

Quantity and Quality: A Standard Reporting Framework for Energy Systems

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Abstract

Energy systems are conventionally reported using scalar energy quantities (joules, kilowatt-hours, megawatt-hours, quads, barrels-of-oil-equivalent, etc.) or power rates (watts, kilowatts, megawatts). This first-law convention is simple and universally adopted, yet it systematically conceals the second-law distinction between energy quantity and accessible work potential. Classical exergy analysis restores this distinction, but reference-state dependence, carrier-specific terminology, and cumbersome formulations have prevented it from becoming a routine operational reporting layer in multi-carrier energy systems.

This paper introduces a standard two-number reporting framework that closes the gap. Every reported energy quantity—whether primary consumption, delivered electricity, fuel inventory, storage asset, or flowing stream—is reported as quantity plus Exergy Factor:

- accumulated energy quantity: (E, f_X)
- power rate: (P, f_X)

where $f_X = X_A/E = \dot{X}_A/P$ is the accessible exergy per unit energy (or per unit power) evaluated at a declared reporting boundary. The framework defines the carrier-level intensive variable as the *exergy voltage*, $\Delta\Phi_A^{(C)} = dX_A/dC$, which yields the universal exergy-flow law $\dot{X}_A = \dot{C} \Delta\Phi_A^{(C)} = f_X P = f_X \dot{E}$. This generalizes voltage-like potentials across electricity, entropy flow (thermal streams), chemical potential, pressure, and mass flow, while cleanly separating stream quality from process irreversibility (second-law efficiency η_X and exergy destruction $\dot{X}_{\text{dest}} = T_0 \dot{S}_{\text{gen}}$).

For thermal streams, entropy is the natural carrier and temperature difference is the thermal exergy voltage, giving the Carnot-form Exergy Factor $f_{X,Q} = 1 - T_c/T_h$. For chemical carriers, an explicit energy-basis convention (LHV, HHV, or tabulated chemical exergy) ensures the factor is unambiguous. Reference dependence is handled transparently through declared conventions (standard for comparability, local/dynamic for dispatch), and the framework is fully compatible with existing standards for energy management (ISO 50001), measurement and verification (IPMVP), life-cycle assessment (ISO 14040), dispatch, and market pricing.

The central practical claim is that supply, demand, storage, and conversion pathways must be matched by both quantity and Exergy Factor. This two-number representation makes visible—and therefore avoidable—the destruction or stranding of work potential that scalar energy accounting hides. Building on the exergy-voltage idea of Li et al. [9] for regional integrated energy systems, this paper proposes the first operational reporting standard that turns exergy voltage into routine practice—compatible with ISO 50001, IPMVP, and ISO 14040—and a sharper lens for the global energy transition.

Keywords: exergy; Exergy Factor; **exergy voltage**; power quality; multi-carrier energy systems; energy quality; **reporting standard**; global energy transition.

Quick Reference

Two-number reporting. Every energy quantity or power rate is reported as quantity plus Exergy Factor:

$$\begin{aligned} \text{accumulated energy: } \mathcal{S}_E &= (E, f_X), \\ \text{power rate: } \mathcal{S}_P &= (P, f_X), \quad P = \dot{E}. \end{aligned}$$

Exergy Factor.

$$f_X = \frac{X_A}{E} = \frac{\dot{X}_A}{P}.$$

f_X is accessible exergy per unit energy (or per unit power) at a declared reporting boundary.

Exergy voltage (carrier-level intensive variable). For carrier C with current \dot{C} ,

$$\Delta\Phi_A^{(C)} = \frac{dX_A}{dC}.$$

Universal exergy-flow law.

$$\dot{X}_A = \dot{C} \Delta\Phi_A^{(C)} = f_X P = f_X \dot{E}.$$

Thermal streams (entropy as carrier, sink T_c , source T_h):

$$\Delta\Phi_A^{(S)} = T_h - T_c, \quad f_{X,Q} = 1 - \frac{T_c}{T_h}.$$

Process performance (kept separate from stream quality):

$$\eta_X = \frac{\text{useful exergy output}}{\text{accessible exergy input}}, \quad \dot{X}_{\text{dest}} = T_0 \dot{S}_{\text{gen}} \geq 0.$$

Reference Exergy Factors (illustrative, sink at 20°C unless noted):

Electricity, mechanical shaft work $f_X \approx 1.000$

Heat at 150°C $f_X = 0.307$

Heat at 80°C $f_X = 0.170$

Heat at 40°C $f_X = 0.064$

Methane, LHV basis $f_X^{\text{LHV}} \approx 1.04$

Methane, HHV basis $f_X^{\text{HHV}} \approx 0.93$

Hydrogen, LHV basis $f_X^{\text{LHV}} \approx 0.98$

Hydrogen, HHV basis $f_X^{\text{HHV}} \approx 0.83$

Matching rule. Supply $(P_s, f_{X,s})$ and demand $(P_d, f_{X,d})$ should be matched in both quantity ($P_s \approx P_d$) and Exergy Factor ($f_{X,s} \approx f_{X,d}$).

1 Introduction

Modern energy systems are increasingly multi-carrier systems. Electricity, heat, hydrogen, chemical fuels, compressed gases, thermal storage, batteries, district heating networks, and industrial waste heat coexist within the same planning and control problem. Yet most operational and policy-level accounting still reports energy as a scalar quantity. A building requires kilowatt-hours; a grid produces megawatt-hours; a waste-heat source is reported in megawatt-hours; a storage asset is rated in megawatt-hours. This representation is compatible with the first law of thermodynamics, but it is incomplete for energy-system design because it hides work potential.

The same issue appears in power reporting. A plant may consume megawatts, a heat loop may deliver megawatts thermal, and an electricity tariff may charge for peak kilowatts. These power quantities describe rate, but not quality. A megawatt of electricity, a megawatt of 80°C heat, and a megawatt of 40°C heat are not equivalent useful-work resources. They may move at the same first-law rate, but they do not carry the same accessible work-potential rate.

Exergy is the standard thermodynamic concept for work potential. In classical engineering, exergy is the maximum useful work obtainable as a system comes into equilibrium with a reference environment [8, 1, 12]. The strength of exergy is that it combines energy quantity and energy quality. The weakness is that it is relational: its value depends on the reference environment, sink, service, boundary, and feasible conversion path. This is not an error in the concept. It is the concept. Exergy is not an intrinsic scalar like internal energy; it is a property of a system in relation to an environment, sink, service, or allowed conversion pathway. The literature has long recognized both the usefulness of exergy and the practical difficulty of reference-environment selection [5, 2].

This paper treats that relational character as the foundation for a practical reporting framework rather than as an obstacle.

Principle 1: Relational work potential. Exergy is fundamentally relational, not absolute. It measures accessible difference: useful work potential exists only when a system has an accessible gradient relative to a sink, service, boundary condition, or allowed conversion path.

