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Dynamic Analysis of Hybrid Water and Energy System in Smart Cities

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Abstract

The relationship between water and energy is commonly referred to as the water and energy nexus which has been studied due to its impact on urban sustainability. This study conducts a comprehensive literature review focusing on the interdependencies between energy and water systems in smart cities through system dynamics modeling. This review will thoroughly identify and analyses existing system dynamics models, their applications, strengths and limitations. This study provides the groundwork for developing an integrated dynamic model that can overcome the identified limitations. It also provides a robust framework that informs smart cities on how to optimize the design and operation of integrated water and energy systems for improved efficiency, reliability and sustainability in the rapidly evolving landscape of smart cities. Currently, there is a notable absence of such models in both research and operational strategies that can effectively manage the complex interdependencies between water distribution networks, energy grids, and renewable energy sources. These complex systems perform under varying demand conditions, environmental challenges and potential disruptions hindering efforts of reduction of energy and water usage to optimize resource efficiency, resilience and overall sustainability in smart cities. The findings offer an adequate framework that guides policies, legislation and contributes to theoretical understanding on how to optimize integrated water and energy system in the rapidly evolving world of smart cities system dynamics modeling and offer strategies aimed at improving hybrid energy and water systems in smart cities.

Keywords
Energy policy, sustainability, efficiency, water and energy nexus, system dynamics

1. Introduction

Water and electricity have a unique relationship in the modern world as one requires the other in a complex system of networks to supply the utility to the customers. This energy and water interaction is important in Smart cities, where there are limited water resources, but extremely high use rates. South Africa's water and energy challenges require urgent, innovative and integrated solutions (Conradie, 2020). The growing demand, infrastructure failures and the climate change risks highlight the need for hybrid water and energy systems in smart cities. By developing a system dynamics model will help with identifying areas that require attention and properly allocate resources. The research study is to investigate the integration of renewable energy sources with water purification, storage and distribution systems in the context of smart cities. The aim is to model and analyse the dynamic interactions between these systems to optimize efficiency, sustainability and reliability.

A smart city is an urban area that makes use of intelligent infrastructure and technology to improve sustainability, efficiency and the standard of living for its citizens. These cities optimize services like water and energy management by integrating real-time monitoring and Internet of Things (IoT) sensors.

By integrating water and energy systems, smart cities may reduce carbon emissions and guarantee sustainable urban growth. This approach improves reliability while promoting environmental sustainability and improved quality of life for urban residents. The integration of both systems in smart cities is an opportunity to develop dynamic models for optimizing water and energy interactions, contributing to sustainable urban development in South Africa (Seidor, 2025).

The increasing demand for water and energy in urban areas, which is driven by population growth and rapid urbanization indicates a significant challenge to sustainable development (Turok & Saladin, 2014). In smart cities such as Mooikloof Mega City the effective management of critical resources is further complicated by their interdependence, energy is required for water treatment and distribution while water is essential for energy production (Balkaran, 2019).This water-energy nexus is often inefficiently managed due to the traditional divided approach in resource planning and operation. Moreover, the integration of renewable energy sources such as solar and wind speeds introduces variability and unpredictability into energy supply further complicating the management of hybrid water and energy systems. Urban infrastructure is also vulnerable to interruptions such as power outages and infrastructure failures which highlight the need for resilient and adaptive systems.

There are currently no dynamic and integrated models in research and operational strategies that can address these challenges effectively. There is limited understanding of how hybrid water and energy systems perform under varying conditions and optimization methods to enhance resource efficiency. This paper highlights the need to review literature on a system dynamics model that will simulate the interdependence between renewable energy sources and water systems that can make use of the advanced technologies, such as IoT devices and real-time monitoring in integrating energy and water systems to ensure the efficient and sustainable operation of these systems in smart cities. The study seeks to investigate system dynamics technology and processes while providing an overview of how system dynamics can be applicable in managing water and energy in a smart city.

1.1 Objectives

The paper aims to provide a comprehensive understanding of use of system dynamics technologies to manage water and energy in smart cities. The proposed study will focus on the following objectives:

- To investigate the historical context and evolution of system dynamics technologies in the smart city.
- To analyse how a system dynamics model can be used for the interactions between water and energy systems.
- To analyse the impact of renewable energy integration on water systems.
- To evaluate the role of IoT and real-time monitoring in improving system performance.
- To propose strategies for enhancing resilient smart city infrastructure in South Africa.

