CHAPTER II

LITERATURE REVIEW

2.1 General Introduction

The integration of HS and high penetration RE into MES with EH has gained significant attention due to the demand for sustainable and efficient energy systems. EHs coordinate multiple energy carriers such as electricity, heat, and fuel with RE to improve overall system efficiency. The directionality and variability of RE are key factors for effective HS integration in both current and future applications. As MES grows in complexity, energy scheduling plays a vital role in optimizing RE and HS operations. Effective energy scheduling is critical not only for balancing supply and demand in real-time, but also for achieving objective function optimization. This literature review examines the current state of research on HS integration, EH models, and optimal MES scheduling, highlighting technological advancements, benefits, challenges, and case studies that demonstrate how HS improves MES performance and sustainability.

2.2 Conventional Electrical Energy Scheduling Problems

According to Power Generation, Operation, and Control (Wood et al., 2013), energy scheduling plays a crucial role in managing the generation and consumption of energy across various sources, aiming to optimize the objective function. In the past, hydroelectric systems involved the complex task of scheduling water releases while satisfying hydraulic and energy demand constraints. When thermal generation was not present, the challenge centered on reservoir management to maximize stored energy through simulation-based scheduling. However, in hydrothermal systems where both hydro and thermal resources are present, the scheduling strategy depended on the dominance and balance of each source. Pseudo-fuel costs could be assigned to hydro units to facilitate cost-based optimization similar to conventional systems. A key aspect of traditional scheduling involves determining when to start up each generating unit, known as unit commitment, and how much power each unit should produce at a given time, known as economic dispatch. These problems were typically solved over a defined planning horizon, such as daily, weekly, or seasonally, to achieve minimum operating cost while maintaining system reliability.

As energy systems have evolved, the concept of optimal scheduling has expanded beyond hydrothermal coordination into more complex MES. MES involves the integration of multiple energy carriers which requires coordinated scheduling across these interdependent subsystems. The focus of MES scheduling shifts toward optimizing several objectives at once, while managing the dynamic interactions among the system components. In this context, the principles of hydrothermal scheduling provide a foundational basis. However, the increasing complexity of MES necessitates the adoption of more advanced methods, including multi-objective optimization techniques, the integration of RE resources, the use of modern energy storage technologies, and probabilistic approaches for planning under uncertainty.

2.3 Trend in Renewable Energy Integration with Hydrogen Storage

In the era of clean energy transition, the integration of RE sources with HS systems has emerged as a promising strategy to address the intermittency of RE and enhance energy system flexibility. Among various RE options, solar and wind energy are particularly well-suited for coupling with HS due to their decreasing costs and technological maturity. In Thailand, the cost of electricity generation from solar energy has significantly dropped, averaging around 2.16 baht/kWh, while wind energy costs average approximately 3.10 baht/kWh. These competitive price points make both solar and wind energy attractive candidates for integration with HS systems. By storing excess energy during periods of high generation and releasing it during low-output periods, HS not only offsets the variability of these sources but also contributes to grid stability and the decarbonization. This synergy supports Thailand's broader commitment to a sustainable and low-carbon energy future (Energy Policy and Planning Office, 2023). Additionally, wind and solar technologies have seen substantial technological advancements, resulting in greater efficiency and reduced costs. Their scalability and adaptability across diverse geographic regions further increase their practicality for widespread HS integration (D'Silva, 2024). Continued improvements in electrolyzer (EL) technologies and energy storage systems (ESS) also enhance the technical and economic viability of using wind and solar energy for hydrogen production (Ikuerowo et al., 2024).

2.4 Literature Overview

This section explores key research areas, including HS application overview, optimal scheduling of MES using EH models under individual objective, and optimal scheduling of MES using EH models under multi-objective. Table 2.1 outlines the HS application overview from existing literature, while Table 2.2 presents studies that address optimal scheduling of MES using EH models focusing on individual objectives. Table 2.3 highlights studies focusing on the optimal scheduling of MES using EH models under multi-objective. Additionally, Table 2.4 elaborates the probabilistic model for optimal scheduling MES using EH. Finally, Table 2.5 shows the research gap between the existing and this study. This review identifies research gaps and suggests future study directions.

Table 2.1 HS application overview

Author and publication year	Topic	Key findings
Cau et al. (2014)	Energy management strategy based on short-term generation scheduling for a renewable microgrid using a hydrogen storage system	The demonstration of modeling a hydrogen storage system, which operates via electrolyzer and fuel cell with Faraday's law. The relationship between the hydrogen pressure in the tank and the amount of stored hydrogen is based on the ideal gas law.
Qadrdan et al. (2015)	Role of power-to-gas in an integrated gas and electricity system in Great Britain	These findings demonstrate that power-to-gas systems can play a key role in balancing energy systems, integrating renewable sources, and reducing operational costs in real-world systems.
Ould Amrouche et al. (2016)	Overview of energy storage in renewable energy systems.	This review highlights the use of existing energy storage technologies, including HS. HS involves the use of electrolyzers to convert surplus electricity into hydrogen, which can then be stored and later converted back into electricity through fuel cells.

Table 2.1 HS application overview (Continued)

Author and publication year	Topic	Key findings
X. Chen et al. (2019)	Optimal Control for a Wind-Hydrogen-Fuel Cell Multi-Vector Energy System	The research shows how the integration of hydrogen storage enhances the stability of the energy supply, compensating for the intermittent nature of wind power. This approach, which coordinates multiple energy vectors, has the potential to improve the efficiency of RE systems in wind-rich areas and encourage broader adoption of renewable technologies.
Osman et al. (2022)	Hydrogen production, storage, utilisation and environmental impacts: a review	This review provides a hydrogen production is defined in various color codes depending on the manufacturing process and cleanliness. It can be categorized into five colors: grey, brown, blue, turquoise, and green hydrogen.
Dash et al. (2023)	A Brief Review of Hydrogen Production Methods and Their Challenges	The review highlights the production of purple hydrogen, which is derived from nuclear energy. Nuclear fission generates heat, which is utilized to produce electricity and subsequently fuel hydrogen production.

