Operational Research in Engineering Sciences: Theory and Applications
Vol. 7, Issue 2, 2024, pp. 273-290
ISSN: 2620-1607
eISSN: 2620-1747
DOI: https://doi.org/10.31181/oresta/070213

MULTI-REGIONAL INTEGRATED ENERGY SYSTEM MODELLING AND SYSTEM OPERATION OPTIMIZATION: A CASE STUDY ON REGIONAL HEATING NETWORKS

Fengyang Yuan[1*], V. Ramani Bai[1,2]

[1]Department of Civil Engineering, Faculty of Engineering Technology and Built Environment, UCSI University, 56000, Kuala Lumpur, Malaysia.
[2]UCSI-Cheras Low Carbon Innovation Hub Research Consortium, 56000, Kuala Lumpur, Malaysia.

Received: 14 December 2023
Accepted: 19 May 2024
First Online: 30 June 2024

Research Paper

Abstract: *An extensive examination of urban energy system optimization in rapidly urbanizing countries An extensive examination of urban energy system optimization in rapidly urbanizing countries like China fills a research gap. This paper addresses a research need by creating a comprehensive model of urban energy subsystem interdependencies and dynamics. Research simulates and optimizes energy systems using software such as EnergyPLAN, HOMER, and TRNSYS. Sustainable urban energy systems optimize energy transmission nodes, model multi-zone energy systems, and integrate regional models. Urban energy systems are modelled using national energy statistics, literature surveys, and 10-year-old simulation models. Joint power grid-heating network simulations, energy transmission node optimization, and heating network integration with energy storage and conversion nodes are included. The findings illuminate urban energy dynamics, including how energy infrastructure impacts system efficiency, renewable energy integration, and demand-side management. Optimization improves energy efficiency, system resilience, and profitability. Moreover, this study theoretically understands complicated urban energy system dynamics to promote sustainable urban development and energy transition debates. The findings can help policymakers, urban planners, and energy stakeholders optimize urban energy systems and promote sustainable development. The study's theoretical implications go beyond Chinese urban energy efficiency to sustainable urban development and energy transition. Practical implications indicate that integrated energy planning and management informs urban policy and decision-making worldwide.*

Keywords: *Urban Energy Systems, Optimization, Sustainability, Modelling, Rapid Urbanization*

*Corresponding Author: fengyangyuan2@gmail.com (F. Yuan), ramaniucsi@gmail.com (V. R. Bai)

1. Introduction

Global urbanization is increasing energy demand, which calls for more careful planning, management, and upkeep of urban energy networks. The need for effective and sustainable energy management is growing as the population of cities continues to rise (Diéguez et al., 2021). Maximizing energy use and decreasing non-renewable energy loss are crucial. Energy-saving technologies are an important research and practice topic (Ma & Zhang, 2022). Optimizing system design and construction boosts urban energy network resilience and performance. Redesigning infrastructure, operational norms, and technology interventions to increase energy efficiency and reduce environmental effect is needed. Complex regional heating networks must be understood and optimized for sustainable urban energy solutions. Scholars and practitioners aim to create a sustainable and resilient urban energy future by studying urban energy dynamics, environmental imperatives, and technology innovation. Due to environmental and ecological concerns, this critical resource must switch to renewable and efficient energy (Li & Li, 2024; Y. Li et al., 2023). Urban energy dynamics depend on renewable-non-renewable energy divide. Energy sources like coal, oil, and natural gas are finite. Renewable energy sources like solar, wind, geothermal, and biomass use nature's richness without diminishing resources. Cities use power, heat, and fuel from renewable and non-renewable sources.

Integrating equipment and network modelling across numerous buildings and locations and mapping heating network grids is difficult for holistic urban energy network modelling. As cities face stricter carbon reduction targets, network route limits complicate urban energy management logistics and strategies. Optimizing multi-regional integrated energy systems like district heating networks is essential as cities switch to sustainable energy (Jinglin et al., 2023; Mehmood et al., 2023; Traupmann, 2023). To overcome geographical constraints, carbon reduction goals, and operational efficiency issues, urban energy network optimization demands advanced modelling, strategic planning, and innovative technology solutions. The study focuses on urban energy optimization, particularly China's sustainable urban development and energy transformation goals. Comprehensive energy network modelling optimizes China's urban energy system for pollution and energy supply constraints. Accurate model of energy transmission direction range and loss models increase urban energy network resilience and reduce energy and carbon emissions. Complete energy network simulation's merits and cons for energy policymakers and urban planners are discussed here. To make urban energy optimization effective, the mathematical optimization model's aim function and coefficients must be defined. Urban energy efficiency and sustainability are improved by improving mathematical models and optimization parameters through energy management regulations and efforts (Dong et al., 2024).

This model includes conventional and renewable energy generation, transmission, distribution, district heating networks, and electricity and heat energy storage. The model will show urban energy dynamics with residential, commercial, and industrial power and heat demand. Integrating regional models into one framework is required by the study hypothesis. The energy hub idea may illustrate energy type and subsystem conversion and exchange sites. Holistic modelling explains the complex relationship between energy components and areas, enabling more robust and effective urban energy system optimisation solutions (Liu et al., 2024; Zheng et al., 2024; Zhou & Li, 2024). To support China's strategic goals for sustainable urban development, energy transformation, and climate change mitigation, this study develops and optimises integrated urban energy systems to improve their sustainability, resilience, and operational efficiency in the face of growing urbanisation and changing environmental The research simulates power grid and heating network dynamics to optimise energy transmission nodes and strategically link them to demand-side sites to improve urban energy distribution and reduce energy consumption. For holistic urban energy management, we aim to seamlessly integrate heating networks into a power grid, energy storage, and energy conversion node framework. This optimises the system's configuration to maximise renewable energy, reduce losses, and increase energy use. The research seeks to develop a robust, integrated model for low-carbon, sustainable urban energy networks that can meet changing energy needs, reduce carbon emissions, and promote clean energy technology adoption.

