

Real-World Application of the KEEP Framework: Global Energy System Analysis (2023)

Abstract

This study applies and calibrates the Kardashev–Vestorp Energy Efficiency Parameter (KEEP) framework to the 2023 global energy system using official data from the International Energy Agency (IEA) and Global Energy Monitor (GEM). KEEP quantifies the installed nameplate primary energy capture capacity required to sustain a civilization’s average useful energy demand P , under specified assumptions about conversion efficiencies and capacity factors.

Using IEA 2023 data (Total Energy Supply, TES: 633 EJ; Final Energy Consumption, FEC: 429 EJ; Electricity Generation: 30,122 TWh) and GEM capacity data (~8.5 TW installed), we estimate that the global electrical sector operates with $KEEP_{elec}/P_{elec} \approx 7.4$ (90% CI: 5.5–10.0), meaning approximately eight watts of installed primary capture capacity must exist for each watt of useful electrical output. From energy balance data, the global primary-to-useful energy multiple is $TES/P_{full} \approx 2.83$, reflecting an overall primary-to-useful efficiency of $\approx 35\%$. In addition, a full multi-source KEEP calculation on a physical-flux basis, aggregating across all primary energy sources with source-specific efficiencies and capacity factors, yields a total illustrative full-system KEEP ≈ 47.71 TW for a ~ 7.1 TW useful load, corresponding to $KEEP_{full}/P_{full} \approx 6.72$. This full-system result is explicitly presented as an order-of-magnitude illustrative example, not as a fully data-driven reconstruction.

The calculated Installed Nameplate Electrical Capacity (INEC) of 8.477 TW agrees with reported capacity within 0.1%, providing strong support for the framework’s parameter choices as a consistency reconstruction. We present parallel analyses using both IEA statistical conventions and physical-flux boundaries, demonstrating how accounting choices affect apparent primary energy shares while leaving $KEEP_{elec}/P_{elec}$ largely unchanged.

Infrastructure burden varies dramatically by source: solar PV requires approximately 6.01× its proportional share of infrastructure (burden ratio), while hydropower requires only 0.39×. Future transition scenarios reveal that solar-heavy pathways require approximately 137% more installed primary capture capacity than nuclear-heavy pathways for equivalent useful output. However, nuclear’s infrastructure advantage must be weighed against Solar’s roughly 60× faster current deployment rate and generally lower levelized costs.

Material considerations suggest that high-KEEP pathways face potential supply chain constraints, with solar-heavy scenarios likely requiring substantially more bulk materials and critical minerals than nuclear-heavy alternatives. KEEP provides a physically grounded infrastructure metric complementary to LCOE, EROI, and emissions analysis. It does not determine optimal technology choice but quantifies the infrastructure dimension of energy system planning.

Keywords: KEEP framework, energy infrastructure, Kardashev scale, capacity planning, IEA, Global Energy Monitor, energy transition

1. Introduction and Framework Definition

1.1 Purpose and Scope

This article applies the Kardashev–Vestorp Energy Efficiency Parameter (KEEP) framework to the 2023 global energy system using official data from the International Energy Agency (IEA) and Global Energy Monitor (GEM). The analysis demonstrates:

- Systematic application of KEEP calculations with authoritative real-world data,
- Consistency verification between calculated and observed infrastructure,
- Comparative analysis of how technology mix affects infrastructure burden,
- Sensitivity and uncertainty quantification for key results.

Terminology note: This study represents an **application and calibration** of the KEEP framework, not an independent validation. True validation would require comparison with independently measured quantities not used in calibration. We use “application” and “consistency check” throughout to reflect this distinction.

Contribution and novelty. This paper’s primary contribution is to introduce and calibrate the KEEP/P metric as an explicitly capacity-based, mix-sensitive infrastructure indicator that is complementary to existing system metrics. Unlike aggregate exergy or efficiency measures, which describe energy flows, KEEP/P quantifies the installed primary capture stock required to sustain a given useful-power level, and thus directly links technology performance (ECE, CF, GE) and mix (f_i) to total infrastructure needs. In contrast to traditional capacity-margin planning or power-density concepts, KEEP aggregates heterogeneous technologies into a single, physically grounded capacity multiplier that is invariant to primary-energy accounting conventions. Finally, unlike EROI, which focuses on energy invested over life cycles, KEEP/P provides a one-number capacity multiplier that is particularly useful for comparing radically different low-carbon pathways (e.g., solar-heavy vs nuclear-heavy) in terms of their implied infrastructure and material burdens for the same useful output.

