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Optimal Planning of a Regional Power-to-X-Based Sector Coupling Framework for Distributed Energy Special Zones

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Abstract

This paper proposes a regional distributed energy operation framework that integrates Power-to-X (P2X)-based sector coupling with Distributionally Robust Optimization (DRO) for distribution network operation environments in special zones established under South Korea's Special Act on the Promotion of Distributed Energy. The conventional South Korean electricity market has primarily operated under a centralized Cost-Based Pool (CBP) structure, where the participation of small-scale renewable energy providers has been limited due to requirements for centralized dispatch generators. To address these structural limitations, the South Korean government introduced the distributed energy special zone policy and has promoted a Peer-to-Peer (P2P)-based electricity trading mechanism that enables direct electricity transactions between renewable energy providers and consumers within regional distribution networks. As a result of these policy initiatives, investment in small-scale renewable energy projects within designated special zones is expected to increase significantly; however, the limited local demand capacity of regional distribution networks simultaneously imposes clear constraints on the accommodation of renewable energy. Therefore, this study applies P2X-based sector coupling technologies to improve the capability to accommodate renewable energy within special zones while simultaneously establishing new energy business models. In addition, DRO is incorporated into the proposed framework to demonstrate the system's economic feasibility and operational robustness under high uncertainty in electricity prices.

Keywords: power to X; distributed energy resources; sector coupling; distribution networks

1. Introduction

The continuous growth in global electricity demand has led to an increasing reliance on fossil fuel-based power generation. In particular, the expansion of thermal power plants not only accelerates the depletion of fossil fuel resources but also contributes significantly to global warming and climate change through large-scale carbon emissions. Consequently, the need for environmentally sustainable alternative energy sources has become increasingly important, prompting many countries to strengthen policy support for the deployment and expansion of Renewable Energy Sources (RES).

In 2021, the 195 countries that signed the Paris Agreement updated their Nationally Determined Contributions (NDC) targets, with the United States, Canada, the United Kingdom, and South Korea setting greenhouse gas reduction targets of 52%, 45%, 68%, and 40%, respectively [1]. These international carbon-reduction commitments have become a key driver of the increase in the share of renewable energy in national energy portfolios. In particular, South Korea, which aims to achieve carbon neutrality by 2050, has identified the

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expansion of renewable energy deployment as a major component of its national energy strategy. To promote renewable energy generation, the government has implemented the Renewable Portfolio Standard (RPS) and Renewable Energy Certificate (REC) schemes [2]. These policy instruments play a crucial role in stimulating private-sector investment in renewable energy projects and in facilitating the expansion of renewable-energy-based electricity markets.

South Korea has also promoted investment in renewable energy through the RPS scheme, while the primary source of electricity market revenue for renewable energy generators participating in the country's Cost-Based Pool (CBP) market is determined by the System Marginal Price (SMP) [3,4]. However, under the centralized electricity market structure, small-scale renewable energy facilities that do not satisfy the eligibility requirements for centrally dispatched generators face significant limitations in market participation. As a result, most privately funded renewable energy projects are developed as small-scale photovoltaic (PV) systems that cannot directly participate in the centralized electricity market.

To improve market accessibility for these small-scale producers, South Korea introduced a Power Purchase Agreement (PPA) mechanism, under which Independent System Operators (ISOs) can directly purchase electricity from Renewable Energy Producers (REPs) without intermediary transactions through the electricity market. Through this framework, renewable energy generators with capacities ranging from 10 kW to 1000 kW are permitted to trade electricity directly with ISOs [5]. Nevertheless, the PPA framework still operates on the assumption that the national power system is a single supply-and-demand region, with the ISO serving as the primary purchaser of electricity from renewable energy producers. Consequently, participating generators are required to pay network usage charges regardless of their installed capacity. Furthermore, although the participation requirements are less restrictive than those of the centralized electricity market, minimum capacity constraints still remain under the PPA framework [6].

As a consequence of these policy and economic factors, the renewable energy sector in South Korea has evolved primarily through large-scale renewable energy development projects supported by joint investments from both the government and private sector, rather than through the widespread deployment of small-scale distributed renewable energy facilities. In particular, large-scale renewable energy projects tend to be concentrated in the southwestern coastal regions of South Korea, where abundant renewable energy resources can be secured to maximize generation profitability.

However, this geographical concentration of renewable energy resources, combined with the existing centralized power system operation structure, has introduced several operational challenges. Most notably, the concentration of electricity demand in the Seoul metropolitan area has led to increasing transmission congestion as large amounts of renewable electricity generated in provincial regions must be delivered over long-distance transmission networks. At the same time, system inefficiencies, including increased network utilization costs and reactive power losses, have become more pronounced [7]. In other words, while large-scale renewable energy facilities are predominantly located in the southwestern regions of the country, electricity demand remains heavily concentrated in metropolitan areas, resulting in a growing geographical imbalance between electricity generation and consumption.

In response, the South Korean government has been promoting a transition from the traditional centralized power system operation paradigm toward a region-based distributed distribution system. This transition aims not only to alleviate the excessive concentration of population and industrial activities in the Seoul metropolitan area but also to establish a more reliable and economically efficient power system. As a key policy initiative supporting

this transition, the Distributed Energy Promotion Act has been enacted and implemented, facilitating the development of decentralized electricity markets and distribution network-centered operational structures based on local energy production and consumption.

Under the Distributed Energy Promotion Act, the South Korean government has designated selected regional distribution networks outside the Seoul metropolitan area as Distributed Energy Special Zones. Within these designated zones, small-scale renewable energy producers are permitted to participate in a Peer-to-Peer (P2P) electricity trading market, allowing them to directly trade electricity with consumers without the mediation of an ISO. This framework alleviates many of the limitations associated with the conventional PPA structure, including capacity-related investment restrictions and constraints arising from transmission and distribution network utilization.

In the conventional centralized electricity market structure, economic value and electricity transactions are distributed among multiple stakeholders, including generation companies, electricity market operators, ISOs, and end-users. In contrast, the P2P trading framework enabled by the Distributed Energy Promotion Act simplifies this transaction structure by establishing a regional electricity market in which small-scale renewable energy producers and end-users can participate directly. Such a framework is expected to enhance regional energy self-sufficiency while simultaneously improving market accessibility for small-scale renewable energy producers.

The concentration of renewable energy developers within Distributed Energy Special Zones is expected to significantly increase the supply of renewable energy within regional distribution networks. At the same time, the introduction of P2P electricity trading is expected to lower electricity prices relative to conventional market structures, thereby attracting new industrial facilities and electricity consumers to these regions. This approach may contribute not only to redistributing population and electricity demand away from the Seoul metropolitan area but also to achieving national carbon neutrality goals through the expanded deployment of renewable energy resources. Furthermore, by promoting localized electricity generation and consumption, the proposed framework has the potential to reduce dependence on long-distance power transmission and alleviate transmission congestion prevalent in the existing centralized power system.

Despite these anticipated benefits, the expansion of renewable energy within Distributed Energy Special Zones is expected to substantially alter regional electricity supply and demand patterns, making the maintenance of supply–demand balance a critical operational challenge. Since energy policies cannot fundamentally change the physical characteristics of power systems, reliable operational strategies that account for renewable energy variability and uncertainty in regional electricity demand are essential for maintaining system stability.

Although significant uncertainties remain regarding future changes in electricity supply and demand within Distributed Energy Special Zones, the policy framework suggests that renewable energy deployment is likely to expand more rapidly than electricity consumption during the initial stages of implementation. Subsequently, the increased supply of renewable energy and the resulting reduction in electricity prices are expected to gradually stimulate additional electricity demand in the region. Therefore, a key challenge for future power system operation is not merely attracting additional renewable energy investments but rather determining how the already expanded renewable energy resources within special zones can be utilized efficiently while ensuring sustainable hosting capacity for renewable energy.

To address these operational challenges, this study proposes an optimal operation framework for Distributed Energy Special Zones based on Power-to-X (P2X)-enabled sector coupling. P2X technologies facilitate the conversion, storage, and utilization of

surplus renewable electricity into various energy forms, including Power-to-Heat (P2H) using electric heat pumps (EHPs), Power-to-Gas (P2G) using Electrolyzers (ELZs), and Power-to-Mobility (P2M) via electric vehicles (EVs) [8,9]. These technologies can mitigate curtailment of renewable energy due to excessive generation while improving energy utilization efficiency and system flexibility by converting electricity into thermal energy, hydrogen, and mobility services. Furthermore, P2X-based sector coupling has emerged as a key enabling technology for future renewable energy-oriented energy systems by establishing strong interconnections among the electricity, heat, and transport sectors.

Several studies have investigated multi-energy-based P2X and sector coupling technologies. Reference [10] analyzed the growing importance of P2X technologies as key enablers of the transition toward carbon-neutral societies and highlighted their potential role in renewable energy-driven hydrogen economies. The study demonstrated that P2X technologies can serve as effective energy conversion pathways for converting electricity into hydrogen and synthetic fuels, thereby addressing challenges associated with renewable energy variability and energy security. Moreover, the authors emphasized that P2X technologies should not be viewed merely as energy storage solutions but rather as strategic technologies that can enhance industrial competitiveness and contribute to long-term economic growth.

