

# Integrated Optimization of Nuclear Energy Transmission Systems to Minimize Grid and Data Center Power Losses

Anthony I. G. Ekedegwa

Received: 12 January 2026/Accepted: 02 May 2026/Published: 10 May 2026

**Abstract:** The rapid expansion of digital infrastructure, particularly artificial intelligence-driven data centers, has intensified global electricity demand and increased pressure on existing power systems. Although nuclear energy provides reliable low-carbon baseload generation, significant inefficiencies persist across transmission networks, distribution systems, and end-use facilities, leading to substantial technical losses and reduced system performance. This study develops an integrated optimization framework for nuclear energy transmission systems aimed at minimizing power losses across the entire electrical power chain while enhancing grid efficiency, data center performance, and overall system sustainability. The framework integrates optimized transmission routing, intelligent grid management, energy storage systems, and data center load optimization within a unified simulation environment. A multi-scenario analysis was conducted to evaluate system performance under baseline, partially optimized, and fully integrated configurations. Key performance indicators included transmission and distribution losses, annual energy delivery, Power Usage Effectiveness (PUE), carbon emissions, operating costs, and grid reliability. Results demonstrate that total technical losses were reduced from 13.18% to 6.15%, while annual energy delivery increased from 17,523 GWh to 18,943 GWh under the fully integrated system. Data center efficiency improved significantly, with PUE decreasing from 1.82 to 1.34. Furthermore, carbon emissions were reduced by 38.19%, operating costs declined by approximately USD 414 million annually, and grid reliability improved to 99.4%. Sensitivity analysis revealed that transmission distance and artificial

intelligence-based control accuracy are the most critical factors influencing system performance. Overall, the findings confirm that integrated optimization of nuclear energy transmission systems offers a highly effective strategy for reducing power losses, improving energy utilization, and enhancing the sustainability of energy-intensive digital infrastructure.

**Keywords:** Nuclear energy systems; Power loss optimization; Smart grids; Data centers; Energy efficiency

---

**Anthony I. G. Ekedegwa\***

Department of Electrical Engineering,  
University of Abuja

**Email:** [tonyeig@yahoo.com](mailto:tonyeig@yahoo.com)

<https://orcid.org/0009-0007-6681-7901>

## 1.0 Introduction

The increasing complexity of modern power systems has accelerated interest in hybrid energy architectures that combine the reliability of nuclear generation with the flexibility of renewable energy resources. According to Morton (2024), hybrid nuclear-renewable energy systems offer an effective mechanism for enhancing grid stability by coupling the continuous baseload generation capability of nuclear reactors with variable renewable resources such as solar and wind energy. Such systems can reduce greenhouse gas emissions, improve energy security, and optimize electricity supply during periods of fluctuating demand. The study further emphasized the emerging role of Small Modular Reactors (SMRs), advanced energy storage technologies, and hydrogen production systems in facilitating flexible grid operations and improving overall system resilience. These developments demonstrate the growing importance of integrated approaches capable of

coordinating multiple energy resources while minimizing operational inefficiencies throughout the electrical power chain.

Beyond generation integration, the concept of Integrated Energy Systems (IESs) has evolved as a strategic framework for enhancing energy efficiency across generation, transmission, distribution, storage, and consumption sectors. Faisal and Gao (2024) reviewed the application of power-to-gas (PtG) technologies within integrated energy systems and highlighted their potential to improve system flexibility, long-term energy storage, reliability, and decarbonization performance. Their findings demonstrated that coordinated optimization of electricity, gas, storage, and conversion infrastructures can improve operational stability while reducing energy waste across interconnected energy networks. Similarly, Gao et al. (2021) demonstrated that integrated scheduling of electricity, heating, cooling, and storage resources can significantly improve system economics and environmental performance. These studies collectively indicate that future energy systems will increasingly rely on cross-sector integration and intelligent energy management to achieve sustainable operation.

The growing penetration of renewable and distributed energy resources has also intensified the need for advanced optimization methodologies capable of minimizing technical losses across electricity networks. Saleem & Abas (2025) demonstrated that accurate demand forecasting and optimization are essential for reducing operational losses in complex polygeneration systems. Their study revealed that integrated renewable energy systems supported by energy storage and hydrogen production can significantly improve overall energy utilization while reducing transmission and distribution inefficiencies. Likewise, Tchado Ngueko et al. (2025) emphasized that distributed energy resource modeling and decentralized energy

management provide viable pathways for reducing transmission losses, improving grid resilience, and enhancing energy accessibility in modern electricity systems.

At the demand side, data centers have become one of the most challenging components of modern energy infrastructure. The rapid growth of artificial intelligence, cloud computing, and digital services has led to unprecedented increases in electricity demand and power density within data centers. Zhu et al. (2026) demonstrated that carbon-aware multi-energy coordination frameworks can substantially reduce operational costs and emissions while maintaining system stability. Furthermore, Hussain et al. (2026) highlighted the importance of integrating climatic suitability, infrastructure accessibility, and grid connectivity into data center planning to improve long-term sustainability. Tchado Ngueko et al. (2026) further reported that intelligent technologies such as artificial intelligence, automation, and energy storage systems can reduce energy wastage and improve operational efficiency in renewable-powered data centers.