Table 2.1 HS application overview (Continued)

Author and publication year	Topic	Key findings
Xiangping Chen et al. (2019)	GA Optimization Method for a Multi-Vector Energy System Incorporating Wind, Hydrogen, and Fuel Cells for Rural Village Applications	This paper presents a genetic algorithm (GA)-based optimization method for a power generation system with hydrogen storage. The method balances fluctuating demand and intermittent wind power, optimizing RE use by converting wind energy into hydrogen and electricity.
Dechjinda and Chayakulkheeree (2024)	Optimal Daily Scheduling of Hybrid Wind-Hydrogen Storage using Particle Swarm Optimization	This study proposes a power system that integrates HS and wind power to minimize daily power losses. The system's performance is evaluated using a PSO-based scheduling algorithm on a modified IEEE 33-bus test system. The results demonstrate that excess wind energy can be effectively utilized for peak shaving, reducing peak load and leading to more efficient loss minimization.

Table 2.2 Optimal scheduling of MES using EH under individual objectives

Author and publication year	**Topic**	**Objective function**	**Method**	**Key findings**
Geidl et al. (2007)	The Energy Hub – A Powerful Concept for Future Energy Systems.	-	-	The research introduces a concept of MES using an EH, where multiple energy carriers convert and store energy for various applications like electricity, heating, cooling, or compressed air. The main challenge is managing the multi-energy flow to utility demand.
Thanh-tung et al. (2016)	Energy Hub Modeling for Minimal Energy Usage Cost in Residential Areas.	Minimize the energy usage cost	Mixed integer programming (MIP)-based general algebraic modeling system (GAMS)	This work demonstrates MES using the EH model, integrating electricity and NG resources and addressing electricity, heating, and cooling load demands, resulting in significant cost reduction.

Table 2.2 Optimal scheduling of MES using EH under individual objectives (Continued)

Author and publication year	Topic	Objective function	Method	Key findings
Ha et al. (2017)	Energy hub modeling to minimize residential energy costs considering solar energy and BESS.	Minimize the residential energy costs	Mixed integer programming (MIP)-based general algebraic modeling system (GAMS)	This study integrates solar energy and battery energy storage (BESS) with electricity and NG to meet electricity, heating, and cooling demands. Full integration of RE and BESS results in the lowest residential energy costs.
Timothée et al. (2017)	Optimum dispatch of a multi-storage and multi-energy hub with demand response and restricted grid interactions.	Minimize the operating cost for a time horizon	Evolutionary algorithm (EA) and PSO	This study compares evolutionary algorithms (EA) and PSO for optimizing a MES with grid, fuel, solar, wind, and thermal demands. Results show dispatch fluctuations, which can be reduced by increasing battery storage capacity.

Table 2.2 Optimal scheduling of MES using EH under individual objectives (Continued)

Author and publication year	Topic	Objective function	Method	Key findings
Zhang et al. (2017)	Optimal Operation of Wind-Solar-Hydrogen Storage System Based on Energy Hub.	Maximize the total operational profits	CPLEX Optimization	This paper provides a model incorporating hydrogen energy, electricity-gas heat loads, TOU scheme, and distributed generation, achieving higher RE penetration and profitability compared to traditional methods.
Javadi et al. (2017)	Optimal scheduling of a multi-carrier energy hub supplemented by battery energy storage systems	Minimize the operating cost	Mixed integer nonlinear programming (MINLP)	This study highlights the critical role of BESS integration in optimizing a MES with electricity and NG, enhancing efficiency, reducing costs, and improving system reliability across electricity, heating, and cooling demands.

Table 2.2 Optimal scheduling of MES using EH under individual objectives (Continued)

Author and publication year	Topic	Objective function	Method	Key findings
Geng and Jia (2020)	Hybrid Genetic Particle Swarm Optimization Based Economical Operation of Energy Hub	Minimize the daily electricity and NG purchasing cost	Hybrid genetic particle swarm optimization (GA-PSO)	This study proposes a hybrid GA-PSO approach to optimize the operation of an EH model involving electricity, NG, and both heat and electricity storage. This enables efficient use of gas turbines, gas boilers, electric chillers, and absorption chillers. The GA-PSO method improves optimizes EH operations, leading to enhances economic performance and system efficiency.

Table 2.2 Optimal scheduling of MES using EH under individual objectives (Continued)

Author and publication year	Topic	Objective function	Method	Key findings
Liu et al. (2021)	Optimal Scheduling Considering Different Energy Hub Model of Integrated Energy System	Minimize the operating costs	LP	This study evaluates three types of EH models based on case-specific scenarios, including power-to-gas (PtG) technology and ESS to meet electricity, heating, and cooling demands from electricity and NG. The optimal configuration lowers energy costs by coupling electricity, gas, and heat networks, and optimizing equipment such as combined heat and power CHP and heat pumps.

Table 2.2 Optimal scheduling of MES using EH under individual objectives (Continued)

Author and publication year	**Topic**	**Objective function**	**Method**	**Key findings**
Wang (2023)	Optimal Scheduling Strategy for Multi-Energy Microgrid Considering Integrated Demand Response	Minimize operating expenses	Mixed integer linear programming (MILP)	The study investigates the optimal scheduling of MES for microgrids using electricity and thermal energy sources. Three energy dispatch schemes are tested, with the third incorporating a demand response strategy showing the best results.