Recent studies have highlighted the growing importance of P2X and sector-coupling technologies as key enablers of renewable energy integration and carbon neutrality. Reference [11] identified P2X as a critical flexibility option for mitigating renewable energy variability and enhancing grid flexibility in future 100% renewable energy systems. Reference [12] demonstrated the techno-economic feasibility of P2X-based e-fuel production systems by integrating renewable-powered electrolysis, carbon capture, and Fischer-Tropsch synthesis. Reference [13] investigated power quality challenges associated with renewable energy-based P2X systems and proposed a digital twin-based operational framework for improving system performance. Reference [14] compared grid-connected and islanded P2X microgrids, showing that hydrogen-based P2X systems can enhance grid resilience and provide long-term energy storage capabilities. Furthermore, Reference [15] incorporated P2G technology into an economic dispatch framework and verified its economic benefits for multiple stakeholders, while Reference [16] evaluated various P2H technologies and identified heat pumps as an effective solution for industrial decarbonization.

In addition to P2X technologies, increasing attention has been directed toward integrated multi-energy systems and sector coupling frameworks. Reference [17] proposed a VPP-based optimization framework that incorporates mobile energy storage to enhance economic performance, grid stability, and carbon reduction in energy communities. References [18,19] developed optimization and energy-flow analysis methodologies for integrated electricity-gas systems, demonstrating that sector coupling technologies such as P2G can effectively improve renewable energy utilization while maintaining computational efficiency and operational fairness among stakeholders. Reference [20] proposed a heat recovery framework for P2X-based energy hubs, showing that waste heat utilization can significantly improve both energy efficiency and economic performance. Finally, Reference [21] provided a comprehensive review of variability mitigation strategies for high-penetration renewable energy systems and emphasized the importance of energy storage, smart grids, VPPs, P2X technologies, and sector coupling in maintaining grid stability and operational flexibility. Collectively, these studies confirm the technical and economic potential of P2X-enabled sector coupling as a promising pathway toward flexible, low-carbon, and highly integrated future energy systems. Reference [22] proposed a bi-level distributed trading framework that integrates P2P energy trading among prosumers with power-to-hydrogen and heat units while considering distribution network operation

constraints. Reference [23] provided a comprehensive review of PtX technologies, including PtH, PtA, and PtM pathways, highlighting their potential for renewable energy balancing, energy storage, and deep decarbonization through integrated hydrogen, ammonia, and methanol production.

In addition to economic operation and renewable energy utilization, the resilience of interdependent infrastructure systems has become an important issue in regional energy planning. Recent studies have shown that extreme events can significantly affect coupled infrastructure systems, such as electricity-watershed networks under drought conditions and electricity-drainage networks under rainstorm disasters. These studies indicate that future energy planning should consider not only the operation of individual energy carriers, but also the coordinated operation and risk propagation of interconnected urban infrastructures. From this perspective, P2X-based sector coupling can be regarded as a potential planning option for improving regional flexibility and coordinated energy utilization under uncertain operating conditions [24].

Previous studies have separately examined P2X technologies, sector-coupled energy systems, P2P electricity trading, and DRO-based uncertainty modeling. However, limited attention has been paid to an integrated planning framework that reflects the policy-driven environment of Distributed Energy Special Zones, where small-scale DERs can participate in P2P electricity trading and uncertain transaction prices affect the economic feasibility of DER and P2X operators. To address this gap, this study proposes a regional energy planning framework that integrates P2P electricity trading, P2X-based sector coupling, and moment-based DRO under the context of South Korea's Distributed Energy Promotion Act. The novelty of this study lies in the policy-reflective integration of these elements rather than in the development of a new standalone DRO algorithm or detailed dynamic P2X component model.

In this study, P2X-based sector coupling technologies are integrated into a regional distribution network to alleviate limitations in renewable energy hosting capacity arising from the increasing penetration of renewable energy resources within Distributed Energy Special Zones. In particular, the proposed framework utilizes P2X technologies to mitigate the variability and generation-concentration characteristics of PV systems while establishing a novel regional energy business model that integrates the electricity, heat, hydrogen, and mobility sectors.

Furthermore, this study investigates the economic feasibility of both small-scale renewable energy producers and P2X operators within a market environment that supports P2P electricity trading. To achieve this objective, uncertainty in P2P electricity prices is modeled using a worst-case assumption, and a series of simulations is conducted under uncertain market conditions. To derive robust operational strategies in the face of such uncertainties, a Distributionally Robust Optimization (DRO) framework is employed. The resulting DRO problem is reformulated as its dual, enabling the derivation of robust optimal solutions for the proposed objective function.

The proposed operational framework considers annual distribution network operation planning and evaluates the impacts of implementing P2X-based sector coupling technologies within Distributed Energy Special Zones designated under the Distributed Energy Promotion Act. Specifically, the study aims to assess the economic performance of regional small-scale renewable energy producers and P2X operators while simultaneously evaluating improvements in renewable energy hosting capacity and regional energy self-sufficiency from the perspective of ISO.

It should be noted that the Distributed Energy Resources (DERs) considered in this study are limited to PV systems, which currently represent the most widely deployed form of small-scale renewable energy generation in South Korea. Furthermore, the overall

electricity trading mechanism is modeled based on the current operational structure of the Korean electricity market and the Distributed Energy Special Zone framework.

The main contribution of this study is not the development of a new standalone DRO algorithm or a detailed dynamic model of individual P2X facilities. Instead, this study proposes an integrated planning framework tailored to Distributed Energy Special Zones under South Korea's Special Act on the Promotion of Distributed Energy. The specific contributions are summarized as follows. First, a policy-reflective regional energy planning model is developed by incorporating P2P electricity trading, consumer price constraints, and reverse-power-flow limitations. Second, P2X-based sector coupling technologies, including P2H, P2G, P2M, HESS, and FC, are integrated to evaluate the utilization of surplus renewable energy and the improvement of regional energy self-sufficiency. Third, uncertainty in P2P electricity transaction prices is addressed using a DRO-based formulation, enabling the economic feasibility and robustness of the proposed framework to be evaluated under adverse market conditions.

It should be noted that the proposed framework does not aim to solve a detailed distribution network optimal power flow problem. Instead, the distribution network is represented at an aggregated regional level to evaluate the long-term planning effects of P2X-based sector coupling. Detailed feeder-level constraints, such as voltage limits, line capacity, network losses, topology, and AC or DistFlow-based power flow equations, are therefore not explicitly modeled. The distribution network interaction is reflected through the regional electricity balance, power exchange with the distribution line, and the reverse-power-flow limitation. Incorporating detailed network constraints remains an important direction for future work.

2. System Modeling

The P2X system considered in this study is designed to operate within a Distributed Energy Special Zone-based sector coupling framework. The energy supply side consists of two sources: a distribution line (DL) and a distributed heat source. Meanwhile, the demand side comprises electricity demand and heat demand, enabling the integrated operation of electrical and thermal energy systems.

In conventional distribution networks in South Korea, small-scale renewable energy facilities below a certain capacity threshold are typically operated for self-consumption purposes and face limitations in participating in electricity markets. In contrast, under the Distributed Energy Promotion Act, DERs located within Distributed Energy Special Zones are permitted to engage directly in P2P electricity trading with end-users and to export a portion of their generated electricity to the DL. However, the amount of electricity supplied to DL cannot exceed 30% of the total renewable energy generation; otherwise, a penalty is imposed. To reflect this operational requirement, the proposed model incorporates an inequality constraint to prevent reversed power flow exceeding the permitted limit.

The reverse-power-flow limitation is discussed in this study as a policy-related consideration under the Distributed Energy Special Zone framework. However, the detailed settlement and sales mechanism for reverse power has not yet been clearly established. Therefore, this study does not explicitly model reverse power flow as a separate electricity export or revenue-generating transaction. Instead, surplus DER generation that cannot be consumed locally or absorbed by P2X facilities is conservatively treated as curtailed power in the simulation model. Figure 1 shows the diagram of the total P2X system.

When renewable energy generation exceeds local electricity demand, temporary surplus electricity may arise. In this study, such surplus energy is absorbed through P2X technologies. Specifically, P2M, P2H, and P2G facilities are utilized to convert and store excess renewable electricity in different energy forms.

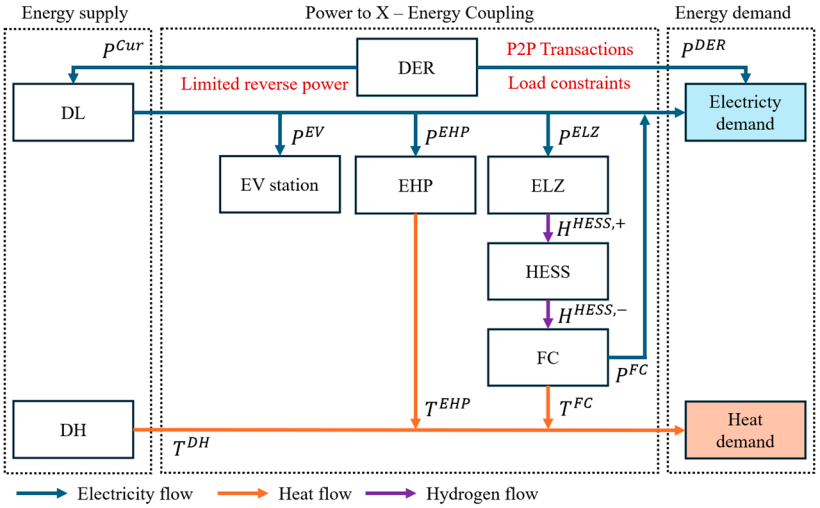


Figure 1. Diagram of Power to X system.