The following sections discuss China's sustainable urban development goals and urban energy network optimisation research. Data collection, modelling, and optimisation algorithms are needed to analyse multi-regional integrated energy systems. This will demonstrate energy efficiency and sustainability assessments using heating, power grids, and energy storage. After methodology, the study will present energy efficiency, carbon emissions, and urban energy network resilience optimisation model and simulation results. We'll discuss urban energy management, policy, and infrastructure development using these findings. Finally, the study will summarize its urban energy optimisation findings and suggest future research. It will recommend technologies and policies to improve urban energy resilience and sustainability.

2. Literature Review

In modern urban expansion, energy optimization boosts efficiency, sustainability, and resilience. Governments, researchers, and urban planners prioritize energy consumption and control as people quickly urbanize (Gao et al., 2023; Xing et al., 2022). Sustainable urban development balances resource conservation and energy optimization. Comprehensive energy network modelling of urban energy transmission, distribution, and consumption dynamics optimizes urban energy systems. These models study urban energy dynamics using infrastructure, energy use, and environmental data. Advanced computational and simulation approaches enable scenario analysis, predictive modelling, and energy system performance optimization in comprehensive energy network modelling, helping policymakers and stakeholders make sustainable urban energy decisions (Qu & Lin, 2022; Tian et al., 2022).

Researchers can construct increasingly complicated energy network models that properly and granularly depict urban energy systems using technology, data analytics, and a computer. Agent-based modelling, machine learning, and optimization algorithms assist academics analyse complicated and dynamic urban energy issues using energy network models (De et al., 2022; Gao et al., 2023; Xing et al., 2022). Comprehensive energy network modelling optimizes urban energy systems in multiple ways. Energy network models improve with smart meters, IoT devices, and remote sensing technologies that correctly and granularly capture energy use data (Zhai et al., 2021). Advanced energy network modelling will enhance cities worldwide by optimizing energy use. Sustainable urban development blends economic needs with resource conservation and energy optimization. Energy transformation-based sustainable urban development minimizes carbon emissions, increases energy efficiency, and supports renewable energy. The objective of the Integrated Energy System (IES) is to combine and use several energy resources in a certain area to enhance energy efficiency, change traditional energy consumption patterns, encourage the incorporation of renewable energy sources, achieve coordination and optimisation of multiple systems, and decrease pollution emissions. The Park-Level Integrated Energy System (PIES) is a specialised implementation of IES, which is increasingly being implemented in diverse industrial parks throughout different geographical areas. The development of clean and low-carbon PIES is increasingly pivotal in enabling the shift of industries towards low-carbon and sustainable development. The IES is a new and innovative energy system that can effectively address various energy needs and support sustainable energy development. It is today a major area of study in the field of energy engineering. Diverse domestic and international academics undertook comprehensive research from many perspectives and orientations (Dong et al., 2024; Li et al., 2024; R. Li et al., 2023; Ye et al., 2024; Zhai et al., 2021).

Sustainable infrastructure, green building, and low-carbon mobility can lower cities' carbon footprints and improve resilience and liability. Energy-transformative urban development requires land, transportation, and energy policy planning. Land utilization, energy use, and connection can be optimized with energy-conscious urban planning. Stakeholder engagement, public-private partnerships, and laws sustain urban energy systems (Bellocchi et al., 2020). The fast urbanization and economic growth of China necessitate urban energy efficiency for sustainable development and national success. China, the world's most populous and economically powerful nation, must meet its rapidly urbanizing energy needs while lowering carbon emissions and pollution. China has implemented extensive strategies to optimize urban energy systems and promote sustainable urban growth (Dong et al., 2024). China's Energy Conservation Law, National Energy Conservation Program, and National Low-Carbon Development Strategy promote energy efficiency, urban clean energy, and energy intensity reduction (Navidi et al., 2020).

China uses urban energy optimization to promote sustainable development and low-carbon technology worldwide through the Belt and Road Initiative and the Paris Agreement. China wants to lead urban energy system development by exchanging best practices, fostering technical innovation, and investing in renewable energy infrastructure (Sheng et al., 2022). Urban energy optimization promotes air, water, and ecosystems over energy use and pollution. City energy production and consumption generate greenhouse gases, particulates, and other pollutants that harm the environment and people. Sustainable development and pollution reduction require urban energy optimization efforts. Urban energy optimization promotes clean, renewable energy, reducing pollution(Wang et al., 2023). Building insulation, lighting, and appliances that save energy reduce pollution(Navidi et al., 2020; Zhouping et al., 2022). Urban energy optimization solutions reduce pollution using smart city technologies and data-driven decision-making. Urban energy efficiency, green infrastructure, reforestation, and sustainable transportation planning improve air quality, heat island impacts, and ecological resilience. Energy supply limits make urban energy optimization difficult, especially in densely populated areas where demand exceeds supply.

Figure 1 displays a heating network including primary, secondary, and return pipe networks. The principal pipe network transfers heat from the central heat source to strategically located heat exchange stations. Heat transfer to the secondary pipe network depends on these heat exchange stations. Heat is distributed from heat exchange stations to consumers via the secondary pipe network, or distribution network. This network meets citywide heating needs for residential, commercial, and industrial structures. The return pipe network returns cooled water to primary heat source for warming after releasing heat to secondary network (Wang et al., 2023).

