energies

MDPI

Article

Optimization Analysis of 100% Renewable Energy Chains Considering Energy Service Demands in Namie Town, Fukushima

Yuma Mochizuki, Keiki Shimura and Hiromi Yamamoto *

Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan;
mochizuki.yuma.s1@dc.tohoku.ac.jp (Y.M.); shimura.keiki.p1@dc.tohoku.ac.jp (K.S.)
* Correspondence: hiromi.yamamoto.c2@tohoku.ac.jp

Abstract

Driven by the 2011 nuclear disaster, Namie Town, Fukushima, is aiming to implement a standalone 100% renewable energy system by 2035 using regional resources. This study clarifies the optimal configuration of a carbon-neutral energy system, focusing on hydrogen's role as a final energy carrier. To achieve this, we developed a linear programming model integrating energy supply, storage, and service demands with hourly temporal resolution. This model determines the optimal installed capacities and hourly operation of all facilities to minimize the total annual system cost. Using this optimization framework, we quantitatively compared an "E case" (electricity supply only) and an "EH case" (combined electricity and hydrogen supply). The results indicate that the EH case optimizes facility capacity through appropriate role allocation between batteries and hydrogen. Specifically, in this case, the hydrogen power generation capacity decreased by 41.3% compared to that in the E case. Furthermore, avoiding hydrogen-to-electricity reconversion losses reduced the required renewable generation by 7.6%, leading to a 6.8% reduction in total system costs. These findings demonstrate that utilizing hydrogen as a flexible carrier connecting supply and demand—rather than merely as a storage medium—effectively achieves energy efficiency and economic viability in regional standalone energy systems.

Keywords: 100% renewable energy systems; hydrogen utilization; energy chain model; optimization; carbon neutrality; energy service demand; Namie Town; sector coupling

1. Introduction

The Japanese government is aiming to achieve carbon neutrality by 2050 by promoting the deployment of renewable energy. In this context, the construction of decentralized energy systems utilizing regional resources is gaining importance in local municipalities. The construction of such decentralized energy systems is also crucial from the perspectives of regional revitalization and improving resilience. Crucially, ensuring energy security has become a pressing issue. The current global geopolitical instability has highlighted the vulnerability of energy supply chains dependent on imported fossil fuels. Thus, transitioning to a self-sufficient energy system utilizing regional resources is essential not only for decarbonization but also for minimizing the risks associated with external energy dependency.

Namie Town, in Fukushima Prefecture, is aiming to achieve sustainable energy independence without relying on nuclear power. This policy was established following the

Academic Editor: Juri Belikov

Received: 27 January 2026
Revised: 16 February 2026
Accepted: 21 February 2026
Published: 24 February 2026

extensive damage caused by the 2011 Great East Japan Earthquake and associated nuclear disaster. In 2023, Namie Town formulated the "Namie Energy Challenge 2035" plan, the goal of which is to achieve carbon neutrality by 2035. Importantly, Namie Town shows significant potential for transitioning to renewable energy resources, such as solar, wind, and hydropower, and the technical infrastructure necessary for constructing a regional energy system. In addition, the town hosts the Fukushima Hydrogen Energy Research Field (FH2R), a large-scale hydrogen production demonstration facility, which provides an established foundation for utilizing hydrogen energy [1].

Energy storage systems (ESSs) are becoming increasingly important as a countermeasure against output fluctuations associated with the expanded deployment of variable renewable energy (VRE). Among ESS technologies, Battery Energy Storage Systems (BESS) are widely recognized for their high reliability and round-trip efficiency, making them highly effective for managing short-term power fluctuations and providing frequency support [2]. However, relying solely on BESS for large-scale, long-duration energy shifting entails economic challenges due to the high capital costs associated with expanding storage capacity [3]. In this context, hydrogen storage (Power-to-Gas: P2G), which allows for large-capacity and long-term storage, is becoming increasingly important for stabilizing energy systems. The utility of P2G technology has been demonstrated in previous studies. For example, Götz et al. [4] conducted a comprehensive review of P2G technology and concluded that converting and storing surplus electricity into gaseous fuels such as hydrogen is technically and economically viable for enhancing the flexibility of energy systems. Similarly, Komiyama et al. [5] performed an optimization analysis targeting the Japanese power system, quantitatively showing that hydrogen storage significantly contributes to reducing grid integration costs and avoiding curtailment in scenarios with large-scale VRE integration. Furthermore, Yamamoto et al. [3] demonstrated that a hybrid storage system, where batteries handle short-term daily cycles and hydrogen storage handles long-term seasonal cycles, is more cost-effective for 100% VRE systems than relying on a single storage technology. Therefore, identifying the optimal role allocation between these technologies is crucial.

Research on regional standalone energy systems is also advancing. Laimon and Yusaf [6] verified the effectiveness of an "Integrated Renewable Energy and Hydrogen System (IREDHS)" through an analysis using system dynamics. Their results clarified that complete energy independence is technically and economically feasible. Meanwhile, Yamamoto et al. [3] aimed to optimize facility capacities and costs by developing a cost-minimization model for a 100% VRE system. Their study demonstrated that a hybrid storage system combining batteries and hydrogen can reduce the costs of stable supply more effectively than a single storage system. They also pointed out the effectiveness of simultaneously supplying both electricity and hydrogen.

Furthermore, integrated system design (sector coupling), which encompasses both the supply and demand sides, has become increasingly important in recent years. Lund et al. [7] proposed the concept of "Smart Energy Systems" that integrate electricity, heating, and transportation infrastructures. They argued that flexibly coupling demands from each sector is essential for realizing a 100% renewable energy system. In a study embodying this concept within the Japanese context, Yamamoto [8] developed an "energy chains model" focusing on "energy service demand." In this model, end-use technologies are selected endogenously to satisfy final service demands such as water heating, air conditioning, and transportation. Furthermore, this study demonstrated that both CO_2 emissions and system costs can be reduced by actively managing certain demand patterns (demand response, DR).

We have previously conducted a cost-optimization analysis of an energy system for Namie Town. In our study, we examined a system that met electricity demands using renewable energy, batteries, and hydrogen storage. However, this model limited the energy demand to electricity and did not account for the entirety of the energy chain, which includes non-electric energy demands. Consequently, the role of hydrogen in a regional standalone 100% renewable energy system has only been evaluated within a limited scope. Specifically, there has been insufficient investigation into the optimal supply distribution when hydrogen is used not only for reconversion to electricity but also directly as a final energy carrier for specific regional industrial and residential service demands.

To clarify the positioning of this study and the proposed system configuration compared to previous research, a comparison of existing solutions is summarized in Table 1. While Xiong et al. [2] and Komiyama et al. [5] analyzed grid-connected systems, they did not address the challenges of supply–demand balancing in standalone environments. Laimon & Yusaf [6] and Yamamoto et al. [3] focused on standalone systems; however, the former relied on system dynamics without cost optimization, and the latter assumed a simplified constant hydrogen demand, which does not reflect the fluctuations of actual end-use services. This study bridges these gaps in the literature by optimizing a standalone system that satisfies hourly varying service demands across electricity, heat, and mobility sectors through the direct utilization of hydrogen.

Table 1. Comparison of this study with existing literature.