Table 2.3 Optimal scheduling of MES using EH under multi-objective

Author and publication year	Topic	Objective function	Method	Key findings
Zidan and Gabbar (2016)	Optimal Scheduling of Energy Hubs in Interconnected Multi Energy Systems	Minimize operation costs and emissions	Weight-sum multi-objective optimization (WSMO)	The paper presents an EH model integrating CHP and gas furnaces to maintain steady-state efficiency, demonstrating that WSMO effectively balances costs and emissions for optimal compromise solutions.
Ma et al. (2017)	Improved Particle Swarm Optimization Algorithm to Multi-objective Optimization Energy Hub Model with P2G and Energy Storage	Minimize the fuel cost of the EH and interaction cost with the main network	Improved multi-objective PSO (MOPSO)	The paper proposes an improved MOPSO with a search variable in velocity updates, enhancing efficiency and selecting compromise solutions from the Pareto front.

Table 2.3 Optimal scheduling of MES using EH under multi-objective (Continued)

Author and publication year	Topic	Objective function	Method	Key findings
Kholardi et al. (2018)	Optimal Management of Energy Hub with Considering Hydrogen Network	Minimize the energy hub operating costs and emissions	WSMO	This study focuses on the hydrogen network management strategy. The electricity-wind power and NG dispatch to meet various demands. It reveals that a weighting strategy of 0.8 and 0.2 results in lower operating costs.
Farah et al. (2020)	Optimal Scheduling of Hybrid Multi-Carrier System Feeding Electrical/Thermal Load Based on Particle Swarm Algorithm	Minimize the energy hub operating costs and emissions	WSMO	This paper studies an integrated RE to assist the dispatch of electricity demand and wood chips to convert to heat demand via biomass. The combination of NG turbine, biomass unit, boiler, and RE is an optimized configuration for an EH, resulting in lower operational costs and reduced emissions.

Table 2.3 Optimal scheduling of MES using EH under multi-objective (Continued)

Author and publication year	Topic	Objective function	Method	Key findings
Mousavi et al. (2022)	Multi-objective Scheduling of an Energy Hub in a Multi-energy System Using Genetic Algorithm	Minimize the operating costs and emissions	WSMO	The study optimizes EH, including CHP and gas furnaces, by using a 0.5 weighting factor in emissions and pricing mechanisms. The results show CHP starts operating when high demand is needed, resulting in lower costs and emissions.
Imeni and Ghazizadeh (2023)	Pave the Way for Hydrogen-Ready Smart Energy Hubs in Deep Renewable Energy System	Minimize the operating costs and emissions	WSMO	This work simulates three scenarios of EH model with HS integration, each with varying weights for operation costs and emissions. The results showed that using hydrogen as the primary energy carrier improved performance, particularly in reducing pollution emissions while TOU tariffs further reduced operation costs.

Table 2.3 Optimal scheduling of MES using EH under multi-objective (Continued)

Author and publication year	**Topic**	**Objective function**	**Method**	**Key findings**
Imeni et al. (2023)	Optimal scheduling of a Hydrogen-Based energy hub considering a stochastic Multi-Attribute Decision-Making approach	Minimize operation costs and emissions	SAUGMECON	This research enhances multi-objective optimization by integrating photovoltaic (PV) and BESS, achieving a better trade-off between economic performance and environmental impact, effectively reducing costs and emissions.
Hassan et al. (2023)	Optimal Day-ahead Management of a Hydrogen-based Energy Hub Considering Different Electrolyzer Technologies	Minimize operation costs and emissions	WSMO	This research optimizes EH management by minimizing day-ahead operating costs and emissions while meeting hydrogen, electricity, and heat demands. Using the WSMO method, results show how different electrolyzers impact costs and emissions.

Table 2.3 Optimal scheduling of MES using EH under multi-objective (Continued)

Author and publication year	**Topic**	**Objective function**	**Method**	**Key findings**
Xu et al. (2024)	A multi-objective operation optimization model for the electro-thermal integrated energy systems considering power to gas and multi-type demand response	Minimize the operation costs, carbon emissions, and energy curtailment rate	MOPSO and VIKOR	This study develops a multi-objective optimization model for electro-thermal integrated energy systems using PtG technology and demand response strategies. The results show PtG technology significantly improves system performance, leading to significant reductions in costs, emissions, and energy curtailment rates.

Table 2.4 Probabilistic model for optimal scheduling MES using EH

Author and publication year	Topic	Uncertainty variables	Method	Key findings
Mohammadi et al. (2017)	Optimal scheduling of energy hubs in the presence of uncertainty- A Review	Demand / the price of energy / solar irradiance etc.	MCS, fuzzy approach, robust optimization, and interval analysis	This review illustrates the recent research about uncertainty methods for MES using EH. This study reflects the uncertainty of modeling, stochastic methods, hybrid techniques, and demand response programs that improve operational costs, system resilience, energy scheduling accuracy, and economic and environmental benefits.

Table 2.4 Probabilistic model for optimal scheduling MES using EH (Continued)

Author and publication year	Topic	Uncertainty variables	Method	Key findings
Honarmand et al. (2021)	A robust optimization framework for energy hub operation considering different time resolutions: A real case study	Electrical, heat, and cooling demand / Photovoltaic (PV) output power	Robust optimization (RO)	This paper presents an optimization framework for real-world energy supply management in an EH. It shows that uncertainties increase total operation costs by 6.41%, mainly due to additional energy procurement and system adjustments. However, including energy storage system (ESS) can reduce costs by 0.87%, demonstrating their effectiveness in improving system flexibility.

