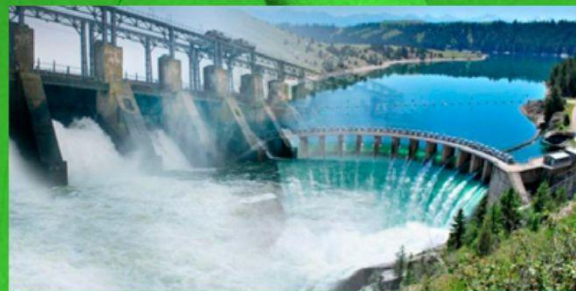


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About the Journal

The Journal of Digital Food, Energy & Water Systems (JD-FEWS) is a peer-reviewed bi-annual publication that publishes recent and innovative deployment of emerging digital technologies in Food, Energy, and Water Systems. Food, energy, and water resources are interconnected scarce resources that require systems and technologies to foster sustainable management and effective utilization. The journal is also interested in articles that explore the nexus between at least two of these resources. The journal considers the following topics as long as they are deployed in the Food, Energy & Water space:

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Integrating Battery Systems with Solar Inverters to Enhance Solar Energy Utilization and Grid Stability for a Sustainable Future: A Review

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Abstract - This study examines the critical role of energy storage solutions in integrating solar photovoltaic systems into the power grid. The focus is retrofitting battery systems to existing transformers and their limitations as direct adjuncts to solar inverters. Advancements in battery technology, including hybrid inverters and smart energy management systems, are explored. The study investigates the advantages of integrated systems, such as improved energy efficiency, enhanced grid stability, and increased self-consumption of solar PV energy. Economic and environmental benefits are also analyzed, including reduced reliance on fossil fuels, lower electricity costs, and decreased CO₂ emissions. Finally, the study addresses large-scale implementation challenges, encompassing grid interconnection, safety protocols, and regulatory frameworks. This work comprehensively overviews current solar energy storage technologies and their importance for a sustainable energy future.

Keywords- Solar Energy Storage, Battery Systems, Solar Inverters, Hybrid Inverters, Smart Energy Management, Advanced Battery Chemistries

1. Introduction

Rising global demand for clean and sustainable energy has extensively increased solar photovoltaic system installation. Solar energy is essential for the broader transition to sustainable energy sources, provides a viable replacement for fossil fuels, and can serve as an on-route method of reducing greenhouse gas emissions. Nevertheless, the discrete nature of solar power generation vis-a-vis sunlight availability significantly limits its ability to be effortlessly absorbed by the electricity grid [3] [21]. The variability of solar irradiance can cause issues with the transmission grids, power quality issues, and, as a result, decreased reliability of electricity supply [12].

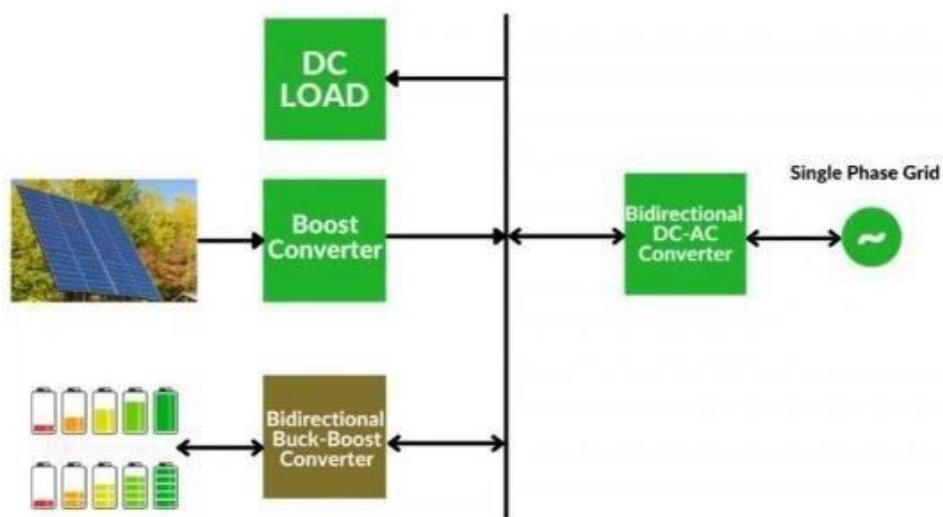


Figure 1: Single-line diagram of a grid-connected solar PV system with battery energy storage. The solar panel is connected to the DC bus through a Boost converter, while the battery storage is linked to the bus via a bidirectional converter. The DC bus also supplies power to a DC load. The system is connected to the grid through another bidirectional converter.

Battery Energy storage systems (BESS) have become a profound solution to overcome the shortcomings of solar intermittency. This way, the BESS can capture all of the extra solar energy during high irradiance levels and hold it for periods when sunlight is absent or low enough to affect electricity production. Integrating BESS with solar inverters, in particular, appears promising for fleet-wide scalability by enabling smart energy management, improved grid stability, and increased self-consumption of solar power [16] [19]. This integration allows for optimized control of power flow between the solar PV system, the battery, and the grid, maximizing solar energy utilization and minimizing reliance on conventional power sources. In this paper, emphasis is placed on BESS integration with solar inverters to increase performance and ease grid integration. Here in this article, we will journey through technological evolutions facilitating integration, such as hybrid inverters, smart energy management systems, and a variety of battery chemistries.

1.1. Research Objectives or Aims of the Paper

Analyze the benefits of solar inverters integrating battery energy storage systems (BESS), such as enhanced energy efficiency, improved grid security, and increased self-consumption for photovoltaics. Battery storage has economic and Environmental Benefits, including reduced reliance on fossil fuels, cheaper electricity bills, and fewer carbon emissions. Identify the barriers and drivers of a mass market for combined solar battery storage systems, including grid connection and safety standards, that need to be addressed on residential and commercial scales.

This paper presents a detailed review of the changing solar energy storage landscape and underlines the significance of such solutions for attaining sustainability in global power consumption. The objective and scope of this paper are to present a review of the existing literature data about solar energy storage technologies, an investigation of different integration topologies and control strategies, as well as discuss some critical challenges along with opportunities equipped by integrated solar-plus-storage systems. Energy storage technologies, specifically battery-based systems, have gained significant research interest due to the increased deployment of solar photovoltaics in power grids for smoothing out the fluctuating nature of the energy supply from solar [9]. BESS presents a possible solution for storing the surplus energy harvested by solar panels in high sunshine hours and discharging it when little to no sunlight is available, allowing an on-demand electrical energy delivery that can operate consistently [22]. This review represents an extensive presentation of the research that has been carried out on solar energy storage technologies, particularly for battery-based systems, including various chemistries and topologies, control strategies, technical challenges, and opportunities.

2. Literature Review

The increasing global demand for energy and growing concerns about climate change have driven the adoption of renewable energy sources, especially solar photovoltaic systems. However, the intermittent nature of solar power generation presents challenges to grid stability and efficient energy utilization. Integrating battery energy storage systems with solar inverters offers a promising solution to address these challenges and enable a sustainable energy future. This literature review examines the current research and development in this area, focusing on key functionalities, benefits, challenges, and future trends of integrating battery systems with solar inverters.

2.1. Battery Chemistries and Suitability for Solar Applications

Many chemistries have been tested for solar energy storage, each with pros and cons. Lithium-ion batteries (LIB) have been popularized due to their increasingly higher energy density, long cycle life, and cheaper prices [23]. Nevertheless, LIBs are highly volatile and require elaborate battery management systems to operate safely. Lead-acid battery (LAB) is a well-known and cost-effective technology with lower energy density and cycle life compared to LIBs [18]. Flow batteries, such as Vanadium redox flow batteries with the capability of decoupled sizing for power and energy capacity, are, in particular, high-performance large-scale storage systems [11]. Nevertheless, flow batteries' energy density and cost are lower than those of LIBs or LABs. Hence, battery chemistry selection is project-specific and driven by many factors, such as cost reduction, better performance, or safety.

2.2. Integration Topologies and Control Strategies

There are many ways that a Battery Energy storage system (BESS) can be connected to solar inverters, each with its potential impact on performance and cost. For a DC coupling system, the BESS is connected directly

to the solar inverters on their bus, which would result in more efficient and lower energetic degradation than an AC coupled system due to fewer power conversion stages [22]. AC-coupled systems tie the BESS into the AC side of a solar inverter, so they are more versatile and modular [17]. Hybrid inverters amalgamate the elements of a solar-based and battery inverter, making it a compact and cost-effective solution [9]. The control strategies that can be applied to BESS operation are rule-based, optimization, and AI approaches. It does so by enabling the optimization of charge or discharge scheduling, management of power flows, and interaction with the grid to achieve maximum system efficiency and stabilize the grid's stability.

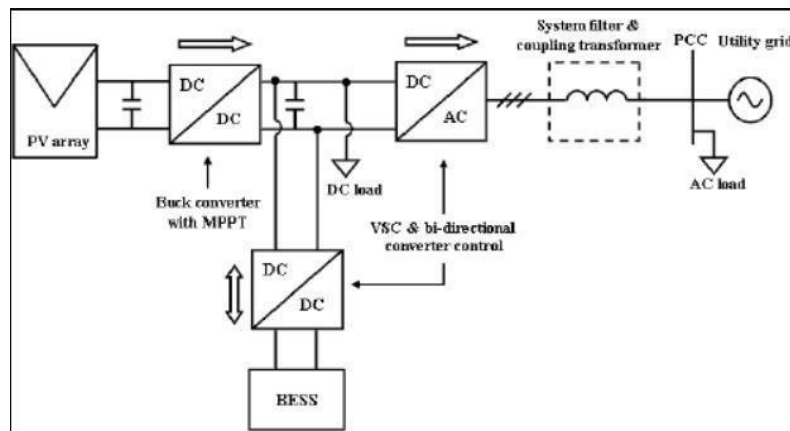


Figure 2: Conceptual System configuration of grid-connected PV with (BESS) [25].

2.3. Technical Challenges and Opportunities

However, integrating battery energy storage systems (BESS) with solar inverters raises technical challenges and opportunities. Since solar is an intermittent power source, grid stability and supply quality (voltage variation and frequency deviation) are essential for large-scale integration. However, such issues could be resolved by adopting some smart ways or technologies discussed by [3]. BESS could be used to provide grid ancillary service, like frequency regulation and voltage support, for better performance in terms of system stability and reliability [6]. Another issue concerns safety because batteries can also be the cause of fires, and their thermal management must be very careful [23]. Smart grid technology provides various new sources of control and communication types, creating numerous opportunities for deeper integration and optimization into the BESS microgrid. The system's performance, safety, and reliability heavily depend on integrating an advanced Battery Management System (BMS) and robust safety protocols in a BESS. Below is a breakdown of key performance metrics, followed by an in-depth discussion of the BMS and safety features essential for the safe operation of the system:

2.4. System Architecture and Design

This system comprises four main hardware components: Solar panels, battery energy storage systems (BESS), Hybrid Inverter, and a Smart Energy Management System. The communication protocols provide the necessary data channels through exchanges between these assortments, leading to coordinated control.

2.4.1. Hardware Components and Communication Protocols

At the heart of this system is a hybrid inverter, which combines that role with a battery inverter [9]. This all- in-one system architecture reduces complexity and cost compared to stand-alone inverters.

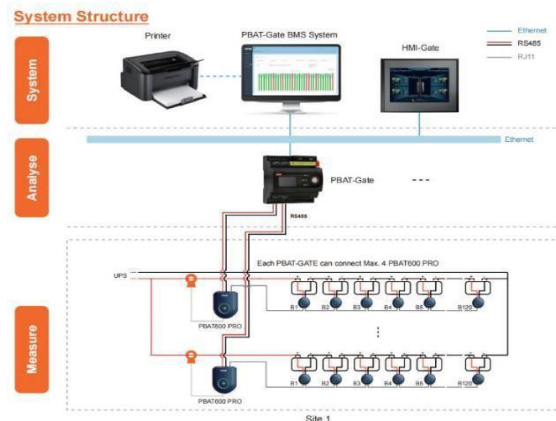


Figure 3: Conceptual System structure for data exchange [24].

The hybrid inverter oversees the incorporated power transfer connection from solar panels and BESS to the grid. BESS stands for battery energy storage system and almost always uses lithium-ion batteries, which are characterized by high energy density, long cycle life span, etc. However, their costs have also been reduced in recent years [23]. Nevertheless, depending on the project requirements and cost considerations, other battery chemistries like lead-acid or flow batteries can be taken into account to support large-scale Renewable Energy Sources (RES) systems [18]. A smart energy management system monitors and performs control of the global operation of each part powered by optimizing an electrical flow between parts in function of user-defined policies but also based on real-time power data. Such data exchange is realized through the use of communication protocols (i.e., Modbus or CAN bus) between these system components, such as a hybrid inverter, BESS itself, and EMS with another grid component [13].

2.4.2. Design Considerations for System Parameters

Selection of system parameters and performance optimization Design considerations for an effective function mapping with a minimum loss, some design considerations have to be taken into account. The capacity of batteries is calculated on the backup hour required, daily energy consumption, and depth of discharge to which the battery can be subjected. The inverter's rating is chosen depending on the highest power output from solar panels and the maximum load demand. Other system parameters, such as charge/discharge rates, voltage levels, and safety features, are also carefully selected to meet the needs of a particular project or grid integration standard. The sizing of battery energy storage systems (BESS) is an important dimension in the design as it is related directly to system output and cost [17]. Optimization algorithms can help decide the BESS size concerning power demand, solar irradiance profiles, and electricity price.

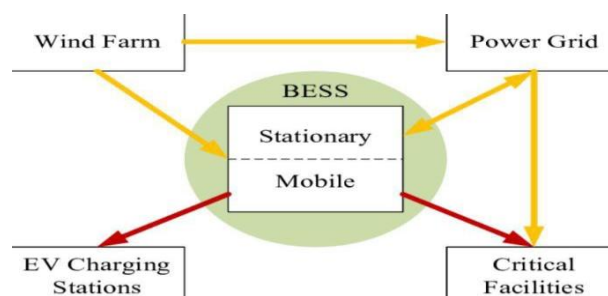


Figure 4: The conceptual framework for the proposed BESS design and applications [26].

The design and optimization of BESS require careful consideration of several parameters to ensure effective operation with minimal losses. The selection of system parameters is crucial for mapping the functions of the BESS to meet specific requirements, such as backup duration, energy consumption, and the depth of discharge (DoD) that the battery can handle. The battery capacity is typically determined based on the required backup time, daily energy consumption, and DoD. For instance, deeper discharges generally reduce the battery's lifespan, making it critical to optimize the DoD for long-term performance and cost-effectiveness. Additionally, the inverter rating is an essential design consideration that should be selected based on the maximum power output from solar panels and the peak load demand. The inverter must be capable of handling both the high peak power from the solar array and the constant power demands of the load. System parameters such as charge/discharge rates, voltage levels, and safety features should also be carefully chosen to meet the project's specific requirements and comply with grid integration standards. The charge/discharge rate ensures that energy is stored and released efficiently without damaging the system components, while safety features like thermal management and overvoltage protection are critical for safe, reliable operation. The sizing of the BESS is directly related to system output, performance, and overall cost. Proper sizing ensures that the system can meet the power demand without overestimating capacity, which could lead to higher upfront costs and inefficiencies. Optimization algorithms can play a key role in determining the optimal size of the BESS, considering factors such as power demand, solar irradiance profiles, and electricity price fluctuations. These algorithms help achieve a balance between cost and performance by identifying the most efficient configuration based on the specific energy needs and financial considerations of the project.

2.4.3. Control Algorithms for Best Operation

To make solar energy storage profitable, advanced control algorithms must be developed to optimize the operation of battery energy storage systems (BESS) systems. Charge/discharge scheduling algorithms tell the BESS when to charge from excess solar energy and discharge it either to match load demand or offer grid services. These power flow management algorithms will control the real-time.

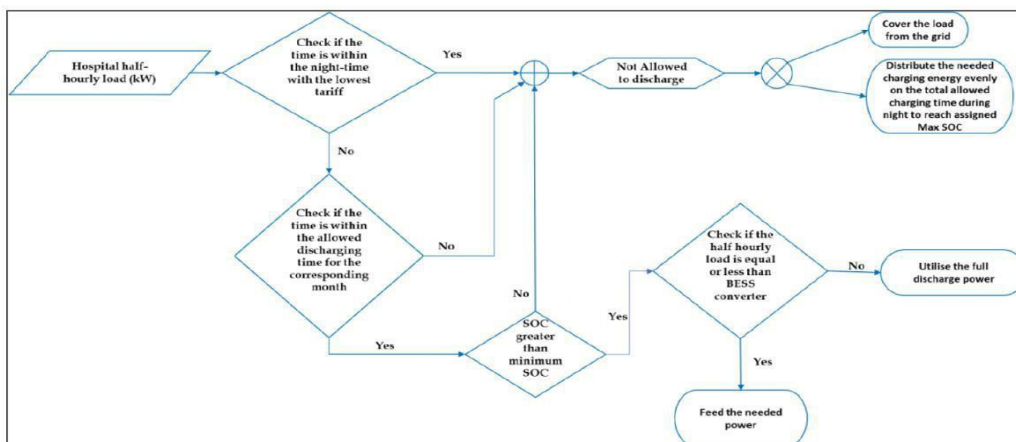


Figure 5: Algorithm of BESS operation for arbitrage with an assigned charge/discharge time [27].

The distribution of energy between the solar panels, battery energy storage systems (BESS), and the grid maintains grid stability and minimizes usage from external sources to maximize the self-consumption of solar-generated electricity. With the help of these algorithms, energy storage with dispatch can be done based on weather forecasting, electricity prices, and grid conditions. This sophisticated control can adapt to changing conditions and optimize the process performance during operation using model-predictive methods or other optimization [16].

3. Methodology

A systems-level approach is employed to evaluate the performance of integrated solar-plus-A systems-level approach is used to evaluate the performance of the integrated solar-plus-storage system, considering both simulated and experimental results. To use PVSYST software to simulate how these systems would

cooperate [5]. It generates detailed models for examples of solar PV generation, battery storage preferences and behaviors (load profiles), and electric grid-provided interaction. Real-world solar irradiance, ambient temperature, and load demand data are accounted for by the simulation model in order to give realistic predictions of how it is likely to perform. Finally, they provide experimental data from a case study of an integrated solar-plus-storage system in a mixed-use building to verify the simulation results and evaluate performance under real-world conditions [2] [4]. The testbed comprises measuring instruments that record data on solar PV generation, battery charging or discharging cycles, and grid power flow.

The performance of the integrated solar-plus-storage system is evaluated based on various key metrics, which span technical (i.e., constituent assets), economic, and environmental criteria.

Considering all charging and discharging losses, the battery energy storage systems (BESS)'s round-trip efficiency is a key indicator of overall energy performance. Energy conversion and utilization effectiveness are evaluated in a hybrid approach using system performance indices like yield factor and wire-to-water energy efficiency [7].

Impact on grid stability, voltage fluctuation, frequency deviation, and grid power factor are evaluated to understand the effect of the integrated system [3]. This includes evaluating the system's provision of grid ancillary services, such as frequency regulation and voltage support [16].

Cost-effective -Economic metrics such as net present cost, levelized energy cost, and payback period are employed to assess the overall system's economic sustainability [5]. The system's efficiency in lowering electricity costs via peak shaving and energy arbitrage is also taken into account [20].

The integration of Solar PV and BESS can significantly reduce greenhouse gas emissions, resulting in lower environmental impact [4]. A life-cycle assessment of the battery system is also considered to evaluate the full environmental impact of technology [1].

4. Results and Discussion

This section will describe the PVsyst simulation report. PVsyst is software for photovoltaic system design and analysis. This report summarizes the simulated performance of a specific grid-connected photovoltaic system.

- ✓ Project and Results Summary provides a high-level overview of the system's characteristics and predicted performance. Key metrics like annual energy production, energy consumption, performance ratio, and solar fraction are typically presented here.
- ✓ General Parameters are details of the system's location, meteorological data used for the simulation, and other relevant environmental factors.
- ✓ PV Array Characteristics describe Information about the photovoltaic modules used in the system, including the number of modules, their rated power, and their arrangement (e.g., tilt angle, azimuth) is found here.
- ✓ System Losses quantifies the various energy losses in the system, such as shading losses, module mismatch losses, and inverter losses. Understanding these losses is crucial for optimizing system design.
- ✓ User's Needs outlines the expected energy consumption profile, which is used as input for the simulation. It may include daily or annual energy demands.
- ✓ Main Results including the more detailed presentation of the simulation results, including monthly and annual energy production, are provided in this section.
- ✓ Loss Diagram is a visual representation of the various energy losses in the system, making it easier to identify areas for improvement.
- ✓ Predefined Graphs are the Standard graphs illustrating the system's performance, such as energy production over time, are included.
- ✓ Single-Line Diagram is a schematic diagram of the system's electrical configuration.
- ✓ Cost of the System is an estimate of the total system cost, which can be helpful for economic analysis.
- ✓ CO₂ Emission Balance is an assessment of the environmental impact of the system in terms of CO₂ emissions avoided.

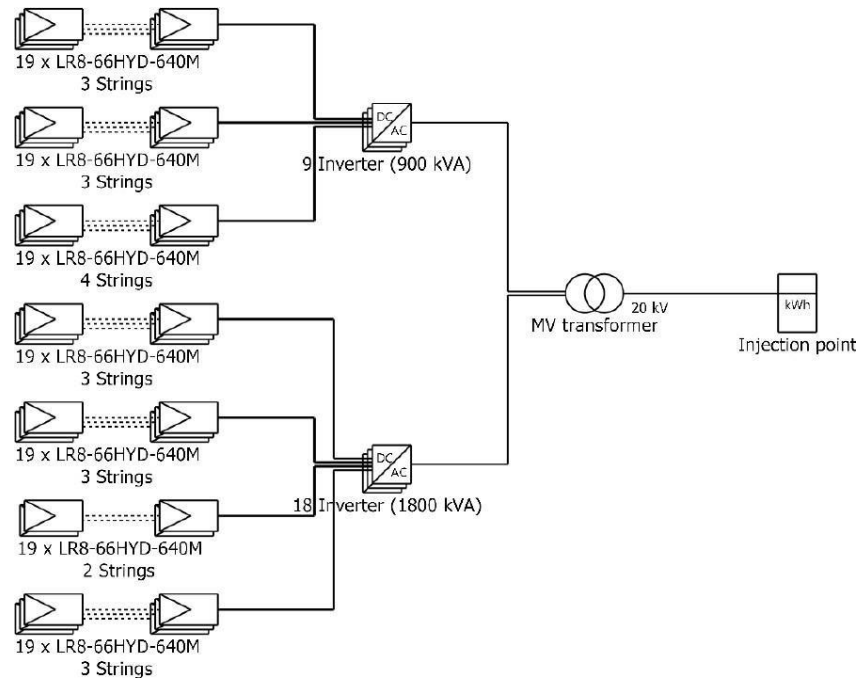


Figure 6: Single-line diagram of a 3.5 MW solar Hybrid power plant with battery energy storage systems (BESS).

4.1. Simulation Results and Experimental Data

Project

Geographical Site	Situation	Project settings
Beldānga,	Latitude 25.40 °N	Albedo 0.20
	Longitude 88.98 °E	
	Altitude 26 m	
	Time zone UTC+6	
Weather data		
Beldānga		
Meteonorm 8.2 (2001-2020), Sat=100% -		

Table 1: Specifies the project's location, usually including the city, region, and country.

The project site's precise coordinates (latitude, longitude, and altitude) are provided, with altitude impacting air pressure and temperature, which in turn affect PV module performance. The Project Settings include parameters such as albedo, which refers to the reflectivity of the ground surface and influences the amount of sunlight reflected onto the PV modules. Weather Data specifies the source of the weather data used in the simulation, which is essential for accurate performance prediction.

System summary

Grid-Connected System		No 3D scene defined, no shadings			
Orientation #1 Fixed plane		Near Shadings		User's needs	
Tilt/Azimuth		no Shadings		Daily consumers	
25 / 20 °				Constant over the year	
				Average	
				3200 kWh/Day	
System information					
PV Array		Inverters		Battery pack	
Nb. of modules		Nb. of units		Storage strategy: Self-consumption	
5472 units		27 units			
Pnom total		Pnom		Nb. of units	
3502 kWp		2700 kWac		60 units	
		total Pnom		Voltage	
		1.297		256 V	
		ratio		Capacity	
				3120 Ah	

Table 2: The System Summary provides a concise overview of the simulated photovoltaic system.

The System Type specifies whether the system is grid-connected (connected to the electricity grid) or stand- alone (off-grid). In this case, the system is "Grid-Connected." The 3D Scene indicates whether a 3D model of the system and its surroundings was used in the simulation to account for shading effects. For this system, "No 3D scene defined" is indicated. The Orientation describes the mounting arrangement of the PV array, such as "Fixed plane" or "Tracking system." In this system, it is a "Fixed plane Tilt/Azimuth 25/20°." Near Shadings indicates whether any nearby objects, such as those close to the PV array, were considered in the simulation. This system has "No Shadings." The PV Array specifies the number of PV modules and the total nominal power of the array in kilowatts peak (kWp), which in this system is "5472 modules, 3502 kWp." The Inverters provide the number of inverters, their total nominal power in kilowatts alternating current (kWac), and the Pnom ratio (the ratio of inverter power to PV array power). In this case, there are "27 inverters, 2700 kWac, Pnom ratio 1.297." The battery pack specifies the storage strategy, number of battery units, voltage, and capacity. According to the battery pack has a "Self-consumption" strategy, with "60 units," "256 V," and "3120 Ah."

Result Summary

Table 3: The Results Summary presents the key performance indicators of the simulated system.

Produced Energy	4373.4 MWh/year	Specific production	1249 kWh/kWp/year	Perf. Ratio PR	80.65 %
Used Energy	1168.0 MWh/year				1.63 %
Apparent energy	4354.3 MVAh/year				

r

The Produced Energy, "4373.4 MWh/year," represents the total amount of electrical energy generated by the PV array over the course of a year, typically expressed in megawatt-hours per year (MWh/year). The Used Energy, "1168.0 MWh/year," is the portion of the produced energy directly consumed on-site, measured in MWh/year. The Apparent Energy, "4354.3 MVAh/year," refers to the total AC energy output of the inverters, considering both active and reactive power components. It is expressed in megavolt-ampere hours per year (MVAh/year). The Specific Production, "1249 kWh/kWp/year," indicates the annual energy production per installed kWp of the PV array, expressed in kilowatt-hours per kilowatt-peak per year (kWh/kWp/year). This metric allows for comparison between systems of different sizes. The Performance Ratio, "80.65%," is a dimensionless value representing the system's overall efficiency, accounting for various losses. It is calculated as the ratio of actual energy yield to the theoretical yield under ideal conditions. Finally, the Solar Fraction, "1.63%," represents the percentage of the total energy demand met by the solar PV system.

Table 4 presents the transposition models (Perez, Hay-Davies, and Isotropic), which specify the models used to calculate the diffuse and circumsolar radiation components on the tilted PV array. The horizon profile, either "Free Horizon" (with no obstructions) or a user-defined profile, is used to calculate shading losses caused by distant obstructions. The user's needs are described as "Daily consumption constant over the year, averaging 3200 kWh/Day," outlining the assumed energy consumption pattern. The storage strategy is defined as "Self-consumption charging strategy when excess solar power is available, and discharging strategy as soon as power is needed," detailing the battery operation plan aimed at maximizing self-consumption of solar energy. The grid injection point specifies the "Power factor Cos(phi) (lagging) 1.000," indicating the power factor at the grid connection point.

General Parameters

Grid-Connected System			No 3D scene defined, no shadings		
Orientation #1					
Fixed plane			Sheds configuration		
Tilt/Azimuth	25 / 20 °		No 3D scene defined		
Horizon			Near Shadings		
Free Horizon			no Shadings		
Storage					
Kind	Self-consumption				
Charging strategy			Discharging strategy		
When excess solar power is available			As soon as power is needed		
Grid injection point					
Power factor					
Cos(phi) (lagging)	1.000				
			Models used		
			Transposition	Perez	
			Diffuse	Perez, Meteonorm	
			Circumsolar	separate	
			User's needs		
			Daily consumers		
			Constant over the year		
			Average	3200 kWh/Day	

PV Array Characteristics

Table 5: The PV array characteristics specifics of the systems used in the simulation.

The operating voltage range of the inverters is between "200-1000 V," and the maximum power output of an inverter at or above 40°C is "110 kWac." The Pnom ratio (DC:AC) is "1.30," representing the ratio of total DC power from the PV array to the total AC power of the inverters. The total nominal DC power of the PV array under standard test conditions is "3502 kWp," and the total surface area occupied by the PV modules is "14768 m²." The maximum AC power output of the system is "2970 kWac," and the number of inverters remains "27 units" with a Pnom ratio of "1.30." The battery system used in the simulation is the "Generic B-Box PRO 13.8" model. The battery pack consists of "5 x 12" units, indicating the number of battery units connected in series and parallel. The minimum state of charge allowed for discharging is "20.0%," and the total energy storage capacity of the battery system is "639.0 kWh."

PV Array Characteristics**Battery Storage****Battery input charger**

Model	Generic
Max. charg. power Max./	8.5 kWdc
Euro effic.	97.0/95.0 %

Battery to Grid inverter

Model	Generic
Max. disch. power Max./	12.8 kWac
Euro effic.	97.0/95.0 %

Table 6: The PV array characteristics specifics of the battery storage systems used in the simulation.

The maximum charging power is 8.5 kW DC, meaning the battery can be charged at a rate up to this limit. The Euro efficiency of 97.0/95.0% likely represents round-trip efficiency, accounting for losses during both the charging and discharging processes. The Battery Grid Inverter manages the flow of electricity from the battery to the electrical grid, converting the DC electricity stored in the battery into AC electricity compatible with the grid. The maximum discharging power is 12.8 kW AC, meaning the battery can discharge power to the grid at a rate up to this limit. Similar to the charging process, the Euro efficiency of 97.0/95.0% reflects the round-trip efficiency, considering losses during both charging and discharging.

Array losses**Array Soiling Losses**

Loss Fraction	3.0 %
---------------	-------

Thermal Loss factor

Module temperature according to irradiance	
Uc (const)	20.0 W/m ² K
Uv (wind)	0.0 W/m ² K/m/s

DC wiring losses

Global array res.	2.6 mΩ
Loss Fraction	1.5 % at STC

LID - Light Induced Degradation

Loss Fraction	2.0 %
---------------	-------

Module Quality Loss

Loss Fraction	-0.8 %
---------------	--------

Module mismatch losses

Loss Fraction	2.0 % at MPP
---------------	--------------

IAM loss factor

Incidence effect (IAM): Fresnel smooth glass, n = 1.526

0°	30°	50°	60°	70°	75°	80°	85°	90°
1.000	0.998	0.981	0.948	0.862	0.776	0.636	0.402	0.000

Table 7: The "Array Losses" quantifies the energy losses that occur between the incident solar radiation and the DC power output of the PV array.

Array Soiling Losses, with a "Loss Fraction" of 3.0%, represent the reduction in energy production caused by dust, dirt, or other forms of soiling on the surface of the PV modules. The thermal loss factor describes how the temperature of the modules affects performance. The constant thermal loss coefficient is given as U_c (const): "20.0 W/m²K," while the wind-dependent thermal loss coefficient is U_v (wind): "0.0 W/m²K/m/s." DC wiring losses are characterized by a "Global array resistance" of 2.6 mΩ and a "Loss Fraction" of 1.5% at Standard Test Conditions (STC). These losses occur due to the resistance of the wiring connecting the PV modules. The "Global array res." represents the total resistance, and the "Loss Fraction" indicates the percentage of energy lost under STC. Light Induced Degradation (LID) accounts for an initial performance drop experienced by some PV modules after exposure to sunlight, with a "Loss Fraction" of 2.0%. Module Quality Loss, with a "Loss Fraction" of -0.8%, reflects losses due to variations in module manufacturing quality, though the negative value suggests a slight performance gain, potentially due to module sorting or binning. Module mismatch losses, with a "Loss Fraction" of 2.0% at Maximum Power Point (MPP), arise from slight variations in the characteristics of individual PV modules, leading to suboptimal performance at the MPP. The IAM (Incidence Angle Modifier) loss factor accounts for the reduction in energy production due to the angle at which sunlight hits the PV modules. The report provides IAM values for different angles of incidence, such as: 0°: 1.000, 30°: 0.998, 60°:

0.948, and 90° : 0.000.

Unavailability of the system

Time fraction	2.0 %
	7.3 days,
	3 periods

Table 8: The unavailability of the system, with a "Time fraction" of 2.0%, "7.3 days," and "3 periods," represents the duration during which the system is not producing energy due to planned maintenance, unplanned outages, or other reasons. This is expressed as a percentage of the total time, the total number of days, and the number of distinct periods of unavailability.

AC wiring losses**Inv. output line up to MV transfo**

Inverter voltage	480 Vac tri
Loss Fraction	0.00 % at STC
Inverter: SUN2000-100KTL-M1-480Vac	
Wire section (27 Inv.)	Copper 27 x 3 x 50 mm ²
Average wires length	0 m

Table 9: AC wiring losses, described as "Inv. output line up to MV transfo, Inverter voltage 480 Vac tri," represent the losses due to the resistance of the AC wiring between the inverters and the medium-voltage transformer. The loss fraction is "0.00% at STC," indicating no energy loss under Standard Test Conditions. The inverter voltage is specified as 480 Vac (three-phase).