Author	Target Area	Grid Connection	Supply Side	Demand Side	Storage Tech	Hydrogen Scope	Time Resolution
Xiong et al. [2]	Local (Wind Farm in Yunnan, China)	Connected	Wind	Elec. (Frequency Support)	Battery, Heat	N/A	0.5 s
Yamamoto et al. [3]	National (Japan)	Off-grid	Solar, Wind	Elec., H_2 (Constant Load)	Battery, H_2 Storage	Power Gen, Direct Supply	1 h
Komiyama et al. [5]	Regional (Tohoku, Japan)	Connected	PV, Wind, Fossil Thermal, Nuclear, etc.	Elec.	Battery, H_2 Storage	Power Gen	10 min
Laimon & Yusaf [6]	Local (Residential/Facility)	Off-grid	Solar, Wind	Elec., Heat, Transport (Sector Coupling)	H_2 Storage	Power Gen, Direct Supply	N/A
Yamamoto [8]	National (Japan)	Connected	PV, Wind, Fossil Thermal, Nuclear, etc.	Elec., Heat, Transport (Sector Coupling)	Battery	Not used	1 h
This Study	Local (Namie, Japan)	Off-grid	PV, Wind, Hydro	Elec., Heat, Transport (Sector Coupling)	Battery, H_2 Storage	Power Gen, Direct Supply	1 h

The objective of this study is to evaluate the allocation of electricity and hydrogen supplies by optimizing the entire energy chain, including non-electric energy demands, within a regional standalone 100% renewable energy system. To achieve this objective, a new energy chain model was developed based on the methodology described by Yamamoto [8]. This model incorporates comprehensive energy service demands across all sectors—industrial, commercial, residential, and transportation—covering specific end-uses ranging from heating and mobility to daily necessities such as cooking and appliance use, and is designed to allow these demands to be satisfied by either electricity or hydrogen. Using the developed model, a quantitative analysis was performed by comparing a case where all demands are supplied solely by electricity with a case where both electricity and hydrogen are utilized. Based on the above, the main contributions of this study are summarized as follows:

- Development of a comprehensive hourly energy chain model: We developed a detailed mathematical model that simulates the hourly energy flow from renewable generation to service demand, explicitly incorporating non-electric demands such as heating and transportation.

- Comparative analysis of energy system configurations: We quantitatively evaluated and compared two scenarios: a system where all service demands are satisfied solely by electricity (E case) and a system where service demands are satisfied by both electricity and direct hydrogen supply (EH case) to determine the optimal system configuration.
- Clarification of hydrogen's role in a standalone energy system: We demonstrated the specific role of hydrogen in mitigating renewable energy curtailment and reducing total system costs, providing insights into the feasibility of a model for 100% local production for local consumption.

2. Overview and Formulation of the Energy Chain Model

2.1. Model Overview

We constructed an energy chain model, as shown in Figure 1, to evaluate a 100% renewable energy-based standalone energy system in Namie Town, Fukushima Prefecture. The primary objective of this model is to evaluate the impact of direct hydrogen utilization on the overall energy system. The system is designed as a standalone model with no connection to external power grids and satisfies all local energy service demands solely through regional renewable energy sources. The objective function is defined as the minimization of the total annual cost of the entire energy chain.

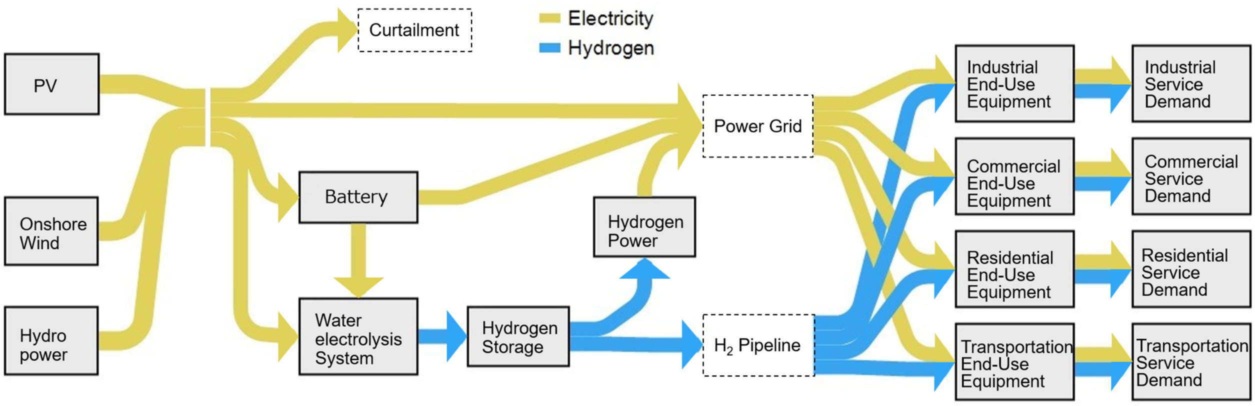


Figure 1. Schematic diagram of the energy chain model. Yellow lines indicate electricity flows, and blue lines indicate hydrogen flows. The width of the lines represents logical connections, not energy quantities. Blocks with solid outlines represent physical technologies (generation, storage, or end-use) and demand sectors. Blocks with dashed outlines represent infrastructure nodes (power grid or H_2 pipeline) and system states (curtailment). Arrows indicate the direction of energy flow from sources to end-use sectors. Note that the energy flows originating from renewable sources represent the theoretical generation potential. "Curtailment" indicates the surplus energy that is not utilized or stored within the system.

On the supply side, solar, onshore wind, and hydropower are assumed to be the primary energy sources. The hourly power generation patterns for each source are input into the model as exogenous data. The generated electricity can be directly supplied to end-use equipment, battery charging, or hydrogen production via water electrolysis systems, and surplus electricity is treated as curtailment. The produced hydrogen is utilized for reconversion to electricity via hydrogen power generation or is directly supplied to end-use equipment after being stored in hydrogen storage tanks. The installed capacities of all facilities—including PV, onshore wind, hydropower, batteries, water electrolysis systems, hydrogen storage tanks, and hydrogen power—are determined endogenously within the model.

On the demand side, the model adopts the concept of energy service demand, as shown in Table 2. Each service demand is satisfied through end-use equipment that consumes either electricity or hydrogen, the choice of which and its respective supply share are determined endogenously through optimization.

Table 2. Energy services and end-use technologies.

Sector	Service	Electric Power	Hydrogen
Industry	Heating	Electric Heater	Hydrogen Burner
	High-Temperature Boiler	Electric Boiler	Hydrogen Boiler
	Low-Temperature Boiler	Electric Boiler, HPWH	Hydrogen Boiler
	Other Electric	Electric Appliances	-
	Other Solid Fuel	Electric Appliances	Hydrogen Appliances
	Other Liquid Fuel	Electric Appliances	Hydrogen Appliances
	Other Gas Fuel	Electric Appliances	Hydrogen Appliances
Commercial	Appliances	Electric Appliances	-
	Cooling	Air Conditioner	Absorption Chiller
	Cooking	Electric Appliances	Hydrogen Appliances
	Water Heating	Electric Water Heater, HPWH	Hydrogen Water Heater
	Space Heating	Air Conditioner	Hydrogen Heater
Residential	Appliances	Electric Appliances	-
	Cooling	Air Conditioner	-
	Cooking	Electric Appliances	Hydrogen Appliances
	Water Heating	Electric Water Heater, HPWH	Hydrogen Water Heater
	Space Heating	Air Conditioner	Hydrogen Heater
Transportation	Road Passenger	EV	FCV
	Road Freight	EV	FCV
	Rail	Electric Train	-
	Aviation and Shipping	-	-

Notes: HPWH, Heat Pump Water Heater; EV, Electric Vehicle; FCV, Fuel Cell Vehicle.

The calculation assumptions are as follows: the target period is the single year of 2035, which Namie Town has designated as the target year for achieving carbon neutrality. The model considers the annual supply–demand balance with a temporal resolution of one hour.

The optimization model was formulated as a linear programming (LP) problem and implemented using GAMS 46.5.0 with the CPLEX solver. The GAMS code was developed and debugged with the assistance of Gemini 3 (Google). The authors have thoroughly reviewed the generated code for logical and technical accuracy and take full responsibility for the methodology.