1.2 What KEEP Measures

Definition. KEEP calculates the installed nameplate primary energy capture capacity required to sustain an average useful energy demand P :

$$\text{KEEP} = \sum_{i=1}^n \frac{f_i \times P}{\text{ECE}_i \times \text{CF}_i \times \text{GE}} \quad (1)$$

where:

- P = useful energy output (W),
- ECE_i = energy conversion efficiency for source i ,
- CF_i = capacity factor for source i ,
- GE = grid/delivery efficiency,
- f_i = fraction of useful output from source i , with $\sum_i f_i = 1$.

KEEP refers to the installed primary capture nameplate capacity that must be built and maintained to supply an average useful demand P , given assumed system performance parameters (ECE_i , CF_i , GE). KEEP is fundamentally a **capacity-planning** metric.

1.3 Aggregation and Comparability Limits

KEEP aggregates heterogeneous physical systems into a single capacity unit:

- Solar: panel aperture intercepting irradiance ($m^2 \rightarrow W$),
- Wind: rotor swept area intercepting kinetic energy ($m^2 \rightarrow W$),
- Hydro: turbines intercepting hydraulic head ($m^3/s \times m \rightarrow W$),
- Nuclear: reactor thermal power (MW_{th}),
- Fossil: combustion systems converting chemical energy (tonnes/year $\rightarrow W$).

When expressing all sources as “TW of installed primary capture capacity,” we are not claiming physical equivalence. KEEP answers:

“What aggregate primary capture nameplate must exist to sustain useful output P under specified efficiencies and utilization rates?”

Two important caveats:

- **No strict physical equivalence.** One TW of KEEP from solar panels represents collector area under typical irradiance and module efficiency; 1 TW from coal represents combustion capacity; 1 TW from nuclear represents reactor thermal nameplate. These infrastructures are physically different; KEEP equates them only by their capacity to sustain a given useful power.
- **Comparative, not literal.** KEEP is most meaningful for comparing how technology mixes change $KEEP/P$. Interpreting the absolute “number of TW” as a literal physical design specification is misleading without technology-specific detail.

$KEEP/P$ is thus an aggregated planning metric, analogous to economy-wide exergy efficiency measures: useful for systems-level and Kardashev-scale comparisons, but not a substitute for detailed engineering or technology-specific planning.

1.3.1 Technology-Specific Interpretation of “Primary Capture Nameplate”

In all that follows, “installed primary capture capacity” is an **equivalent** rather than a literal engineering nameplate. Formally, for each source i we define a notional primary capture nameplate N_i (W) such that:

$$\bar{P}_i = N_i \times ECE_i \times CF_i \times GE,$$

where $\bar{P}_i = f_i P$ is the average useful output attributed to source i . Given \bar{P}_i and our assumed ECE_i , CF_i , and GE , we invert this relation to obtain:

$$N_i = \frac{f_i \times P}{ECE_i \times CF_i \times GE} = KEEP_i.$$

Thus, $KEEP_i$ should be read as the **equivalent primary capture nameplate** required to sustain the observed useful output for source i , given our physical performance parameters.

The mapping between this equivalent nameplate and engineering nameplate differs by technology:

- **Solar PV.** We define ECE_{PV} as the ratio of AC electrical output at full irradiance to the incident solar irradiance on the module aperture at a standard test condition ($\approx 1,000 \text{ W/m}^2$), including module, inverter, and BOS losses (Table 3.1). The capacity factor CF_{PV} is defined in the usual way, as the ratio of long-term average AC electrical output to **electrical** nameplate. When we form

$$N_{PV} = \frac{f_{PV} \times P}{ECE_{PV} \times CF_{PV} \times GE},$$

we are therefore normalizing back to an equivalent intercepted solar flux at the module plane under the reference irradiance. For PV, $KEEP_{PV}$ is thus best interpreted as a **resource-flux-normalized equivalent capture capacity** rather than a literal sum of electrical nameplates.