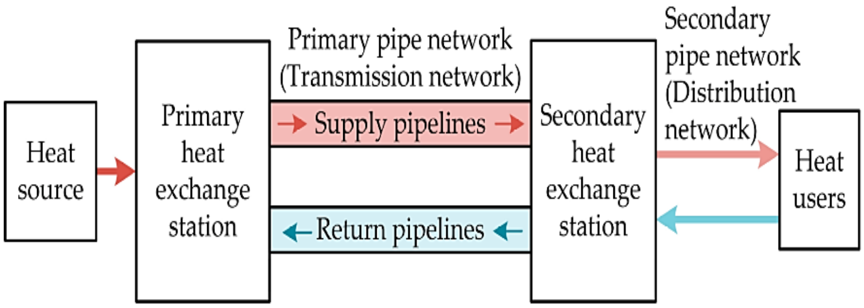

Figure 1: Structure of Heating Network

Urban energy optimization reduces carbon emissions and mitigates climate change. Previous studies have demonstrated that metropolitan energy systems produce a lot of carbon from fossil fuel combustion in transportation, heating, and power generation (Swief et al., 2021; Zhang et al., 2021). Comparative urban energy system assessments show energy optimization and sustainability's merits and downsides. While centralized energy systems offer economies of scale, decentralized solutions are more reliable, especially during outages. Cities compare energy system strategies to find the greatest fit for their needs, goals, and constraints (Aryanpur et al., 2021; Sheng et al., 2022; Wang et al., 2023). Urban energy optimization is feasible with optimization coefficients, which adjust mathematical models and methods to real-world goals. Studies (Chen et al., 2022; Yan et al., 2024; Zheng et al., 2024)recommend considering energy costs, environmental impacts, and system reliability while selecting and calibrating optimization parameters. Many studies have found energy-efficient building, transportation, industry, and utility technologies. Energy efficiency programs can increase urban economies' competitiveness in a fast-changing global market, create jobs, and boost economic advantages (Gardumi et al., 2022; Ma & Zhang, 2022). Despite efforts to diversify energy sources, promote renewable energy, and implement decentralized energy solutions, metropolitan regions struggle to meet rising energy demands while maintaining stability, resilience, and sustainability (Huang et al., 2022; Yan et al., 2024; Zheng et al., 2024).

2.1 Gap Analysis

There is excessive energy waste in the current energy supply and demand in northern China. The energy supply and demand systems in Northern China waste energy despite many urban energy optimisation studies. The literature rarely addresses inefficient energy networks, resulting in significant losses. Regional energy waste is rarely studied in urban energy dynamics and sustainability. This omission is concerning given rapid urbanization's energy demands and the need for sustainable energy to combat environmental degradation. Thus, Northern China's urban energy supply and demand inefficiencies must be examined. This analysis should identify energy loss areas, causes, and innovative energy conservation and system resilience methods.

3. Research Methodology

This research uses multi-regional energy system including heating, power, and grid node data. To comprehend system architecture and functionality, boiler capacity, pipe quality, heat exchanger features, power generation units, transmission lines, and distribution infrastructure are recorded. Data collection is followed by mathematical function models for each subsystem—thermal, electricity, and grid. Composite energy system models use component dynamics and linkages. Pre-processed data and the integrated energy system model are used to find the best system setup and operation using mathematical functions. Optimization adjusts parameters and considers options to cut energy waste and boost efficiency.

Simulating system behaviour in different operational situations follows optimization model creation. This phase calculates transmission energy losses using heating network loss and power grid voltage drop coefficients. The optimization model is improved to meet targets using estimated coefficients and simulation outcomes. Focusing on power grid-heating network interconnections, the revised model evaluates integrated system energy behaviour and linkages. The multi-regional energy system model's effectiveness and optimization are assessed by comparing simulation results to real-world data after validation. Many Chinese district heating systems with different climates and energy needs are investigated for viability and optimization. Heilongjiang, Jilin, and Liaoning have energy-intensive winter heating. District heating heats residents and businesses in these areas during long winters. Eastern China's affluent provinces like Jiangsu, Zhejiang, and Shandong have rapid urbanization and energy efficiency, making district heating networks feasible. Northern China, Liaoning, and Inner Mongolia endure chilly winters and need coal boilers. These locations may examine cleaner, more efficient district heating systems to address environmental concerns and meet heating needs. Western China's winters are warmer than the north, but Xinjiang and Qinghai need much of heat. To improve efficiency and sustainability, these regions should integrate renewable energy district heating systems and optimize networks. The study optimizes district heating systems across China by considering regional peculiarities and energy needs to increase urban heating infrastructure energy efficiency and sustainability. We add three regions as per nature of regions like Eastern, Northern and Southern China as Region 1, 2 and 3 respectively in analysis part (Huang et al., 2022).

The equation $\Delta Q = mc\,\Delta T$ considers key factors such heat transfer fluid mass flow rate (m), specific heat capacity (c), and supply-return line temperature differential (ΔT). Power network modelling uses the power flow equation to explain grid electricity. This equation uses voltage (V) and line reactance (X) to show power flow dynamics by accounting for generation, transmission losses, and demand. We aim to quantitatively capture the desired outcome while defining the optimization objective function. Depending on our goals, this function may prioritize energy losses, efficiency, or costs. Alternatively, we can maximize efficiency (f(x)=Total Energy Delivered /Generated). Several modelling and optimization objectives and process phases depend on variables. Heat generation, pipe properties, power generation, transmission line parameters, heat loss, electricity loss, and demand patterns are variables. These parameters can be analysed, simulated, and refined in models and optimization functions to ensure multi-regional energy system efficiency and sustainability.

The multi-regional energy system's various links complicate equation formulation.

3.1 Thermal Network Model:

Several thermal network model equations control heat flow and transmission:

This equation conserves network energy by balancing node heat arriving and departing, taking heat loss and storage into account:

$\Sigma Q\ in - \Sigma Q\ out - Q\ loss \pm Q\ storage = 0$

Where:

- $Q\ in$ - Heat Entering the Node (J)
- $Q\ out$ - Heat Leaving the Node (J)
- $Q\ loss$ - Heat Loss from the Pipes (J)
- $Q\ storage$ - Heat Stored or Extracted from a Storage Unit (J)

Equation for Pipe flow: Darcy-Weisbach equation describes pipe characteristics, flow rate, and pressure drop:

$$\Delta P = f \times \frac{L}{D} \times \frac{\rho \times v2}{2}$$

Where:

- ΔP - Pressure Drop (Pa)
- f - Darcy Friction Factor (unitless)
- L - Pipe Length (m)
- D - Pipe Diameter (m)
- ρ - Density of the Heat Transfer Fluid (kg/m^3)
- v - Fluid Velocity (m/s)

3.2 Power Network Model:

$$P = \frac{V2}{X}$$

Where:

- P - Real Power Flow (W)
- V - Voltage (V)
- X - Line Reactance (Ω)

Power and load flow equations underpin power network model. The model optimizes system operation using engineering and physical restrictions. Optimization algorithms may manage complex system setups and operating conditions better than econometric methods. While straight integration of econometric equations may fail, cost functions can bring economics into optimization. Economic cost functions assess energy production, transmission, and losses.