2. Literature Review

A dynamic analysis of hybrid water and energy systems in smart cities involves studying how a combined system of water and energy works and changes over time between water and energy systems in a smart city. A system dynamics model can be used to analyze multi scenarios and multi-attributes of the water and energy interaction over time. This helps in making the city more efficient and to see how water and energy systems respond to various scenarios such as during droughts, power outages and high demand, computer simulations and models used. This involves using computer simulations and models to see how water and energy systems behave under different conditions such as during droughts, power failures, or peak demand times. Hybrid water and energy systems use both traditional and renewable sources such as solar-powered water pumps or hydropower for electricity generation.

In summary, this analysis will assist smart cities to better use their water and energy resources in problem forecasting, resource management and the development of more resilient and sustainable urban systems. The escalating global freshwater scarcity, projected to reach a 40% gap between supply and demand by 2030, presents a critical challenge, particularly in regions like South Africa where a 17% deficit is anticipated by the same year (du Plessis, 2023).In order to maintain economic growth and the well-being of society, this emerging challenge calls for an urgent and significant investment in water infrastructure. Given that water delivery and treatment are energy-intensive operations, the interconnectedness of water and energy often referred to as the water-energy nexus requires that solutions take a comprehensive approach to both resources. Water shortages could double by the middle of the century due to urban sprawl patterns in new constructions, highlighting the urgent need for integrated urban planning that takes resource efficiency into account (du Plessis, 2023; Matlakala & Mona, 2024).

2.1. Hybrid water and energy system

The water and energy nexus is the term used to describe the interaction between water and energy, which has been researched due to its implications for urban sustainability (Hussey & Pittock, 2012).While the generation of energy (such as hydroelectric and thermal power plants) is dependent on water availability and while the water treatment, distribution, and wastewater management demand significant power inputs (Hussey & Pittock, 2012; Matlakala, et al., 2021).The topic of integrating these two systems in smart cities is advancing with the goals of increasing resilience and increasing efficiency. However, most of the existing studies focus on sector specific optimizations rather than holistic, integrated approaches Figure 1 pertains to the relationship between water and Energy which is in separatable and adopting an integrated approach to address challenges like rising demand and scarcity. (GIZ, 2016)

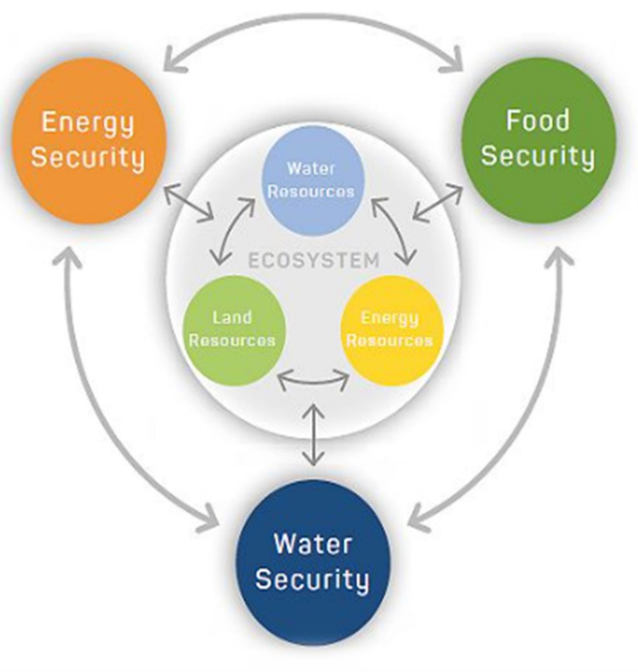

Figure 1**.** The path to Water and Energy Nexus **(GIZ, 2016)**

Recent research also emphasizes the importance of dynamic modelling to capture the interdependencies between water and energy systems. Tools such as EPANET have been used to simulate urban water and energy interactions (Zhao, et al., 2020). However, existing studies and models often rely on static or linear approaches which fail to account for real-time fluctuations in demand and renewable energy variability. Studies highlight the need for real-time adaptive models that incorporate Internet of Things (IoT) data for enhanced predictive capabilities (Qazi, et al., 2020).

Optimization plays a crucial role in improving the performance of hybrid water and energy systems. Various methodologies have been applied which includes the use of the demand forecasting and irregularities in water and energy networks (Chen, et al., 2022). Although these approaches have shown promising results, a lack of practical application because of financial, technological and governance issues is still a challenge. Significant threats to system stability include severe weather, power outages, and equipment malfunctions (Rajan, et al., 2022).