The proposed reporting standard represents every accumulated energy stream with two numbers:

$$\mathcal{S}_E = (E, f_X), \quad (1)$$

or, for power rates,

$$\mathcal{S}_P = (P, f_X), \quad P = \dot{E}. \quad (2)$$

Here E is energy quantity, P is power, and f_X is the Exergy Factor. The Exergy Factor is accessible exergy per unit energy, or accessible exergy rate per unit power:

$$f_X = \frac{X_A}{E}, \quad f_X = \frac{\dot{X}_A}{P} = \frac{\dot{X}_A}{\dot{E}}. \quad (3)$$

Thus,

$$X_A = f_X E, \quad \dot{X}_A = f_X P = f_X \dot{E}. \quad (4)$$

A stream reported as 100 MWh is therefore incomplete. Under the proposed standard it would be reported as, for example,

$$(100 \text{ MWh}, f_X = 0.17), \quad (5)$$

which immediately implies

$$X_A = 17 \text{ MWh}_{\text{ex}}. \quad (6)$$

Likewise, a 10 MW stream at the same Exergy Factor would be reported as

$$(10 \text{ MW}, f_X = 0.17), \quad (7)$$

which implies

$$\dot{X}_A = 1.7 \text{ MW}_{\text{ex}}. \quad (8)$$

The same logic applies to any reported energy quantity, not only flowing streams. Whether the number on the page is a primary-energy total, a delivered electricity figure, a fuel inventory, a stored kWh, or an instantaneous flow, the framework pairs it with an Exergy Factor:

- Electricity delivered: (1 MWh, $f_X \approx 1.00$)
- 80°C district heat: (1 MWh, $f_X = 0.170$)
- 40°C low-grade heat: (1 MWh, $f_X = 0.064$)
- Primary natural-gas consumption (LHV basis): (1 TWh_{LHV}, $f_X^{\text{LHV}} \approx 1.04$)
- Crude-oil primary energy in barrels-of-oil-equivalent: (BoE, f_X) on the declared energy basis.

The unit attached to E is whatever unit is already in use by the reporter—joules, kilowatt-hours, megawatt-hours, terawatt-hours, quads, barrels-of-oil-equivalent, billion cubic feet converted to TWh, tonnes of coal converted to GJ, and so on—and the Exergy Factor expresses what fraction of that first-law quantity is accessible useful work.

The contribution is not that the ratio X/E has never appeared in exergy literature. Related concepts include energy quality factor, energy grade, exergy ratio, and exergy index [2]. Nor is the contribution that voltage-like analogies have never been used in integrated energy systems; prior work has proposed exergy-voltage, exergy-potential difference, and exergy-impedance for regional integrated energy systems [9]. The contribution is the systematic coupling of three elements: a carrier-agnostic intensive potential, a normalized two-number descriptor applicable to any reported energy quantity, and explicit supply-demand matching by work potential.

The practical thesis is:

$$\text{Energy quantities should not be reported alone.} \quad (9)$$

Instead,

$$\text{Every reported energy quantity should carry its Exergy Factor.} \quad (10)$$

This enables energy systems to match both quantity and work-potential grade.

2 Background: Energy Quantity, Exergy, and Reference Dependence

Energy is conserved. Exergy is not. The distinction follows directly from the first and second laws of thermodynamics. In a process that generates entropy, useful work potential is destroyed even though total energy is conserved. For a reference environment at T_0 , the Gouy–Stodola theorem gives

$$X_{\text{dest}} = T_0 S_{\text{gen}}, \quad (11)$$

and, in rate form,

$$\dot{X}_{\text{dest}} = T_0 \dot{S}_{\text{gen}} \geq 0. \quad (12)$$

For a simple closed system relative to an environment (T_0, p_0) , physical exergy is commonly written as

$$X = (U - U_0) + p_0(V - V_0) - T_0(S - S_0), \quad (13)$$

with chemical, kinetic, and potential contributions added as required. For a steady-flow stream, the specific flow exergy is commonly expressed as

$$\psi = (h - h_0) - T_0(s - s_0) + \sum_i (\mu_i - \mu_{i,0})x_i + \frac{v^2}{2} + gz. \quad (14)$$

These formulas are indispensable for detailed engineering calculations, but they can be cumbersome as a universal reporting language for multi-carrier energy systems. The immediate difficulty is reference dependence. A stream can have zero exergy relative to one environment and positive exergy relative to another. This implies a key conceptual correction:

$$\text{Exergy is not absolute energy. Exergy is accessible difference.} \quad (15)$$

Prior analyses of exergy reference environments show that reference selection is not merely a numerical detail; it affects interpretation, comparison, and sustainability decisions [5]. Energy quality and energy grade literature likewise recognizes ambiguity in terminology and benchmark selection, while also emphasizing the need to extend energy-quality concepts to more general forms of energy [2]. While prior work has proposed exergy-voltage analogies for modeling regional integrated energy systems [9], this paper makes the concept routine by pairing it with a universal two-number stream descriptor and an explicit supply–demand matching rule. The framework proposed here preserves the relational nature of exergy while making reporting simple enough for energy-system operation.

3 Core Definitions

Definition 1: Accessible exergy. Accessible exergy, X_A , is the useful work potential of a stream at a specified reporting boundary, relative to the declared reference sink, service requirement, carrier definition, and operational constraints of the system being analyzed.

The word *accessible* is retained in X_A because the reporting boundary and reference sink must be declared. It is not retained in the name of the normalized reporting variable. The proposed normalized variable is simply the Exergy Factor.

Definition 2: Exergy Factor. The Exergy Factor f_X of an energy stream is accessible exergy per unit energy:

$$f_X = \frac{X_A}{E}. \quad (16)$$

For a power flow, the same factor is accessible exergy rate per unit power:

$$f_X = \frac{\dot{X}_A}{P} = \frac{\dot{X}_A}{\dot{E}}. \quad (17)$$

Its reporting unit is J_{ex}/J , MW_{ex}/MW , or MWh_{ex}/MWh , depending on whether the stream is reported as a rate or an accumulated quantity.

Definition 3: Two-number energy and power reporting. Any reported energy quantity is represented by

$$\mathcal{S}_E = (E, f_X), \quad (18)$$

and any power rate by

$$\mathcal{S}_P = (P, f_X), \quad P = \dot{E}. \quad (19)$$

Here E is the conventional first-law energy quantity in whatever unit is already used for reporting or accounting (J, kWh, MWh, TWh, quads, barrels-of-oil-equivalent, billion cubic feet converted to an energy unit, tonnes of coal converted to GJ, and so on), and P is the corresponding power

rate. The quantity E may be accumulated over an interval, integrated from a flowing stream, drawn from a storage inventory, or aggregated as a primary-energy total—the framework is agnostic to which. The accessible exergy or accessible exergy rate is recovered directly by

$$X_A = f_X E, \quad \dot{X}_A = f_X P = f_X \dot{E}. \quad (20)$$

No separate quality factor is required for power; the Exergy Factor applies identically to both accumulated quantities and instantaneous rates.

