Analysis and Simulation of Dynamic Evolution Mechanism of Exergy in Time-Varying Energy Networks

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Abstract

Exergy is an indicator for measuring energy quality, which profoundly reveals the essence of work capability loss during energy transfer processes. To investigate the dynamic evolution mechanism of ? in time-varying energy networks, this paper formulates the constitutive relations among physical quantities in energy networks based on energy network theory, presents a generalized expression for ?, including forming a generalized description of ? and ? loss equations based on the second law of thermodynamics, while simultaneously introducing an energy level factor to evaluate energy quality; analyzes the dynamic evolution processes of different forms of ? in energy transmission pipes (lines), including electrical exergy, thermal exergy, and pressure exergy, and presents the output equation for ? and efficiency calculation methods; analyzes the dynamic evolution process of ? in energy conversion equipment, and conducts analysis on the loss amount, storage amount, and efficiency of ?; finally, performs dynamic simulation on the dynamic evolution process of ? in an integrated energy system through specific case studies. The content studied in this paper can fully exploit the energy efficiency potential of integrated energy systems, laying a solid theoretical foundation for better realization of energy cascade utilization.

Full Text

Analysis and Simulation of Exergy Dynamic Evolution Mechanism in Time-Varying Energy Networks

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ABSTRACT: Exergy is an index for measuring energy quality that reveals the essence of work capacity loss during energy transfer processes. To investigate the dynamic evolution mechanism of exergy in time-varying energy networks, this paper establishes constitutive relations between physical quantities in energy networks based on energy network theory and presents generalized expressions of exergy, including generalized descriptions and exergy loss equations derived from the second law of thermodynamics, while introducing an energy level factor to evaluate energy quality. The dynamic evolution processes of different exergy forms in energy transfer tubes (lines) are analyzed, including electric exergy, thermal exergy, and pressure exergy, with output equations and efficiency calculation methods provided. The dynamic evolution of exergy in energy conversion equipment is also examined through analysis of exergy loss, storage, and efficiency. Finally, dynamic simulation of exergy evolution in an integrated energy system is performed through a specific case study. The research content fully taps the energy efficiency potential of integrated energy systems and lays a solid theoretical foundation for better realization of energy cascade utilization.

KEY WORDS: exergy; time-varying energy networks; energy network theory; integrated energy systems; energy efficiency potential

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1. Generalized Expression of Exergy in Energy Networks

Exergy refers to the portion of energy that can be converted into useful work under environmental conditions, reflecting energy quality. The first law of thermodynamics states that energy is conserved and its value is greater than or equal to exergy. The second law of thermodynamics indicates that energy conversion processes have clear directionality—for instance, electrical energy can be completely converted into thermal energy, but thermal energy cannot be fully converted into electrical energy. Consequently, some energy inevitably degrades into unusable energy during transfer and conversion processes, and this irreversible loss constitutes exergy destruction.

1.1 Constitutive Relations and Unified Symbols for Physical Quantities in Energy Networks The physical quantities in energy networks fall into four categories: generalized displacement (basic extensive quantity) F, generalized flow variable (flow rate of basic extensive quantity) j, generalized intensive quantity c, and generalized momentum X. Their constitutive relations are: $Rc = j = LCj$. Table 1 details the physical quantities and symbols for different energy networks, including electrical, thermal, hydraulic, and mechanical energy networks, covering the four types of generalized variables as well as energy power, exergy power, and energy level coefficients.