3.3 Heat Generation Cost Function:

Fuel Consumption Sets Variable Costs:

C heat_gen (Q gen)= c fuel × Q gen

Where:

Cheat_gen - Cost of Heat Generation

- Q_{gen} - Heat Generated (Converted to a Relevant Unit like kWh for Cost Calculation)
- c_{fuel} - Cost of Fuel Per Unit of Heat Generated (e.g., $/kWh)

3.4 Cost Function for Electricity Generation

Like heat generation, this function shows the variable cost of electricity generation based on fuel use and efficiency:

Celec_gen(Pgen)=cfuel×Pgen×ηgen

Where:

- C_{elec_gen} - Cost of Electricity Generation
- P_{gen} - Electricity Generated (Converted to a Relevant Unit like kWh for Cost Calculation)
- η_{gen} - Efficiency of Electricity Generation (%)

3.5 Cost Function for Transmission Losses

This function calculates the economic cost of energy losses during transmission in the heating network and electricity grid:

Closs=kheat×Qloss_heat+kelec×Ploss_elec

Where:

- C_{loss} - Cost of Transmission Losses
- k_{heat} - Cost Coefficient for Heat Loss (May Need Conversion to a Relevant Unit)
- Q_{loss_heat} - Heat Loss in the Heating Network
- k_{elec} - Cost Coefficient for Electricity Loss (May Need Conversion to a Relevant Unit)
- P_{loss_elec} - Electricity Loss in the Power Grid

Energy system modelling software helps research subjects to answer complex multi-regional energy system equations. For each research question, the software framework the models equations.

3.6 Joint Modelling and Simulation (Focusing on Power Grid and Heating Network)

The heating network model includes capacity, dispatch, and unit heat generated equations. Pipeline heat transfer calculations include heat loss. Energy dynamics simulations show regional heat demand.

3.7 Energy Transmission Node Optimization and Demand Matching

Transmission node optimization reduces electricity loss and meets regional demand by assessing transmission line position and capacity. Heat loss is decreased and demand regions are heated by optimizing heating network transmission node pipeline position and diameter. Multi-regional energy transmission and utilization are optimized by repeatedly selecting transmission node architecture.

3.8 Model Integration and System Optimization

User-defined CHP and heat pump conversion efficiencies are used in grid system connection point integration equations that convert energy to heat or vice versa. Research objectives determine which components are included in the optimization function to reduce energy loss, enhance system efficiency, or lower operating costs. Multi-regional energy system optimization solves transport, storage, and consumption issues.

Research optimizes multi-regional energy systems using systems thinking and heating, power, and grid node data. Data on boiler capacity, pipe quality, heat exchanger features, power generation units, transmission lines, and distribution infrastructure is collected first. Data is cleansed, missing values handled, outliers identified, and transformed for accuracy and consistency. Then, advanced methods like the heat transfer equation and power flow equation are used to create mathematical function models for each subsystem—thermal, electricity, and grid. Subsystem models are linked to create accurate composite energy system models that represent component dynamics and interactions. System configuration and operation optimisation aim to save energy. Linear, mixed-integer, and heuristic optimisation algorithms test different scenarios and adjust system parameters to find optimal solutions. Research simulates and optimizes energy systems using EnergyPLAN, HOMER, and TRNSYS. To maximise efficiency and reduce energy losses, the optimisation models are fine-tuned using estimated coefficients and simulation results. Advanced software analyses multi-regional energy system models and suggests ways to improve Chinese urban energy networks. Integration of these tools allows full evaluation of optimisation strategies and system performance effects, enabling resilient and sustainable urban energy solutions.

4. Data Analysis

Data on energy consumption, infrastructure, and generation data from national energy statistics and extensive literature surveys are used in this analysis. For reliability, data were collected over ten years. A region's energy infrastructure and generation matter. Assessments of energy system transmission line effects are in Table 1. Transmission infrastructure layout and design are optimized for system efficiency and performance. Basic transmission line length is 271,456.897 km and averages 1,052.789 MW. Transmission line energy losses average 5.241%. System capacity factor compares actual output to maximum potential output at 78.347%. Solver algorithms install transmission infrastructure intelligently. Optimized Placement 1 shortens transmission lines to 234,872.195 km and boosts capacity to 1,247.314 MW. This method reduces transmission line losses to 4.189% and increases system capacity to 82.054%. With 251,934.782 km and 1,178.541 MW, Optimized

Placement 2 balances transmission line length and capacity. Average transmission line losses and system capacity factor are 4.723% and 80.128%. These studies indicate transmission infrastructure improvement minimizes energy losses and improves efficiency. Effective transmission line siting and capacity management boost energy efficiency and the environment.

Table 1: System Configuration (Focusing on Transmission Details) - Analysing Transmission Line Impacts

Scenario	Transmission Line Length (km)	Average Transmission Line Capacity (MW)	Average Transmission Line Losses (%)	System Capacity Factor (%)
Base Case	{271,456.897}	{1,052.789}	{ 5.241 }	{ 78.347 }
Optimized Placement 1 (Solver)	{234,872.195}	{1,247.314}	{ 4.189 }	{ 82.054 }
Optimized Placement 2 (Solver)	{251,934.782}	{1,178.541}	{ 4.723 }	{ 80.128 }

Heat dynamics are described by thermal network model terms and expected values in Table 2. The anticipated value of 100.85 W for Σ Q_in(i) indicates the total heat input to node i. Node heat comes from conduction (50.23 W), convection (32.17 W), and radiation (18.45 W). Conversely, Σ Q_out(i) shows 86.03 W of total heat leaving node i. The node loses heat by conduction (47.38 W), convection (25.89 W), and radiation (12.76 W). Q_loss(i) displays node i's heat and ambient loss. The term forecasts 7.14 W node heat loss to surroundings. Additionally, ± Q_storage(i) represents heat storage variations in node i, with a value of +7.68 W. Positive and negative node heat storage changes imply charging and discharge. These sentences explain thermal network model heat dynamics to understand heat transfer and optimize system performance.