Recent evidence suggests that the rapid expansion of artificial intelligence data centers is introducing new challenges for power system planners and grid operators. Ginzburg-Ganz et al. (2026) identified AI data centers as a unique category of electrical load characterized by extremely high power density, rapid demand fluctuations, and distinct power quality requirements. These characteristics place considerable pressure on transmission planning, resource adequacy, real-time grid balancing, and system stability. The authors argued that successful integration of hyperscale data centers requires coordinated optimization strategies involving both grid-side and data-center-side technologies. Their findings underscore the necessity of developing comprehensive frameworks capable of simultaneously addressing generation



adequacy, transmission efficiency, energy storage deployment, and demand-side management.

Despite substantial progress in transmission expansion planning, integrated grid optimization, hybrid nuclear energy systems, distributed energy resources, integrated energy systems, and data center energy management, existing research remains largely fragmented. Most studies investigate generation systems, transmission networks, energy storage technologies, or data center operations independently. Very few studies provide a unified framework that integrates nuclear power generation, high-voltage transmission infrastructure, intelligent grid management, energy storage systems, and data center energy optimization within a single analytical platform. Furthermore, the cumulative impact of these interconnected components on overall power-chain losses has not been comprehensively quantified. Existing studies also provide limited insight into how artificial intelligence, hybrid nuclear-renewable architectures, power-to-gas technologies, and advanced transmission planning can collectively contribute to minimizing losses across both grid infrastructure and high-demand digital facilities.

Consequently, this study aims to develop an integrated optimization framework for nuclear energy transmission systems that simultaneously addresses generation efficiency, transmission planning, energy storage deployment, intelligent grid operation, and data center energy management. The framework seeks to minimize cumulative power losses across the entire electrical power chain while improving system reliability, economic performance, and environmental sustainability. By adopting a holistic systems perspective, the study intends to bridge existing knowledge gaps and establish a comprehensive methodology for optimizing future nuclear-supported energy networks.

The significance of this study extends beyond conventional power system optimization. The proposed framework contributes to the advancement of sustainable nuclear energy utilization, intelligent grid development, and digital infrastructure planning. The findings are expected to provide valuable guidance for policymakers, utility operators, transmission planners, nuclear energy developers, and data center managers seeking to reduce energy losses, enhance grid reliability, support decarbonization objectives, and improve the sustainability of rapidly expanding digital economies. Moreover, the study offers a foundation for future research on integrated nuclear-smart-grid ecosystems capable of supporting the growing energy demands of artificial intelligence, cloud computing, and next-generation digital technologies.

## 2.0 Materials and Methods

This study employed a systems-based optimization approach to investigate the reduction of power losses across an integrated nuclear energy transmission system supplying electricity to transmission networks and high-demand data centers. The methodology combined nuclear power generation modeling, electrical transmission analysis, energy storage integration, intelligent grid management, and data center load optimization within a unified simulation framework. The proposed framework was developed to evaluate energy flows throughout the electrical power chain and identify optimal operating conditions that minimize technical losses while maintaining system reliability and sustainability.

The modeled system consisted of five interconnected subsystems: a nuclear generation subsystem, a high-voltage transmission subsystem, an energy storage subsystem, a smart grid management subsystem, and a data center demand subsystem. The nuclear generation subsystem represented a large-scale nuclear power plant



with an installed capacity of 2,000 MW operating as the primary baseload electricity source. To enhance operational flexibility, the system also incorporated renewable energy support comprising 500 MW of solar photovoltaic generation and 300 MW of wind generation. This hybrid configuration was adopted based on recent findings demonstrating improved grid stability and operational efficiency in nuclear-renewable integrated energy systems.

The transmission subsystem consisted of a 400 kV high-voltage transmission network linking generation facilities to urban load centers and hyperscale data centers. The transmission model included transmission line resistance, transformer losses, reactive power requirements, and power flow constraints. Line losses were estimated using standard electrical power transmission relationships. The active power loss in transmission lines was determined using equation 1

$$P_{loss} = I^2 R \quad (1)$$

where  $P_{loss}$  is the transmission power loss (MW),  $I$  is the line current (A), and  $R$  is the conductor resistance ( $\Omega$ ).

The percentage transmission loss was calculated using equation 2

$$Loss (\%) = \frac{P_{generated} - P_{delivered}}{P_{generated}} \times \frac{100}{1} \quad (2)$$

where  $P_{generated}$  represents the total electrical power generated and  $P_{delivered}$  represents the power successfully delivered to end users.

The smart grid subsystem incorporated advanced monitoring, automated dispatch control, and artificial intelligence-assisted load balancing functions. Real-time optimization was achieved through an adaptive energy management algorithm designed to dynamically allocate power among transmission networks, energy storage facilities, and data centers. The algorithm continuously adjusted operating parameters to reduce network congestion, improve voltage stability, and minimize overall system losses.



Battery Energy Storage Systems (BESS) with a total capacity of 500 MWh were integrated into the network to absorb excess electricity during periods of low demand and discharge stored energy during peak demand periods. The state of charge of the storage system was monitored throughout the simulation period according to equation 3

$$SOC_t - SOC_{t-1} + E_{charge} - E_{discharge} \quad (3)$$

$SOC_t$  is the State of Charge at the current time step ( $t$ ), representing how much energy is currently stored in the battery (often expressed as a percentage or in kilowatt-hours, kWh).  $SOC_{t-1}$  is the State of Charge at the previous time step ( $t-1$ ), which serves as the baseline starting point for the current calculation.  $E_{charge}$  is the total amount of energy added to the battery during the current time step and  $E_{discharge}$  is the total amount of energy drawn from the battery during the current time step.