Table 1 Physical quantities and symbols of different energy networks

Network Type	Generalized Displacement F_i	Generalized Flow j_i	Generalized Intensity c_i	Generalized Momentum X_i	Energy Power P_i	Exergy Power P_{xi}	Energy Level e_i
Electrical	Charge q_F / C	Current q_j / A	Voltage U_c / V	Flux linkage X_y / Wb	Electric power P_e	Electric exergy P_{xe}	Electric level e_e
Thermal	Entropy s_F / J · K^{-1}	Entropy flow s_j / J · K^{-1} · s^{-1}	Temperature T_c / K	Temp-time integral T_X / K · s	Thermal power P_h	Thermal exergy P_{xh}	Thermal level e_h
Hydraulic	Volume v_F / m^3	Volume flow v_j / m^3 · s^{-1}	Pressure P_c / Pa	Pressure momentum P_X / Pa · s	Pressure power P_p	Pressure exergy P_{xp}	Pressure level e_p
Mechanical	Angular displacement ω_F / rad	Angular velocity ω_j / rad · s^{-1}	Torque t_c / N · m	Angular momentum t_X / N · m · s	Mechanical power P_j	Mechanical exergy P_{xj}	Mechanical level e_j

1.2 Generalized Description of Exergy The basic parameters describing system state include two categories: intensive quantities and extensive quantities, where extensive quantities further comprise basic extensive quantities, energy, and exergy. Any form of exergy in a system can be expressed as a function of intensive and extensive variables. System exergy originates from differences in intensive quantities between the system and its environment, yielding the following generalized differential expression for any form of exergy:

$$dE_{xi} = (c_i - c_{i0})dF_i \quad (1)$$

where subscript i denotes quantities related to the i-th energy form, E_{xi} is exergy, and c_{i0} is the dead-state value of the intensive quantity. The term $c_{i0}dF_i$ represents the unusable portion of energy. Based on Eq. (1), we examine the macroscopic changes in energy quality during microscopic transfer processes, using thermal system analysis as an example (Fig. 1).

Fig. 1 Schematic diagram of energy quality analysis of thermal system

Consider heat transfer from a constant heat source at temperature T_{1c} in System I to another constant heat source at T_{2c} in System II, with the temperature dead-state value T_{0c} remaining constant. The first law gives $T_{1c}dS_1 = T_{2c}dS_2$, while the second law shows that entropy continuously increases during the $S_1 \to S_2$ process, with unusable energy increasing from $T_{0c}dS_1$ to $T_{0c}dS_2$. Consequently, the exergy E_{xh2} of System II is less than E_{xh1} of System I. This analysis reveals that heat transfer involves exergy destruction, resulting in lost work capacity and degraded thermal energy quality. Thus, maintaining constant energy quantity sacrifices energy quality, while preserving energy quality requires losing greater energy quantity.

1.3 Generalized Exergy Loss Equation Combining Eq. (1) with the Lagrangian method yields the dynamic balance equation for exergy:

$$\frac{\partial E_{xi}}{\partial t} + \nabla \cdot \mathbf{J}_{Exi} = (c_i - c_{i0})s_i \quad (2)$$

where $\mathbf{J}_{Exi}$ is exergy flux density, $\mathbf{J}_i$ is basic extensive quantity flux density, and s_i is the source intensity of basic extensive quantities. The left side represents the time rate of change of exergy per unit volume; the right side terms represent net exergy influx across volume boundaries, exergy generated from interconversion between different exergy forms driven by intensive quantity differences, and exergy generated with basic extensive quantity sources.

Since energy in integrated energy systems typically transfers through cylindrical tubes (lines), integrating Eq. (2) over the volume and rearranging yields:

$$\int_A^B \frac{\partial E_{xi}}{\partial t} dV = \int_A^B (c_i - c_{i0})s_i dV - \int_A^B \nabla \cdot \mathbf{J}_{Exi} dV \quad (3)$$

where subscripts A and B represent energy input and output cross-sections, respectively, and g_x is a length-dependent function of basic extensive quantities during energy transfer.

The two terms on the left side of Eq. (3) represent the exergy destruction generated during energy transfer between cross-sections A and B per unit time:

$$P_{xD} = P_D - c_0 j_D \quad (4)$$

where P_{xD} is exergy destruction from cross-section A to B, P_D is available energy consumption during transfer, and $c_0 j_D$ represents available energy loss from irreversibility. Thus, exergy destruction during energy transfer comprises both consumed available energy and irreversibility-induced losses, equaling the volume' s exergy change rate minus exergy converted under intensive quantity differences and exergy generated with basic extensive quantity sources.