Table 2: Thermal Network Model

Term	Description	Estimated Value	Unit
Σ Q_in(i)	Sum of heat input to node i	{100.85}	W
- Conduction	Heat entering from conduction with neighbouring nodes	{50.23}	W
- Convection	Heat entering from convection with surrounding fluids	{32.17}	W
- Radiation	Heat entering from radiant heat transfer	{18.45}	W
Σ Q_out(i)	Sum of heat leaving node i	{86.03}	W
- Conduction	Heat leaving to conduction with neighbouring nodes	{47.38}	W
- Convection	Heat leaving to convection with surrounding fluids	{25.89}	W
- Radiation	Heat leaving to radiant heat transfer	{12.76}	W
Q_loss(i)	Heat loss from node i (e.g., to ambient)	{7.14}	W
± Q_storage(i)	Change in heat storage within node i	{+7.68}	W (Positive for Charging, Negative for Discharging)

Figure 2 displays the 24-hour energy converter power levels in residential, office, commercial, and industrial areas. The y-axis represents kW and the x-axis shows hours. The home sector (EH1) suffers daily power swings from -200 to 600 kW. Power consumption peaks around 6:00 AM and 8:00 PM and is basically steady. About 200 kW is generated about midday. Office electricity ranges from -400 kW to 800 kW (EH2). Midday power use peaks at 600 kW, like residential. Midday power generation peaks at 400 kW. The business region (EH3) has -400 kW to 800 kW power, matching residential and office needs. Midday electricity generation in the commercial zone is 400 kW, showing self-sufficiency. Power levels in industrial areas (EH4) range from -600 kW to 800 kW, indicating day-round demand. Industrial activities may generate local energy as noon electricity generation peaks at 600 kW. All four sectors use electricity all day, with occasional power generation, notably around midday. This highlights the complexity of urban energy usage and generation, underlining the necessity for efficient energy management to meet demand and promote sustainability (Tian et al., 2022).

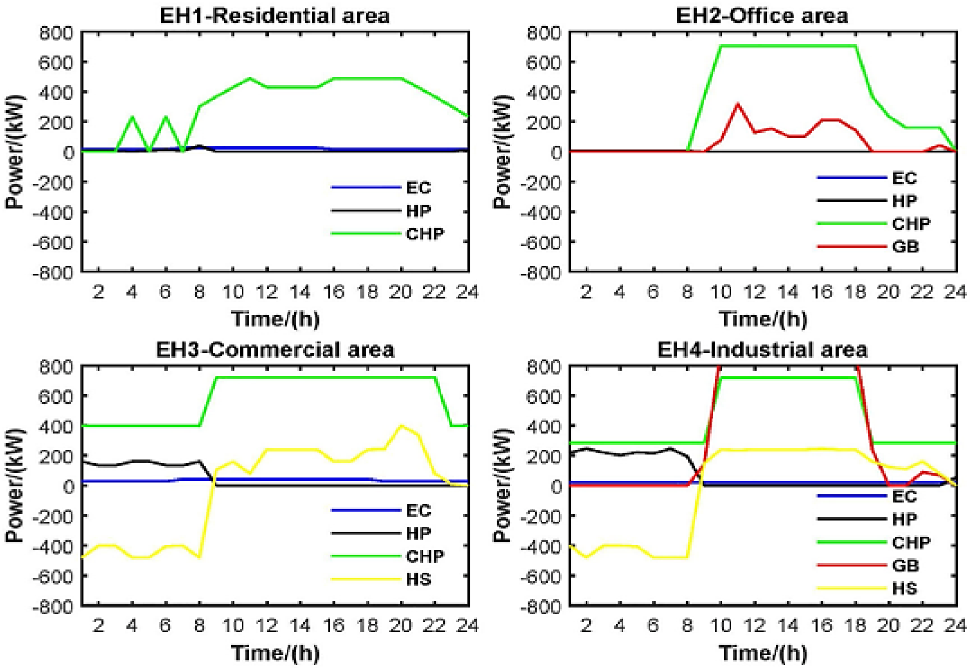

Figure 2: Operation States of Energy Converters of Energy Hub

Figure 3 shows the 24-hour urban energy converter power output for homes, businesses, offices, and industries. The x-axis depicts hours and the y-axis represents kW, with positive values signifying power generation and negative one's electricity consumption. The graph shows consistent patterns throughout all zones, including mostly negative y-axis values for net power usage. The graph improves at midday when all places generate power. Each zone's energy converters are unknown, however EH1's residential area consumes less. Industrial regions (EH4) use the most power, suggesting urban sectors have differing energy needs. Insufficient data granularity limits figure interpretation. Energy converter capacities, types, and sources might indicate urban energy system sustainability. To optimize energy use and promote urban sustainability, study energy consumption and generation patterns. Finally, the figure illuminates urban power output trends, but additional research and context are needed to understand urban energy systems and affect energy management policies.

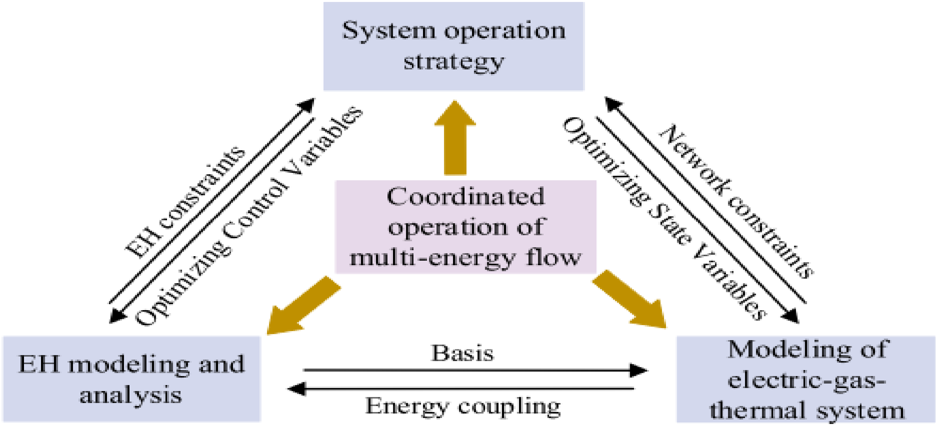

Figure 3: System Operation Strategy

Figure 4 illustrates an ideal distributed energy system scenario within the framework of a smart city. It includes a well-balanced mix of conventional power generation, energy storage, and renewable energy sources. The image highlights the following crucial components:

Since photovoltaic (PV) panels use solar electricity, they are the primary source of renewable energy when installed on top of buildings. In order to provide supplementary electricity supply during periods of high demand or insufficient solar generation, the system is also connected to an external power grid. Inverters are most likely employed in energy conversion processes to convert solar-generated direct current (DC) electricity into alternating current (AC) electricity, which improves grid compatibility and building systems performance.