AC losses in Transformers**MV transfo**

Medium voltage	20 kV
Transformer parameters	
Nominal power at STC	3.43 MVA
Iron Loss (24/24 Connexion)	2.70 kVA
Iron loss fraction	0.08 % at STC
Copper loss	43.45 kVA
Copper loss fraction	1.27 % at STC
Coils equivalent resistance	3 x 0.85 mΩ

Table 10: The AC losses in transformers

The "Medium voltage" is specified as 20 kV, indicating the voltage level of the medium voltage transformer. The nominal power at Standard Test Conditions (STC) is "3.43 MVA," representing the nominal apparent power of the transformer. The iron loss, specified as "2.70 kVA," refers to the power loss due to hysteresis and eddy currents in the transformer core, also known as no-load losses. "24/24 Connexion" indicates continuous operation. The iron loss fraction is "0.08% at STC," representing the iron losses as a percentage of the nominal power at STC. The copper loss is "43.45 kVA," representing the power loss due to the resistance of the transformer windings, also known as load losses. The copper loss fraction is "1.27% at STC," expressing the copper losses as a percentage of the nominal power at STC. The coils' equivalent resistance is "3 x 0.85 mΩ," representing the combined resistance of the transformer windings.

Daily consumers, Constant over the year, average = 3200 kWh/day

Annual values

	Nb.	Power	Use	Energy
		W	Hour/day	Wh/day
Lamps (LED or fluo)	20000	10/lamp	4.0	800000
TV / PC / Mobile	15000	80/app	2.0	2400000
Stand-by consumers			24.0	96
Total daily energy				3200096

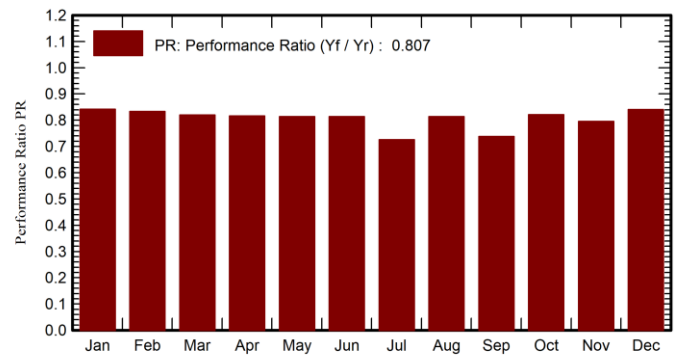
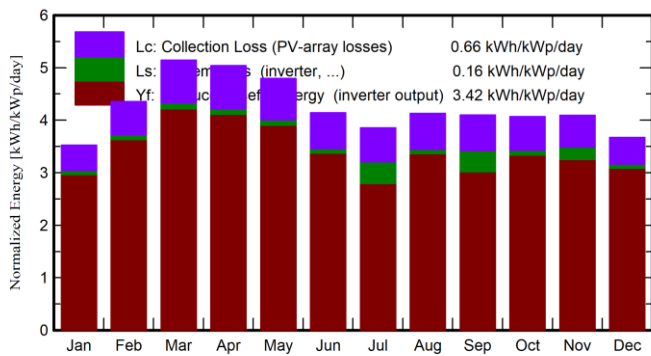
Table 11: The "Detailed User's Needs" of the expected energy consumption profile.

Daily consumers indicate a typical consumption pattern that remains constant throughout the year, with an average of 3200 kWh/day. This means that while daily energy consumption may vary throughout the year, the average daily consumption is 3200 kWh. The table provides power and energy consumption for various appliances or categories, including lamps, washing machines, dishwashers, TVs, computers, and others.

				Main Results			
System Production							
Produced Energy		4373.4	MWh/year	Specific production		1249 kWh/kWp/year	
Used Energy		1168.0	MWh/year	Perf. Ratio PR Solar		80.65 %	
Apparent energy		4354.3	MVAh/year	Fraction SF		1.63 %	
Battery aging (State of Wear)							
Cycles SOW		99.2	%				
Static SOW		90.0	%				
Economic evaluation							
Investment				Yearly cost		LCOE	PR
Global	605,334.00	USD		Annuities	57,139.25	USD/yr	
Specific	0.17			Run. costs	66,412.70		
USD/Wp				USD/yr Payback period	1.7		
				years			
Normalized productions (per inst)				alled kWp) Ratio;		Performance	
				Balances and main results			
Legends							
GlobHor	Global horizontal irradiation			EArray	Effective energy at the output of the array		
DiffHor	Horizontal diffuse irradiation			E_User	Energy supplied to the user		
T_Amb	Ambient temperature			E_Solar	Energy from the sun		
GlobInc	Global incident in coll. plane			E_Grid	Energy injected into grid		
GlobEff	Effective Global, corr. for IAM and shadings			EFrGrid	Energy from the grid		

Table 12: The "Main results" summarize the key performance indicators of the simulated PV system.

	GlobHor kWh/m ²	DiffHor kWh/m ²	T_Amb °C	GlobInc kWh/m ²	GlobEff kWh/m ²	EArray MWh	E_User MWh	E_Solar MWh	E_Grid MWh	EFrGrid MWh
January	91.7	56.0	16.97	109.3	103.2	331.0	99.2	1.50	320.9	97.7
February	106.2	61.9	20.03	122.0	115.5	365.9	89.6	1.27	354.9	88.3
March	147.2	81.3	24.14	159.4	150.7	470.6	99.2	1.53	456.4	97.7
April	151.8	87.0	26.13	151.2	142.6	443.9	96.0	1.50	430.3	94.5
May	158.2	101.3	28.10	148.7	139.9	435.5	99.2	1.78	422.2	97.4
June	134.5	92.3	28.86	124.3	116.7	363.9	96.0	2.11	352.2	93.9
July	128.7	86.1	29.33	119.5	112.1	348.7	99.2	2.15	301.8	97.1
August	133.4	93.3	29.46	128.0	120.2	374.8	99.2	1.76	363.0	97.4
September	119.4	69.6	28.27	123.1	115.9	359.8	96.0	1.50	316.4	94.5
October	114.2	74.4	26.71	126.1	119.0	372.5	99.2	1.55	361.0	97.6
November	100.4	56.1	22.31	122.8	116.2	366.9	96.0	1.31	340.9	94.7
December	92.2	56.1	18.64	113.9	107.5	344.5	99.2	1.13	334.4	98.1
Year	1477.8	915.5	24.94	1548.3	1459.4	4578.0	1168.0	19.09	4354.3	1148.9



Yearly Production, E_Grid, is 4354.3 MWh/year, representing the total net AC energy delivered to the grid over the year. Specific Production, at 1249 kWh/kWp/year, indicates the PV array's annual energy production per installed kWp (kilowatt-peak). The Performance Ratio (PR) is 80.65%, a critical indicator of the system's overall efficiency. It represents the ratio of actual energy produced to the theoretical energy that could be generated under ideal conditions, and it is calculated as:

$$PR = \frac{E_{Grid}}{GlobInc * P_{nom} * 1000}$$

E_Grid is the yearly energy delivered to the grid.

GlobInc is the yearly global incident irradiation on the collector plane.

P_nom is the nominal power of the PV array in kWp.

Solar Fraction (SF), at 1.63%, indicates the percentage of the user's total energy demand met by the PV system. A higher SF reflects greater energy independence. It is calculated as:

$$SF = E_{Used} / E_{Load}$$

E_Used is the energy used directly from the PV system.

E_{Load} is the total energy demand of the user.

E_{Used} , at 1168 MWh/year, represents the total energy consumed directly from the PV system, either by the load or for charging a battery (if present). E_{App_Grid} , at 4354.3 MVAh/year, is the energy delivered to the grid, accounting for both active (real) and reactive power. The total Produced Energy is 4373.4 MWh/year, representing the total annual energy generated by the PV array. GlobHor, at 1477.8 kWh/m²/year, is the total solar energy received on a horizontal surface, while GlobEff, at 1459 kWh/m²/year, is the solar energy effectively received by the tilted PV panels.

Table 13 presents several factors influencing the energy production of the PV system. Global horizontal irradiation is 1478 kWh/m², representing the total solar radiation received on a horizontal surface at the project location. This is the baseline for calculating the potential energy available to the PV system. The Global incident in the collector plane is increased by 4.8%, reflecting the added irradiation due to the tilted orientation of the PV modules, which receive more direct sunlight than a horizontal surface.

The Soiling loss factor is -3.0%, accounting for reduced incident irradiation caused by dust, dirt, snow, or other debris on the PV module surface. The IAM factor (Incidence Angle Modifier) reduces irradiation by 2.8%, compensating for the reduction in light transmission through the module cover glass due to non-perpendicular incidence angles.

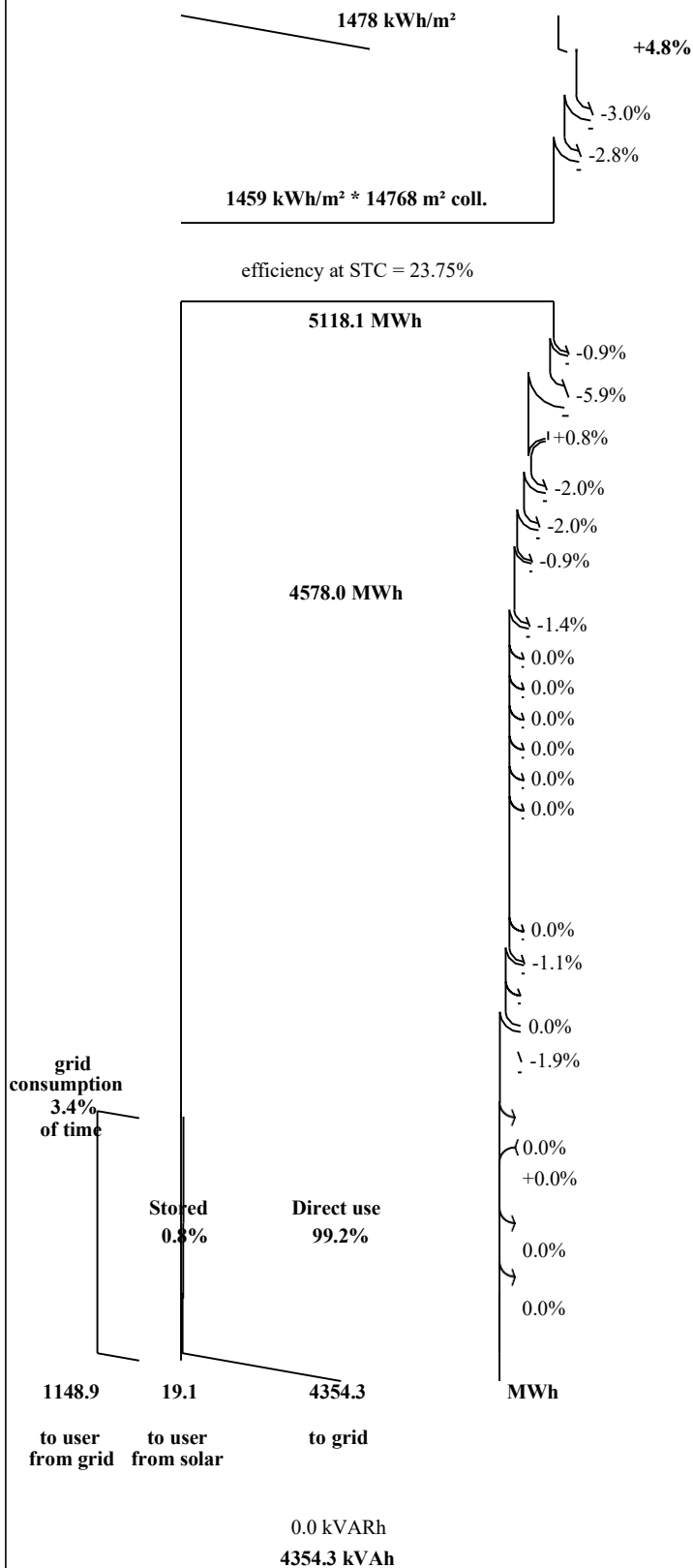
Effective irradiation on the collectors is 1459 kWh/m², which is the solar irradiation that effectively reaches the PV modules after factoring in soiling and IAM losses. This value is multiplied by the total collector area of 14,768 m² to calculate the total incident energy. The PV conversion efficiency at STC is 23.75%, representing the percentage of incident solar energy converted into DC electrical power under Standard Test Conditions.

The Array nominal energy (at STC efficiency) is 5118.1 MWh, indicating the theoretical energy the PV array could produce if it operated at its STC efficiency throughout the year. PV loss due to irradiance level is -0.9%, accounting for efficiency reductions at lower irradiance levels compared to STC. PV loss due to temperature is -5.9%, representing the decrease in efficiency due to elevated operating temperatures.

Module quality loss is +0.8%, indicating a slight overperformance relative to nominal specifications due to variations in module quality and manufacturing tolerances. LID (Light-induced degradation) results in a -2.0% loss, reflecting the initial performance drop in PV modules upon exposure to sunlight. Module array mismatch loss is -2.0%, due to variations in the electrical characteristics of individual PV modules within the array.

Ohmic wiring loss is -0.9%, reflecting the energy lost due to the resistance of the wiring connecting the PV modules. Array virtual energy at MPP (Maximum Power Point) is 4578.0 MWh, which is the DC energy produced by the PV array after all module-related losses. Inverter loss during operation is -1.4%, representing the energy lost during DC to AC conversion by the inverter. Inverter night consumption is 0.0%, meaning no energy is consumed by the inverter during nighttime operation.

AC ohmic wiring loss is -0.2%, which is the energy lost due to the resistance of the AC wiring connecting the inverter to the grid. Finally, the Net energy to the grid is 4374.6 MWh, representing the final amount of AC energy delivered to the grid after accounting for all system losses. This is the net energy yield of the PV system.

Loss Diagram**Global horizontal irradiation****Global incident in coll. plane**

Soiling loss factor

IAM factor on global

Effective irradiation on collectors

PV conversion

Array nominal energy (at STC effic.)

PV loss due to irradiance level

PV loss due to temperature

Module quality loss

LID - Light induced degradation

Module array mismatch loss

Ohmic wiring loss

Array virtual energy at MPP

Inverter Loss during operation (efficiency)

Inverter Loss over nominal inv. power

Inverter Loss due to max. input current

Inverter Loss over nominal inv. voltage

Inverter Loss due to power threshold

Inverter Loss due to voltage threshold

Night consumption

Available Energy at Inverter Output

Cos(phi) = 1.000

AC ohmic loss

Medium voltage transfo loss

MV line ohmic loss

System unavailability

Battery IN, charger loss Battery

Stored Energy balance

Battery Storage

Battery global loss

(5.2% of the battery contribution)

Battery OUT, inverter loss

Dispatch: user and grid reinjection

Reactive energy to the grid: Aver. cos(phi) = 1.000

Apparent energy to the grid

Table 13: The Loss Diagram represents the energy flow and losses in the simulated PV system.
Cost of the systems**Installation costs**

Item	Quantity units	Cost USD	Total USD
PV modules LR8-66HYD-640M	5472	90.00	492,480.00
Inverters SUN2000-100KTL-M1-480Vac	27	3,250.00	87,750.00
Batteries	60	350.00	21,000.00
Installation Global installation cost per module	5472	0.75	4,104.00
		Total	605,334.00
		Depreciable asset	601,230.00

Operating costs

Item	Total USD/year
Maintenance	
Provision for inverter replacement	24,300.00
Provision for battery replacement	8,100.00
Total (OPEX)	32,400.00
Including inflation (7.00%)	66,412.70

System summary

Total installation cost	605,334.00 USD
Operating costs (incl. inflation 7.00%/year)	66,412.70 USD/year
Useful energy from solar	19.1 MWh/year
Energy sold to the grid	4354 MWh/year
Cost of produced energy (LCOE)	0.0283 USD/kWh

Financial analysis
Detailed economic results (USD)

Year	Electricity sale	Loan principal	Loan interest	Run. costs	Deprec. allow.	Taxable income	Taxes	After-tax profit	Self-cons. saving	Cumul. profit	% amorti.
0	0	0	0	0	0	0	0	0	0	0	0.0%
1	435,426	14,766	42,373	32,400	30,062	330,592	0	345,887	1,992	347,879	59.9%
2	435,426	15,799	41,340	34,668	30,062	329,357	0	343,619	1,992	693,490	119.6%
3	435,426	16,905	40,234	37,095	30,062	328,036	0	341,192	1,992	1,036,674	179.1%
4	435,426	18,089	39,050	39,691	30,062	326,623	0	338,596	1,992	1,377,262	238.4%
5	435,426	19,355	37,784	42,470	30,062	325,111	0	335,817	1,992	1,715,071	297.4%
6	435,426	20,710	36,429	45,443	30,062	323,493	0	332,845	1,992	2,049,907	356.1%
7	435,426	22,160	34,980	48,624	30,062	321,762	0	329,664	1,992	2,381,563	414.5%
8	435,426	23,711	33,428	52,027	30,062	319,909	0	326,260	1,992	2,709,815	472.7%
9	435,426	25,371	31,769	55,669	30,062	317,927	0				
10	435,426	27,146	29,993	59,566	30,062	315,806	0	318,721	1,992	3,355,137	588.0%

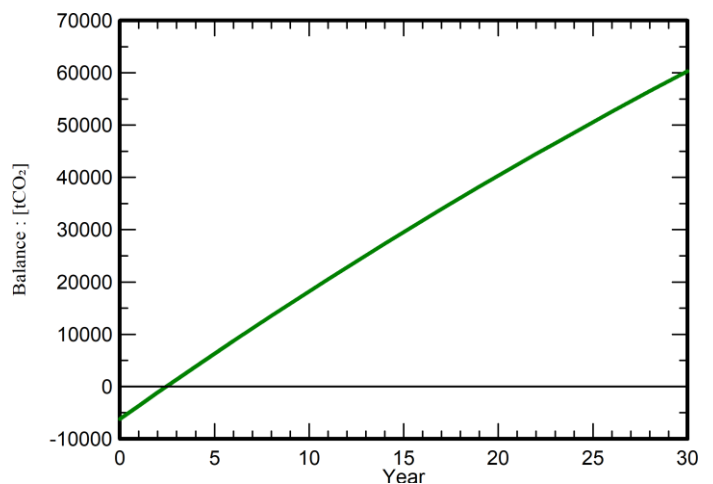
11	435,426	0	29,047	28,093	63,736	30,062	313,537	0	314,551	1,992	3,671,681	645.1%
12	435,426	0	31,080	26,059	68,197	30,062	311,108	0	310,090	1,992	3,983,762	701.7%
13	435,426	0	33,256	23,884	72,971	30,062	308,510	0	305,316	1,992	4,291,070	758.0%
14	435,426	0	35,583	21,556	78,079	30,062	305,730	0	300,208	1,992	4,593,270	813.8%
15	435,426	0	38,074	19,065	83,545	30,062	302,755	0	294,743	1,992	4,890,005	869.1%
16	435,426	0	40,739	16,400	89,393	30,062	299,573	0	288,895	1,992	5,180,891	923.9%
17	435,426	0	43,591	13,548	95,650	30,062	296,167	0	282,637	1,992	5,465,520	978.1%
18	435,426	0	46,643	10,497	102,346	30,062	292,523	0	275,942	1,992	5,743,454	1031.7%
19	435,426	0	49,908	7,232	109,510	30,062	288,624	0	268,777	1,992	6,014,223	1084.7%
20	435,426	0	53,401	3,738	117,175	30,062	284,451	0	261,112	1,992	6,277,326	1137.0%
Total	8,708,529	0	605,334	537,451	1,328,254	601,230	6,241,594	0	6,237,490	39,837	6,277,326	1137.0%

Table 14: The cost of the systems

Breakdown and Analysis: PV Modules: A total of 5472 modules, priced at \$90 each, amounting to a total of \$492,480. Inverters: 27 inverters, each costing \$4,500, bringing the total to \$121,500. Batteries: 60 batteries, priced at \$350 each, totaling \$21,000. Installation Costs: At \$0.75 per module, the total installation cost amounts to \$4,104. Operating Costs: Annual operating costs, including maintenance, insurance, and land costs, are \$66,412. Useful Energy: The system generates 19.1 MWh/year of useful energy. Energy Sold to the Grid: The system delivers 4354 MWh/year to the grid. Levelized Cost of Energy (LCOE): The calculated LCOE is \$0.0283/kWh.

CO₂ Emission Balance

Total:	60326.8 tCO ₂
Generated emissions	
Total:	6221.65 tCO ₂
Source:	Detailed calculation from table below
Replaced Emissions	
Total:	76698.3 tCO ₂
System production:	Grid
Lifecycle Emissions:	584gCO ₂ /kWh
Source:	IEA List
Country:	Bangladesh
Lifetime:	30 years
Annual degradation:	1.0 %

Saved CO₂ Emission vs. Time

System Lifecycle Emissions Details

Table 15: The CO₂ Emission of the systems

Item	LCE	Quantity	Subtotal
			[kgCO ₂]
Modules	1713 kgCO ₂ /kWp	3502 kWp	5998082
Supports	3.90 kgCO ₂ /kg	54720 kg	213150
Inverters	386 kgCO ₂ /	27.0	10419

Total Generated Emissions: 60,326.8 tCO₂ represents the total lifecycle emissions associated with the production, installation, operation, and decommissioning of the PV system.

Replaced Emissions: 76,698.3 tCO₂ reflects the amount of CO₂ emissions that would have been released by conventional power generation. This value is calculated based on the system's annual energy production of 4,377.76 MWh and the grid's CO₂ intensity of 584 gCO₂/kWh.

Functional simulation using the PVSYST software was carried out to forecast performance from the integrated solar-plus-storage under different grid scenarios. The simulations accounted for solar irradiance profiles, load demand variations. The outcome shows that the coupling system can effectively cut down grid power consumption by applications, especially in peak hours of demand, and then increase the self-sufficiency fraction of solar energy. The simulations also demonstrate the grid-stabilizing capabilities of the battery energy storage systems (BESS) by providing ancillary services, such as frequency regulation and voltage support. The simulation results presented in this paper were further proven by the experimental data collected from a case study of a mixed-use building. The experiment included instrumentation to monitor the solar PV output, battery charge or discharge cycles, and grid power flow. The result of the data analysis confirmed a measurable system efficiency in peak demand reduction and self-consumption increase.

4.2. Advantages and Limitations

This integration approach presented has several advantages over the existing solutions. The system architecture is simplified, and costs are lower in comparison with using separate inverters by utilizing a hybrid inverter [9]. It is integrated with an algorithm and intelligent system that optimizes the management of energy and sun-gathering more efficiently, particularly at solar time. However, this approach has its own limitations as well. battery energy storage systems (BESS) can require high initial capital while battery prices continue to drop [23]. Batteries are impacted by temperature and cycling frequency, which also influence their performance and lifespan. The sizing and management of BESS are essential for achieving maximum benefits with long-term reliability [17].

4.3. Economic and Environmental Benefits

Battery energy storage systems (BESS) can be combined with solar inverters, and it provides good economic and environmental benefits. The system can reduce the price of electricity by reducing how much grid power needs to be consumed during peak hours, and when used in conjunction with Time-of-use pricing [15]. In addition to the cost reduction, peak shaving and energy arbitrage can provide additional savings [20]. Solar PV integrated with BESS also significantly decreases greenhouse gas (GHG) emissions, thus enhancing the overall cleanliness and sustainability in the future [4]. The impact of the battery system itself must be further assessed through a life-cycle assessment [1]. Proving out the value proposition of integrated solar-plus-storage systems is a bedrock piece, and quantifying these economic and environmental benefits is central to scaling up. Research has demonstrated that aggregated clean technologies like solar PV and BESS can incur significant cost-saving benefits for emissions abatement [14]. More research and development on advanced battery technologies and smart grid integration strategies can add to the economic and environmental benefits of such systems.

BESS can mitigate fluctuations in solar power output, providing grid services such as frequency regulation and voltage support, improving grid stability and reliability, particularly with increasing solar PV system penetration. [29] highlights the importance of smart inverters and grid-supporting functions in maintaining grid stability with high PV penetration. [30] discusses power quality enhancement using a unified power quality conditioner with grid-integrated solar PV systems. [37] emphasizes the role of smart inverters in managing high levels of distributed energy resource integration, including solar PV and BESS, and their impact on grid stability in South Africa.

BESS can store excess solar energy during peak production and discharge it during low or no generation periods,

maximizing self-consumption and reducing grid reliance. [30] Analyzing the techno-economic feasibility of grid-connected residential rooftop PV systems with BESS demonstrates increased self-consumption and economic benefits. [38] discusses the prediction of optimal battery capacities for solar energy systems using machine learning, aiming to maximize efficiency for residential solar power.

BESS can mitigate power quality issues like voltage sags and swells caused by solar power intermittency. [30] Focuses on enhancing power quality using a unified power quality conditioner (UPQC) in grid-integrated solar PV systems.

Maximizing self-consumption and providing grid services with BESS can reduce electricity bills and generate revenue through grid ancillary services markets. [31] analyzes the economic aspects of integrating solar inverters in Nigerian healthcare centers. [30] also presents an economic feasibility analysis of residential rooftop PV systems with BESS.

Increased solar energy utilization reduces reliance on fossil fuels, lowering greenhouse gas emissions and promoting a smaller carbon footprint.

5. Challenges and Future Directions

5.1. Key Challenges and Barriers

High initial costs still represent a substantial cost barrier, especially when applied to residential and small commercial level scales [22]. Though battery prices are decreasing, larger cost reductions are necessary for greater market penetration [23]. Battery life decreases as a function of the number and frequency of charge or discharge cycles [10]. Since a second life supports economic operation for longer times, that would eventually help increase the return on investment. Researching advanced battery chemistries and thermal solutions will fail to solve this because they enable previously unsolved problems with that technology.

Key technical and regulatory challenges must be addressed to integrate a high level of solar-plus-storage capacity into the existing grid infrastructure. Next-generation grid management tactics and regional regulatory frameworks that encourage connection and grid stability are needed to accommodate the seamless shift.

The absence of industry standards for battery energy storage systems (BESS), specifically with respect to communication protocols, could impede interoperability, limiting system flexibility [13]. Compatibility among the parts has to be maintained, and various components should work in harmony, as we already see happen when there are standardized efforts.

Both battery fires and thermal runaway events need to be mitigated through the development of appropriate safety measures, such as advanced battery management solutions [18]. Life cycle assessment and subsequent recycling initiatives should also be considered for implementation to minimize the environmental impact of battery manufacturing and disposal [6].

BESS costs remain a barrier to widespread adoption. [30] addresses the economic feasibility of residential PV systems with BESS, considering initial costs. Battery performance degradation over time impacts system lifespan and cost-effectiveness. Ensuring BESS safety and reliability is crucial for widespread deployment. Clear standards and regulations are needed for seamless BESS integration with existing grid infrastructure. [29] mentions IEEE 1547-2018 standards for inverter performance.

5.2. Potential Solutions and Future Research Directions

Studies of advanced battery chemistry, such as solid-state batteries [8] and flow batteries, are one alternative that may offer better performance, mitigate safety concerns, or even prolong the life span.

Advanced grid management algorithms and control strategies can be developed to improve the operation of integrated solar-plus-storage systems and thereby support better grid stability [16].

Coordination and standardization of industry-wide standards are established for battery energy storage systems (BESS) and communication protocols; it can help ensure interoperability, which will make integrating those systems easier.

Policy and Regulatory Support Solar-plus-storage systems are an emerging technology, and government policies and incentives have a critical role in fostering the market uptake of solar-plus energy storage solutions while driving down costs.

The Public Knowledge Campaign Increasing consumer demand for solar-plus-storage will, in turn, drive the market with greater public awareness about the benefits of paired systems.

Research continues on next-generation battery technologies with higher energy density, longer lifespan, and lower

cost.

Developing more efficient and reliable power electronics for grid integration is crucial [33]. Reviews multilevel inverter topologies for grid-connected

5.3. Emerging Technologies and Trends

AI and machine learning techniques can be applied to battery management optimization, solar generation prediction, and grid integration. Blockchain creates new business models for solar-plus-storage systems and enables peer-to-peer energy trading. IoT-enabled Devices and Sensors make the monitoring and control of integrated systems possible, enhancing performance and reliability at the foundation level.

Advanced inverters with grid-forming capabilities and sophisticated control algorithms are crucial for managing bidirectional power flow between the solar PV system, BESS, and the grid. [32] explores improved inverter control techniques for enhanced hosting capacity of solar PV with BESS. [33] reviews multilevel inverter topologies for grid-connected solar PV systems. [29] emphasizes the role of smart inverters in grid stability with high PV penetration. [37] provides a review of smart inverter capabilities for managing high levels of distributed energy resources (DER) integration, including solar PV and BESS, in South Africa's power grid.

Intelligent Electro-magnetic systems (EMS) optimize BESS charging and discharging based on solar generation, load demand, and grid conditions. [34] discusses grid-connected solar panels with BESS, highlighting energy management. [38] mentions the development of a machine learning tool for predicting optimal battery size for residential solar power systems, which can be considered a part of an advanced energy management system.

Different battery chemistries offer varying performance characteristics in energy density, power density, cycle life, and cost. Selecting the appropriate technology is crucial for system performance and economic viability.

Robust communication and monitoring systems are necessary for the integrated system's real-time data acquisition, control, and performance monitoring. [35] discusses the role of smart electronics in solar-powered grid systems for enhanced efficiency and reliability. [36] explores innovative solar energy integration for efficient grid electricity management and advanced electronics applications.

6. Conclusion

In this research, the integration of battery energy storage systems (BESS) along with solar inverters is studied, increasing the penetration level and making it useful for grid stability. Using a combination of conceptual on-site data and energy modeling, the results suggest that cohesive solar-plus-storage systems can effectively displace loads from grid electricity with particularly strong performance in terms of increasing self-consumption of solar by moving more production into periods when it is being produced (avoid using power generated at non-peak times) thus also contributing to reduced reliance upon peak demand or imported generation sources. In addition, BESS could be leveraged into the grid's ancillary services like frequency regulation and voltage support to improve the stability and reliability of the power system. However, challenges like high upfront costs and short-lived batteries have not gone away even through the development of advanced battery technologies; optimum strategies to integrate these into a smart grid system with policies that support this are starting to be found.

Solar inverters are an essential platform to integrate BESS on the utility, commercial, and residential scale for optimal utilization of renewable energy production. This would make the transition from a carbon baseline electricity power system to a greener future possible. For example, it allows storing over any excess solar energy produced by the day irradiance period during the night economic time. It enables a round-the-clock, reliable supply of clean energy, irrespective of the shining sun. It not only lowers the dependence on fossil fuels but also improves grid stability and resilience, especially as the integration of intermittent energy sources continues to grow.

Battery technologies, power electronics, and grid management systems are all improving for the future of solar energy storage. Emerging technologies like solid-state batteries, advanced artificial intelligence, and blockchain will soon take integrated solar plus storage systems even further in terms of performance improvements and added safety measures that will bring down overall economic viability. With these technologies becoming more mature and costs continuing to decrease, solar-plus-storage solutions are well positioned to become a mainstay of the future sustainable energy system for providing an abundance of reliable and affordable electricity amid carbon emissions constraints that will underpin our lives in our homes, businesses, or communities.

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A Spider Wasp Optimizer-Based Deep Learning Framework for Efficient Citrus Disease Detection

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Abstract—Managing citrus diseases is important for lowering crop losses and raising the economic value of citrus output. To provide a novel approach for the identification and classification of three significant citrus diseases—Citrus Canker, Citrus Greening, and Citrus Black Spot—this study uses a Deep Convolutional Neural Network (DCNN) optimized using the Spider Wasp Optimizer (SWO). Traditional disease diagnosis methods heavily rely on expert visual inspection, which is often subjective and time-consuming. To overcome these drawbacks, the proposed SWO-DCNN model automates hyperparameter tuning, improving classification accuracy and reducing computation time. Citrus image datasets containing both healthy and infected samples were pre-processed using grayscale conversion, normalization, and augmentation, and then trained using a 10-fold cross-validation technique. Performance evaluations based on sensitivity, specificity, false positive rate, accuracy, and identification time show that the SWO-DCNN outperforms the conventional DCNN in every disease category. With accuracies of 96.22%, 96.51%, 95.70%, and 97.04% for the classification of Black Spot, Greening, Canker, and overall healthy/non-healthy, respectively, the SWO-DCNN significantly reduced false positive rates and recognition times. This paper contributes to knowledge by presenting the Spider Wasp Optimizer, a hyperparameter tuning technique for deep learning models used to identify agricultural diseases. The SWO-DCNN framework offers a dependable and scalable approach for automated citrus disease classification by enhancing model performance and computational efficiency. This innovation supports precision farming initiatives and provides a reliable alternative to traditional diagnostic methods, which may improve export quality control and reduce citrus farming's financial losses.

Keywords— Citrus Disease Detection, Deep Convolutional Neural Network (DCNN), Spider Wasp Optimizer (SWO), Hyperparameter Optimization

1 Introduction

Reducing crop losses and increasing agricultural productivity depend on efficiently managing pests and diseases. Infections and physical defects on fruit peels drastically reduce market value in citrus cultivation, resulting in trade restrictions in extreme situations.

Citrus canker, citrus greening, and citrus black spot (CBS) are the most destructive of these diseases because of their aggressive infection rates and long-term economic impact. These diseases significantly reduce fruit quality and yield, often rendering produce unmarketable for export [1-2]. For example, citrus greening (Huanglongbing) has been linked to widespread losses in Asia, Africa, and the Americas, leading to severe economic consequences for

citrus producers [3]. Even minor infections or physical defects on fruit peels drastically reduce market value and may result in trade restrictions imposed by importing countries [4].

Historically, disease diagnosis in citrus production has relied on manual visual inspection and microscopic analysis, methods which, while useful, are often subjective, time-consuming, and dependent on expert availability [5]. These conventional approaches may not scale efficiently in large orchards or regions experiencing labor shortages, leading to inconsistent sorting and undetected spread of infections.