1.4 Energy Level Factor The energy level factor e is introduced to evaluate energy quality. For the i-th energy form in a system, the energy level factor e_i equals the ratio of exergy differential to energy differential:

$$e_i = \frac{dE_{xi}}{dE_i} = \frac{c_i - c_{i0}}{c_i} \quad (5)$$

Analysis shows that when $c_i = c_{i0}$, exergy becomes zero; when $e_i = 1$, the intensive quantity' s dead-state value c_{i0} is zero, and energy numerically equals exergy, representing maximum exergy. Higher system energy levels indicate greater exergy proportions in energy, more work performed on external systems, and more significant energy utilization value.

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2. Dynamic Evolution Mechanism of Specific Exergy Forms

Based on material motion forms in energy networks, different exergy types emerge: electric exergy from charge movement in electrical networks, thermal exergy from entropy flow in thermal networks, and pressure exergy from volume flow in hydraulic networks. The following analysis examines dynamic evolution mechanisms of specific exergy forms between control volume cross-sections A and B in tubes (lines) based on time-varying models from energy network theory.

2.1 Electric Exergy Dynamic Evolution In electrical networks, electric exergy represents the maximum useful work capability of charged systems under electric fields. From charge conservation with source intensity $q_s = 0$, Eq. (4) yields the electric exergy power loss equation:

$$P_{xeD} = P_{eD} + U_{0c} j_q \quad (6)$$

where P_{xeD} is electric exergy destruction from cross-section A to B, P_{eD} is electric energy loss, and U_{0c} is the voltage dead-state value (typically zero as ground potential). Thus, electric exergy loss equals electric energy loss, with electric energy level $e_e = 1$.

Using parallel double transmission lines as an example, the time-varying equivalent model (Fig. 2) shows resistance R_e converting some electric energy to low-grade thermal energy through heating (exergy destruction), capacitance C_e reflecting exergy storage effects related to voltage U_c variation rate, and inductance L_e reflecting exergy inertia effects related to current j_q variation rate. Electric exergy power loss calculation follows the same method as electric power loss, obtainable from circuit theory.

Fig. 2 Time-varying equivalent model of power transfer process

2.2 Thermal Exergy Dynamic Evolution In thermal networks, pipeline fluids undergo convective heat transfer driven by pressure differences. Thermal exergy represents maximum useful work capability due to temperature differences from the environment. From Eq. (4), the thermal exergy power loss equation is:

$$P_{xhD} = P_{hD} - T_{0c} j_s \quad (7)$$

where P_{xhD} is thermal exergy loss, P_{hD} is thermal energy loss, j_s is entropy flow, g_{sx} is the entropy source function varying with pipeline length, and T_{0c} is the temperature dead-state value (typically ambient temperature). From Eq. (5), thermal energy level $e_h < 1$, indicating low-grade energy.

Analysis of Eq. (7) shows thermal exergy loss comprises thermal energy loss and irreversibility-induced losses from heat transfer and diffusion, equaling the rate of total thermal exergy change (unsteady term) minus thermal exergy generation. Using one-dimensional single-layer cylindrical pipe heat transfer as a concrete example, the energy network theory yields the convective heat transfer equivalent gyrator (GY) model shown in Fig. 3.

Fig. 3 Time-varying equivalent model of convective heat transfer process

In Fig. 3, T_{Ac} is input temperature, T_{Bc} is temperature within the micro-control volume, C_h is thermal capacitance, and R_h is total radial thermal resistance of the pipe wall. The energy loss in the micro-control volume is:

$$P_{hcD} + P_{hrD} + P_{haD} = j_s T_{Bc} - j_s T_{Ac} \quad (8)$$

where P_{hcD} is thermal power stored in the capacitance element under heat storage effects (energy accumulated in the pipe due to fluid temperature variation over time), P_{hrD} is thermal power lost on the resistance element (heat leakage along the pipe from conduction and convection), and P_{haD} is thermal power loss corresponding to irreversible dissipation from energy level degradation. e_{hA} is the energy level at the control volume input, and e_{hB} is the thermal energy level within the control volume.