Definition 4: Exergy voltage. Building on the exergy-voltage concept introduced by Li et al. [9] for regional integrated energy systems, the carrier-level intensive variable of this framework is the *exergy voltage*: for a carrier C ,

$$\Delta\Phi_A^{(C)} = \frac{dX_A}{dC}. \quad (21)$$

The unit is J_{ex} per unit carrier. This voltage-like potential generalizes across all carriers (electricity, entropy, chemical species, pressure, mass) and forms the foundation of the proposed reporting framework.

Proposition 1: Carrier-normalized exergy flow. If exergy is transported by a carrier C with carrier current \dot{C} , then

$$\dot{X}_A = \dot{C} \Delta\Phi_A^{(C)}. \quad (22)$$

Proof. From the definition $\Delta\Phi_A^{(C)} = dX_A/dC$. Differentiating X_A with respect to time gives

$$\frac{dX_A}{dt} = \frac{dX_A}{dC} \cdot \frac{dC}{dt} = \Delta\Phi_A^{(C)} \dot{C}. \quad \blacksquare \quad (23)$$

Combining the carrier-normalized form with the energy- and power-normalized forms yields the central equation of the framework:

$$\dot{X}_A = \dot{C} \Delta\Phi_A^{(C)} = f_X P = f_X \dot{E}. \quad (24)$$

This equation is the generalized analogue of electrical power:

$$\dot{W} = I \Delta V. \quad (25)$$

Electrical voltage is therefore one special case of a broader exergy-potential family.

4 Reference-State Handling and Dynamic Exergy Factors

The framework does not eliminate reference dependence. It standardizes how reference dependence is reported. Because exergy is relational, a value of f_X is not complete unless the reference convention is declared. A practical report should therefore record the stream as

$$\mathcal{S} = (E, f_X \mid R, B, O) \quad (26)$$

or, for power,

$$\mathcal{S}_P = (P, f_X \mid R, B, O), \quad (27)$$

where R is the reference sink or environment, B is the measurement boundary, and O is the class of operationally available conversion paths. The public-facing reporting interface remains two numbers, but the metadata specify how f_X was computed.

Organizations may choose different reference conventions for different purposes. For cross-project inventories, a fixed standard environment such as $T_0 = 298.15$ K and $p_0 = 101.325$ kPa can improve comparability. For operational dispatch, a local reference is often more physically

meaningful: the local ambient temperature, a district-heating return temperature, a condenser temperature, a chilled-water loop, a seasonal ground temperature, or another actual sink. The framework remains valid in each case because f_X is a relational quantity. Changing the sink changes the Exergy Factor just as changing the electrical reference node changes a reported voltage.

This suggests two implementation rules.

- 1. Comparable reporting rule.** When comparing organizations, assets, or life-cycle inventories, use a declared standard reference convention and report it with the stream metadata.
- 2. Operational dispatch rule.** When dispatching, controlling, or valuing a local energy system, use the actual accessible sink or service boundary, because that is the reference state that determines real work potential.

Dynamic operation does not weaken the framework. It simply turns Exergy Factor into a time series. For a time-varying stream,

$$f_X(t) = \frac{\dot{X}_A(t)}{P(t)} = \frac{\dot{C}(t) \Delta\Phi_A^{(C)}(t)}{\dot{E}(t)}. \quad (28)$$

Over a reporting interval Δt , the exergy-weighted average Exergy Factor is

$$\bar{f}_{X,\Delta} = \frac{\int_{\Delta} f_X(t) \dot{E}(t) dt}{\int_{\Delta} \dot{E}(t) dt}, \quad (29)$$

provided the denominator is nonzero. For thermal dispatch,

$$f_{X,Q}(t) = 1 - \frac{T_{\text{sink}}(t)}{T_{\text{source}}(t)}. \quad (30)$$

Thus a district heating operator can compute $f_{X,Q}(t)$ from measured supply and return temperatures, while a building operator can compute it from supply temperature and an ambient or service sink convention. A market could report both a standard Exergy Factor for comparability and an operational Exergy Factor for real-time dispatch.

This dual reporting resolves a common objection. Fixed 25°C reference conditions are useful for comparability, while local time-varying reference conditions are useful for operations. The proposed standard allows both, as long as the reference convention is declared.

5 Carrier Family and Units

Different energy carriers naturally have different potential units. Electricity uses volts, chemistry uses joules per mole, pressure uses pascals, mass-flow potentials use joules per kilogram, and heat can use kelvin when entropy is the carrier. All of them can be normalized into the same Exergy Factor f_X .

Table 1: Carrier-specific exergy voltage units and exergy-flow forms.

Carrier C	Carrier current \dot{C}	Exergy voltage $\Delta\Phi_A^{(C)}$	Unit	Exergy flow
Electric charge	$I = \dot{q}$	Electric potential difference ΔV	$\text{J/C} = \text{V}$	$\dot{X}_A = I \Delta V$
Entropy	\dot{S}	Temperature difference $T_h - T_c$	$\text{J}/(\text{J/K}) = \text{K}$	$\dot{X}_A = \dot{S}(T_h - T_c)$
Mole amount	\dot{n}_i	Chemical potential difference $\Delta\mu_i$	J/mol	$\dot{X}_A = \sum_i \dot{n}_i \Delta\mu_i$
Volume	\dot{V}	Pressure difference Δp	$\text{J/m}^3 = \text{Pa}$	$\dot{X}_A = \dot{V} \Delta p$
Mass	\dot{m}	Specific work potential $\Delta\psi$	J/kg	$\dot{X}_A = \dot{m} \Delta\psi$

Table 1 should not be read as implying that every carrier is identical. It shows a common structure: exergy flow equals carrier current times accessible potential difference. The carrier determines the natural unit of potential. The reporting layer then converts those carrier-specific potentials into a common normalized factor, $f_X = X_A/E$ or $f_X = \dot{X}_A/P$.

6 Thermal Streams: Entropy as the Carrier

Thermal energy is often reported as heat, Q , but entropy is the more natural carrier for thermal exergy. Heat is energy transferred because of a temperature difference. Entropy is the extensive quantity whose flow reveals the work potential of that temperature difference. For reversible heat transfer,

$$\delta Q_{\text{rev}} = T dS. \quad (31)$$

For a heat source at T_h and a sink at T_c , the maximum reversible work rate is

$$\dot{X}_A = \dot{Q} \left(1 - \frac{T_c}{T_h} \right). \quad (32)$$

Using $\dot{Q} = T_h \dot{S}$ gives

$$\dot{X}_A = T_h \dot{S} \left(1 - \frac{T_c}{T_h} \right) = \dot{S}(T_h - T_c). \quad (33)$$

Thus,

$$\Delta\Phi_A^{(S)} = T_h - T_c. \quad (34)$$

Principle 2: Thermal exergy voltage. When entropy is the carrier, temperature difference is the thermal exergy voltage: $\Delta\Phi_A^{(S)} = T_h - T_c$.