2.2. Objective Function

The objective function is the minimization of the total annual cost (TC) of the entire energy chain. The total annual cost TC is defined by Equation (1):

$$TC = \sum_{gen} CAP_{gen} \cdot uc_{gen} \cdot dep_{gen} + \sum_{ess} CAP_{ess} \cdot uc_{ess} \cdot dep_{ess} + \sum_{tech} FACCOST_{tech} + \sum_{tech} CVSTECH_{tech}, \quad (1)$$

where

- TC is total annual cost of the energy chains;
- gen is power generation facilities (PV, onshore wind power, hydropower, and hydrogen power);

- *ess* is energy storage systems (battery, hydrogen storage, and water electrolysis systems);
- *CAP* is installed capacity of each facility;
- *uc* is capital cost per unit capacity;
- *dep* is annualized cost rate (depreciation rate);
- *tech* is end-use technology;
- *FACCOST* is capital cost of end-use technology;
- *CVSTECH* is cost of final energy delivery and associated charges.

Here, CVSTECH represents the additional costs required to adjust the final energy unit price in the model to the market energy price [8]. For hydrogen, the data for gas fuel are used as a substitute; specifically, the cost is defined as the difference between the gas fuel market price and the primary energy unit price. For electricity, it is calculated as the difference between the retail electricity price and the average power generation cost, accounting for transmission and distribution costs as well as business profits. These costs were estimated based on 2010 data and are assumed to be equivalent in 2035.

The annualized cost rate *dep* is defined as the sum of the capital recovery factor—calculated from the discount rate (assumed to be 3% in this study) and the service life of each facility—and the operation and maintenance (O&M) cost rate. The specific parameters for each facility are detailed in Section 3.

2.3. Main Constraints

The primary constraints of the energy chain model are described below, following the flow from the demand side to the supply side.

2.3.1. Energy Service Demand Balance

Equation (2) defines the balance between the annual energy service demand and the hourly energy service demand.

$$\sum_{day,hr,tech} SDT_{day,hr,tech} \cdot servtech_{tech,i} = d_i, \quad (2)$$

where

- *day* is day;
- *hr* is hour;
- *i* is type of energy service;
- *SDT* is hourly energy service demand;
- *servtech* is matrix representing the correspondence between *tech* and *i*;
- *d* is annual energy service demand.

2.3.2. Final Energy Consumption

The final energy consumption (*INPUT*) required to satisfy the service demand in each time step (*SDT*) is calculated using Equation (3).

$$\sum_{en} INPUT_{day,hr,en,tech} \cdot eff_{tech} \cdot techen_{tech,en} = SDT_{day,hr,tech}, \quad (3)$$

where

- *en* is classification of final energy (electricity or hydrogen);
- *INPUT* is final energy consumption;
- *eff* is energy efficiency of the end-use technology;
- *techen* is matrix representing the correspondence between *en* and tech.

2.3.3. Secondary Energy Supply

The secondary energy supply (*SUP*) required to provide the final energy consumption (*INPUT*) calculated in Equation (3) is determined by Equation (4). This equation accounts for transmission and distribution losses, calculating the gross energy amount that must be supplied to the grid or pipelines to satisfy the end-use demand. The calculated *SUP* serves as the demand constraint in the subsequent supply–demand balance equations (Equation (5) for electricity and Equation (6) for hydrogen).

$$SUP_{day,hr,en}(1 - eneloss_{en}) = \sum_{tech} INPUT_{day,hr,en,tech}, \tag{4}$$

where

- *SUP* is secondary energy supply;
- *eneloss* is secondary energy loss rate (set to 4.2% for electricity and 0% for hydrogen in this study).

2.3.4. Power Supply–Demand Balance

Equation (5) is used to ensure the supply–demand balance for the electricity sector at each time step. The total amount of electricity generated and battery discharging must equal the total electricity consumption, including demand, storage charging, and curtailment.

$$\begin{aligned} &PVG_{day,hr} + WINDG_{day,hr} + HYDG_{day,hr} + BATDIS_{day,hr} + HTG_{day,hr} \\ &= CURTAIL_{day,hr} + ELECTROLYSIS_{day,hr} + BATCH_{day,hr} + SUP_{day,hr,elec}, \end{aligned} \tag{5}$$

where

- *PVG* is PV generation;
- *WINDG* is onshore wind power generation;
- *HYDG* is hydropower generation;
- *BATDIS* is battery discharging;
- *HTG* is hydrogen power generation;
- *CURTAIL* is curtailment;
- *ELECTROLYSIS* is electricity for water electrolysis;
- *BATCH* is battery charging;
- $SUP_{day,hr,elec}$ is electricity supply.

2.3.5. Hydrogen Supply–Demand Balance

Similarly, the supply–demand balance for the hydrogen sector is defined by Equation (6). This constraint ensures that the hydrogen discharged from storage is allocated either to hydrogen power generation or to the hydrogen supply pipeline to meet the demand.

$$HTSTDIS_{day,hr} = HTGIN_{day,hr} + SUP_{day,hr,hyd}, \tag{6}$$

where

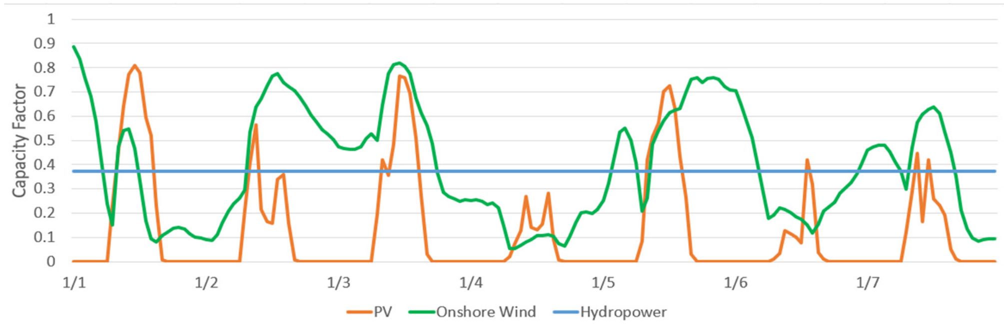
- *HTSTDIS* is hydrogen storage discharging;
- *HTGIN* is hydrogen input for power generation;
- $SUP_{day,hr,hyd}$ is hydrogen supply.

3. Data for the Energy Chain Model

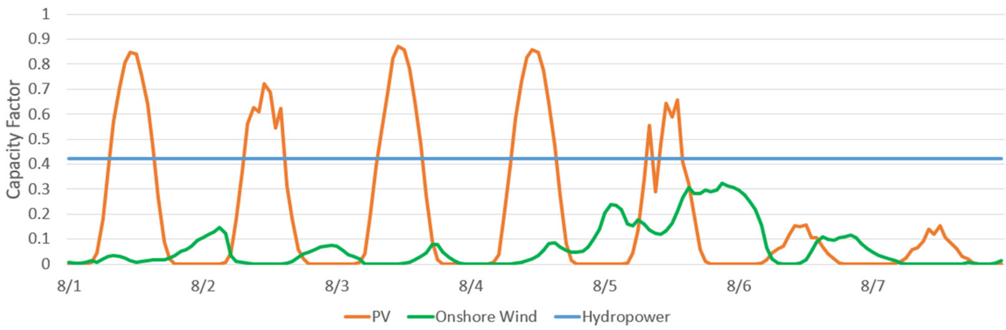
3.1. Supply-Side Data

3.1.1. Hourly Renewable Energy Generation Patterns

The hourly power generation patterns for renewable energy were developed using the following methods and data. The PV generation pattern was calculated based on the method described in [9], using hourly solar radiation [10] and temperature data [11] from Namie Town. Specifically, this calculation explicitly accounts for the temperature coefficient of the PV modules, incorporating the effect of ambient temperature on conversion efficiency. The onshore wind power generation pattern was based on locations with favorable wind conditions in the southern part of Namie Town. This pattern was generated using simulation tools [12,13]. The hydropower generation pattern was developed based on the monthly water discharge data for hydropower plants in the Tohoku region [8]. Figure 2 illustrates the hourly capacity factors of these renewable energy sources for representative weeks in winter (1–7 January) and summer (1–7 August).



