

## Article

# System-Level Dynamic Modeling and Cross-Domain Disturbance Propagation of an Electricity–Hydrogen–Heat Coupling Subsystem for Integrated Transportation Hubs

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## Abstract

Integrated transportation hubs are characterized by fast-varying and strongly coupled electricity, hydrogen-refueling, and thermal demands driven by traffic activities. To characterize their short-term dynamic interactions, this paper develops a compact system-level model of a core electricity–hydrogen–heat coupling subsystem comprising a PEM electrolyzer, a hydrogen storage tank, a fuel cell, and a thermal side. Power- and temperature-dependent off-design models are established for the PEM electrolyzer and fuel cell, while a lumped-parameter thermodynamic model with real-gas correction is developed for the hydrogen storage tank. The electrolyzer and fuel-cell models achieve calibration MAPEs of 0.39% and approximately 0.81%, respectively, against published reference data. Two typical disturbance scenarios are then investigated. Under a 30 kW electrical-load step, the grid-power deviation is reduced from a peak of approximately 29.4 kW to about 9.1 kW, while the hydrogen-refueling-demand disturbance produces only a minor thermal-side temperature variation. The results reveal distinct propagation magnitudes and time-scale characteristics across the electrical, hydrogen, and thermal domains. The proposed framework provides a compact and physically interpretable tool for short-term cross-domain dynamic analysis of integrated transportation hubs.

**Keywords:** integrated transportation hub; electricity–hydrogen–heat coupling; PEM electrolyzer; hydrogen storage tank; fuel cell; dynamic modeling



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## 1. Introduction

Integrated energy systems (IESs) coordinate multiple energy carriers, such as electricity, hydrogen, and heat, and provide an effective pathway for improving renewable-energy utilization, operational flexibility, and supply resilience [1–3]. With the development of hydrogen technologies, electrolyzers, hydrogen storage units, and fuel cells have gradually become key links connecting electricity, hydrogen, and heat networks, making electricity–hydrogen–heat coupling systems an important research direction in IESs [4–7]. Recent studies have investigated electricity–hydrogen–heat integrated energy systems from the perspectives of optimal scheduling, source–load coordination, low-carbon operation, and

fuel-cell waste heat recovery [8,9]. However, most of these studies mainly focus on economic dispatch and low-carbon optimization, while the short-term dynamic propagation of disturbances among electricity, hydrogen, and heat remains insufficiently addressed.

As energy and transportation systems become increasingly integrated, integrated transportation hubs are becoming important terminal scenarios for multi-energy coupling applications. Airports, high-speed railway stations, urban rail transit transfer centers, and comprehensive passenger terminals involve not only conventional electrical and thermal demands for lighting, ventilation, information equipment, and station operation, but also emerging energy-service demands such as electric-vehicle charging and hydrogen refueling [10,11]. Transportation hubs involve large-scale, time-varying, and multi-energy demands, making dynamic electricity–hydrogen–heat modeling necessary for short-term disturbance propagation analysis.

Existing studies provide useful foundations for electricity–hydrogen–heat system modeling. Zeng et al. incorporated PEM electrolyzer dynamic temperature and pipeline-network heat storage into a scheduling-oriented electricity–hydrogen–heat model [12]. Nevertheless, these studies are primarily oriented toward day-ahead scheduling or economic operation analysis, and the dynamic transmission path of traffic-driven electrical-load and hydrogen-refueling disturbances through the electrolyzer, hydrogen storage tank, fuel cell, and thermal side has not been sufficiently clarified.

Unlike previous studies focusing mainly on day-ahead scheduling or steady-state optimization, this study investigates seconds-to-minutes disturbance propagation across electricity, hydrogen, and heat networks in integrated transportation hubs. A compact system-level dynamic framework is developed with three main contributions. First, power- and temperature-dependent off-design models are established for the PEM electrolyzer and fuel cell to represent efficiency and heat-release variations under non-rated conditions. Second, a lumped thermodynamic hydrogen-storage model incorporating mass and energy conservation and real-gas effects is formulated to capture the coupling among hydrogen mass, temperature, and pressure. Third, the component models are integrated into a unified nonlinear state-space framework to analyze typical cross-domain disturbances and assess the effects of the electrolyzer regulation coefficient and initial hydrogen storage level on system dynamics.

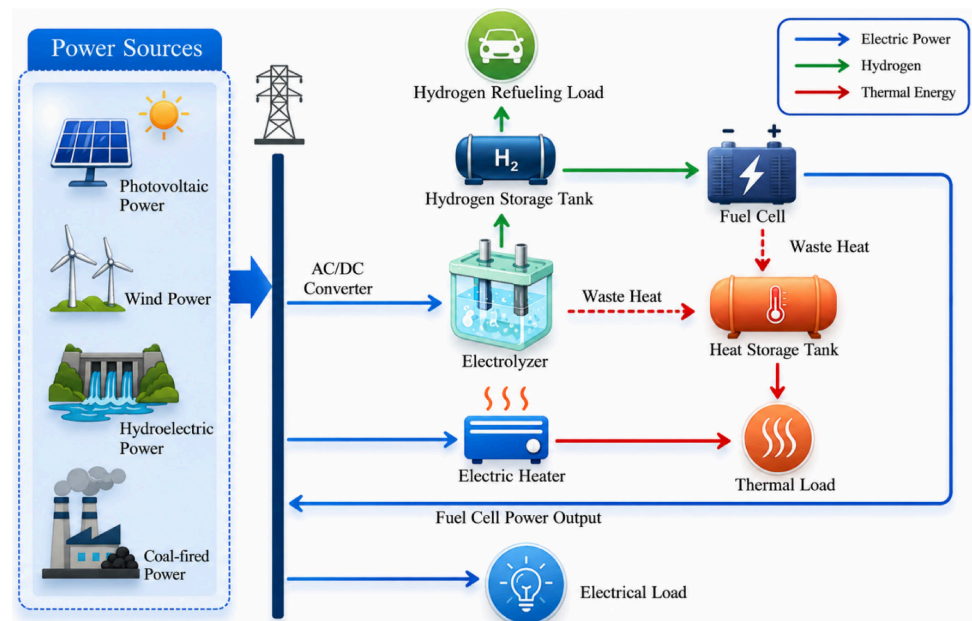
## 2. System Construction and Assumptions

### 2.1. Electricity–Hydrogen–Heat Coupling Chain in an Integrated Transportation Hub

As shown in Figure 1, the subsystem includes an external power grid; a PEM electrolyzer; a hydrogen storage tank; a fuel cell; a waste-heat recovery unit; and terminal electrical, hydrogen-refueling, and thermal loads. The electrolyzer and fuel cell serve as bidirectional coupling devices between electricity, hydrogen, and heat, while the hydrogen storage tank provides short-term buffering for hydrogen imbalance. The typical load types considered in this study are summarized in Table 1.