The Exergy Factor for heat is

$$f_{X,Q} = \frac{\dot{X}_A}{\dot{Q}} = 1 - \frac{T_c}{T_h}. \quad (35)$$

This is the Carnot factor. It is also the simplest form of the quantity-plus-Exergy-Factor reporting standard for thermal streams.

Entropy clarifies why heat quality changes with temperature. One megawatt-hour of electricity can ideally become one megawatt-hour of work. One megawatt-hour of heat cannot generally

become one megawatt-hour of work because heat carries entropy. The usable part is the part associated with an entropy flow crossing a temperature potential difference. Internally generated entropy has no corresponding useful potential difference; it increases the amount of energy that must be rejected and reduces the work obtainable from the same first-law energy quantity. This is why exergy destruction is proportional to entropy generation.

For example, let the sink be $T_c = 20^\circ\text{C} = 293.15\text{ K}$. Heat delivered at $T_h = 80^\circ\text{C} = 353.15\text{ K}$ has

$$f_{X,Q} = 1 - \frac{293.15}{353.15} = 0.170. \quad (36)$$

Therefore,

$$1\text{ MWh of } 80^\circ\text{C heat} \rightarrow 0.170\text{ MWh}_{\text{ex}}. \quad (37)$$

The same heat stream reported as power would be

$$1\text{ MW of } 80^\circ\text{C heat} \rightarrow 0.170\text{ MW}_{\text{ex}}. \quad (38)$$

Heat delivered at $40^\circ\text{C} = 313.15\text{ K}$ relative to the same sink has

$$f_{X,Q} = 1 - \frac{293.15}{313.15} = 0.064, \quad (39)$$

so

$$1\text{ MWh of } 40^\circ\text{C heat} \rightarrow 0.064\text{ MWh}_{\text{ex}}. \quad (40)$$

The energy quantity is the same in both cases. The work potential is not.

This example exposes why scalar energy accounting is structurally incomplete. A megawatt-hour of electricity, a megawatt-hour of 80°C heat, and a megawatt-hour of 40°C heat are not equivalent streams. Under the proposed reporting framework, they would be reported as approximately

$$\text{electricity: } (1\text{ MWh}, f_X \approx 1), \quad (41)$$

$$80^\circ\text{C heat: } (1\text{ MWh}, f_X = 0.170), \quad (42)$$

$$40^\circ\text{C heat: } (1\text{ MWh}, f_X = 0.064). \quad (43)$$

7 Chemical Carriers and Energy-Basis Convention

Chemical carriers are essential to any multi-carrier energy standard because fuels, hydrogen, ammonia, synthetic hydrocarbons, biomass, and chemical process streams store work potential in composition.

For a reacting or mixing stream, chemical exergy is associated with chemical-potential differences relative to a declared reference environment. In carrier form,

$$\dot{X}_{A,\mu} = \sum_i \dot{n}_i \Delta\mu_i, \quad (44)$$

where $\Delta\mu_i = \mu_i - \mu_{i,R}$ is the chemical potential difference between the stream and the reference convention. For a tabulated standard chemical exergy e_{ch} on a mass basis,

$$\dot{X}_{A,\mu} = \dot{m} e_{\text{ch}}. \quad (45)$$

The Exergy Factor for a chemical carrier is then

$$f_{X,\mu}^{(B)} = \frac{e_{\text{ch}}}{h_B}, \quad (46)$$

where h_B is the declared energy basis. Common choices include lower heating value, higher heating value, Gibbs free energy of reaction, or another process-specific first-law denominator. The superscript (B) is optional in ordinary stream reports but should be used whenever ambiguity is possible.

This convention is necessary because chemical energy quantities are often reported using heating-value conventions rather than a unique universal denominator. As a result, a chemical Exergy Factor can exceed unity when the denominator is lower heating value. This does not violate the second law. It means the denominator is a selected accounting basis, not an absolute total energy inventory. To avoid confusion, a chemical stream report should always identify both the Exergy Factor and its basis:

$$(E, f_X^{\text{LHV}}) \quad \text{or} \quad (E, f_X^{\text{HHV}}). \quad (47)$$

Standard chemical exergy tables are themselves reference-dependent and are typically based on a model of the atmosphere, hydrosphere, and lithosphere at standard conditions [10, 12, 11]. This is consistent with the proposed framework. The reference convention is declared, and the resulting work-potential factor is reported.

Table 2: Illustrative chemical Exergy Factors under different energy bases. Values are rounded engineering figures at standard conditions, using tabulated chemical exergy and common heating-value data. The example shows why the energy basis must be declared.

Fuel	Chemical ex- ergy	LHV basis	HHV basis	Reporting impli- cation
Hydrogen, H ₂	$e_{\text{ch}} \approx$ 117.1 MJ/kg	$h_{\text{LHV}} \approx$ 120.0 MJ/kg, $f_X^{\text{LHV}} \approx 0.98$	$h_{\text{HHV}} \approx$ 141.8 MJ/kg, $f_X^{\text{HHV}} \approx 0.83$	Same fuel, differ- ent factor because the denominator changes.
Methane, CH ₄	$e_{\text{ch}} \approx$ 51.9 MJ/kg	$h_{\text{LHV}} \approx$ 50.0 MJ/kg, $f_X^{\text{LHV}} \approx 1.04$	$h_{\text{HHV}} \approx$ 55.5 MJ/kg, $f_X^{\text{HHV}} \approx 0.93$	$f_X^{\text{LHV}} > 1$ is a basis effect, not a claim of more- than-complete work conversion.

For market and policy interfaces that prefer a bounded factor, HHV is often the cleaner denominator for combustion fuels because it includes the condensation energy of product water. For device comparison in industries that already use LHV, f_X^{LHV} may be acceptable, provided it is labeled. The proposed standard does not force one denominator across all chemical applications. It requires the denominator to be declared. This basis distinction explains why hydrogen policy debates frequently conflate LHV/HHV energy claims with actual work potential.

The Exergy Factor is always computed on the declared energy basis of the reported quantity E (LHV, HHV, or another process-specific denominator). This ensures the framework works seamlessly with existing primary-energy statistics that report natural gas in volume, oil in barrels, or coal in mass: the quantity E is first converted to the chosen energy unit (TWh, GJ, BoE, etc.), then paired with its f_X on the same basis. No new physical-unit conventions are required for adoption.