P2M utilizes EVs operating within the region as mobile energy storage systems to absorb surplus electricity. Recent research has also investigated advanced control and modulation strategies for EV charging systems. Reference [25] proposed an extended hybrid modulation method for wireless power transfer-based EV charging to achieve multi-stage constant-current charging. Their results showed that advanced modulation strategies can improve charging efficiency and support effective charging-stage control, indicating that EV charging infrastructure planning should also consider the development of efficient charger control technologies.

P2H converts excess electricity into thermal energy to satisfy local heat demand. In addition, P2G converts surplus electricity into green hydrogen for storage, which can subsequently be reconverted into electricity and thermal energy through FCs. Through this integrated structure, surplus renewable energy can be effectively utilized while enhancing overall system flexibility.

The proposed framework provides several benefits for different stakeholders. Small-scale renewable energy producers can mitigate the risks associated with renewable energy curtailment and reverse power flow while improving economic performance. From an ISO perspective, the framework can enhance renewable energy hosting capacity within Distributed Energy Special Zones and improve regional energy self-sufficiency by providing FC-based supplementary energy during periods of low renewable energy generation. For end-users, direct contracts with renewable energy producers through the P2P market provide access to electricity at prices below conventional retail tariffs, thereby reducing overall energy costs.

2.1. Power to X Modeling

This study focuses on evaluating the impacts of sector coupling implementation within distribution networks located in Distributed Energy Special Zones established under the Distributed Energy Promotion Act. To achieve this objective, a long-term planning optimization framework with an annual time horizon is employed. Therefore, rather than explicitly modeling the dynamic characteristics of individual P2X facilities, the proposed framework emphasizes the long-term effects of energy conversion and utilization enabled by P2X technologies. Accordingly, the dynamic response characteristics of each P2X component are assumed to be ideal, and the overall system is formulated using the following linear energy conversion models.

$$T_t^{EHP} = P_t^{EHP} COP_t \eta^{EHP}, \forall t \quad (1)$$

$$COP_t = \frac{T_H}{T_H - T_L}, \forall t \tag{2}$$

$$0 \le P_t^{EHP} \le C^{EHP}, \forall t \tag{3}$$

$$P_t^{EV} \le \overline{P_t^{EV}}, \forall t \tag{4}$$

$$0 \le P_t^{EV} \le C^{EV}, \forall t \tag{5}$$

$$H_t^{ELZ} = \frac{P_t^{ELZ}\eta^{ELZ}}{HHV_{H2}}, \forall t \tag{6}$$

$$P_t^{ELZ} \le C^{ELZ}, \forall t \tag{7}$$

$$P_t^{FC} = H_t^{FC} HHV_{H2} \eta^{FC,P}, \forall t \tag{8}$$

$$T_t^{FC} = H_t^{FC} HHV_{H2} \eta^{FC,T}, \forall t \tag{9}$$

$$\eta^{FC} = \eta^{FC,T} + \eta^{FC,P} \tag{10}$$

$$0 \le P_t^{FC} \le C^{FC}, \forall t \tag{11}$$

$$H_t^{HESS,+} = \eta^{HESS} H_t^{ELZ}, \forall t \tag{12}$$

$$H_t^{HESS,-} = \eta^{HESS} H_t^{FC}, \forall t \tag{13}$$

$$HSOC_t = HSOC_{t-1} + H_t^{HESS,+}\eta^{HESS} - H_t^{HESS,-}/\eta^{HESS}, \forall t \tag{14}$$

$$HSOC_{t=0} = 0.5C^{HESS} \tag{15}$$

$$H_t^{HESS,+} \le C^{HESS}\text{C_rate} \tag{16}$$

$$H_t^{HESS,-} \le C^{HESS}\text{C_rate} \tag{17}$$

$$P_t^{\Omega_{DER}} = P_t^{PV}\frac{G_t}{G_{ref}}\left[1 - \beta(T_{cell} - T_{cell}^{STC})\right], \forall t \tag{18}$$

$$P_t^{DER} = \sum_{\forall \Omega_{DER}} P_t^{\Omega_{DER}} \tag{19}$$

Equation (1) represents the thermal output model of the EHP utilized in the P2H system. The equation describes the conversion of electrical energy into thermal energy by considering both the Coefficient of Performance (COP), which varies according to ambient temperature, and the operational efficiency of the EHP. Equation (2) defines the COP calculation model applied to the EHP, while Equation (3) imposes an upper bound on the thermal output according to the installed EHP capacity.

Equation (4) represents the output model of the EV-based P2M system. Since EVs directly consume electricity supplied through EV charging stations without undergoing an additional energy conversion process, the available output is constrained by the regional EV penetration level and user mobility patterns. Equation (5) defines the capacity constraint of the EV charging station.

Equation (6) describes the hydrogen production model of the ELZ, where electrical energy is converted into hydrogen energy based on the Higher Heating Value (HHV) and electrolyzer efficiency. The resulting hydrogen production is expressed in units of kilograms. Equation (7) represents the capacity constraint of the ELZ. Equations (8) and (9) describe the electrical and thermal output models of FC, respectively. Similar to the ELZ, the FC model considers the HHV of hydrogen and the conversion efficiency of the device to transform hydrogen into electricity and thermal energy. Equation (10) defines the overall FC efficiency as the sum of electrical and thermal efficiencies, while Equation (11) imposes an upper output limit according to the installed FC capacity.

The ELZ and FC are modeled as hydrogen production and consumption facilities, respectively, and are linked through a hydrogen mass balance relationship to ensure the conservation of hydrogen energy within the system. Consequently, the amount of hydrogen that can be consumed by the FC is limited by the quantity of hydrogen produced by the ELZ. The produced hydrogen is stored in a Hydrogen Energy Storage System (HESS). Equation (12) represents the charging process of hydrogen generated by the ELZ into the HESS, whereas Equation (13) describes the discharge process through which stored hydrogen is supplied to the FC. Equation (14) defines the charging and discharging operation of the HESS. Equation (15) represents the initial SOC constraint of the HESS, which is set to 50% of the installed HESS capacity. Equations (16) and (17) represent the charging and discharging limit constraints of the HESS considering the C-rate. In this study, the C-rate is set to 50%.

It should be noted that the P2X component models adopted in this study are simplified linear representations for long-term planning analysis. Therefore, detailed operational characteristics such as part-load efficiency, ramping limits, minimum output constraints, startup/shutdown behavior, storage losses, and detailed charging/discharging dynamics are not explicitly considered. These simplifications may lead to optimistic estimates of system flexibility and economic performance, because actual P2X facilities may operate with lower efficiency or limited responsiveness under partial-load and transient operating conditions. Accordingly, the results of this study should be interpreted as planning-level estimates, and the incorporation of detailed nonlinear and dynamic operational constraints remains an important topic for future research.

Equations (18) and (19) represent the output model of an individual Distributed Energy Resource (DER) unit and the aggregated output model of all DERs, respectively. As discussed previously, most small-scale renewable energy facilities in South Korea are based on PV technology. Therefore, all DERs considered in this study are modeled as PV systems located within the Distributed Energy Special Zone.

As previously noted, this study focuses on evaluating the long-term operational impacts of P2X technologies within Distributed Energy Special Zones over an annual planning horizon. Accordingly, the system model is simplified to an appropriate level of detail. Dynamic operating states, equipment failures, and nonlinear efficiency characteristics associated with partial-load operation are not explicitly considered. Instead, the overall system is formulated using linear energy conversion models. Finally, these individual component models are integrated into a unified multi-energy system through the following energy balance equations.

$$P_t^D = P_t^{DL} + P_t^{DER} + P_t^{FC} - P_t^{ELZ} - P_t^{EHP} - P_t^{EV} - P_t^{CUR}, \forall t \tag{20}$$

$$T_t^D = T_t^{DH} + T_t^{FC} + T_t^{EHP}, \forall t \tag{21}$$

Equation (20) represents the electricity energy balance constraint. In the proposed framework, electricity supply consists of power imported from the DL, renewable electricity generated by DER, and electricity produced by the FC. On the demand side, electricity consumption includes regional electricity demand, the operating power required by P2X facilities for surplus renewable energy utilization, and renewable energy curtailment. Through this formulation, the proposed model simultaneously considers power supply–demand balance and renewable energy utilization within the Distributed Energy Special Zone.