**Table 1.** Typical energy-use scenarios in integrated transportation hubs.

| Load Type               | Symbol           | Description                                                                                                                                          |
|-------------------------|------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| Electrical load         | $P_L$            | Comprehensive electrical demand of the transportation hub, including lighting, ventilation, information equipment, and traffic-service-related loads |
| Hydrogen refueling load | $\dot{m}_{load}$ | Hydrogen demand caused by external refueling services                                                                                                |
| Thermal load            | $Q_L$            | Station heating, domestic hot water, and other auxiliary thermal demands                                                                             |



**Figure 1.** Energy system diagram of integrated transportation hub.

## 2.2. Model Assumptions and Study Scope

To balance model fidelity and computational efficiency, several simplifying assumptions are adopted. The electrical subsystem is represented as an aggregated coupling bus, while voltage/frequency dynamics, line-flow constraints, converter losses, and electromagnetic transients are not modeled separately. System-level equivalent models are used for the PEM electrolyzer and fuel cell without explicitly resolving microscopic electrochemical processes. The hydrogen storage tank is treated as a lumped control volume with uniform gas temperature, neglecting spatial temperature gradients and internal flow details, while the thermal subsystem is represented by a first-order lumped model. Accordingly, the proposed framework is intended for seconds-to-minutes cross-domain disturbance analysis rather than detailed electrical-network, electrochemical, or spatial thermal studies.

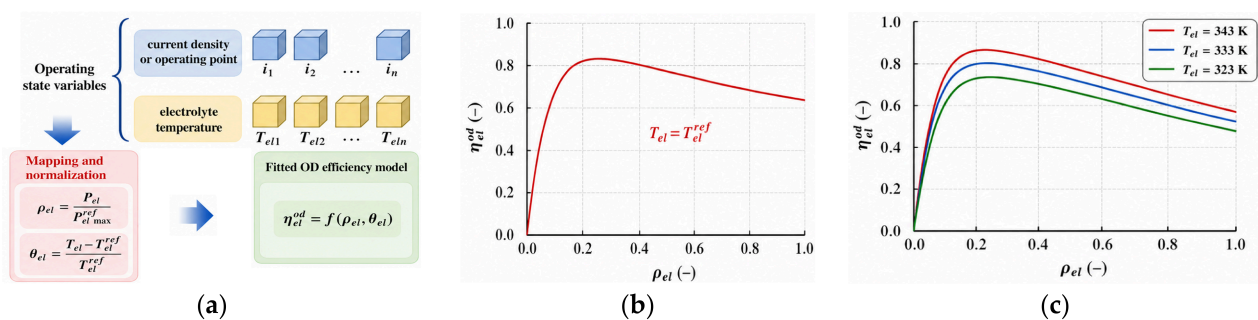
## 3. Modeling of Key Equipment and Coupling System

### 3.1. PEM Electrolyzer Modeling Framework

Existing PEM electrolyzer models can generally be divided into system-level simplified models and mechanistic or semi-empirical models. Simplified models usually describe the relationship between electrical power input and hydrogen production using constant efficiency or linear conversion coefficients, which makes them convenient for integrated energy system scheduling and steady-state analysis [13–15]. However, these models cannot adequately capture the variations in hydrogen production efficiency and heat generation under off-design conditions, especially the effects of operating power and temperature on the conversion process.

Mechanistic and semi-empirical models further consider electrochemical polarization, membrane conduction, temperature, pressure, and mass balance processes. Dale et al. expressed the cell voltage as the sum of reversible voltage and different overpotential terms, Awasthi et al. developed a dynamic PEM electrolyzer model to analyze temperature- and pressure-dependent characteristics, and Yigit and Selamet investigated the dynamic response of high-pressure PEM electrolysis systems [16–18]. These models provide stronger physical interpretability, but they require many parameters and are difficult to directly embed into the system-level dynamic coupling analysis considered in this study.

A trade-off between model fidelity and computational complexity is therefore necessary. Previous studies have shown that PEM electrolyzer efficiency is closely related to current density, temperature, and membrane characteristics [19,20]. Since current density and detailed electrochemical parameters are often difficult to obtain in integrated energy system applications, they can be mapped to system-level variables such as per-unit input power and equivalent temperature. Xiong et al. further demonstrated that the electrolyzer input–output power relationship can be well approximated over a wide operating range, while electrolyte temperature introduces an overall shift in the conversion relationship [21]. Building on this insight, the present study retains input power and electrolyte temperature as the two key state variables and establishes a simplified off-design PEM electrolyzer model suitable for dynamic analysis of the electricity–hydrogen–heat coupling subsystem. Figure 2a illustrates the mapping process from operating state variables to normalized fitting variables adopted in this paper; Figure 2b shows that there is a clear fitting relationship between electrolyzer efficiency and per-unit input power at the reference temperature; Figure 2c further demonstrates that the efficiency–per-unit power curve shifts under different temperature conditions. Therefore, the per-unit input power and temperature deviation are introduced into the system-level model to achieve a balance between model compactness and state-variable representability.



**Figure 2.** Modeling framework of the PEM electrolyzer. (a) Variable mapping and normalization procedure; (b) relationship between  $\eta_{el}^{od}$  and  $\rho_{el}$  at the reference temperature; (c) fitted curves of  $\eta_{el}^{od}$  versus  $\rho_{el}$  under different temperatures.

The per-unit input power of the electrolyzer is defined as

$$\rho_{el} = \frac{P_{el}}{P_{el}^{max}} \quad (1)$$

The electrolyte temperature deviation term is defined as

$$\theta_{el} = \frac{T_{el} - T_{el}^{ref}}{T_{el}^{ref}} \quad (2)$$

where  $P_{el}$  denotes the actual input power of the electrolyzer,  $P_{el}^{max}$  is the rated input power of the electrolyzer,  $T_{el}$  represents the equivalent temperature of the electrolyte, and  $T_{el}^{ref}$  is the reference temperature.

The off-design (OD) efficiency of the PEM electrolyzer is expressed as a simplified fitting form consisting of a power term and a temperature term:

$$\eta_{el}^{od} = \eta_{el,0} + \alpha_{el}\rho_{el} + \gamma_{el}\rho_{el}^2 + \beta_{el}\theta_{el} \quad (3)$$

where  $\eta_{el,0}$  is the baseline efficiency under reference operating conditions;  $\alpha_{el}$  and  $\gamma_{el}$  are the linear and quadratic coefficients of the power term, respectively, capturing the nonlinear

dependence of efficiency on operating load; and  $\beta_{el}$  is the temperature term coefficient, representing the efficiency shift induced by electrolyte temperature deviation. Accordingly, the hydrogen production rate of the electrolyzer can be expressed as

$$\dot{m}_{el} = \frac{\eta_{el}^{od} P_{el}}{LHV_{H_2}} \quad (4)$$

where  $\dot{m}_{el}$  is the hydrogen production rate of the electrolyzer, and  $LHV_{H_2}$  represents the lower heating value of hydrogen.

A first-order inertia link is adopted to describe the dynamic response of input power:

$$T_{el,p} \frac{dP_{el}}{dt} + P_{el} = P_{el}^{ref} \quad (5)$$

or equivalently:

$$\dot{P}_{el} = \frac{1}{T_{el,p}} (P_{el}^{ref} - P_{el}) \quad (6)$$

where  $P_{el}^{ref}$  is the reference power command of the electrolyzer, and  $T_{el,p}$  denotes the power dynamic time constant of the electrolyzer. This formulation is used to characterize the dynamic lag between the control command and the actual operating power of the device.