Chemical Exergy Factors also vary slightly with environmental composition, temperature, pressure, and humidity. For gaseous fuels, sensitivity studies show that chemical exergy varies with ambient conditions, with hydrogen being more sensitive than methane [4]. This supports the same implementation logic used for thermal streams: fixed standard values are appropriate for cross-project comparison, while local or time-varying values are appropriate for operational dispatch when the variation matters.

8 Supply-Demand Matching in Quantity and Exergy Factor

The reporting framework becomes most powerful when applied to both sides of an energy transaction. A supply stream can be represented in rate form as

$$\mathcal{S} = (P_s, f_{X,s}), \quad (48)$$

and a demand or service requirement as

$$\mathcal{D} = (P_d, f_{X,d}). \quad (49)$$

Energy systems should match both quantity and Exergy Factor:

$$P_s \approx P_d, \quad (50)$$

and

$$f_{X,s} \approx f_{X,d}. \quad (51)$$

The same logic applies over a reporting interval by replacing P with accumulated energy E .

Principle 3: Quantity-factor matching. Energy systems should match both energy or power quantity and Exergy Factor.

Three cases follow immediately:

1. **Good match:** $f_{X,s} \approx f_{X,d}$. The supply has the right quantity and the right work-potential grade for the demand.
2. **Wasteful match:** $f_{X,s} \gg f_{X,d}$. A high-exergy source is used for a low-exergy service. The service may be satisfied, but excess work potential is destroyed, stranded, or degraded unless cascaded to another use.
3. **Insufficient match:** $f_{X,s} < f_{X,d}$. The supply cannot satisfy the demanded work-potential grade without an upgrading process, such as a heat pump, compressor, electrolyzer, or other conversion device.

A simple mismatch index is

$$\Delta f_X = f_{X,s} - f_{X,d}. \quad (52)$$

For a matched power quantity P_m , the avoidable exergy oversupply associated with using a higher-grade source for a lower-grade demand is

$$\dot{X}_{\text{mismatch}} = P_m \max(0, f_{X,s} - f_{X,d}). \quad (53)$$

For an interval quantity E_m , the corresponding accumulated mismatch is

$$X_{\text{mismatch}} = E_m \max(0, f_{X,s} - f_{X,d}). \quad (54)$$

This quantity is not automatically destroyed. A system with cascaded heat recovery, storage, or multi-service dispatch may use it elsewhere. But if no such pathway exists, the mismatch becomes exergy destruction or exergy loss.

The most common example is low-temperature heating. Electricity has $f_X \approx 1$ at the point of use because electrical work can be converted completely into other forms of work under ideal conditions. Low-temperature space heat may have f_X between roughly 0.03 and 0.15, depending on source and sink temperatures. Direct electric resistance heating can satisfy the energy quantity but is usually a poor Exergy Factor match. A heat pump is superior because it uses a smaller quantity of high- f_X work to upgrade a larger quantity of low- f_X heat, thereby improving the service delivered per unit of exergy consumed.

9 Separating Stream Factor from Process Irreversibility

A critical feature of the proposed framework is that stream reporting and process performance remain separate. The stream descriptor is

$$\mathcal{S} = (E, f_X) \quad \text{or} \quad \mathcal{S}_P = (P, f_X). \quad (55)$$

The process descriptor is

$$\eta_X, \dot{X}_{\text{dest}}. \quad (56)$$

Definition 5: Second-law efficiency. For a conversion process, define the exergy efficiency as

$$\eta_X = \frac{\text{useful exergy output}}{\text{accessible exergy input}}. \quad (57)$$

For a reversible process,

$$\eta_X = 1, \quad (58)$$

and

$$\dot{X}_{\text{dest}} = 0. \quad (59)$$

For an irreversible process,

$$\eta_X < 1, \quad (60)$$

and

$$\dot{X}_{\text{dest}} > 0. \quad (61)$$

The exergy destruction is

$$\dot{X}_{\text{dest}} = T_0 \dot{S}_{\text{gen}}. \quad (62)$$

The accounting sequence is therefore

$$E \longrightarrow X_A = f_X E \longrightarrow X_{\text{useful,out}} = \eta_X X_A, \quad (63)$$

or, in rate form,

$$P \longrightarrow \dot{X}_A = f_X P \longrightarrow \dot{X}_{\text{useful,out}} = \eta_X \dot{X}_A. \quad (64)$$

The first arrow is a stream reporting operation. The second arrow is a process performance operation.

This separation resolves an ambiguity that often appears when exergy-quality concepts are applied operationally. The Exergy Factor describes the stream at a specified reporting boundary. Reversibility describes the process that transforms one stream into another. A stream can have high f_X and still be wasted in an irreversible device. A stream can have low f_X and still be valuable if it is well matched to a low- f_X demand.

10 Concrete Numerical Illustrations

Table 3 shows simple illustrative stream reports. The exact value of f_X depends on the reporting boundary and reference sink. The purpose of the table is to show how streams become immediately comparable when energy quantity and Exergy Factor are reported together.

Table 3: Illustrative two-number stream reports. Thermal values use a sink at 20°C unless noted.

Stream	Conventional report	Two-number report
Electricity	1 MWh or 1 MW	(1 MWh, $f_X \approx 1.000$) or (1 MW, $f_X \approx 1.000$)
Heat at 40°C	1 MWh _{th}	(1 MWh, $f_X = 0.064$)
Heat at 80°C	1 MWh _{th}	(1 MWh, $f_X = 0.170$)
Heat at 150°C	1 MWh _{th}	(1 MWh, $f_X = 0.307$)
Mechanical shaft work	1 MWh	(1 MWh, $f_X \approx 1.000$)
Methane, LHV basis	1 MWh _{LHV}	(1 MWh, $f_X^{\text{LHV}} \approx 1.04$)
Hydrogen, LHV basis	1 MWh _{LHV}	(1 MWh, $f_X^{\text{LHV}} \approx 0.98$)

10.1 Low-temperature heat: resistance heating versus heat pump

Consider a demand for 1.00 MWh of heat delivered at 40°C to a sink at 20°C. From Eq. (31), the service Exergy Factor is

$$f_{X,d} = 1 - \frac{293.15}{313.15} = 0.064. \quad (65)$$

Thus the demanded useful exergy service is

$$X_d = (1.00 \text{ MWh})(0.064) = 0.064 \text{ MWh}_{\text{ex}}. \quad (66)$$

Now compare electric resistance heating and a heat pump with coefficient of performance COP = 3.

Table 4: Two-number comparison of resistance heating and a heat pump for 1.00 MWh of 40°C heat, with $T_c = 20^\circ\text{C}$.

Case	Input exergy	Delivered service exergy	η_X	Key result
Resistance heat	1.00 MWh _{ex}	0.064 MWh _{ex}	6.4%	Satisfies the heat quantity but uses high-grade electricity for a low-grade service. Unmatched input exergy is about 0.936 MWh _{ex} .
Heat pump, COP = 3	0.333 MWh _{ex}	0.064 MWh _{ex}	19.2%	Provides the same heat service with 0.667 MWh _{ex} less high-grade input than resistance heating.