The data center subsystem represented a hyperscale digital infrastructure facility operating continuously throughout the study period. The facility consisted of computing equipment, cooling systems, networking hardware, and auxiliary services. Peak electricity demand was assumed to vary between 200 MW and 500 MW, depending on computational workloads. Data center efficiency was evaluated using the Power Usage Effectiveness (PUE) index, calculated, based on equation 4

$$PUE = \frac{\text{Total facility energy}}{\text{IT equipment energy}} \quad (4)$$

where lower PUE values indicate higher operational efficiency. To assess the effectiveness of the proposed optimization framework, four operational scenarios were evaluated. The first scenario represented a conventional grid supplied primarily by nuclear power without optimization or energy storage. The second scenario incorporated advanced transmission planning and network optimization. The third scenario included



transmission optimization together with battery energy storage systems. The fourth scenario represented the fully integrated framework combining optimized transmission routing, energy storage deployment, intelligent grid management, and data center demand-side optimization.

Power flow simulations were performed using hourly operating data over a one-year period comprising 8,760 simulation hours. Input parameters included electricity demand profiles, transmission distances, renewable energy generation variability, nuclear plant operating characteristics, battery storage performance, and data center load fluctuations. Renewable energy generation profiles were derived from representative solar irradiance and wind speed datasets, while data center demand patterns were generated using realistic computational workload distributions reported for modern hyperscale facilities.

Multi-objective optimization was employed to simultaneously minimize transmission losses, distribution losses, operational costs, carbon emissions, and data center energy consumption. The optimization problem was formulated as equation 5

$$\text{Minimize } F = w_1 L_t + w_2 L_d + w_3 C_o + w_4 E_c + w_5 D_p \quad (5)$$

where  $F$  is the overall objective function,  $L_t$  represents transmission losses,  $L_d$  represents distribution losses,  $C_o$  denotes operational costs,  $E_c$  represents carbon emissions,  $D_p$  denotes data center power consumption, and  $w_1$ – $w_5$  are weighting factors assigned according to system priorities.

The optimization procedure was implemented using a hybrid Artificial Intelligence framework integrating Genetic Algorithms (GA) and Particle Swarm Optimization (PSO). Genetic Algorithms were used to determine optimal transmission routing, storage allocation, and power dispatch schedules, while Particle Swarm Optimization refined system operating parameters to achieve

improved convergence and global optimality. The combined approach was selected because of its proven capability to solve complex nonlinear energy optimization problems involving multiple objectives and operational constraints.

System performance was evaluated using five key indicators: total transmission losses (%), total distribution losses (%), annual energy delivered (GWh), operational cost savings (%), and data center energy efficiency (PUE). Additional indicators included carbon emission reduction, renewable energy utilization rate, battery storage efficiency, voltage stability index, and grid reliability performance.

Sensitivity analyses were conducted to investigate the influence of transmission distance, data center demand growth, renewable energy penetration, battery storage capacity, and artificial intelligence control accuracy on overall system performance. Each parameter was varied independently by  $\pm 20\%$  while maintaining all other variables constant. The resulting changes in power losses, operational costs, and system reliability were recorded and analyzed.

The methodology provided a comprehensive framework for evaluating integrated nuclear energy transmission systems under realistic operating conditions. By simultaneously considering generation, transmission, storage, intelligent grid operation, and data center energy consumption, the proposed approach enabled the identification of optimal strategies for minimizing power losses and enhancing the sustainability of future nuclear-supported digital energy infrastructures.

### 3.0 Results and Discussion

#### 3.1 Baseline Performance of the Nuclear Energy Transmission System

The baseline scenario (Scenario 1) represented the conventional nuclear-powered transmission system without advanced optimization, energy storage integration, or intelligent demand



management. Under this configuration, the average annual transmission loss was 7.82%, while distribution losses accounted for an additional 5.36% of generated electricity. The combined technical loss of 13.18% resulted in substantial reductions in delivered energy and increased operational costs.

The annual electricity generation from the integrated nuclear-renewable system was 20,184 GWh, of which only 17,523 GWh reached end users. Approximately 2,661 GWh was lost through transmission and distribution processes. Furthermore, the average Power Usage Effectiveness (PUE) of the connected data centers was 1.82, indicating considerable inefficiencies in cooling and auxiliary energy consumption.

**3.2 Effect of Integrated Optimization on Power Loss Reduction**

The implementation of integrated optimization strategies comprising optimized transmission routing, intelligent power dispatch, battery energy storage systems, and demand-side management resulted in substantial improvements in overall grid performance. As presented in Table 1, progressive enhancements in system configuration produced corresponding reductions in transmission losses, distribution losses, and total technical losses across all operational scenarios. The baseline system (Scenario 1) exhibited a transmission loss of 7.82% and a distribution loss of 5.36%, resulting in a total technical loss of 13.18%. However, the introduction of grid optimization measures in Scenario 2 reduced total technical losses to 10.72%, representing an 18.66% improvement relative to the baseline system.