2.2. Smart Cities

Smart cities are cities that use modern technologies and data analytics to improve the standard of living for citizens, maximise infrastructure and services, and foster sustainable economic growth (Gracias, 2023). Smart city initiatives are expanding rapidly throughout the world with the goals of enhancing public services, fostering cleaner environments, and increasing local communities' competitiveness through innovation (Cambra-Fierro, 2023; Oladunmoye, 2023).

Various sensors are used to collect data in the context of the internet of things (Bellini, et al., 2022). They are made up of several different sensors, including ones for light, humidity, temperature, and many more. The collected data is also stored in the cloud, which is another Internet of Thing’s aspect (Yang, 2024). Since nothing is intelligent without sensors, having accurate and efficient sensors is crucial to the automation process. Smart cities may significantly support the development of eco-friendly and energy-efficient practices that protect the planet's natural resources by reducing dependency on traditional energy sources (Hammi , et al., 2018). Figure 2 shows the various smart city applications for IoT devices (Atik-Ur-Rehman, 2023).

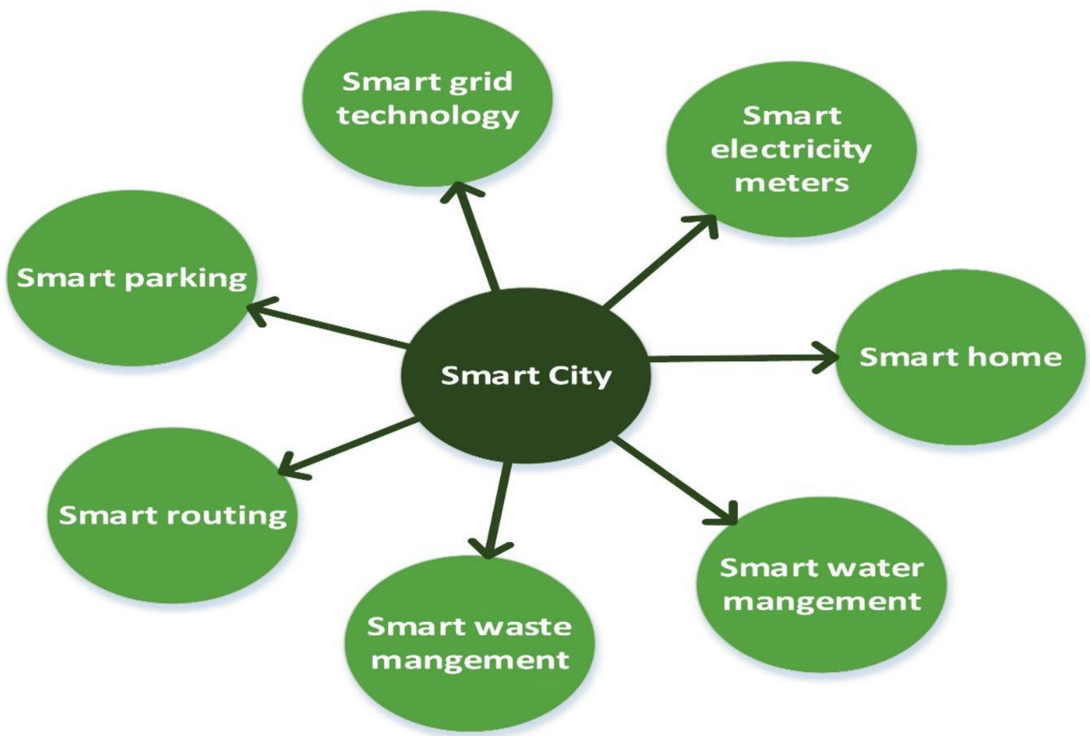

Figure 2. Flow architecture of smart city IoT applications (Atik-Ur-Rehman, 2023)

Through cooperative efforts involving local governments, businesses, non-profit organizations, and citizens, smart cities also address diverse urban challenges like traffic congestion, air pollution, crime rates, waste management, and inefficient energy usage (Oladunmoye, 2023; Kozhakhmet, 2023). To address these problems, smart infrastructure and services have been developed, such as air quality sensors and smart traffic signals (Kozhakhmet, 2023). Environmental performance, for instance, is positively impacted by smart city investments, especially those related to human capital and information and communication technology (ICT), according to research conducted in China (Mengmeng, et al., 2023).