This example does not claim the heat pump is reversible. It separates the stream report from the process efficiency. The heat pump's second-law efficiency is COP/COP_{Carnot}, where

$$\text{COP}_{\text{Carnot}} = \frac{T_h}{T_h - T_c} = \frac{313.15}{20} = 15.66, \quad (67)$$

so COP = 3 gives

$$\eta_X \approx \frac{3}{15.66} = 0.192. \quad (68)$$

This is the same value obtained by dividing the useful heat-service exergy by the electrical exergy input. The point is not that the heat pump eliminates irreversibility. The point is that the two-number framework reveals the large exergy penalty of using high-grade electricity directly for low-grade heat.

10.2 District heating cascade

Consider a district heating network with 1.00 MWh of total heat demand composed of two services: 0.40 MWh at 80°C and 0.60 MWh at 40°C, with the same 20°C sink. The Exergy Factors are

$$f_X(80^\circ\text{C}) = 0.170, \quad (69)$$

and

$$f_X(40^\circ\text{C}) = 0.064. \quad (70)$$

If the whole network is supplied uniformly at 80°C, the stream report is

$$(1.00 \text{ MWh}, 0.170), \quad (71)$$

with 0.170 MWh_{ex} supplied. If the network uses grade-matched cascade reporting, the service requirement is

$$(0.40 \text{ MWh}, 0.170) + (0.60 \text{ MWh}, 0.064), \quad (72)$$

with service exergy

$$X_d = (0.40)(0.170) + (0.60)(0.064) = 0.106 \text{ MWh}_{\text{ex}}. \quad (73)$$

The mismatch hidden by a single-temperature report is approximately

$$X_{\text{mismatch}} = 0.170 - 0.106 = 0.064 \text{ MWh}_{\text{ex}}. \quad (74)$$

Table 5: District heating example showing the mismatch index. The single-temperature strategy reports all heat at 80°C; the cascade strategy reports service-specific Exergy Factors.

Strategy	Two-number report	Exergy accounted	Implication
Single-temperature supply	(1.00 MWh, 0.170)	0.170 MWh _{ex}	Treats all demand as if it required 80°C heat. This hides over-grade heat delivered to lower-temperature loads.
Grade-matched cascade	(0.40 MWh, 0.170) + (0.60 MWh, 0.064)	0.106 MWh _{ex}	Reveals the lower work-potential requirement of the mixed service portfolio. Approximate avoidable mismatch: 0.064 MWh _{ex} .

The cascade example is deliberately simple, but it demonstrates the operational value of the reporting standard. A district heating network can satisfy the same first-law heat demand while using less high-grade work potential if supply temperatures, return temperatures, storage, and heat pumps are dispatched according to Exergy Factor rather than heat quantity alone.

10.3 Chemical stream example: methane versus hydrogen basis effects

The chemical example in Table 2 can be stated as a stream report. If 1.00 MWh of methane is reported on an LHV basis, then using $f_X^{\text{LHV}} \approx 1.04$ gives

$$(1.00 \text{ MWh}_{\text{LHV}}, f_X^{\text{LHV}} = 1.04) \Rightarrow X_A \approx 1.04 \text{ MWh}_{\text{ex}}. \quad (75)$$

If the same methane fuel is reported on an HHV basis, then

$$(1.00 \text{ MWh}_{\text{HHV}}, f_X^{\text{HHV}} = 0.93) \Rightarrow X_A \approx 0.93 \text{ MWh}_{\text{ex}}. \quad (76)$$

The physical fuel has not changed. The denominator has. The reporting standard therefore requires the energy basis to be visible.

For hydrogen, the same logic gives

$$(1.00 \text{ MWh}_{\text{LHV}}, f_X^{\text{LHV}} = 0.98) \quad \text{or} \quad (1.00 \text{ MWh}_{\text{HHV}}, f_X^{\text{HHV}} = 0.83). \quad (77)$$

This matters for hydrogen policy, fuel blending, electrolyzer dispatch, ammonia synthesis, synthetic-fuel production, and industrial heat applications. Without an explicit Exergy Factor and basis, a fuel comparison can accidentally mix first-law heating-value conventions with second-law work-potential claims.

10.4 Dynamic sink example for real-time heat valuation

Consider a 70°C heat stream. If the operational sink is a 20°C return or ambient condition, then

$$f_X = 1 - \frac{293.15}{343.15} = 0.146. \quad (78)$$

If the accessible sink rises to 35°C during a warm period or because a return line is poorly cooled, then

$$f_X = 1 - \frac{308.15}{343.15} = 0.102. \quad (79)$$

The same heat stream has the same energy quantity, but **its accessible work potential falls by about 30%**. A dynamic reporting system would compute $f_X(t)$ continuously and then aggregate with Eq. (25). This is directly analogous to time-varying electricity prices, weather-dependent heat-pump performance, and carbon-intensity time series. The calculation is not a conceptual barrier; it is a metering and data-interface problem.

11 Measurement and Reporting Protocol

A practical reporting standard should be computable from ordinary measurements. The following protocol is intended for engineering use.

1. **Define the reporting boundary.** Specify where the stream is measured and what service or sink defines accessibility.
2. **Declare the reference convention.** Record R , such as a fixed standard environment, local ambient condition, return-line temperature, condenser sink, or service temperature.
3. **Identify the carrier.** Select the carrier variable C : charge, entropy, mole amount, volume, mass, or another physically measurable carrier.
4. **Measure the energy or power quantity.** Report E for accumulated energy or $P = \dot{E}$ for a power rate in standard units such as J, kWh, MWh, W, kW, or MW.
5. **Compute the exergy voltage.** Use the carrier-specific potential difference, such as ΔV , $T_h - T_c$, $\Delta\mu$, Δp , or $\Delta\psi$.
6. **Compute accessible exergy.** Use

$$X_A = \int \Delta\Phi_A^{(C)} dC, \quad (80)$$

or, for steady streams,

$$\dot{X}_A = \dot{C} \Delta\Phi_A^{(C)}. \quad (81)$$

7. **Compute Exergy Factor.** Use

$$f_X = \frac{X_A}{E} \quad (82)$$

or

$$f_X = \frac{\dot{X}_A}{P} = \frac{\dot{X}_A}{\dot{E}}. \quad (83)$$

8. **Report the stream.** Report (E, f_X) or (P, f_X) , with f_X in $\text{J}_{\text{ex}}/\text{J}$, $\text{MW}_{\text{ex}}/\text{MW}$, or $\text{MWh}_{\text{ex}}/\text{MWh}$, and attach the reference metadata (R, B, O) .

9. **Report the process separately.** For devices or conversions, report η_X and \dot{X}_{dest} .