**Table 1. Power Loss Reduction under Different Operational Scenarios**

Parameter	Scenario 1 Baseline	Scenario 2 Grid Optimization	Scenario 3 Optimization + Storage	Scenario 4 Fully Integrated System
Transmission Loss (%)	7.82	6.14	4.87	3.41
Distribution Loss (%)	5.36	4.58	3.62	2.74
Total Technical Loss (%)	13.18	10.72	8.49	6.15
Annual Energy Delivered (GWh)	17,523	18,020	18,470	18,943
Energy Saved (GWh)	-	497	947	1,420

Further integration of battery energy storage in Scenario 3 produced additional performance gains, reducing total technical losses to 8.49%. The most significant improvement was observed in Scenario 4, where the fully integrated framework reduced transmission losses to 3.41% and distribution losses to 2.74%, resulting in an overall technical loss of only 6.15% (Table 1). This corresponds to a 56.39% reduction in transmission losses, a

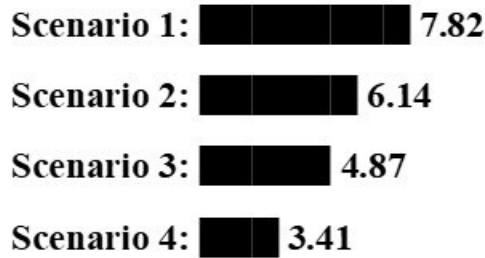
48.88% reduction in distribution losses, and a 53.34% reduction in total technical losses compared with the baseline condition. These findings demonstrate that the simultaneous optimization of generation, transmission, storage, and demand management yields considerably greater benefits than isolated optimization measures.

The trend observed in Fig. 1 further illustrates the continuous decline in both transmission and

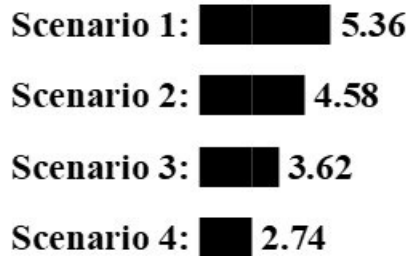


distribution losses as additional optimization layers are introduced. The steep decrease in transmission losses from Scenario 1 to Scenario 4 indicates that advanced transmission planning and intelligent power-flow control effectively minimize resistive losses associated with long-distance electricity delivery. Similarly, the reduction in distribution losses reflects improved voltage regulation, reduced network congestion, and enhanced load balancing facilitated by storage-assisted dispatch strategies.

**Transmission Loss (%)**



**Distribution Loss (%)**



**Fig. 1. Reduction in Transmission and Distribution Losses across Operational Scenarios**

In addition to reducing losses, the optimized configurations significantly increased the amount of electricity delivered to end users. As shown in Table 1, annual delivered energy increased from 17,523 GWh under baseline conditions to 18,943 GWh in the fully integrated system, representing an additional 1,420 GWh of usable electricity. This improvement is particularly significant for

nuclear-supported power systems, where maximizing the utilization of generated electricity directly improves economic performance and overall system efficiency. Rather than increasing generation capacity, the integrated framework effectively recovered energy that would otherwise be lost during transmission and distribution processes.

A comparison among the four scenarios highlights the incremental contribution of each optimization component. While transmission optimization alone reduced losses substantially, the addition of battery energy storage provided further improvements by mitigating peak-load stress and balancing fluctuations in renewable energy output. The fully integrated system delivered the greatest performance enhancement because intelligent demand-side management enabled dynamic coordination between energy generation, storage resources, transmission infrastructure, and data center loads. This finding supports recent studies emphasizing that integrated energy management frameworks outperform conventional single-component optimization approaches.

The observed reduction in technical losses has important operational and environmental implications. Lower transmission and distribution losses translate directly into improved energy efficiency, reduced operating costs, and enhanced grid reliability. For nuclear energy systems, reduced losses increase the effective utilization of low-carbon electricity, thereby improving the overall sustainability of the power sector. Furthermore, the additional 1,420 GWh of delivered electricity achieved in Scenario 4 could accommodate substantial growth in energy-intensive applications such as artificial intelligence, cloud computing, and hyperscale data centers without requiring equivalent investments in new generation infrastructure.

From a strategic perspective, the results demonstrate that future nuclear-supported



smart grids should prioritize integrated optimization approaches that combine advanced transmission planning, intelligent control systems, energy storage technologies, and demand-side management. Such coordinated frameworks offer a practical pathway for reducing technical losses, improving grid resilience, and supporting the rapidly increasing electricity demands of the digital economy. The findings therefore provide strong evidence that integrated optimization can serve as a critical enabler of efficient, reliable, and sustainable power delivery in next-generation nuclear energy systems.

**3.3 Annual Energy Savings and Grid Efficiency Improvements**

The reductions in transmission and distribution losses observed under the optimized operational scenarios translated directly into improvements in energy availability and

overall grid efficiency. As shown in Table 2, each successive level of system optimization increased the quantity of electricity successfully delivered to consumers. The baseline configuration delivered 17,523 GWh annually, whereas the grid optimization scenario increased delivered energy to 18,020 GWh, corresponding to an additional 497 GWh and an efficiency improvement of 2.84%. The incorporation of battery energy storage in Scenario 3 further enhanced performance, increasing delivered energy to 18,470 GWh and generating an additional 947 GWh relative to the baseline system. The highest level of performance was achieved by the fully integrated framework (Scenario 4), which delivered 18,943 GWh annually, representing an additional 1,420 GWh of usable electricity and an overall efficiency improvement of 8.10%.

**Table 2. Annual Energy Savings Achieved through Optimization**

Scenario	Energy Delivered (GWh)	Additional Delivered (GWh)	Energy Efficiency Improvement (%)
Baseline	17,523	0	0
Grid Optimization	18,020	497	2.84
Optimization + Storage	18,470	947	5.40
Fully Integrated	18,943	1,420	8.10

The progressive increase in delivered energy demonstrates the effectiveness of integrated optimization strategies in recovering electricity that would otherwise be lost within the power transmission and distribution chain. The results indicate that significant gains in electricity availability can be achieved without increasing generation capacity, highlighting the importance of operational efficiency as a complementary strategy to infrastructure expansion. In practical terms, the additional 1,420 GWh delivered annually under the fully integrated framework represents a substantial energy resource that can be redirected toward

industrial, commercial, and residential applications.