The rapid urban population growth is raising the demand for basic resources including water, energy, and transportation (Paes, 2023). Despite being among the nations with the fastest rates of urbanization, Nepal challenges such inadequate municipal infrastructure and significant natural disaster risks, making the creation of smart cities a new path toward sustainable development (Dixit, 2023). Effective management of natural resources is also critical.
The growth of smart cities is also influenced by larger social and economic factors. Through mechanisms like technology resource allocation and industry development, smart city construction has been demonstrated to significantly promote technological innovation, especially in China (Shu, 2023), However, there is also possibility that smart cities could worsen already-existing inequalities, particularly along the line of technology (Caragliu, 2023). One reason for this concern is the impact of multinational firms on the agendas of local authorities on urban transformations (Caragliu, 2023).

A comprehensive strategy is necessary for smart city administration to be effective. Given that there is no universally accepted definition of what a "smart city" is, part of this involves knowing how the public views the idea (Michelotto, 2023; Spice, 2023). To prevent resource misallocation and accomplish stated goals, local governments must deliberately choose which aspects, such as transportation, governance, or the environment, to emphasize in their smart city efforts (Manjón-Antolín, 2023). To prevent resource misallocation and accomplish stated goals, local governments must deliberately choose which aspects, such as transportation, governance, or the environment, to emphasize in their smart city efforts (Aljowder, 2023; Ghazinoory, 2023).

The idea of urban metabolism, which views a city as a living thing with inputs and outputs, offers a helpful framework for evaluating the sustainability and health of a city by measuring waste outputs and resource flows (Wang, 2023). Policies intended to create resilient and equitable urban settings can be informed by this approach (Damianou, 2023). Understanding these intricate relationships can be facilitated by visual resources, such as those that illustrate the scope of smart cities or possible collaborations. Network analysis, for example, can map trade-offs and synergies between various smart city metrics, offering insights into the interactions between different dimensions (Vanli, 2023). Figure 3 shows how different aspects of smart cities are interdependent and might clash. To create comprehensive and successful smart city initiatives, it is essential to comprehend these interactions (Wang, 2023).

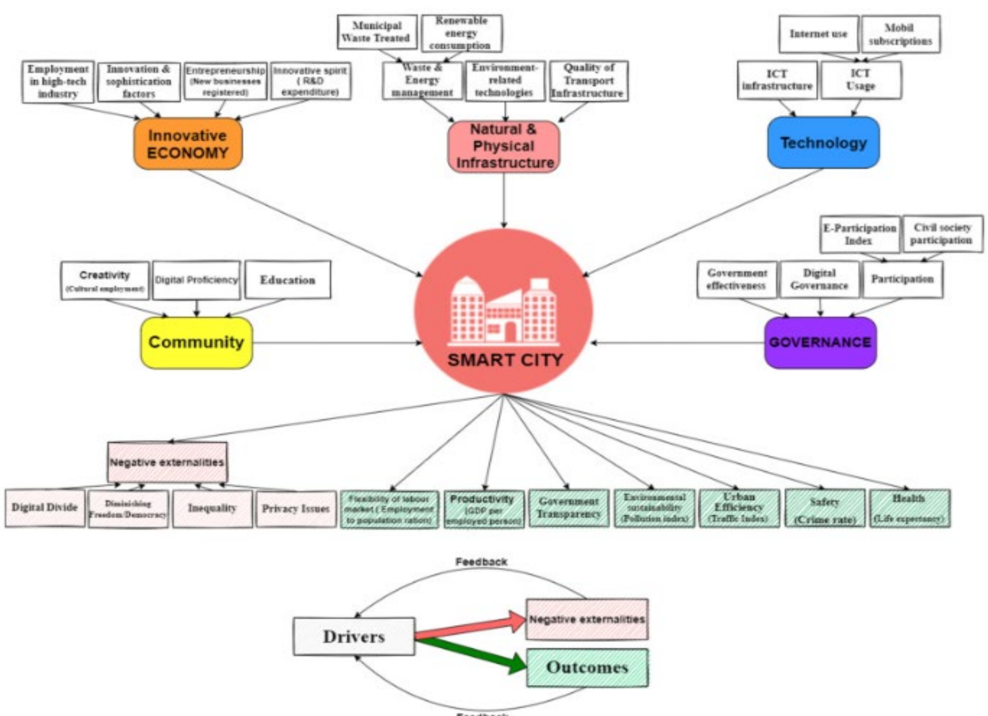

Figure 3. Synergistic/Trade-off Interactions Between Smart City Dimensions (Vanli, 2023)