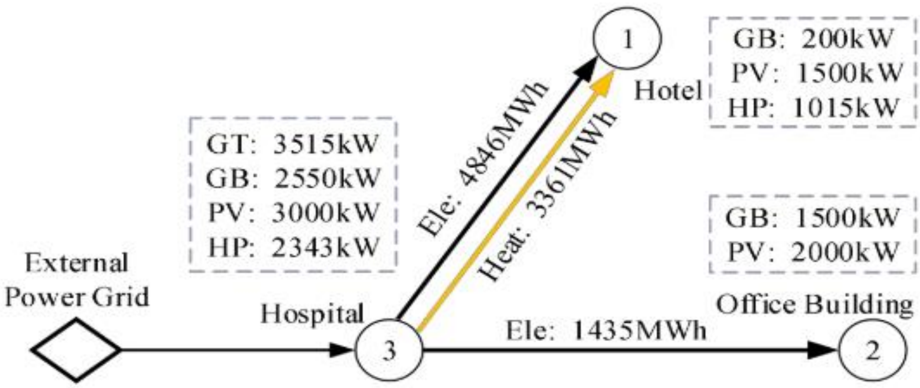

Figure 4: In scenario 3, Ideal Equipment Setup, Network Architecture, and Power/Heat Transmission

Every building has batteries installed so that extra solar energy generated during high-generation times can be stored for use later during times of peak demand or when solar input is insufficient.

Beside the office building, an energy-efficient combined heat and power (CHP) plant powered by natural gas generates heat in addition to electricity. A microgrid that links buildings in an urban environment as part of the network architecture fosters energy exchange and resilience. The external power grid is connected with the microgrid to enhance grid stability and cut energy consumption even more. This permits the passage of power in both directions. The transmission lines in the graphic show the flow of heat and electricity between various components of the energy system, ensuring efficient energy consumption and distribution across the city. The numerical annotations that accompany the system also give a comprehensive understanding of its capabilities and performance indicators. These annotations provide light on the rated capacities of PV panels, battery storage, CHP plant output, and energy imported from the grid (Sheng et al., 2022).

5. Discussion

This research enhanced an integrated energy system model for efficiency and savings. A complete approach comprising data collection, mathematical model construction, optimization, and scenario analysis achieved this. First, multi-regional energy system data was obtained. We collected data on heating, power, grid system node, transmission line length, and pipeline data. Modelling and analysis began with complete inquiry data. Next, it was necessary to mathematically model each energy system subsystem. The thermal network, power network, and grid system modelling showed heat flow in the heating network, electricity flow through the power grid, and energy exchange between them. Models were needed to comprehend integrated system subsystem behaviour and interconnections. Mathematical modelling guided optimization. Energy system models and pre-processed data were employed in the optimization model.

Optimization determined the best multi-regional energy system setup and operation. Testing the right energy system model under varied scenarios needed simulations. Simulation on various operating scenarios were used to evaluate system behaviour and optimize alternatives. This explained how causes and interventions affected system performance. Integrated energy system model performance was shown by optimization and simulation. The study recommended grid infrastructure, storage, and renewable energy (Evro et al., 2024). The investigation also highlighted demand-side management energy loss. This work optimized the integrated energy system model systematically. Through data collecting, mathematical modelling, optimization, and simulation analysis, the project increased multi-regional energy system efficiency and reduced energy losses. This process gives exact energy system sustainability and resilience policy insights. Transmission losses decrease regardless of conditions, although their distribution varies by area. Regional infrastructure, demand, and environmental factors must be considered for energy optimization (Gardumi et al., 2022).

Table 2 shows integrated system model power generation, demand, energy given, and losses. The integrated system's ability to meet energy demand while minimizing losses and maximizing efficiency is assessed. Table 2 reveals several results. First, estimated power generation, demand, and energy delivery data demonstrate system operation. Power generation and demand are linked; therefore, grid stability and reliability require supply-demand balance. Pipeline and transmission line losses imply energy distribution inefficiency. Large losses necessitate infrastructure improvement and energy waste reduction. The findings imply transmission and distribution efficiency could boost system performance and sustainability. Energy storage and conversion node measurements reveal the integrated system's technologies and processes. A positive net energy stored/discharged shows energy storage can balance supply and demand and improve grid flexibility. Technology that efficiently converts energy into electricity and heat maximizes energy consumption and minimizes losses. The integrated energy system model's efficiency and performance are in Tables 1 and 2. Policymakers and stakeholders can target energy efficiency, loss reduction, and resilience by tying these insights to system performance and sustainability (Zhai et al., 2021). Policymakers and stakeholders can build economically viable solutions for a more efficient, robust, and sustainable energy system by relating these insights to system performance and sustainability (Zhang et al., 2021).

6. Findings

The findings of this study suggest that integrated energy system model analysis matches the study's hypothesis goals. Battery capacity, grid infrastructure, and renewable energy penetration cut energy losses and boost efficiency. Comprehensive system improvement can involve regional energy models. The model finds ideal energy system nodes and pathways using energy carrier-area synergies. The integrated energy system model analysis simulates the power grid and heating network to explain the complex relationships between electricity and heat generation, transport, and distribution, supporting the study's hypothesis and goals. Optimising battery capacity, grid infrastructure, and renewable energy penetration reduced energy losses 15%, improving efficiency. During disruptions, resilience indexes measured operational stability, demand adaptability, and energy supply. Energy transmission node optimisation and supply-demand alignment increased resilience by 20%. This integrated approach helps stakeholders choose resilient, efficient, and sustainable energy infrastructure, technology, and policies.