This procedure makes the framework compatible with existing metering. Electrical meters already provide \dot{E} or interval E ; voltage and current already provide carrier potential and carrier current. Thermal systems already measure temperatures and heat flows. Chemical systems already use composition, flow, and chemical potential or heating-value tables. Pressure systems already measure pressure and volume flow. The proposed change is not a new sensor requirement in most cases. It is a new reporting layer.

12 Interface with Existing Standards, Dispatch, and Markets

The proposed framework is intended to extend existing accounting practices rather than replace them. ISO 50001 provides a management-system framework for improving energy performance through policies, targets, measurement, and continual improvement [7]. IPMVP provides a framework for measuring, computing, and reporting energy or water savings from efficiency projects [3]. ISO 14040 describes the principles and framework for life-cycle assessment, including goal and scope definition, inventory analysis, impact assessment, and interpretation [6]. These standards and protocols are concerned primarily with reliable energy, cost, resource, or environmental accounting.

The proposed two-number framework adds a second-law layer. In an ISO 50001-style energy management system, (E, f_X) and (P, f_X) can be used as supplemental energy performance indicators that distinguish energy consumption from work-potential consumption and peak power from peak accessible exergy rate. In IPMVP-style measurement and verification, savings can be reported as both energy savings and exergy savings:

$$\Delta E = E_{\text{baseline}} - E_{\text{post}}, \quad (84)$$

$$\Delta X_A = (f_X E)_{\text{baseline}} - (f_X E)_{\text{post}}. \quad (85)$$

For power-sensitive applications, the analogous reporting quantity is

$$\Delta \dot{X}_A = (f_X P)_{\text{baseline}} - (f_X P)_{\text{post}}. \quad (86)$$

In life-cycle assessment, Exergy Factor can serve as a thermodynamic inventory attribute attached to energy and material flows, helping distinguish a low-temperature waste-heat stream from electricity or chemical fuel even when their first-law energy quantities are equal.

For dispatch and pricing, the natural implementation is time-series accounting. Each interval t carries a stream report

$$\mathcal{S}_P(t) = (P(t), f_X(t)). \quad (87)$$

An operator then tracks both energy and exergy throughput:

$$E_{\Delta} = \int_{\Delta} P(t) dt, \quad (88)$$

$$X_{A,\Delta} = \int_{\Delta} f_X(t) P(t) dt. \quad (89)$$

A tariff, dispatch optimizer, or market product can therefore report both $\$/\text{MWh}$ and $\$/\text{MWh}_{\text{ex}}$, or it can use MWh_{ex} as an additional settlement attribute. This is especially relevant for heat, where $f_X(t)$ changes with supply temperature, return temperature, ambient conditions, and the available sink. It is also relevant for fuels, where the standard Exergy Factor is stable enough for inventory reporting but operating conditions and final services determine whether that work potential is well matched or destroyed.

This compatibility is important for adoption. The framework should not require energy managers to abandon MWh, MW, cost, emissions, or life-cycle reporting. It should require every reported MWh or MW to carry its work-potential factor. The practical reporting upgrade is therefore:

$$\text{MWh} \longrightarrow (\text{MWh}, \text{MWh}_{\text{ex}}/\text{MWh}), \quad (90)$$

and

$$\text{MW} \longrightarrow (\text{MW}, \text{MW}_{\text{ex}}/\text{MW}). \quad (91)$$

13 Implications for Energy Systems

The proposed standard changes the accounting interface of energy systems. Today, many planning models ask whether energy quantity balances:

$$\sum \dot{E}_{\text{supply}} = \sum \dot{E}_{\text{demand}}. \quad (92)$$

A second-law-aware system should also track accessible work potential:

$$\sum f_{X,s} P_s \geq \sum f_{X,d} P_d + \dot{X}_{\text{dest}} + \dot{X}_{\text{loss}}. \quad (93)$$

This expression does not replace mass, charge, momentum, or energy balances. It augments them with work-potential accounting.

The most direct applications are:

1. **Energy-market design.** Electricity, fuels, heat, and storage products can be reported using both MWh and MWh_{ex} , or both MW and MW_{ex} , making low-grade and high-grade services more transparent.
2. **District heating and cooling.** Networks can report not only heat quantity and heat power but Exergy Factor at the point of delivery, discouraging unnecessary high supply temperatures and revealing the true value of waste heat.
3. **Industrial heat recovery.** Waste-heat streams can be ranked by (E, f_X) and (P, f_X) and matched to demands by f_X rather than by energy quantity alone.
4. **Building electrification.** Heat pumps can be evaluated as exergy-matching devices, not merely as devices with a coefficient of performance.
5. **Chemical carriers.** Hydrogen, methane, ammonia, and synthetic fuels can be compared using declared Exergy Factor bases, preventing hidden inconsistencies between LHV, HHV, and chemical-exergy accounting.
6. **Storage comparison.** Batteries, hydrogen, pumped hydro, compressed air, and thermal storage differ not only in MWh but in Exergy Factor and carrier-specific exergy voltage.

The framework also clarifies why some high-level energy metrics can mislead. A system can conserve energy while destroying exergy. A decarbonization pathway can reduce emissions while still misallocating high-exergy resources to low-exergy services. A two-number reporting standard makes those failures visible.

14 Implications for the Global Energy Transition

The global energy transition is not only a problem of producing enough low-carbon energy. It is also a problem of matching the right kind of energy to the right service. Scalar energy accounting makes this difficult because it reports how much energy moves while hiding how much useful work potential is being consumed, degraded, stranded, or destroyed.

A quantity-plus-Exergy-Factor reporting standard can improve the transition in several practical ways.

First, it makes avoidable waste visible. Electrification is essential, but not every electrified pathway uses high-grade electricity with equal effectiveness. Low-temperature heat, industrial heat, compressed gases, fuels, batteries, and thermal storage have different work-potential grades. Reporting (E, f_X) and (P, f_X) reveals when high-grade resources are being used for low-grade services without recovery, cascading, or upgrading logic.

Second, it improves heat-system decisions. Much of the transition will involve heat: building heating, industrial process heat, data-center heat rejection, district energy, thermal storage, and waste-heat recovery. Heat quantity alone is not enough. Temperature, sink conditions, and accessibility determine whether heat is valuable, recoverable, or effectively stranded. Exergy Factor provides a compact way to rank thermal resources by useful work potential.

Third, it clarifies the role of hydrogen and fuels. Hydrogen, ammonia, methane, methanol, and synthetic fuels are often compared using first-law energy quantities and heating-value conventions. The Exergy Factor does not decide policy by itself, but it forces the energy basis and work-potential claim to be visible. This can prevent comparisons that mix LHV, HHV, chemical exergy, and end-use service requirements without declaring the denominator.