A lumped-parameter heat balance equation is adopted to describe the electrolyte temperature dynamics. The input power drives the electrolysis reaction and generates heat, part of which is lost to the environment through thermal resistance, and part is transferred to the thermal side:

$$C_{el} \frac{dT_{el}}{dt} = P_{el} - \dot{m}_{el} LHV_{H_2} - \frac{T_{el} - T_a}{R_{el}} - Q_{el} \quad (7)$$

where  $C_{el}$  is the equivalent heat capacity of the electrolyzer,  $R_{el}$  denotes the equivalent thermal resistance of the electrolyzer,  $T_a$  is the ambient temperature, and  $Q_{el}$  represents the thermal power released by the electrolyzer to the thermal side.

The heat released by the electrolyzer to the thermal side is no longer simply fixed as a certain proportion of the input power but depends on the temperature difference between the electrolyte and the thermal side:

$$Q_{el} = k_{hex,el} (T_{el} - T_h) \quad (8)$$

where  $k_{hex,el}$  is the equivalent heat transfer coefficient between the electrolyzer and the thermal side, and  $T_h$  is the equivalent temperature of the thermal side. With the consideration of temperature state, the heat release and storage processes exhibit higher regulation flexibility.

### 3.2. Hydrogen Storage Tank Model

In integrated energy system studies, hydrogen storage tanks are commonly described using simplified mass-balance models, in which the stored hydrogen level is updated according to charging and discharging flows, and the pressure–mass relationship is corrected using a compressibility factor. Such models are compact and easy to integrate, but they cannot fully characterize the dynamic coupling among mass, temperature, and pressure under high-pressure hydrogen storage conditions.

More detailed thermodynamic models usually treat the hydrogen tank as a control volume and describe the charging and discharging processes based on mass conservation, energy conservation, heat transfer, and real-gas state equations. Hosseini et al. analyzed compressed hydrogen storage from a thermodynamic perspective, Hu et al. developed

a thermodynamic model for hydrogen storage systems in refueling stations, and Li et al. pointed out that the selection of the state equation and the description of tank-wall heat transfer are crucial for high-pressure hydrogen storage modeling [22–24]. In addition, the choice of real-gas state equation affects the calculation accuracy of pressure and temperature during fast filling processes [25].

Overall, simplified models are convenient for system-level applications but have limited physical fidelity, whereas complete thermodynamic models provide higher accuracy but involve greater parameter complexity. Following a similar rationale, a lumped-parameter thermodynamic model is adopted for the hydrogen storage tank. Mass conservation, energy conservation, heat exchange, and a real-gas-corrected state equation are retained to describe the main coupling relationship among stored hydrogen mass, average temperature, and pressure, while spatial temperature distribution and internal flow details are neglected.

Let  $m_H$  denote the hydrogen storage mass in the tank; then, the mass conservation equation can be expressed as

$$\frac{dm_H}{dt} = \dot{m}_{el} - \dot{m}_{fc} - \dot{m}_{load} \quad (9)$$

where  $\dot{m}_{fc}$  denotes the hydrogen consumption rate of the fuel cell.

According to the energy conservation relationship of open systems, the energy balance of hydrogen in the storage tank can be expressed as

$$\frac{d(m_H u_H)}{dt} = \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out} + Q_H \quad (10)$$

where  $u_H$  is the specific internal energy of hydrogen in the storage tank,  $h_{in}$  and  $h_{out}$  are the specific enthalpies of hydrogen entering and leaving the storage tank, respectively, and  $Q_H$  is the heat exchange power between the hydrogen in the storage tank and the tank wall or the environment.

The thermal state of hydrogen in the storage tank is affected not only by the enthalpy flow during hydrogen charge and discharge but also by the heat exchange process with the outside. In this paper, the heat exchange power is further equivalently expressed as

$$Q_H = U_H A_H (T_w - T_H) \quad (11)$$

where  $U_H A_H$  is the equivalent heat transfer parameter of the hydrogen storage tank,  $T_w$  is the tank wall temperature, and  $T_H$  is the average temperature of hydrogen in the storage tank. For the present system-level simulations, the tank-wall temperature is approximated by the ambient temperature as a first-order thermal boundary condition. This approximation neglects the transient thermal storage of the tank wall and is therefore intended for moderate short-term hydrogen-flow variations rather than high-rate fast-filling processes.

The above energy conservation relationship is further rearranged into the dynamic form of average temperature:

$$m_H c_{v,H} \frac{dT_H}{dt} = \dot{m}_{in} (h_{in} - u_H) - \dot{m}_{out} (h_{out} - u_H) + U_H A_H (T_w - T_H) \quad (12)$$

where  $c_{v,H}$  is the constant-volume specific heat capacity of hydrogen. Combined with the mass flow rate expression, it can be further written as

$$m_H c_{v,H} \frac{dT_H}{dt} = \dot{m}_{el} (h_{in} - u_H) - (\dot{m}_{fc} + \dot{m}_{load}) (h_{out} - u_H) + U_H A_H (T_w - T_H) \quad (13)$$

To characterize the relationship between hydrogen storage pressure, hydrogen storage mass and hydrogen storage temperature, this paper adopts a real-gas-corrected state equation, which is expressed as

$$p_H = \frac{Z_H m_H R_H T_H}{V_H} \quad (14)$$

where  $V_H$  is the effective volume of the hydrogen storage tank,  $R_H$  is the gas constant of hydrogen, and  $Z_H$  is the compressibility factor. When the operating range is narrow,  $Z_H$  can be approximately characterized by a constant value or a piecewise fitting method.

To retain the computational efficiency and algebraic solvability required for system-level dynamic simulation, the hydrogen compressibility factor is approximated as a linear function of normalized pressure and temperature. The normalized variables are defined as

$$\bar{p}_H = \frac{p_H}{p_{\text{ref}}}, \bar{T}_H = \frac{T_H - T_{\text{ref}}}{\Delta T_{\text{ref}}}, \quad (15)$$

where  $p_{\text{ref}} = 1 \text{ MPa}$ ,  $T_{\text{ref}} = 320 \text{ K}$ , and  $\Delta T_{\text{ref}} = 20 \text{ K}$ . The compressibility factor is then expressed as

$$Z_H = a_0 + a_1 \bar{p}_H + a_2 \bar{T}_H, \quad (16)$$

where  $a_0$ ,  $a_1$ , and  $a_2$  are dimensionless fitting coefficients obtained by least-squares fitting to compressibility-factor data generated using the Redlich–Kwong equation over the specified pressure–temperature range. Since the pressure and temperature variables are normalized, all fitting coefficients are dimensionless. The approximation is applied only within the investigated operating range and is not intended for extrapolation to substantially different thermodynamic conditions. Its accuracy is further evaluated against the Peng–Robinson equation in Section 5.1.

The Peng–Robinson equation is subsequently employed as an independent thermodynamic benchmark to assess the accuracy of the proposed algebraic approximation [25].

Capacity constraints are set for the hydrogen storage tank:

$$m_H^{\min} \leq m_H \leq m_H^{\max} \quad (17)$$

where  $m_H^{\min}$  and  $m_H^{\max}$  denote the minimum and maximum allowable hydrogen storage mass of the tank, respectively.