(**a**)



(**b**)

Figure 2. Hourly capacity factor of renewable energy sources in Namie Town: (**a**) winter (1–7 January); (**b**) summer (1–7 August).

3.1.2. Upper Limits for Renewable Energy Installed Capacity

Upper limits were established for the installed capacity of each renewable energy facility. These values are based on the deployment potential published by the town [1]. The specific upper limits are 105.9 MW for PV, 1086.0 MW for onshore wind power, and 3.8 MW for hydropower.

3.1.3. Techno-Economic Parameters for Facilities

Table 3 presents the primary technical and economic parameters for each facility. The capital costs for power generation facilities were determined for the year 2035, calculated through linear interpolation using the projected costs for 2030 and 2040 [14]. The costs for batteries, hydrogen storage tanks, and water electrolysis systems were set in accordance with the data provided in [5].

Table 3. Techno-economic parameters for power generation and energy storage systems.

	Capital Cost [JPY/kW]	Capital Cost [JPY/kWh]	Efficiency	Capacity Factor	Operating Range (SoC/Load)	Lifetime [Years]	O&M Rate
PV	148,000			0.162		25	0.032
Onshore Wind	272,000			0.264		25	0.040
Hydropower	640,000			0.460		40	0.025
Battery (Storage)		20,000			≥0.2, ≤0.8	20	0.030
Battery (PCS)	60,000		0.800		≤0.8	20	0.030
Hydrogen Storage		1400			≥0.2, ≤0.8	20	0.030
Water Electrolysis System	60,000		0.821		≤0.8	20	0.030
Hydrogen Power	209,000		0.570		≤0.8	40	0.044

Notes: PCS is Power Conversion System; SoC is State of Charge. For the water electrolysis system, the capital cost represents the combined costs of the electrolyzer and the hydrogen compressor. The efficiency is calculated as the system efficiency, accounting for the power consumption of the compressor.

3.2. Demand-Side Data

3.2.1. Energy Service Demand Estimation

We estimated the energy service demand for Namie Town in 2035 using the procedure outlined below. As a prerequisite for the estimation, the sectoral demand structure from 2010 (prior to the 2011 earthquake) was assumed to be maintained.

In the first step, the energy service demand for Fukushima Prefecture in 2010 was calculated. This calculation utilized the energy consumption statistics of Fukushima Prefecture in 2010 [15] and the estimation method for prefecture-level energy service demand described in [16].

In the second step, the calculated demand for Fukushima Prefecture was apportioned to Namie Town based on statistical indicators to estimate the demand for Namie Town in 2010. The indicators used for apportionment varied by sector: the value of manufactured goods shipments [17] was used for the industrial sector, the number of employees [18] for the commercial sector, and the population [19] for the residential and transportation sectors.

In the third step, the 2010 demand was scaled based on the population ratio to obtain the energy service demand for Namie Town in 2035 (Table 4). Specifically, the ratio between the population in 2010 (20,905 people) [19] and the estimated population for 2035 (7923 people) based on the town's reconstruction plan [20] was applied.

Table 4. Estimated annual energy service demand in Namie Town for 2035.

Sector	Service	Energy Service Demand [TJ]	Sector	Service	Energy Service Demand [TJ]
Industry		99.9	Residential		184.6
	Heating	11.8		Appliances	19.4
	High-Temperature Boiler	24.3		Cooling	50.8
	Low-Temperature Boiler	16.7		Cooking	4.9
	Other Electric	23.8		Water Heating	27.4
	Other Solid Fuel	7.4		Space Heating	82.1
	Other Liquid Fuel	14.6	Transportation		19.8
	Other Gas Fuel	1.3		Road Passenger	11.2

Table 4. *Cont.*

Sector	Service	Energy Service Demand [TJ]	Sector	Service	Energy Service Demand [TJ]
Commercial		136.2		Road Freight	8.3
	Appliances	23.8		Rail	0.3
	Cooling	26.6		Aviation and Shipping	0
	Cooking	9.5	Total		440.5
	Water Heating	29.1			
	Space Heating	47.3			

Regarding "Aviation and Shipping" in the transportation sector, the demand was assumed to be zero. This is because there are no airports or large-scale port facilities in Namie Town.

3.2.2. Hourly Patterns of Energy Service Demand

The hourly demand patterns for each end-use technology listed in Table 2 were, in principle, based on the electricity demand patterns described in [8]. The hourly patterns for hydrogen demand were also set to be identical to the electricity demand patterns of the corresponding categories. It should be noted that these hourly demand patterns reflect seasonal variations, particularly regarding space heating and cooling demands, which fluctuate significantly between the summer and winter months. In addition, considering the characteristics and applications of energy carriers, individual settings were applied to the following items.

First, conventional electric and gas water heaters are assumed to be instantaneous types without hot water storage functions, and energy is supplied immediately when there is demand. The demand pattern for the residential sector was set based on the hot water load pattern provided in [21]. The pattern for the commercial sector was calculated as a weighted average of business-type-specific hot water load patterns [22,23], using the number of employees by business type in Namie Town in 2009 [24] as weights.

Second, the settings for FCVs are as follows. For passenger vehicles, the customer arrival pattern at gas stations [25] was applied. For freight vehicles, the demand pattern of electrical equipment in the commercial sector was applied.

Third, the settings for DR target equipment are as follows. For the electricity demand of HPWHs and EVs, the total daily demand was fixed at 1/365 of the annual demand. Under this constraint, the hourly demand pattern within each day is determined endogenously through optimization.

3.2.3. Data for End-Use Technologies

Table 5 presents the primary parameters for the end-use technologies, which include the energy efficiency and costs of each. These parameters were all determined for the target year 2035, with values calculated through linear interpolation using the data for 2030 and 2040 provided in [8].

Table 5. Techno-economic parameters for representative end-use technologies in 2035.

Sector	Service	End-Use Technology	Energy Efficiency	Cost [JPY/GJ-Service]
Industry	Heating	Electric Heater	0.83	89
		Hydrogen Boiler	0.48	96
	High-Temperature Boiler	Electric Boiler	0.95	89
		Hydrogen Boiler	0.85	96
	Low-Temperature Boiler	Electric Boiler	0.95	88
		HPWH	4.25	687
		Hydrogen Boiler	0.95	96

Table 5. *Cont.*

Sector	Service	End-Use Technology	Energy Efficiency	Cost [JPY/GJ-Service]
Commercial	Cooking	Electric Appliances	0.79	1723
		Hydrogen Appliances	0.56	1436
	Water Heating	Electric Water Heater	0.95	222
		HPWH	3.75	2227
		Hydrogen Water Heater	0.95	313
	Space Heating	Air Conditioner	5.51	299
		Hydrogen Heater	0.84	313
Residential	Water Heating	Electric Water Heater	0.95	886
		HPWH	3.55	3340
		Hydrogen Water Heater	0.91	1251
Transportation	Road Passenger	EV	0.42	30,017
		FCV	0.21	30,017
	Road Freight	EV	0.42	8802
		FCV	0.21	8802

Since reference [8] does not provide individual datasets for hydrogen-using equipment, the parameters for these technologies—excluding FCVs—were assumed to be equivalent to those for gas-fueled technologies. For FCVs, the specific data available in [8] were utilized.

4. Results and Discussion

4.1. Simulation Cases

The following two calculation cases were established to quantitatively evaluate the impact of the role of hydrogen on system configuration and economic rationality. This analysis compares the conventional approach, utilizing hydrogen solely as an electricity storage medium, with an approach utilizing hydrogen directly as a final energy carrier.

- E case: In this case, end-use technologies are limited to electricity-consuming equipment, and all energy service demands are satisfied by electricity. However, the use of hydrogen storage and hydrogen power generation is permitted.
- EH case: In this case, both electricity- and hydrogen-consuming equipment are considered end-use technologies. For each energy service demand, the choice between electricity and hydrogen as the energy carrier is determined endogenously through optimization to minimize the total system cost.
- The calculation parameters, including the upper limits for renewable energy installed capacity, facility investment costs, and energy service demands, are identical for both cases.