Combining Eqs. (7) and (8) yields the dynamic evolution equation for thermal exergy in the control volume:

$$P_{xhBP} - P_{xhAP} = P_{hcD} + P_{hrD} + P_{haD} - T_{0c} j_s \quad (9)$$

where P_{xhBP} is output thermal exergy power and P_{xhAP} is input thermal exergy power from the control volume. Fig. 4 illustrates the dynamic process of thermal exergy transfer in a single-layer cylindrical pipe.

Fig. 4 Diagram of thermal exergy dynamic evolution in single-layer cylindrical pipe

From Fig. 4, the thermal exergy transfer efficiency in the pipe is easily obtained as:

$$\eta_{xh} = \frac{P_{xhBP}}{P_{xhAP}} = \frac{T_{Bc} - T_{0c}}{T_{Ac} - T_{0c}} \quad (10)$$

2.3 Pressure Exergy Dynamic Evolution In fluid networks, pressure exergy represents the maximum useful work capability of systems under different pressure environments. With volume source intensity $v_s = 0$, Eq. (4) gives the pressure exergy power loss equation:

$$P_{xpD} = P_{pD} - P_{0c} j_v \quad (11)$$

where P_{xpD} is pressure exergy power loss during pressure energy transfer, P_{pD} is pressure energy loss, j_v is volume flow rate, and P_{0c} is the pressure dead-state value.

Using circular pipeline fluid pressure energy transfer as an example, the energy network theory yields the universal equivalent model shown in Fig. 5. For one-dimensional pipe flow with flat fluid lines, normal-direction pressure and gravity forces balance, ignoring pipeline/fluid elastic/linear deformation and generally neglecting convection terms.

Fig. 5 Time-varying equivalent model of pressure energy transfer process

In Fig. 5, P_{Ac} is pressure at cross-section A, P_{Bc} is pressure at cross-section B, j_v is volume flow rate, C_v is fluid capacitance, R_v is fluid resistance, and L_v is fluid inductance. The energy loss in the micro-control volume during pressure energy transfer is:

$$P_{pcD} + P_{prD} + P_{plD} + P_{paD} = j_v P_{Bc} - j_v P_{Ac} \quad (12)$$

where P_{pcD} is pressure power stored in the capacitance element, P_{prD} is pressure power loss along the pipe from fluid viscosity or wall roughness, P_{plD} is pressure power stored in the inductance element, and P_{paD} is pressure power loss from irreversible energy level degradation. e_{pA} is the energy level at the pressure input, and e_{pB} is the pressure energy level at the output.

From an energy perspective, capacitance and inductance elements function as follows: fluid capacitance characterizes compressibility, related to pressure variation rate, storing kinetic energy as pressure potential energy like a capacitor stores electric field energy (negligible at steady/low-frequency states); fluid inductance characterizes inertia, causing flow acceleration under inertia effects during high-frequency motion and subsequent pressure changes, storing pressure energy as kinetic energy like an inductor stores magnetic field energy. Thus, pressure and kinetic energy interchange during fluid transfer without loss in reversible processes.

Combining Eqs. (11) and (12) yields the dynamic evolution equation for pressure exergy in the control volume:

$$P_{xpBP} - P_{xpAP} = P_{pcD} + P_{prD} + P_{plD} + P_{paD} - P_{0c}j_v \quad (13)$$

where P_{xpBP} is output pressure exergy power and P_{xpAP} is input pressure exergy power. The pressure exergy transfer efficiency in the pipe is:

$$\eta_{xp} = \frac{P_{xpBP}}{P_{xpAP}} = \frac{P_{Bc} - P_{0c}}{P_{Ac} - P_{0c}} \quad (14)$$

3. Dynamic Evolution of Exergy in Energy Conversion Equipment

Energy conversion equipment couples different energy sub-networks, with induction motors and centrifugal pumps being the most common types. The following analysis examines exergy evolution mechanisms based on time-varying equivalent models from energy network theory.