Pressure constraints are set as follows:

$$p_H^{\min} \leq p_H \leq p_H^{\max} \quad (18)$$

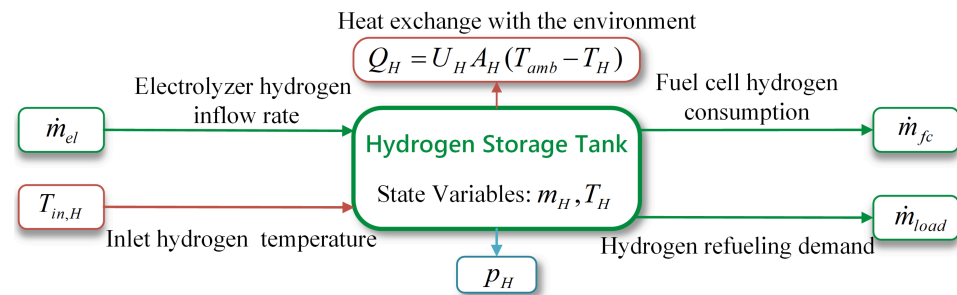
where  $p_H^{\min}$  and  $p_H^{\max}$  denote the minimum and maximum allowable operating pressure of the tank, respectively.

Considering that the hydrogen charge and discharge processes of the storage tank are limited by equipment capacity, this paper further sets constraints on the hydrogen charge and discharge rates:

$$\begin{cases} 0 \leq \dot{m}_{in} \leq \dot{m}_{in}^{\max} \\ 0 \leq \dot{m}_{out} \leq \dot{m}_{out}^{\max} \end{cases} \quad (19)$$

where  $\dot{m}_{in}^{\max}$  and  $\dot{m}_{out}^{\max}$  denote the maximum hydrogen charge rate and maximum hydrogen discharge rate, respectively.

A schematic diagram of the lumped-parameter thermodynamic model of the hydrogen storage tank is shown in Figure 3.



**Figure 3.** Schematic diagram of the lumped-parameter thermodynamic model of the hydrogen storage tank. Green denotes hydrogen mass-flow-related variables and paths, red denotes thermal variables and heat-transfer paths, and blue denotes the tank-pressure variable.

### 3.3. Mathematical Formulation of Fuel-Cell Model

Fuel-cell models in integrated energy system studies can also be classified into system-level simplified models and more detailed thermodynamic or mechanistic models. Simplified models usually describe fuel cells using fixed electrical efficiency or fixed heat-to-power ratios, which makes them suitable for economic dispatch and energy-hub-based optimization [26,27]. However, these models generally neglect efficiency variations under different load and temperature conditions and cannot accurately describe the coupling between electrical output and recoverable heat.

Several studies have further investigated the combined heat and power characteristics and waste heat recovery potential of fuel cells. Zhan et al. considered fuel-cell waste heat recovery in the scheduling of a wind–photovoltaic–hydrogen energy system, Pourrahmani et al. analyzed the dynamic response of an integrated fuel cell and battery system, and Evrin and Dincer evaluated the energy and exergy performance of a hydrogen fuel-cell system [9,28,29]. These studies indicate that fuel cells are not only electricity conversion devices but can also serve as thermal-side coupling sources in integrated energy systems.

From the mechanistic perspective, Fu et al. showed that PEMFC electrical and thermal outputs exhibit clear nonlinear coupling under different operating currents and temperatures, indicating that static efficiency or fixed heat-to-power-ratio models are insufficient for representing actual operating behavior [30]. Therefore, this study adopts a system-level off-design fuel-cell model, retaining output power and equivalent temperature as key variables to describe efficiency deviation, hydrogen consumption, and recoverable heat output. This enables the fuel cell to be integrated with the electrolyzer, hydrogen storage tank, and thermal side within a unified electricity–hydrogen–heat dynamic framework.

The fuel-cell electrical output increases with hydrogen input power, but the incremental gain gradually diminishes. In addition, the effect of temperature becomes more pronounced at higher operating power. The per-unit output power of the fuel cell is defined as

$$\rho_{fc} = \frac{P_{fc}}{P_{fc}^{max}} \quad (20)$$

The equivalent temperature deviation term of the fuel cell is defined as

$$\theta_{fc} = \frac{T_{fc} - T_{fc}^{ref}}{T_{fc}^{ref}} \quad (21)$$

where  $P_{fc}$  denotes the actual output power of the fuel cell,  $P_{fc}^{max}$  is the rated output power of the fuel cell,  $T_{fc}$  represents the equivalent temperature of the fuel cell, and  $T_{fc}^{ref}$  is the reference temperature.

On this basis, the off-design electric efficiency of the fuel cell is expressed as

$$\eta_{fc}^{od} = \eta_{fc,0} + c_1 \rho_{fc} + c_2 \rho_{fc}^2 + d_1 \theta_{fc} + d_2 \rho_{fc} \theta_{fc} \quad (22)$$

where  $\eta_{fc,0}$  is the baseline electric efficiency under reference operating conditions;  $c_1$  and  $c_2$  are the linear and quadratic power term coefficients, respectively, which are used to describe the nonlinear efficiency variation under different load levels;  $d_1$  is the temperature term coefficient, which characterizes the direct impact of temperature deviation on efficiency;  $d_2$  is the power–temperature cross term coefficient, which captures how temperature variations modulate the efficiency deviation under different load levels.

The hydrogen consumption rate of the fuel cell can be expressed as

$$\dot{m}_{fc} = \frac{P_{fc}}{\eta_{fc}^{od} LHV_{H_2}} \quad (23)$$

where  $\dot{m}_{fc}$  is the hydrogen consumption rate of the fuel cell.

To describe the dynamic tracking process of the fuel cell to power commands, this paper also adopts a first-order inertia link to represent its output power dynamic:

$$T_{fc,p} \frac{dP_{fc}}{dt} + P_{fc} = P_{fc}^{ref} \quad (24)$$

or equivalently:

$$\dot{P}_{fc} = \frac{1}{T_{fc,p}} (P_{fc}^{ref} - P_{fc}) \quad (25)$$

where  $P_{fc}^{ref}$  is the reference output power command of the fuel cell, and  $T_{fc,p}$  is the power dynamic time constant of the fuel cell.

In this paper, the difference between the chemical energy input and the electric power output of the fuel cell is regarded as the total heat release:

$$Q_{fc}^{gen} = \dot{m}_{fc} LHV_{H_2} - P_{fc} \quad (26)$$

where  $Q_{fc}^{gen}$  is the total heat generation power of the fuel cell. Furthermore, to describe the coupling process between the fuel cell and the thermal side, an equivalent heat transfer relationship is adopted to represent the recoverable waste heat output:

$$Q_{fc} = k_{hex,fc} (T_{fc} - T_h) \quad (27)$$

where  $k_{hex,fc}$  is the equivalent heat transfer coefficient between the fuel cell and the thermal side,  $T_h$  is the equivalent temperature of the thermal side (consistent with the definition in the electrolyzer model), and  $Q_{fc}$  is the recoverable thermal power released by the fuel cell to the thermal side.