- **Wind.** We take ECE_{wind} to represent the fraction of kinetic energy flux through the rotor swept area that is delivered as AC electrical output at the generator terminals, combining an effective Betz-limited aerodynamic efficiency and drivetrain losses (Table 3.1). The capacity factor CF_{wind} is again defined relative to electrical nameplate. $KEEP_{wind}$ therefore corresponds to an equivalent intercepted kinetic energy flux through the rotor at a representative design wind speed.
- **Hydro, nuclear, fossil.** For hydropower, ECE_{hydro} is defined relative to the hydraulic head power at the turbine inlet; for nuclear and fossil plants, ECE_i is defined relative to reactor thermal power or fuel chemical energy flow. In these cases, the primary capture nameplate is much closer to the usual thermal or hydraulic nameplate of the plant.

In summary, for all technologies we maintain the common formal structure

$$KEEP_i = \frac{f_i \times P}{ECE_i \times CF_i \times GE},$$

but the physical realization of 1 TW of KEEP differs by source. For solar and wind in particular, KEEP is deliberately **resource-flux-normalized**: it tells us how much equivalent intercepted solar or kinetic flux would be required, under our assumed efficiencies and utilization rates, to supply a given useful output. This is adequate for cross-technology comparison of infrastructure burden, but it should not be confused with aggregating conventional electrical nameplates.

1.4 Physical Flux vs. Statistical Primary Energy

Primary energy can be defined by two conventions:

- **IEA convention:**
 - Non-thermal renewables are counted at electrical output (100% “efficiency” by definition),
 - Thermal sources are counted at chemical/thermal energy content.

- **Physical-flux approach:**
 - All sources are traced back to flux intercepted by infrastructure:
 - Solar: irradiance on panel aperture,
 - Wind: kinetic flux through rotor area,
 - Hydro: hydraulic head power at turbine,
 - Nuclear: reactor thermal power.

We present TES by source under both conventions (Section 5), and show that while TES shares change significantly (especially for solar and wind), the KEEP values for a given useful output are determined by ECE, CF, and GE rather than accounting conventions.

“89,000 TW” clarification: the ~89,000 TW of solar irradiance intercepted by Earth is natural **potential**, not built capacity. KEEP measures **installed capture capacity**, not total environmental flux.

1.5 INEC: Installed Nameplate Electrical Capacity

The Installed Nameplate Electrical Capacity (INEC) represents the rated capacity of electrical generators:

$$INEC_i = \frac{\bar{P}_{gen,i}}{CF_i}, \quad (2)$$

where $\bar{P}_{gen,i}$ is average electrical power from source i at generator terminals. INEC is calculated without GE in the denominator because nameplate capacity is measured at the generator, before transmission losses.

INEC excludes end-use efficiency considerations. KEEP, by contrast, traces back to primary energy capture and accounts for all conversion stages through to useful output.

1.6 What KEEP Does Not Measure

Table 1.1: What KEEP Does Not Measure

Metric	What It Measures	Relationship to KEEP/ P
LCOE	Economic cost per unit energy	KEEP is cost-agnostic
EROI	Energy return on energy invested	KEEP is complementary
Carbon intensity	Emissions per unit energy	KEEP is emissions-agnostic
Deployment rate	Speed of capacity addition	KEEP measures infrastructure stock, not flow
Material intensity	Tonnes of material per MW	Correlated with KEEP/ P , not directly measured
Resource limits	Material or land constraints	KEEP/ P is suggestive but not sufficient alone
Fuel cycle infra	Mining, processing, transport	Not included in KEEP

Metric	What It Measures	Relationship to KEEP/P
Decommissioning	End-of-life requirements	Not included in KEEP

Technologies with low KEEP/P can still be undesirable if they are expensive, slow to deploy, or face material/land constraints. KEEP/P should be used alongside LCOE, EROI, emissions, deployment rates, and resource assessments.

1.7 Electrical Sector vs. Full Energy System

We develop three related metrics:

Table 1.2: Scope Comparison (2023)

Metric	Definition	Value (2023)
Electrical $KEEP_{elec}/P_{elec}$	Power generation only (30,122 TWh)	$\approx 7.4\times$ (primary focus)
Primary-to-useful multiple	TES/P_{full} (flow, not KEEP)	$\approx 2.8\times$ ($\approx 1/35\%$ efficiency)
Full multi-source $KEEP_{full}/P_{full}$ (phys. flux)	All primary sources with per-source d_i	$\approx 6.72\times$

- The electrical $KEEP_{elec}/P_{elec} \approx 7.4$ is rigorously derived in Section 6.
- The $TES/P_{full} \approx 2.83$ multiple is the inverse of the global primary-to-useful efficiency (Section 4): it describes average primary throughput per unit useful output, **not** installed nameplate.
- The full multi-source $KEEP_{full}/P_{full} \approx 6.72$ is computed by applying Eq. (1) to all primary energy sources on a physical-flux basis (Section 7.1), using representative per-source ECE, CF, GE, and end-use efficiencies; this yields a total illustrative full-system $KEEP \approx 47.71$ TW and $KEEP_{full}/P_{full} \approx 47.71/7.1 \approx 6.72$.