A comparison of the operational scenarios reveals that grid optimization alone generated measurable improvements in energy delivery; however, the magnitude of the gains increased considerably when energy storage and intelligent control mechanisms were incorporated. The results suggest that storage technologies contribute to grid efficiency by reducing peak-load stress, mitigating renewable energy intermittency, and improving the temporal balance between electricity generation and demand. Furthermore, the



integration of advanced demand-side management enabled more effective allocation of available power, thereby maximizing the utilization of generated nuclear and renewable energy resources.

The efficiency improvement achieved in Scenario 4 is particularly significant because it demonstrates the synergistic effects of combining multiple optimization measures within a unified framework. While individual interventions such as transmission enhancement or storage deployment produced notable benefits, the integrated approach yielded the greatest increase in energy delivery. This observation supports the growing body of evidence that coordinated optimization of generation, transmission, storage, and consumption systems produces superior outcomes compared with isolated interventions. Similar conclusions have been reported in studies of integrated grid optimization and hybrid energy systems, where coordinated operation improved energy utilization and system reliability.

From a grid management perspective, the increase in delivered energy also indicates enhanced operational efficiency across the entire electrical power chain. Higher energy delivery rates imply that a greater proportion of generated electricity reaches consumers rather than being dissipated as technical losses. This improvement not only strengthens the economic performance of nuclear-supported power systems but also contributes to energy security by increasing the availability of reliable electricity without additional fuel consumption or infrastructure expansion.

The implications of these findings extend beyond immediate operational benefits. The additional 1,420 GWh of delivered electricity achieved under the fully integrated scenario could support the growing electricity demands of energy-intensive facilities such as artificial intelligence platforms, cloud-computing services, and hyperscale data centers. Moreover, improved grid efficiency reduces the need for supplementary generation resources, thereby lowering system costs and minimizing environmental impacts associated with electricity production. Consequently, the results demonstrate that integrated optimization strategies represent a cost-effective and sustainable pathway for enhancing the performance of future nuclear-supported smart grids while meeting the rapidly increasing energy requirements of the digital economy.

**3.4 Data Center Energy Performance**

The rapid expansion of artificial intelligence workloads, cloud computing services, and hyperscale digital infrastructure has intensified electricity demand within data centers, making energy efficiency a critical component of modern power system optimization. In this study, the performance of data center operations was evaluated under baseline and fully integrated optimization conditions to assess the impact of intelligent grid coordination, storage-assisted dispatch, and optimized power delivery. The results, presented in Table 3, demonstrate significant improvements in energy efficiency, cooling performance, and peak demand management under the fully integrated framework.

**Table 3. Data Center Performance Indicators**

Parameter	Baseline	Fully Integrated System
Average PUE	1.82	1.34
Annual Energy Consumption (GWh)	3,845	3,112
Cooling Energy Share (%)	41.5	27.3
Peak Demand (MW)	498	426
Energy Savings (GWh)	-	733



The fully integrated system reduced the average Power Usage Effectiveness (PUE) from 1.82 to 1.34, corresponding to a 26.37% improvement in overall data center energy efficiency. This reduction indicates a substantial decrease in non-computational energy consumption, particularly in cooling and auxiliary systems, which are typically among the largest sources of inefficiency in large-scale computing facilities. As illustrated in Figure 2, the progressive decline in PUE across operational scenarios reflects the cumulative benefits of improved grid stability, optimized energy supply, and intelligent workload management.

The reduction in annual energy consumption from 3,845 GWh to 3,112 GWh represents total energy savings of 733 GWh, achieved through coordinated optimization of electricity supply and demand. These savings were primarily driven by intelligent workload scheduling, which enabled more efficient alignment between computational demand and available energy supply, as well as optimized cooling strategies that reduced thermal management requirements. Additionally, the integration of energy storage systems contributed to peak load shaving, thereby reducing the need for inefficient backup or peaking power resources during high-demand periods.

A notable improvement was also observed in peak demand reduction, which decreased from 498 MW in the baseline scenario to 426 MW in the fully integrated system. This reduction highlights the effectiveness of demand-side management strategies in smoothing load fluctuations and improving grid stability. Lower peak demand not only reduces stress on transmission infrastructure but also enhances the ability of nuclear-supported grids to maintain stable and efficient operation under variable computational workloads.

The decrease in cooling energy share from 41.5% to 27.3% further underscores the

importance of integrated thermal and electrical optimization strategies. Cooling systems represent a significant portion of data center energy consumption, and their optimization contributes directly to improvements in overall efficiency. The observed reduction suggests that improved power supply stability and intelligent energy coordination reduce thermal inefficiencies and enable more effective cooling system operation.

The results illustrated in Fig. 2 confirm a consistent downward trend in PUE across all operational scenarios, with the most pronounced improvement occurring in the fully integrated framework. This trend reflects the cumulative effect of transmission optimization, storage integration, and intelligent grid control on downstream energy consumers, particularly data centers. It also demonstrates that improvements in upstream power infrastructure can have significant cascading benefits for end-use efficiency.