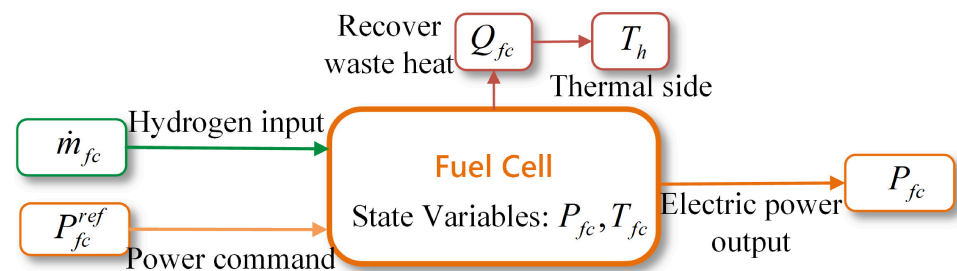
On this basis, the dynamics of the fuel-cell equivalent temperature can be given by the lumped-parameter heat balance equation:

$$C_{fc} \frac{dT_{fc}}{dt} = Q_{fc}^{gen} - Q_{fc} - \frac{T_{fc} - T_a}{R_{fc}} \quad (28)$$

where  $C_{fc}$  is the equivalent heat capacity of the fuel cell,  $R_{fc}$  is the equivalent thermal resistance of the fuel cell, and  $T_a$  is the ambient temperature. The first term on the right side of the equation represents the total heat generated during the power generation process of

the fuel cell, the second term represents the recoverable heat released to the thermal side, and the third term represents the heat loss dissipated to the environment.

The modeling framework of the fuel cell is illustrated in Figure 4.



**Figure 4.** Schematic diagram of the thermoelectric coupling model of the fuel cell. Color coding: green denotes hydrogen input, orange denotes electrical power and power commands, and red denotes recoverable waste heat and thermal-side variables.

### 3.4. Thermal Side Model Formulation

Compared with the electrical side, the thermal side exhibits considerably greater inertia, which provides inherent buffering against short-term demand fluctuations. Its dynamic evolution is governed by three factors: the equivalent heat capacity of the system, the waste heat supplied by the electrolyzer and fuel cell, and the thermal load demand.

Let  $T_h$  denote the equivalent temperature state of the thermal side, and  $C_h$  denote its equivalent heat capacity, then the dynamic equation of the thermal side can be expressed as

$$C_h \frac{dT_h}{dt} = Q_{el} + Q_{fc} - Q_L - k_{loss}(T_h - T_{env}) \quad (29)$$

In this system-level formulation,  $T_h$  denotes the equivalent average temperature of the thermal subsystem rather than the temperature at a specific physical location.  $C_h$  represents the aggregated thermal capacitance of the heat-transfer medium and thermally active components, while  $k_{loss}$  characterizes the equivalent heat loss from the thermal subsystem to the ambient environment. These parameters are treated as lumped nominal parameters for the present numerical study, and the model is intended to capture the dominant first-order thermal inertia rather than spatial temperature distributions or detailed heat-exchanger dynamics.

The dynamic variation of the thermal side state is jointly determined by waste heat input and thermal load consumption.

## 4. Construction of Unified Electricity–Hydrogen–Heat Coupling Model

Drawing on the component models developed in Sections 3.1–3.4, the electricity–hydrogen–heat coupling subsystem is cast into a unified nonlinear state-space representation:

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ (x_5) \\ x_6 \\ x_7 \end{bmatrix} = \begin{bmatrix} P_{el} \\ T_{el} \\ P_{fc} \\ T_{fc} \\ m_H \\ T_H \\ T_h \end{bmatrix} \quad (30)$$

The reference powers of the electrolyzer and the fuel cell are taken as the system control inputs, and the input vector is defined as

$$u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} P_{el}^{ref} \\ P_{fc}^{ref} \end{bmatrix} \quad (31)$$

The external load variations under the typical energy consumption scenario of the transportation hub are taken as the disturbance inputs, and the disturbance vector is defined as

$$d = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix} = \begin{bmatrix} P_L \\ \dot{m}_{load} \\ Q_L \end{bmatrix} \quad (32)$$

The system state equation can be uniformly written as

$$\dot{x} = f(x, u, d) \quad (33)$$

where the vector function  $f(\cdot)$  consists of the power and temperature dynamics of the electrolyzer, the power and temperature dynamics of the fuel cell, the mass and temperature dynamics of the hydrogen storage tank, and the thermal side temperature dynamics.

The output vector is defined as

$$y = \begin{bmatrix} P_g \\ p_H \\ \dot{m}_{el} \\ \dot{m}_{fc} \\ Q_{el} \\ Q_{fc} \end{bmatrix} \quad (34)$$

where the grid input power satisfies the electric side power balance relationship:

$$P_g = P_L + P_{el} - P_{fc} \quad (35)$$

The output equation can be expressed as

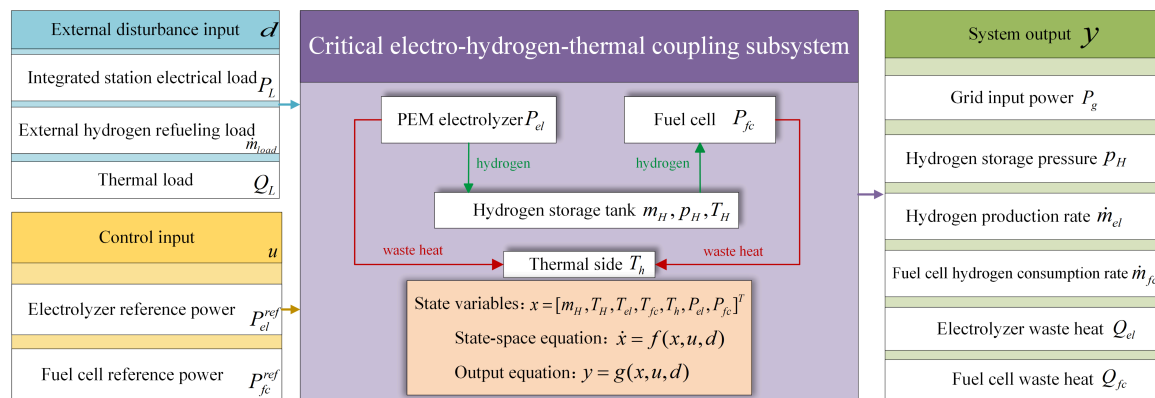
$$y = g(x, u, d) \quad (36)$$

In summary, the unified state-space model of the key electricity–hydrogen–heat coupling subsystem established in this paper can be expressed as

$$\begin{cases} \dot{x} = f(x, u, d) \\ y = g(x, u, d) \end{cases} \quad (37)$$

The block diagram of the unified modeling framework is shown in Figure 5. This state-space representation provides a unified interface for subsequent disturbance simulation and parameter sensitivity analysis.

The adopted state-space formulation directly represents hydrogen-mass and thermal-energy accumulation through continuous-time balance equations while retaining the device-level dynamics required for the seconds-to-minutes analysis considered here.