4.2. Energy Carrier Configuration by Energy Service

Figure 3 shows the energy supply configuration by energy service demand in the EH case. Overall, the results indicate that electrification is dominant across most sectors. Specifically, high-efficiency heat pump systems, including air conditioners for space heating and HPWHs for water heating, were selected in the residential and commercial sectors. Similarly, EVs were chosen as the primary technology for transportation services.

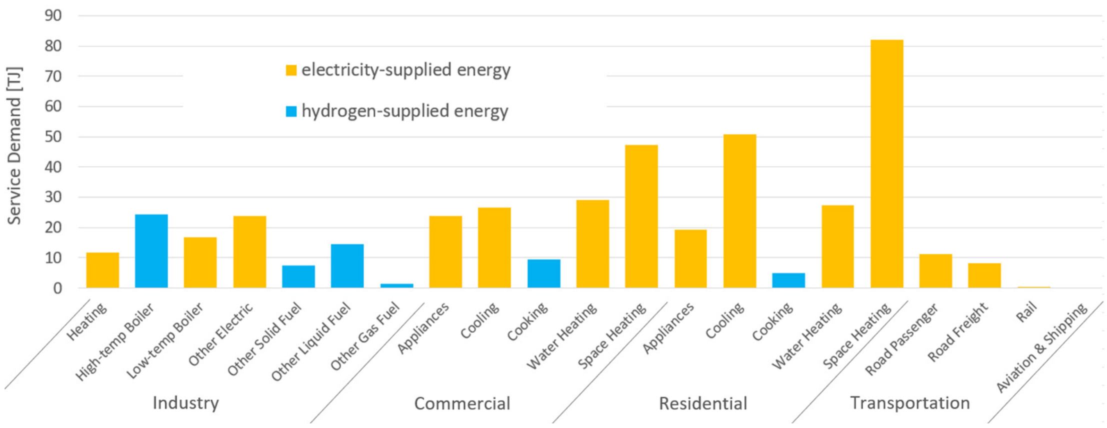


Figure 3. Breakdown of energy supply carriers for each service demand in the EH case.

In contrast, hydrogen was selected for applications where it offers a specific advantage. A clear distinction based on temperature range was observed in industrial boiler demand: electrification was selected for low-temperature boilers, whereas hydrogen was selected for high-temperature boilers. Hydrogen was also selected for cooking demands in the commercial and residential sectors.

These results clarify the distinct roles of electricity and hydrogen based on the energy efficiency and cost-effectiveness of the available end-use technologies.

4.3. Installed Capacities

Table 6 shows the installed capacities for both cases. Overall, the EH case resulted in smaller capacities for both power generation and storage facilities compared to the E case. Specifically, the PV capacity decreased by 7.0 MW (8.7%). Significant reductions were identified especially in hydrogen-related facilities: the hydrogen storage capacity decreased by 339.9 MWh (13.5%), and the hydrogen power generation capacity saw a substantial reduction of 3.8 MW (41.3%).

Table 6. Installed capacities.

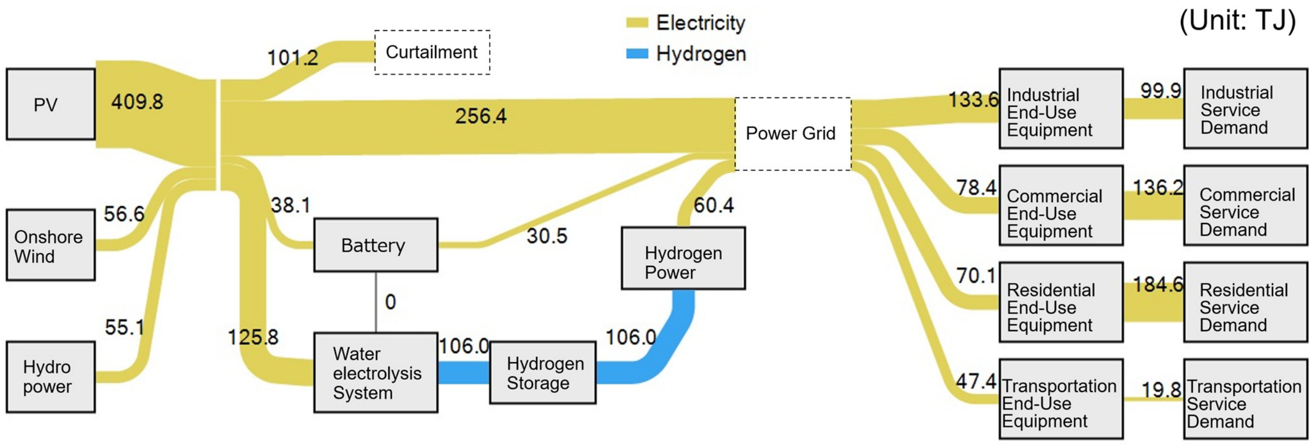
	E Case	EH Case
PV [MW]	80.2	73.2
Onshore Wind [MW]	6.8	6.4
Hydropower [MW]	3.8	3.8
Battery (Storage) [MWh]	55.8	52.5
Battery (PCS) [MW]	7.1	6.6
Hydrogen Storage [MWh]	2515.8	2175.9
Water Electrolysis [MW]	31.5	31.4
Hydrogen Power [MW]	9.2	5.4

Notes: Water electrolysis denotes the rated capacity of the electrolyzer. The system implicitly includes a hydrogen compressor sized to match the production rate.

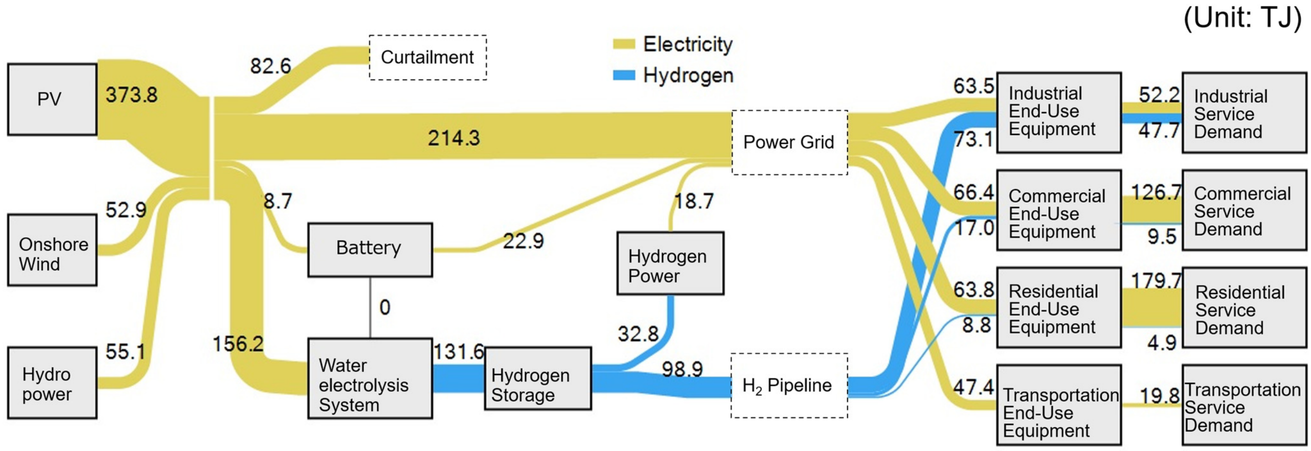
The primary factor for this difference in capacity lies in the method of hydrogen utilization. In the E case, the system must rely on power supply from batteries and hydrogen power generation to compensate for shortages in renewable energy generation. This necessitates large-scale hydrogen power generation facilities and large fuel reserves (hydrogen storage) to handle long-term fluctuations. In contrast, in the EH case, a portion of the energy service demand is satisfied directly by hydrogen. This reduces the amount of energy that must pass through the hydrogen power generation process for reconversion into electricity. Consequently, it will be possible to downsize the hydrogen power generation equipment, which will also lead to a reduction in the required hydrogen storage capacity.