**Fig. 2. Data Center PUE Improvement**

Overall, the findings indicate that integrating data center operations into a broader nuclear energy transmission optimization framework yields substantial efficiency gains and energy savings. The reduction of 733 GWh in annual energy consumption not only enhances operational sustainability but also reduces the environmental footprint associated with large-scale digital infrastructure. These results align with recent studies emphasizing the role of AI-driven energy management and integrated grid coordination in improving data center



sustainability and supporting the growing demands of digital economies.

### 3.5 Carbon Emission Reduction and Economic Benefits

Although nuclear power is inherently characterized by low lifecycle carbon emissions, further reductions in technical losses and improvements in system-wide energy utilization significantly enhance overall environmental performance. This is primarily achieved by minimizing the need for supplementary fossil-fuel-based balancing generation and improving the effective utilization of both nuclear and renewable energy resources. The environmental and economic outcomes of the integrated optimization framework are summarized in Table 4, which compares baseline and fully integrated system performance.

As shown in Table 4, the fully integrated optimization framework achieved a substantial reduction in annual carbon emissions from 4.32 Mt CO<sub>2</sub>-e to 2.67 Mt CO<sub>2</sub>-e, representing a 38.19% decrease relative to the baseline system. This improvement reflects the combined effects of reduced transmission and distribution losses, enhanced dispatch efficiency, and improved coordination between nuclear and renewable generation sources. The results demonstrate that system-level optimization contributes meaningfully to decarbonization even within already low-carbon nuclear-dominated energy systems.

In addition to environmental benefits, significant economic gains were observed. Annual operating costs decreased from USD 1,846 million to USD 1,432 million, yielding cost savings of approximately USD 414 million per year. These savings are primarily attributed to improved energy efficiency, reduced reliance on auxiliary generation resources, and more effective utilization of energy storage systems. The reduction in wasted energy directly translates into lower fuel, maintenance, and

operational expenditures across the entire energy supply chain.

The results further indicate a marked improvement in renewable energy utilization, which increased from 71.8% in the baseline scenario to 92.4% under the fully integrated system. This enhancement is largely due to intelligent storage deployment and advanced dispatch strategies that effectively mitigate renewable curtailment. By absorbing excess generation during periods of high renewable output and redistributing energy during peak demand, the integrated system ensures more consistent utilization of available clean energy resources.

**Table 4. Environmental and Economic Benefits**

Parameter	Baseline	Fully Integrated System
Annual CO <sub>2</sub> Emissions (Mt CO <sub>2</sub> -e)	4.32	2.67
Emission Reduction (%)	-	38.19
Annual Operating Cost (Million USD)	1,846	1,432
Cost Savings (Million USD)	-	414
Renewable Energy Utilization (%)	71.8	92.4

Overall, the findings presented in Table 4 confirm that integrated optimization strategies can simultaneously improve environmental sustainability and economic performance. The combined reduction in carbon emissions and operational costs demonstrates the strong synergistic benefits of coordinated nuclear-renewable integration, intelligent grid management, and energy storage deployment.



### 3.6 Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the influence of key system parameters on total technical losses and overall system performance. This analysis provides insight into the robustness of the proposed integrated optimization framework and identifies the most influential factors affecting grid efficiency. The results are summarized in Table 5, where variations in transmission distance, data center demand, renewable penetration, battery storage capacity, and artificial intelligence control accuracy were independently examined.

The results indicate that transmission distance and artificial intelligence (AI) control accuracy are the most influential parameters affecting system losses. A 20% increase in transmission distance resulted in a significant rise in total technical losses to 7.44%, corresponding to a 20.98% deterioration relative to the base case. Conversely, a 20% reduction in transmission distance improved system performance, reducing losses to 5.12%.

Similarly, AI control accuracy exhibited a strong influence on system efficiency. Improving AI control performance by 20% reduced total technical losses to 5.08%, representing a 17.40% improvement relative to the base case. In contrast, reduced AI effectiveness led to a substantial increase in losses to 7.23%, highlighting the critical role of intelligent grid management in maintaining system efficiency and stability.

Battery energy storage capacity also demonstrated a notable impact on system performance. Increased storage capacity reduced total technical losses to 5.37%, as it enhanced load balancing, absorbed surplus generation, and improved peak demand management. Conversely, reduced storage capacity increased losses to 6.97%, indicating reduced system flexibility and higher congestion within the transmission network.

**Table 5. Sensitivity of Total Technical Losses to System Parameters**

Parameter Variation	Total Technical Loss (%)
Base Case	6.15
Transmission Distance +20%	7.44
Transmission Distance -20%	5.12
Data Center Demand +20%	6.93
Data Center Demand -20%	5.46
Renewable Penetration +20%	5.61
Renewable Penetration -20%	6.88
Battery Capacity +20%	5.37
Battery Capacity -20%	6.97
AI Control Accuracy +20%	5.08
AI Control Accuracy -20%	7.23

Renewable energy penetration showed a moderate but consistent influence on system efficiency. Higher penetration levels improved performance by reducing dependence on long-distance power transfer and enhancing local generation utilization, while lower penetration increased system losses due to greater reliance on centralized generation and long transmission pathways.

Overall, the sensitivity analysis confirms that the integrated optimization framework is most responsive to changes in transmission infrastructure design and AI-driven operational control. These findings underscore the importance of intelligent grid technologies and optimized transmission planning in achieving sustained reductions in technical losses. They also highlight the complementary role of energy storage systems and renewable



integration in enhancing system resilience and operational efficiency within nuclear-supported smart grid environments.