**Figure 5.** Unified state-space framework of the core electricity–hydrogen–heat coupling subsystem.

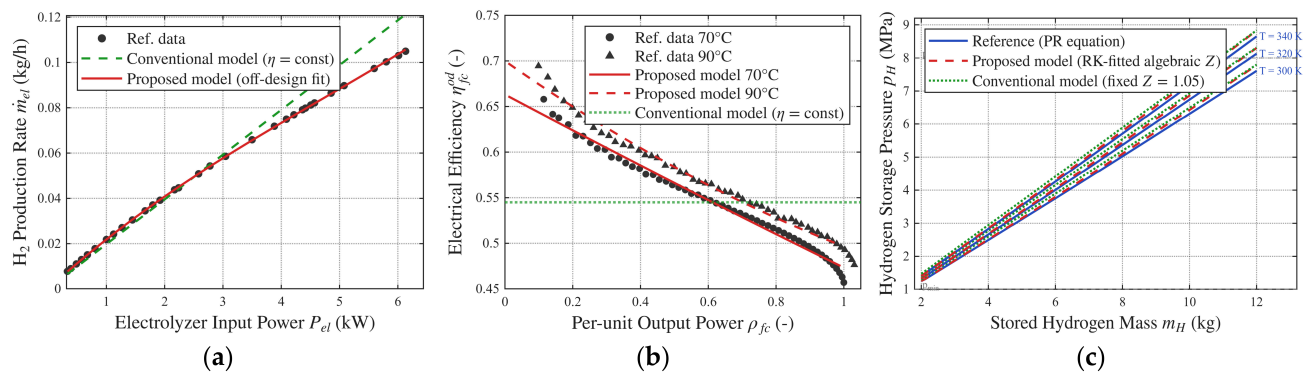
## 5. Simulation Results and Discussion

### 5.1. Component Model Calibration and Benchmark Comparison

To assess the representation capability of the proposed component models, calibration and benchmark comparisons are conducted for the PEM electrolyzer, fuel cell, and hydrogen storage tank. For the PEM electrolyzer, the model coefficients are identified using the published experimental current–voltage characteristics of a 6 kW PEM electrolyzer stack at 60 °C reported in Ref. [16]. The corresponding input power and hydrogen production rate are calculated from the reported stack voltage, current, and Faraday-based hydrogen production relationship. Therefore, the comparison between the proposed model and these experimental data is intended to evaluate the goodness of fit of the compact system-level formulation rather than its predictive accuracy against an independent dataset. Similarly, the coefficients of the fuel-cell model are identified from published electro-thermal performance data at 70 °C and 90 °C [30] and the resulting errors should be interpreted as calibration errors. For the hydrogen storage tank, no experimental calibration is performed in this study. Instead, the Peng–Robinson (PR) equation of state is employed as a thermodynamic benchmark, while the proposed model uses an algebraic compressibility-factor approximation fitted from the Redlich–Kwong (RK) equation over the considered operating range. The conventional model adopts a fixed compressibility factor of ( $Z = 1.05$ ). Accordingly, the hydrogen-storage comparison represents a model-to-model benchmark rather than experimental validation [25,31].

As shown in Figure 6a, the conventional fixed-efficiency model exhibits noticeable deviations from the published PEM electrolyzer data at both low and high power levels, whereas the proposed off-design formulation reproduces the nonlinear trend of the calibration dataset more closely. Figure 6b shows that the conventional constant-efficiency fuel-cell model cannot reproduce the load-dependent efficiency variation, while the proposed formulation provides a closer representation of the published data at both 70 °C and 90 °C. Figure 6c compares the two system-level hydrogen-storage formulations with the PR equation-of-state benchmark. The fixed- $Z$  model consistently overestimates the pressure, whereas the RK-based algebraic approximation more closely follows the PR benchmark over the investigated mass and temperature ranges.

To further quantify the comparison, the mean absolute percentage error (MAPE) is adopted. MAPE measures the average relative deviation between the model output and the reference data, and a smaller value indicates better agreement with the reference trend. The calculated errors are summarized in Table 2.



**Figure 6.** Component-level calibration and benchmark comparisons. (a) PEM electrolyzer; (b) fuel cell; (c) hydrogen storage tank.

**Table 2.** Error metrics for component-model calibration and thermodynamic benchmark comparison.

| Device                | Temperature | Conventional Model MAPE | Proposed Model MAPE |
|-----------------------|-------------|-------------------------|---------------------|
| PEM electrolyzer      | 60 °C       | 8.5761%                 | 0.3927%             |
| Fuel cell             | 70 °C       | 7.7599%                 | 0.8084%             |
|                       | 90 °C       | 7.8576%                 | 0.8140%             |
| Hydrogen storage tank | 300 K       | 3.5913%                 | 1.3403%             |
|                       | 320 K       | 3.4843%                 | 1.2853%             |
|                       | 340 K       | 3.3904%                 | 1.2357%             |

As summarized in Table 2, the proposed PEM electrolyzer and fuel-cell formulations exhibit substantially lower calibration errors than the corresponding fixed-efficiency models when reproducing the published reference datasets. For the hydrogen storage tank, the proposed RK-based algebraic approximation also shows closer agreement with the PR thermodynamic benchmark than the conventional fixed-Z formulation. These results demonstrate that the proposed compact formulations provide improved representation of the reference relationships used for model construction and are therefore adopted in the subsequent system-level dynamic analysis.

### 5.2. Case Study

Step disturbances are used as controlled benchmark inputs to characterize short-term cross-domain responses and compare disturbance propagation across the electricity–hydrogen–heat subsystem.

The simulation parameters are listed in Table 3. Fitting coefficients are obtained from the corresponding reference data or thermodynamic relationships, while other lumped parameters are assigned representative engineering values for system-level dynamic analysis. To ensure a transparent and reproducible disturbance-response benchmark, a constrained proportional regulation strategy is adopted for the PEM electrolyzer and fuel cell. For an electrical-load disturbance  $\Delta P_L$ , the reference powers are defined as

$$\begin{aligned} P_{el}^{ref} &= \text{sat} \left( P_{el,0} - K_{el} \Delta P_L; P_{el}^{\min}, P_{el}^{\max} \right) \\ P_{fc}^{ref} &= \text{sat} \left( P_{fc,0} + K_{fc} \Delta P_L; P_{fc}^{\min}, P_{fc}^{\max} \right) \end{aligned} \quad (38)$$

where  $K_{el}$  and  $K_{fc}$  denote the regulation coefficients of the electrolyzer and fuel cell, respectively. The saturation operator limits the commanded powers within the prescribed operating ranges, and the external grid supplies the remaining power imbalance. For

hydrogen-refueling disturbances, a rule-based benchmark response is adopted, in which the electrolyzer is commanded to increase its operating power, while the fuel cell is correspondingly derated to reduce hydrogen consumption. The purpose of this benchmark control is not to optimize system operation but to provide a fixed and reproducible response mechanism for examining cross-domain disturbance propagation.