3.1 Induction Motor Through electromagnetic induction, an induction motor converts electric power P_e generated by input voltage U_c and induced current j_q into mechanical power from induced torque t_c and coil rotational speed ω_j. Mechanical energy is high-quality energy with energy level coefficient 1, so mechanical exergy power P_{xj} equals mechanical energy power.

Based on energy network theory, the induction motor is equivalent to a gyrator (GY) with modulus k_m, yielding the time-varying equivalent model in Fig. 6.

Fig. 6 Time-varying equivalent model of induction motor

In Fig. 6, $R_{m\omega}$ characterizes motor speed difference, R_{mf} characterizes bearing and rotor friction, L_{mx} characterizes rotor inertia, C_{mk} characterizes shaft compliance, and k_m is the motor torque conversion coefficient ($U_c = k_m\omega_j$, used for energy equation formulation). The exergy loss during energy conversion is:

$$P_{j\omega D} + P_{jfD} + P_{jlD} + P_{jcD} = j_qU_c - \omega_jt_c \quad (15)$$

where $P_{j\omega D}$ is rotational mechanical power loss, P_{jfD} is friction mechanical power loss, P_{jlD} is inductance-stored mechanical power, and P_{jcD} is capacitance-stored mechanical power. The output mechanical exergy power P_{xj} and induction motor exergy efficiency η_{Gh} are:

$$P_{xj} = \omega_jt_c - P_{jfD} - P_{j\omega D} \quad (16)$$

$$\eta_{Gh} = \frac{P_{xj}}{P_{xe}} = \frac{\omega_j t_c - P_{jfD} - P_{j\omega D}}{j_q U_c} \quad (17)$$

3.2 Centrifugal Pump A centrifugal pump converts mechanical power P_j from torque t_c and angular velocity ω_j into fluid pressure power P_p from pressure P_c and flow rate j_v, raising fluid pressure. The mechanical energy for rotating components is typically supplied by an induction motor, and the exergy increasing fluid pressure is called effective work.

Based on energy network theory, the centrifugal pump is equivalent to a gyrator (GY) with modulus r_p, yielding the equivalent model in Fig. 7.

Fig. 7 Time-varying equivalent model of centrifugal pump

In Fig. 7, R_{pf} characterizes rotor friction, L_{px} characterizes rotor inertia, $R_{p\xi}$ characterizes leakage, R_{pr} characterizes valve outlet pressure loss, and r_p is the impeller gyrator modulus ($t_c = r_p P_c$, used for energy equation formulation). The exergy loss during energy conversion is:

$$P'_{jfD} + P'_{jlD} + P_{p\xi D} + P_{prD} = \omega_j t_c - j_v P_c \quad (18)$$

where P'_{jfD} is impeller mechanical power loss (mainly from rotor friction), P'_{jlD} is stored mechanical power, $P_{p\xi D}$ is volumetric power loss (from leakage), and P_{prD} is hydraulic power loss (from valve outlet pressure loss).

Considering the non-zero pressure dead-state value, some pressure energy cannot convert to useful work, creating irreversible energy loss $P_{0c} j_v$. Thus, when mechanical energy converts to fluid pressure energy, the output pressure exergy power P_{xp} and centrifugal pump exergy efficiency η_{Bh} are:

$$P_{xp} = j_v P_c - P_{prD} - P_{p\xi D} - P_{0c} j_v \quad (19)$$

$$\eta_{Bh} = \frac{P_{xp}}{P_{xj}} = \frac{j_v P_c - P_{prD} - P_{p\xi D} - P_{0c} j_v}{\omega_j t_c} \quad (20)$$

From Eqs. (16) and (19), Fig. 8 illustrates the dynamic exergy evolution during the process of converting electric energy to pressure energy in IES energy conversion components.