Automated image-based categorization methods are now the main emphasis due to computer vision and machine learning (ML) developments. Deep learning models, particularly Convolutional Neural Networks (CNNs), have been successfully used to detect citrus disease from images of fruit and leaves [6]. These systems overcome the drawbacks of human sorting, like inconsistent standards and low productivity [7].

The biggest challenge that remains despite CNNs' advancements in plant disease identification is their inability to recognize numerous diseases or multiple instances of the same disease in a single image. This multi-class classification problem is significantly influenced by the hyperparameter choices made during neural network training [8-9]. Hyperparameters such as learning rates, batch sizes, and weight initializations must be carefully considered to produce high-performing models. Many metaheuristic algorithms have been studied to automate and optimize this process, including Genetic Algorithms [10], Parameter Setting-Free Harmony Search (PSF-HS) [11], Particle Swarm Optimization (PSO) [9], and Multi-level Particle Swarm Optimization (MPSO) [12]. Despite improving model performance, these techniques are often computationally demanding and challenging to implement.

Convolutional neural networks (CNNs), a recent advancement in deep learning, have significantly improved the capacity to recognize and categorize plant diseases. Ref [13] conducted a comprehensive analysis of 121 papers that used CNNs and found significant trends and gaps in literature. [14] demonstrated the potential of edge computing in agriculture using real-time cloud-based systems that used AWS DeepLens, which produced realistic deployments with an accuracy of 98.78%. As an extension of these developments, [15] proposed PlantXViT, a hybrid Vision Transformer–CNN model that surpassed 93.00% accuracy across multiple datasets. [16] employed unsupervised deep learning with multispectral imaging for powdery mildew identification, and emphasized the significance of spectral data.

Studies have also been conducted on specific crops. Though [17] investigated deep learning techniques for apple leaf disease classification, [18] looked at performance trade-offs across multiple deep learning models. Ref [19] introduced a 14-layer Deep CNN trained on a large dataset of 147,500 images containing a no-leaf class and 58 disease categories. The model's accuracy was 99.97% using techniques like neural style transfer, Generative Adversarial Network (GAN), and picture augmentation.

Citrus crops have received a lot of attention. A customized Self-Structured CNN outperformed MobileNet in terms of accuracy and efficiency (99.00%), according to [20]. [21] developed a dense CNN that can recognize 27 disease categories in six crops with a cross-validation accuracy of 99.58%. Ref [6] trained a CNN with 94.55% accuracy using the Citrus and PlantVillage datasets. Furthermore, a Convolutional Neural Network Long Short-Term Memory (CNN–LSTM) hybrid model outperformed K-Nearest Neighbor (KNN), Support Vector Machine (SVM), and standalone CNNs in citrus illness classification, achieving 96.00% accuracy. Advanced sensor technology improved the detection even more. [22] used hyperspectral cameras and stacked autoencoders installed on Unmanned Aerial Vehicles (UAVs) to detect Huanglongbing (HLB) with 99.72% accuracy. Additionally, [23] used hyperspectral imaging and Partial Least Squares Discriminant Analysis (PLS-DA) to identify HLB with 96.40% accuracy.

[24] took citrus photos at three different stages of pest infestation and then used different optimizers to analyze four CNN models. Visual Geometry Group-16 (VGG-16) with stochastic gradient descent (SGD) performed best in the early stages of infestation, while AlexNet with SGD performed exceptionally well in the later stages, achieving an accuracy of up to 99.34%. The study confirmed the effectiveness of CNNs in controlling pests.

Multimodal strategies have also shown promise. [25] developed a soft attention-based fusion model that classified nutrient deficiencies and HLB with 97.89% accuracy by combining Red, Green, Blue (RGB), and hyperspectral data. Deep CNN frameworks with different picture sizes and severity-level classification using VGGNet were able to distinguish between healthy and sick citrus fruits with up to 99.00% accuracy, according to [26-27]. [28] achieved 99.84% accuracy in classifying eight peel states in Ruby Red grapefruit using hyperspectral imaging and VGG-16. To increase accuracy, [29] divided diseased areas before classifying them. Similarly, CNN-based citrus disease diagnosis was shown to outperform conventional techniques like KNN and SVM by [30]. Additional developments include a two-stage CNN developed by [31] with a 94.37% accuracy rate in detecting black spots, canker, and HLB. [32] used segmented citrus leaf photos and obtained 96.00% accuracy.

Despite these successes, hyperparameter tuning remains a challenge. Therefore, this study integrated the Spider Wasp Optimizer (SWO) with a Deep CNN to enhance the detection of three key citrus diseases: canker, greening, and black spot.

Recent advancements in metaheuristic optimization have led to the development of algorithms to improve convergence speed, robustness, and search-space diversity in high-dimensional problems. The Spider Wasp Optimizer (SWO) has garnered significant attention due to its biologically inspired design and effective balance between exploration and exploitation [33].

SWO is inspired by the hunting and reproductive behaviour of solitary spider wasps (Pompilidae family), which paralyse spiders, lay eggs on them, and use them as hosts for larval development. This natural predator-prey interaction has been translated into a mathematical framework for solving optimization problems. The algorithm functions in two main phases:

1. Exploration (Paralysing Behaviour):

Spider wasps randomly explore the search space to discover high-potential regions, maintaining diversity and preventing premature convergence to local optima.

2. Exploitation (Egg-Laying Behaviour):

Once a promising region is identified, the optimizer intensifies its search around that area, refining solutions for improved precision and faster convergence.

This dual-phase mechanism enables a dynamic transition between global search and local refinement, addressing a key challenge in metaheuristic optimization [33]. SWO incorporates Bayesian-inspired probabilistic learning, allowing it to refine its belief about the best regions in the search space based on previous evaluations. This approach reduces the number of evaluations needed to reach optimal solutions, making it suitable for complex, high-dimensional tasks such as hyperparameter tuning in deep learning models [34-35]. Compared to classical metaheuristics like Harmony Search, Genetic Algorithms (GA), and Particle Swarm Optimization (PSO), SWO demonstrates several unique advantages:

- **Balanced Dual Behaviour:** Its biologically inspired two-phase mechanism ensures a more effective balance between exploration and exploitation [36].
- **Probabilistic Decision Making:** It adapts its strategy based on population feedback using Bayesian principles.
- **High-dimensional Optimization Efficiency:** SWO excels in tuning complex parameters such as learning rates, number of layers, batch sizes, and neuron counts in deep networks [37].

Several enhanced variants of SWO have emerged, expanding its applicability:

- **Multiple-strategy SWO (MS-SWO):** Integrated Lévy flights and adaptive mechanisms to improve performance on engineering design problems [38].
- **Boosted SWO (BSWO):** Improved feature selection in high-dimensional datasets [35].
- **Binary SWO:** Achieved robust classification accuracy for intrusion detection in Industrial IoT applications [39].

These adaptations confirm the algorithm's relevance for neural network training and other tasks involving nonlinear, high-dimensional search spaces. Despite its promising capabilities, SWO remains underexplored in the field of agricultural image analysis. This study represents one of the first efforts to apply SWO for plant disease classification using deep learning. Specifically, the SWO-DCNN model was used to optimize critical hyperparameters of a Deep Convolutional Neural Network (DCNN) for citrus disease detection. The optimizer dynamically adjusted parameters such as learning rate, number of convolutional layers, number of neurons, and weight initialization schemes. To achieve these goals, the study aims to:

- (i) develop an enhanced Deep Convolutional Neural Network (DCNN) using the Spider Wasp Optimizer (SWO) for optimal hyperparameter tuning.
- (ii) design a robust citrus fruit disease detection and classification system based on the proposed SWO-DCNN model.
- (iii) implement the system using MATLAB R2020a.
- (iv) analyse the system's accuracy, sensitivity, specificity, false positive rate, and average recognition time.

Organization of the Paper

The remainder of this paper is structured as follows:

Section 2 presents the methodology adopted, including image acquisition, preprocessing, model formulation, and the integration of the Spider Wasp Optimizer with the DCNN.

Section 3 discusses the implementation of the proposed technique and presents the evaluation metrics and experimental results.

Section 4 provides a detailed discussion of the findings, comparisons with existing techniques, and implications of the results.

Section 5 concludes the paper and offers suggestions for future research directions.

2 Methodology

The methodology adopted in this study comprises four main stages and are outlined as follows: Data acquisition, data pre-processing, model formulation, and performance evaluation. Pre-processing entails removing noise and other undesirable components from the citrus photos by filtering, cropping, normalizing, and converting them to greyscale. Deep Convolution Neural Network was utilized to identify and categorize infected citrus images from non-infected citrus images, and Spider Wasp Optimizer was utilized to choose valuable features from the extracted features. Performance metrics like sensitivity, specificity, false positive rate, and overall accuracy were used to assess the outcome.

2.1 Acquisition of Citrus Images

The citrus fruit disease dataset used in this study was obtained from the publicly available Kaggle repository titled “Orange Diseases Dataset” by Jonathan Silva. This dataset comprises high-quality images captured under real-world agricultural conditions, including four clearly labeled categories: Citrus Black Spot, Citrus Greening, Citrus Canker, and Healthy samples. Its structured organization, visual clarity, and accurate annotations reinforce the dataset's credibility, making it suitable for supervised machine learning applications.

A total of 2,500 images were curated for this study, comprising 1,000 healthy samples and 1,500 diseased samples distributed equally across the three disease categories. To enhance intra-class variability and reduce overfitting, data augmentation techniques such as horizontal flipping, $\pm 15^\circ$ rotation, and contrast adjustment were applied. All images were resized to 600×600 pixels without altering their content. After augmentation and cleaning, the dataset comprised 2,500 images: 500 for each disease class and 1,000 healthy samples, as shown in Table 1.

A 10-fold stratified cross-validation approach was used to ensure balanced training and testing, effectively addressing the mild class disparity and supporting generalizable model performance. The validity of the dataset is supported by recent scholarly work. For instance, [40] developed a CNN-based citrus fruit disease diagnosis system and validated its effectiveness using the same dataset, achieving high classification performance. Similarly, [41] employed CNN-extracted features in conjunction with traditional machine learning classifiers to distinguish between lemon and orange diseases using this dataset, demonstrating its suitability for diverse classification approaches. These studies confirm the dataset's reliability, structured labeling, and compatibility with modern deep learning pipelines.

Table 1: Class-wise Distribution of Citrus Image Dataset After Augmentation

Class	Number of Images
Citrus Black Spot	500
Citrus Greening	500
Citrus Canker	500
Healthy (No Disease)	1000
Total	2500

2.2 Pre-processing of Citrus Images

To perform pre-processing, the coloured image was converted to grayscale, and the citrus vectors were normalized by taking the average and deducting it from each vector. This was done to purge the citrus images of noise and other undesirable components. The images were transformed into black-and-white, or grayscale, images with pixel values ranging from 0 to 255. In MATLAB, each grayscale image was expressed and saved as a matrix, which was then transformed into a vector image for use in subsequent procedures. To facilitate the normalization process, a citrus vector conversion was made.

A histogram equalization system was applied during the normalization process to improve contrast and increase the intensity range of the converted grayscale images. This improved the grayscale images' brightness so that the structure of each citrus fruit could be seen more clearly. Any shared characteristics among the citrus images were eliminated during the normalization process, leaving each one with its distinct traits. The common features were discovered by averaging the citrus vectors across the whole training set (citrus images). The average citrus vector was then subtracted from each citrus vector to create a normalized citrus vector.

2.3 Formulation of Spider Wasp Optimizer based Deep Convolutional Neural Network (DCNN)

The Spider Wasp Optimizer (SWO) employs a probabilistic model to represent the behaviour of candidate solutions in the search space. This model estimates the likelihood that a given set of hyperparameters will yield high-performing results. The probabilistic approach enables the optimizer to adjust its search strategy dynamically by balancing exploration and exploitation during each iteration [33].

In particular, SWO leverages concepts from Bayesian optimization, a technique that uses probabilistic surrogate models (e.g., Gaussian processes) to guide the selection of the next promising solution based on past observations [35, 42]. Unlike grid search or random search, Bayesian optimization intelligently samples the hyperparameter space to reduce the number of evaluations needed to find an optimum. This makes it well-suited for tuning deep learning models where training is computationally expensive.

In the SWO framework, the optimizer updates its belief about the best regions of the search space after evaluating each candidate. This adaptive learning mechanism helps accelerate convergence and ensures efficient exploration of complex, high-dimensional hyperparameter spaces. The following is the basic procedure for using Spider Wasp optimizer to optimize DCNN:

1. The search space for hyperparameters was defined. The search space contained all the hyperparameters that could be changed for a specific DCNN model. For example, learning rate and weight parameters.
2. The optimizer was constructed using a starting set of hyperparameters chosen at random from the search space.
3. The DCNN model was trained using the chosen hyperparameters, and the performance metric (such as accuracy or loss) was computed.
4. The optimizer adjusted its probabilistic model in response to the DCNN model's performance.
5. This update chose which set of hyperparameters to evaluate next based on the optimizer's existing probabilistic model.
6. Steps three and four are repeated until the optimizer converges on the ideal set of hyperparameters.

One of the main advantages of the Spider Wasp optimizer is its ability to adjust multiple hyperparameters simultaneously. This is important because the interactions between different hyperparameters often affect the performance of DCNN models.

2.4 CNN Parameter Selection using Spider Wasp Optimizer

Achieving optimal performance in deep learning applications requires the careful tuning of hyperparameters such as the number of layers, number of neurons per layer, learning rate, activation functions, and weight initialization schemes. These hyperparameters significantly influence deep convolutional neural networks' learning dynamics and generalization ability (DCNNs) [43-44].

Manual tuning or exhaustive methods like grid search can be inefficient and computationally expensive, particularly for high-dimensional and non-linear search spaces. Consequently, population-based metaheuristic optimization techniques—such as the Spider Wasp Optimizer (SWO)—have emerged as effective tools for automatic hyperparameter optimization due to their gradient-free nature and balance between exploration and exploitation [33, 38].

The following steps outline how the Spider Wasp optimizer was used to choose CNN's parameters:

- (i) Define the search space: The first step involved defining the hyperparameter search space. This required setting ranges for each hyperparameter that could be adjusted, such as the learning rate and weight parameters [44].
- (ii) Configure the optimizer: A starting set of hyperparameters had to be entered into the Spider Wasp optimizer. From the designated search area, these were selected at random [33].
- (iii) Train the CNN model: The original set of hyperparameters was used to train the CNN model on the training dataset. This required adjusting the weights per the optimizer's method and moving data forward and backward across the network.
- (iv) Determine the performance metric: After the model was trained, its performance was evaluated using a validation dataset. A performance metric, such as accuracy or mean squared error (MSE), was computed to achieve this [45].
- (v) Update the optimizer: The Spider Wasp optimizer adjusted its probabilistic model of the hyperparameters' behavior by choosing the subsequent set of hyperparameters to assess using the present probabilistic model.

- (vi) Steps iii–v were repeated until the optimizer reached a consensus on the ideal set of hyperparameters [34-35].
- (vii) Test the finished model: After the optimal hyperparameters were identified, the final CNN model was trained using the selected hyperparameters on the entire training dataset. Finally, an alternative test dataset assessed the model's performance [46-47].

2.5 Feature Extraction and Classification using SWO-DCNN

SWO's chosen hyperparameters were used to train the DCNN model. This involved moving data through the network both forward and backward and modifying the weights according to the optimizer's algorithm. Performance metrics, such as accuracy or mean squared error (MSE), were used to assess the model's performance on a validation dataset. Using the full training dataset and the ideal hyperparameters identified by the SWO, the final DCNN model was trained. Lastly, a different test data set was used to evaluate the model's performance. It should be noted that the optimizer guides the search process during training by using a probabilistic model of the hyperparameters' behavior. Compared to other optimization methods that use a grid search or random search approach, the optimizer can explore the search space more effectively. The block diagram that depicts the developed system's process flow is shown in Figure 1, while the flowchart illustrating the trained and tested citrus using SWO-DCNN is depicted in Figure 2.

Algorithm 1: Spider Wasp Optimized based CNN

Input:

CNN parameters, such as weights, layers, and filters,

N: the size of the initial population,

 N_{min} : The minimum size of the population,

CR: The rate of crossover,

TR: The threshold for hunting and maturing behaviour

 t_{max} : Maximum number of generations

Output:

Optimized CNN parameters $\overrightarrow{SW}^*$

Step 1: Initialization

For $i = 1, 2, \dots, N$, initialize N female wasp individuals $\overrightarrow{SW}_i$ for using

$$\overrightarrow{SW}_i(t) = \vec{L} + \vec{p} \times (\vec{H} - \vec{L})$$

Where:

t is the generation index

 $\vec{L}, \vec{H}$: Lower and upper bounds of the parameter space $\vec{p}$: A $D - \text{dimensional}$ random vector generated using Roulette Wheel Selection

Step 2: Fitness Evaluation

Evaluate the fitness of each, $\overrightarrow{SW}_i$ and identify the best individual $\overrightarrow{SW}^*$

Step 3:

Set $t = 1$ (initialize general counter)Step 4: while $t < t_{max}$, do:

Step 5:

Generate ρ_6 using roulette-based probabilistic control

Step 6

If $\rho_6 < TR$: Hunting and Nesting BehaviourFor $i = 1$ to N , do

- Apply hunting/nesting update strategies to $\overrightarrow{SW}_i$
- Compute fitness $f(\overrightarrow{SW}_i)$
- Increment generation count: $t = t + 1$

End For

Step 7

Else: Mating Behaviour

For $i = 1$ to N , do

- Select male partner $\overrightarrow{SW}_m$
- Apply uniform crossover:
$$\overrightarrow{SW}_i(t+1) = \text{Crossover}(\overrightarrow{SW}_i(t), \overrightarrow{SW}_m(t), CR)$$
- Increment generation count: $t = t + 1$

End For

End if

Step 8: Memory Saving and Population Update

Update Population Size

$$N = N_{min} + (N - N_{min}) \times K$$

Where k is a decay factor to reduce population gradually and avoid local optima

End While

Step 9: Return best solution $\overrightarrow{SW}^*$ as the optimal CNN parameters.

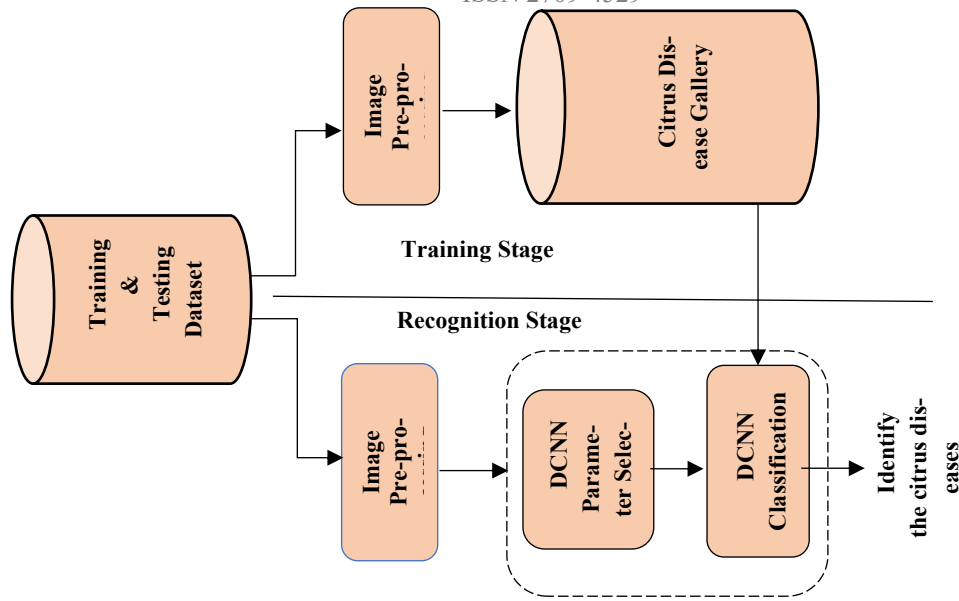


Fig. 1: The block diagram representing the process flow of the developed system

3 Implementation of Developed Technique for Citrus Fruit Disease

An online database of citrus fruit disease data was used to create an interactive Graphic User Interface (GUI) application. MATLAB (2020a) toolboxes for image processing, deep learning, and optimization were used in GUI's design. The implementation was done on a computer system with a particular configuration using the MATLAB software package.

3.1 Evaluation Metrics

The accuracy of the developed system is the ability to detect a citrus fruit with a disease or exclude a citrus fruit without a disease, and it is usually described in terms of sensitivity, specificity, and false positive rate (FPR).

Accuracy: is the proportion of citrus fruits with or without abnormalities (e.g., Citrus Canker, Citrus Greening, or Citrus Black Spot) that the system was able to correctly identify, and is given by equation 1:

$$\text{Accuracy} = \frac{TP + TN}{TP + FN + TN + FP} \times 100\% \quad (1)$$

Sensitivity is the proportion of citrus fruit with abnormalities that the system can correctly identify. Sensitivity is defined in equation 2

$$\text{Sensitivity} = \frac{TP}{TP + FN} \times 100\% \quad (2)$$

Specificity shows the system's capacity for identifying non-diseased citrus fruits. Specificity is defined in equation 3

$$\text{Specificity} = \frac{TN}{FP + TN} \times 100\% \quad (3)$$

The False Positive Rate (FPR) is the proportion of healthy citrus fruits wrongly classified as diseased to the proportion of all healthy samples citrus fruits.

$$\text{FPR} = \frac{FP}{FP + TN} \times 100\% \quad (4)$$

3.1.1 Performance of the system using the BS dataset

Table 2 displays the results of the DCNN and SWO-DCNN methods using Black spot datasets. The table shows that the DCNN method had a false positive rate of 8.74%, an accuracy of 93.90% at 69.02 seconds, a sensitivity of 95.02%, and a specificity of 91.26%. At 46.19 seconds, the SWO-DCNN approach also had an accuracy of 96.22%, a sensitivity of 96.68%, a specificity of 95.15%, and a false positive rate of 4.85%. The SWO-DCNN method

was better than the DCNN method when it came to recognition accuracy, sensitivity, specificity, and the rate of false positives.

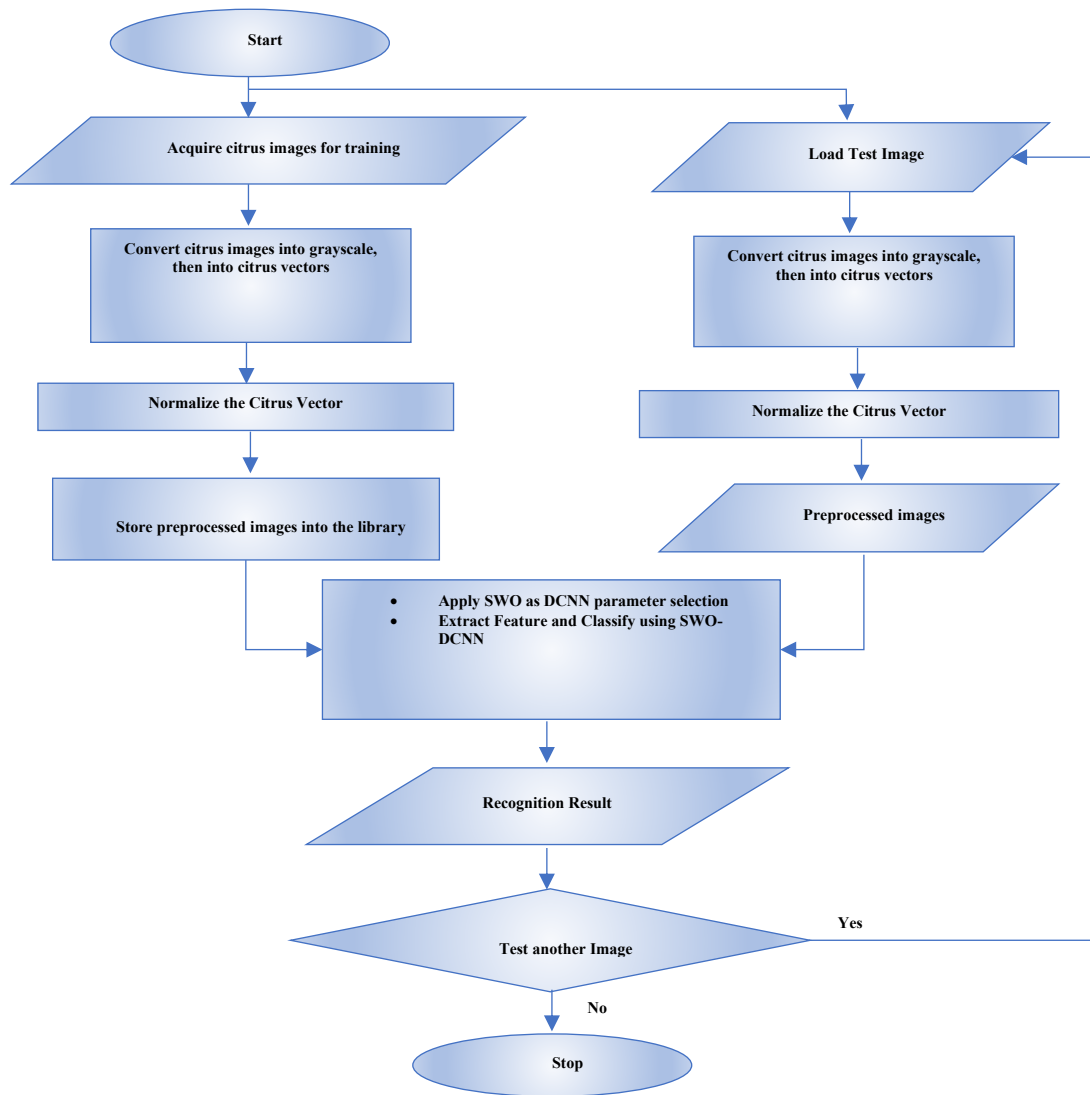


Fig. 2. Flowchart of the SWO-DCNN

3.1.2 Performance of the system using the Greening dataset

Table 2: Findings using BS datasets from the DCNN and SWO-DCNN techniques

Technique	FPR (%)	Specificity (%)	Sensitivity (%)	Accuracy (%)	Recognition Time (seconds)
DCNN	8.74	91.26	95.02	93.9	69.02
SWO-DCNN	4.85	95.15	96.68	96.22	46.19

Table 3 shows the results of the DCNN and SWO-DCNN methods using Greening datasets and performance markers. The table says that the DCNN method had a false positive rate of 7.98%, a sensitivity of 95.81%, a specificity of 92.02%, and an accuracy of 94.68% at 68.90 seconds. The SWO-DCNN approach also has a sensitivity of 97.12%, a specificity of 95.09%, an accuracy of 96.51%, and a false positive rate of 4.91% at 45.89 seconds. This finding shows that the SWO-DCNN method was superior to the DCNN method in terms of recognizing things, being sensitive, specific, and having a low false positive rate.

3.1.3 Performance of the system using the Canker (CCK) dataset

Table 4 shows the results of the DCNN and SWO-DCNN methods using Canker datasets concerning the performance indicators. The table shows that the DCNN method had a false positive rate of 9.52%, an accuracy of 93.41% at 68.59 seconds, a sensitivity of 94.67%, and a specificity of 90.48%. The SWO-DCNN method got similar results in 46.44 seconds, with a false positive rate of 5.71%, a sensitivity of 96.31%, a specificity of 94.29%, and an accuracy of 95.70%. Table 2a shows that the SWO-DCNN method was better than the DCNN method in terms of false positive rate, sensitivity, specificity, and recognition accuracy.

3.1.4 Evaluation of Results using the Healthy and Non-Healthy dataset

Table 5 shows the results of the DCNN and SWO-DCNN methods using Healthy and Non-Healthy datasets and performance indicators. The table shows that the DCNN method has a sensitivity of 95.85%, a specificity of 90.88%, an accuracy of 94.36%, and a false positive rate of 9.12% at 202.17 seconds. The SWO-DCNN approach, on the other hand, had a false positive rate of 4.66%, a sensitivity of 97.77%, a specificity of 95.34%, and an accuracy of 97.04% in 136.86 seconds. Table 4.2b shows that the SWO-DCNN method did better than the DCNN method in terms of false positive rate, sensitivity, specificity, and recognition accuracy.

4 Discussion of Results

This part discusses the experimental data and the citrus disease detection and classification system's overall recognition time, accuracy, FPR, sensitivity, and specificity. Table 6 shows the combined results for SWO-DCNN and DCNN based on the datasets used.

Table 3: Findings using Greening datasets from DCNN and SWO-DCNN techniques

Technique	FPR (%)	Specificity (%)	Sensitivity (%)	Accuracy (%)	Recognition Time (seconds)
DCNN	7.98	92.02	95.81	94.68	68.90
SWO-DCNN	4.91	95.09	97.12	96.51	45.89

Table 4: Findings using Canker (CCK) datasets from DCNN and SWO-DCNN techniques

Technique	FPR (%)	Specificity (%)	Sensitivity (%)	Accuracy (%)	Recognition Time (seconds)
DCNN	9.52	90.48	94.67	93.41	68.59
SWO-DCNN	5.71	94.29	96.31	95.70	46.44

Table 5: Findings using Healthy and Non-Healthy datasets from DCNN and SWO-DCNN techniques

Technique	FPR (%)	Specificity (%)	Sensitivity (%)	Accuracy (%)	Recognition Time (seconds)
DCNN	9.12	90.88	95.85	94.36	202.17
SWO-DCNN	4.66	95.34	97.77	97.04	136.86

Table 6: Findings of SWO-DCNN and DCNN combined according to the datasets

Technique	Black spot	Greening	Canker	Healthy/non-healthy
Accuracy (%)				
DCNN	93.90	94.68	93.41	94.36
SWO-DCNN	96.22	96.51	95.70	97.04
Sensitivity (%)				
DCNN	95.02	95.81	94.67	95.85
SWO-DCNN	96.68	97.12	96.31	99.29
Specificity (%)				
DCNN	91.26	92.02	90.48	90.88
SWO-DCNN	95.24	97.92	97.37	95.00
Recognition time (sec)				
DCNN	69.02	68.90	68.59	202.17
SWO-DCNN	74.94	49.52	72.27	167.94

4.1 Performance Evaluation of Recognition Rates

Figures 3, 4, 5, 6, and 7 show that the SWO-DCNN method did better than the DCNN in terms of accuracy, specificity, and sensitivity for all dataset categories utilized in this study. Table 6 shows that the SWO-DCNN method was better at recognizing the black spot, greening, canker, and healthy/non-healthy datasets than the DCNN method by 4.81%, 8.33%, 7.89%, and 7.33%, respectively. The recognition accuracy increased, resulting in improved performance because SWO adjusted the DCNN parameters to make them more discriminated against.

Also, the SWO-DCNN technique had a greater specificity of 9.00%, 8.04%, 10.53%, and 3.57% for the black spot, greening, canker, and healthy/non-healthy datasets than the DCNN technique did. Also, the SWO-DCNN method was 3.81%, 8.33%, 8.33%, and 8.73% more sensitive than the DCNN method for black spot, greening, canker, and healthy/non-healthy datasets.

The adaptive threshold of SWO-DCNN is responsible for the technique's superior performance over DCNN in terms of sensitivity, specificity, and FPR. Additionally, this supported the findings of [47], who noted that choosing the right parameters could improve the recognition accuracy rate. According to [48], parameters tuned using the SWO algorithm improved the classification accuracy rate, and the SWO provides more accuracy than the current method. By using parameter selection, [46] were able to attain high classification rates and very high discriminating parameters.

Considering the outcome, the combination of the DCNN and SWO approach improves accuracy, specificity, sensitivity, and FPR for every dataset employed in the research. This suggests that, compared to the current DCNN methodologies, the SWO-DCNN technique produced higher-quality results. Hence, the SWO-DCNN technique did better than the DCNN technique on the measures listed above when it came to finding and classifying citrus diseases.