**Table 3.** Main simulation parameters and nominal operating conditions.

| Parameter                                       | Symbol         | Value  | Unit           | Source/Identification                               |
|-------------------------------------------------|----------------|--------|----------------|-----------------------------------------------------|
| electrolyzer rated power                        | $P_{el}^{max}$ | 60     | kW             | Representative engineering value                    |
| reference temperature                           | $T_{el}^{ref}$ | 353.15 | K              | Literature-based/representative operating condition |
| power dynamic time constant of the electrolyzer | $T_{el,p}$     | 5      | s              | Representative engineering value                    |
| equivalent heat capacity                        | $C_{el}$       | 200    | kJ/K           | Lumped engineering assumption                       |
| equivalent thermal resistance                   | $R_{el}$       | 2.5    | K/kW           | Lumped engineering assumption                       |
| equivalent heat transfer coefficient            | $k_{hex,el}$   | 0.7    | kW/K           | Lumped engineering assumption                       |
| fuel cell rated power                           | $P_{fc}^{max}$ | 30     | kW             | Representative engineering value                    |
| reference temperature                           | $T_{fc}^{ref}$ | 353.15 | K              | Literature-based/representative operating condition |
| power dynamic time constant of the fuel cell    | $T_{fc,p}$     | 2      | s              | Representative engineering value                    |
| equivalent heat capacity                        | $C_{fc}$       | 180    | kJ/K           | Lumped engineering assumption                       |
| equivalent thermal resistance                   | $R_{fc}$       | 2      | K/kW           | Lumped engineering assumption                       |
| equivalent heat transfer coefficient            | $k_{hex,fc}$   | 0.5    | kW/K           | Lumped engineering assumption                       |
| tank volume                                     | $V_H$          | 2      | m <sup>3</sup> | Representative system parameter                     |
| initial hydrogen mass                           | $m_H(0)$       | 8      | kg             | Initial condition                                   |
| initial tank temperature                        | $T_H(0)$       | 315    | K              | Initial condition                                   |
| ambient temperature                             | $T_{amb}$      | 298    | K              | Environmental condition                             |
| equivalent heat capacity                        | $C_h$          | 500    | kJ/K           | Lumped engineering assumption                       |
| heat transfer parameter                         | $U_H A_H$      | 30     | W/K            | Lumped engineering assumption                       |
| electrolyzer regulation coefficient             | $K_{el}$       | 0.5    | -              | Benchmark control parameter                         |
| fuel-cell regulation coefficient                | $K_{fc}$       | 0.2    | -              | Benchmark control parameter                         |

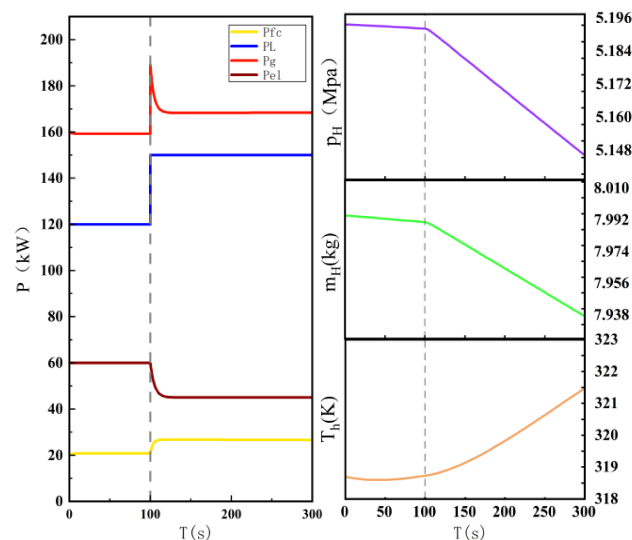
All simulations were implemented in MATLAB R2025a/Simulink using the variable-step automatic solver selection. The simulation time was 300 s, with a relative tolerance of  $1 \times 10^{-3}$ , while the maximum step size and absolute tolerance were determined automatically by Simulink. The proposed model contains seven state variables and consists mainly of algebraic relations and first-order differential equations, without involving iterative optimization procedures. No numerical divergence or abnormal oscillation was observed within the investigated operating conditions.

#### 5.2.1. Dynamic Response to an Electrical-Load Step Disturbance

Scenario 1 considers a 30 kW step increase in the aggregated electrical load, from 120 to 150 kW at  $t = 100$  s. This disturbance is used as a controlled stress test to evaluate the short-term electrical-to-hydrogen/thermal propagation characteristics. Figure 7 shows the dynamic responses of the main state and power variables.

Following the 30 kW electrical-load step, the grid input power exhibits a peak deviation of approximately 29.4 kW and subsequently settles at about 9.1 kW above its pre-disturbance value within approximately 20 s, indicating that nearly 70% of the load increment is compensated by the electrolyzer and fuel-cell regulation. During the subsequent 200 s, the hydrogen inventory decreases by approximately 0.055 kg, and the tank pressure decreases by about 0.036 MPa. Meanwhile, the thermal-side temperature increases

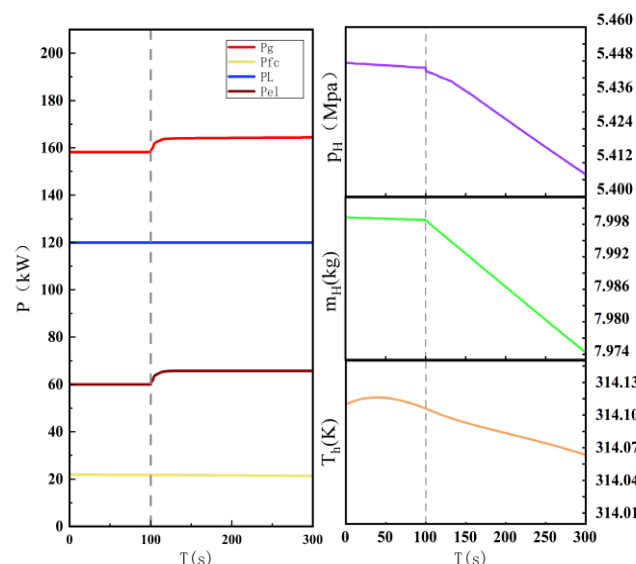
by approximately 2.9 K. This thermal response results from the redistribution of recoverable heat between the electrolyzer and fuel cell: electrolyzer derating reduces its heat contribution, whereas increased fuel-cell output raises waste-heat recovery. The relatively large thermal inertia further causes the thermal response to evolve more slowly than the electrical variables.



**Figure 7.** Dynamic response to the step increase of electric load.

#### 5.2.2. Dynamic Response to a Hydrogen-Refueling-Demand Step Disturbance

Scenario 2 considers a controlled step increase in hydrogen-refueling demand. In this case, the station hydrogen load  $\dot{m}_{load}$  increases stepwise from its nominal value of  $2.0 \times 10^{-5}$  kg/s to  $1.5 \times 10^{-4}$  kg/s at  $t = 100$  s. Figure 8 presents the resulting dynamic responses of the electricity–hydrogen–heat coupling subsystem.



**Figure 8.** Dynamic response to the hydrogen-refueling-demand step disturbance.

The hydrogen-refueling disturbance increases the grid input power by approximately 6.3 kW, with the electrical response approaching its new operating level within about 30 s. Over the following 200 s, the hydrogen inventory and tank pressure decrease by approximately 0.026 kg and 0.037 MPa, respectively. In contrast, the thermal-side temperature changes by only about 0.03 K. The increased electrolyzer operation enhances

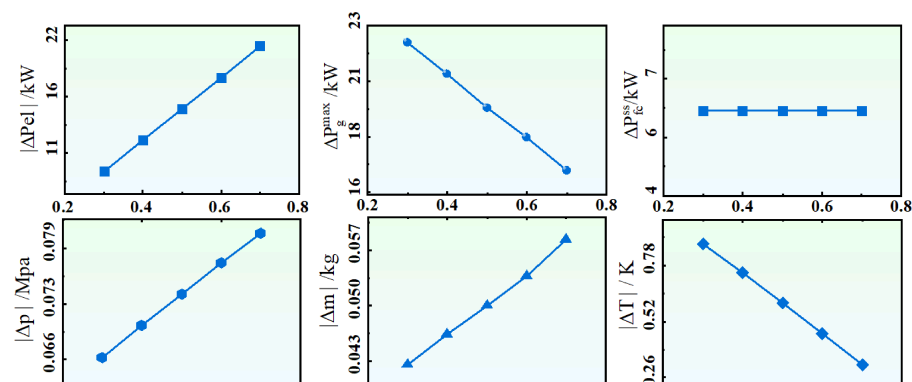
its recoverable heat contribution, whereas fuel-cell derating reduces fuel-cell waste heat; these opposing effects partially offset each other. Together with the relatively large thermal capacitance, this leads to a weak and slow thermal-side response under the investigated operating condition.