Fig. 8 Dynamic evolution diagram of exergy in induction motor and centrifugal pump

4. Case Study Analysis

This section presents a case study of an integrated energy system (Fig. 9) containing a 4-node electrical network and 6-node thermal network, powered by a combined heat and power (CHP) unit with a heat-to-electricity ratio of 1.3. Electrical network node 3e connects to the power source; nodes 1e and 2e have loads of 0.15 MW each; node 4e is a slack bus connecting to the main grid. Thermal supply network nodes 1h and 2h have loads of 0.3 MW; node 3h connects to the heat source, with a symmetric return network. The heat source and circulation pump connect supply and return networks, with the pump driven by an induction motor.

Fig. 9 Topological diagram of a regional comprehensive energy system

The fluid medium is water. Dead-state values are: voltage $U_{0c} = 0$ V, pressure $P_{0c} = 0.1$ MPa, temperature $T_{0c} = 10$°C (ambient). Heat load outlet temperature $T_{Oc} = 50$°C; heat source supply temperature $T_{Sc} = 99.9$°C. A lumped-parameter model is adopted with CHP heat source outlet temperature held constant. Simulation step size is 0.01 s, duration 200 s. Thermal load h_{2f} undergoes a step change from 0.3 MW to 0.32 MW. Using MATLAB, time-varying energy network equations are constructed, solved via fourth-order Runge-Kutta method for state variables, and the proposed exergy analysis method is applied for simulation and discussion.

4.1 Energy Network Equation Formulation Drawing from circuit graph theory, the energy network graph corresponding to Fig. 9 is shown in Fig. 10. Thermal and hydraulic networks share the same graph (common nodes and branches) but contain different components. Dashed lines in Fig. 10(a) represent the return network.

Fig. 10 Diagram of energy network of a regional comprehensive energy system

In the fluid network, state variables are selected based on the number of energy storage elements: pipe-end temperatures for the thermal network, and pipe flow rates and end pressures for the hydraulic network. This yields 16 state variables (6 temperature, 4 pressure, and 6 volume flow variables), enabling 16 equations. Combining with energy coupling elements provides 3 additional equations, totaling 19 state variables and 19 equations. In the electrical network, 2 voltage magnitude variables are set for nodes 1e and 2e, plus 3 voltage angle variables (excluding node 4e). Using generalized Kirchhoff' s laws and exergy power equations, the state equations $f(\cdot)$ and output equations $g(\cdot)$ are:

$$\begin{cases} \dot{x} = f(x, u) \\ y = g(x, u) \end{cases} \qquad (21)$$

4.2 Simulation and Analysis 1) Fluid network state variable dynamic response is shown in Fig. 11, including heat source outlet mass flow M_{out}, heat load 2 inlet mass flow M_{in}, heat source return temperature T_r, and heat load 2 supply temperature $T_{s,\text{load}}$.

Fig. 11 Fluid network state variable response

Fig. 11 shows M_{out} increasing 3.3% from 2.99 kg/s to 3.09 kg/s, while M_{in} rises 6.4% from 1.52 kg/s to 1.62 kg/s. T_r decreases from 49.125°C to 49.101°C then slowly rises, stabilizing at 49.151°C after 100 s. $T_{s,\text{load}}$ drops from 97.14°C to 96.82°C, finally stabilizing at 97.18°C after 90 s. Both temperature changes are minimal (<0.1%). The thermal network exhibits large inertia and long dynamic response times.

Analysis reveals that in thermal networks, temperature changes at heat sources and loads are extremely small, leaving node energy levels essentially unchanged, while water mass flow variations are the primary factor affecting thermal energy quantities at loads and sources.