Equation (21) represents the thermal energy balance constraint. The thermal energy supply consists of heat from the distributed heat source (DH) and thermal energy generated by the FC and the EHP. Although excess thermal energy can generally be managed more easily than excess electricity due to its waste-heat characteristics, this study models the

thermal energy balance as an equality constraint to prevent excessive heat generation during energy conversion and electricity trading processes and to improve overall energy utilization efficiency. As a result, unnecessary thermal energy dissipation is minimized, allowing the operational efficiency of the sector-coupled integrated energy system to be more realistically represented.

2.2. Objective Function

The objective function of this study is formulated to maximize the total benefit of the sector-coupled energy system within a Distributed Energy Special Zone. The primary revenue-generating entities are DER and P2X operators. Since DER operators directly participate in P2P electricity trading with end-users, maximizing supplier profits and minimizing consumer costs can be considered conflicting objectives from a mathematical perspective.

However, under realistic market conditions, end-users have little incentive to participate in P2P electricity trading if no economic advantage is offered relative to conventional electricity tariffs. Therefore, the electricity price offered by DER and P2X operators must be lower than the existing retail electricity tariff or, at a minimum, provide economic benefits through reduced electricity costs or mitigation of progressive tariff burdens.

Accordingly, the proposed objective function is formulated to maximize the economic benefits of DER and P2X operators while simultaneously incorporating electricity price constraints that ensure the economic attractiveness of P2P trading for end-users. In other words, although the direct minimization of consumer electricity costs is not explicitly included as an independent objective, consumer benefits are implicitly accounted for by designing the P2P trading framework to provide economic advantages over conventional electricity pricing schemes.

$$f_{DER}(x) = \sum_{\forall t} P_t^{DER} \mathbb{C}_t^{P2P} - \sum_{\forall \Omega^{der}} \left(\mathbb{C}_{\Omega^{der}}^{OPEX} + \mathbb{C}_{\Omega^{der}}^{CAPEX} \right) C^{\Omega^{der}}, \forall t \tag{22}$$

$$f_{P2X}(x) = \sum_{\forall t} P_t^{FC} \mathbb{C}_t^{P2P} + P_t^{EV} \mathbb{C}_t^{EV} + \mathbb{C}_t^{Heat} \left(T_t^{FC} + T_t^{EHP} \right) - \sum_{\forall \Omega^{p2x}} \left(\mathbb{C}_{\Omega^{p2x}}^{OPEX} + \mathbb{C}_{\Omega^{p2x}}^{CAPEX} \right) C^{\Omega^{p2x}}, \forall t \tag{23}$$

$$f(x) = f_{DER}(x) + f_{P2X}(x), \forall t \tag{24}$$

$$\mathbb{C}_t^{P2P} \leq \mathbb{C}_t^{ELE}, \forall t \tag{25}$$

Equation (22) represents the objective function associated with DER operators, incorporating both electricity sales revenue and capital investment costs. Since this study assumes a planning framework in which additional DER facilities are installed within the Distributed Energy Special Zone, the economic performance of DER operators is evaluated by considering revenues from electricity sales together with capacity-dependent capital investment costs.

Equation (23) represents the economic benefits associated with the operation of P2X facilities. These benefits include revenues generated from P2H, P2M, P2G, and FC operations, as well as the additional value derived from enhanced renewable energy utilization. At the same time, the capital and operational costs of the corresponding P2X facilities are incorporated into the formulation. This structure enables a comprehensive assessment of the economic feasibility of P2X-based sector coupling technologies.

Finally, Equation (24) integrates the benefits of both DER and P2X operators and defines the annual planning objective function for the sector-coupled integrated energy system within the Distributed Energy Special Zone. The resulting objective function is formulated as a total benefit maximization problem that simultaneously considers enhanced renewable energy hosting capacity and improved economic operational efficiency.

Meanwhile, Equation (25) represents a pricing constraint that limits the upper bound of the P2P electricity trading price rather than explicitly including end-user electricity cost minimization in the objective function. This constraint ensures that the P2P electricity trading price remains below the conventional retail electricity tariff, thereby preserving the economic incentive for end-users to participate in the P2P electricity market.

3. Optimization Methodology

3.1. Distributionally Robust Optimization Formulation

Although the P2P electricity trading framework implemented within Distributed Energy Special Zones enables DER operators to participate in electricity markets without network usage charges and allows small-scale renewable energy facilities to engage in electricity trading, the associated transaction prices remain highly uncertain. To attract end-users and encourage participation in P2P contracts, appropriate electricity prices must be established through either fixed-price or variable-price mechanisms. Furthermore, as enforced by the constraint in Equation (20), the P2P electricity trading price must remain below the conventional retail electricity tariff to ensure economic benefits for consumers.

Therefore, this study incorporates uncertainty in P2P electricity trading prices into the optimization framework through DRO. The objective is to demonstrate that both DER-based P2P electricity trading and P2X-enabled sector coupling remain economically viable even under worst-case market conditions. The following formulation presents the fundamental DRO framework by distinguishing between deterministic and uncertain decision variables and explicitly characterizing their respective roles in the optimization problem.

$$f(x,\xi) = \max_{\forall x} \min_{\xi \sim p \in \mathbb{P}} c^T x + \mathbb{E}[Q(x,\xi)] \tag{26}$$

In the above formulation, the first term represents the deterministic component of the objective function, whereas the second term corresponds to the component that contains uncertainty. The uncertain parameter in the second term is assumed to follow an unknown probability distribution. Under the DRO framework, the optimization problem is formulated such that the uncertain component is evaluated under the worst-case probability distribution within a predefined ambiguity set, while the decision variables are optimized to achieve the best possible performance against this adverse scenario. In other words, DRO seeks robust decision solutions that remain economically effective even under the most unfavorable realization of uncertainty.

In this study, the P2P electricity trading price is treated as the uncertain parameter because future transaction prices within Distributed Energy Special Zones are expected to exhibit significant variability due to market participation, regional demand fluctuations, and evolving trading mechanisms. Accordingly, the cost-related term is modeled as an uncertain variable within the DRO framework, and the generic DRO formulation is reformulated into the following problem structure tailored to the proposed sector-coupled energy system.

$$\min_{P[\mathbb{C}_t^{P2P}] \sim p \in \mathbb{P}} \mathbb{E}[Q(x,\xi)] = \min_{P[\mathbb{C}_t^{P2P}] \sim p \in \mathbb{P}} \mathbb{E}\left[\sum_{\forall \Omega^{der}} \sum_{\forall t} \mathbb{C}_t^{P2P} \left(P_t^{\Omega^{der}} + P_t^{FC} \right) \right] \tag{27}$$

Equation (27) represents a reformulated expression of the uncertainty-dependent component of the DRO model, where the function containing the uncertain variables is explicitly separated and adapted to the proposed framework. Since the primal objective function is formulated as a maximization problem, the uncertainty-dependent component is modeled as a minimization problem. Consequently, the optimization seeks the worst-

case realization of the uncertain variables within the ambiguity set, while simultaneously maximizing the overall system benefit. This max–min structure enables the proposed framework to identify robust operational strategies that remain economically feasible under the most adverse uncertainty conditions.

3.2. Solving Process for DRO

As discussed previously, a conventional DRO formulation typically contains nested minimization and maximization operators and is often nonlinear in nature, making it computationally challenging to solve directly. Therefore, many studies reformulate DRO problems into tractable optimization models through approaches such as the Column-and-Constraint Generation (C&CG) algorithm or duality-based reformulation techniques. These approaches enable commercial optimization solvers to efficiently obtain robust solutions.

In this study, the DRO problem is solved through a dual reformulation approach. To facilitate this process, it is first necessary to define an ambiguity set, which represents the family of probability distributions that characterize the uncertain variables. The ambiguity set specifies the range of plausible probability distributions that the uncertain parameters may follow and serves as the foundation for identifying the worst-case distribution within the DRO framework.

$$\mathcal{P} = \begin{cases} \sum_{n=1}^{N} p_{n,t} = 1 \\ \sum_{n=1}^{N} p_{n,t} \mathbb{C}_{n,t}^{P2P} \le \gamma_1, \qquad ,\forall t \\ \sum_{n=1}^{N} p_{n,t} \left(\mathbb{C}_{n,t}^{P2P} - \widehat{\mathbb{C}_{n,t}^{P2P}} \right)^2 \le \gamma_2 \end{cases} \tag{28}$$

Equation (28) defines the ambiguity set adopted in this study. The first constraint requires that the sum of the probability weights across all sampled realizations of the uncertain cost variable equal 1, ensuring that the resulting probability vector is a valid probability distribution. The second and third constraints, parameterized by γ_1 and γ_2, restrict the allowable ranges of the mean and variance of the sampled uncertain variables, respectively. Specifically, γ_1 controls the allowable deviation of the expected value of the uncertain P2P price from its empirical mean, while γ_2 controls the allowable deviation of the variance from its empirical variance. Larger values of γ_1 and γ_2 expand the ambiguity set by allowing a wider range of probability distributions, which generally leads to more conservative solutions. Conversely, smaller values restrict the ambiguity set around the empirical moment information and produce solutions closer to the nominal case. These constraints characterize the ambiguity set by limiting the deviation of candidate probability distributions from the empirical statistical information. These constraints characterize the ambiguity set by limiting the deviation of candidate probability distributions from the nominal statistical information.