### 5.3. Parameter Sensitivity Analysis

Based on the above disturbance simulations, the electrolyzer regulation coefficient is analyzed under the electrical-load disturbance scenario, while the initial hydrogen storage state is examined under the hydrogen-refueling disturbance scenario. Here,  $K_{el}$  characterizes the regulation intensity of the electrolyzer, and  $m_H(0)$  represents the initial hydrogen-side buffering level. These two parameters are selected because they represent fundamentally different regulation mechanisms:  $K_{el}$  characterizes active controllability on the electrical side, while  $m_H(0)$  reflects passive buffering capacity on the hydrogen side.

#### 5.3.1. Sensitivity Analysis of Electrolyzer Regulation Coefficient

Sensitivity analysis is conducted with  $K_{el}$  set to 0.3, 0.4, 0.5, 0.6 and 0.7, respectively, and Figure 9 presents the variation patterns of the system's key indicators under different  $K_{el}$  values.

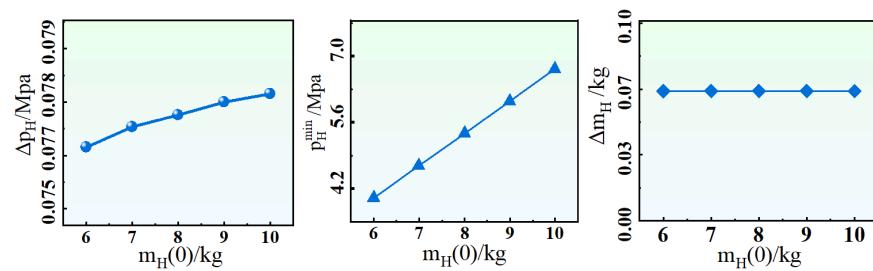


**Figure 9.** Sensitivity analysis with respect to parameter  $K_{el}$ . Here,  $|\Delta P_{el}|$  represents the absolute change in electrolyzer input power;  $\Delta P_g^{\max}$  denotes the maximum change in grid input power;  $\Delta P_{fc}^{ss}$  represents the steady-state change in fuel-cell output power; and  $|\Delta p|$ ,  $|\Delta m|$ , and  $|\Delta T|$  denote the absolute changes in hydrogen storage pressure, stored hydrogen mass, and thermal-side equivalent temperature, respectively.

The results show that increasing  $K_{el}$  strengthens electrolyzer-side load regulation, thereby reducing the grid support requirement. Meanwhile, deeper electrolyzer power reduction decreases hydrogen production and modifies the hydrogen and thermal responses. Since  $K_{fc}$  remains fixed in this sensitivity analysis, the fuel-cell response changes only slightly. These results indicate that  $K_{el}$  primarily affects the distribution of short-term electrical regulation and its subsequent propagation to the hydrogen and thermal subsystems.

#### 5.3.2. Sensitivity Analysis of Initial Hydrogen Storage State

Comparative simulations are performed with  $m_H(0)$  set to 6, 7, 8, 9, and 10 kg, respectively, while the other parameters are kept fixed at the corresponding sensitivity-analysis baseline. Figure 10 presents the variation patterns of the system's key indicators under different initial hydrogen inventories.



**Figure 10.** Sensitivity analysis with respect to parameter  $m_H(0)$ . Here,  $\Delta p_H$  and  $\Delta m_H$  represent the changes in hydrogen storage pressure and stored hydrogen mass, respectively;  $p_H^{\min}$  denotes the minimum hydrogen storage pressure during the disturbance.

The results show that increasing the initial hydrogen inventory raises the minimum tank pressure during the disturbance, thereby increasing the pressure margin above the prescribed minimum operating limit. This indicates that a higher initial storage state enhances the passive buffering capability of the system against hydrogen-refueling disturbances. Meanwhile, under the same disturbance duration and control strategy, the variation in stored hydrogen mass remains nearly unchanged, suggesting that the net hydrogen consumption is mainly determined by the external refueling demand and device regulation strategy rather than the initial storage level. It should also be noted that, due to the nonlinear pressure–mass relationship, pressure fluctuations may become more pronounced in the high-storage range. Overall, a higher initial hydrogen inventory provides a larger pressure reserve under the considered disturbance but may also lead to stronger pressure variations.

These sensitivity results highlight the complementary roles of active electrical-side regulation and passive hydrogen-side buffering. The electrolyzer regulation coefficient affects the allocation of short-term electrical regulation, while the initial hydrogen inventory influences the available pressure margin during refueling disturbances. Their coordinated consideration may therefore support system-level operating assessment under the investigated conditions.

## 6. Conclusions

This study developed a compact system-level dynamic model of an electricity–hydrogen–heat coupling subsystem for integrated transportation hubs. Power- and temperature-dependent off-design models were established for the PEM electrolyzer and fuel cell, while the hydrogen storage tank was represented using coupled mass and energy balances with a real-gas correction. The component models were integrated into a unified nonlinear state-space framework for short-term disturbance analysis.

The simulations reveal clear cross-domain dynamic characteristics. Under a 30 kW electrical-load step, the grid input exhibits a peak deviation of approximately 29.4 kW and subsequently approaches a deviation of about 9.1 kW, indicating that nearly 70% of the load increment is compensated by coordinated electrolyzer and fuel-cell regulation. During the following 200 s, the hydrogen inventory decreases by approximately 0.055 kg, the tank pressure decreases by about 0.036 MPa, and the thermal-side temperature increases by approximately 2.9 K. Under the hydrogen-refueling-demand disturbance, the grid input increases by approximately 6.3 kW, while the hydrogen inventory and tank pressure decrease by about 0.026 kg and 0.037 MPa, respectively, with only a slight thermal-side temperature variation of approximately 0.03 K. These results indicate distinct propagation magnitudes and time-scale characteristics across the electrical, hydrogen, and thermal domains.

The sensitivity analysis shows that the electrolyzer regulation coefficient  $K_{el}$  mainly affects active electrical-side regulation, whereas the initial hydrogen inventory influences passive hydrogen-side buffering and the available pressure margin.

The main limitations of the present study arise from the use of lumped-parameter component models, representative engineering parameters, an aggregated electrical interface, and idealized step disturbances. Consequently, detailed electrical-network dynamics, spatial thermal distributions, and stochastic traffic-driven demand variations are not explicitly represented. Future work will incorporate measured operating data, time-varying traffic-derived demand profiles, and more detailed coordinated control strategies.

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