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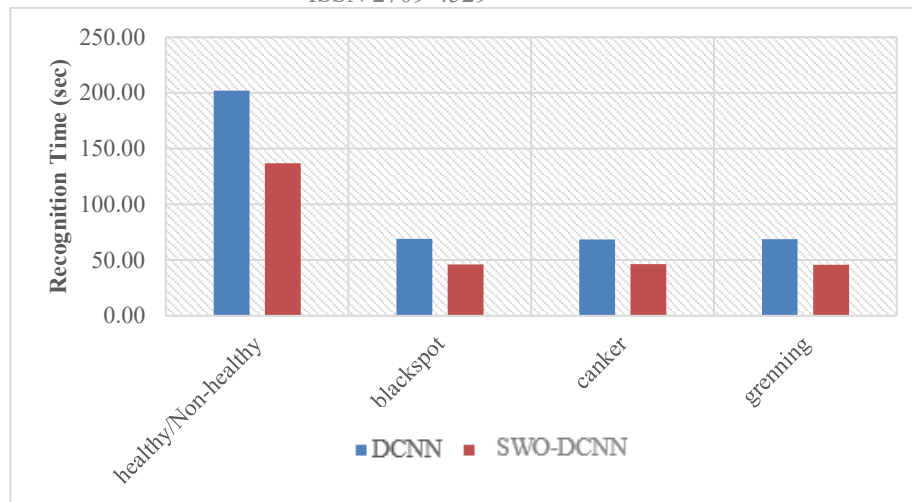


Fig. 3: Comparing the Citrus disease detection and classification system's total recognition time

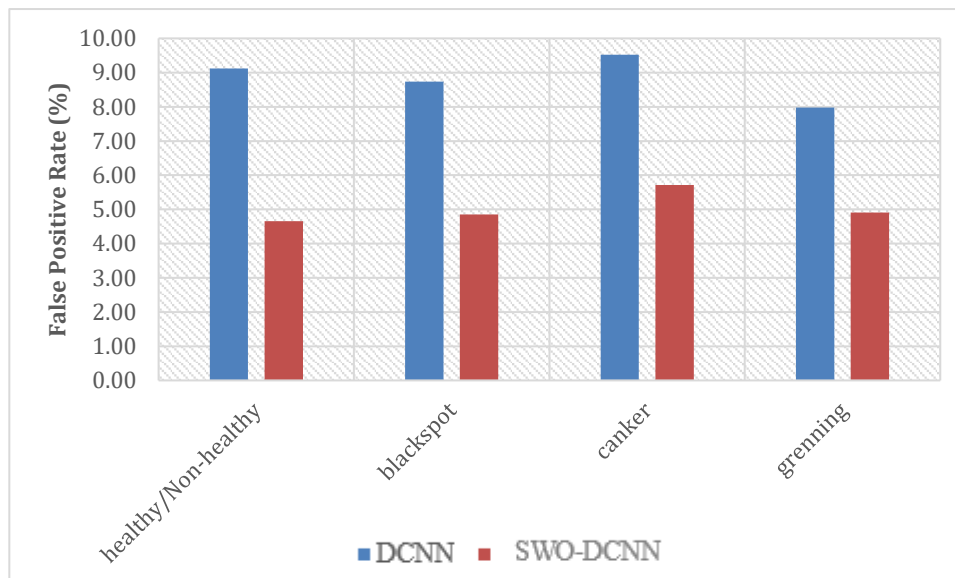


Fig. 4: FPR comparison for citrus disease classification and detection systems

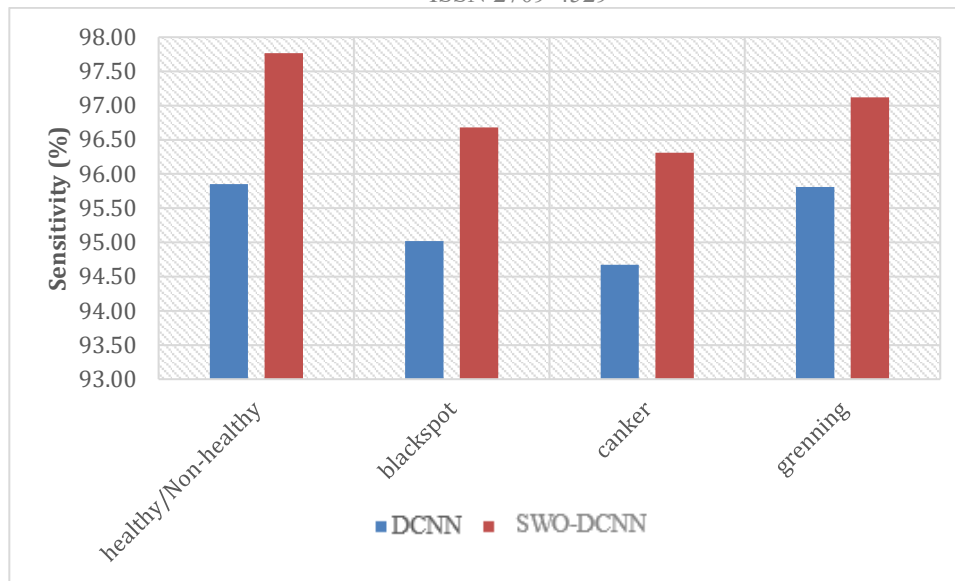


Fig. 5: Sensitivity comparison of citrus disease classification and detection systems

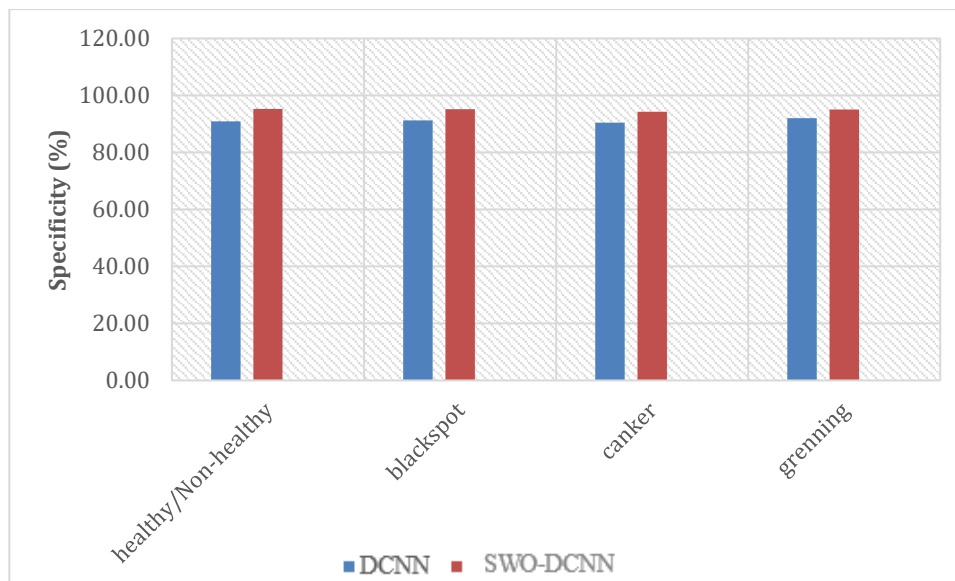


Fig. 6: Comparison of Citrus Disease Detection and Categorization System Specificity

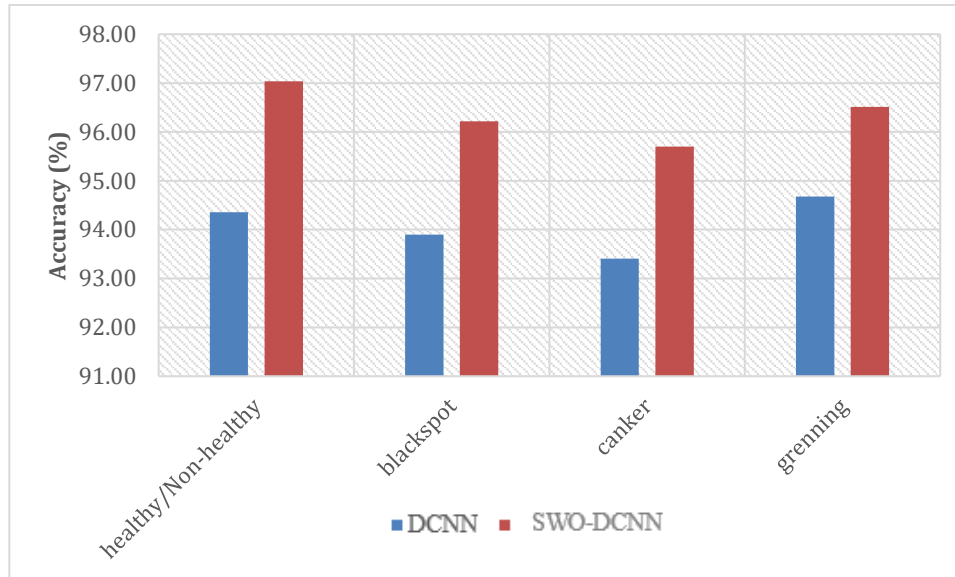


Fig. 7: Comparison of Citrus Disease Detection and Classification System Recognition Accuracy

4.2 Comparative Analysis with Other Optimizers

Additional tests were carried out to evaluate the effectiveness of the proposed Spider Wasp Optimizer (SWO). For these tests, the same DCNN architecture was used along with the following optimizers: Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Bayesian Optimization (BO).

Each optimizer was applied to tune the hyperparameters of the DCNN. The tuned parameters included learning rate, batch size, number of neurons, and weight initialization. The performance was evaluated under identical conditions. It was also performed on the same citrus disease datasets using four metrics: Accuracy, Sensitivity, Specificity, and False Positive Rate (FPR). The result of this analysis is shown in Table 7.

Table 7. Performance Comparison of SWO vs. GA, PSO, and BO

Optimizer	Accuracy (%)	Sensitivity (%)	Specificity (%)	FPR (%)	Avg. Time (s)
SWO-DCNN	97.04	97.77	95.34	4.66	136.86
GA-DCNN	95.23	94.22	92.22	7.78	169.30
PSO-DCNN	95.75	95.21	93.72	6.28	157.64
BO-DCNN	96.14	96.02	94.90	5.10	146.84

The SWO-DCNN outperformed all other optimizers regarding classification accuracy, sensitivity, and FPR, while maintaining a relatively shorter computation time. Bayesian Optimization showed competitive results, but the SWO was more consistent across all performance indicators. Genetic Algorithm had the longest computation time.

These results align with findings by [33], [42], and [47], who noted the superior convergence behavior and adaptability of the SWO in high-dimensional search spaces.

5 Policy and Practical Implications

The integration of the Spider Wasp Optimizer (SWO) with a Deep Convolutional Neural Network (DCNN) for citrus disease classification presents several practical and policy-relevant contributions to precision agriculture and food system resilience.

From a practical standpoint, the proposed SWO-DCNN model provides a fast, accurate, and automated method for detecting major citrus diseases—Citrus Black Spot, Citrus Greening, and Citrus Canker. Early and precise identification of these diseases reduces the need for broad-spectrum pesticide use, lowers production losses, and enhances crop quality. These improvements translate into higher yields and better market access, especially for export-grade citrus fruits where phytosanitary compliance is mandatory. In terms of economic contribution, timely disease detection minimizes crop rejection rates and reduces the financial burden of post-infection treatments. By improving disease surveillance, farmers can reduce yield losses—often estimated at 20–40% in severely infected fields—thus improving profitability. Additionally, the use of AI-based decision support systems reduces reliance on manual labour and expert inspections, enabling scalable disease monitoring in large orchards. This aligns with ongoing efforts to reduce production costs while maintaining high-quality standards in the agri-food supply chain.

The beneficiaries of this model include:

- Smallholder and commercial citrus farmers benefit from reduced losses and higher productivity.
- Agri-tech companies and researchers who can incorporate the SWO-DCNN framework into mobile apps or drone-based surveillance tools.
- Government agencies and policymakers can use technology to inform phytosanitary policies, enhance food security, and ensure compliance with international trade standards.
- Exporters and food processors benefit from improved fruit grading and disease-free produce, ensuring market competitiveness.

From a policy perspective, this research supports digital agriculture transformation policies, such as those articulated by the FAO, African Union, and national agricultural innovation strategies. Integrating AI-optimized disease detection into national agricultural extension programs can enhance decision-making and promote sustainable farming practices. Furthermore, public investment in open-access datasets and infrastructure to deploy such technologies in rural settings would amplify the impact.

6 Limitations of the Study

While the proposed Spider Wasp Optimizer (SWO)–based Deep Convolutional Neural Network (DCNN) model demonstrated high accuracy in detecting citrus diseases, several limitations should be acknowledged:

1. **Model Sensitivity to Image Quality:** The deep learning model's accuracy is dependent on the clarity, resolution, and proper annotation of input images. Images with low resolution, occlusion, or mixed disease symptoms may challenge the classifier's ability to correctly label instances, potentially increasing false positives or negatives.
2. **Limited Disease Categories:** The current model was trained to detect only three citrus diseases—Citrus Black Spot, Citrus Greening, and Citrus Canker—alongside healthy samples. Other prevalent citrus diseases or overlapping conditions were not included, restricting the model's utility for broader diagnostic tasks.
3. **Real-time Deployment Challenges:** The system has not yet been field-tested in real-time scenarios using camera feeds or integrated with agricultural IoT platforms. The current results are based on static image datasets and cross-validation, leaving room for further validation in operational agricultural settings.

7 Conclusion

This research evaluated the essential parameters of the SWO-DCNN technique for a citrus disease detection and classification system. The evaluation of the devised technique included 1,790 images that were divided into four groups: black spot (BS), greening (GS), canker (CCK), and healthy/non-healthy. The created SWO-DCNN was used to train and test these images at varied threshold settings.

The new SWO-DCNN method had better identification accuracy, fewer false positives, higher sensitivity, shorter computation time, and higher specificity in all the tests. This result explains that in terms of accuracy, false positive rate, sensitivity, computational time, and specificity, the developed technique outperformed the other techniques considered in this study. The SWO-DCNN technique can be used to deal with challenges in trying to detect and classify citrus diseases. Based on the results of this study, the following are suggested:

- i. Other feature extraction and fusion algorithms can also be introduced in the future to further examine the system's performance and possibly improve upon the results obtained.
- ii. Aquilla Optimizer algorithm could be hybridized with other high-convergence speed algorithms, such as the Reptile Search Algorithm (RSA), and the Dwarf Mongoose Optimization Algorithm (DMOA).

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Techno-Economic Assessment of Smart Photovoltaic-Water Infrastructure Development for a Residential Community in Peri-Urban Ikorodu, Lagos State, Nigeria

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Abstract: Potable water demand in the peri-urban Lagos State has necessitated the development of strategic combined power and water infrastructure. The techno-economic viability assessment of a smart photovoltaic-water treatment system in peri-urban Ikorodu, Lagos State was effected as an extenuation approach to pervasive insufficient potable water provision under the State's integrated clean water initiatives. An energy technology foresight analysis methodology was used. The study determined an appropriate infrastructural option – a combined 180 kW smart PV, 400 m³/day smart water treatment system requiring 0.65 acres of land and generating 146,000 litres of potable water annually. The smart PV-water plant initiative was considered to have acceptable risk (Payback period between 16.29 to 18.41 years; Return on Investment = 5.43%) and viability at the minimum water price of \$ 2.08/m³. It also had cost savings of \$ 73,000/year relative to the water vendor supply option. The study recommended a reduction in plant operating costs to improve the viability of the smart PV-water treatment system. The study concluded that the smart PV-water treatment system project was technologically attainable, economically viable, and eco-friendly, and consequently recommended its establishment in the study area.

Keywords: Smart photovoltaic-water treatment plant; Urban and regional water planning; South-West Nigeria water infrastructure; Technology and project foresight analysis; Critical power-water infrastructure; Off-grid electric power systems, Mini-grid potable water systems

1.0 Introduction

A modern water supply system is an essential critical infrastructure for a technologically advanced nation. Water is a strategic natural resource for human existence, and water provision is critical to the industrial, agricultural, transport, commercial and housing sectors of the economy [1, 2, 3]. Modern water supply systems are organised as public or privately-owned utilities, and entail drinking water sources, raw water collection locations, water purification facilities, water storage facilities, pumping stations, water distribution systems, and municipal wastewater disposal systems [4, 5, 6]. Improved access to modern water systems has positive implications on the development of people and the economies of their communities; thus, it is imperative for governments to guarantee the provision of this critical infrastructure to their people [6, 7, 8, 9].

Developed States typically showcase advanced water supply systems, with the ability to get drinkable water from any tap on demand [6, 7, 8, 9]. These advanced water supply systems more often than not incorporate smart technologies in enhancing operations for the collection, treatment, distribution, consumption, monitoring, and management of water resources [11, 12, 13, 14]. The advanced water supply system is the desire of developing States; inopportunately, these States exhibit weak water supply systems, lack potable water, and present with limitations of technical inadequacies, restricted financing, uncontrolled population growth, water paucity, environmental contamination, and the unavailability of basic modern, or even advanced, water supply infrastructure [5, 6, 7, 8, 9, 10].

In Lagos State, a sub-national unit of a developing State, Nigeria, a distinguishing feature of the State Development Plan 2052 is the aspiration for a reliable, accessible water supply, and the attainment of advanced municipal water supply infrastructure for sustainable socio-economic development [8, 15, 16, 17]. Lagos State has a daily potable water demand of 2.16 billion litres, yet its public supply system – comprising three major waterworks (Ije, Ishasi, and Adiyen), 27 mini-waterworks, and 10 micro-waterworks – produces only 960 million litres. Just 35% of urban residents receive public water, forcing 65% to depend on informal sources such as wells/boreholes, water vendors, and rainwater [8, 15, 16, 17]. This severe shortfall underscores urgent infrastructure deficits. Public water distribution faces multiple challenges, including pipeline leaks, illegal connections, overuse, and contamination. These issues are worsened by rapid population growth, weak policies, poor infrastructure investment, aging pipelines, climate change, unreliable electricity, and unregulated private wells and boreholes [8, 15, 16, 17].

Lagos State's rapid population growth rate, high urbanization, economic growth, and increase in standard of living have accelerated municipal spatial expansion and advanced new settlements, including the development of peri-urban gated communities with residents in the middle-to-high income bracket.

Lagos State's rapid population growth, intense urbanization, economic expansion, and rising living standards have spurred significant municipal sprawl. This has led to the emergence of new settlements, particularly peri-urban gated communities catering to middle- and high-income residents [18, 19, 20, 21]. These communities' potable water demand further outstrips the municipal water supply, and their residents heavily rely on the previously identified private water sources, which more often than not, are procured at exorbitant rates [22, 23]. The limitations in public critical infrastructure investments foster water utility deficiencies which are projected to fester into the foreseeable future [24].

Specific State efforts for the mitigation of the water utility limitations include formulating, instituting and establishing policy reform and infrastructural development measures – the Lagos Water Supply Master Plan (2011), the Lagos State Water Supply Project (LSWSP), the Lagos State Water Regulatory Commission, and the various State water supply schemes [6, 9, 17, 28, 29, 30]. These measures are aspired to rehabilitate existing and institute new infrastructural projects for increased access to and improved efficiency of the public water supplies, regulate water vendors and other private water system providers, and provide a safe and improved water supply through strategic smart infrastructure development [10, 16, 29, 30, 31]. Existing research on Lagos State's potable water challenges highlights the government's efforts to integrate off-grid solutions into its energy and water policies [8, 16, 17, 24]. Key issues identified include inadequate piped water coverage, risks of groundwater contamination, and limited private sector involvement. Proposed solutions range from off-grid desalination projects to community-based initiatives [8, 15, 17, 24].

The strategic domestic water infrastructure development planning entails targets of 3.12 billion litres/day and US\$ 13 billion in critical investments by 2035, with focus on substantial devolved public and private sector investments (technological and financial) in innovative urban water supply initiatives such as the smart solar powered municipal water infrastructure [24, 25, 26, 28, 29, 30, 31]. A pre-investment assessment of private-public partnership (PPP) in municipal utility infrastructure development has indicated community willingness to pay for water at a reasonable rate [24, 32, 33].

The smart photovoltaic-municipal water infrastructure is a dual smart-technology system – an intelligent water infrastructure powered by a smart photovoltaic system [34, 35, 36, 37]. The configuration is a self-sufficient off-grid structure that supplies electricity to a localized municipal water system for a restricted group of customers, and helps minimize the electricity and water consumption with more efficient and cost-effective monitoring networks [34, 35, 36, 37].

According to EMSD [38], Enhar [39], City Energy [40], Singh and Ahmed [41], Tuser [42], Antzoulatos *et al.*, [43], and Global Water Center [44], the smart photovoltaic-municipal water infrastructure uses inverters, sensors, automated controls, and smart meters to provide real-time data on the energy-water systems. The further reported that the inverters, operational as system intelligence, convert the PV panel DC output to AC; printed circuit board (PCB) designs enable power storage in batteries for when there is no sunlight; Internet of Things (IoT)-enabled sensors measure physical parameters and detect leaks, water losses and system inefficiencies; smart meters track PV power system energy use and water system consumption trends; automated controls control enable remote system operations, maximizing energy production and efficient water distribution. In addition, mobile apps/web portals facilitate billing systems, as well as power and water quality monitoring and control; wireless communication networks connect components and cloud platforms for centralized data storage; and data analytics empowers consumption patterns projections and operations optimization, so as to ensure instantaneous cost-effective sustainable water usage, reliable water quality assurance, and optimum waste reduction.

This infrastructure is considered appropriate intervention technology due to the abundance and reliability of sunlight in Lagos State [45], the equipment's relative affordability, environmental friendliness, and significant potential for employment and wealth creation [38, 39, 40].

Inopportunately, the State reform efforts and water infrastructure development planning schemes have been ineffectual due to the limitations in state and private actor capabilities to adequately execute a robust techno-economic assessment of the critical PV-water infrastructure initiative, which is essential for planning and operation [45, 46]. Consequently, it is imperative to provide this strategic assessment of the smart PV-water infrastructure initiative as a vital policy intervention for the peri-urban residential gated communities in Lagos State.

In this study, a techno-economic assessment of the proposed smart PV-water infrastructure was executed using appropriate engineering project management methods. The specific objectives were to assess the water consumption in a selected residential area; determine the technological specifications for the proposed smart PV-water system; ascertain its techno-economic viability; and examine potential techno-economic, environmental, and policy benefits consequent to its successful deployment.

The study is significant as it provides critical policy intelligence on a novel smart PV-water supply system for Lagos State.

The remainder of this paper is organized as follows: Section 2.0 provides the methodology and materials used in the study, while Section 3.0 presents the results and discussion. Conclusions and recommendations are presented in Section 4.0.

2.0 Materials and Methods

The study utilised an energy technology foresight analysis (ETFA) framework. This framework is a systematic, participatory process encompassing intelligence gathering for informed decision-making vital to the advancement of a desired energy future. Methods are of three natures: Quantitative, Semi-quantitative, and Qualitative, and entail extrapolation, Delphi Techniques, and Strategic assessments, which may be deployed independently or interactively [47, 48, 49, 50, 51].

2.1 Location of Study Area

According to Cityscape [52] and NigeriaGalleria [53], Ikorodu is a city located in north-east Lagos State, Nigeria. The Lagos Lagoon bounds the municipality to the south, Ogun State to the north, and Epe Division to the east. The city (Population: 1 million) is the 12th largest in the country, while its Local Government Area is the second largest in the State. Ikorodu is the fastest growing part-exurb of the Lagos metropolis, consequent to ever-increasing inflow of people from neighbouring areas attracted by its proximity to Lagos, approximately 37 km away, and separated by only the Lagos Lagoon. Ikorodu has significant industrial activities comprising farming, manufacturing, and trading. Ikorodu

comprises many public primary and secondary schools and two tertiary institution – Caleb University and Lagos State University of Science and Technology.

Ikorodu was purposefully chosen for the study because of the significant number of new peri-urban, government-approved, middle-to-high-income, gated communities for the ever-growing city population. Specifically, a proposed Public-Private Partnership (PPP)-based middle-income, gated community, with 155 3-bedroom semi-detached buildings, was purposively selected for the study. Residents in the housing estate will be predominantly middle-income, well-educated (Master's degree or equivalent professional qualification) and have an average of 3 children per family.

2.2 Assessment of Potable Water Consumption in the Selected Gated Community

This section determined potable water consumption in the gated community in peri-urban Ikorodu, Lagos State.

2.2.1 Determination of the population in the selected gated community

Estate Population = Number of Residents per Building X Number of Buildings X 2

...Eqn. 1

2.2.2 Determination of potable water needs in the gated community

Estate Water Needs = Estimated Annual Water Demand X Estimated Water Reserves or Slack ...Eqn. 2

Assuming daily domestic water consumption per capita of 150 Litres [24, 54],

a) *Daily Estate Water Demand = Estate Population X 150L per capita* ...Eqn. 3

b) *Monthly Estate Water Demand = (a) X 30 days per month* ...Eqn. 4

c) *Annual Estate Water Demand = (a) X 365 days per year* ...Eqn. 5

d) *Estimated Water Reserves or Slack:*

i. *Daily Extra Water Supply per Residence = 50 L [24]* ...Eqn. 5

ii. *Daily Extra Water Provision in Estate =*

(i) X Total Number of Residences ...Eqn. 6

iii. *Monthly Extra Water Supply in Estate = (ii) X 30 Days* ...Eqn. 7

iv. *Total Monthly Water Supply to the Estate =*

Monthly Estate Water Demand + Monthly Extra Water Supply in Estate...Eqn. 8

It is assumed that the initial pumping of water into the Estate's water supply system would have a slack of 5 days.

Thus,

Projected Water Reserves for 5 Days =

Daily Estate Water Demand + Daily Estate Extra Water Supply) X 5 Days ...Eqn. 9

2.3 Determination of Technological Specifications for the Proposed Smart PV-Water Treatment System

The technological specifications entail determining the sizes of the water treatment plant and the smart PV system to meet the electric power demand of the water plant.

2.3.1 Estimated daily water demand for water treatment plant design

$$= \frac{\text{Total monthly water demand in estate L/days}}{30 \text{ days}} \quad \dots \text{Eqn. 11}$$

2.3.2 Design specification for smart water treatment plant (SWTP)

Assuming the water treatment plant operates at 75% efficiency,

$$\text{SWTP design specification definition} = \frac{\text{Estimated daily water demand}}{0.75} \quad \dots \text{Eqn. 12}$$

2.3.3 Determining the size of the corresponding smart PV System

Assuming a moderate energy efficient system with electricity requirement of approximately 4 kWh/m³ and operational time of 15 hours/day [24]

$$a. \text{ Daily energy demand} = \text{daily water demand} \times \text{electricity requirement} \quad \dots \text{Eqn. 13}$$

$$b. \text{ Power Load Demand} = \frac{\text{Daily energy demand}}{\text{power system operational time}} \quad \dots \text{Eqn. 14}$$

Assuming the power plant operates at 75% efficiency,

$$c. \text{ Power Plant Sizing} = \frac{\text{Power Load Demand}}{0.75} \quad \dots \text{Eqn. 15}$$

2.3.4 Determination of land area for the smart PV-water treatment system

- (a) For the Smart PV Power Plant:

Basic panel area is measured at 9 m²/kW [45]

Added Infrastructure at 15% of basic panel area = Basic panel area $\times$ 1.15
 $\dots \text{Eqn. 16}$

- (b) For the Smart Water Treatment Plant:

Basic plant area estimated at 1.54 m²/m³ [24]

Added Infrastructure at 25% of basic plant area = Basic plant area $\times$ 1.25

$\dots \text{Eqn. 17}$

$$\text{Total Land Area for Smart PV-Water Treatment System} = (a) + (b) \quad \dots \text{Eqn. 18}$$

2.4 Techno-Economic Specifications for the Smart PV-Water Treatment System

The techno-economic analysis of the smart PV-water treatment system entailed estimating the total initial investment (sum of capital costs and cash-in-hand) and the total annual operating costs and evaluating the system's economic viability using appropriate techniques. The capital costs include costs for the smart PV-water treatment system, the ancillary buildings and facilities, and the land. The cash-in-hand is equivalent to the total operating costs for one year. The total annual operating costs include costs for labour, energy, materials, depreciation, and other costs) [45, 46, 55, 56, 57, 58].

A project financial management template specifying the proportion of each cost article comparative to the total initial investment and annual operating costs was established based on data from technical reports, expert opinion, manufacturers' and equipment vendors' price lists, local water vendors' rates, and project financial analysis reports [55, 56, 57, 58]. This template was substantiated by engineering project financial management specialists under the Nigerian Society of Chemical Engineers and the Nigerian Society of Engineers (Obafemi Awolowo University, Ile-Ife, branches). Project economic viability analysis entailed determining the levelised costs of water and the Net Present Value (NPV), Payback Period, and Return on Investment of the project [55, 56, 57, 58].

2.5.1 Determination of the initial investment (fixed capital and cash-in-hand)

- i. The water treatment plant cost was determined from the conversion factor detailing average costs for a smart unit at \$ 8.22/m³ [45], entailing the following costs:
 - a. Design and engineering @ 15%
 - b. Equipment and materials @ 50%
 - c. Construction and installation @ 20%
 - d. Smart Features (IoT/Automation) @ 15%
- ii. The power plant cost was determined from the conversion factor detailing average costs for a smart PV system at \$ 1.60/W [45], entailing the following costs:
 - a. Solar panels @ \$ 0.30/W

- b. Inverters @ \$ 0.15/W
 - c. Mounting Structures @ \$ 0.10/W
 - d. Battery @ \$300/kWh
 - e. Balance of systems @ \$ 0.15/W
 - f. Installation and Labour @ \$ 0.30/W
 - g. Smart system integration @ \$ 15,000.00
 - h. Other costs @ \$ 15,000.00
- iii. Land costs were estimated from the cost of residential land in Ikorodu-Lagos at determined \$ 1,510.00 per plot, with 6 plots equivalent to an acre of land [59].
- iv. Costs of ancillary structures (the buildings and facilities) were estimated at 10% of the costs of the smart water treatment plant. This estimate was premised on engineering economics and project management experts' advice.
- v. Cash-in-hand is a working capital type necessary to meet extant, short-term obligations [47, 48]. The cash-in-hand was estimated to be equivalent to the first year's annual operating costs, premised on expert opinion.

2.5.2 Determination of the total annual operating costs

The total annual operating costs, comprising preliminary operating costs and depreciation, were calculated using a determined financial template.

- i. Preliminary operating costs were estimated using the equation:

$$\text{Preliminary Annual Operating Costs} = 10\% \text{ of the Smart PV-Water treatment plant Capital Cost} \quad \dots \text{Eqn. 19}$$

The annual operating costs template, as developed for this study [46, 56, 57, 58]:

Costs	(%)
Depreciation (2.1%)	28.55
Labour	25.50
Energy	18.10
Materials	18.02
Other costs (insurance, taxes, etc)	9.83
<i>Total Operating Costs (Annual)</i>	<i>100</i>

- ii. Depreciation was analysed using the Straight-Line method [55, 57, 58]. The salvage value for the Smart PV-Water Treatment System as well as the administrative buildings and facilities, was assumed at 10% of their initial investment based on engineering project management specialists' recommendations.

$$\text{Salvage Value} = 10\% \text{ of Initial Investment} \quad \dots \text{Eqn. 20}$$

$$\text{Annual Depreciation} = \frac{\text{Initial Investment} - \text{Salvage Value}}{\text{Number of Years}} \quad \dots \text{Eqn. 21}$$

$$\text{Annual Depreciation (\%)} = \frac{\text{Annual depreciation}}{\text{Initial Investment}} \times 100\% \quad \dots \text{Eqn. 22}$$

2.5.3 Determination of levelized cost of the smart PV-water treatment system

The levelized cost of the potable water from the smart PV-water treatment system is the net cost of installing the smart system divided by its expected lifetime potable water output. Basically, it estimates the minimum unit price of potable water needed to break even over its expected lifetime [55, 57, 58].

Levelized Cost of Potable Water Production

$$= \frac{\text{sum of costs over lifetime}}{\text{sum of potable water produced over lifetime}} \quad \dots \text{Eqn. 23}$$

OR

$$= \frac{\text{Initial investment} + \text{Lifetime Operations costs}}{\text{potable water produced/year} \times \text{Project lifespan}} \quad \dots \text{Eqn. 24}$$

The time value of the annual operating costs was assumed to be constant over the project's 25-year lifespan, equal to its costs at Year 1 [55, 57, 58].

Accordingly,

$$\text{Total value of project lifecycle operating costs} = 25 \text{ years} \times \text{First year costs} \quad \dots \text{Eqn. 25}$$

The Present value of a future sum of money is estimated by discounting it at a preferred compound interest rate [55, 57, 58]:

$$\text{Present Value (PV)} = F(P/F, I, N) \quad \dots \text{Eqn. 26}$$

Where,

F = future cash flow, and

(P/F, I, N) = the discounting factor for calculating the time value of money [55, 57, 58].

The Interest Rate (I) of 30% is Nigeria's commercial loan interest rate as determined by the Central Bank of Nigeria (CBN) as of November 30, 2024. The number of years (N) is 1 year.

2.5.4 Determination of the estimated minimum annual revenue for the potable water initiative

With the levelised cost of potable water calculated, and the extant price of vendor purchased water determined, the preferred price per unit of potable water for this study was assumed as the midpoint between these costs.

Consequently, the minimum annual revenue for the potable water initiative to justify it as a going concern is [55, 57, 58]:

$$\text{Minimum annual revenue} = \text{annual potable water production} \times \text{price per unit} \quad \dots \text{Eqn. 27}$$

2.5.5 Determination of Net Present Value, Payback Period, and Return on Investment for the potable water initiative

- i. The Net Present Value (NPV) is a financial metric for evaluating an investment's viability (or otherwise). An investment is considered viable if the NPV is greater than or equal to zero [55, 57, 58].

Net Present Value (NPV)

$$= \text{Total Annual Revenues discounted to the Present} - \text{Total Annual Costs discounted to the Present} \quad \dots \text{Eqn. 28}$$

- ii. The Payback Period depicts the minimum time required for an investment to pay for itself. Shorter payback periods indicate an investment's attractiveness, principally with respect to risk; consequently, the payback period is a veritable tool in project planning and risk assessment [55, 57, 58].

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Annualized expected cash inflow}} \quad \dots \text{Eqn. 29}$$

- iii. The Return on Investment (ROI) is a financial performance metric used for evaluating investment profitability or efficiency. The ROI, presented in percentages, measures an investment's returns relative to its costs. The ROI is also used as a veritable tool in project planning and risk assessment [55, 57, 58].

$$\text{Annual Return on Investment (ROI)} = \frac{\text{Annual Net Profit}}{\text{Initial Investment}} \times 100 \% \dots \text{Eqn. 30}$$

2.6 Analytical Tools

The study adopted an Energy Technology Foresight Analysis (ETFA) framework as its methodological foundation. For Section 2.2 (Assessment of Potable Water Consumption in the Selected Gated Community), the analysis employed industrial process calculation methodologies. Section 2.3 (Determination of Technological Specifications for the Proposed Smart PV-Water Treatment System) incorporated comprehensive plant design calculations. Section 2.4 (Techno-Economic Specifications of the Smart PV-Water Treatment System) utilised engineering economic analysis techniques, including Straight-Line Depreciation, Net Present Value analysis, Levelized Cost of Water (LCoW) technique, Payback Period and Return on Investment assessments, complemented by descriptive statistics for robust financial evaluation.

3.0 Results and Discussions

This section presents the key findings of the research and their interpretation.