Table 2.4 Probabilistic model for optimal scheduling MES using EH (Continued)

Author and publication year	Topic	Uncertainty variables	Method	Key findings
Thang et al. (2022)	Stochastic optimization in multi-energy hub system operation considering solar energy resource and demand response	Electrical, heat, and cooling demand / electrical prices / output power of RE	A scenario reduction technique	The study uses PDF to model uncertain parameters such as solar energy resources, energy demand, and electricity prices. It uses clustering and scenario reduction techniques to reduce uncertainties. Incorporating uncertainties improves system robustness and reduces total operational costs by 2.0-14.5% compared to deterministic approaches.

Table 2.4 Probabilistic model for optimal scheduling MES using EH (Continued)

Author and publication year	Topic	Uncertainty variables	Method	Key findings
Ranjbarzadeh et al. (2022)	A probabilistic model for minimization of solar energy operation costs as well as CO_2 emissions in a multi-carrier microgrid (MCMG)	Cost of electricity / the load for AC electricity / the power sourced from PVPs	2m+1 point estimate	This work models uncertainties in solar generation and power prices using the 2m+1 point estimation method to minimize costs and emissions. Incorporating uncertainty raises operational costs but enhances system resilience, leading to adjusted energy storage scheduling and demand response for a more conservative operation strategy.

2.5 HS Application Overview

In the modern era, ESS are widely utilized in electric power systems, particularly with the integration of high levels of RE penetration. The primary function of ESS is to enhance the flexibility of the electrical grid. Notably, ESS can efficiently mitigate power fluctuations caused by the variable nature of RE sources (Ould Amrouche et al., 2016). ESS are increasingly adopting HS technologies due to the clean energy production from RE sources and the ability to store energy in various forms. Ould Amrouche et al. (2016) highlighted the mechanisms of HS, categorizing it into gaseous, liquid, and chemical forms. In HS operations, RE can be converted into hydrogen gas through an EL. When excess energy is generated, it can be stored as hydrogen or later converted back to electricity via a fuel cell (FC). Additionally, hydrogen production is mentioned in Osman et al. (2022) research. They are defined in various color codes depending on the manufacturing process and cleanliness. It can be categorized into five colors: grey, brown, blue, turquoise, and green hydrogen. Grey hydrogen is produced from fossil fuels such as NG through steam reforming, emitting around 10 tons of CO_2 during the process. It's commonly used in petroleum-based chemicals and ammonia production. Brown hydrogen, derived from coal gasification, also releases significant CO_2. Blue hydrogen mitigates these emissions by employing carbon capture and storage. Turquoise hydrogen, generated via methane pyrolysis, produces solid carbon soot instead of CO2. Green hydrogen, the cleanest form of hydrogen, is produced from RE sources like wind and solar, offering significant environmental benefits without greenhouse gas emissions. However, its production faces challenges related to system efficiency and the intermittent nature of RE sources. Integrating HS can mitigate these issues by storing excess energy during peak production, ensuring a stable hydrogen supply during low-generation periods. HS also enhances the efficiency of RE systems by capturing surplus energy that would otherwise be wasted, converting it into hydrogen for various applications. Then, Dash et al. (2023) proposed the production of purple hydrogen, which is derived from nuclear energy. By utilizing the high temperatures generated from uranium fission, nuclear power plants can produce steam that drives turbines for electricity generation without direct greenhouse gas emissions. This thermal energy can also support various hydrogen production methods, making purple hydrogen a promising option for sustainable energy transition. Different types of hydrogen production are displayed in Fig. 2.1 (Dash et al., 2023; Osman et al., 2022).

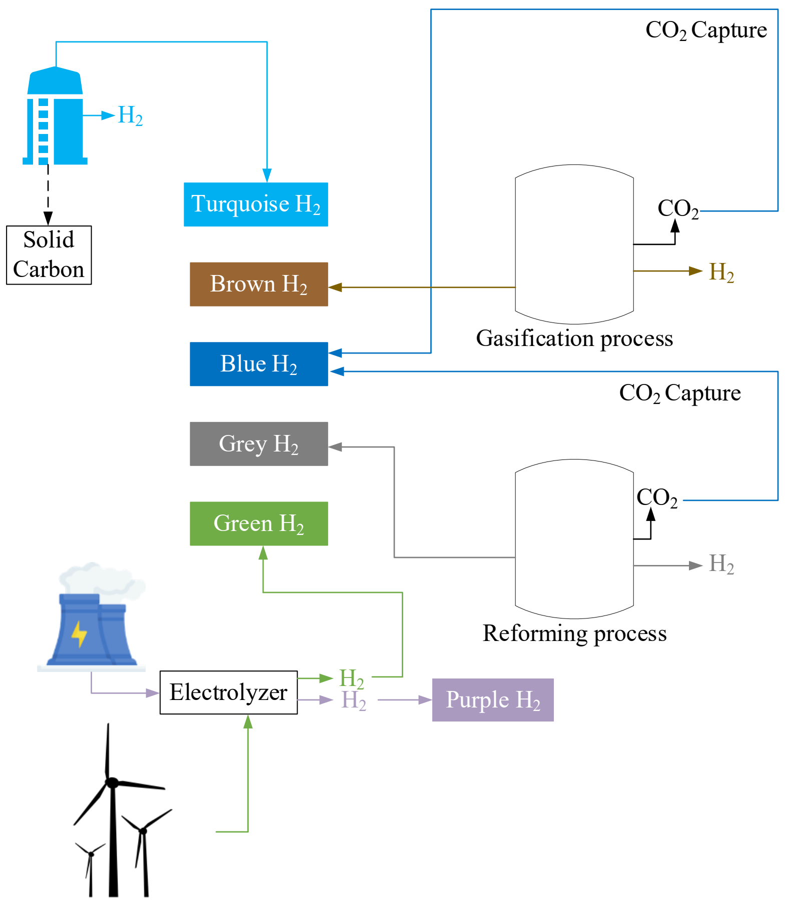

Figure 2.1 Different types of hydrogen production

In applying HS in an electricity system, Cau et al. (2014) proposed the scheduling for a renewable microgrid using a HS system. With HS integration, the model of HS utilizes Faraday's law to determine the molar flow and can convert back to power. The hydrogen pressure in the tank can be modeled based on the ideal gas law. To identify the amount of hydrogen in the tank, the pressure in the tank plays a role in telling how much hydrogen is left. In the following year, the work of Qadrdan et al.