2.3. Household trends on Water usage and Energy usage

One important factor influencing the relationship between water and energy is household consumption patterns. In South Africa, electric geysers account for about 40% of residential electricity use for water heating. This adds to the strain on the grid and increases the demand for electricity. To reduce household energy usage and carbon emissions, policies such installing solar water heating systems have been proposed. Solar water heating systems may have various impacts on household energy consumption and a thorough evaluation of their technical, financial, and environmental impacts is still required (Kakaza, 2015; Nwodo, 2021; Agyekum, 2024; Curry, 2017).

The average municipal bills (water and electricity) increased from R161 in 1996 to R2,028 in 2020, indicating a large increase in real expenses and a significant increase in the financial burden on households. To increase affordability and sustainability, this rising cost emphasizes the necessity of integrated resource management. Water scarcity is made worse by the problem of "non-revenue water," which refers to water losses from leaks and poor water quality. This problem costs municipalities a substantial amount of revenue (Veriava, 2019; Scheihing, 2020; Zahra, 2022).

Smart City projects use cutting-edge technologies to better manage energy and water resources in order to address these linked issues. For example, smart grids allow for more accurate modeling of residential electricity consumption, which is essential for demand management and carbon reduction initiatives. Smart water heating systems provide strategies to increase energy efficiency and conserve resources by combining smart solutions with renewable energy. By taking into account variables like as unstable water supply and the energy costs related to pumping and storage, model predictive control systems can maximize energy and water management in cities (Abdeljebbar, 2021; Gaonwe, 2022; Wanjiru, 2016).

Time-of-use (TOU) pricing structures and demand-side management are two crucial components of smart management of energy and water nexus. In order to reduce peak demand and pressure on the system, TOU pricing encourages consumers to move energy-intensive activities to off-peak hours by signaling the true cost of electricity at various times. Additionally, this opens up arbitrage opportunities, allowing customers to take advantage of cheaper electricity costs during off-peak hours. For instance, using a dishwasher at 2 AM rather than 6 PM enables customers to buy power at a reduced cost. To balance the grid, load shifting can be used for water heating, a major domestic energy consumption.

Additionally, in smart cities like Mooikloof, the integration of green infrastructure including green roofs has been considered for its ability to support the water and energy nexus. These kinds of solutions can help regulate resource flows in urban settings and have beneficial impacts on the environment (Meng, 2023).

Furthermore, an integrated strategy that recognizes the complex water and energy relationship is necessary to manage household water and energy usage in smart cities. Addressing issues include deteriorating infrastructure and increasing expenses. To improve efficiency and sustainability, strategies should include installing smart technologies like grid management systems and SWH, encouraging energy-efficient appliances and practices, and optimizing water demand management through behavioral understanding (Murwirapachena, 2021; Kakaza, 2015; Ritchie, 2022; Abdeljebbar, 2021).

3. Systematic Literature Review Methodology

3.1 Overview

This study follows a quantitative research methodology, analysing the relationships between energy and water systems in the context of smart cities using system dynamics modeling. To provide robust and useful outcomes, this process is structured around a few important research questions, thorough database searches, exact keyword usage, stringent inclusion/exclusion criteria, and methodical data extraction and analysis. The research aims to assess how integrated water and energy management can enhance efficiency, resilience and sustainability in urban environments. Its broad research challenges are diverse. Specifically, the key research questions include:

3.1.1 How can hybrid water and energy systems be dynamically modeled to optimize the interdependencies between water distribution networks, energy grids, and renewable energy sources?

3.1.2 How can hybrid water and energy systems be optimized for resilience and performance under varying demand conditions and potential disruptions such as power outages or infrastructure failures?

3.1.3 What policies, frameworks, and stakeholder collaborations are required to successfully integrate hybrid water and energy systems into existing urban infrastructure and smart city designs?

3.1.4 How do hybrid water and energy systems compare to traditional divided infrastructure in terms of cost-effectiveness, sustainability, and resilience?

The literature review on the quantitative elements of hybrid water-energy systems is guided by these issues looked at collectively, especially when it comes to smart cities and urban environments (Li, et al., 2025; Wang, et al., 2022). System dynamics modeling can manage numerous interlinked technical and non-technical aspects that make up the extensive complexity of the water-energy nexus (Ahmad, 2020).