3.1 Potable Water Consumption Estimates for the Gated Community

The gated community's population was estimated at 1,550 residents. The community demonstrated a calculated monthly water demand of 6.98 million litres plus 1.70 million litres reserve capacity, yielding a total monthly demand of 8.68 million litres. This equates to 289.33 thousand litres/day (186.67 litres/capita/day) – the assumed benchmark for the PV-water treatment system design. These specifications exceed Nigeria's (20-50 litres) and EU's (50-150 litres) norms but remain below US standards (300-380 litres) [24]. The elevated planning and design parameters are not considered inappropriate as they account for Nigeria's endemic potable water scarcity and municipal water infrastructure failures, necessitating robust storage capacities across built environments.

Table 1: Potable Water Consumption Estimates for the Gated Community in Ikorodu, Lagos State

S/N	Technological Specification	Quantity
1.	Population of Gated Community	1550 people
2.	Domestic Water Needs of Gated Community:	
	a. Daily water demand	
	b. Monthly water demand	232,500 Litres (232.5 m ³)
	c. Annual water demand	6,975,000 L (6,975 m ³)
	d. Monthly water reserve/slack	84,862,500 L (84,862.5 m ³)
	e. Total Monthly Water Needs	1,705,000 L (1,705 m ³) 8,680,000 L (8,680 m ³)
3.	Daily water demand for smart water treatment plant design specification	289,333.33 L (289.3 m ³)
4.	Daily water demand per capita in the Gated Community	186.67 L (0.1867 m ³)

3.2 Technological Specifications for the Smart PV-Water Treatment System

The smart water treatment plant was designed for a nominal capacity of 400 m³/day operating at 75% efficiency (Table 2). System analysis revealed an associated daily electricity demand of 1,600 kWh. Given the planned 15-hour daily operation window, this translates to a required pump power load of 106.67 kW. To meet this demand at 75% conversion efficiency, the photovoltaic system was sized at 177.77 kW (approximated to 180 kW). The integrated PV-water treatment system requires an estimated 0.65 acres (2,631 m²) of land area for installation.

From a technology foresight perspective, the derived technical specifications provide robust foundations for strategic planning of potable water initiatives throughout Nigeria's South-West geopolitical zone, particularly within the Greater Lagos Metropolitan Area. These calculations align with three critical frameworks: (i) regional development priorities, (ii) national water infrastructure agendas, and (iii) the United Nations Sustainable Development Goal 6 (Clean Water and Sanitation). The quantified parameters enable evidence-based decision-making for sustainable water infrastructure deployment across the region.

Table 2: Technological Specifications for the Smart PV-Water Treatment System

S/N	Technological Specification	Quantity
1.	Design specification of a smart water treatment plant assuming 75% efficiency.	386 m ³ /day (approximated to 400 m ³ /day)
2.	Domestic Electricity/Power Supply Demand for the Smart Water Treatment System	
	a. Daily electricity demand for the smart treatment plant @ 4kWh/m ³	1600 kWh/day
	b. Average power load of installed pumps required for 15 hrs/day operations	106.67 kW
3.	Design specification of a smart PV power plant for a water treatment system, assuming 75% efficiency	177.77 kW (approximated to 180 kW)
4.	Land Area for Smart PV-Water Treatment System:	
	a. Smart PV plant (basic panel area + accessories)	1,863 m ² (0.46 acres, 2.76 plots)
	b. Smart water treatment plant (basic area + accessories)	768.75 m ² (0.19 acres, 1.14 plots)
	c. Total land area	2,631.75 m ² (0.65 acres, 3.9 plots) (Approximated to 4 plots)

3.3 Techno-economic Analysis of the Smart PV-Water Treatment System

The smart PV-water treatment system requires a total investment of \$1.83 million, consisting of \$1.63 million in capital expenditures and \$204.2 in available cash reserves. Annual operating costs are projected at \$204.2 thousand, with the most significant expenses being plant and building depreciation (\$58,320) and labour (\$52,080) (Table 3). The levelized water production cost was \$1.58/m³, which is \$1.00/m³ lower than the prevailing rate of \$2.58/m³ in Ikorodu, Lagos. By implementing a consumer price for water at \$2.08/m³, a profit margin of \$0.50/m³ can be achieved, resulting in estimated annual revenue and profit of \$303,680 and \$99,440, respectively, based on an annual production volume of 146,000 m³. Project financial viability is further supported by a positive Net Present Value (NPV) of \$1,834,414.80 over the 25-year lifespan, a payback period ranging between 16.29 and 18.41 years, and a Return on Investment (ROI) of 5.43%, all of which indicate manageable risk. The techno-economic analysis confirms that the smart PV-water treatment system can sustainably supply potable water to the peri-urban gated community in Ikorodu, Lagos, at \$2.08/m³, balancing cost-competitive pricing, managed financial risk, and strong long-term viability. The implementation of the project is technically and economically justifiable and therefore recommended for execution.

Table 3: Techno-Economic Assessment of the Smart PV-Water Treatment System

Costs	(US\$)
<i>Capital Costs</i>	
400 m ³ /day Smart Water Treatment Plant	
180 kW Smart PV System	1,200,000.00
Land	300,000.00
Administrative Building + Facilities	6,040.00
Cash-in-Hand	120,000.00
<i>Total Investment</i>	204,240.00
	1,830,280.00
<i>Operations Costs (Annual)</i>	
Depreciation	58,320.00
Labour	52,080.00
Energy	36,960.00
Materials	36,810.00
Other costs	20,070.00
<i>Total Operating Costs (Annual)</i>	204,240.00
Annual Water Production	
Salvage value of Smart PV-Water System	146,000 m ³
Levelized cost of Water	\$ 304,425.00
Extant price of Water in 25-Litre kegs in Ikorodu	\$ 1.58/m ³
Estimated selling price of Water	\$ 2.58/m ³
Profit margin	\$ 2.08/m ³
Estimated Annual Revenues	\$ 0.50/m ³
Estimated Annual Profits	\$303,680.00
Net Present Value (NPV)	\$ 99,440.00
Payback Period	\$ 1,834,414.80
Annual Return on Investment	16.29 – 18.41 years
	5.43%

3.4 Socio-economic Benefits of the Smart PV-Water Treatment System in peri-urban Ikorodu, Lagos State

The water supply infrastructure in Lagos State remains critically inadequate, forcing residents to depend on alternative sources such as water vendors and private wells/boreholes for domestic needs. Research by Ogundari [24] confirms that households currently pay approximately \$2.58/m³ for vended water. This study's analysis reveals that a proposed smart PV-water treatment system could produce water at a significantly lower levelized cost of \$1.58/m³ – 38.8% cheaper than current vendor prices – demonstrating strong market potential. Even when priced at \$2.08/m³ to ensure project viability, the system would still undercut vendor rates by 19.4%. Implementation would yield substantial economic benefits, including annual savings of \$73,000 for Ikorodu's gated community residents (Table 4), while simultaneously providing reliable access to clean water. Beyond cost advantages, the system would address critical public health needs through guaranteed water quality, representing economic and social improvement over existing water supply solutions.

Table 4: Comparative Costs of Water Consumption: Water Vendor vs Smart PV-Water System

Source of Water	Water Consumption (m ³ /Year)	Cost of Water (\$/m ³)	Total Costs/Yr (\$)
Water Vendor	146,000	2.58	376,680.00
Smart PV-Water System	146,000	2.08	303,680.00
Savings		0.50	73,000.00

4.0 Conclusion and Recommendation

This study evaluated the techno-economic feasibility of implementing a smart PV-powered water treatment system to address potable water needs in Ikorodu, a peri-urban region of Lagos State, as a strategic input to domestic clean water development in Nigeria. Using Energy Technology Foresight Analysis, the research examined water demand, patterns, technical requirements, and economic factors to determine an optimal configuration: a hybrid 180 kW PV system, coupled with a 400 m³/day water treatment plant requiring 0.65 acres of land. The proposed system could produce 146,000 m³ of clean water annually while demonstrating financial viability at a competitive price of \$2.08/m³ –offering \$73,000 in annual savings compared to existing water vending alternatives. While the project shows promising technological feasibility, environmental benefits, and acceptable risk levels (with a 5.43% ROI and 16–18-year payback period), the study suggests enhanced viability further by reducing operational costs, particularly the substantial 30% bank interest rate. The findings strongly support implementing this sustainable water solution in the target community as it effectively combines technical achievability, economic sustainability, and ecological advantages.

Future efforts should prioritize expanding the smart PV-water treatment system to other underserved communities, adapting designs to local conditions through feasibility studies. Research should investigate integrating IoT-based smart water grids and hybrid renewable energy systems to boost reliability. Policy development must focus on creating supportive frameworks and financing mechanisms to enable wider adoption. Long-term monitoring should assess environmental and economic impacts while optimizing costs through innovative financing and scaled deployment. Successful implementation will require community education programs and local technician training to ensure sustainable operation. These combined technical, policy, and social interventions will help scale this sustainable water solution across Lagos State and Nigeria.

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A Proposed Framework for the Adoption of the Fourth Industrial Revolution Technologies in Municipal Water Governance in South Africa

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Abstract—The Sustainable Development Goal 6 (SDG 6), which focuses on ensuring universal access to water for all, remains at the center of the sustainable development agenda; however, its realisation continues to be hindered by the persistent water governance challenges. This is particularly concerning given the critical role that effective governance plays in addressing the global water crisis. The advent of the Fourth Industrial Revolution (4IR) technologies offers transformative potential to strengthen municipal water governance systems. Yet, the adoption and implementation of these technologies, especially within South African district municipalities, has been notably slow. Using a selected district municipality in the Eastern Cape in South Africa, the paper aims to develop a framework to facilitate the adoption of 4IR technologies in municipal water governance. Adopting a qualitative research approach, the study purposively selected participants from the municipal officials, stakeholders, and experts who provided insights into the challenges and opportunities associated with 4IR adoption. Data was collected through semi-structured interviews and analysed thematically. The findings reveal a slow uptake of 4IR innovations, underpinned by capacity, infrastructure, and policy gaps. The paper, therefore, proposes a contextually grounded framework designed to guide and accelerate digital transformation within rural municipalities. Thus, the framework provides a roadmap and direction in accelerating the integration of 4IR technologies to strengthen municipal water governance, foster inclusive technological advancement, and ensure that rural communities are not excluded from the benefits of digital innovation. The paper, therefore, underscores the urgency of this shift by highlighting that the 4IR is rapidly transforming all sectors. Consequently, the failure of district municipalities serving both urban, semi-urban, and rural areas to adopt 4IR technologies risk deepening existing disparities and leaving rural municipalities further behind.

Keywords—Fourth Industrial Revolution, Water Governance, Sustainable Development Goal 6, Municipal, Innovation, South Africa

1 Introduction

The 2024 report on the Sustainable Development Goals (SDGs) for water and sanitation reveals that access to properly managed drinking water has risen from 69% to 73%, while access to sanitation has risen from 49% to 57% [55]. Notwithstanding this rise, the report additionally indicates that as of 2022, populations of 2.2 billion and 3.5 billion continue to lack these fundamental services [54]. Similarly, ref [16] opines that nearly 30% of humanity still lacks access to safely accessible, affordable, and reliable water services. Likewise, the United Nations [54] extended report on SDGs recorded that information gaps exist concerning water quality data [56]. The report recorded a decline in water quality where data was available, and where it was absent, it reported the challenges posed by the situation in ensuring proactive measures [56]. Furthermore, the National Water Security Report of 2023 reported on the challenges in ensuring effective governance, highlighting issues such as poor coordination, inadequacy in funding, and deficiencies in institutional and professional capacity, which all threaten water security [34].

The above information renders achieving Sustainable Development Goal 6 by 2030 nearly unfeasible. The claim corresponds with the [64] and the 2023 SDG Synthesis report on water and sanitation, which recorded that attaining the SDGs for water and sanitation necessitates a sixfold enhancement in the existing progress rates for safely managed drinking water and a fivefold enhancement for properly managed sanitation for these goals to be achieved by 2030 [57]). Likewise, [59] contend that the SDGs will not be met in the original time frame due to issues of global crises such as COVID-19, governance impairments, financial gaps, and other SDGs that require a more extended time frame to be achieved.

South Africa is not immune to the above situation, but rather a reflection of the above statistics, where access to basic water remains challenging. The 2022 reports by the Department of Water and Sanitation and Statistics South Africa [1] reflect that despite a significant increase in access to water (from 61.7% in 2002 to 88.7% in 2021) due to water reforms and deployed water strategies, a significant population (3.4 million households) still lacks access to freshwater resources. To this end, two decades later, the institutional reforms and policy developments remain a work in progress [15].

While the situation above indeed can be intensified by external pressures such as climate change, urbanization, and population increase, this paper argues that the fundamental issue resides in governance challenges [57],[16],[1], underscoring the essentiality of the concept in addressing water challenges [23]. Nevertheless, the importance of governance is undermined as the concept continues to persist as a considerable impediment, as noted by [3] and [49], who observed that the water crisis remains a governance crisis.

However, this paper concedes that without adequate political, administrative, and policy frameworks to direct decision-making, advancements in attaining water-related objectives, such as SDG 6, would remain inadequate as they will fail to withstand external constraints [15],[16]. Governance problems, therefore, frequently obstruct the fair and effective administration of water resources, undermining the promise of access to water for all [1], [35].

Given this background, it is undeniable that effective water governance is crucial for addressing water-related complexities by guaranteeing efficiency, effectiveness, equity, and sustainability in the utilization and distribution of limited resources at the local level [24],[3]. The claim is essential, particularly in the 21st century, characterized by the prevalence of natural disasters such as climate change and droughts [35]. Additionally, this perspective holds considerable importance in developing nations such as South Africa, particularly for rural water service authorities, which inherently possess unique contextual backgrounds characterized by elevated poverty and unemployment rates [22].

The preceding argument underscores the importance of effective water governance as a crucial solution to global water concerns. However, despite the broad acknowledgement of the concept of water governance, water-related problems continue to persist (Organisation for Economic Co-operation and Development (OECD) 2011 and 2021 as cited by [3], underscoring the necessity for a transformation in municipal water governance and a change in the approach to how water challenges have been addressed.

The above claim aligns with [59] observations that there is still hope amidst all these challenges being faced in the efforts to achieve the SDGs, as technological advancements have brought new solutions to the forefront with low-cost digital technologies, even having the power to assist the poor and marginalized. This paradigm shift entails moving from traditional to digital water governance, which includes leveraging innovative strategies such as the Fourth Industrial Revolution technologies for effective water governance [57]. Thus, the emergence of the

Fourth Industrial Revolution (4IR) offers novel solutions for water-related concerns [43],[11] indicating an urgent need for innovative strategies.

Nevertheless, there has been a slow adoption of the 4IR technologies to enhance water governance in municipalities despite their promises and potential opportunities in addressing water governance challenges [63], [46], [12]. Similarly, the Bonn Dialogue for Results (2021), as cited by [57], asserts that while many innovations exist, deployment, implementation, and upscaling challenges remain prevalent.

To this end, this paper noted a dearth of literature concerning water governance and 4IR frameworks that municipalities can use as roadmaps when adopting and implementing the fourth industrial revolution technologies to enhance their water governance. This paper, therefore, provides a foundation and guideline for adopting 4IR technologies in municipal water governance through the proposed framework. Using the OR Tambo District Municipality (ORTDM), Eastern Cape in South Africa as a case study, the framework is designed particularly for district municipalities, especially those serving rural areas with distinct contextual problems.

The proposed framework offers a foundational approach for municipalities such as ORTDM that lack strategic roadmaps to direct the transformation in their water governance. Thus, the framework seeks to assist rural water authorities in adopting Fourth Industrial Revolution technologies to harness the potential benefits offered by the 4IR era, ensure that they are not left behind as they enhance their water governance, improve their service delivery, and work towards the achievement of the SDGs (Goal 6) targets for 2030.

2 Literature Review

2.1 Defining Water Governance

The concept of water governance has been widely debated in the literature, with scholars approaching it from various theoretical and practical lenses [24]. Some view it as a technical and administrative tool for implementing water policy, while others emphasize its democratic and political dimensions involving participation and accountability (Castro, 2007; Woodhouse & Muller, 2017, as cited by [49]). Although definitions vary from focusing on institutional arrangements and decision-making processes to actor networks and power dynamics, the literature converges on the understanding that water governance involves how decisions about water are made, who participates in those decisions, and the mechanisms that guide access and distribution, as cited by [49] and [24].

The above varied perspectives show water governance's contested nature, ranging from technical administration to deeply political processes. To this end, this paper understands water governance to encompass the social aspects of water-related issues, including decision-making regarding water scarcity, flooding, and pollution [57]. The paper further views the concepts to encompass the inputs (e.g., stakeholder engagement), processes (e.g., decision-making mechanisms), and outputs (e.g., transparency, efficiency, and equity), which collectively address the “who”, “what”, “why,” and “how” of water management [3]. Being at the forefront of the water crisis, this paper argues that improving water governance requires urgent attention, underscoring the need to integrate Fourth Industrial Revolution (4IR) technologies to enhance water governance.

2.2 Defining the Fourth Industrial Revolution

The Fourth Industrial Revolution is characterized by the convergence of technological breakthroughs with the physical, biological, and digital systems converging, resulting in new lifestyles and integrated workflows [37]. The revolution encompasses various novel technologies, innovative forms of economic interconnectivity with digitalization, and information and communication technology (ICT), which are crucial components of 4IR developments [4]. Furthermore, the 4IR encompasses automation, intelligent systems, and data-informed decision-making [21]. Similarly, [14] contend that 4IR represents a new era of cyber-physical systems beyond mere automation. The 4IR era is therefore expected to have a stronger and wider impact on the economy and communities [37]. Thus, these disruptive technologies reduce distances, break down barriers, and connect people worldwide, thus enhancing global integration and deepening interconnectedness. As a result, essential services like water, energy, healthcare, education, and the economy are increasingly digitized and reliant on 4IR technologies [38].

2.3 Leveraging the Fourth Industrial Revolution to enhance water governance

Literature indicates that various Fourth Industrial Revolution technologies may be used to advance water governance and assist in achieving the sustainable development goals for water and sanitation [65], [47], [29]. According to [66], a comprehensive compilation of 4IR technologies has been identified, drawing upon the works of De Azevedo et al. (2019) and Poljak (2018) among others. This compilation encompasses a range of technologies, including but not limited to Big Data and Analytics, Autonomous Robots, Simulation, Internet of Things (IoT), Augmented Reality, Additive Manufacturing, Cloud Computing, Cybersecurity, and Horizontal and Vertical System Integration [66]. These technologies are said to have the potential to transform the water sector. Nevertheless, [29] posits that the application of 4IR technologies in the water sector requires a combination of these technologies, methods, and digital solutions instead of stand-alone approaches. Similarly, a study by [67] elaborated on 4IR technologies such as artificial intelligence, Big data, IoT, blockchain, drones, remote sensing, and virtual and augmented reality have been widely applied in Latin America's water and sanitation sector. While there was a consensus among the above authors, [66] further underscores the significance of cybersecurity technologies as critical in the digital transformation of the water sector. On the other hand, [65] emphasizes the importance of 4IR technologies, such as artificial intelligence, in achieving decentralization following the failure of a centralized societal system and how essential these technologies are in monitoring and creating smart cities.

The above-discussed Fourth Industrial Revolution technologies have been regarded as essential in transforming the water sector by offering potential benefits such as sustainability in operations and economic growth for the water sector, which they refer to as "Digital Water" or "Water 4.0" [42]. Some of these benefits include, but are not limited to, leak identification, for instance, through sensors, smart metering, and predictive analytics, which can detect issues, educate consumers, foresee potential failures, and result in improved water conservation and sustainable water services [16].

Adding to the benefits of integrating 4IR technologies in municipal water governance, 4IR technologies have the potential to improve efficiency through effective resource utilization [31], data-driven decision making and improve water quality through monitoring [67]. In addition, predictive technologies in the 4IR era enable proactive measures in infrastructure maintenance and asset management [29]. Likewise, these technologies may reduce the environmental impacts through predictive analysis, which assists in putting proactive measures in place in managing natural catastrophes such as flooding and droughts [63] and improve public participation and stakeholder involvement through breaking geographical boundaries [38]. Thus, such a digital transformation in water governance offers previously unattainable operational efficiency enhancements [48].

While 4IR offers transformative opportunities for water service authorities in South Africa and globally, it also introduces threats and risks, including cybersecurity vulnerabilities, job displacements, exacerbation of the digital divide [32], and inequitable distribution of benefits [18]. Therefore, it is essential to balance leveraging 4IR technologies and upholding the principles of effective water governance, such as equity, effectiveness, and sustainability [14].

Significantly, the risks associated with 4IR technologies can be mitigated through thoughtful and context-sensitive implementation. To this end, [4] put forwards three recommendations arguing that there is the need to consider contextual issues as opposed to specific technologies; technologies ought to be developed to augment human autonomy and decision-making rather than presuming they will govern behavior; and that forthcoming innovations must be deliberately crafted with integrated values and providing room for continuous discourse at each phase. Likewise, [32] underscore the need for careful planning and emphasize the need to prevent the adopted technologies from becoming obsolete or misaligned with local needs, as such outcomes would ultimately undermine the very rationale for their adoption. Similarly, the [44] warns the adopters that while it is necessary to learn from international practices, there is a need to avoid copying; instead, water services authorities should only adopt what is appropriate to their context based on their priorities and adapt what is needed to carve a credible space for themselves in the global community.

While the above-mentioned measures are crucial in mitigating the negative impacts of 4IR, key pillars should be considered to ensure successful adoption. For instance, [4], [20], and [62] emphasised the need for basic and digital infrastructure, while [31] and [60] argued that there is a need for sufficient funding as initial investments

in 4IR are costly. Other scholars, such as [17] and [47], raise concerns regarding the skills and expertise demanded by 4IR, while [52] and [19] emphasises the need to address issues related to technology resistance. Other aspects include the importance of strong and visionary leadership ([7], [40], collaborations and partnerships [9], and training [62]. While these studies provided the basis and key factors to be considered when adopting 4IR technologies, they were not focused on municipal water governance, which is considered a fundamental human right and a basic need that should be accessible, reliable, and affordable.

Nevertheless, based on the above discussions, this paper argues that when properly managed, the 4IR technologies have the potential to promote fundamental human rights and constitutional mandates, such as those outlined in Chapter 2 of the South African Bill of Rights, including increased freedom, improved health, enhanced educational opportunities, and reduced economic insecurity [4].

Various scholars have researched using the Fourth Industrial Revolution technologies in the water sector. The research area has, therefore, garnered heightened interest as a prospective remedy to the intricate and escalating water management challenges. Illustrations of such studies include research conducted by [61], which examined the potential of blockchain technology with intricate flow systems to transform water governance. Their analysis underscored opportunities to improve openness and efficiency in water management. Ref [11] investigated the incorporation of Fourth Industrial Revolution technologies into the water, energy, and food nexus, demonstrating the interrelation of these essential sectors. Ref [42] concentrated on the modeling and optimization of water systems, highlighting the capacity of data-driven methodologies to enhance water resource management. [10] presented a hierarchical, multilayer network for water management utilizing Industry 4.0 tools in another study. Their platform amalgamates company operations and sensor networks, providing a comprehensive best-practice solution for data optimization and complete digitalization of the water sector.

Additionally, [5] concentrated on advancing real-time, Internet of Things (IoT)-integrated water quality management systems. Their proposed method employs sensors to assess water quality parameters, rendering it appropriate for residential use. Additionally, a study conducted by [6] introduced an IoT-based framework for monitoring water quality to safeguard health and well-being. Likewise, the United Nations 2023 SDG6 Synthesis report provides an overview of the importance of innovation to accelerate SDG 6, emphasizing the need for funding, an enabling environment, and innovative educational methods to accelerate innovation [57].

Nevertheless, while these studies have a different focus, they all relate to applying 4IR technologies in the water sector and show the growing recognition of how these technologies can improve water management. However, to our knowledge, no study has offered a water governance and 4IR framework that provides a blueprint or guideline for how the Water service authorities can integrate these technologies to enhance water governance with specific reference to the OR Tambo District Municipality, Eastern Cape, South Africa. This was deemed important as the adoption and implementation of these technologies requires context-specific and customized approaches when engaging innovations in water governance [16],[57], underscoring the need for this research

This paper, therefore, proposes a water governance and 4IR framework that can guide the transformation. Underscoring the importance of this framework, this paper contends that the 4IR era is an unavoidable transformation that all aspects of the human economy must embrace to achieve maximum efficiency, effectiveness, resilience, sustainability, and equity in public institutions and particularly in water institutions at the local level, especially when they are faced with economic trajectories [11].

3 Diffusion Innovation Theory

The adoption and implementation of 4IR technologies in municipal water governance vary globally, ranging from early adopters to laggards, a situation that the Diffusion Innovation Theory better explains. The diffusion innovation theory was developed by Rogers (1962). The theory provides the basis on which innovations in technology spread among a population. Describing the DIT, [51] refers to the theory as the process by which an innovation is communicated through certain channels over time among the members of social systems. The theory is based on five qualities that are considered important in technological diffusion. These qualities include the consistency of technology with the values and needs of the users (compatibility); the benefits of the technology

(relative advantage); the extent to which technology can be experimented with on a limited basis (trialability); the ease of use (simplicity) and how quick the technology's benefits can be observed (observable results) [11],[50].

Additionally, the theory posits four elements of diffusion of innovation: communication, communication channels, time, and social systems [11]. Regarding innovation, the theory postulates that for any technology to be considered innovative, it should be perceived as new, even if it has existed for a long time. The second component refers to the communication channels, which are the process whereby participants create and share information or reach conclusions. [50] states five communication channels which include knowledge (the why, how and what of the innovation); persuasion (attitudes towards the innovation based on the degree of uncertainty); decision (this stage the user can accept or reject the innovation); implementation (the use put the innovation into practice) and confirmation (the user decides to use the innovation but needs further support to cement their acceptance decision or uncertainty attitude). The third component of time entails the period during which people adopt innovation. According to [13] and [50], the innovation process has five categories of adoption that are followed during the introduction of technology. Innovators, making up 2.5% of the social system, are the first to embrace new ideas and innovations. At 13.5%, early adopters have the highest opinion leadership and influence within their communities. The early majority, comprising 34%, adopts innovations ahead of the average member, playing a key role in the diffusion process. The late majority, also 34%, are more skeptical and adopt innovations only after the average member. Lastly, laggards, representing 16%, are the slowest to adopt innovations due to their preference for tradition and past practices. The fourth component is the social system, which comprises integrated groups sharing common goals to address societal problems and is often influenced by a social structure [11].

The Diffusion of Innovation Theory (DIT) components provide a solid foundation for developing a water governance and 4IR framework by highlighting the varying rates at which 4IR technologies are adopted across different water service authorities. This framework accounts for the distinct characteristics of stakeholders, from innovators who can act as pioneers to laggards who require strong incentives, support, and evidence to embrace these technologies. By recognizing these differences, the proposed framework advocates for a phased implementation strategy aligned with the innovation adoption curve. Tailoring communication, resources, and support to each group ensures a smoother integration of 4IR technologies into water governance, enabling more effective and widespread adoption. This strategic approach will accelerate the diffusion of 4IR innovations, addressing critical water challenges more sustainably and efficiently.

4 Methodological Approach

The paper utilized a qualitative case study research methodology to contextualize the proposed framework and address the current gaps in adopting and implementing 4IR technologies. The qualitative research entailed collecting and analyzing empirical literature and non-numerical data to contextualize opinion, understand the experience, and review concepts [33]. Semi-structured interviews were conducted with twenty-eight (n=28) participants selected through purposive sampling and snowballing sampling techniques. The selected sample size was supported by [2], who asserted that a sample between twelve and twenty is recommended for qualitative studies. However, the current research focused on ensuring that a point of saturation is reached to ensure that enough data is collected [8]. The sampling method adopted ensured that data were collected from knowledgeable respondents on the subject under investigation [58].

The participants included municipal officials, councilors, stakeholders, the Fourth Industrial Revolution, and water governance experts involved in ORTDM municipal water governance. The researchers also engaged experts in 4IR, and water governance as think tanks to provide their insights regarding the subject under investigation. The use of semi-structured interviews and the adopted methodological approach provided for the collection of thick, rich, and in-depth data, which was deemed critical for developing the proposed framework [27]. The interviews were conducted in person and for those busy participants, they were conducted online via Microsoft Teams over an average of sixty minutes. This approach allowed flexibility for participants while enabling the researcher to collect as much data as possible [53].

Additionally, literature and document reviews were conducted to supplement empirical data. The literature reviews explicitly entailed reproducing and systematically synthesizing, evaluating, and identifying the existing

data collected that was not for the primary purpose [41]. A thematic analysis was applied to analyze the data. The approach followed familiarizing and categorizing data, coding, defining, and refining the themes. While the researchers recognized the presence of software such as NVivo and Atlas Ti, which can be used when analysing qualitative data, the current paper adopted a manual approach. This approach aligned with [25] observations that manual data analysis is crucial for early researchers as it helps them understand and grasp the fundamentals of data analysis and may prepare them to adopt any form of analysis in the long run, including the computerized methods. Ethical considerations such as anonymity, confidentiality, voluntary participation, and informed consent guided research [68]. Furthermore, trustworthiness was upheld during the research paper, emphasizing ensuring that the findings are credible and accurate.

The adopted research methodology therefore ensured the collection of rich and in-depth data concerning the challenges in water governance and the views and perspectives regarding the adoption of 4IR technologies in municipal governance, which was deemed necessary for the development of the proposed framework. Furthermore, the adopted methodology was grounded in the idea that the qualitative aspects of water should be prioritized as much as the technical components. To this end, the researcher sought to understand the current water governance challenges, the current state of technology adoption, and suggestions on how technology adoption can be accelerated to enhance water governance in ORTDM.

5 Findings

The following section provides the findings of the study.

5.1 Water Governance Challenges in the OR Tambo District Municipality

The study findings revealed various water governance challenges manifesting in capacity, accountability, information, funding, and administrative gaps. Respondents interviewed revealed that the municipality is facing challenges in terms of capacity, with major challenges coming in the form of a lack of technical skills and insufficient training and development. One participant stated, “We do not have enough technical staff, and this poses a challenge in our operations”. In addition, participation revealed that infrastructural challenges, such as poorly maintained, old, dilapidated, inadequate, and non-completed schemes, exacerbate water governance challenges. Experts interviewed further confirmed these findings, arguing that infrastructural challenges are prevalent in South African municipalities.

Respondents further revealed that the municipality is experiencing funding gaps that manifest in low revenue collection, budgeting process deficiencies, and grant funding complexities. One participant stated “In some cases, monies have to be returned to National Treasury if the rollover of grants is not approved,” while another participant stated “Our revenue collection is low, and this makes it difficult to meet the demands and needs of our communities due to these financial constraints”.

Another major challenge was the information gap manifested through fragmented data sets, deficiencies in reporting quality, accurate and timely information, and dependency on external sources for some of the crucial information, such as the South African Weather Services for meteorological data. One participant stated, “We have to wait for updates from the South African Weather Services as we do not have internal systems in our organisation, which makes it difficult for us to be proactive; rather, we are always reacting after floods occur”. Participants further revealed accountability gaps manifest through weak oversight, regulatory mechanisms, and participation and stakeholder involvement deficiencies. Lastly, participants revealed gaps in the administrative systems of the municipality, with emphasis being put on deficiencies in planning and coordination across departments, which were reflected by failure to meet deadlines, resulting in rollover of funds and the silo approach adopted by departments. These water governance challenges stem from institutional, systematic, and contextual issues within the district municipality.

5.2 Current State of Technology Adoption in ORTDM’s Water Governance

The above section presented the various water governance challenges that exist in ORTDM. However, the findings further revealed that the district municipality has already started to use some 4IR technologies to address

some of these challenges. Some of the notable 4IR initiatives include an outsourced telemetry system to monitor their water levels and address information related challenges. One municipal official stated “We do have a telemetry system which shows us our water levels from our reservoirs, but at the moment the system is not working, and we cannot fix it as it is outsourced.” However, when the data was collected, the system was not working. Data collected revealed that the municipality outsourced the system due to funding constraints to address issues such as skills and equipment needed.

The municipality also has an e-recruitment system used by the human resource department. One municipal official stated, “We have an e-recruitment system, but we just use it to receive applications only”. The data collected revealed that the system is underutilised as it is used only for submitting the curriculum vitae. Respondents indicated that the rest of the processes, including the initial screening, were done manually.

In addition, the municipality has a functional website and uses social platforms such as Twitter, now known as X, Facebook, and WhatsApp. A municipal official stated, “We have social media platforms which are Facebook, X, and WhatsApp groups where we share some of the municipal communications, for instance, when there are disruptions of water services or information regarding natural disasters”. However, data collected revealed that these platforms are underutilised as tools to enhance water governance. For instance, there is limited staffing in this communication department; these websites can have the option of chatbots, which will facilitate communication across the communities and the municipalities with regard to queries and complaints that were revealed to be remaining unattended. Additionally, through data analytics, information and data collected from these social media can aid in decision-making. However, the study findings revealed that the municipality rarely utilises such information in this regard.

Regarding the adoption and implementation process, the study findings further revealed that while discussions on adopting further 4IR technologies, such as smart meters, were already in place along with other initiatives discussed above. One participant stated, “There are already discussions on the adoption of smart meters, but we don’t have an official document in place yet”. Upon further probing, the respondent further stated, “Yes we have already started using some of these technologies, for instance, the telemetry system, but we do not have a framework or document that guides us in this digital transformation”. The study findings, therefore, revealed that the municipality does not have a framework that guides the adoption and implementation process. Therefore, such a situation may cause a problem, resulting in a slow adoption and underutilization of the 4IR technologies, which are crucial to enhancing municipal water governance. This is because without a clear plan and framework to guide the transition, it will be difficult to establish the key pillars required to embrace 4IR, such as the funding mechanisms, supportive regulations, and capacity required in terms of skills and infrastructure.