4.4. Energy Flow

Figure 4 shows the annual energy flows for both cases. The primary structural difference between the two cases lies in the utilization pathway of the produced hydrogen.



(**a**)



(**b**)

Figure 4. Annual energy flow diagram (unit: TJ): (**a**) E case; (**b**) EH case.

In the E case, all produced hydrogen (106.0 TJ) is sent to hydrogen power generation for reconversion to electricity. This pathway incurs significant energy losses due to the two-stage conversion process consisting of water electrolysis and hydrogen power generation.

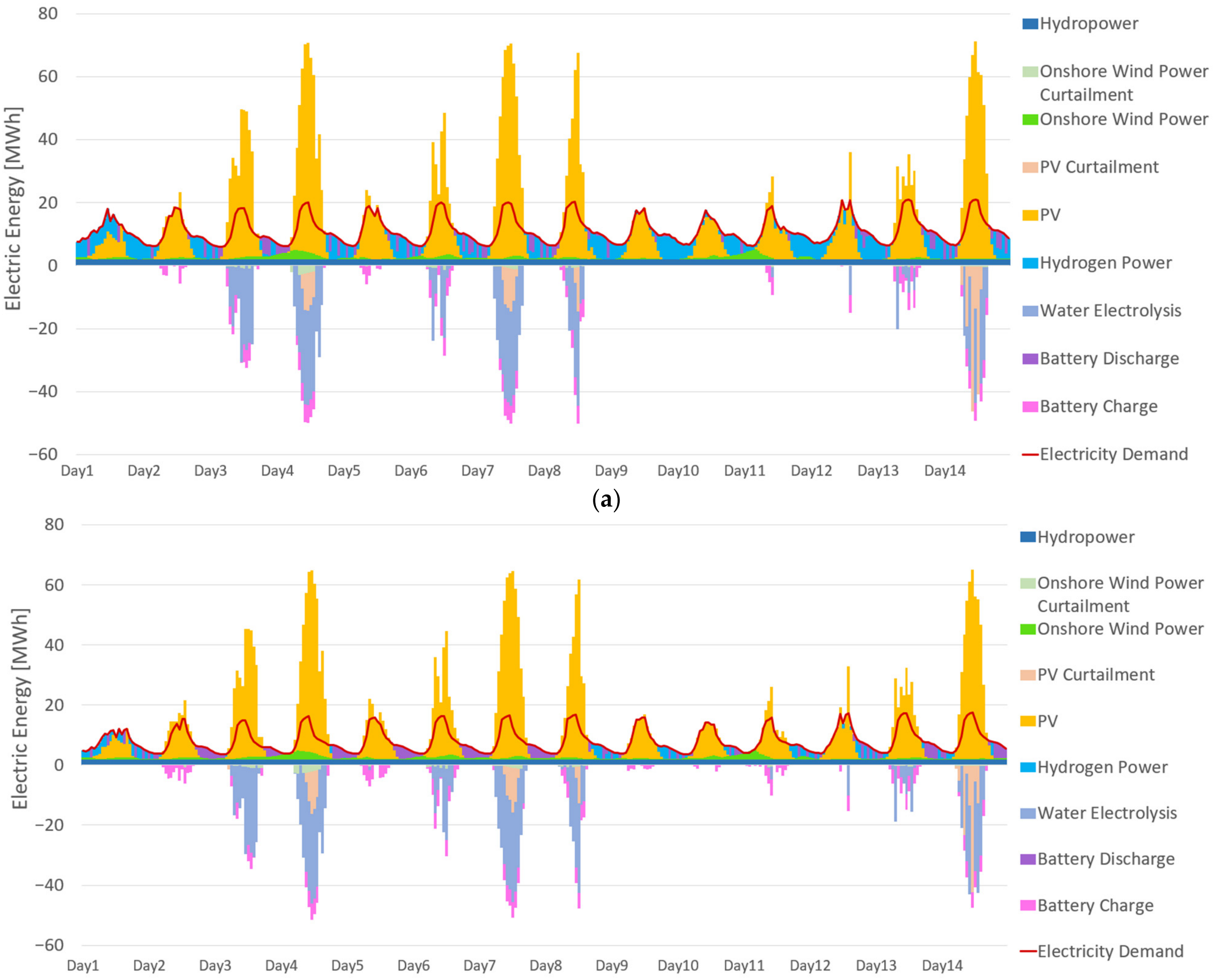
In contrast, in the EH case, approximately 75% (98.9 TJ) of the produced hydrogen is supplied directly to end-use equipment. The input allocated to the reconversion to electricity (via hydrogen power generation), which causes efficiency degradation, is limited to approximately 25% (32.8 TJ).

This difference in conversion efficiency is reflected in the required total annual electricity generation. To satisfy the same level of service demand, the total annual electricity generation required is 481.8 TJ in the EH case, compared to 521.5 TJ in the E case. The EH case succeeds in reducing the total generation by 39.8 TJ (7.6%), confirming that the direct utilization of hydrogen contributes to the effective use of surplus renewable energy and the reduces required installed capacities.

Furthermore, the amount of output curtailment is reduced by 18.6 TJ, from 101.2 TJ in the E case to 82.6 TJ in the EH case (18.4%). This demonstrates that the diversification of hydrogen applications allowed for more flexible absorption of VRE generation, thereby suppressing curtailment.

4.5. Hourly Electricity Supply–Demand Balance

Figure 5 shows the simulation results of the hourly electricity supply and demand balance for a 14-day period in July, which includes intervals of decreased VRE generation.



(**a**)

(**b**)

Figure 5. Hourly electricity supply–demand balance: (**a**) E case; (**b**) EH case.

In the E case, the system requires a hydrogen power generation capacity of 9.2 MW. The primary determinant of this capacity is the constraint requiring all energy service demands to be met solely by electricity. This leads to significant power deficits during periods of low VRE generation. Batteries are unsuitable for large-scale, long-duration power supply due to their high capital costs; conversely, hydrogen storage is economically advantageous for adjusting large-scale energy imbalances due to its low capital costs. Consequently, the E case system generates extensive hydrogen power during periods of VRE shortage.

In the EH case, the system downsizes the hydrogen power generation capacity through direct hydrogen supply and battery utilization. The rationale for this configuration is that the direct supply of hydrogen as the final energy for specific service demands reduces the overall electricity load, which consequently narrows the supply–demand gap during periods of low VRE generation. When the power deficit is small and manageable through short-cycle adjustments, the use of batteries is advantageous for minimizing energy losses due to their high round-trip efficiency of 80.0%. As a result, the role of hydrogen power generation in the EH case becomes limited, enabling the optimization and downsizing of facility capacities.

4.6. System Costs and Comparison with Conventional Energy Supply

Figure 6 shows the breakdown of annual costs, with the total annual cost of the E case normalized to 1. Compared to the E case's total cost of JPY 3.27 billion, the EH case achieved a cost reduction of 6.8% (JPY 3.05 billion). An analysis of the breakdown reveals that the largest contribution to the cost reduction comes from PV facilities, followed by hydrogen power generation and hydrogen storage facilities. The primary factor is that the direct utilization of hydrogen in the EH case significantly reduced the need for reconversion into electricity (via hydrogen power generation), which involves high energy losses.