The constant (n) denotes the number of samples used to discretize the uncertain variable. A larger value of (n) provides a finer representation of the underlying uncertainty and allows the resulting probability distribution to more closely approximate a continuous distribution, thereby improving the accuracy of the obtained solution. In contrast, a smaller value of (n) results in a coarser discrete representation of uncertainty, which may reduce the reliability and robustness of the optimization results.

The DRO formulation adopted in this study is a moment-based DRO model. Therefore, the ambiguity set is not constructed from sampled probability distributions. Instead, the uncertain P2P electricity transaction price is represented by a finite discrete support consisting of 100 possible price realizations. The probability associated with each price

realization is treated as an uncertain variable, and the DRO model determines the worst-case probability distribution over these realizations.

The ambiguity set is defined using moment information of the uncertain P2P price. Specifically, the probability values are constrained to satisfy probability normalization, while the mean and variance of the uncertain price are restricted within predefined bounds. The empirical mean and variance are obtained from electricity transaction cost data in South Korea. Under this formulation, the DRO problem evaluates the system performance against the worst-case probability distribution that satisfies the prescribed moment information.

When the ambiguity set is defined as in Equation (28), the original optimization problem with uncertain parameters is transformed into one that optimizes over probability distributions rather than deterministic variables alone. Consequently, the uncertainty-dependent component of the objective function must be reformulated in terms of expected values with respect to the candidate probability distributions. However, the resulting expectation-based formulation remains computationally intractable in its original form and cannot be solved directly. The corresponding reformulated objective function is presented in Equation (29).

$$\min_{p_{n,t} \sim p \in \mathbb{P}} \sum_{n=1}^{N} \left[\sum_{\forall t} p_{n,t} \mathbb{C}_{n,t}^{P2P} (P_{DER,t} + P_{FC,t}) \right] \tag{29}$$

Here, the number of samples denotes the number of discrete support points of the uncertain P2P electricity price, not the number of sampled probability distributions. In this study, 100 possible price realizations are used, and their probabilities are optimized to derive the worst-case distribution. The empirical mean and variance used in the ambiguity set are obtained from electricity transaction cost data in South Korea.

Furthermore, unlike conventional robust optimization, the probability variables themselves are treated as uncertain decision variables within the DRO framework. As a result, the expectation-based objective function contains products of variables and becomes a non-convex optimization problem. In this formulation, the original deterministic electricity price parameter is replaced by a probability-weighted uncertain price representation. Consequently, the optimization problem can be interpreted as determining the worst-case probability distribution associated with the uncertain electricity prices, while the ambiguity set defined previously governs the feasible range of these probability distributions.

To address this computational challenge, the proposed DRO formulation is reformulated through dualization, allowing the problem to be solved within an MILP-compatible framework. Specifically, the inner minimization problem associated with the uncertain probability distribution is transformed into its dual counterpart. Equation (30) presents the resulting dual objective function, which appears in the form of a supremum problem and serves as the foundation for deriving a tractable deterministic equivalent of the original DRO formulation.

$$\sup_{\lambda, \mu_1, \mu_2} \lambda - \sum_{\forall t} \mu_{1,t} \gamma_1 - \sum_{\forall t} \mu_{2,t} \gamma_2 \tag{30}$$

The dual variables introduced in this reformulation correspond to the dual counterparts of the equality and inequality constraints that define the ambiguity set. Specifically, each dual variable is associated with a particular statistical constraint governing the admissible probability distributions, including the normalization condition and the moment-based bounds imposed on the uncertain parameters.

For practical implementation and interpretation, the dual formulation can be further expressed using the variables and parameters defined in the proposed sector-coupled energy system model. By substituting the corresponding cost-related uncertainty terms into the dual objective function and incorporating the associated dual feasibility conditions, the resulting optimization problem can be reformulated as the complete dual problem

shown in Equation (31). This reformulation transforms the original Distributionally Robust Optimization problem into a tractable deterministic equivalent while preserving the worst-case uncertainty representation embedded within the ambiguity set.

$$\begin{aligned}
&\max_{\forall\Omega^{p2x},\forall\Omega^{der},\lambda,\mu_1,\mu_2} \quad \lambda + \sum_{\forall t}\left(\mathbb{C}_t^{Heat}T_{FC,t} + \mathbb{C}_t^{EV}P_{EV,t} + \mathbb{C}_t^{H_2}H_{2,t} - \mu_{1,t}\gamma_1 - \mu_{2,t}\gamma_2\right) \\
&\qquad\qquad + \sum_{\forall\Omega^{der}}\left(\mathbb{C}_{\Omega^{der}}^{OPEX} + \mathbb{C}_{\Omega^{der}}^{CAPEX}\right)C_{\Omega^{der}} + \left(\mathbb{C}_{\Omega^{p2x}}^{OPEX} + \mathbb{C}_{\Omega^{p2x}}^{CAPEX}\right)C_{\Omega^{p2x}} \\
&\text{s.t.} \\
&\lambda - \left(\mu_1\mathbb{C}_{n,t}^{P2P} + \mu_2\left(\mathbb{C}_{n,t}^{P2P} - \widehat{\mathbb{C}_{n,t}^{P2P}}\right)^2\right) \le \mathbb{C}_{n,t}^{P2P}(P_{DER,t} + P_{FC,t}), \forall n, \forall t \\
&\mu_1, \mu_2 \ge 0
\end{aligned} \tag{31}$$

In conventional linear programming duality theory, the dual variables associated with equality constraints in the primal problem are unrestricted in sign. In contrast, the sign of the dual variables corresponding to inequality constraints depends on the direction of the primal constraints. Consequently, the sign restrictions imposed on dual variables are directly determined by the mathematical form of the primal constraints.

To maintain nonnegative dual variables, it is common practice to formulate inequality constraints in a standardized form. In particular, for a primal maximization problem, constraints are typically expressed such that the variable terms are less than or equal to the corresponding constant terms. Under this formulation, the associated dual variables remain nonnegative, which simplifies both the theoretical interpretation and numerical implementation of the dual problem. The underlying relationship between the primal constraint direction and the sign of the corresponding dual variable can be demonstrated through the following derivation.

$$\begin{aligned}
&\max_x c^T x \\
&\text{s.t.} \\
&\mathrm{A}x \le \mathrm{b}, \quad x \le 0
\end{aligned} \tag{32}$$

When a nonnegative dual variable is multiplied by both sides of the linear constraint in the above formulation, the following relationship can be obtained. Since the dual variable is nonnegative, the direction of the inequality is preserved during the multiplication process. This property allows the primal constraint to be incorporated into the Lagrangian or dual formulation while preserving the inequality, as shown below.

$$\begin{aligned}
&\max_x c^T x \\
&\text{s.t.} \\
&y^T\mathrm{A}x \le y^T\mathrm{b}, \quad x \le 0
\end{aligned} \tag{33}$$

Furthermore, if the condition $y^T A \ge c^T$ is satisfied, it follows that $y^T Ax \ge c^T x$. Combined with the primal feasibility condition $Ax \le b$ and the nonnegativity of the dual variables, the following relationship can be established as $y^T b \ge y^T Ax \ge c^T x$. Since $c^T x$ corresponds to the primal objective function value. $y^T b$ always provides an upper bound on the primal maximization objective. Consequently, among all feasible values of $y^T b$, the smallest one yields the tightest upper bound and therefore corresponds to the optimal value of the dual problem. This observation forms the foundation of strong duality in linear programming.

As a result, the final dual formulation can be expressed as shown below. Under the adopted primal constraint structure, the associated dual variables remain nonnegative,

which is consistent with the standard duality framework for maximization problems with less-than-or-equal-to inequality constraints.

$$\begin{aligned} &\inf_x b^T y \\ &\text{s.t.} \\ &y^T \mathrm{A} \leq c^T, \quad y \leq 0 \end{aligned} \tag{34}$$

In this formulation, the additional constraint $y^T A \geq c^T$ is essential because it establishes the relationship between the dual variables and the primal objective function coefficients. Without this constraint, the dual problem would not provide a valid upper bound on the primal objective value. Furthermore, the dual variables must satisfy the prescribed sign restrictions, which, under the adopted primal formulation, require them to remain nonnegative.

More generally, the sign of the dual variables depends on the structure of the primal problem, including whether the objective function is formulated as a maximization or minimization problem, the sign restrictions imposed on the primal decision variables, and the directions of the inequality constraints. As a result, different primal formulations can lead to different dual sign conventions. In this study, the ambiguity-set constraints are formulated in a manner that allows all associated dual variables to remain nonnegative, thereby facilitating a stable and tractable dual reformulation. Consequently, the proposed DRO model can be successfully transformed into its dual counterpart while preserving the original worst-case uncertainty representation.