(2015) proposed a power-to-gas (PtG) concept, which is converting electricity to hydrogen using an electrolysis process. The model of Great Britain assessed the HS within an integrated gas and electricity system. According to the findings, generating hydrogen from electricity can lower wind curtailment in high wind scenarios and lower the total cost of running the Great Britain gas and electricity network. After that, X. Chen et al. (2019) and Xiangping Chen et al. (2019) studied a power generation system incorporating HS and wind energy, initially wind energy is converted into electrical energy, with a portion of this electricity used for water electrolysis to produce hydrogen for energy storage. This hydrogen can then be converted back into electricity using FC during peak electrical demand. An analytical model has been developed to coordinate energy conversion among mechanical, electrical, and chemical forms. The proposed system is designed to meet the electrical needs of a rural village in the UK, helping to balance intermittent RE supplies with fluctuating demand and improving overall system efficiency. A genetic algorithm (GA) is employed as the optimization strategy to determine the operational scheme for this multi-vector energy system. Four case studies are conducted using real-world measurement data. The novelty of this study lies in its GA-based optimization methods aimed at maximizing wind energy utilization. In recent years, Dechjinda and Chayakulkheeree (2024) introduced a modified IEEE-33 bus test system, a distribution power system that incorporates hybrid wind and HS integration using load and wind profiles specific to Thailand. The primary objective of this research is to minimize daily energy loss through optimal daily scheduling based on PSO. The study is divided into two cases: the conventional IEEE-33 bus test system and the modified version. A comparison of the two systems reveals that the modified IEEE-33 bus test system, with its hybrid wind-HS integration, effectively reduces daily energy losses through the proposed approach.

2.6 Optimal Scheduling MES using EH under Individual Objectives

Recently, with modern technology, the incorporation of several different energy systems that are composed of many energy carriers is paving the way for a more sustainable future (Imeni et al., 2023). One of the most significant characteristics of MES is that it has multiple energy carriers, not only electricity. Synergies among different types of energy are seen to provide a substantial capability for system development (Geidl et al., 2007). The MES is the solution to decrease the operating cost and promote carbon neutrality. EH concept is used to consider efficiently supplying energy in each section using many kinds of energy. Geidl et al. (2007) demonstrated the EH is a system where multiple energy carriers, such as electricity and NG, are converted, conditioned, and stored to provide services like electricity, heating, cooling, or compressed air. It acts as an interface between various energy infrastructures and consumer loads. EH utilizes technologies like combined heat and power (CHP), transformers, and heat exchangers. Examples of EHs include industrial plants, large buildings, urban districts, and island energy systems. Figure 2.2 shows an example of an energy hub and outlines this modeling concept. A coupling matrix represents the conversion of power from input to output in an energy hub, based on the converter's structure and efficiency. Storage devices require time and energy as key variables. Different flow models, ranging from general to detailed, can be used for hydraulic and electric networks, depending on the level of analysis. Interconnectors can also be modeled like energy hubs, using coupling matrices to describe energy flow. However, this work does not optimize objective function rather, it is a discovery and raises questions about EH design, operation, energy storage, and impact on the system.