Unless explicitly stated, references to $KEEP_{elec}/P_{elec}$ in this paper refer to the electrical-sector value of $7.4\times$. We present $TES/P_{full} \approx 2.8$ as a global efficiency multiple, and a separate physical-flux full $KEEP_{full}/P_{full} \approx 6.72$ as an **illustrative** whole-system capacity multiplier.

1.8 Scope and Limitations

Key limitations:

- Significant regional variation in energy mixes and performance,
- 2023 treated as a static snapshot,
- Useful energy P inferred from end-use efficiencies ($\pm 14\%$),
- Aggregation of heterogeneous infrastructures into a single scalar metric,
- No explicit economic or deployment-timeline modelling,
- Fuel-cycle infrastructure and decommissioning excluded,

- Land use and materials only discussed qualitatively and at order-of-magnitude level.

2. Global Energy Data (IEA 2023)

2.1 Total Energy Supply

Table 2.1: Total Energy Supply by Source (IEA 2023)

Source	TES (TJ)	TES (EJ)	TES (TW)*	Share
Oil	191,612,174	191.61	6.075	30.24%
Coal	175,947,669	175.95	5.579	27.77%
Natural Gas	144,146,098	144.15	4.571	22.75%
Biofuels & Waste	56,014,379	56.01	1.776	8.84%
Nuclear	29,919,241	29.92	0.949	4.72%
Solar, Wind & Other	20,752,505	20.75	0.658	3.27%
Hydropower	15,308,404	15.31	0.485	2.42%
Total	633,700,470	633.7	20.093	100.00%

*1 TW·year = 31.536 EJ. $633.7 \text{ EJ} \div 31.536 \text{ EJ}/(\text{TW}\cdot\text{year}) \approx 20.093 \text{ TW}$; we use $\approx 20.1 \text{ TW}$.

2.2 Disaggregation of Solar, Wind & Other Renewables

Table 2.2: Renewable Disaggregation (IEA 2023)

Source	Generation (TWh)	Share of Category	TES (TW)
Wind	2,333.1	56.3%	0.374
Solar PV	1,604.6	39.1%	0.257
Solar thermal	15.5	0.4%	0.0026
Geothermal	98.1	2.4%	0.0157
Tide	0.9	0.02%	0.00013
Other	47.5	1.2%	0.0079
Total	4,099.8	100%	0.658

IEA uses the **direct equivalent** method for non-thermal renewables (electricity \equiv primary).

2.3 Electricity Generation

Table 2.3: Electricity Generation by Source (IEA 2023)

Source	Generation (TWh)	Power (TW)*	Share
Coal	10,687.10	1.220	35.48%
Natural Gas	6,647.50	0.759	22.07%
Hydropower	4,395.90	0.502	14.59%
Nuclear	2,740.50	0.313	9.10%
Wind	2,333.10	0.266	7.75%
Solar PV	1,604.60	0.183	5.33%
Oil	778.1	0.089	2.58%
Biofuels	656.5	0.075	2.18%
Waste	116.3	0.013	0.39%
Geothermal	98.1	0.011	0.33%
Other	63.9	0.007	0.21%
Total	30,121.60	3.439	100.00%

*Power (TW) = TWh ÷ 8,760 h/year.

2.4 Installed Electrical Capacity

Table 2.4: Installed Capacity and Implied Capacity Factors (GEM 2023 + IEA/IRENA)

Source	Reported Capacity (GW)	Generation (TWh)	Implied CF
Coal	2,155	10,687	56.6%
Natural Gas	1,850*	6,648	41.0%
Oil	350*	778	25.4%
Hydropower	1,188	4,396	42.2%
Nuclear	394	2,741	79.3%
Wind	875	2,333	30.4%
Solar PV	1,500**	1,605	12.2%
Geothermal	15	98	74.1%
Bioenergy	145***	656	60.8%
Other	-	180	-
Total	8,472	30.122	40.5%

* GEM aggregates oil and gas at 2,063 GW; split estimated from generation shares and typical CFs.