The general formulation of the final dual problem is expressed as Equation (35).

$$\begin{aligned} &\max_{x,\lambda,\mu_1,\mu_2} \quad \lambda - \mu_{1,t}\gamma_1 - \mu_{2,t}\gamma_2 + c^T x \\ &\text{s.t.} \\ &\lambda - d^T \mu_1 + e^T \mu_2 \leq g \\ &\mu_1, \mu_2 \geq 0 \end{aligned} \tag{35}$$

4. Case Study

4.1. Basic Data

The case study presented in this paper investigates the operation of a distribution network located within a Distributed Energy Special Zone established under South Korea's Distributed Energy Promotion Act. The primary objective is to identify the economic limitations that DER operators may encounter under scenarios with continuously increasing renewable energy penetration and to demonstrate that these limitations can be effectively overcome through the incorporation of P2X-based sector coupling technologies. Through comparative simulations, the study evaluates the impacts of renewable energy expansion on DER profitability and examines how sector coupling can enhance renewable energy utilization and overall system performance.

The energy demand patterns, PV generation profiles, price signals, and EV charging patterns applied in the simulation were constructed using average data patterns for South Korea in 2025. The numerical information is shown in Figure 2.

Although the proposed framework performs annual planning optimization, representative monthly profiles are adopted to improve computational efficiency. Specifically, the simulation utilizes representative monthly electricity demand, heat demand, PV generation, and energy price data to characterize seasonal variations throughout the year. The corresponding datasets employed in the case study are illustrated in Figure 3.

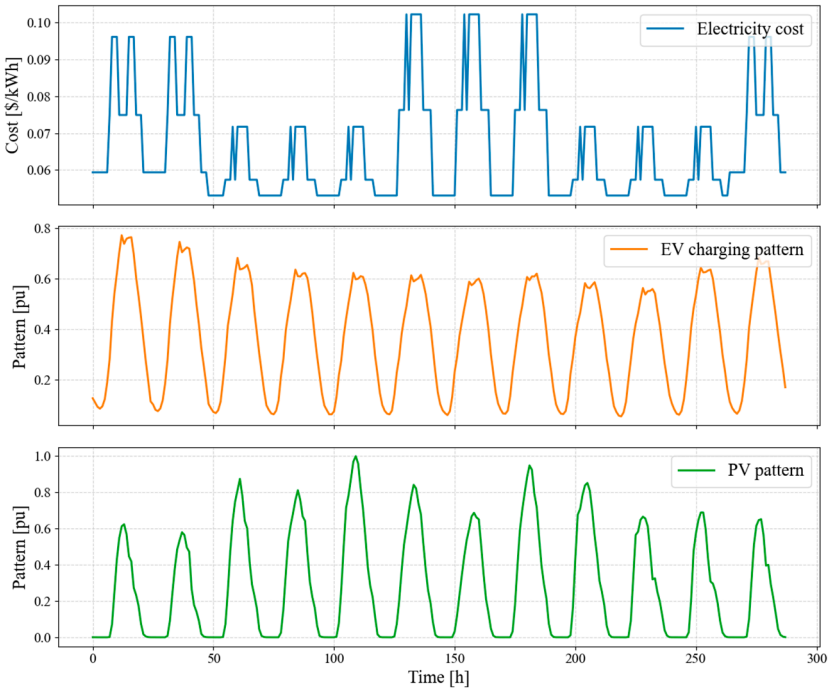


Figure 2. Basic information scheduling.

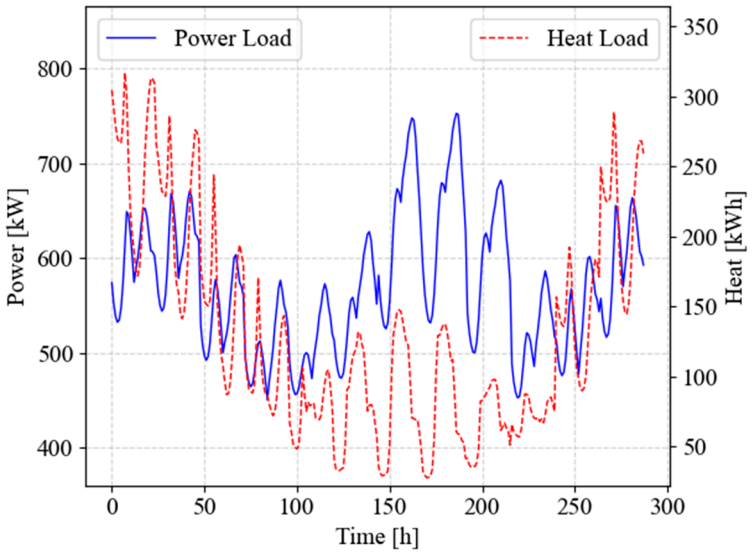


Figure 3. Power and heat load scheduling.

The load profiles adequately capture the seasonal characteristics of regional energy demand. As shown in Figure 2, both electricity and heat demands increase during the winter season due to heating requirements. In contrast, during the summer season, heat demand decreases while electricity demand rises as a result of increased cooling loads. These seasonal variations provide a realistic representation of the operating conditions encountered within the proposed distribution network.

The case study uses representative monthly profiles to reflect seasonal variations in electricity demand, heat demand, and PV generation. These profiles are not direct measurements from a specific distribution feeder, but typical planning-level profiles constructed based on publicly available statistical data and general seasonal demand and renewable generation characteristics. For each month, a representative 24-h profile is generated and applied to the corresponding number of days in that month. The monthly operation results are then aggregated to obtain annual performance indicators. Therefore, the simulation

results should be interpreted as annual planning-level estimates rather than measured feeder-level operation results.

The technical and economic parameters of the facilities considered in the simulation are summarized in Table 1.

Table 1. Facilities information.

	CAPEX	OPEX	Life Span [Year]	Ref.
PV	1000 [$/kW]	20 [$/kW]	25	[26]
ELZ	1400 [$/kW]	20 [$/kW]	15	[27]
HESS	800 [$/kg-H2]	16 [$/kg-H2]	25	[28]
FC	3000 [$/kW]	3000 [$/kW]	20	[29]
EHP	900 [$/kW]	18 [$/kW]	20	[30]

Table 1 summarizes the technical and economic parameters of the sector coupling facilities considered in the optimization model. However, the specifications of the EV charging station associated with the P2M technology are not included in the table. Unlike the other facilities, the capacity of the EV charging station depends primarily on the proportion of EV users within the target region. Therefore, in this study, the EV charging station capacity is determined based on the average EV penetration rate in South Korea and is fixed at 300 kW throughout the simulation. The 300 kW EV charging capacity was determined by considering the practical demand scale of the target distribution network and the expected EV penetration level. According to Reference [31], the average annual electricity consumption per capita in South Korea is approximately 5400 kWh. Based on this value, the peak demand level considered in this study corresponds to a small-scale distribution network serving approximately 1000–1500 residents. Assuming the average EV penetration level in South Korea, approximately 200–300 residents in the target area are expected to operate EVs. Therefore, based on Reference [32], the 300 kW EV charging capacity is considered a reasonable planning-level assumption for representing the aggregated charging demand of approximately 300 EVs.

Furthermore, this study assumes an idealized distribution network environment. Since the primary objective is to investigate the optimal operation of a sector-coupled energy system integrated with a distribution network, detailed power flow characteristics of the distribution network are not explicitly modeled. Instead, the analysis is conducted from an energy balance perspective, assuming ideal power transfer conditions within the distribution network.

4.2. Simulation Results

As discussed previously, this study aims to evaluate the economic performance of DER operators and the potential benefits of P2X technologies under scenarios with increasing renewable energy penetration. Accordingly, the simulation results are obtained under a series of renewable energy penetration scenarios in which total renewable energy generation ranges from 60% to 150% of the annual electricity demand.

Table 2 presents the economic performance of DER operators without the incorporation of P2X-based sector coupling technologies. Specifically, the table illustrates how the benefits obtained by DER operators vary as renewable energy capacity increases within the Distributed Energy Special Zone.

Table 2. Simulation results for Case 1: non-P2X.

	Penetration Level of DER [%]				
	60 (2000 kW)	**80 (2800 kW)**	**110 (3500 kW)**	**130 (4200 kW)**	**150 (5000 kW)**
Benefit [$/yr]	143,579	155,550	163,622	168,951	172,424
Cost [$/yr]	8998	12,597	15,746	18,896	22,495
Total benefit [$/yr]	134,581	142,953	147,876	150,055	149,929
Curtailed energy [kWh/yr]	31,635	61,491	93,584	127,253	161.995
Benefit/capacity of DER [$/kW]	71.78	55.55	46.75	40.22	34.48

Since P2X technologies are not incorporated in this scenario, the only investment cost considered is the capital cost associated with renewable energy deployment. As renewable energy capacity increases without sufficient P2X facilities to absorb surplus generation, renewable energy curtailment rises significantly. This increase in curtailed energy directly translates into economic losses for DER operators by reducing the amount of renewable electricity that can be effectively utilized or traded.

This effect can be more clearly observed through the economic benefit per unit capacity of DER installations. Under ideal operating conditions, this indicator should remain relatively constant regardless of renewable energy capacity expansion. However, the results presented in Table 2 show a continuous decline in the economic benefit per unit capacity as DER capacity increases. This trend indicates that the marginal economic value of additional renewable energy capacity decreases due to the growing mismatch between renewable energy generation and local demand, resulting in increased curtailment and reduced revenue opportunities for DER operators.

