January 2024].

Eskom, 2023. *Weekly System Status Report – 2023 Week 52 (25/12/2023 – 31/12/2023),* Johannesburg: Eskom Hodlings SOC Ltd.

Farand, C., 2022. *South Africa approves $8.5bn energy transition investment plan.* [Online]
Available at: https://www.climatechangenews.com/2022/10/20/south-africa-approves-8-5bn-energy-transition-investment-plan/#:~:text=South%20Africa's%20cabinet%20has%20approved,coal%20and%20towards%20clean%20energy.
[Accessed June 2023].

Ferrer-Martí, L., Domenech, B., García-Villoria, A. & Pastor, R., 2013. A MILP model to design hybrid wind–photovoltaic isolated rural electrification projects in developing countries. *European Journal of Operational Research,* 226(2), pp. 293-300.

Friedrich, J., Ge, M., Pickens, A. & Vigna, L., 2023. *This Interactive Chart Shows Changes in the World's Top 10 Emitters,* Washington, D.C.: World Resources Institute.

Grubb, M., Drummond, P., Poncia, A. & Mcdowall, W., 2021. Induced innovation in energy technologies and systems: A review of evidence and potential implications for CO2 mitigation. *Environmental Research Letters,* 16(4), p. 043007.

He, C. et al., 2023. Multi-objective optimization for hydrogen-mixed combined heat and power (CHP) plants considering economic and environmental factors based on MILP. *Electric Power Systems Research,* Volume 221, p. 109442.

Hirwa, J. et al., 2023. Optimizing design and dispatch of a resilient renewable energy microgrid for a South African hospital. *Applied Energy,* Volume 348, p. 121438.

Humada, A. M. et al., 2020. Modeling of PV system and parameter extraction based on experimental data: Review and investigation. *Solar Energy ,* pp. 742-760.

IEA, 2023. *Clean energy investment is extending its lead over fossil fuels, boosted by energy security strengths.* [Online]
Available at: https://www.iea.org/news/clean-energy-investment-is-extending-its-lead-over-fossil-fuels-boosted-by-energy-security-strengths
[Accessed July 2023].

IEA, 2023. *CO2 emissions.* [Online]
Available at: https://www.iea.org/energy-system/fossil-fuels/coal
[Accessed 12 July 2023].

IEA, 2023. *Tracking Clean Energy Progress 2023,* Paris: IEA.

International Energy Agency (IEA), 2023. *Will solar PV and wind costs finally begin to fall again in 2023 and 2024?,* Paris: International Energy Agency (IEA).

International Energy Agency (IEA), 2024. *Electricity 2024: Analaysis and forecast to 2026,* Paris: International Energy Agency.

International Energy Agency, 2021. *Energy system of Europe,* Paris: International Energy Agency.

International Energy Agency, 2021. *Energy system of United States,* Paris: International Energy Agency.

International Energy Agency, 2021. *Global energy system,* Paris: International Energy Agency.

International Energy Agency, 2022. *Energy system of China,* Paris: International Energy Agency.

International Energy Agency, 2022. *Renewable electricity generation,* Paris: International Energy Agency.

IPCC, 2023. *Climate Change 2023 Synthesis Report,* Geneva: s.n.

IRENA, 2023. *Renewable Power Generation Costs in 2022,* Abu Dhabi: International Renewable Energy Agency .

Jahandideh-Tehrani, M., Bozorg-Haddad, O. & Loáiciga , H. A., 2020. Application of particle swarm optimization to water management: an introduction and overview. *Environmental Monitoring and Assessment volume,* Volume 192, pp. 1-18.

Jain, S. & Jain, P. K., 2017. The rise of Renewable Energy implementation in South Africa. *Energy Procedia,* Volume 143, pp. 721-726.

Jeffreys Bay Wind Farm, 2024. *Jeffereys Bay Wind Farm.* [Online]
Available at: https://jeffreysbaywindfarm.co.za/wind-energy/the-wind-turbine/
[Accessed January 2024].

Ju, L. et al., 2023. Robust Multi-objective optimal dispatching model for a novel island microenergy grid incorporating biomass waste energy conversion system,. *Applied Energy,* Volume 343, p. 121176.

Lamedica, R. et al., 2018. A MILP methodology to optimize sizing of PV - Wind renewable energy systems. *Energy,* 165(Part B), pp. 385-398.

Li, R. et al., 2022. Cost-optimal operation strategy for integrating large scale of renewable energy in China's power system: From a multi-regional perspective. *Applied Energy,* Volume 325, p. 119780.

Lopion, P., Markewitz, P., Stolten, D. & Robinius, M., 2019. Cost Uncertainties in Energy System Optimization Models: A Quadratic Programming Approach for Avoiding Penny Switching Effects. *Energies,* 12(20), p. 4006.

Marocco, P. et al., 2021. An MILP approach for the optimal design of renewable battery-hydrogen energy systems for off-grid insular communities. *Energy Conversion and Management,* Volume 245, p. 114564.

Mathebula, N. E. & Masiya, T., 2022. Governance Issues and State Capture at Eskom and Transnet: A Kingdon's Multiple Streams Theory for Policy Studies. *African Journal of Governance and Development,* 11(1.1), pp. 146-163.

Mehedi, H. et al., 2023. Power generation expansion planning approach considering carbon emission constraints. *Global Energy Interconnection,* 6(2), pp. 127-140.

Nallolla, C. A., P, V., Chittathuru, D. & Padmanaban, S., 2023. Multi-Objective Optimization Algorithms for a Hybrid AC/DC Microgrid Using RES: A Comprehensive Review. *Electronics,* 12(4), p. 1062.