2) Exergy evolution in the thermal network is shown in Fig. 12, including heat source supply thermal exergy $P_{xh,s}$, heat load h_{2f} consumption thermal exergy $P_{xh,\text{load}}$, heat source unusable energy $P_{h0,s}$, heat load h_{2f} unusable energy $P_{h0,\text{load}}$, and thermal network pipe energy loss $P_{h,\text{pipe}}$.

Fig. 12 Dynamic evolution diagram of exergy in thermal network

Fig. 12 shows heat source supply thermal exergy $P_{xh,s}$ increasing 3.17% from 0.57 MW to 0.59 MW; heat load h_{2f} consumption thermal exergy $P_{xh,\text{load}}$ rising ~6.68% from 0.269 MW to 0.287 MW; heat source unusable energy $P_{h0,s}$ increasing 3.46% from 0.0635 MW to 0.0657 MW; heat load unusable energy $P_{h0,\text{load}}$ rising 6.52% from 0.0309 MW to 0.0329 MW; and pipe energy loss $P_{h,\text{pipe}}$ increasing 7.58% from 0.0343 MW to 0.0369 MW.

The simulation results indicate that the percentage increase in mass flow at the heat source exceeds that of return temperature, so supply thermal energy increases. With constant heat source temperature and unchanged thermal energy level, both heat source supply thermal exergy $P_{xh,s}$ and unusable energy $P_{h0,s}$ increase with thermal energy. At the heat load, supply temperature rise increases thermal energy level, reducing the exergy loss proportion, but this reduction is smaller than the heat load increase magnitude. Consequently, heat load h_{2f} thermal exergy consumption $P_{xh,\text{load}}$ increases while unusable energy $P_{h0,\text{load}}$ also increases. Moreover, unusable energy at the source exceeds pipe energy loss $P_{h,\text{pipe}}$, while unusable energy at the load approximates $P_{h,\text{pipe}}$. This demonstrates that focusing solely on network energy losses is insufficient—unusable energy magnitude also requires attention. In this case, the simulation shows this portion exceeds pipe energy loss proportionally and should not be neglected.

3) To meet the increased load demand, the centrifugal pump outlet must provide more pressure exergy. Fig. 13 shows exergy evolution in the hydraulic/electrical networks and energy coupling elements, including induction motor supply electric exergy $P_{xe,s}$, centrifugal pump outlet pressure exergy

$P_{xp,s}$, pipe pressure energy loss $P_{p,\mathrm{pipe}}$, energy coupling element loss P_{coupling}, and electrical network energy loss $P_{e,\mathrm{pipe}}$.

Fig. 13 Dynamic evolution diagram of exergy in hydraulic/electric power network and energy coupling elements

Fig. 13 shows centrifugal pump outlet pressure exergy $P_{xp,s}$ rising 3.5% from 2,618 W to 2,709 W. The pump' s pressure exergy converts from the induction motor' s electric exergy, with electric exergy $P_{xe,s}$ decreasing 1.08% from 4,527 W to 4,478 W. Increased pipe flow raises pipe pressure energy loss $P_{p,\mathrm{pipe}}$. Initially, as pipe-end pressure decreases over time, the capacitance element absorbs negative power whose absolute value exceeds positive power absorbed by resistance and inductance, making $P_{p,\mathrm{pipe}}$ temporarily negative. Pipe pressure energy loss stabilizes at 3.1 W from an initial 2.8 W—essentially negligible. Total coupling element loss P_{coupling} changes minimally from 1,586.7 W to 1,587.2 W, though the process exhibits significant oscillation from energy storage elements. As heat source supply thermal energy increases, power source electric energy increases accordingly, raising electrical network energy loss $P_{e,\mathrm{pipe}}$ by 9.5% from 0.0337 MW to 0.0369 MW.