In contrast, Table 3 presents the results obtained when P2X-based sector coupling technologies are incorporated under the same renewable energy expansion scenarios. The comparison enables a direct evaluation of the extent to which P2X technologies can mitigate renewable energy curtailment and improve the economic performance of DER operators within the Distributed Energy Special Zone.

Table 3. Simulation results for Case 2: P2X-sector coupling.

	Penetration Level of DER [%]				
	60 (2000 kW)	**80 (2800 kW)**	**110 (3500 kW)**	**130 (4200 kW)**	**150 (5000 kW)**
Benefit [$/yr]	578,224	642,117	676,260	719,759	722,671
Cost [$/yr]	38,651	66,241	78,855	98,635	99,317
Total benefit [$/yr]	539,573	575,875	597,404	621,124	623,353
Curtailed energy [kWh/yr]	5840	12,861	33,171	52,073	86,306
Benefit/capacity of DER [$/kW]	269.78	205.67	170.69	147.9	124.67

When P2X technologies are incorporated into the system, the amount of curtailed renewable energy is significantly reduced compared with the conventional DER expansion scenario. As a result, the economic benefit per unit capacity of DER installations is substantially improved. Nevertheless, it is not possible to maintain the same level of unit-capacity benefit observed under low DER penetration scenarios across all renewable energy penetration levels. This limitation arises because the DER portfolio considered in this study primarily consists of PV systems, which can be deployed relatively easily and economically but inherently produce highly concentrated power outputs during specific periods of the day. Consequently, it is difficult to absorb and utilize all surplus renewable generation in a perfectly efficient manner.

In theory, this issue could be mitigated by substantially increasing the capacities of ELZs and EHPs. However, such an approach would result in oversized P2X facilities designed primarily to accommodate short-duration peak PV generation periods. During nighttime and low-irradiance periods, when PV output is limited, the utilization rates of ELZs and EHPs would become significantly lower, leading to poor asset utilization and economically inefficient investment decisions. Therefore, even with the deployment of P2X technologies, the results indicate that excessively high DER penetration levels may gradually reduce both economic performance and overall energy utilization efficiency. This observation represents an important finding of the present study.

The exceptionally high benefit values observed in the simulation results are primarily attributed to the strong economic potential of the business models enabled by P2X technologies. Compared with conventional DER electricity trading revenues, P2X facilities can generate additional value streams through thermal energy sales, hydrogen-based energy production, and EV charging services. Consequently, even when the same amount of surplus renewable energy is utilized, the diversified revenue opportunities provided by P2X technologies can yield substantially greater economic returns than those achievable through electricity trading alone. Table 4 presents the optimal capacities of the installed P2X facilities under the various renewable energy penetration scenarios.

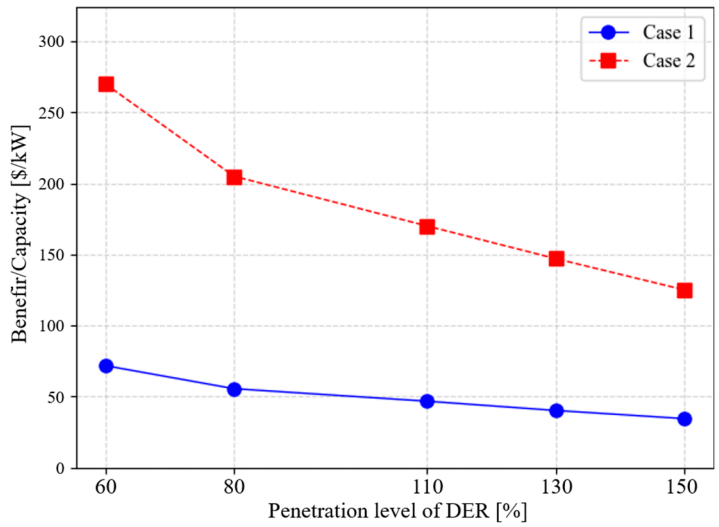
Table 4. Optimal P2X capacities for each scenario.

	Penetration Level of DER [%]				
	60 (2000 kW)	**80 (2800 kW)**	**110 (3500 kW)**	**130 (4200 kW)**	**150 (5000 kW)**
ELZ [kW]	250	535	620	900	900
HESS [kg-H2]	30	70	80	90	90
FC [kW]	120	190	230	260	260
EHP [kW]	90	90	80	80	80
EV station [kW]	300	300	300	300	300

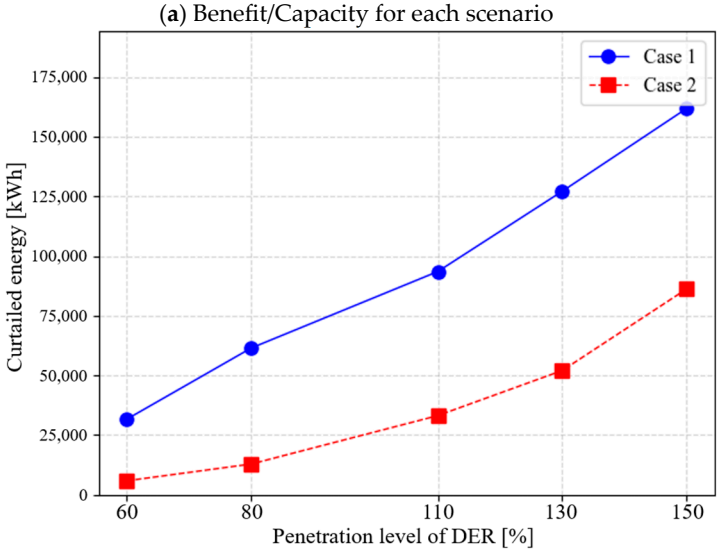
The optimal capacity allocation results also reveal several important findings. The first observation is the capacity stabilization and eventual reduction of EHP installations. Given a limited amount of renewable electricity supplied by DERs, the optimization framework must determine which P2X technologies can generate the greatest economic value from the available energy. In this sense, the allocation of renewable energy among different P2X technologies resembles a competitive resource allocation process. Since the objective function aims to maximize the overall system benefit, the optimization results indicate that P2G and P2M technologies provide greater economic returns than P2H under the considered market conditions. Consequently, as PV capacity increases and additional P2X deployment becomes feasible, the optimal strategy gradually shifts from EHP expansion toward increased ELZ capacity, resulting in a reduction of EHP capacity while prioritizing investments in P2G technologies.

The second key finding is the capacity saturation of P2X facilities. This phenomenon is closely related to the generation profile of PV systems. Beyond a certain level of renewable energy penetration, the optimization no longer increases P2X capacity despite further growth in PV installations. This result suggests the existence of a practical limit beyond which the economic benefits obtained from additional P2X capacity become smaller than the corresponding investment costs. As a consequence, the optimal solution favors accepting a higher level of renewable energy curtailment while maintaining the existing P2X capacities and operational strategies. This finding highlights the existence of an economically optimal balance between renewable energy expansion and sector coupling infrastructure investment.

Figure 4 illustrates the trends of curtailed energy and the economic benefit per unit DER capacity for both cases under the different renewable energy penetration scenarios.



(**a**) Benefit/Capacity for each scenario



(**b**) Curtailed energy for each scenario

Figure 4. Results comparison between Case 1 and Case 2.

The graphical results provide a clearer illustration of the performance gap between the two cases as renewable energy penetration increases. Although the distribution network incorporating P2X-based sector coupling consistently outperforms the conventional system across all DER penetration scenarios, the magnitude of the improvement varies significantly with renewable energy penetration levels. At relatively low DER penetration levels, the benefits of P2X technologies are particularly pronounced, resulting in substantial reductions in renewable energy curtailment and significant improvements in economic performance. However, as DER penetration continues to increase, the marginal benefits provided by P2X technologies gradually diminish.

This finding suggests that, while attracting additional DER investments and deploying P2X technologies are effective strategies for enhancing renewable energy utilization within Distributed Energy Special Zones, these measures alone may not be sufficient under extremely high renewable energy penetration conditions. The results imply that future distribution network planning should consider not only increasing DER capacity but also diversifying the composition of DER resources rather than relying predominantly on PV

systems. Such diversification could further improve system flexibility and mitigate the limitations associated with highly concentrated PV generation profiles.

Figure 5 presents the optimal scheduling results for the representative 24-h operating periods corresponding to Scenarios 1, 3, and 5 for each month of the year.