NASA POWER Project, 2023. *POWER | DAVe.* [Online]
Available at: https://power.larc.nasa.gov/beta/data-access-viewer/
[Accessed 24 January 2024].

Nasiri, N., Banaei, M. R. & Zeynali, S., 2022. A hybrid robust-stochastic approach for unit commitment scheduling in integrated thermal electrical systems considering high penetration of solar power. *Sustainable Energy Technologies and Assessments,* Volume 49, p. 101756.

National Treasury, 2023. *2023 Budget Review Eskom Debt Relief,* Pretoria: National Treasury Department .

Ndenze, F., 2023. *PRESIDENT RAMAPHOSA DECLARES NATIONAL STATE OF DISASTER IN ELECTRICITY CRISIS.* [Online]
Available at: https://www.parliament.gov.za/news/president-ramaphosa-declares-national-state-disaster-electricity-crisis
[Accessed 14 June 2023].

Nijsse, F. J. et al., 2023. The momentum of the solar energy transition. *Nature Communications,* 14(1), p. 6542.

Nocedal, J. & Wright, S. J., 2006. Chapter 16: Quadratic Programming. In: *Numeric Optimization: Springer Series in Operations Research and Financial Engineering.* New York: Springer, pp. 448-492.

Overen, O. K. & Meyer, E. L., 2022. Solar Energy Resources and Photovoltaic Power Potential of an Underutilised Region: A Case of Alice, South Africa. *Energies,* 15(13), p. 4646.

Pierce, W. & Le Roux, M., 2022. *Statistics of utility-scale power generation in South Africa,* Pretoria: CSIR .

Potrč, S., Čuček, L., Martin, M. & Kravanja, Z., 2021. Sustainable renewable energy supply networks optimization – The gradual transition to a renewable energy system within the European Union by 2050. *Renewable and Sustainable Energy Reviews,* Volume 146, p. 111186.

Presidential Climate Commission, 2021. *SOUTH AFRICA'S NDC TARGETS FOR 2025 AND 2030,* Cape Town: Presidential Climate Commission.

Pryor, S. C., Barthelmie, R. J., Bukovsky, M. S. & Leung, L. R., 2020. Climate change impacts on wind power generation. *Nature Reviews Earth & Environment,* pp. 1-17.

Rehman, S. et al., 2022. Wind and wind power characteristics of the eastern and southern coastal and northern inland regions, South Africa. *Environmental Science and Pollution Research,* Volume 29, pp. 85842-85854.

Rehman, S. et al., 2021. Wind and wind power characteristics of the eastern and southern coastal and northern inland regions, South Africa. *Environmental Science and Pollution Research,* pp. 85842-85854.

Safari, S., Ardehali, M. M. & Sirizi, M. J., 2013. Particle swarm optimization based fuzzy logic controller for autonomous green power energy system with hydrogen storage. *Energy Conversion and Management,* Volume 65, pp. 41-49.

SAPVIA, 2021. *SAPVIA.* [Online]
Available at: https://sapvia.co.za/jinkosolar-n-type-mono-module-set-a-new-world-record-reaching-the-highest-conversion-efficiency-of-23-01/

Sharma, R., Kodamana, H. & Ramteke, M., 2022. Multi-objective dynamic optimization of hybrid renewable energy systems. *Chemical Engineering and Processing - Process Intensification,* Volume 170, p. 108663.

Singh, G. K., 2013. Solar power generation by PV (photovoltaic) technology: A review. *Energy,* Volume 53, pp. 1-13.

South African Government , 2024. *Renewable Independent Power Producer Programme,* Pretoria: South African Government.

The MathWorks Inc., 2023. *MATLAB update 7 (R2023b),* Natick: The MathWorks Inc.

Tong, W., 2020. *Wind Power Generation and Wind Turbine Design.* Online ed. Southampton: WIT Press.

van der Merve, W. & Brent, A. C., 2020. Evaluating the Energy Potential of Solar PV Located on Mining Properties in the Northern Cape Province of South Africa. *Sustainability,* 12(14), p. 5857.

WASA Project Team, 2020. *Wind Atlas for South Africa.* [Online]
Available at: https://wasaproject.info/
[Accessed January 2024].

Wood, A. J., Wollenberg, B. F. & Sheblé, G. B., 2013. *Power generation, operation, and control..* 1st ed. s.l.:John Wiley and Sons.

World Bank Group , 2020. *SOLARGIS.* [Online]
Available at: https://solargis.com/maps-and-gis-data/download/south-africa

World Meteorological Organization, 2024. *Climate change indicators reached record levels in 2023: WMO.* [Online]
Available at: https://wmo.int/news/media-centre/climate-change-indicators-reached-record-

levels-2023-wmo#:~:text=The%20global%20mean%20near%2Dsurface,1.27%C2%B10.13%20%C2%B0C.
[Accessed 20 March 2024].

Wu, X., Zhao, W., Wang, X. & Li, H., 2021. A MILP-Based Planning Model of a Photovoltaic/Diesel/Battery Stand-Alone Microgrid Considering the Reliability. *IEEE,* 12(5), pp. 3809-3818.

Yelle, L. E., 1979. The learning curve: Historical review and comprehensive survey. *Decision Sciences ,* Volume 10, pp. 302-328.

Zhao, N. & You, F., 2020. Can renewable generation, energy storage and energy efficient technologies enable carbon neutral energy transition?. *Applied Energy,* Volume 279, p. 115889.

Zhu, J., 2015. Power System Basics. In: *Optimization of Power System Operation.* Hoboken: John Wiley & Sons, Inc., pp. 2-10.