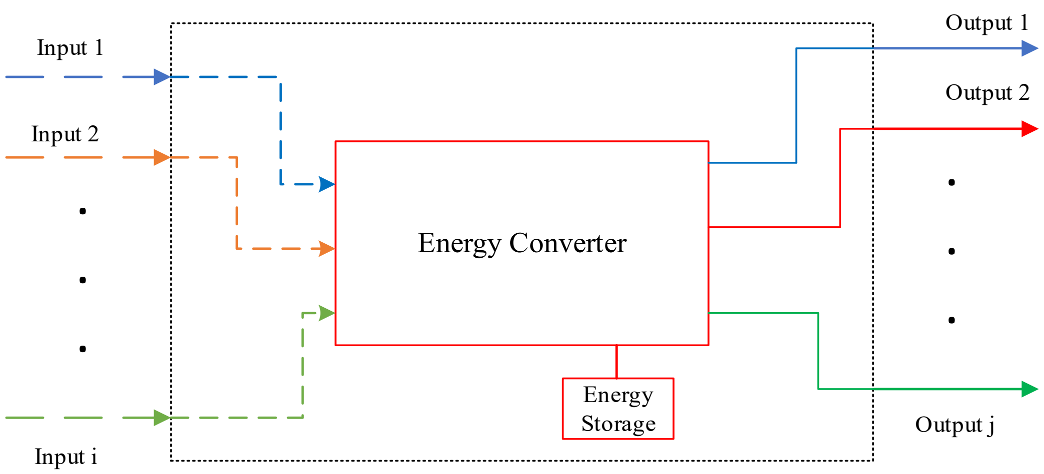

Figure 2.2 The example of an energy hub and outlines this modeling concept

Thanh-tung et al. (2016) proposed a model of residential area load including electricity and heat from dispatching a multi-energy source (electricity and NG). Using mixed integer programming (MIP) based-general algebraic modeling system (GAMS) software to minimize the energy usage cost. The optimal results show that off-peak energy demand is primarily supplied by the grid, while normal and peak-hour demand is partially met by converting heat energy to electricity, reducing system peaks, and lowering customer costs. The integration of multiple energy types improves electricity supply reliability. In the next year, Ha et al. (2017) presented an integrating battery energy storage systems (BESS), photovoltaic panels (PVP), and solar energy to residential areas model. The case study is divided into four scenarios, each comprising variations such as with or without BESS and PV systems. The energy usage cost minimization using MIP-GAMS illustrates that the result in each case is decreasing. When PV and BESS are integrated, the total energy costs are lowest. Also, Zhang et al. (2017) delve into a model that takes into account hydrogen energy, electricity-gas heat load, time-of-use electricity pricing, and distributed generation. They also employ electrolytic bath, FC, and energy storage technologies to provide a multi-energy joint optimization model based on an energy hub. The objective function is maximizing the total operational profits through adjusting the distribution coefficient of energy conversion in the scheduling period. CPLEX optimization is used to obtain optimal solutions. The outcome demonstrates that the suggested model outperforms the conventional operating mode without using hydrogen in terms of RE penetration and profitability. Furthermore, Javadi et al. (2017) focused on BESS integration to enhance the operational efficiency of a multi-carrier EH through optimal scheduling. The EH consists of various components, including micro-combined heat (mCHP), electric heat pumps (EHP), boilers, absorption chillers, and battery storage with the energy management problem modeled using mixed-integer nonlinear programming (MINLP). The optimization aims to reduce costs and improve battery life by considering energy prices and battery state of charge. Simulation results highlight the importance of optimizing energy storage, leading to lower operational costs, better load management, and improved system reliability. Moreover, Timothée et al. (2017) investigated the optimal dispatch of a multi-storage and multi-energy hub, integrating solar PV panels, WTs, boilers, internal combustion generators (ICG), and cogeneration plants, alongside both heat and electricity storage systems. The study employed an evolutionary algorithm (EA) for optimization and compared the results with PSO. Results highlighted the volatility in dispatch strategies, which could be mitigated by increasing battery storage capacity. The results indicate that both the battery and ICG are utilized to meet peak power demand and export electricity to the grid when prices are elevated. In terms of heat demand, the boiler operates at full capacity, with the cogeneration plants unit contributing a smaller portion of the heat supply compared to the boiler. The research emphasizes the importance of optimizing energy hubs to manage demand, renewable variability, and grid interactions, ensuring cost-effective and efficient energy distribution. In the next three years, Geng and Jia (2020) proposed a hybrid genetic algorithm and particle swarm optimization (GA-PSO) strategy, which combines PSO with GA to solve the optimal operation of EH. The EH model is comprised of electricity storage and heat storage coordinated with a gas turbine, gas boiler, electric chiller, and absorption chiller to dispatch electricity, heat, and cooling demand. When comparing a proposed algorithm GA-PSO with the conventional PSO, the results emphasize that GA-PSO significantly enhances convergence capability while also demonstrating a better economy in optimizing EH operations. In the next year, Liu et al. (2021) studied an EH model in different energy integrated. The study separated three kinds of EH cases to assess how different combinations of energy equipment. The components of EH include a boiler, cogeneration unit, chiller boiler, electric heat pump, and ESS to dispatch electricity, heat, and cooling demand from electricity and NG as a source. The optimization process aims to minimize the total operating cost of the energy system, ensuring efficient energy utilization and balancing between different energy sources. The result shows that the optimal EH configuration is the most collaborative of energy. It can significantly reduce energy costs by coupling electricity, gas, and heat networks while optimizing the use of equipment like CHPs and heat pumps. In the previous year, Wang (2023) proposed the strategy of optimal scheduling for multi-energy microgrids that integrates electricity and thermal energy sources, considering demand response and ESS integration. Using a mixed-integer linear programming model solved by CPLEX, the study simulates the operation of a grid-connected microgrid consisting of FC, WTs, solar panels, and thermal storage. Three different energy dispatch schemes are tested, with the third scheme incorporating demand responses showing the best results. This scheme not only reduces operational costs but also turns grid interactions into profit opportunities by smoothing energy demand and optimizing the use of RE and storage. The research demonstrates how integrating IDR can enhance system flexibility, lower costs, and promote sustainable energy use.

2.7 Optimal Scheduling MES using EH under Multi-Objective

In the research that focuses on multi-objective, Zidan and Gabbar (2016) presented an EH scheduling during different seasons of the year to minimize the costs and CO_2 emissions. The EH model proposed CHP and gas furnace as a steady state efficiency conversation, to coordinate with electricity to dispatch load. GA optimization is utilized for an individual objective function, including the costs and CO_2 emissions considered. The study is separated into three main cases, which are scheduling EH in each objective only and scheduling EH with two objective functions. The result shows each case has a different schedule for the best individual solution. When using the WSMO technique to balance between two objectives, the compromise solution is found to be an intermediate result between the optimal solutions of each objective. Then, Ma et al. (2017) proposed the improved PSO to multi-objective optimize EH model. The model of this work focuses on PtG operation, to schedule in each component is obtained from optimize variable by PSO. The main goal of this operation is to minimize the fuel cost of EH and to minimize the cost of interaction with the main power grid. To find the optimal solution for the two objectives considered, the improved MOPSO is used for balancing the two objectives by selecting from the Pareto front. The result focuses on the efficiency of improved MOPSO when compared with traditional MOPSO, the improved MOPSO has more optimization than MOPSO. Additionally, Kholardi et al. (2018) focus on the hydrogen network as one of the main networks that are connected to the EH. With the management strategy, the wind power from a WT is connected to electricity to dispatch several demands and NG is the power source to dispatch heat load and assist the electricity demand. Under the pricing mechanism, the operating costs are used to find the optimal managed energy in each sector. Also, the emissions factor is considered as the second objective. By MILP optimization, the two objectives are solved completely separately. The WSMO is the easiest to balance two objectives and is used to find the optimal solution between two objectives. This study is separated into three cases which define a different weighting coefficient for both objectives. In the third scenario, where the weighting coefficients are set to 0.8 and 0.2 respectively, the EH's management results in a lower operating cost compared to the other scenarios due to the defined weighting strategy. Furthermore, Farah et al. (2020) studied a traditional EH that integrated RE to assist the dispatch of electricity demand and wood chips to convert to heat demand via biomass generator. Each objective function consists of the energy hub operating cost and emissions. Utilizing PSO is an effort to solve individual objective functions and using WSMO to balance the optimal solution of two objectives. The case study of EH serves five local sites, including campus restaurants, an office building, 100 residential, a school campus, and a hotel with different scenarios such as with or without RE. The results indicate that the optimal configuration for the EH combines a natural gas turbine, biomass unit, boiler, and RE. This setup achieves both lower operational costs and reduced emissions. The carbon emissions in this model are primarily influenced by using biomass and RE. Moreover, Mousavi et al. (2022) proposed a GA algorithm that aims to solve the optimization problem in EH which includes CHP and gas furnaces to coordinate dispatch heat and electricity demand. The objective function consists of the operating cost and emissions. To assess the multi-objective problem in this work is utilized the simplest method is WSMO, the weighting factor is 0.5 in each objective.