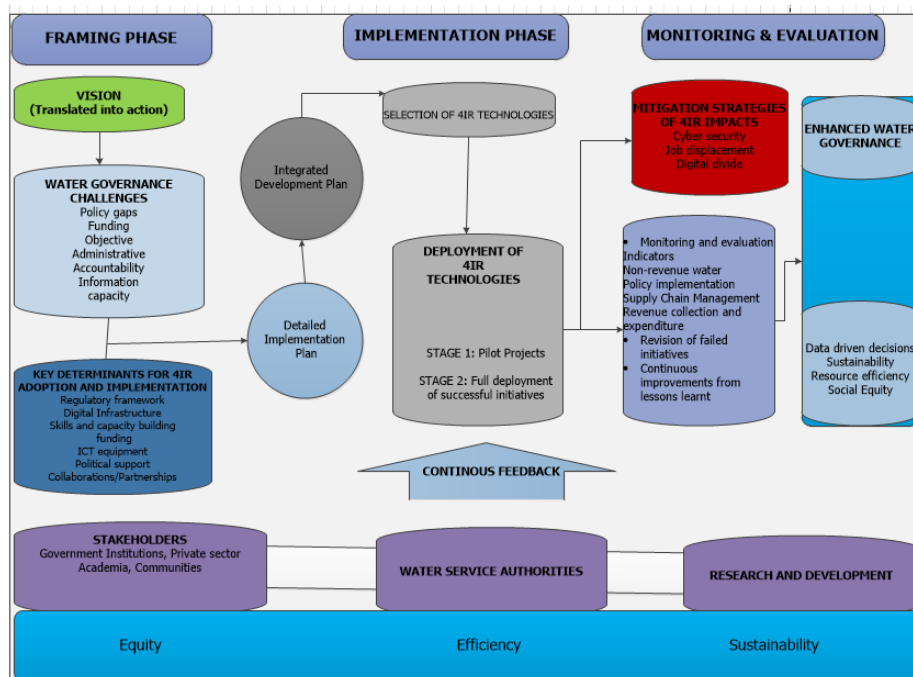
5.3 Measures Required to Accelerate Technology Adoption in ORTDM

The study findings revealed that the stakeholders involved in ORTDM’s water governance were optimistic about the adoption of 4IR technologies to enhance water governance. Municipal officials revealed the need for assistance in funding technological advancements, highlighting funding constraints as a major issue. One participant stated, “With the current financial state, we will require funding to support us because, as a municipality, we are already financially constrained”. Other officials highlighted the need for reskilling and upskilling if they are to go forward with scaling up adoption. Experts interviewed in 4IR highlighted the need for the national government to support municipalities such as ORTDM in rural areas with poor digital infrastructure, as connectivity is essential in adopting 4IR technologies. In addition, experts in water governance emphasized the need for integration across spheres of government and departments, funding, and collaborations as essential for accelerating technology adoption. Given these findings, the research recommends a proposed framework that may accelerate the adoption of 4IR technology in ORTDM by providing a roadmap or blueprint to guide the transition.

6 Proposed Framework for the Adoption and Implementation of 4IR Technologies in Municipal Water Governance

The proposed Water Governance and 4IR Framework for municipalities presented in Figure 6.1 is intended to assist policymakers and guide water service authorities in adopting 4IR technologies to enhance their water governance. The framework was shaped and heavily influenced by the empirical results, existing literature, and the Diffusion Innovation Theory, making it more realistic as it incorporates the current realities that water service authorities face. As a result, the framework is unique and contextualized for the OR Tambo District Municipality and other municipalities in a context similar to ORTDM. The framework was made easy and simple to understand to cater to a diverse audience who would be involved in the process and can be readily translated into operational terms.

Figure 6.1. Water Governance and the Fourth Industrial Revolution (4IR) Framework for Municipalities



Source: The Researcher (2025)

The framework, therefore, comprises three phases: the framing phase, the implementation phase, and the monitoring and evaluation phase. The details of the framework are further discussed below.

PHASE 1: FRAMING/IDENTIFICATION

The framing/ identification phase comprises three main sections: the vision, the recognition of the water governance challenges, and the key determinants for success.

• Vision

The proposed framework emphasizes the need for the municipalities to have a well-articulated vision, as it is critical in adopting and implementing 4IR in water governance. This vision should provide a strategic direction, foster innovation, and shape the processes and systems that guide the implementation. By setting a strategic direction, a clear vision enables ORTDM, and other municipalities to prioritize initiatives that align with their long-term goals in serving their primary responsibilities. Furthermore, the vision should foster innovation by encouraging the exploration of innovative ways, such as using smart technologies that address specific community needs and developmental goals. This forward-thinking approach ensures that technological advancements are not adopted for modernization but are utilized to enhance the core responsibilities of water governance. Equity,

efficiency, and sustainability should be at the core of municipal vision, ensuring effective water governance. This community-centric approach guarantees that the benefits presented by the technology advancements are felt by all, promoting inclusivity and fairness in resource distribution and efficiency in municipal operations. As such, it can be emphasized that municipalities should not be driven by the mere need to adopt technology but should instead use it to fulfill their primary responsibility. Additionally, a vision incorporating technological integration helps shape policy and regulatory frameworks for water governance. It also guides the adoption and implementation of 4IR technologies, such as attracting investments and collaborating with technology providers and other stakeholders.

- **Identification of water governance challenges**

Water service authorities should understand their current operations towards the set vision. It is crucial to understand the challenges they face regarding water governance. In this case, the challenges identified include capacity, policy, administrative, objective, information, funding, and accountability gaps [23]. After identifying the challenges faced, municipalities should identify areas in which the Fourth Industrial Revolution technologies can be applied to address the identified challenges. In addition, there is a need to understand the reasons behind the existing challenges so that the correct technologies are adopted. Understanding the underlying causes and root problems enables the resources to be channeled to the correct areas [23].

- **Key determinants of the adoption and implementation of 4IR technologies**

This framework is grounded in an optimistic view that digital transformation in the public sector should not be seen as a panacea for government problems and that the introduction of digital technologies does not automatically create a better government unless several conditions are met [52]. In line with this view, the framework recognises that ORTDM and other water service authorities, along with other stakeholders, need to work together and make sure that the pre-conditions for the adoption and implementation of 4IR technologies are met if these institutions and the citizens at large are to harness the benefits presented by the 4IR era [45]. The key determinants and preconditions include:

Policy and Regulatory Frameworks: Municipalities should ensure that they have a strong regulatory framework to guide the adoption process. A strong policy and regulatory framework are critical in protecting the communities and the water service authorities from the harm brought by the Fourth Industrial Revolution. While there is a need for national water policies that guide the adoption of 4IR technologies, municipalities such as ORTDM can work with the current water policies and formulate institutional policies and governance frameworks that guide the process of using the 4IR technologies. These policies should address various aspects such as skills development, infrastructure enhancement, funding mechanisms, and regulatory frameworks. By implementing such policies, ORTDM can create an attractive environment for the growth of the adoption of 4IR technologies in their water governance. However, these policies and frameworks should support the integration of 4IR technologies and prepare the citizens and water service authorities, particularly those in rural municipalities who are at risk of being left behind, to be prepared for the transformative impacts of the 4IR.

Digital Infrastructure: Municipalities need to understand the digital infrastructure in the areas where they intend to deploy the 4IR technologies. This is a crucial component as it determines the types and models of technologies that should be adopted, for what reasons, and for which benefits they should yield. Issues such as connectivity and bandwidth can be considered in the infrastructure. This framework emphasizes the importance of proactively addressing digital infrastructure deficiencies. This includes exploring alternative, cost-effective innovations like the Elon Musk Starlink Project. However, effective implementation and regulation of such initiatives necessitate robust intervention from the national government. Another critical aspect that requires attention regarding the infrastructure issue is adopting alternative energy sources, given the level of load shedding and unreliable electricity in South Africa. Municipalities should look forward to the use of solar energy, and this aspect should be considered when adopting technologies. By addressing these issues, South Africa can bridge the digital divide and promote inclusive development, ensuring equitable access to 4IR technologies to communities and water entities in rural areas and ensuring that the potential benefits of the revolution are enjoyed without leaving anyone behind.

Digital Skills: The framework emphasises the need to address digital skills challenges, which remain one of the obstacles hindering this transformation. Training, upskilling, and reskilling should be a priority. Municipalities

should utilise 4IR technologies to address the skills gap by addressing physical geographical barriers, as some skills can be obtained through online learning. In addition, the framework emphasizes an integrated approach from all stakeholders, such as all education departments, the Department of Science and Technology, local government, and the private sector, to work together in addressing the skills gap. For instance, ORTDM can partner with Walter Sisulu University in its jurisdiction to help with capacity development. To achieve such integration, the government should be positioned as a strong adopter of emerging technologies in municipal water governance to motivate investments and funding for skills to necessitate the adoption of 4IR technologies in municipal water governance [39]. When adopted, such an integrated approach will provide training programs and foster skill development initiatives as these entities can equip organizations with the expertise needed to drive effective 4IR adoption in water governance.

Soft Skills: Beyond digital skills, this framework emphasizes complementing technical proficiencies with softer leadership skills. The approach not only fast-tracks the pace at which these technologies are embraced but also ensures that 4IR technologies lead to effective water governance. The 4IR era demands creative processes like strategic planning, research, and development to become crucial, demanding skills to recognize, generate, and implement new opportunities [36]. To this end, the framework emphasizes the need for senior leadership in the municipality to develop competencies such as data interpretation, data analytics, open-mindedness, fostering global networks, and agility of thought to adapt to the changing technological environment [26].

The framework posits that such soft skills facilitate the transition to 4IR technologies and enable leaders to advocate for skill acquisition among their teams. For instance, fostering collaborations through academia and the municipality, in this case, Walter Sisulu and ORTDM, as they are both stakeholders in water governance in the same area. Given the municipality's budget, such approaches will allow ORTDM to fast-track its pace in utilizing 4IR technologies to improve its water governance within affordable means. Thus, the successful adoption and implementation of 4IR demands more specialised skills beyond basic digital literacy, as cited by [28].

Collaborations and Partnerships: The framework emphasizes the need for the municipalities to establish strong partnerships and collaborations if they successfully embrace 4IR technologies in their municipal water governance. The approach follows the recognition that with their current capabilities, most South African water service authorities, such as ORTDM, which are in rural areas, are not sufficiently capacitated to fully adopt and implement 4IR technologies in their water governance. To this end, established collaborations and partnerships provide a chance for the municipality to address the current needs, adopt new technologies, and without adding more strain to its already financial burden. For instance, in the case of ORTDM, it has Walter Sisulu University within its jurisdiction. These collaborations can be used in pilot projects, capacity building, upskilling, and re-skilling. This helps the municipality to alleviate the financial burden, which was revealed in the findings as one of the obstacles in adopting and implementing 4IR with its water governance.

Funding: A key component of the framework is funding. As such, the framework posits that with the current financial state of municipalities, more funding for the adoption and implementation of 4IR technologies may be needed. Alternative mechanisms should be sought to supplement the existing financing. Therefore, the framework emphasizes the need for collaboration and partnerships so that they can assist in some areas and relieve the financial burden. For instance, state universities may provide training and capacity building as part of their community engagement initiatives. Such approaches will, therefore, provide shared opportunities and benefits for both the municipalities and tertiary institutions. Moreover, tertiary institutions such as Walter Sisulu University (WSU) in ORTDM can conduct research using these municipalities. They can implement pilot projects for the municipality, and will be part of the research for students as they engage in their academic milestones. Additional municipalities should be forward in approaching the government, donors, and funders and applying for grants to supplement their funding. The government at large should have grants to support the adoption of 4IR initiatives in water governance, just like how they have ones to support infrastructure.

Information Communication Technologies: Municipalities should invest in basic information and communication technologies and equipment that support the adoption and implementation of 4IR technologies. ICTs should be addressed and given equal importance as the one given to the issue of digital infrastructure, such as bandwidth, internet connectivity, storage, and base stations. 4IR technologies require gadgets that support specific software and technologies. As such, municipalities must ensure they invest in these basic ICT gadgets, such as mobile phones, laptops, and internet gadgets that support the 4IR technologies.

Political support: Political support is essential for successfully integrating 4IR technologies in municipal water governance. While collaboration, partnerships, and community engagement are crucial in providing input for informed decision-making, the ultimate decisions in municipalities rest with the municipality's political structures. Additionally, political support plays a significant role in influencing communities by raising awareness, providing assurance, and motivating the adoption of these technologies. Their support ensures that technological initiatives are aligned with the needs and expectations of the community, fostering a more effective and inclusive approach to water governance.

- **Detailed Implementation Plan linked to the Water Service Development Plan**

The Framework emphasizes the need for a roadmap, strategy, or implementation plan, linked to the municipality's Integrated Development Plan (IDP) or Water Service Development Plan. The link is important as the IDP is the key strategic document guiding municipal operations in South Africa. As such, the link will enable the 4IR initiatives to be pushed forward as part of the municipal goals and strategies. The implementation plan should be informed by information from the framing phase. It should detail the municipal vision and challenges concerning water governance. It should specify the key stakeholders involved and the partnerships and collaborations. It should identify the key regulations and policies that will guide the implementation and the mechanisms to address infrastructure, capacity, and funding issues, among other areas of concern. Additionally, the document should elaborate on a set mechanism for monitoring and evaluation, with key indicators in place. While the document should recognize the benefits to be achieved from the deployed technologies, it should also highlight the challenges of using technologies, such as how issues of data justice and governance will be addressed, as well as issues of retrenchment and cybersecurity, among others. The framework emphasizes the importance of this implementation document because the stakeholders can use it for monitoring and evaluation, it can be used to source funding from donors, and it guides the municipality on implementing these technologies.

PHASE 2: IMPLEMENTATION

After the framing phase, the framework includes the implementation phase. The phase involves the selection of technologies for deployment. The selection of technologies is guided by various factors identified in the framing phase. If the municipality has managed to secure collaborations from universities or the private sector, it can utilise the technologies. Likewise, if the municipality has managed to secure funding, it can therefore select and deploy certain technologies. Additionally, other municipal realities such as the available skills, the alignment of the technology to the policies, and the compatibility of the available 4IR technologies to the digital infrastructure highly determine which and when the technologies can be implemented.

Therefore, at this stage, the municipality should have the exact areas they want to improve and know their capacity and capabilities in terms of which technologies can be afforded. The stage will therefore involve deploying technologies, with the first stage being pilot projects. These may include the use of systems such as Enterprise Resource Planning systems to ensure an integrated approach in the municipal administration systems. In the context of ORTDM, another example may be deploying a pilot project on smart water metering in one of its communities or using artificial intelligence and data analytics to inform decision-making. After pilot projects, depending on the results produced, the technologies can be deployed on a full scale, terminated, or improved. Continuous feedback should guide this approach to rectify all errors and corrections on time. Additionally, as soon as the technologies are deployed, strategies to deal with the adverse effects of technology are implemented. These should be detailed in the implementation plan from the previous phase.

PHASE 3: MONITORING AND EVALUATION

The framework emphasizes the need for monitoring and evaluation when adopting and implementing 4IR technologies in water governance. This aspect is essential in assessing whether the deployed technologies serve the purpose for which they were adopted. This will also ensure that the technologies are not adopted for mere adoption but to serve communities' needs through enhanced water governance. Various indicators should be implemented to check the results against planned targets. For instance, when leak detection technologies are put in to reduce non-revenue water, then non-revenue water can be measured to see if the leak detectors are working. Also, the response time and reported burst pipes can be among the set indicators. Smart metering in households can be used to assess water consumption, etc. The above steps should be underlined by four crucial aspects: continuous feedback, stakeholder engagement, research, and development, which are conscious of equity, efficiency, and sustainability as underlying values, as explained below.

- **Continuous Feedback**

A key component of the framework is continuous feedback. This component is essential, particularly in adopting and implementing 4IR technologies to enhance water governance, as the technology adopted is meant to serve the community's needs. As such, there is a need to check whether the intended goals are being achieved continuously. To this end, feedback should be incorporated throughout the lifecycle (planning, development, implementation, evaluation) of the adopted 4IR initiatives and managed via structured loops that emphasize practical insights rather than being regarded as an afterthought [30]. The above approach will ensure that issues such as usability, accessibility, relevance, acceptability, trialability, and sustainability issues can be assessed with correctional measures being put in place, terminated, or checked for possible continuity of the technologies. This approach will help save resources, address user resistance, and ensure effective results from the deployed technologies, as the limitations will be addressed in time. Moreover, ORTDM's research and development division must be pivotal in coordinating these initiatives to guarantee that feedback channels are accessible and representative. Particular emphasis must be placed on incorporating disadvantaged and vulnerable populations, who are frequently the most impacted by poor water governance yet are the least represented due to obstacles such as limited access to internet platforms or community forums. Guaranteeing their inclusion is not merely an equity issue but is crucial for formulating responsive, inclusive, and successful water governance plans.

- **Stakeholder Involvement and Community Engagement**

The proposed framework underscores the critical importance of stakeholder engagement, including academia, government institutions, the private sector, and local communities, in successfully adopting 4IR technologies within water governance. Meaningful engagement ensures that diverse voices, especially those of marginalised and vulnerable groups, are heard and considered throughout the decision-making process. This is particularly crucial given that these groups often bear the impact of negative consequences when technologies are adopted without inclusive planning.

Stakeholder involvement enhances transparency and accountability and fosters informed decision-making by leveraging different actors' collective knowledge, experiences, and perspectives. In the context of municipalities like ORTDM, where the adoption of 4IR technologies is still emerging, stakeholder engagement provides valuable platforms for learning, knowledge exchange, and identifying best practices and trends that can guide implementation efforts. Decisions regarding which technologies to adopt and when and how to implement them should be made by the input of all relevant stakeholders. Early and continuous engagement, particularly with local communities, is essential in building trust, reducing resistance to change, and fostering a sense of ownership in the transformation process. Finally, while broad engagement is essential, the framework acknowledges the central role of Water Services Authorities (WSAs) in this process. As implementers responsible for water service provision and governance, Water Service Authorities should coordinate stakeholder interests, mediate competing perspectives, and ensure that the core objective of improving service delivery through 4IR technologies is achieved.

- **Research And Development**

A key component in the framework is the need for extensive research and development. Adopting 4IR technologies in water governance requires extensive research from the initial phase to the monitoring and evaluation phase. Research enables the municipalities to have enough data to make informed decisions, explore various existing opportunities, and identify potential and available opportunities for partnerships and collaborations. Additionally, research informs policy decisions and policy reforms. It is critical in determining issues such as capacity building and sourcing funding. Hence, sound research and development are needed to inform the cycle of adopting the 4IR technologies.

7 Conclusion

The discussion above demonstrates that while integrating the Fourth Industrial Revolution technologies presents a compelling opportunity to transform water governance, it must be approached with a well-articulated and context-specific implementation framework. Without such a foundation, adopting these technologies risks worsening existing inequities and placing additional strain on struggling municipalities. At the same time, opting not to engage with 4IR technologies is not a viable alternative, as the transformation effects are already reshaping all

sectors and communities. As 4IR is already reshaping every sector, Water Services Authorities that fail to evolve will inevitably be left behind.

In response to this urgent need, the paper proposed a practical framework integrating 4IR technologies within the broader water governance agenda. Grounded in the realities of ORTDM, the framework offers a structured, inclusive, and sustainable pathway for municipal transformation. It ensures that innovation is not a source of disparity but a tool for enhancing equity, resilience, and service delivery. More importantly, the framework emphasizes the need for community-centered and technology-driven vision supported by an enabling environment, including collaboration, robust regulation, and continuous capacity development. The framework further underscores the necessity for stakeholder engagement and iterative feedback to guide and refine the implementation process. Ultimately, the proposed framework serves as a comprehensive roadmap for municipalities like ORTDM and those with similar contexts to navigate the digital transformation in a way that strengthens water governance and secures sustainable, equitable service provision in contemporary water governance.

8 Policy Implications of Study Findings

The current study findings are important in advancing and accelerating the adoption of the fourth Industrial Revolution technologies in municipal water governance locally, nationally, and globally. Such an acceleration may improve water governance, thus assisting in achieving local, regional, and internal obligations related to water service provision, such as the SDG 6. The study findings further provided for the “how” part in which such an acceleration can be achieved by revealing the need for an integrated support system to accelerate technology adoption in municipalities. Water institutions, government departments, communities, private organisations and Higher and tertiary institutions need to work together through collaboration, partnerships, community engagement, skilling, policy and regulation, funding, and donations to support municipalities. More importantly, the study findings revealed the need for water service authorities as institutions with the mandate to provide water services to be at the forefront in seeking opportunities to drive the transformation. One way highlighted is to have a strategic document which guides the digital transitions, as such a document assists in seeking the above discussed support by providing stakeholders with the vision of the municipality.

9 Study Limitations and Areas of Future Research

The study was conducted using OR Tambo District Municipality, which may present limitations in generalizing the framework. Furthermore, the study sample did not include the communities that are the users of these advocated technologies, which may present a limitation in the application of the framework. While the proposed framework incorporates advocates for a community-centred approach in the adoption of the 4IR technologies, future research may look to use a survey to understand the perspectives of the communities in the district municipality regarding their views on technology adoption to enhance water governance.

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12 Authors Contributions

Clarity Hutete- Conceptualization, data collection, data analysis, and writing the original draft, review, and editing.

Shikha Vyas-Doorgapersad- Review and editing the original draft and generated the plagiarism report.

Nqobile Sikhosana- Review and editing of the original draft and second draft from reviewers.

13 AI Generative Tools

No AI generative tools were used.

Analysing Metropolitan Municipal Water Services Delivery Performance in South Africa: A Comparative Assessment of Household Access, Water Quality, and Households' Satisfaction

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Abstract—This paper investigates the water service delivery performance of metropolitan municipalities in South Africa between 2022 and 2024. This enables adequate understanding of the prevailing conditions of water service delivery in the metros and thus forms the basis for service enhancement intervention. Using a conceptual framework that combined principal-agent, equity, and public value theories, this study analyzes a combination of secondary quantitative data on water service delivery performance across metropolitan municipalities in South Africa. The data was sourced from various government databases to pursue the study objectives of exploring water access, water quality, and households' water service satisfaction. The findings revealed a significant disparity in the performance of the metros in water service delivery. While the City of Cape Town and Ekurhuleni demonstrated consistent water service excellence, Buffalo City, Nelson Mandela Bay, and Mangaung struggled with incessant water interruptions and declining water safety. Despite the robust water infrastructure status as reported in WQI, systemic challenges, such as leaking water pipes and institutional inefficiency, undermine reliable water service delivery among metros in South Africa. This paper thus concludes that for South Africa to effectively address the persistent water service delivery challenges confronting it and efficiently achieve SDG 6 by 2030, there is the need for crucial investment in water management technology, establish water service delivery taskforce across metros, invest in wastewater treatment technologies, establish a national water management training institute to regular provide trainings to metro staff. Lastly, inter-metro best practices sharing must be entrenched, while a public database with updated water performance data must be made available to support water research. These recommendations emphasize inter-metro collaboration, technological integration, and policy reforms to address systemic gaps and enhance public satisfaction with water service delivery.

Keywords—Water Quality, Households' satisfaction, Metropolitan Municipalities, Water Service Delivery, Public Value

1 Introduction

To ensure the health and well-being of people, access to safe and sufficient drinking water is crucial [1, 2]. However, the intensity of water scarcity across the world in the last three decades has been unprecedented [3, 4], with severe scarcity in arid and semi-arid countries [5], such as South Africa, where drought and ecological degradation have been prominent [6, 7]. To better sharpen this submission, [8] presented the following statistics: South African urban centres currently harbour over 64% of South Africans, with about 36% living in rural and informal settlements and without a matching water supply [9]. The statistics indicated the slow pace with which South Africa is moving towards achieving Sustainable Development Goal 6 (SDG 6) and SDG 6.3 [10]. Specifically, SDG 6, target 3, aimed at improving water quality, wastewater treatment, and safe water reuse [11, 12, 13], matching the elements fundamental to South Africa's water security and broader sustainable development agenda.

Therefore, achieving SDG 6 is strategic to South Africa and fundamental to achieving the constitutional mandate of ensuring access to safe water for all South Africans [14]. The leading government department responsible for providing water services is the Department of Water and Sanitation (DWS). This body coordinates water governance systems in the country, and it has recognised the critical interconnectedness of SDG 6.3 with the other seven (7) targets in SDG 6, in addition to numerous other SDG development priorities. The DWS is advocating for various government units to adopt a collaborative approach to address the water shortage problem in South Africa.

Despite the efforts of the national government to address the problem of water service delivery in the country, the expected improvement has yet to be recorded. According to the General Household Survey (GHS) conducted by Statistics South Africa (Stats SA) in 2023, for instance, between 2018 and 2023, 87-89% of households in the country still lacked access to piped or tap water in their dwellings [15]. In addition, there have been complaints about the quality of drinking water supplied to households in the country [16]. These highlight the inadequacy of the water supply, both in quantity and quality.

A unit of government strategic to water service delivery in South Africa is the Metropolitan Municipalities. These metros, as they are often referred to, coordinate water service delivery to households in the country [17]; however, they are confronted with many challenges in doing this [17, 18, 19, 20, 21], thereby creating widespread dissatisfaction among South Africans [22, 23]. This dissatisfaction is rooted in the inability of the Department of Water and Sanitation (DWS), the national body in charge of water governance, to ensure proper coordination of metropolitan municipalities for adequate water service delivery.

To enhance the water service delivery experience of households in South Africa, especially at the metropolitan municipality level, given its central role in water service provision, there is a need to understand the prevailing water access, quality, and households' satisfaction level. Until these are ascertained, suggesting policy actions towards addressing metropolitan municipalities' challenges in water supply, such as decaying water infrastructure [22, 24], financial mismanagement [25], inadequate skilled manpower [8, 18], and institutional inefficiency [18] might be temporary and less effective. This is given the need to appreciate the magnitude of the situation, in line with recent data, to better plan for effective and efficient intervening policy actions.

Sequel, this paper:

- i. assess household water supply in each metropolitan municipality in South Africa between 2022 and 2024.
- ii. investigate the quality of water supplied to each metropolitan municipality in South Africa between 2022 and 2024.
- iii. identify the water service delivery satisfaction level of households in metropolitan municipalities in South Africa.
- iv. recommends actionable policy initiatives to improve water service delivery among metropolitan municipalities in South Africa.

One basic factor motivated the scope of the study (2022 to 2024). Addressing issues with social service delivery, such as water supply, required the adoption of recent literature and reports to guarantee the recency of the problem being addressed. As supported by [26], focusing on a limited but recent timeframe enables the timely identification of findings that can inform effective recommendations.

While there are existing studies on metropolitan municipality water service delivery performance in South Africa, this study expands their scope by encompassing more areas and recent data. For instance, in the study by [27] that assesses water service delivery performance, the focus was on the cities of Tshwane, Cape Town, and

eThekweni, leaving five other metropolitan municipalities unassessed. This study addressed this gap by covering all eight metropolitan municipalities in South Africa and reassessing the three cities' water service delivery status to establish possible improvements. Furthermore, this paper provided recent insight into the findings of [28] that, aside from actual water service delivery improvements, other factors such as psychological and behavioural influences affect households' water service delivery experience. While the study relied on the General Household Survey dataset from 2015 to 2017, this study uses the Water Services Barometer Survey of 2022, a more recent dataset, to ascertain the level of households' satisfaction with water service delivery using the indicators of drinking water safety and water quality index score.

The findings of this study would not only complement existing studies on the subject but would also inform policy and operational recommendations for improving water service delivery in each metropolitan municipality and South Africa, generally. Furthermore, it would directly support and contribute to the achievement of SDG 6 [29], South African National Development Plan (NDP) and the fulfilment of the mandate of the South African Constitution (1996) in section 27(1)(b) that "Everyone has the right to have access to sufficient food and water" [1].

2 Literature review

2.1 Structure of water service delivery in South Africa

Several policies and legislative frameworks guide water service delivery in South Africa. The essence of these is to ensure orderliness in the provision of water services among the constituent components of the country. Leading in these frameworks is the constitution of the country. For instance, in Act 108 of the 1996 constitution of the Republic of South Africa, Section 27(1)(b) established the inalienable rights of all South Africans to water in sufficient quantity [1]. In addition, Section 152 and Schedule 4B stressed that municipalities were assigned the core responsibility of providing water services to communities. However, only metropolitan municipalities are so mandated, with a few from municipalities in categories B and C.

Other legislations backing up the constitution in its recognition of the right of all South Africans to basic water supply are Water Services Act 108 of 1997 [1]; National Water Act 36 of 1998 that addresses the structure of water resource management; Municipal Structures Act 117 of 1998 that segregate power, functions and responsibilities among the various categories of municipalities. Buttressing this Act was the Municipal Systems Act 32 of 2000, which reassigned water service delivery, integrated development planning, performance management, and public participation to municipalities. In buttressing this, [1] noted that related Acts such as the Municipal Systems Act, the Municipal Structures Act, and the subsequent Amendment Act (Act No. 33 of 2000) divided the municipalities into categories A, B, and C, each having distinct responsibilities. Lastly, the Municipal Finance Management Act 56 of 2003 provided guidelines on the financial management framework for municipalities. This includes budget requirements, revenue, and supply chain management.

Aside from these acts, several policy initiatives such as the National Water Resource Strategy (NWRS-2), the Free Basic Water Policy of 2001, and the Strategic Framework for Water Services of 2003, also support the earlier-mentioned legislative frameworks. Within the purview of these policy strategies were mechanisms for water conservation, tariff structure, and minimum water standards. Adjoining regulatory agencies created to ensure efficient and effective water service delivery in South Africa are the Water Services Authority, the Department of Water and Sanitation, and the South African National Standards (SANS 241:2015), which determine water quality standards.

The constitution, regulations, and Acts position the Department of Water and Sanitation (DWS) as the major body for regulating water service delivery at the national level in the country. As captured in Figure 1, the DWS works in conjunction with several national departments, such as the National Treasury, the Corporate Governance and Traditional Affairs (COGTA), health, the Water Research Commission (WRC), etc. Below the DWS at the national level is the provincial level, which comprises provincial departments, water boards, and the provincial oversight bodies. Right after the province is the local government, which is structured into three categories of A (8 Metropolitan Municipalities), B (44 District Municipalities), and C (205 Local Municipalities).

While DWS coordinates water services delivery, the actual duty of providing water services to households is reserved for municipalities, spearheaded by Metropolitan Municipalities [1]. Despite the critical role of metros in

water service delivery, adequate information on their performance is yet to be sufficiently studied, given that most water service reports are either based on national or provincial assessments. Given this gap, this paper assesses the performance of metropolitan municipalities in South Africa using water supply and quality metrics.

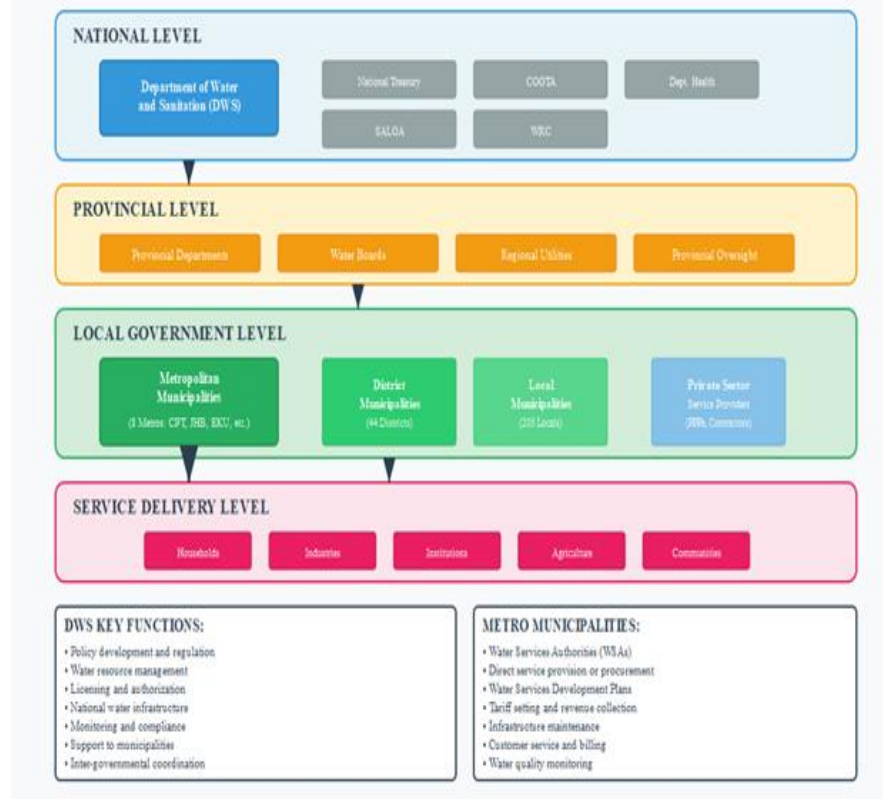


Figure 1: South African Water Services Delivery Governance Structure

2.2 Metropolitan Municipal Performance Measurement Framework

Two key metrics were used to measure the water service delivery performance of metropolitan municipalities in South Africa: water quantity and quality. Three basic indicators of equity, accountability, and satisfaction were adopted to ascertain the appropriateness of water supply in terms of quantity. However, a combination of the National Drinking Water Standard, SANS241:2015, and the Blue Drop Risk Rating (BDRR) is used for water quality assessment. While the former focuses on the constituting chemical components of drinking water, the latter measures the health risks associated with water.

2.3 Theoretical Framework

Public service is uniquely different from commercial services, where affordability or capacity to pay determines access. In accessing public services such as water, equity remains the watchword, often captured as fairness regardless of status or affiliation. Providing water in South Africa falls within the purview of metropolitan municipalities as enshrined in the constitution and several Acts. In discharging this sacred responsibility, equity must be observed. Explaining access to public services such as water can be done using several theories.