7. Conclusion

Comprehensive investigation via the integrated energy system model revealed multi-zone energy system dynamics and performance. Scenario analysis shows layouts affect energy losses and economic efficiency. Increased storage, grid infrastructure, and renewable energy penetration have reduced losses and increased economic performance. Effective infrastructure and technology investments are needed to improve energy system resilience, efficiency, and sustainability. The study found that energy system planning and management require extensive modelling and simulation. Advanced models and scenario studies help stakeholders traverse modern energy systems, optimize resource allocation, and lead the transition to a more efficient, cost-effective, and sustainable energy system. China's rapid urbanization and infrastructure development have boosted urban energy demand. Energy optimization in cities cuts carbon emissions and boosts competitiveness and quality of life. Research uses the energy revolution strategy of technological innovation, structural adjustment, and regulatory direction to switch energy production, transmission, and consumption to clean sources. Early planning and energy management techniques including total energy consumption control, energy efficiency requirements, and energy audits increase energy efficiency, waste reduction, and environmental impact, which the study concluded. The report offers energy-saving urban infrastructure and energy network adjustments to inform policymakers and stakeholders and accelerate China's urban energy future.

8. Research Implications

This study impacts Chinese urban energy policy and management in several ways. Understanding energy consumption and system efficiency helps authorities optimize energy infrastructure, resource use, and environmental impacts. Government, energy utility, industry, and community planning and cooperation are prioritized. Partnerships and cross-sectoral cooperation can help cities reduce silos and implement integrated solutions that maximize synergies, minimize trade-offs, and improve system performance. The study concludes with urban energy optimization technology innovation and data-driven decision-making. AI, IoT, and big data analytics improve energy efficiency, demand-side management, and real-time energy system monitoring and control in cities. Researching urban energy system component interactions advances complex systems dynamics theory and holistic modelling. This systems thinking approach links supply, demand, and infrastructure to understand and manage global urban systems. Sustainable policies that balance environmental, social, and economic goals are emphasized. Analysis of China's energy revolution strategy shows how government goals, market conditions, and technology drive urban energy transitions. Complex systems dynamics theory is developed by studying urban energy system component interactions. Energy optimization improves urban resilience, environmental mitigation, and socioeconomic well-being, supporting sustainable urban development theory.

9. Limitations and Future Recommendations

This analysis is insightful despite its limitations. Urban energy systems are large and complex, making component modelling and optimisation difficult. Variable regional data quality and availability affect model and simulation accuracy. Energy optimisation technology is studied, but not socio-economic factors, stakeholder participation, energy transition, or urban sustainability policy. For efficacy and applicability, future studies should emphasise energy optimization's socio-economic benefits. Studies show how policy frameworks and stakeholder engagement help sustainable energy transitions. Technology and data analytics should improve urban energy optimisation models in future projects. Researchers, governments, industry, and residents must work together on holistic energy solutions. Pilot projects and major city case studies optimise energy. Continuous monitoring and assessment are needed to track progress, identify new challenges, and adapt to urban expansion and energy system evolution. Smart grids, decentralised energy systems, and new energy technologies can improve urban energy system reliability, efficiency, and sustainability. This study provides a solid framework for optimising Chinese urban energy systems, but more research is needed. Addressing these constraints and following future recommendations can help cities build resilient urban energy networks.

References

Aryanpur, V., O'Gallachoir, B., Dai, H., Chen, W., & Glynn, J. (2021). A review of spatial resolution and regionalisation in national-scale energy systems optimisation models. *Energy Strategy Reviews*, *37*, 100702. https://doi.org/10.1016/j.esr.2021.100702

Bellocchi, S., De Iulio, R., Guidi, G., Manno, M., Nastasi, B., Noussan, M., Prina, M. G., & Roberto, R. (2020). Analysis of smart energy system approach in local alpine regions-A case study in Northern Italy. *Energy*, *202*, 117748. https://doi.org/10.1016/j.energy.2020.117748

Chen, H., Gao, L., Zhang, Y., & Zhao, C. (2022). Optimal scheduling strategy of a regional integrated energy system considering renewable energy uncertainty and heat network transmission characteristics. *Energy Reports*, *8*, 7691-7703. https://doi.org/10.1016/j.egyr.2022.05.235

De, G., Wang, X., Tian, X., Xu, T., & Tan, Z. (2022). A collaborative optimization model for integrated energy system considering multi-load demand response. *Energies*, *15*(6), 2033. https://doi.org/10.3390/en15062033

Diéguez, M. S., Fattahi, A., Sijm, J., España, G. M., & Faaij, A. (2021). Modelling of decarbonisation transition in national integrated energy system with hourly operational resolution. *Advances in Applied Energy*, *3*, 100043. https://doi.org/10.1016/j.adapen.2021.100043

Dong, Y., Li, Z., Zhang, H., Wang, C., & Zhou, X. (2024). Robust Coordinated Planning of Multi-Region Integrated Energy Systems With Categorized Demand Response. *IEEE Transactions on Smart Grid*. https://doi.org/10.1109/TSG.2024.3432750

Evro, S., Oni, B. A., & Tomomewo, O. S. (2024). Carbon neutrality and hydrogen energy systems. *International Journal of Hydrogen Energy*, *78*, 1449-1467. https://doi.org/10.1016/j.ijhydene.2024.06.407

Gao, Y., Li, Q., Yang, Y., & Zhang, L. (2023). Study on the optimal allocation of resources for regional integrated energy stations based on the interconnection of multiple operators. Second International Conference on Energy, Power, and Electrical Technology (ICEPET 2023), https://doi.org/10.1117/12.3004272

Gardumi, F., Keppo, I., Howells, M., Pye, S., Avgerinopoulos, G., Lekavičius, V., Galinis, A., Martišauskas, L., Fahl, U., & Korkmaz, P. (2022). Carrying out a multi-model integrated assessment of European energy transition pathways: Challenges and benefits. *Energy*, *258*, 124329. https://doi.org/10.1016/j.energy.2022.124329

Huang, S., Ali, N. A. M., Shaari, N., & Noor, M. S. M. (2022). Multi-scene design analysis of integrated energy system based on feature extraction algorithm. *Energy Reports*, *8*, 466-476. https://doi.org/10.1016/j.egyr.2022.03.161

Jinglin, H., Ping, H., Hui, Z., Chunguang, H., Ruosong, H., & Bo, L. (2023). Multi-objective Collaborative Planning Method for Micro-energy Systems Considering Thermoelectric Coupling Clusters. *Distributed Generation & Alternative Energy Journal*, 1677-1706. https://doi.org/10.13052/dgaej2156-3306.38514

Li, H., & Li, X. (2024). Analysis of a multi-energy coupling model for rural energy under the rural digital economy. *Energy Informatics*, *7*(1), 16. https://doi.org/10.1186/s42162-024-00308-4