Fourth, it improves storage valuation. Storage assets are commonly compared by MWh, but storage value depends on the quality of the stored energy and the service it can satisfy. A battery, a hot-water tank, compressed air, hydrogen, and pumped hydro can all be described by energy quantity, but they do not carry the same Exergy Factor or serve the same demand grades. Reporting storage as quantity plus Exergy Factor makes this distinction explicit.

Fifth, it gives institutions a simple supplemental metric. Energy managers, auditors, life-cycle analysts, investors, and market operators do not need to abandon existing MWh, MW, cost, emissions, or efficiency metrics. They can add Exergy Factor as a quality field attached to each reported stream. This is the central adoption advantage: the framework can be layered onto existing energy accounting rather than replacing it.

The practical implication is that the transition should optimize not only for low-carbon energy quantity, but also for low-carbon useful work potential. A clean MWh still has to be used intelligently. Reporting every stream as quantity plus Exergy Factor can help identify where useful work potential is being wasted, where low-grade energy can be matched to low-grade demand, and where upgrading technologies such as heat pumps, compressors, electrolyzers, or thermal networks are thermodynamically justified.

15 Implementation Challenges and Scope

Several practical issues must be addressed before a two-number exergy-reporting layer could become routine.

First, reference conventions must be standardized by use case. A national inventory may require fixed reference conditions, whereas a local heat-network controller should use local accessible sinks. This is not a contradiction. It is a reporting-design problem.

Second, thermal streams require temperature-resolved data. Reporting a single MWh value for a mixed waste-heat stream is not enough. The framework is most useful when heat is

binned by temperature, time, and location. The same principle applies to pressure, chemical composition, and storage state of charge.

Third, chemical Exergy Factors require a declared energy basis. Lower heating value, higher heating value, Gibbs free energy, and full chemical exergy can yield different ratios. A reporting rule must specify the denominator used in $f_X = X_A/E$.

Fourth, access is partly infrastructural. A waste-heat stream may have nonzero thermodynamic work potential but no practical value if no heat exchanger, thermal network, storage asset, or nearby demand exists. The proposed solution is to declare the reporting boundary and operational constraint metadata, then report process availability separately through η_X and \dot{X}_{dest} .

Fifth, real-time operation requires data governance. Dynamic Exergy Factors depend on measured temperatures, flow rates, pressures, compositions, and reference conventions. Operators will need clear rules for interval length, sensor quality, missing data, and whether a value is standard, local, or operational. These are solvable measurement and verification issues, not objections to the thermodynamic framework.

Sixth, market adoption requires compatibility with existing energy, emissions, and cost metrics. The proposal is not to replace kWh accounting but to prevent kWh accounting from hiding thermodynamic quality.

The framework has several boundaries. It is an engineering and accounting proposal, not a new thermodynamic law. It does not claim that Exergy Factor is an intrinsic property of matter. It is a reporting-boundary property. This is unavoidable because exergy itself is relational. It also does not replace detailed exergy balances for plant design. Instead, it provides a compact reporting interface that can guide screening, dispatch, benchmarking, and communication.

Path to adoption. The fastest practical route to demonstrating the framework is through targeted pilots in domains where exergy mismatch is already visible. Three are especially well suited. First, district heating and cooling networks already meter supply and return temperatures continuously, so (P, f_X) and $f_X(t)$ can be computed from existing instrumentation; a Nordic or European fourth-generation district-heating operator could publish exergy-aware tariffs alongside conventional MWh tariffs within a single heating season. Second, hydrogen and synthetic-fuel policy frameworks are actively debating LHV versus HHV reporting conventions, and a declared-basis Exergy Factor would resolve cross-pathway comparisons (electrolysis, methanation, ammonia synthesis) that currently mix energy bases. Third, working groups within ISO 50001, ISO 14040, and IPMVP could prototype (E, f_X) as a supplemental performance indicator without altering existing first-law accounting. These three pilot tracks—one operational, one policy, one standards—would collectively establish the reference conventions, data formats, and verification practices needed for broader adoption.

16 Conclusion

This paper proposes a single change to how energy systems report what they produce, store, deliver, and consume: every reported energy quantity should carry an Exergy Factor. The result is a two-number reporting standard— (E, f_X) for any energy quantity and (P, f_X) for any power rate—that pairs the conventional first-law number with a dimensionless factor expressing how much of that quantity is accessible useful work. The framework applies uniformly to primary-energy totals, delivered electricity, fuel inventories, storage assets, and flowing streams, in whatever unit is already in use (J, kWh, MWh, TWh, quads, BoE, etc.), and augments existing first-law accounting—ISO 50001, IPMVP, ISO 14040, dispatch, and life-cycle assessment—without replacing it. It is the first operational reporting standard that turns the second-law distinction between energy quantity and accessible work potential into routine practice.

Underneath the reporting layer sits a single carrier-agnostic flow law,

$$\dot{X}_A = \dot{C} \Delta\Phi_A^{(C)} = f_X P = f_X \dot{E}, \quad (94)$$

where the exergy voltage $\Delta\Phi_A^{(C)} = dX_A/dC$ generalizes the role of electrical voltage across every carrier—entropy for thermal streams, chemical potential for fuels and reactions, pressure for compressed gases, and specific work potential for mass flow. This relation unifies the second-law treatment of all energy carriers while preserving full thermodynamic rigor and backward compatibility with existing first-law accounting.

The framework treats exergy as fundamentally relational and makes that relational character practical: reference conventions are declared explicitly, thermal quality is expressed through entropy as carrier (temperature difference = thermal exergy voltage), and chemical streams carry an explicit energy-basis label (LHV, HHV, or chemical exergy). Stream quality is reported separately from process performance (second-law efficiency and exergy destruction), enabling clear supply–demand matching by both quantity and work-potential grade.

Energy systems should no longer report streams as scalar quantities alone. Every supply, demand, storage asset, and conversion pathway must be described by quantity plus Exergy Factor. This single change makes visible the avoidable destruction and stranding of useful work potential that conventional accounting conceals. It equips planners, operators, market designers, and policymakers with a practical second-law layer that augments—without replacing—existing energy, cost, emissions, and life-cycle metrics.

For the global energy transition, the implication is direct and urgent. Decarbonization cannot succeed by optimizing only for low-carbon energy quantity. It must also optimize for the intelligent matching of low-carbon useful work potential to real services. The two-number reporting framework proposed here gives institutions a simple, actionable tool to do exactly that—revealing where high-grade resources are wasted on low-grade tasks, where low-grade heat can be productively cascaded, and where upgrading technologies such as heat pumps, electrolyzers, and thermal networks are thermodynamically justified. Widespread adoption of (E, f_X) and (P, f_X) reporting would sharpen decision-making across district energy, building electrification, industrial heat recovery, hydrogen and synthetic-fuel policy, storage valuation, and multi-carrier system control.

The transition needs more than cleaner electrons and molecules. It needs clearer accounting of what those electrons and molecules can actually do. This standard provides that clarity.

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