Under the emissions factor and pricing mechanism, the result shows CHP starts operating when high demand is needed, resulting in lower costs and emissions. In the previous year, Imeni and Ghazizadeh (2023) explored how to optimally and efficiently manage a hydrogen-ready sustainable EH model that incorporates hydrogen. They framed the issue as a multi-objective optimization problem with two key objectives: minimizing the operating costs of the EH and reducing CO_2 emissions. These objectives are combined using the WSMO method. The study examined three different scenarios (Case A, B, and C), each with varying weights assigned to operation costs and emissions. The findings indicated that using hydrogen as the primary energy carrier in a MES significantly improved performance, particularly in lowering pollution emissions. Additionally, the implementation of an integrated demand response program (IDRP), which uses time-of-use (TOU) tariffs to manage electrical and heat loads, further contributed to reducing the operation costs of the hydrogen-ready smart energy hub. However, the WSMO method still faces challenges in determining the optimal weights for each objective. Then, Imeni et al. (2023) extended their previous work by incorporating photovoltaic (PV) and BESS into the system and enhancing the solution efficiency of the multi-objective optimization problem by employing the Simple Augmented e-Constraint (SAUGMECON) method. Moreover, the HS is modeled using molar flow calculations, and the ideal gas law is applied to determine the hydrogen quantity in the storage tank, resulting in a more complex formulation. The result demonstrates that it is possible to find an optimal trade-off between these objectives, providing a range of solutions based on different weightings. This study significantly improves both economic performance (by reducing operational costs) and environmental impact (by minimizing emissions), while effectively handling the inherent in RE generation. Additionally, Hassan et al. (2023) presented the EH model, including RE, grid interconnection, BESS, NG, CHP, furnace, and HS. The main study aims to examine to assess their impact on EH performance between two technologies of EL that as a component of HS include solid oxide (SOEC) and proton exchange membrane (PEM). the EH operation that serves hydrogen fuel-cell vehicles, battery electric vehicles, and heat demands. MILP is used to optimize management problems which comprise minimizing the EH day-ahead operating cost and minimizing the emissions that are produced inside the EH while meeting the hydrogen, electricity, and heat demands. This study utilizes WSMO to balance between two objectives. The results indicate that SOEC EL has lower operating costs and emissions compared to PEM EL. However, SOEC consumes more NG to offset internal heat losses, while the PEM EL requires more electricity due to its lower efficiency. At present, Xu et al. (2024) proposed a multi-objective operation optimization model for electro-thermal integrated energy systems (IES) that incorporates PtG technology and demand response (DR) strategies. The model categorizes electro-thermal loads into various types, including fixed, reducible, transferable, translational, and heating loads, and establishes corresponding DR strategies. The optimization model aims to minimize total cost, carbon emissions, and energy curtailment rates. In a case study, after 500 iterations, 20 non-dominated solutions are generated, with the best solution identified using the VIKOR approach. The optimal values achieved included total cost, carbon emissions, and energy curtailment rates, demonstrating that PtG technology significantly enhances system performance. This led to notable reductions in total costs, carbon emissions, and energy curtailment rates. Additionally, the implementation of DR strategies contributed to further improvements in each respective objective.