A thorough search was carried out across multiple reliable scientific databases to provide an adequate and current literature review. These included IEEE Xplore, Google Scholar and ScienceDirect, which were given preference for their organised indexing and quality control, providing a higher number of peer reviewed and thoroughly assessed papers, while Google Scholar offered a wide initial search and made citation tracking easier. To fully capture the multidisciplinary character of the water and energy nexus in smart cities, this multi-database approach is essential. (Li, et al., 2025).

To develop a thorough list of keywords and search terms that covered the main points of the study topics, a combination of the search terms such as water and energy nexus, System dynamic modeling, Smart cities planning, Urban infrastructure failure, Renewable energy, Sustainability and energy policies.

The technical, operational, environmental, economic, and policy issues pertinent to hybrid water and energy systems in urban areas were considered (Pedro, 2025; Bouramdane, 2023).In order to narrow down an extensive amount of literature and focus on the most pertinent and outstanding findings, the requirements for inclusion and exclusion were thoroughly observed. Following papers criteria were included:

- Papers published between 2014 and 2025 to ensure currency with recent advancements and challenges in smart city development and sustainable resource management (Li, et al., 2025).
- Publications that include systematic review papers, conference proceedings from respectable scientific organizations and peer-reviewed journal articles such as IEEE Xplore, Elsevier, and Springer. This ensures methodological consistency and academic integrity.
- Specifically focusing on issues of efficiency, resilience, sustainability, dynamic modeling and integrated water and energy systems in urban cities (Li, et al., 2025; Stercke, 2020).

Following research was not included if they:

- Focused solely on rural water and energy nexus analyses without specific urban applications.
- Were theoretical debates or opinion pieces that lacked empirical data or quantitative modeling.
- Inadequate dynamic modeling and optimization methodologies
- Did not specifically address how water and energy systems are interdependent.

4. Data Collection

The paper screening and selection process followed a systematic approach, all obtained data from the database searches were compiled. The remaining papers titles and abstracts were then compared to the predetermined inclusion and exclusion criteria. papers that didn't meet the research requirements were excluded (Egieya, 2024). The following crucial data was carefully extracted for every selected paper:

- The research data that includes the author or authors, journal, year of publication and scope.
- Types of dynamic model used such as System Dynamics and stocks, flows, feedback loops variables were considered (Pedro, 2025).
- Water systems such as distribution networks and wastewater treatment,
- Energy systems such as the grid and renewable sources.
- Parameters such as energy use, water demand, cost, carbon emissions and resilience indicators that are used for optimization (Li, et al., 2025; Bouramdane, 2023).
- Quantitative key findings outcomes related to cost-effectiveness comparisons, resilience enhancements, sustainability advantages, or improvements in efficiency.
- Identified policy recommendations, regulatory frameworks, or stakeholder engagement strategies proposed in the study (Wang, et al., 2022; Bouramdane, 2023).
- The authors acknowledge any limitations as well as recommendations for further research.

The gathered data was arranged into different topics that matched the research questions. A quantitative technique was used for analysis. This involved identifying common trends, methodologies and findings across studies, as well as identifying best practices for dynamic modeling and optimization. Based on stated measures of cost effectiveness, sustainability, and resilience, a comparative analysis was conducted to evaluate the overall effectiveness of hybrid systems against traditional infrastructure. (Li, et al., 2025; Pedro, 2025). This systematic approach allows for a robust evaluation of integrated water and energy management strategies in smart cities such as System review flow chart illustrated in Figure 4.