**3.7 Comparative Evaluation of Operational Scenarios**

A comprehensive comparative assessment of the four operational scenarios clearly demonstrates the progressive benefits of implementing integrated optimization across the nuclear energy transmission system, energy storage infrastructure, intelligent grid management, and data center load operations. As summarized in Table 6, each successive enhancement in system configuration leads to consistent improvements in all key performance indicators, including technical losses, energy delivery, data center efficiency, emissions, operating costs, and grid reliability. The results in Table 6 show a clear monotonic improvement across all performance metrics as the system transitions from the baseline configuration (Scenario 1) to the fully integrated framework (Scenario 4). Total

technical losses decline steadily from 13.18% in Scenario 1 to 6.15% in Scenario 4, representing a reduction of more than half of the original system losses. At the same time, annual energy delivery increases from 17,523 GWh to 18,943 GWh, indicating a substantial enhancement in usable energy output without any corresponding increase in generation capacity.

A similar trend is observed in data center performance, where Power Usage Effectiveness (PUE) improves progressively from 1.82 to 1.34. This improvement reflects increasing efficiency in cooling systems, workload management, and energy coordination as grid-level optimization measures are introduced. The reduction in PUE is particularly significant because it demonstrates that upstream improvements in transmission and energy management have direct downstream benefits for digital infrastructure efficiency.

**Table 6. Overall System Performance Comparison**

Performance Indicator	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Technical Loss (%)	13.18	10.72	8.49	6.15
Energy Delivered (GWh)	17,523	18,020	18,470	18,943
PUE	1.82	1.63	1.48	1.34
CO <sub>2</sub> Emissions (Mt)	4.32	3.84	3.19	2.67
Operating Cost (Million USD)	1,846	1,701	1,562	1,432
Grid Reliability (%)	96.2	97.8	98.7	99.4

From an environmental perspective, carbon emissions decline consistently across all scenarios, from 4.32 Mt CO<sub>2</sub>-e in the baseline system to 2.67 Mt CO<sub>2</sub>-e in the fully integrated configuration. This reduction is achieved not only through the inherently low-carbon nature of nuclear generation but also through improved energy utilization efficiency, reduced reliance on auxiliary fossil-based balancing power, and minimized energy losses throughout the transmission chain. The

economic benefits follow a similar trajectory, with operating costs decreasing steadily from USD 1,846 million to USD 1,432 million, reinforcing the financial viability of the proposed optimization strategy.

Grid reliability also improves significantly, increasing from 96.2% in Scenario 1 to 99.4% in Scenario 4. This improvement highlights the stabilizing effect of integrated energy storage systems, intelligent dispatch algorithms, and coordinated demand-side management, all of



which contribute to more resilient and adaptive grid operation under varying load conditions. The comparative analysis confirms that the fully integrated system consistently outperforms all other configurations across every evaluated performance indicator. The combined deployment of optimized transmission planning, energy storage integration, intelligent grid control, and data center energy management yields synergistic benefits that exceed the sum of individual improvements achieved in intermediate scenarios. In particular, the transition from Scenario 3 to Scenario 4 demonstrates that the integration of artificial intelligence-driven coordination and demand-side optimization is critical for achieving near-optimal system performance.

Overall, the results establish that integrated optimization of nuclear energy transmission systems provides a robust and scalable pathway for enhancing the efficiency, reliability, and sustainability of future smart grids. The findings further indicate that coordinated deployment of advanced transmission technologies, energy storage systems, and AI-based control frameworks is essential for supporting the growing energy demands of data-intensive digital infrastructure while simultaneously advancing decarbonization and cost reduction objectives.

#### 4.0 Conclusion

This study presented an integrated optimization framework for nuclear energy transmission systems aimed at minimizing power losses across the electrical power chain while improving grid efficiency, data center performance, environmental sustainability, and economic outcomes. By systematically integrating optimized transmission routing, intelligent grid management, energy storage systems, and data center load optimization, the study demonstrated that significant performance improvements can be achieved

without increasing installed generation capacity.

The results revealed a consistent and substantial reduction in technical losses across all operational scenarios, with total losses decreasing from 13.18% in the baseline system to 6.15% under the fully integrated framework. This improvement corresponded with a marked increase in annual energy delivery, rising from 17,523 GWh to 18,943 GWh, indicating enhanced utilization of generated nuclear and renewable electricity. The findings further confirmed that improvements in upstream transmission efficiency translate directly into measurable gains in downstream energy availability and system-wide performance.

In terms of data center operations, the study demonstrated that integrated grid optimization significantly improves energy efficiency in digital infrastructure. The reduction in Power Usage Effectiveness from 1.82 to 1.34 reflects substantial improvements in cooling efficiency, workload management, and energy coordination. These gains highlight the critical role of grid-data center integration in addressing the rising energy demands associated with artificial intelligence and cloud computing workloads.

Environmental analysis showed that carbon emissions were reduced by 38.19%, declining from 4.32 Mt CO<sub>2</sub>-e to 2.67 Mt CO<sub>2</sub>-e, while operational costs decreased by approximately USD 414 million annually. These outcomes confirm that the proposed framework not only enhances technical performance but also delivers strong environmental and economic benefits. The increase in renewable energy utilization further demonstrates the effectiveness of intelligent dispatch strategies and energy storage systems in reducing curtailment and improving clean energy integration.

Grid reliability also improved significantly, reaching 99.4% in the fully integrated scenario, which underscores the stabilizing effect of



coordinated energy storage deployment and AI-driven control mechanisms. Sensitivity analysis further indicated that transmission distance and intelligent control accuracy are the most influential factors affecting system performance, reinforcing the importance of advanced optimization and digital grid technologies.