Equity theory

This theory was proposed by Homans in 1958 [30] and later enhanced by Adams in 1965 [31]. Equity theory, as posited by [31, 32], examines the extent to which members of an entity perceive fairness and justice in how they are treated. In ascertaining fairness without bias, the theory compares what the first and second person receives. Based on the extent of difference in this, the feeling of equity or inequity is established [32]. The postulations of this theory fit the engagement between the government and the people when it comes to social service delivery issues, such as access to water [33]. Given the South African constitutional pronouncement that “Everyone has the right to have access to sufficient food and water”, access to water must not be class or location-centric, such as focusing on urban areas to the neglect of the rural areas, as it is currently reported in the literature [7, 8, 18, 22, 26, 34].

The theory explains all the possible forms of discrimination in water supply to households in South Africa. Without eliminating these discriminations, [30] furthered that it could lead to citizens’ dissatisfaction [22, 23, 30, 31, 35] with the government and its agencies. Despite the relevance of the equity theory in explaining equity as an indispensable component of water service delivery, the theory fails to comment on other indicators for ascertaining social service performance, such as accountability and satisfaction. Given this gap, the paper explores other theories.

Principal-Agent Theory

The principal-agent theory was propounded by Holmstrom & Milgrom in 1991 [36] and it leverages on the understanding that government services are usually delivered indirectly through its agencies and intermediaries [37]. The theory assumes that principals, in their characteristic manner, lack operational competency and provide only a narrow mandate [38]; thus, the need for agents, who are strategically chosen experts [39], to pursue pre-set goals [37]. Just as observed in the provision of social service delivery, such as water, the national government of South Africa, as mandated by the constitution, is to provide citizens access to water of the right quality and quantity [40, 41]. However, this service is indirectly delivered through municipalities, which are more competent and closer to the people to do this efficiently and effectively.

In this mix, the principal-agent theory, as buttressed by [37], allows a kind of information asymmetry that eliminates accountability. This asymmetry enables the agent to prey on the process [36, 42, 43] and thus culminate in service inefficiency. From this information gap, challenges hindering effective water service delivery by metropolitan municipalities, such as financial mismanagement [25] and institutional inefficiency [18], manifest. Even though in this case, the principal through DWS regulates and monitors the activities of metropolitan municipalities [1], the service inefficiency persists [42].

From this theory, this paper extracts the indicator of accountability in the relationship between the government and its agents managing water service delivery in South Africa. To what extent does the government hold the metropolitan municipalities accountable for water service delivery to households? The extent to which this is done is significant in measuring the performance of these metros in water service delivery.

Public Value Theory

To complete the circle, there is a need for service feedback from households. Given this need, the third theory-public value theory, was adopted. This theory, proposed by Moore in 1995 [44], examines public service delivery from the people’s value perspective [45]. It seeks to direct government efforts towards value creation [45, 46, 47, 48], thereby enhancing the government’s effectiveness [47]. In essence, it proposes the involvement of people in the choice of government actions and inactions [44]. In the delivery of water service, this theory suggests that there is a need for the integration of communities in the process. Aside from creating a sense of importance in the minds of the people, it could also facilitate the development of responsible water use and water infrastructure protection. The core values that are of importance in the delivery of social services, such as water, as proposed by this theory, are effectiveness in service delivery, trust in government and its agencies, transparency [47], and public participation in the service delivery process [46]. This theory, therefore, offers the theoretical platform for evaluating water service delivery performance [49] in the South African municipalities to understand the extent to which the service incorporates public values through public satisfaction.

2.4 Integrated theoretical model

Individually, none of the theories had the combined indicators adopted in this paper; each complements the others. To better explain how the theories integrate to explain metropolitan water service delivery, Figure 2 was prepared using draw.io, an illustration design programme.

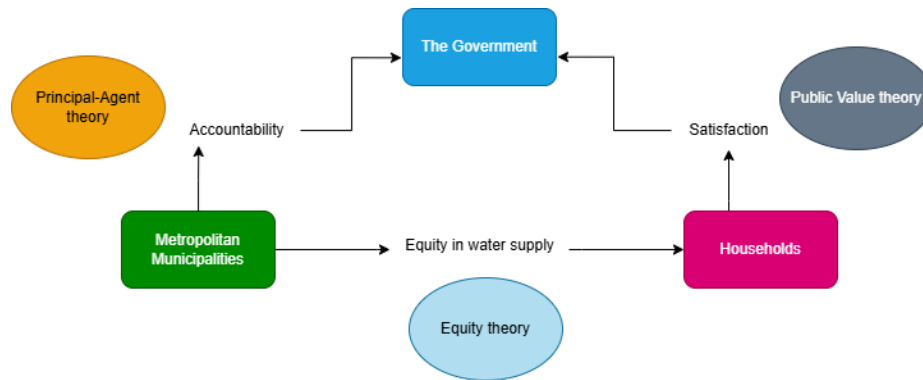


Figure 2: Integrated Measurement Indicator for Water Service Delivery Performance.

In the delivery of public services, three distinct parties are involved - the government, its delivery agency, and the people. Different mechanisms guide the interaction among these entities. As depicted in Figure 2, principal-agent theory explains the interaction between the government and its agencies, where the agency is accountable to the government, its principal. Also, a reasonable level of service equity is expected between the agency and the people (households). It is here that the equity theory assumed relevance, while between the households and the government, the public value theory emphasizes the importance of service feedback, with which satisfaction or dissatisfaction could be expressed.

Simply put, metropolitan municipalities in South Africa are responsible for supplying water to residents in the appropriate quantity and quality. In explaining this mandate, three relevant theories have been discussed, with each contributing one indicator to explaining the water delivery performance of metropolitan municipalities. Given each limitation, as individual frameworks, and the strengths in combining the three, the integrated model presented in Figure 2 was adopted.

3 Research methodology

3.1 Data Sources and Analysis

In pursuit of the objectives of this paper, existing quantitative secondary data were adopted from a public database. Aside from saving time and eliminating the administrative hurdle associated with primary data collection from government agencies and households, the adopted data repositories maintained by municipalities, provinces, and the national government offer data in an organized and condensed format, making it easy for extraction. Thus, data for this paper were sourced from:

- i. Stats SA (Department: Statistics South Africa). Accessed on 4th July 2025; 11:42 am. https://www.statssa.gov.za/?page_id=1854&PPN=Report-03-01-83. Report-03-01-83 - The state of basic service delivery in South Africa: Analysis of Census 2022 data, 2022. Publication date & time: 31 October 2024 @ 14:30.
- ii. Stats SA (Department: Statistics South Africa). Accessed on 5th July 2025 @ 11:52 am. https://www.statssa.gov.za/?page_id=1854&PPN=P0302. P0302 - Mid-year population estimates, 2024. Publication date & time: 30 July 2024 @ 11:00.
- iii. Blue Drop Progress Report (2023). Department of Water & Sanitation, South Africa. Accessed on 4th July 2025 @ 11:54 am <https://ws.dws.gov.za/IRIS/latestresults.aspx>.

- iv. Blue Drop Progress Report (2022). Department of Water & Sanitation, South Africa. Accessed on 4th July 2025 @ 11:54 am. https://ws.dws.gov.za/iris/releases/2021_BD_PAT_report_final-28Mar22_MN_web.pdf
- v. No Drop Report (National), 2023. A document from the Department of Water and Sanitation. Accessed on 5th July 2025 @ 18:52. https://ws.dws.gov.za/IRIS/releases/ND_2023_Report.pdf
- vi. The Water Service Barometer Study (2022). User perceptions of the current provision of water services in South Africa. A document of the Water Research Commission (WRC) research project. Accessed on 5th July 2025 @ 10:01 am. <https://www.wrc.org.za/wp-content/uploads/mdocs/TT%20909.pdf>

Numerical survey data were extracted from the sources above, sorted based on structural similarity, merged, and descriptively analysed using frequency and percentages to gauge the extent of the prevalence of the adopted indicators.

3.2 Data coverage

The data used in this paper spanned the period from 2022 to 2024. The motivation for this is that addressing issues with social service delivery, such as water supply, requires the adoption of recent data and reports to guarantee the recency of the problem being addressed. As supported by [26], focusing on a limited but recent timeframe enables the timely identification of findings that can inform effective recommendations.

3.3 Study area

This study focused on the Category A municipalities, often referred to as Metropolitan Municipalities or simply Metros. This is due to their direct involvement in the provision of water services to households in their constituency [50]. Data on water supply in these metropolitan municipalities from 2022 to 2024 was extracted and analysed from the public reports by government departments and agencies in South Africa.

There are eight metropolitan municipalities in South Africa (see Figure 3), and all, as listed below, are covered in this paper.

- i. Buffalo City
- ii. City of Cape Town
- iii. City of Ekurhuleni
- iv. City of Johannesburg
- v. City of Tshwane
- vi. eThekweni
- vii. Mangaung, and
- viii. Nelson Mandela Bay.

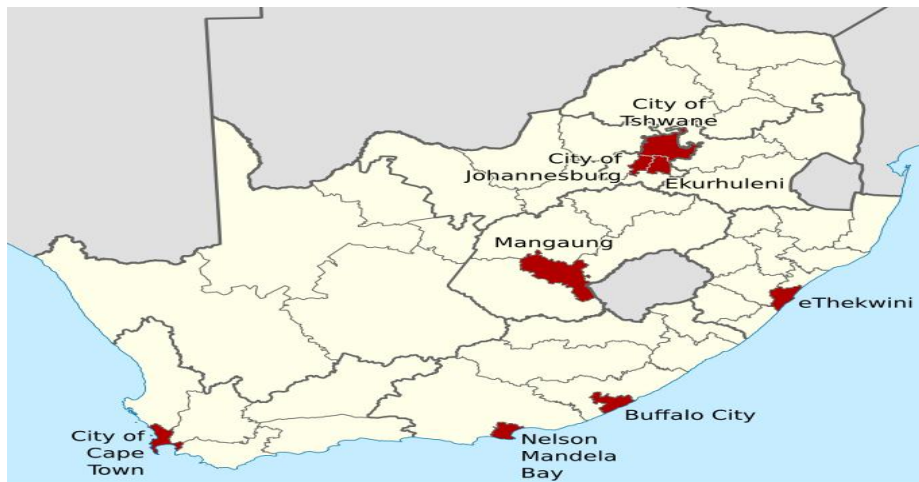


Figure 3: Map of South Africa showing the Eight Metropolitan Municipalities
 Source: Google Image Search

3.4 Limitations in the adopted data

Despite that, the data adopted in this paper is robust and current; it is still prone to the following limitations:

- i. Adequacy: This paper required data on water access, drinking water quality, and households' water service delivery satisfaction. Although complete data on each of these indicators were found for the years 2022, 2023, and 2024, water access and drinking water quality data were found for 2022 and 2023, while household satisfaction data were found for 2022.
- ii. Data Bias: The data adopted in this paper were harvested from government agencies' databases, including the one on household satisfaction level. Criticism could arise on the need for a non-government-conducted survey to ascertain households' water service delivery satisfaction experience.

Even though the limitations above exist, they do not fundamentally compromise the validity of this study's contributions to understanding water service delivery dynamics in South Africa. Specifically, this paper focuses on relational analysis between service indicators rather than absolute measurements, making it robust to systematic biases. The findings of the paper provide invaluable insights into the nexus among water access, quality, and satisfaction that remain valid despite the temporal and data source limitations mentioned. Furthermore, the approach adopted in this paper aligns with established practices in development research where perfect data is scarcely available, especially when relying on secondary data, making researchers work with the best available evidence. The robustness of limitations combined with transparent acknowledgment ensures that conclusions drawn are scientifically sound and practically relevant for policy development.

3.5 Ethical considerations

In the use of public data such as those made available by Statistics South Africa and DWS, the ethical requirements are that:

- a. The data should not be altered. Though researchers can decompose the data to extract what is needed in a study, data fabrication is unethical and rejected. Thus, this study adopted correct data without any kind of alteration.
- b. Proper acknowledgement: In this study, all data sources are adequately acknowledged.

4 Results and analysis

4.1 Performance metrics

An integrated model formed from Equity, Principal-Agent, and Public Value theories (see Figure 2) is adopted to ascertain the performance of metropolitan municipalities in water service delivery. The model adopted equity in access, accountability, and public satisfaction as performance metrics. These metrics have assumed prominence in ascertaining the performance of water service delivery [51, 52].

Access to Improved Water Sources by Households in Metropolitan Municipalities

Access refers to the extent to which people can get water when needed. According to [1], unrestricted access to water is a universal right, and the South African government is committed to ensuring it. To measure access in this study, data on water supply to households were extracted from [1, 2]. According to the 2022 census data in South Africa, households could be classified into four categories regarding how they access water. While 59.7% of households in the country access water inside their dwellings, 22.7% of households get water from within their yard, 8.9%, outside their yard, and 8.7% had no access to water. This country overview indicated that about 91.3% of households have access to water. However, for a more detailed assessment of water access, especially at the metropolitan municipality level, given their role in water service delivery in the country, Figure 4 was presented.

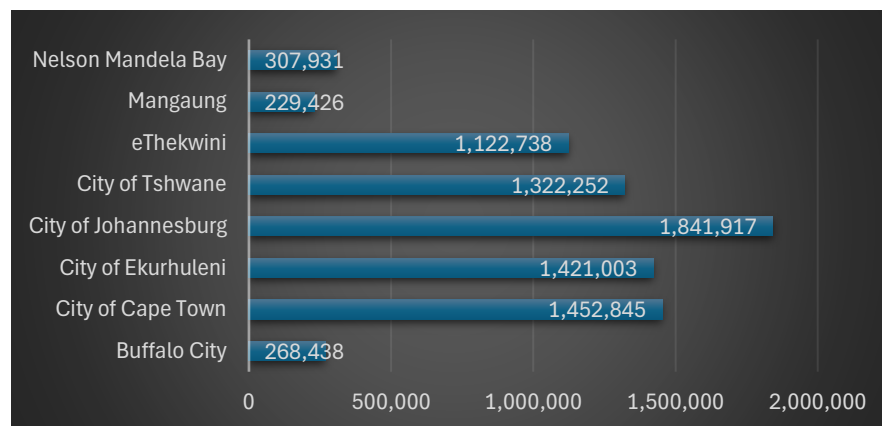


Figure 4: Number of Households in each Metropolitan Municipality in South Africa

Source: [51]

Table 1 presents further information to complement that in Figure 4. Table 1 presents information on the percentage of water distribution in the eight metropolitan municipalities in South Africa. Table 1 allows for water supply comparison over a period of three years. In 2022, the average percentage of water access by households was 96.2 out of the 7,966,550 households in the country [1], indicating a significant water supply to South Africans. An in-depth study of the data enables metro comparison. For instance, in the cities of Tshwane and Buffalo City, the lowest water supply percentages of 94.2 and 94.3 were recorded, indicating the need for improved water service delivery in the areas. By 2023, an improvement of 1.6% and 2.4% was recorded in the two cities, respectively. In 2024, however, while the City of Tshwane experienced a further boost in the percentage of households' access to water, a decline of 1.1% was recorded in Buffalo City, showing that the improvement observed in 2023 was not sustained in the following year.

In the City of Cape Town, even though access to water services by households was impressive, the city further enhanced its coverage to include an additional 2.2% in 2023, which was sustained in 2024. This emphasized the city's concerted effort in promoting the achievement of the South African constitution's mandate of ensuring unhindered access to safe drinking water. In line with this trend, a continuous increase in households' water access from 2022 through 2024 can be observed in the Cities of Ekurhuleni and Johannesburg. This underscores the investment effort in these metropolitan cities. However, in eThekweni, Mangaung, and Nelson Mandela Bay, there

are fluctuations in the percentage of households' water access, showing the need for a proper study of these cases to understand the factors creating the instability in water service access.

Table 1: Percentage distribution of household water supply to Metropolitan Municipalities in South Africa.

Metropolitan Municipalities	2022	2023	2024
Buffalo City	94.3	96.7	95.6
City of Cape Town	97.6	99.8	99.8
City of Ekurhuleni	98.2	98.6	99.3
City of Johannesburg	97.6	98.9	99.6
City of Tshwane	94.2	95.8	96.5
eThekweni	95	95.3	94.9
Mangaung	95.4	91.7	96.2
Nelson Mandela Bay	97.5	87.6	98.2

Source: Curated from reports from [1, 2, 15].

Access to water is just a component of effective water service delivery. Equally important is the extent to which households experience water service interruption. To analyze this trend, Table 2 is presented to profile the percentage distribution of households that reported water service interruption, at least for two days, in the metropolitan municipalities.

Table 2: Percentage distribution of households that reported water interruption (at least two days) by Metropolitan Municipalities in South Africa.

Metropolitan Municipalities	2022	2023	2024
Buffalo City	34.8	66.7	27.5
City of Cape Town	5.8	28.8	6.9
City of Ekurhuleni	11.8	38.3	17.4
City of Johannesburg	18.3	37.7	25.3
City of Tshwane	17.1	47.3	23.2
eThekweni	61.2	53.3	28.6
Mangaung	37.9	44.6	21.8
Nelson Mandela Bay	46.0	43.8	40.3

Source: Curated from reports from [1, 2, 15].

In Table 2, indications of significant water interruption can be noticed in almost all focus areas. For example, between 2022 and 2024, it is only in eThekweni and Nelson Mandela Bay that a steady reduction in the percentage of water interruptions could be noticed. In every other metropolitan municipality, the rate has continued fluctuating, thereby discrediting the vague assumption that water service delivery in the focused areas is effective, given the data in Table 1. Exploring the factors responsible for the concerning water service delivery interruption rate would require comparing the adopted data in this study with contemporary literature on the subject.

Quality of Water Supplied to Households in Metropolitan Municipalities of South Africa

The overall well-being of an individual is dependent on the extent of hygiene observed in what is consumed. As water is an indispensable component of what people consume daily, ensuring its safety has remained an essential concern to governments. Accountability, as extracted from the principal-agent theory, is adopted to report the quality of water supplied by metropolitan municipalities in this study. This is to explore the extent to which metropolitan municipalities complied with the directives of their principal and the national government to provide safe drinking water to their constituencies. In ensuring water safety, the South African government adopted a

National Drinking Water Standard, SANS 241:2015. This standard relies on a web-assessment tool, Blue Drop Risk Rating (BDRR), for assessing drinking water compliance with chemical and microbiological components.

In the BDRR assessment, five risk indicators of Design Capacity, Operational Capacity, Water Quality Compliance, Technical Skills, and Water Safety Plan were adopted to address drinking water's risk assessment requirements as contained in the SANS 241:2015 standards. The BDRR formular is: $BDRR = (A \times B) + C + D + E$

Where the weighting factor is based on the following five risk indicators:

A - Design Capacity: Larger plants present a higher risk as they supply water to a larger population.

B - Operational Capacity: Plants operating above their installed capacity present a higher risk as their capability is compromised to deliver safe drinking water.

C - Water Quality Compliance: C1 Microbiological (70%) + C2 Chemical (30%).

D - Technical Skills: Poor technical, management, and maintenance skills base present a collective and individual high risk.

E - Water Safety Plan: The absence of a WaSP, risk-defined monitoring programme based on full SANS 241 assessment and implementation of actions to reduce risk, would represent a high risk due to non-compliance with SANS 241 requirements and lack of risk-management procedures.

The proportional risk allocation between the components is 35:35:20:10 for A/B: C: D: E.

Therefore, full BDRR formular = $(35\% (A \times B)) + [35\% C (70\% C1 \text{ (Micro compliance X monitoring compliance)} + 30\% C2 \text{ (Chemical compliance x monitoring compliance)}] + 20\% D + 10\% E$.

A BDRR value is calculated for each water supply system in South Africa, as provided in Blue Drop Reports [16, 52]. A BDRR %deviation is used in this study and calculated using the following formular: $BDRR\% \text{ deviation} = BDRR / BDRR_{max} \times 100$. Where $BDRR_{max}$ = Maximum BDRR of the water supply system. The BDRR% deviation is a calculated unit of risk measurement that indicates the variance of a BDRR value before it reaches its maximum BDRR value. This unit of measurement allows the Department of Water and Sanitation to compare all sizes and types of water treatment plants equally. All water supply systems are categorised according to their risk rating, placing them in one of four categories as reflected in Table 3.

Table 3: BDRR Risk Rating Categorization.

Low	Medium	High	Critical
<50%	50%<70%	70%<90%	90%<100%

In the rating, the lower the risk percentage, the better the water safety for household consumption. In this study, the BDRR rating data for 2022 and 2023 were found in the Stats SA database, with that of the year 2024 yet to be updated. Given this data limitation, the water quality status for only 2022 and 2023 was provided and discussed as captured in Table 4.

Table 4: Metropolitan Municipality BDRR rating for 2022 and 2023.

Metropolitan Municipalities	2022	2023	Status
Buffalo City	31.6%	41.7%	↓
City of Cape Town	25.7%	31.0%	↓
City of Ekurhuleni	33.3%	29.2%	↑
City of Johannesburg	34.7%	29.2%	↑
City of Tshwane	35.2%	33.1%	↑
eThekweni	32.6%	31.6%	↑
Mangaung	72.5%	36.2%	↑
Nelson Mandela Bay	31.9%	45.9%	↓

Source: Curated from reports from [1, 15].

In Table 4, the BDRR rating for metropolitan municipalities indicated mixed results. While improvements in the quality of water supplied were reported in the cities of Ekurhuleni, Johannesburg, Tshwane, eThekweni, and Mangaung, the opposite was recorded in Buffalo City, the city of Cape Town, and Nelson Mandela Bay, indicating the need for crucial effort in assessing the factors responsible for this water quality decline. When this BDRR rating overlaps with the water interruption data in these three metros in 2022 and 2023, a new perspective emerges.

For instance, in 2022, the water interruption rate in Buffalo city was 34.8% with an increase of 31.9% in 2023. This increase in the rate of water interruption is further worsened by the declining water quality rating reported in Table 4, thereby indicating the need to examine the issues surrounding this emerging scenario.

Similarly, in the City of Cape Town, an increase of 23% in the percentage of water interruption (for at least two days) from 5.8% in 2022 to 28.8% in 2023 raises some concern. This was further complicated by the decline in the quality of water in the city from 25.7% to 31%. Even though the water risk rating is still in the low category, there is a need to watch this trend to avoid the rating from moving from the current low risk category to the medium category. Out of the three metropolitan municipalities with a declining water risk rating, only Nelson Mandela Bay recorded a reduction in water interruption between 2022 and 2023. Even though a sustained water interruption reduction is equally recorded in 2024 as indicated in Table 2, there is still some concern with the quality of water being supplied in the metro, especially given the closeness of the 2023 risk rating category.

In all other metropolitan municipalities, considerable improvements in the risk rating of water supplied were reported, with the best improvements noticed in Mangaung, where the risk rating declined from the High-risk category (72.5%) in 2022 to a Low-risk rating category (36.2%) in 2023. This showed the extent of effectiveness in the strategy deployed by the metro in addressing the challenges with the quality of their water supply to households. To explore the connection between the level of water interruption and the water risk rating on the quality of water service delivery infrastructure available in the metropolitan municipalities, the data on the Water Infrastructure Quality Index (WIFI) is provided in Figure 5.

According to [1], WIFI classifies engineering infrastructure based on the level of services that households have access to. There are five categories of infrastructure classification using WIFI (namely: no service (1), minimum (2), basic (3), intermediate (4), and full service (5)). This classification is calculated based on the water service delivery infrastructure condition in each metropolitan municipality [1]. In the South African water regulation, a WIFI of above 4.5 indicated best access to improved water services among metropolitan municipalities. The score of the various metropolitan municipalities in the country in 2022 is as depicted in Figure 5.

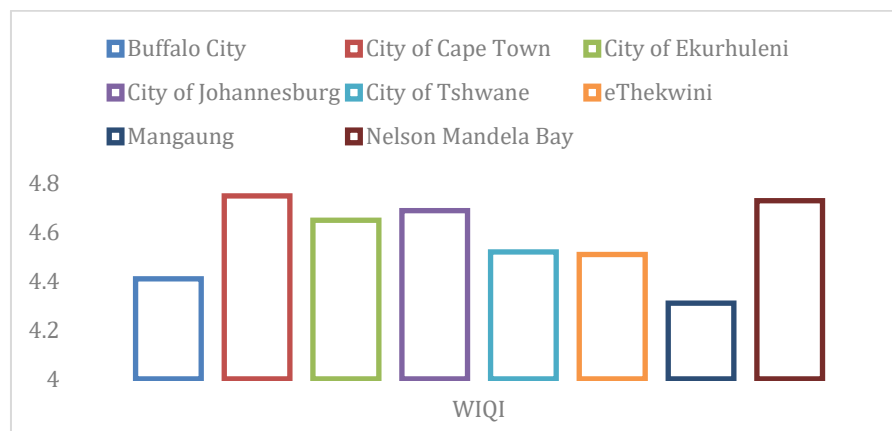


Figure 5: Water service infrastructure quality index by metro in 2022.

In all the metropolitan municipalities in South Africa, the minimum WIFI score was 4.31 (Mangaung), with others scoring as high as 4.75 (City of Cape Town), indicating good access to improved water service, thereby complementing the data in Table 1. However, the level of water interruption experienced by households in focus areas, despite the excellence of water infrastructure in the metros is concerning. Even though access to water services delivered by metropolitan municipalities was laudable in 2022, this study held that adequate attention is yet to be paid to other factors, aside from the quality of water infrastructure, that have a bearing on reducing cases of water interruption by metropolitan municipalities.

Even though this study could not access the BDRR rating for the years 2024 and that of WIFI for 2023 and 2024, insight from the available data provided a valid platform for exploring the water quality dimensions in South Africa. This limitation was further enhanced by the findings of contemporary literature on the subject.

Public Satisfaction with Household Water Supply in Metropolitan Municipalities

In ascertaining public satisfaction with water supply by metropolitan municipalities in South Africa, there is a need for specialized data on the user perceptions of water provision services in the country. Given the extensive resources associated with getting this data from the primary source, this study adopted the Water Services Barometer Study 2022. This report emanated from the concerted efforts of the Water Research Commission (WRC) and the South African Local Government Association (SALGA) in exploring the perception of households on water provision services in the country. The survey was built on similar early initiatives of 2011 and 2015 to ascertain the present water service delivery satisfaction status of water service users in the country. Using a combination of close-ended questionnaires and structured interviews designed around 12 questions focusing on the perception of households on water delivery services, the survey reported a dual service experience of South Africans. In urban areas, 79% of the respondents indicated satisfaction with water quality, while in the rural areas, 64% laud the quality of water services, 12% stated that drinking water is sourced from rivers and wells, rather than from taps, so they do not know about tap water service quality. This further established the disparity in water service delivery between the urban and rural areas of South Africa [26].

To further explore the spread of users' experience on water service delivery in South Africa, Table 5 is presented. In the table were three indicators of drinking water safety, water service quality, and overall customer satisfaction. The first indicator was calculated using the percentage of responses on drinking water safety. In this regard, the higher the percentage, the higher the respondents' satisfaction with water safety in each metro. The service quality perception score calculated a composite score out of 10 for respondents' perceptions across 14 aspects of municipal water and sanitation services. The perceived Service Quality Index (SQI) scores were interpreted as: 9 or more out of 10 = outstanding; 7 or more, but less than 9 = very good; 6 or more but less than 7 = good; 5 or more but less than 6 = adequate; and less than 5 = disappointing/requires urgent improvement. Four aspects of water and sanitation services were explored to ascertain the extent of customers' satisfaction with the overall water services. These aspects were the level of metropolitan municipality's water services (water quality, water supply, maintenance of sewage pipes, meter readings), water tariffs, metro municipality's sanitation services (the toilets they supply, maintenance of sewage pipes, sewage treatment), and sanitation service charges. Thus, the formula adopted for calculating the customer satisfaction index was:

$$\text{Index} = \frac{\text{Total score}}{20 - (\text{sum of NAs} \times 5) \times 10}.$$

Table 5: Households' water services delivery satisfaction score

Metropolitan Municipalities	% of Drinking Water Safety	Service Quality Index Score	Customer Satisfaction Index Score
Buffalo City	57	6.33	6.97
City of Cape Town	73	7.00	7.30
City of Ekurhuleni	89	6.90	7.32
City of Johannesburg	89	6.16	6.86
City of Tshwane	100	6.64	6.69
eThekweni	85	6.45	6.91
Mangaung	76	6.12	6.82
Nelson Mandela Bay	53	6.09	6.84

Source: Extract from the Water Services Barometer Study (2022).

In Table 5, there were indications of water safety concerns in seven of the eight metropolitan municipalities in South Africa. This is given by the percentage of responses in favour of the subject. Aside from the City of Tshwane, the extent to which households are satisfied with the safety standards of drinking water is less than 100%, with the lowest water quality confidence in Nelson Mandela Bay and Buffalo City. Furthermore, the service quality index score was at its lowest in Nelson Mandela Bay, Mangaung, and the City of Johannesburg, showing the need for improved water service delivery in these areas. Overall, only the City of Cape Town had a "very good" score in service quality, with none reaching the outstanding service quality status.

The customer satisfaction index score is adopted to ascertain South Africans' general satisfaction with water service delivery. As shown in Table 5, none of the metropolitan municipalities scored below the “adequate score” grade; however, the data showed the yearnings of the South African people for improved water service delivery. Aside from the Cities of Cape Town and Ekurhuleni, where the satisfaction index score was “very good”, other metros’ performance was just considered “good”. As there were no data on households’ water satisfaction level for 2023 and 2024, the conclusion of this paper shall be in line with that of 2022.

5 Discussions

This section is structured in line with the objectives of the paper.

5.1 Households’ water access in Metropolitan Municipalities in South Africa

Water is an indispensable component of people’s daily diet [1]. Even medically, people have been encouraged to take water in a reasonable quantity, especially in arid countries of Africa such as South Africa [6, 7]. In the country, and mostly in the metropolitan municipalities, supplying water to households has been challenging [17], given several impediments confronting the water sector. To streamline the policy approach to addressing this trend, this study examines the current water service delivery performance of each metropolitan municipality in the country. From the findings of the study, it was evidenced that in 2022, access to water service delivery was in four categories of access to water inside dwellings (59.7%), access to water with the yard (22.7%), access to water outside the yard (8.9%), and households without water supply access (8.7%). Overall, 91.3% of households had access to water in South Africa, indicating a significant water service coverage in the country in 2022. However, significant water service performance variation exists among metropolitan municipalities regarding water access. While impressive water supply records were evidenced in the Cities of Ekurhuleni, Cape Town, Johannesburg, and Nelson Mandela Bay, other metros, such as Mangaung, eThekweni, Buffalo City, and the City of Tshwane, trailed behind.

Also, in 2023 and 2024, this performance variation persists with sustained improvements in the Cities of Cape Town (an increase of 2.2% in 2023 and maintained in 2024), Ekurhuleni, and Johannesburg. This demonstrates consistency in the commitment of these metropolitan municipalities to water service delivery. However, metros with low water supply performance were the City of Tshwane (94.2%) and Buffalo City (94.3%), indicating the dire need for improved water service delivery in these metros. In addressing this trend in these metros, however, there is a need to factor in the inconsistency, notably visible in Buffalo City here in 2023, where water access improved by 2.4%, but declined by 1.1% in 2024. Unlike in Tshwane, where water access improvement was sustained in 2023 (1.6% increase) and 2024 (0.7% improvement). A similar performance fluctuation could be noticed in eThekweni, Mangaung, and Nelson Mandela Bay, indicating the need for a detailed analysis of the factors responsible for the performance instability. While commenting on water service inconsistency among metropolitan municipalities in South Africa, [8] emphasised this inconsistency in Nelson Mandela Bay.

Another important indicator for assessing households’ water service delivery performance is the frequency of water interruptions. This paper found that significant water interruptions occurred in all metropolitan municipalities, and these interruptions lasted for at least two days. Within the focused period (2022 and 2024), only eThekweni and Nelson Mandela Bay displayed steady improvement in reducing the occurrence of water interruptions, thereby demonstrating service reliability. However, trends could be observed in Buffalo City, Cities of Cape Town, Ekurhuleni, Johannesburg, Tshwane, and Mangaung, where surges in the frequency of water interruptions characterized the year 2023. This calls for a dedicated study of the factors responsible for this surge in these metros in 2023. While confirming the inconsistencies with water service delivery in Tshwane, Mangaung, and Nelson Mandela Bay, [50] added that similar service deficiencies are also true of the cities of Ekurhuleni, Johannesburg, eThekweni, and Buffalo City.

In comparing water supply access with the extent of water interruption, an insight emerged into the effect of water interruption on water service quality. This effect demonstrated that persistent water interruptions could indicate water supply quality issues beyond water access metrics. On water interruption among metropolitan municipalities, [55] buttressed that water service is inadequate, especially in Nelson Mandela Bay, where residents were averse to paying for water services. The literature offers insight in explaining the factors causing water interruptions among metropolitan municipalities in South Africa. Decaying water infrastructure [22, 24], financial

mismanagement [25], inadequate skilled manpower [8, 18], and institutional inefficiency [18] are a few of the hindrances confronting metros in the delivery of water services to households.

5.2 Households' water service quality in Metropolitan Municipalities in South Africa

Given the extent of data available on drinking water quality among metropolitan municipalities (2022-2023), this study found that Ekurhuleni, Johannesburg, Tshwane, eThekweni, and Mangaung demonstrated improved water quality during the focused period. The most significant improvement is particularly in Mangaung, where the BDRR rating dropped from high (72.5%) to low (36.2%). Concerns could be observed in the trend in Buffalo City, City of Cape Town, and Nelson Mandela Bay, where the BDRR rating increases, thereby indicating a reduction in drinking water quality in these metros. More particularly, the trend in Buffalo City is most concerning, given that within 2022 and 2023, the city experienced a significant water interruption level from 34.8% in 2022 to 66.7% in 2023. In the same period, the water quality drops, showing a dual failure in water access reliability and safety, further validating the need for a detailed analysis of what is going on in the metropolitan municipality.