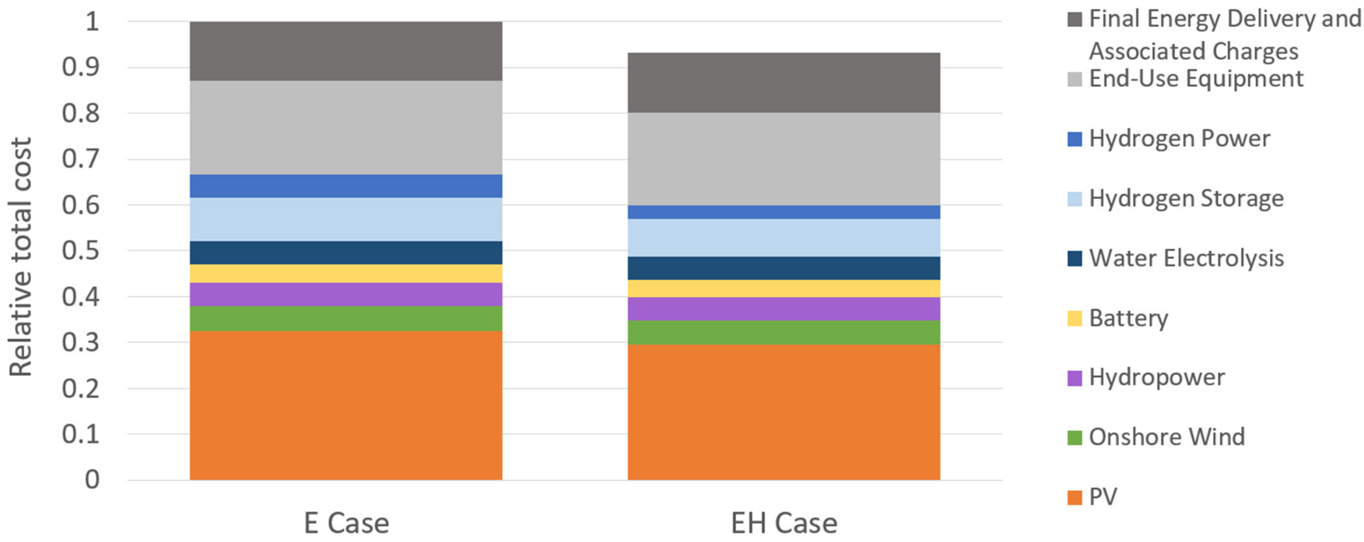


Figure 6. Breakdown of annual system costs normalized to the E case. The total normalized costs are 1.00 for the E case and 0.93 for the EH case. The specific contributions of each component (E case/EH case) are as follows: PV (32.5%/29.6%), onshore wind (5.5%/5.1%), hydropower (5.1%/5.1%), battery (4.1%/3.9%), water electrolysis (5.0%/5.0%), hydrogen storage (9.4%/8.1%), hydrogen power (5.1%/3.0%), end-use equipment (20.4%/20.3%), and final energy delivery and associated charges (12.9%/13.1%).

To provide a benchmark for comparison, we estimated the total annual cost assuming that all energy demands in each sector are met through external procurement via the power grid and natural gas (as a substitute for hydrogen). Based on 2023 unit prices from [26], this baseline cost was calculated to be approximately JPY 1.85 billion. For a valid comparison, we utilized the EH case's annual cost excluding end-use equipment costs, which amounts to JPY 2.39 billion. Comparing these figures, the proposed standalone system currently faces challenges regarding economic competitiveness against the conventional, fossil-fuel-dependent energy supply. However, this cost gap is expected to narrow in the future due to risks of fossil fuel price fluctuations and the impact of carbon pricing, which is anticipated to be fully implemented.

In addition, the CO_2 emission reduction effect was evaluated. Under the external procurement scenario, assuming that the same levels of electricity and heat demand are met using the current CO_2 emission factors for grid electricity and city gas [27], the annual CO_2 emissions are estimated at approximately 31.3 kt-CO_2. Therefore, the introduction of the proposed system is expected to contribute to an annual reduction of about 31.3 kt-CO_2.

4.7. Challenges and Risks with the Approach of 2035

While this study demonstrates the theoretical feasibility and economic rationality of a 100% renewable energy system in 2035, several challenges and risks must be addressed for its realization.

First, economic risks remain a significant barrier. Although the EH case reduces costs compared to the E case, the calculated energy cost is still higher than current market prices dependent on fossil fuels. Achieving competitiveness requires continuous cost reductions in renewable technologies and policy support such as carbon pricing.

Second, regarding infrastructure development, although Namie Town hosts the Fukushima Hydrogen Energy Research Field (FH2R) as a foundation for hydrogen production, the downstream infrastructure is underdeveloped. The proposed system assumes the widespread deployment of hydrogen distribution pipelines and hydrogen end-use technologies (e.g., hydrogen boilers). Constructing these new infrastructures to connect production sites with demand centers requires substantial lead time and investment.

Third, social acceptance and land regulations are essential. In the specific context of Namie Town, a significant portion of the renewable energy potential is located in areas affected by radioactive contamination (e.g., Difficult-to-Return Zones). Therefore, large-scale deployment requires not only consensus building with local residents regarding landscape preservation but also overcoming complex regulatory hurdles related to land use in these restricted areas.

Finally, regarding the transition pathway, in this study, we conducted a "snapshot analysis" focusing on the optimal state in the target year (2035). Moving from the current grid-connected power system to a standalone system involves technical and operational risks during the transition period. Future work should investigate stepwise development scenarios that integrate existing infrastructure with the gradual introduction of hydrogen technologies.

5. Conclusions

In this study, the effects of directly utilizing hydrogen as a final energy carrier were evaluated for a 100% renewable energy standalone energy system in Namie Town, Fukushima, in 2035. To achieve this, a model of the energy chains considering energy service demands was constructed, and a comparative analysis was performed between the E case and the EH case. The main findings obtained from this study are summarized in the following two points.

1. Optimization of facility capacities through appropriate role allocation between electricity and hydrogen: The appropriate allocation of roles between electricity and hydrogen in end-use technologies contributes to the optimization of generation and storage facility capacities. In the E case, 9.2 MW of hydrogen power generation capacity was required to compensate for shortages in renewable energy generation. In contrast, the EH case optimized the system by assigning complementary roles to batteries and hydrogen. Specifically, batteries were utilized for immediate supply–demand balancing, while hydrogen was prioritized for direct final use in applications such as industrial high-temperature boilers and cooking, where it avoids the significant energy losses associated with reconversion to electricity. This role differentiation suppressed the peak electricity demand in the EH case, leading to a reduction in hydrogen power generation capacity by approximately 41.3% compared to the E case.
2. Improvement of system efficiency and cost reduction by avoiding hydrogen power generation: The EH case demonstrates that prioritizing the direct utilization of hydrogen for specific final energy demands—such as industrial high-temperature boilers and cooking—improves overall system efficiency. By supplying hydrogen directly to these end-uses, the system avoids the substantial energy losses inherent in the reconversion

process. Consequently, the EH case reduced the total amount of renewable energy generation required to satisfy the same level of service demand by 7.6% compared to the E case. This improvement in energy conversion efficiency across the energy chains directly led to a 6.8% reduction in the total annual system cost, primarily through the downsizing of renewable energy- and hydrogen-related facilities.

Consequently, in a 100% renewable energy standalone regional energy system, utilizing hydrogen as an energy carrier that flexibly connects the demand and supply sides—rather than merely as a long-term electricity storage medium—is effective for achieving both decarbonization and economic efficiency. These findings demonstrate that the diversified application of hydrogen contributes significantly to the optimization of regional energy systems. Future research will evaluate system designs for regions with high energy density.

Finally, several limitations remain to be addressed to ensure the practical feasibility of the system. First, since this study presents a snapshot analysis of the 2035 target, future work must evaluate the transitional pathway from the current state and address structural changes in service demand driven by the town's reconstruction. Second, the current model does not explicitly account for reserve margins. Therefore, to enhance system robustness, it is crucial to incorporate detailed reliability analyses that account for equipment failures, forecast uncertainties, and long-term meteorological variations beyond the single-year dataset.