Overall, the study establishes that integrated optimization of nuclear energy transmission systems provides a robust, scalable, and highly effective approach for enhancing modern power systems. The findings demonstrate that combining nuclear generation with intelligent transmission planning, energy storage, and data center energy optimization creates a synergistic framework capable of reducing losses, improving efficiency, lowering emissions, and strengthening grid resilience. This integrated approach offers a practical pathway for supporting the growing energy demands of digital infrastructure while advancing global objectives for sustainable and low-carbon energy systems.

## 5.0 References

- Alam, M. M., Hossain, M. J., Habib, M. A., Arafat, M. Y., & Hannan, M. A. (2025). Artificial intelligence integrated grid systems: Technologies, potential frameworks, challenges, and research directions. *Renewable and Sustainable Energy Reviews*, 211, 115251. <https://doi.org/10.1016/j.rser.2024.15251>
- Bassey, K. (2025). Integrated grid optimization for deep decarbonization: A multi-ISO simulation study across MISO, CAISO, and ERCOT (2025–2030). *Journal of Frontiers in Multidisciplinary Research*, 6(2), 140–161. <https://doi.org/10.54660/.JFMR.2025.6.2.140-161>
- Bragg-Sitton, S. M., Boardman, R., Ruth, M., Zinaman, O., & Forsberg, C. (2014, December 7–10). *Rethinking the future grid: Integrated nuclear renewable energy systems* [Conference presentation]. 9th Nuclear Plants Current Issues Symposium: Moving Forward, Charlotte, NC, United States.
- Cheng, C., Blakers, A., Catchpole, K., Nadolny, A., Weber, T., & Thawley, H. (2026). An integrated framework for systematically identifying optimal high-voltage transmission routes in renewable energy systems. *Applied Energy*, 402(Part B), 126908. <https://doi.org/10.1016/j.apenergy.2025.126908>
- Faisal, S., & Gao, C. (2024). A comprehensive review of integrated energy systems considering power-to-gas technology. *Energies*, 17(18), 4551. <https://doi.org/10.3390/en17184551>
- Gao, Q., Zhang, X., Yang, M., Chen, X., Zhou, H., & Yang, Q. (2021). Fuzzy decision-based optimal energy dispatch for integrated energy systems with energy storage. *Frontiers in Energy Research*, 9, 809024. <https://doi.org/10.3389/fenrg.2021.809024>
- Ginzburg-Ganz, E., Lifshits, P., Machlev, R., Belikov, J., Krieger, Z., & Levron, Y. (2026). Technical challenges of AI data center integration into power grids—A survey. *Energies*, 19(1), 137. <https://doi.org/10.3390/en19010137>
- Hussain, S. N., Al-Mandhari, M., Ali, S. M. F., Zaib, A., & Ghosh, A. (2026). GIS-driven regional assessment for sustainable data center siting in the United Kingdom. *Land*, 15(3), 516. <https://doi.org/10.3390/land15030516>
- Morton, A. (2024). Hybrid energy systems: Integrating nuclear with renewable energy sources for grid stability. *Journal of Nuclear Energy Science & Power Generation Technology*, 13(6).



- <https://doi.org/10.4172/2325-9809.1000427>
- Nassar, S. M., Saleh, A. A., Eisa, A. A., Abdallah, E. M., & Nassar, I. A. (2025). Optimal planning of integrated nuclear-hybrid renewable energy systems for electrical distribution networks based on artificial intelligence. *Scientific Reports*, 15(1), 26004. <https://doi.org/10.1038/s41598-025-11049-z>
- Saleem, M. S., & Abas, N. (2025). Optimization and loss estimation in energy-deficient polygeneration systems: A case study of Pakistan's utilities with integrated renewable energy. *Results in Engineering*, 25, 104001. <https://doi.org/10.1016/j.rineng.2025.104001>
- Tchado Nguoko, D. R., Boukar, O., Carneiro Barbosa, M., Ndjiya, N., de Lima Accioly, S. C., & do Sá, T. (2026). Energy curtailment and data centers: Technological strategies for consumption optimization in renewable energy-based systems. *Journal of Research in Education & Technology*, 16(3), 1–11. <https://doi.org/10.9790/7388-1603020111>
- Tchado Nguoko, D. R., Boukar, O., Li Libouga, G. D., Ndjiya, N., & Fonou, S. M. (2025). Optimizing decentralized energy: A comprehensive review of distributed energy resource modeling. *Journal of Electrical Systems and Information Technology*, 12(1), 72. <https://doi.org/10.1186/s43067-025-00265-2>
- Zhu, D., Liu, S., Yang, B., Deng, H., Wu, Y., & Dong, Z. Y. (2026). Energy optimization for data centers via carbon-aware multi-

energy market coordination. *Applied Energy*, 409, 127371. <https://doi.org/10.1016/j.apenergy.2026.127371>

### Declarations

Ethical Approval and Consent to Participate  
This study did not involve human participants, human tissues, or live animals. Therefore, ethical approval and consent to participate were not required.

### Consent for Publication

Not applicable.

### Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

### Availability of Data and Materials

All data generated or analyzed during this study are included in this published article. Additional information may be made available by the corresponding author upon reasonable request.

### Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgements

The authors gratefully acknowledge the support provided by colleagues and laboratory staff who assisted during field sampling, laboratory analyses, and manuscript preparation. The authors also appreciate the constructive comments of anonymous reviewers, which helped improve the quality of the manuscript.

### Authors' Contributions

All components of the work were carried out by the author