Equally, in the City of Cape Town, there was an indication of a rapid water service. For instance, the water interruption rate moved from 5.8% in 2022 to 28.8% in 2023, showing a 23% increase. Furthermore, the risk of drinking water quality moved from 25.7% to 31%, indicating a significant quality concern in the water service in the metro. In Nelson Mandela Bay, a mixed performance was recorded as the metro reported a decrease in the rate of water interruption, a positive score, but as regards water quality, it recorded a negative score, given the increased BDRR rating, pushing the metro towards the medium-risk category.

Furthermore, the WIQI assessment showed an excellent water infrastructure status across all metropolitan municipalities in South Africa. More closely, in this regard, the City of Cape Town had the highest WIQI score (4.75), indicating access to improved water services, while Mangaung recorded the lowest score (4.31), also indicating a commendable water service infrastructure. This infrastructure further complements the improved water supply recorded across the metropolitan municipalities within the study period. An emerging concern, however, is the level of water interruption recorded, despite the excellent status of water service infrastructure. There is a need to explore other factors that could explain the increasing water interruptions besides the infrastructure deficit.

5.3 Households' water service delivery satisfaction in Metropolitan Municipalities in South Africa

Relying on the Water Services Barometer Survey, this paper finds a moderate but concerning water service delivery satisfaction landscape across South African metropolitan municipalities. Even though none of the metros fall below the 'adequate' satisfaction level, systemic underperformance is evident, especially as none of the metros achieved the 'outstanding' service status. A deeper insight into the findings of this paper showed that seven out of the eight metros in the country indicated water safety satisfaction gaps, with Buffalo City and Nelson Mandela Bay showing the most significant concern, as noticed in the low drinking water safety score.

The findings further positioned the City of Cape Town and Ekurhuleni as the most satisfying metros in water service delivery, even though others had a slightly lower score. The absence of any metro within the 'outstanding' satisfaction metrics shows systemic performance improvement opportunities for all metros. This thus underscores the need for a sector-wide reform. Lastly, there is an established disparity in urban-rural water service delivery. Bridging this gap is important and urgent.

5.4 Recommendations on the factors hindering effective water service delivery in the South African Metropolitan Municipalities

Challenges confronting the water service delivery sector in South Africa are both general and peculiar. The general challenge found in this study was the need for a sector-wide service delivery reform to enable users' experience of water services to reach 'outstanding' status. Even though WIQI data showed the availability of excellent water infrastructure across metropolitan municipalities, the incidence of water leakage invalidates this claim, further necessitating investment in infrastructural maintenance. In the works of [22, 24], recent investment in the maintenance of water infrastructure has been low, which has occasioned continuous water loss due to leaking pipes. Other general challenges that might explain the fluctuating water service delivery performances as found in this paper were suggested in the literature, such as inadequate skilled manpower [8, 18].

The city of Mangaung has a significant challenge in maintaining a steady water supply, given the high rate of water interruptions in the metro. In support of this finding were [56], who equally reported that Mangaung faces severe drought that has occasioned water shortage in the municipality. Although in a mild proportion, sharing in this challenge is eThekweni and Nelson Mandela Bay [8, 57].

Given the findings of this paper and the complementary information from supporting literature, this paper proposes the following actionable policy initiatives for water service delivery improvements among metropolitan municipalities in South Africa:

- a. To address the issues with critical underperforming metropolitan municipalities, such as Nelson Mandela Bay, Buffalo City, Mangaung, and the City of Johannesburg, there is a need for:
 - i. The establishment of a water service delivery task force in each of the metros with dedicated national oversight.
 - ii. The metropolitan municipalities should foster best practices exchange between high-performing (City of Cape Town and Ekurhuleni) and low-performing ones.
- b. To enhance water quality, there is a need for the deployment of real-time water quality monitoring platforms. This will enable a timely response to water safety cases among metros. The DWS should coordinate this to minimise procurement and management costs associated with the required technology.
- c. To minimise the incidence of incessant water interruption, using Internet of Things (IoT) sensors and data analytics, the DWS should develop a predictive maintenance system that issues notifications of possible infrastructure damage.
- d. To enhance the capacity of water management officials, there is a need for the establishment of a national water management training institute that focuses on training metro staff in the best practices in water management and water service delivery.
- e. Specifically, this paper is faced with significant data absence in many of the adopted water service indicators in this study. It is arising from this that this paper recommends a regular and periodic data update on the public databases of public service bodies to support social-service-oriented studies and researchers.

6 Conclusion

This paper explored water service delivery performance across metropolitan municipalities in South Africa between 2022 and 2024. Specifically, the paper adopted three basic measurement indicators of water access, water quality, and household water services satisfaction. The findings revealed a significant disparity in the performance of the metros. While the City of Cape Town and Ekurhuleni demonstrated consistent water service excellence, Buffalo City, Nelson Mandela Bay, and Mangaung struggled with incessant water interruptions and declining water safety. Despite the robust water infrastructure status reported in WIQI, systemic challenges, such as leaking water pipes and institutional inefficiency, undermine reliable water service delivery among metros in South Africa.

This paper thus concludes that for South Africa to effectively address the persistent water service delivery challenges before it and efficiently achieve SDG 6 by 2030, there is the need for crucial investment in water management technology, establish water service delivery taskforce across metros, invest in wastewater treatment technologies, establish a national water management training institute to regular provide trainings to metro staff. Lastly, inter-metro best practices sharing must be entrenched, while a public database with updated water performance data must be made available to support water research.

There are two major limitations in this study. Firstly, the paper examined water service delivery performance in the eight metropolitan municipalities in South Africa, leaving close to fifty other municipalities in Categories B and C, unattended. Secondly, adequate data to enable objective period comparison was lacking. Subsequent studies could investigate water service delivery performance in the uncovered municipalities, focusing on the peculiar factors responsible for the observed performance trends. Furthermore, studies need to explore primary data sources, especially from households, to triangulate existing public survey reports.

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Declarations

Author Contributions

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Data Availability Statement

The data used in this study is publicly available at the websites of various agencies of the South African government.

Assessing the Dynamics of kilowatt per capita in Nigeria; Evidence from Non-Seasonal ARIMA modeling

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Abstract - Using data from 1990 to 2023, this study examines the suitability of a non-seasonal ARIMA (0,1,1) model with drift for short-term forecasting of Nigeria's annual per-capita electricity consumption (kWh). ACF/PACF analysis was used to determine the model specification, which was ARIMA (0,1,1) with drift ($\mu = 1.6456$). The mean of the first differences was subtracted to estimate the drift. A moving average coefficient ($\theta = -0.2246$) was obtained by maximum likelihood estimation, and a Ljung-Box test ($p = 0.2941$) verified the model's adequacy and showed no discernible residual autocorrelation. Per-capita electricity use is expected to rise gradually between 2024 and 2026, with prediction intervals increasing over time to reflect growing uncertainty. These findings imply that the parsimonious ARIMA (0,1,1) with drift is a useful and interpretable tool for policy and planning in situations with limited data since it accurately captures the central trend in Nigeria's per-capita electricity consumption and offers trustworthy short-term forecasts.

Key words: Non-seasonal ARIMA, Kilowatt Per capita, Dynamics, Ljung-box

1 Introduction

1.1 Background of the study

The use of energy is an important marker of a nation's economic growth and its society's welfare. In the case of Nigeria, where energy access is still a major concern, knowing the consumption trends helps plan infrastructural development in the country, helps to grow its economy, and improves corpus sustainability [1]. Despite having large reserves of fossil fuels and renewable energy, Nigeria's erratic electricity supply makes the population heavily depend on alternative, and more often than not, more inefficient sources [14]. Recently, the kilowatt per capita metric has emerged as a useful normed measurement of electricity usage which factors in population growth for longitudinal and international comparisons [4]. In most developing countries, including Nigeria, reliable access to electricity remains a persistent challenge despite growth in the population base and increased energy demand. Nigeria, the most populous nation in Africa, continues to face low power generation, poor distribution, and infrastructural decay, all impacting electricity consumption per capita [2].

An understanding of electricity consumption per capita trends is required to inform energy policy, organize infrastructural investment planning, and monitor achievements in sustainable development [15]. Time series modeling provides a robust instrument for analyzing such dynamics, allowing researchers and policymakers to determine underlying patterns and make reliable predictions.

While some research has applied seasonal ARIMA or hybrid models to explain global energy consumption trends [5], a knowledge gap within the literature for non-seasonal ARIMA modeling of per capita electricity consumption in Nigeria has existed. This study aims to fill this gap by investigating the pattern over time and short-run behavior of per capita electricity consumption via a non-seasonal ARIMA model. The research adds to improved knowledge of energy demand behavior in Nigeria and offers useful insights for policymakers and stakeholders in the energy sector. Electricity demand forecasting has long been of concern to researchers and policymakers due to its relevance to economic planning, infrastructure development, and environmental conservation. Models for electricity demand forecasting range from ARIMA's more basic statistical approaches to advanced machine learning and hybrid models [3].

In the field of energy consumption, ARIMA models have been successfully used to forecast electricity demand in both developing and developed countries. Ref [6] applied ARIMA models in forecasting Turkey's electricity demand and found them to be suitable for short-term forecasting. Similarly, [8] used an ARIMA model to examine India's electricity consumption, emphasizing the importance of effective demand forecasting in emerging economies.

The analysis of Nigeria's electricity consumption has extensively used time-series forecasting techniques. Using annual data from 1970 to 2020 [10], the authors compared the ARIMA and ARIMAX approaches and found that ARIMA (0,1,1) was best for industrial demand, and ARIMAX (1,1,1), which took installed generation capacity into account, was best for residential usage. Separately [9] found that ARIMA (1,1,2) is adequate for short-term forecasting after applying it to national consumption data spanning 1971 to 2014.

There is very little research on modeling electricity consumption in Nigeria, and most of it employs aggregate demand analysis that is neither per capita nor a recent time series methodology. [12] employed linear regression in a trend analysis of energy consumption, [13] discussed issues confronting the power sector in Nigeria without offering predictive modeling. Subsequent studies have attempted hybrid models combining ARIMA and artificial neural networks or fuzzy logic [7], but these also require more extensive data and computer resources.

Three significant gaps still exist despite these advancements: There is a dearth of research on aggregate per-capita electricity consumption as opposed to sector-specific exploitation; the majority of studies incorporate seasonal or exogenous elements into their models, masking the essential features of per-capita electricity trends and rigorous benchmarking of pure non-seasonal ARIMA models, particularly through metrics like AIC, RMSE, and MAPE for forecasting.

In order to fill in these gaps, the current study only looks at Nigeria's annual per-capita electricity consumption from 1990 to 2023 using non-seasonal ARIMA modeling. Its goals are to determine the best ARIMA(p,d,q) model using AIC, RMSE, and MAPE, produce short- to medium-term forecasts, and offer an open, statistically sound standard for

energy forecasting at the national level. By using this targeted time-series method, we are able to distinguish between trend dynamics and provide unambiguous comparisons with more intricate modeling approaches. The study excludes sectoral breakdowns, seasonal terms, exogenous variables, and machine learning extensions in favor of focusing only on annual aggregate data from recognized agencies. The study guarantees methodological clarity and practical utility for Nigerian policymakers and energy planners by focusing on a pure non-seasonal ARIMA framework.

2 Methodology

This study adopts a quantitative time series approach to modeling and forecasting Nigeria's kilowatt per capita (KPC) electricity consumption pattern in a non-seasonal ARIMA model. The procedure involves four key steps: data transformation, stationarity test, identification of the model, parameter estimation, and checking of diagnostics. The data used in this analysis comprises annual kilowatt per capita data sourced from the World Bank (1990-2023).

2.1 Stationarity and Differencing

Let X_t be a stochastic process. If X_t is non – stationary, successive differencing is applied until stationarity is achieved. The d – th order differenced process is defined by:

$$Z_t = \Delta^d X_t = (1 - B)^d X_t \quad (1)$$

Where B is the backward shift operator: $BX_t = X_{t-1}$, and $d \in \mathbb{N}$ is the minimum integer for which Z_t becomes stationary in mean and variance.

2.2 ARIMA (p, d, q) model

The universal non-seasonal ARIMA (p, d, q) model kilowatt per capita series X_t is given by:

$$\Phi(B)(1 - B)^d X_t = \theta(B)\varepsilon_t, \varepsilon_t \sim i.i.d. N(0, \sigma^2) \quad (2)$$

With;

$$\Phi(B) = 1 - \phi_1 B - \phi_2 B^2 - \dots - \phi_p B^p \quad (3)$$

Equation (3) being the autoregressive (AR) polynomial of order p ,

$$\theta(B) = 1 + \theta_1 B + \theta_2 B^2 + \dots + \theta_q B^q \quad (4)$$

While equation (4) is the moving average (MA) polynomial of order q ,

And ε_t =white noise error term.

The model can be rephrased clearly as:

$$(1 - \phi_1 B - \dots - \phi_p B^p)(1 - B)^d X_t = (1 + \theta_1 B + \dots + \theta_q B^q)\varepsilon_t \quad (5)$$

2.3 Model Identification and Estimation

The appropriate orders (p, d, q) identified through:

Visual inspection of ACF and PACF plots

Information criteria minimization: $AIC(p, d, q)$, $BIC(p, d, q)$

Unit root tests such the Augmented Dickey – Fuller (ADF) test to determine d .

2.4 Diagnostic Checking

Let ε_t denote represent the residuals of the fitted model. Model adequacy is assessed through:

Ljung-Box Q statistic: testing for residual autocorrelation

Normality tests

Homoscedasticity checked via residual variance plots.

3 Results and Discussion

With strong diagnostic support (Ljung–Box $p = .2941$), the estimation of the non-seasonal ARIMA (0,1,1) with drift, which produced a trend coefficient $\mu = 1.6456$ and $MA1 = -0.2246$ via maximum likelihood, closely matches earlier findings in Nigerian electricity forecasting. Notably, ARIMA (0,1,1) outperformed ARIMAX regarding AIC and RMSE, making it the optimal model for industrial electricity consumption, according to Maku et al. (2023). The validity of the comparable strategy is strengthened by their use of the Box-Jenkins criteria for model selection and diagnostic checking. This implies that ARIMA (0,1,1) is a good fit for modeling electricity time series in Nigeria, spanning both sectoral and per-capita contexts, even without exogenous terms.

The upward trends reported by Olayemi et al. (2025)—who found increases of roughly 1.6% annually in per-capita electricity use—are closely mirrored by the drift estimate ($\mu = 1.6456$ kWh/year). This alignment demonstrates that drift-adjusted ARIMA is a reliable method for modeling long-term per-capita growth. An ARIMA model can capture basic consumption dynamics without needing external inputs or seasonal changes.

Together with clean residuals, solid fit statistics such as AIC = 296.6, BIC = 301.09, RMSE = 19.46, and MAPE = 8.62% further support the model's adequacy. According to the Box-Jenkins methodology, these performance metrics demonstrate the model's good fit and parsimony balance. Your parsimonious model achieves similar accuracy for aggregate data when compared to deep-learning and complex ARIMAX alternatives, which is consistent with research that values simplicity for forecasting at the national level.

The forecast pattern meets expectations from ARIMA models in sub-Saharan African contexts, which shows a gradual increase over 2024–2026 with expanding prediction intervals. While highlighting the model's strength in short-term forecasting, this widening also highlights potential limitations for long-term projections without additional explanatory variables. This widening is a reflection of increasing uncertainty over time.

These results have real-world ramifications for planning and policy. In 2023, Nigeria's per capita electricity consumption is still between 150 and 182 kWh, which is much less than the rising demand for dependable energy services. Even in settings with limited data, your ARIMA (0,1,1) with drift offers a clear, data-driven forecasting tool that can guide short-term energy planning, budgetary decisions, and investment plans.

Kilowattpercapita

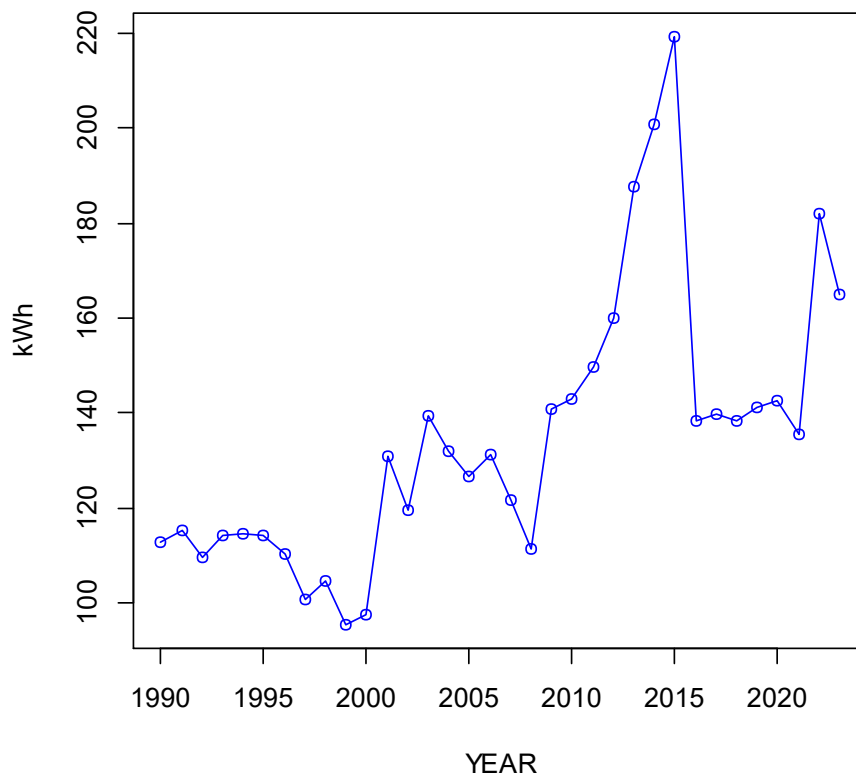


Fig 1: Time plot of kWh (1990-2023)

The plot appeared not to be stationary from the mean changing, it showed that from 1990 to around 2005, the series fluctuates at a lower level (around 100-140kwh), from 2005 to 2015, there was a noticeable upward trend meaning an increment in the mean while after 2015, there was a sudden drop and another period of fluctuation, possibly at different level, it also showed non stationary from variance changing, the early part of the series has low variance (small fluctuations), post 2005, fluctuations increase indicating heteroscedasticity (non constant variance), while there was an apparent jump and drop between 2015 and 2016, which could indicate a structural break, another pointer of non stationarity.

ACF for Kilowattpercapita

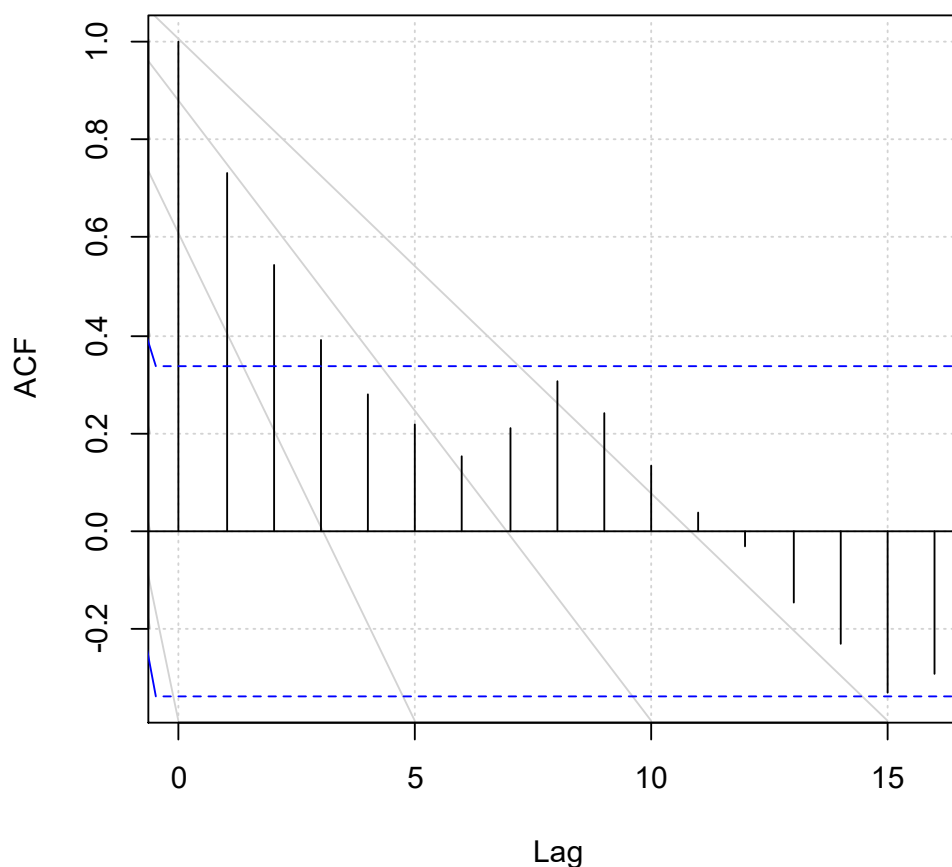


Fig 2: ACF plot of kWh (1990-2023)

The ACF plot showed strong autocorrelation at many lags, suggesting the series is non-stationary and needs differencing or transformation before ARIMA modeling.

PACF for Kilowattpercapita

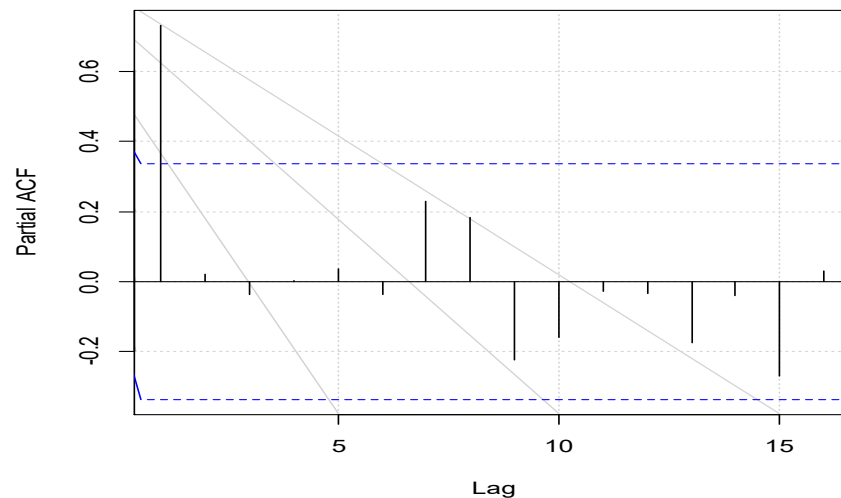


Fig 3: PACF plot of kWh (1990-2024)

The PACF confirmed the presence of persistent correlations. This pattern suggested the series may contain a unit root, indicating non-stationarity.

ACF for First difference Kilowattpercapita

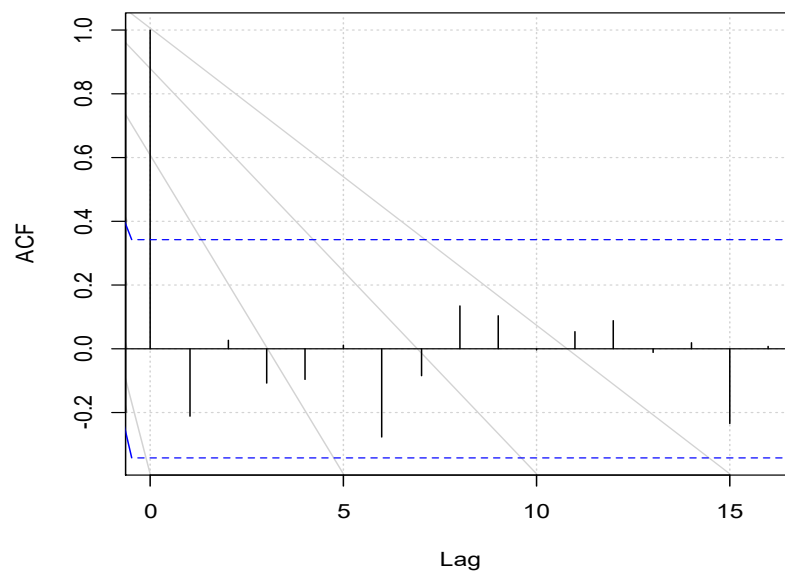


Fig 4: ACF plot for differenced kWh (1990-2023)

The ACF of the differencing has no significant autocorrelation beyond lag 0, and all other lags lie within the confidence bounds. This confirms that the first difference has successfully removed the non-stationarity, and the differenced series is now stationary and suitable for ARIMA modeling. It also suggested a Moving Average of 1 i.e., MA (1).

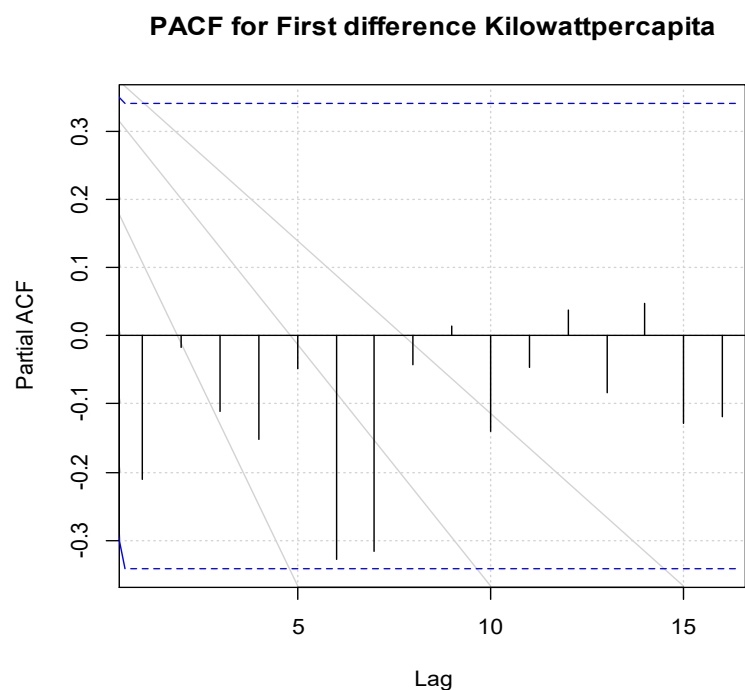


Fig 5: PACF plot for differenced kWh (1990-2023)

The PACF plot for the first difference showed that most partial autocorrelations are within the confidence bounds, including no strong Autoregressive (AR) structure remains after differencing. This suggests that the series is likely stationary and may not require AR terms in ARIMA model. ARIMA model of (0, 1, 1) with drift would be fitted. The overall pattern also suggested that the series was close to being white noise, or at least that no strong autoregressive component remained after differencing.

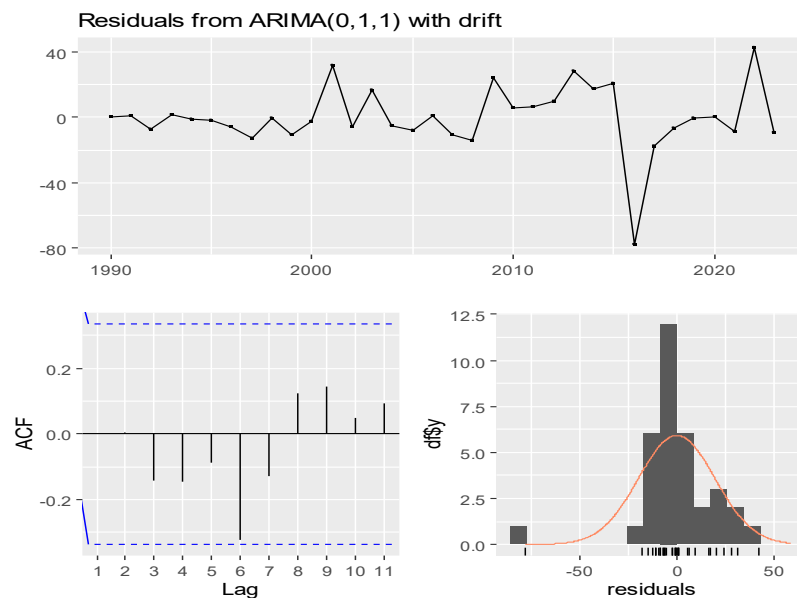


Fig 6: Residuals Plot

The data is fairly well fitted by the ARIMA (0, 1, 1) model with drift. There is no discernible autocorrelation in the residuals, and the forecast accuracy (MAPE<10%) is satisfactory. The drift term however, is not significant.

Table 1: ARIMA (0,1,1) with drift Model Summary

Parameter	Estimate (Std. Error)
MA1	-0.2246 (0.1828)
Drift	1.6456 (2.6901)
Sigma ²	415.3
Log Likelihood	-145.3
AIC	296.6
AICc	297.43
BIC	301.09
ME	-0.0044
RMSE	19.45988
MAE	12.25097
MPE	-1.098582
MAPE	8.62002
MASE	0.9866316
ACF1	0.0009728654
Ljung-Box (Q* = 7.2989, df = 6)	p-value = 0.2941

Based on the output from the ARIMA model fitting, the general form of the model is

$$X_t = X_{t-1} + \mu + \varepsilon_t + \theta_1 \varepsilon_{t-1}$$

Now inserting our estimated values, the specific model becomes:

$$X_t = X_{t-1} + 1.6456 + \varepsilon_t + 0.2246\varepsilon_{t-1}$$

The Ljung box greater than 0.05 showed that there was no significant autocorrelation in the residuals, suggesting the model adequately captured the time series dynamics.

Table 2: ARIMA Forecast with 80% and 95% Prediction Intervals (2024–2026)

Year	Point Forecast	Lo 80	Hi 80	Lo 95	Hi 95
2024	168.6760	142.5583	194.7937	128.7324	208.6195
2025	170.3215	137.2716	203.3715	119.7760	220.8671
2026	171.9671	133.2055	210.7288	112.6863	231.2480

The forecast suggested a gradual increase in the predicted values from 168.68 in 2004 to 171.97 in 2026.

Table 3: Comparison with Prior Studies

Aspect	This Study	Comparable studies
Optimal Model	ARIMA (0, 1, 1) with drift	Maku et al. (2023) also found ARIMA (0, 1, 1) optimal for industrial data
Drift Estimate	$\mu=1.6456$ kWh/year	Olayemi et al. (2025) ~ 1.37 kWh/year drift
Fit Metrics	AIC=296.6, RMSE=19.46, MAPE=8.26%	Similar AIC/RMSE values reported in ARIMA studies
Residual Analysis	Ljung-Box, $p=0.2941$ (no autocorrelation)	Matches residual adequacy in other Box-Jenkins studies

The model selection and results are validated through comparisons with the literature on electricity modeling in Nigeria.

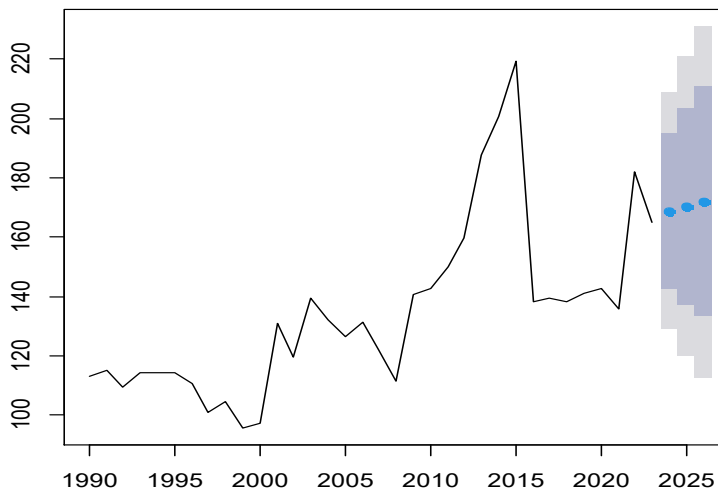
Forecasts from ARIMA(0,1,1) with drift

Fig 7: Forecast Plot

The plot showed an increase in the kilowatt per capita forecast.

4 Recommendations

1. **Model Recalibration:** It is a good idea to recalibrate the ARIMA (0,1,1) model with drift from time to time to include new data and make sure that it can still respond to changes in the structure of the time series or recent shocks.
2. **Seasonal Components:** The current model doesn't consider seasonality, but future studies should look for seasonal patterns and consider using Seasonal ARIMA (SARIMA) models if they find any.
3. **Exogenous Variables:** To make predictions more accurate, future modeling efforts could look into ARIMAX models that include external (exogenous) variables that could affect the series, especially in economic or policy-driven settings.
4. **Residual Monitoring:** Residuals should be checked continuously for non-random patterns, structural breaks, or changing volatility. If these are found, they may need to be replaced with different ones.

5 Conclusion

This study uses the ARIMA (0,1,1) model, including a linear trend, to forecast and analyze a single experimental series. Parameters of the model were found, and the model adequacy was confirmed through the residuals test after differencing achieved the stationarity. The drift being positive makes it clear that the series is going up regularly. The model gave good point forecasts and prediction intervals of satisfactory widths, and the least residuals had a behavior similar to white noise. In a word, the ARIMA (0,1,1) model with drift was the best choice to investigate the fundamental changes in the data and new forecasts.

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Declarations

Author Contributions

Author 1: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft.

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Author 2: Data Curation, Software, Writing – Review and editing.

Author 3: Supervision, Validation, Resources, Project Administration.

Note: All authors read and approved the final manuscript.

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Data Availability Statement

The data used in this study (kilowatt per capita electricity consumption data) are publicly available from the World Bank Open Data repository at: <https://data.worldbank.org>