Author Contributions: Conceptualization, Y.M. and H.Y.; methodology, Y.M., K.S., and H.Y.; software, Y.M. and H.Y.; validation, K.S. and H.Y.; formal analysis, Y.M. and K.S.; investigation, Y.M. and K.S.; resources, H.Y.; data curation, Y.M. and K.S.; writing—original draft preparation, Y.M.; writing—review and editing, K.S. and H.Y.; visualization, Y.M.; supervision, H.Y.; project administration, H.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by a research grant from Tohoku Electric Power Co., Inc.

Data Availability Statement: The data presented in this study are available from the corresponding author upon reasonable request.

Acknowledgments: During the preparation of this manuscript, the authors used Gemini 3 (Google) for the purposes of summarizing draft text, translating Japanese drafts into English, generating the reference list, performing formatting checks, and generating and debugging the computer code used for the optimization model. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare that his study received funding from the organization mentioned in the "Funding" section. The funder had no role in the study design, data collection or analysis, decision to publish, or preparation of the manuscript.

Abbreviations

The following abbreviations are used in this manuscript:

BESS	Battery Energy Storage System
DR	Demand Response
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
HPWH	Heat Pump Water Heater
P2G	Power-to-Gas
PCS	Power Conversion System
PV	Photovoltaics
SoC	State of Charge
VRE	Variable Renewable Energy

References

1. Namie Town. Comprehensive Plan for Global Warming Countermeasures of Namie Town. Available online: https://www.town.namie.fukushima.jp/site/zcn-hydrogen/32846.html (accessed on 7 January 2026). (In Japanese)
2. Xiong, L.; Li, T.; Huang, S.; Li, P.; Wang, Z.; Sun, Z.; Niu, T. Optimized Sizing of ESSs in Non-Array Formed Wind Farm for Frequency Support Considering Multi-Directional Wake Effect. *IEEE Trans. Sustain. Energy*, **2025**; *early access*. [CrossRef]
3. Yamamoto, H.; Fujioka, H.; Okano, K. Cost analysis of stable electric and hydrogen energy supplies derived from 100% variable renewable resources systems. *Renew. Energy* **2021**, *178*, 1165–1173. [CrossRef]
4. Götz, M.; Lefebvre, J.; Mörs, F.; Koch, A.M.; Graf, F.; Bajohr, S.; Reimert, R.; Kolb, T. Renewable Power-to-Gas: A technological and economic review. *Renew. Energy* **2016**, *85*, 1371–1390. [CrossRef]
5. Komiyama, R.; Otsuki, T.; Fujii, Y. Energy modeling and analysis for optimal grid integration of large-scale variable renewables using hydrogen storage in Japan. *Energy* **2015**, *81*, 537–555. [CrossRef]
6. Laimon, M.; Yusaf, T. Towards energy freedom: Exploring sustainable solutions for energy independence and self-sufficiency using integrated renewable energy-driven hydrogen system. *Renew. Energy* **2024**, *222*, 119948. [CrossRef]
7. Lund, H.; Østergaard, P.A.; Connolly, D.; Mathiesen, B.V. Smart energy and smart energy systems. *Energy* **2017**, *137*, 556–568. [CrossRef]
8. Yamamoto, H. Estimation of the Effects of Electrification and Demand Response of Electric Appliances Using a Model Considering Japan's Energy Chains. *J. Jpn. Soc. Energy Resour.* **2019**, *40*, 220–231. (In Japanese) [CrossRef]
9. Yamamoto, H.; Bando, S.; Sugiyama, M. Development of a Power Generation Mix Model Considering Multiple Operation Modes and the Load Frequency Control Capacity of Thermal Power Plants. *CRIEPI Res. Rep.* **2013**, *Y12030*, 1–46. (In Japanese)
10. New Energy and Industrial Technology Development Organization (NEDO). Solar Radiation Database Web Application. Available online: https://appww2.infoc.nedo.go.jp/appww/index.html (accessed on 5 January 2025). (In Japanese)
11. Japan Meteorological Agency. Historical Weather Data Download. Available online: https://www.data.jma.go.jp/risk/obsdl/ (accessed on 5 January 2025). (In Japanese)
12. Staffell, I.; Pfenninger, S. Renewables.ninja. Available online: https://www.renewables.ninja/ (accessed on 5 January 2025).
13. Staffell, I.; Pfenninger, S. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy* **2016**, *114*, 1224–1239. [CrossRef]
14. Agency for Natural Resources and Energy. List of Specifications for Each Power Source. Available online: https://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/index.html (accessed on 5 August 2025). (In Japanese)
15. Agency for Natural Resources and Energy. Energy Consumption Statistics by Prefecture. Available online: https://www.enecho.meti.go.jp/statistics/energy_consumption/ec001/ (accessed on 5 August 2025). (In Japanese)
16. Shimura, H.; Yamamoto, H. Analysis of Energy Chains in Eastern Japan Considering Regional Maldistribution of Renewable Energy Sources and Transmission Line Capacity. In Proceedings of the 41st Conference on Energy, Systems, Economics and Environment, Tokyo, Japan, 28–29 January 2025; No. 2–3. (In Japanese)
17. Ministry of Economy, Trade and Industry. 2010 Census of Manufactures—Report by Municipality and Industrial Classification. Available online: https://www.e-stat.go.jp/stat-search/database?statdisp_id=0003094938 (accessed on 5 August 2025). (In Japanese)
18. Statistics Bureau of Japan. 2010 Population Census—Basic Complete Tabulation on Industry. Available online: https://www.e-stat.go.jp/stat-search/database?statdisp_id=0003052127 (accessed on 5 August 2025). (In Japanese)
19. Statistics Bureau of Japan. 2010 Population Census—Basic Complete Tabulation on Population and Households. Available online: https://www.e-stat.go.jp/stat-search/database?statdisp_id=0003038586 (accessed on 5 August 2025). (In Japanese)
20. Namie Town. Town, People, and Job Revitalization Comprehensive Strategy for Namie Town (2nd Phase). Available online: https://www.town.namie.fukushima.jp/soshiki/2/12325.html (accessed on 5 August 2025). (In Japanese)
21. Suda, R.; Oka, T. Analysis of Hot Water Supply Load and Simultaneous Use of Hot Water for Urban Collective Housing Based on Field Measurement. *Trans. Soc. Heat. Air-Condit. Sanit. Eng. Jpn.* **2001**, *80*, 49–58. (In Japanese) [CrossRef]
22. Heat Pump & Thermal Storage Technology Center of Japan (HPTCJ). Hourly Load Patterns by Industry. Available online: https://www.hptcj.or.jp/technical/point/hot_water_supply/ (accessed on 5 August 2025). (In Japanese)
23. Hasegawa, I.; Otsuka, M.; Murakami, S. Study on Development of a Hot Water Supply System Simulation Tool for Calculating Energy Saving Performance Considering Load Fluctuations: Development of Calculation Method and Application to Resource and Energy Saving Design. *Trans. Soc. Heat. Air-Condit. Sanit. Eng. Jpn.* **2022**, *306*, 23–32. (In Japanese)
24. Statistics Bureau of Japan; Ministry of Economy, Trade and Industry. 2009 Economic Census for Business Frame. Available online: https://www.e-stat.go.jp/stat-search/files?tclass=000001035251&cycle=0 (accessed on 5 August 2025). (In Japanese)
25. Miyazaki, S.; Yanagawa, Y. Automated Scheduling for Gas Stations. *J. Jpn. Soc. Prod. Manag.* **2006**, *12*, 85–91. (In Japanese) [CrossRef]

26. Energy Data and Modelling Center (EDMC), The Institute of Energy Economics, Japan (IEEJ). *EDMC Handbook of Energy & Economic Statistics in Japan 2025*; IEEJ: Tokyo, Japan, 2025. (In Japanese)
27. Ministry of the Environment. GHG Emissions Accounting, Reporting and Disclosure System: List of Calculation Methods and Emission Factors. Available online: https://policies.env.go.jp/earth/ghg-santeikohyo/calc.html (accessed on 12 February 2026). (In Japanese)