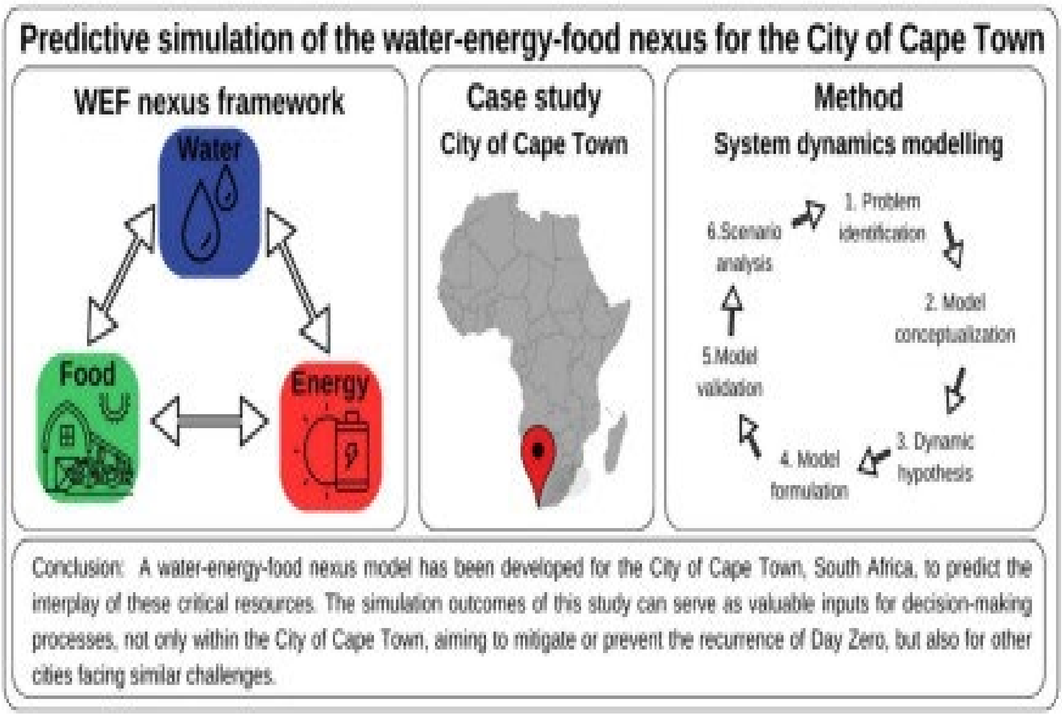

Figure 4.Systematic review flow chart **(Egieya, 2024)**

5. Results and Discussion

Understanding the relationship between water and energy in smart cities has improved significantly, according to the review research of current literature. However, there are still several important research gaps that limit hybrid water and energy systems from being fully optimized, resilient and sustainably integrated into smart city plans. Addressing these gaps requires focused future research and interdisciplinary collaboration **(Ahmad, 2020; Li, et al., 2025; Wang, et al., 2022)**. Even though there is significant progress in water and energy integration research, the following key gaps remain:

- There is a notable gap in comprehensive dynamic models that explicitly optimize the integration of diverse renewable energy sources such as solar and wind with corresponding energy storage solutions such as batteries and hydro storage within the urban water-energy nexus (Wang, et al., 2022).
- The research mostly addresses resilience in general terms like droughts, as seen in Cape Town. However, there is a lack of dynamic comprehensive modeling for a broader spectrum of potential disruptions, including localized infrastructure failures such as power outages and cyber-attacks on control systems (Ahmad, 2020).
- There is a need for standardised methodologies to quantify the cost effectiveness, sustainability and resilience of hybrid water and energy systems compared to traditional, siloed infrastructure. This gap is critical for informed decision-making and policy formulation. (Ahmad, 2020; Bouramdane, 2023).
- There are limited policies that are not only technically sound but also economically viable and socially equitable (Pedro, 2025).

The simplified connection between energy and water, referring to the mind mapping tool of causal loop diagram is illustrated in Figure 5. The expected outcomes will be to identify key inefficiencies in current water and energy consumption, renewable energy integration in water systems.