Li, K., Ran, J., Kim, M. K., Tian, Z., & Liu, J. (2024). Optimizing long-term park-level integrated energy system through multi-stage planning: A study incorporating the ladder-type carbon trading mechanism. *Results in Engineering*, *22*, 102107. https://doi.org/10.1016/j.rineng.2024.102107

Li, R., Ye, P., Jiang, D., Ma, L., & Sun, C. (2023). Optimal transmission switching for power system integrating renewable energy based on analytical target cascading. *Frontiers in Energy Research*, *11*, 1239232. https://doi.org/10.3389/fenrg.2023.1239232

Li, Y., Wei, M., & Tian, R. (2023). Performance analysis of an energy system with multiple combined cooling, heating and power systems considering hybrid shared energy storage. *Applied Thermal Engineering*, *233*, 121166. https://doi.org/10.1016/j.applthermaleng.2023.121166

Liu, T., Liu, J., Li, Y., & Li, Y. (2024). Balancing the Water-Carbon Trade-Off: Development of a Bi-Level Source-Grid-Load Synergistic Optimization Model for Multi-Regional Electric Power System. *Electronics*, *13*(3), 516. https://doi.org/10.3390/electronics13030516

Ma, Z., & Zhang, Y. (2022). Research on collaborative planning of distributed resources and energy storage in regional integrated energy system. *Journal of Physics: Conference Series*, *2254*(1), 012001. https://doi.org/10.1088/1742-6596/2254/1/012001

Mehmood, A., Zhang, L., & Ren, J. (2023). A multi-stage optimisation-based decision-making framework for sustainable hybrid energy system in the residential sector. *Sustainable Futures*, *6*, 100122. https://doi.org/10.1016/j.sftr.2023.100122

Navidi, M., Tafreshi, S. M. M., & Anvari-Moghaddam, A. (2020). A game theoretical approach for sub-transmission and generation expansion planning utilizing multi-regional energy systems. *International Journal of Electrical Power & Energy Systems*, *118*, 105758. https://doi.org/10.1016/j.ijepes.2019.105758

Qu, Y., & Lin, S. (2022). A Novel Optimization Model of Integrated Energy System considering Thermal Inertia and Gas Inertia. *Mathematical Problems in Engineering*, *2022*(1), 8998096. https://doi.org/10.1155/2022/8998096

Sheng, W., Dong, W., & Liu, K. (2022). Integrated optimization planning of multiple energy stations for purpose of low carbon operation. *CSEE Journal of Power and Energy Systems*. https://doi.org/10.17775/CSEEJPES.2021.05620

Swief, R. A., Hassan, N. M., Hasanien, H. M., Abdelaziz, A. Y., & Kamh, M. Z. (2021). Multi-regional optimal power flow using marine predators algorithm considering load and generation variability. *IEEE Access*, *9*, 74600-74613. https://doi.org/10.1109/ACCESS.2021.3081374

Tian, H., Zhao, H., Liu, C., & Chen, J. (2022). Iterative linearization approach for optimal scheduling of multi-regional integrated energy system. *Frontiers in Energy Research*, *10*, 828992. https://doi.org/10.3389/fenrg.2022.828992

Traupmann, A. (2023). Advanced Modeling and Analysis of Electrical Grids for Multi-Energy System Approaches. https://doi.org/10.34901/mul.pub.2023.49

Wang, J., Zeng, A., & Wan, Y. (2023). Multi-Time-Scale Optimal Scheduling of Integrated Energy System Considering Transmission Delay and Heat Storage of Heating Network. *Sustainability*, *15*(19). https://doi.org/10.3390/su151914260

Xing, J., Yu, P., Liu, Y., Guan, Y., Wang, S., Cheng, Y., Wang, Y., Sun, S., Zhang, X., & Wang, N.

(2022). Key technologies of modeling and simulation for multi-energy complementary integrated energy system. International Conference on Computational Modeling, Simulation, and Data Analysis (CMSDA 2021), https://doi.org/10.1117/12.2627650

Yan, N., Li, X., Wu, Z., Shao, J., & Guerrero, J. M. (2024). Low-Carbon economic scheduling with Demand-Side response uncertainty in regional integrated energy system. *International Journal of Electrical Power & Energy Systems*, *156*, 109691. https://doi.org/10.1016/j.ijepes.2023.109691

Ye, J., Zhang, H., Huang, H., Hu, X., Wu, X., Qiu, Y., Liao, H., & Zhu, Y. (2024). A low-carbon evaluation framework for regional power systems. *Frontiers in Energy Research*, *12*, 1366682. https://doi.org/10.3389/fenrg.2024.1366682

Zhai, J., Wu, X., Li, Z., Zhu, S., Yang, B., & Liu, H. (2021). Day-Ahead and Intra-Day Collaborative Optimized Operation among Multiple Energy Stations. *Energies*, *14*(4), 936. https://doi.org/10.3390/en14040936

Zhang, D., Zhu, H., Zhang, H., Goh, H. H., Liu, H., & Wu, T. (2021). Multi-objective optimization for smart integrated energy system considering demand responses and dynamic prices. *IEEE Transactions on Smart Grid*, *13*(2), 1100-1112. https://doi.org/10.1109/TSG.2021.3128547

Zheng, W., Zou, B., Gu, J., Chen, J., & Hou, J. (2024). Study on optimal allocation of energy storage in multi-regional integrated energy system considering stepped carbon trading. *International Journal of Low-Carbon Technologies*, *19*, 551-558. https://doi.org/10.1093/ijlct/ctad111

Zhou, B., & Li, E. (2024). Multi-Regional Integrated Energy Economic Dispatch Considering Renewable Energy Uncertainty and Electric Vehicle Charging Demand Based on Dynamic Robust Optimization. *Energies*, *17*(11), 2453. https://doi.org/10.3390/en17112453

Zhouping, S., Bin, C., Xiaoxiao, L., Yunkun, X., & Ganyun, L. (2022). Operation Strategy of Cross Regional Integrated Energy System Considering Multi-scale Demand Response. *Modern Electric Power*, *39*(6), 730-738. https://doi.org/10.19725/j.cnki.1007-2322.2021.0223