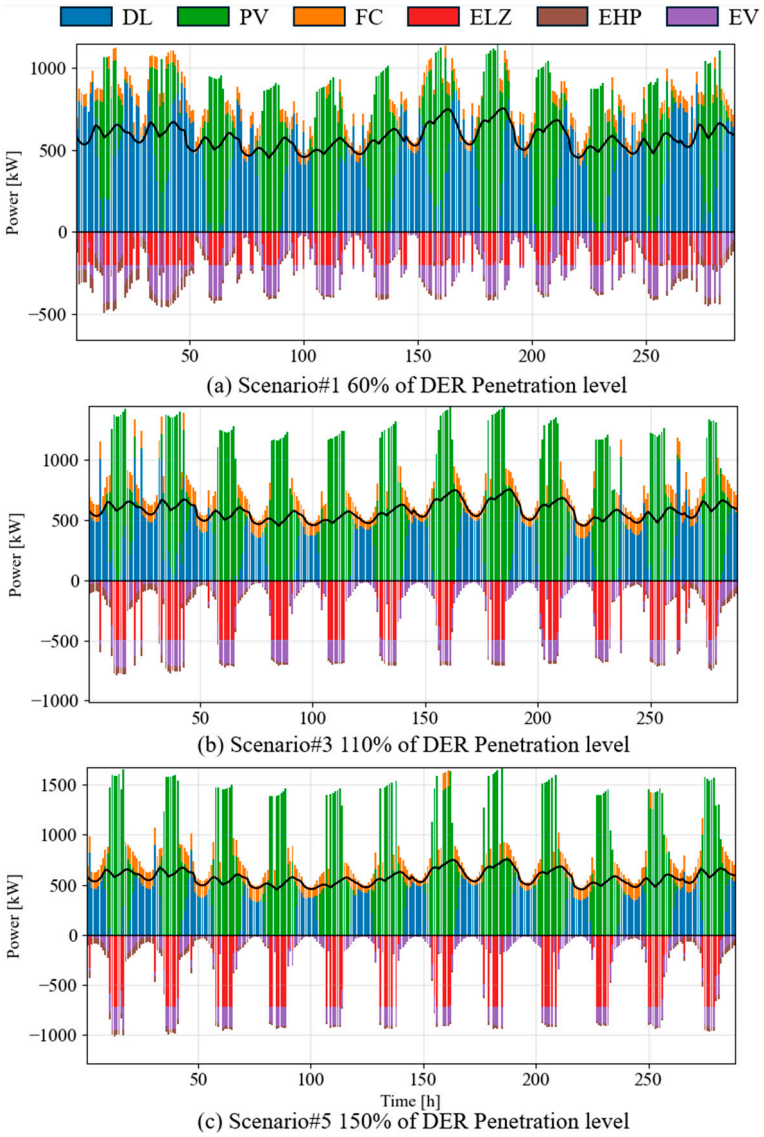


Figure 5. Optimal scheduling of sector coupling for each scenario in Case 2.

4.3. Comparative Analysis of Uncertainty Modeling Approaches

In this study, DRO was employed to reflect the uncertainty of price signals whose probability distribution is not explicitly known. However, since the extent to which the level of uncertainty affects the economic results was not sufficiently clarified, an additional comparison is conducted using empirical electricity cost data and conventional robust optimization to quantitatively examine the impact of uncertainty modeling. Table 5 presents the comparison results among different optimization methods for Case 2 under the highest DER penetration rate of 150%.

Table 5. Simulation results for each uncertainty optimization method in Case 2.

	Uncertainty Model		
	Deterministic	**RO**	**DRO**
Benefit [$/yr]	859,268	630,018	722,671
Cost [$/yr]	102,091	92,923	99,317
Total benefit [$/yr]	757,537	537,095	623,353
Curtailed energy [kWh/yr]	88,079	79,200	86,306
Benefit/capacity of DER [$/kW]	133.05	101.95	124.67

As shown in the numerical results, the deterministic optimization case provides the best economic performance because it directly uses the empirical price data without considering adverse uncertainty. In contrast, conventional robust optimization derives the worst-case solution within a predefined bounded uncertainty set, regardless of the underlying probability distribution of the data. As a result, the RO case shows a relatively large difference from the deterministic result.

Although the conservativeness of RO depends on how the uncertainty bounds are defined before optimization, directly applying an excessively conservative solution under limited distributional information may lead to a significant gap between numerical results and practical engineering outcomes. Therefore, careful attention is required when interpreting RO-based results.

The proposed DRO model provides a less conservative solution than conventional RO because the worst-case distribution is constrained by the ambiguity set constructed from empirical moment information. At the same time, it remains more conservative than deterministic optimization because it still considers adverse uncertainty in the price signal. These results indicate that the proposed DRO framework can provide meaningful numerical information for system investors and operators when making planning decisions under uncertain P2P electricity prices.

However, depending on the structure of the objective function, the results do not necessarily show a monotonic increase or decrease for all indicators. For example, curtailed energy and the optimal capacities of individual facilities do not always improve or deteriorate consistently according to the applied uncertainty optimization method. This indicates that these indicators can vary as a result of optimizing the cost-based objective function considered in this study. Therefore, if facility planning and economic evaluation are to be analyzed independently, a more advanced optimization framework, such as a multi-objective formulation, should be considered in future research.

To further examine the sensitivity of the proposed DRO framework, additional numerical results are presented in Table 6 by varying the DRO parameters.

Table 6. Sensitivity analysis of DRO ambiguity-set parameters in Case 2.

γ_1	γ_2	**Total Benefit [$/yr]**	**Benefit/Capacity of DER [$/kW]**
0.01	0.06	731,458	126.24
0.03	0.05	727,090	125.44
0.05 (Ref)	0.10 (Ref)	722,671	124.67
0.10	0.15	711,347	122.72
0.15	0.20	698,400	120.48

Based on the parameter values adopted in this study, smaller values of the ambiguity-set parameters restrict the range of admissible distributions. As a result, the search for the worst-case distribution becomes more limited, leading to a relatively less conservative solution. In contrast, larger parameter values expand the feasible range of worst-case

distributions, allowing the DRO model to identify more conservative and less favorable outcomes. These numerical results clearly reflect the degree of conservativeness introduced by the DRO formulation and its impact on the optimization results.

5. Conclusions

This study investigated the economic value that DERs can obtain within distribution networks located in Distributed Energy Special Zones, where P2P electricity trading is permitted under South Korea's Distributed Energy Promotion Act. To support renewable energy utilization and examine the long-term economic viability of expanding DER installations, a P2X-based sector coupling framework was incorporated into a regional energy planning model.

Since P2P electricity trading introduces transaction prices that cannot be predetermined and are subject to considerable uncertainty, electricity trading prices were modeled as uncertain variables and incorporated into the optimization framework through DRO. The proposed approach enables the quantitative evaluation of price uncertainty and provides robust planning-level operational strategies under adverse market conditions. The simulation results indicate that P2X-based sector coupling can improve the economic performance of the proposed business model by increasing renewable energy utilization and reducing renewable energy curtailment within the assumed planning framework.

However, because the DER portfolio considered in this study primarily consists of PV systems, the inherent generation characteristics of PV may still lead to renewable energy accommodation limitations under high DER penetration scenarios. Although sector coupling technologies can help mitigate this issue, the results suggest that aggregated regional energy systems with P2X facilities may eventually face economic and operational limits in accommodating continuously increasing renewable energy penetration.

It should also be noted that the proposed model does not include detailed distribution-network constraints, such as feeder topology, voltage limits, line capacity, network losses, and power flow equations. Therefore, the results should be interpreted as planning-level estimates rather than detailed feeder-level operational outcomes. Future research will extend the proposed framework by considering realistic distribution network topologies, power flow constraints, and optimal siting and sizing strategies for P2X facilities. In addition, coordinated operation within VPP frameworks, resilience metrics, extreme-event scenarios, and coupled infrastructure risks will be investigated to further evaluate the economic, operational, and resilience-oriented value of P2X technologies in regional energy planning.

In addition, comprehensive sensitivity analysis considering CAPEX and OPEX variations, EV penetration, hydrogen price, heat price, P2P price uncertainty, ambiguity-set parameters, and DER penetration level should be conducted in future research to further improve the reliability and generality of the proposed planning framework.

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Conflicts of Interest: The author declares no conflict of interest.

Nomenclature

Variables

T_t^{EHP}, P_t^{EHP}	Thermal output and power input of EHP
P_t^{EV}	EV charging power
H_t^{ELZ}, P_t^{ELZ}	Hydrogen output and power input of ELZ

$H_t^{FC}, T_t^{FC}, P_t^{FC}$	Hydrogen input, thermal output, and power output of FC
$H_t^{HESS,+}, H_t^{HESS,-}$	Charging and discharging hydrogen of HESS
$HSOC_t$	State of Charge of HESS
$P_t^{\Omega_{DER}}$	Power output of each DER facility
P_t^{DER}	Total power output of DER
P_t^{CUR}	Curtailed power
P_t^{DL}	Distribution line power
$C^{\Omega^{p2x}}$	The capacity of each facility
Parameters	
P_t^D, T_t^D	Power and thermal demand
$\mathbb{C}_t^{P2P}$	P2P transactions price
$\mathbb{C}_t^{EV}$	EV charging fee
$\mathbb{C}_t^{Heat}$	Heat energy price
$\mathbb{C}_t^{ELE}$	Electricity price
$\mathbb{C}_{\Omega^{p2x}}^{OPEX}, \mathbb{C}_{\Omega^{p2x}}^{CAPEX}$	OPEX and CAPEX of each facility
Sets	
Ω^{der}	DER facility set
Ω^{p2x}	P2X facility set

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