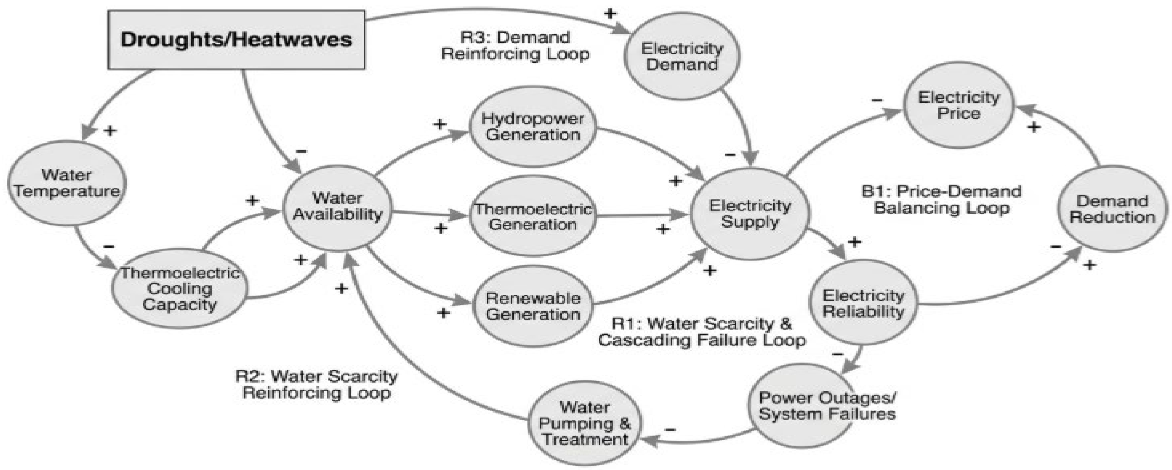

Figure 5.Mind mapping tool of causal loop diagram

In summary, to address these literature gaps, a more detailed population dynamics model can be developed, complemented by additional sub-models to evaluate the required facilities and infrastructure, ultimately improving the resilience of the nation's water and energy networks.

5.1 Proposed Improvements

Studies highlight the need for real-time adaptive models that incorporate Internet of Things (IoT) data for enhanced predictive capabilities for future demand planning considerations for Water and Energy Management Systems in Smart Cities to include several factors to contemplate when making more detailed decisions on energy and water provision.

5.2 Validation

Validation of findings across multiple sources, involves assessing how effectively the reviewed models address the interdependencies between energy and water systems and their implications for efficiency, resilience and sustainability. For example, direct water and energy links, such as the energy required for pumping water, can be quantified with specific formulas, allowing for validation of energy consumption figures provided in the literature review. This systematic approach ensures that the insights derived are robust and supported by proof of evidence, making the overall literature review a validated source for understanding integrated water and energy management strategies in smart cities.

5.3 Benefits of conducting a literature review on energy and water systems

Conducting a comprehensive literature review on water and energy nexus models offers substantial benefits, primarily by integrating existing knowledge, identifying critical research gaps and establishing a robust foundation for future investigations and policy development in urban environments. This systematic approach is essential for understanding the complex interdependencies between water and energy systems, especially in the context of smart cities where integrated resource management is crucial for sustainability, resilience, and efficiency (Naeem, 2023; Ahmad, 2020).

Mapping the most recent developments in water and energy nexus modeling is one of the literature review's most important benefits. This involves identifying the types of models employed, such as System Dynamics models, their applications, strengths, and limitations. (Pedro, 2025; Ahmad, 2020) The literature review clearly identified these limitations such as the need for models that can dynamically optimize the operational interactions between water distribution networks, energy grids and intermittent renewable energy sources. Furthermore, the literature review assists in establishing clear benchmarks for cost-effectiveness, sustainability and resilience. This comparative analysis can quantify the benefits in terms of reduced energy consumption for water treatment and pumping, decreased water losses and improved overall resource security. (Wang, et al., 2022; Ahmad, 2020)

6. Conclusion

Integrating renewable energy and water systems in smart cities is a complex but rewarding process. It requires a combination of technical skills, stakeholder engagement and ongoing data integration to ensure it remains relevant and accurate. By focusing on the below areas will close the identified gaps, ultimately assisting in creating truly smart and sustainable cities:

- Focus on developing dynamic models that utilize multi-objective optimization techniques to simultaneously consider economic costs, energy efficiency, water conservation, greenhouse gas emissions, and resilience indicators (Yang, 2024; Ahmad, 2020). These models should specifically incorporate diverse renewable energy portfolios, distributed generation, and advanced energy storage systems, exploring their optimal placement and operation within urban water distribution networks and energy grids. The aim is to move beyond single-objective optimization to balance competing demands effectively.
- Developing detailed scenario based simulations that analyse hybrid water and energy systems against a wide range of potential disruptions is crucial (Egieya, 2024). This includes modeling cascading failures, incorporating real time data feeds from smart city infrastructure to enhance predictive capabilities and enable proactive adaptive strategies (Bouramdane, 2023).
- A more comprehensive integration of socio-economic factors into system dynamics models is needed (Pedro, 2025).

The integration of advanced technologies in energy and water systems can also provide critical solutions to the challenges posed by peak demand scenarios, renewable energy fluctuations, and system vulnerabilities. Developing simplified causal loop diagrams that incorporate these interactions can further assist in understanding and optimizing these complex systems as well as the integrated actions that support behavioral changes are necessary to maintain water and energy usage decreases (Mapuka, 2024; Matimolane, 2023). Addressing these gaps requires focused future research and collaboration across disciplines.

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