2.8 Probabilistic model for optimal scheduling MES using EH

The uncertainties in EH optimization arise from various sources, including variable renewable generation (wind and solar), market fluctuations, consumer behavior, and environmental changes. Ignoring these uncertainties can lead to inaccurate scheduling, increased operational costs, and suboptimal decision-making. To address these challenges, different uncertainty modeling approaches have been explored. Mohammadi et al. (2017) reviewed the literature on methods for dealing with uncertainty in the optimal scheduling of EH. Probabilistic methods rely on PDF to model uncertainties, with MCS being a widely used but computationally intensive technique. Alternatively, scenario-based stochastic optimization improves computational efficiency by reducing the number of uncertainty scenarios. Another approach involves fuzzy logic, this method enables more realistic energy scheduling by addressing vague or imprecise system parameters. In contrast, robust optimization (RO) provides different strategies for handling uncertainty. RO ensures optimal performance in worst-case scenarios by defining uncertainty sets, making it a conservative yet reliable approach. Honarmand et al. (2021) The study developed an optimization framework to address uncertainties in the operation of an energy hub for a hospital in Hamedan, Iran. It considered variations in electrical, cooling, and heating loads, as well as PVPs output power. The results showed a 6.41% increase in total operation costs due to uncertainties, primarily due to additional energy procurement and system adjustments. The study also examined the role of energy storage systems in mitigating uncertainty impacts, finding that when storage systems are excluded, operation costs increased by 0.87%. The study also examined the effects of different time resolutions and contingency analysis. Thang et al. (2022) developed a stochastic optimization framework to address uncertainties in MES, focusing on solar energy generation, energy demand, and electricity prices. They used Beta PDF for solar energy generation and normal PDF for electricity prices and demand fluctuations. The study used a clustering technique to classify distributions into distinct states, forming a scenario matrix. The SCENRED tool in GAMS is used to reduce scenarios to 10. The results showed that incorporating uncertainties in the framework improved system robustness and reduced total operational costs by 2.0-14.5% compared to deterministic approaches. Ranjbarzadeh et al. (2022) studied a probabilistic optimization approach to address uncertainties in solar energy production and electricity market prices within a multi-carrier microgrid. The 2m+1 point estimation method is used to model uncertainties efficiently while minimizing computational complexity. This method estimates the statistical properties of uncertain variables, such as solar power output and electricity prices, by focusing on a limited number of evaluation points. Compared to traditional MCS, which require many samples, the 2m+1 approach significantly reduces computational burden while maintaining a high level of accuracy in uncertainty modeling. The study shows that incorporating uncertainty into the optimization framework increases operational costs but improves resilience to renewable energy fluctuations and market conditions. The model adjusts energy storage system scheduling and demand response strategies to mitigate price volatility and intermittent solar generation. This results in a more conservative strategy, increasing costs but improving system robustness.

This study addresses a research gap by proposing an EH model that fully integrates green hydrogen production from HS. Previous works used a mix of RE and grid power, making hydrogen not fully green. Additionally, past research primarily used the WSMO method for solving multi-objective problems. To enhance this, the study introduces FMOO, a novel approach in EH research. Furthermore, the uncertainties of RE and load are considered. To analyze these uncertainties more effectively, a probabilistic approach is incorporated, leading to a more accurate and optimized model.

Table 2.5 The research gap between the existing and this study

Works	*Interconnect multi-energy*					*Objectives*				*Type of hydrogen*		*Method*
	Electricity	NG	WTs	PVPs	H_2	TOC	TCE	EP	Others	Grey	Green	
Thanh-tung et al. (2016)	✓	✓				✓						MIP

Table 2.5 The research gap between the existing and this study (Continued)

Works	*Interconnect multi-energy*					*Objectives*				*Type of hydrogen*		*Method*
	Electricity	NG	WTs	PVPs	H_2	TOC	TCE	EP	Others	Grey	Green	
Javadi et al. (2017)	✓	✓				✓						MINLP
Geng and Jia (2020)	✓	✓				✓						GA-PSO
Liu et al. (2021)	✓	✓				✓						LP
Ha et al. (2017)	✓	✓		✓		✓						MIP
Wang (2023)	✓	✓	✓	✓		✓						MILP
Zhang et al. (2017)	✓		✓	✓	✓				✓		✓	CPLEX
Zidan and Gabbar (2016)	✓	✓	✓	✓		✓	✓					- GA WSMO
Ma et al. (2017)	✓	✓	✓			✓			✓			- Improved MOPSO
Kholardi et al. (2018)	✓	✓	✓		✓	✓	✓			✓		- MILP WSMO
Farah et al. (2020)	✓	✓	✓	✓		✓	✓					- PSO WSMO

Table 2.5 The research gap between the existing and this study (Continued)

Works	*Interconnect multi-energy*					*Objectives*				*Type of hydrogen*		*Method*
	Electricity	NG	WTs	PVPs	H_2	TOC	TCE	EP	Others	Grey	Green	
Mousavi et al. (2022)	✓	✓				✓	✓					- GA WSMO
Hassan et al. (2023)	✓	✓	✓			✓	✓					- MINLP WSMO
Imeni and Ghazizadeh (2023)	✓	✓	✓		✓	✓	✓			✓		- MINLP WSMO
Imeni et al. (2023)	✓	✓	✓		✓	✓	✓			✓		- MINLP - SAUGMECON
Xu et al. (2024)	✓	✓	✓	✓		✓	✓		✓			- MOPSO VIKOR
Honarmand et al. (2021)	✓	✓		✓		✓						- MINLP RO
Thang et al. (2022)	✓	✓		✓		✓						- MINLP A scenario reduction
Ranjbarzadeh et al. (2022)	✓	✓		✓		✓	✓					- MILP - WSMO and FMOO 2m+1 point estimation
This work (Proposed)	✓	✓	✓	✓	✓	✓	✓	✓			✓	- PSO-LP - FMOO MCS

2.9 Chapter Summary

The concept of MES has gained significant attention due to the increasing integration of RE resources and energy storage technologies. Section 2.2 introduces the conventional approach to electrical energy scheduling problems, highlighting its importance in managing the supply-demand balance and enhancing system performance. Building on this, Section 2.3 outlines the trends in RE resources, emphasizing investments in wind and solar power as well as technological advancements, which directly influence the selection of appropriate RE types for HS integration. Consequently, Section 2.5 of this chapter contains a comprehensive literature review that focuses on HS application overview. Section 2.6 investigates optimal scheduling of MES using EH models that focus on individual objectives such as minimizing operating costs or carbon emissions. Meanwhile, Section 2.7 delves into studies on optimal scheduling of MES using EH models under multi-objective optimization, emphasizing the need for compromise solutions to balance multiple objectives effectively. Then, Section 2.8 demonstrates a probabilistic model, which describes an uncertainty scenario, leading to determining an optimal scheduling solution to handle uncertainty. Lastly, by combining the knowledge from these reviews, Table 2.5 provides a summary of the identified research gaps, highlighting areas that require further exploration.