Analysis shows that increased thermal load raises energy losses in thermal, hydraulic, electrical networks and coupling elements, with corresponding changes in energy inputs and outputs. Total system energy includes CHP-generated electricity and heat. The energy utilization process involves: (1) electrical network electric energy converting to low-grade thermal energy through resistances, creating exergy loss; (2) thermal network thermal energy losing unusable energy to the environment, with the remainder being thermal exergy that dissipates during fluid flow due to thermal resistance and capacitance, generating new unusable energy losses at loads; (3) energy coupling elements where the induction motor consumes electric energy with mechanical losses during electric-to-mechanical conversion, then drives the centrifugal pump where mechanical energy converts to pressure energy with pressure losses and accompanying unusable energy losses at the pump outlet, finally delivering pressure exergy to drive fluid flow and meet load demand; (4) hydraulic network pipe pressure losses from fluid resistance, inductance, and capacitance that are nearly negligible compared to thermal exergy losses, though the driving pump cannot be ignored. Throughout this integrated energy system' s energy utilization process, energy quality is maintained at essentially constant energy levels while sacrificing greater energy quantity, producing correspondingly more unusable energy.

4) Fig. 14 shows total exergy transfer efficiencies in thermal/electrical networks and energy coupling elements. Thermal network thermal exergy efficiency starts at 94.4%, dynamically oscillates significantly from system energy storage effects, and finally stabilizes at 94.2% (a 0.2% decrease). Heat load h_{2f} output thermal exergy increment exceeds input increment, benefiting from increased pipe flow and temperature, though pipe thermal exergy loss also increases numerically, leaving thermal exergy transfer efficiency unchanged. Electrical network electric exergy efficiency decreases from 93.1% to 92.6% (a 0.5% reduction). Coupling element exergy efficiency increases from 57.8% to 60.5% (a 2.7% gain).

Fig. 14 Exergy efficiency in thermal/electric power network and energy coupling elements

Analysis reveals that coupling element exergy efficiency below 61% implies flow exergy cost exceeds electricity price by at least 1/0.61 times. When coupling element efficiency improves by 2.7%, thermal exergy efficiency doesn't increase, yet electricity quality far exceeds thermal energy quality. Therefore, while improving coupling element exergy efficiency is important, avoiding or reducing energy grade degradation deserves greater consideration. Additionally, increased fluid velocity raises heat transfer coefficients but also increases pressure drop, requiring more pressure exergy compensation from the centrifugal pump. If the relative pressure drop increase is substantial, the cost of higher velocity outweighs the benefits. Thus, benefits under different operating conditions cannot be generalized, and flow rates are typically rated for most operating conditions rather than short-term maximums from energy storage effects. Larger pipe diameters can increase flow rates, obtain more thermal exergy, and reduce flow energy losses, but also increase equipment costs, requiring trade-off considerations.

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5. Conclusions and Outlook

This paper analyzes the dynamic evolution mechanism of exergy in time-varying energy networks based on energy network theory. Starting from universal exergy formulas and combining energy level definitions, exergy balance equations in time-varying energy networks are derived. Simulation of a CHP integrated energy system under load disturbances yields the following conclusions and outlook:

1) The dynamic evolution mechanism of exergy in networks can analyze quality degradation and losses during different energy transfer and conversion processes, compensating for energy analysis that only addresses quantity losses, and providing reasonable guidance for improving energy system efficiency.
2) As integrated energy system uncertainties increase, the proposed energy network theory-based analysis method provides theoretical foundation and simulation approaches for studying system energy efficiency during nonsteady processes.
3) Exergy efficiency should be promoted as a comprehensive benefit evaluation index for integrated energy systems. The difference in calculation methods between exergy efficiency and energy efficiency means optimization results targeting each will necessarily differ. Truly achieving energy cascade utilization must consider exergy efficiency indicators.

4) Maximum exergy efficiency doesn' t guarantee minimum total operating costs. Building upon this paper's dynamic exergy behavior analysis, exergy economics principles can be referenced to construct exergy-based economic indicators.

This research establishes theoretical foundations for multi-objective optimization of integrated energy systems considering energy efficiency and exergy economic costs, holding profound significance for integrated energy system optimal operation, planning, and integrated energy services.

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Note: Figure translations are in progress. See original paper for figures.