** Includes distributed/rooftop PV (global total ~1,500 GW). GEM utility-scale only is 685 GW.

*** Includes waste-to-energy facilities.

3. Technology Parameters

3.1 Energy Conversion Efficiency (ECE)

Table 3.1: Energy Conversion Efficiency Values and Derivations

Source	ECE	Derivation / Basis	σ
Solar PV	0.20	22% module × 97% inverter × 94% system BOS	0.03
Wind	0.38	Betz practical (~45%) × drivetrain (~85%)	0.04
Hydro	0.90	Turbine (~93%) × generator (~97%)	0.02
Nuclear	0.33	LWR Rankine cycle	0.02
Coal	0.38	Subcritical/supercritical blend	0.03
Gas (fleet)	0.48	CCGT/OCGT/steam weighted average	0.03
Oil (power)	0.38	Steam + diesel blend	0.04
Biofuels	0.30	Direct combustion, gasification, biogas	0.05
Geothermal	0.12	Low-grade thermal, binary/flash	0.03
Other	0.30	Assumed average	0.05

Examples:

- Wind ECE: Betz limit (59.3%) × practical aerodynamic (76%) × drivetrain (85%) → ≈0.38.
- Gas ECE: 0.48 from a global mix of 55% CCGT ($\eta \approx 0.55$), 25% OCGT ($\eta \approx 0.38$), 20% steam ($\eta \approx 0.35$).

3.2 Capacity Factors

Table 3.2: Capacity Factors (from IEA/GEM 2023)

Source	CF (calc.)	CF (used)	Determinant
Nuclear	79.3%	0.793	Baseload
Geothermal	74.1%	0.741	Continuous
Biofuels/Waste	60.8%	0.608	Feedstock-limited
Coal	56.6%	0.566	Baseload + cycling
Hydropower	42.2%	0.422	Seasonal, dispatch

Source	CF (calc.)	CF (used)	Determinant
Gas (fleet)	41.0%	0.410	CCGT + peakers
Wind	30.4%	0.304	Resource-limited
Oil	25.4%	0.254	Peaking/backup
Solar PV	12.2%	0.122	Diurnal + weather

We assume $\pm 5\%$ relative CF uncertainty in the Monte Carlo analysis.

3.3 Grid and Delivery Efficiency

- Electrical T&D: $GE_{elec} \approx 0.92 \pm 0.02$,
- Fuel transport: $GE_{fuel} \approx 0.97 \pm 0.02$.

All electrical KEEP calculations use $GE = 0.92$.

4. Useful Energy Estimation (Primary-Energy Based)

4.1 TES as the Starting Point

$$TES_{2023} = 633.7 \text{ EJ/year} \approx 20.1 \text{ TW} (\approx 20.1 \text{ TW}).$$

4.2 Primary \rightarrow Final \rightarrow Useful Chain

From IEA:

$$FEC_{2023} = 429.11 \text{ EJ/year} \approx 13.61 \text{ TW}.$$

Primary-to-final efficiency:

$$\eta_{p \rightarrow f} = \frac{FEC}{TES} \approx \frac{13.61}{20.1} \approx 0.677.$$

Allocating FEC by carrier and applying end-use efficiencies η_{end} yields:

$$P_{full} \approx 7.06 \text{ TW}.$$

Final-to-useful efficiency:

$$\eta_{f \rightarrow u} = \frac{P_{full}}{FEC} \approx \frac{7.06}{13.61} \approx 0.52.$$

Combined primary-to-useful efficiency:

$$\eta_{p \rightarrow u} = \eta_{p \rightarrow f} \eta_{f \rightarrow u} \approx 0.675 \times 0.52 \approx 0.352$$

We adopt:

$$P_{\text{full}} \approx 7.1 \pm 1.0 \text{ TW.}$$

4.3 Primary-to-Useful Multiple

Relative to TES:

$$\frac{P_{\text{full}}}{\text{TES}} \approx \frac{7.1}{20.1} \approx 0.353.$$

Thus, the primary-to-useful energy multiple is:

$$\frac{\text{TES}}{P_{\text{full}}} \approx \frac{20.1}{7.1} \approx 2.83.$$

This 2.83× factor is **not** a KEEP/*P* in the strict sense. It measures an **average energy throughput**: how many watts of primary energy flow must be consumed per watt of useful output, given the global chain efficiency (~35%). It does not include capacity factors explicitly nor distinguish nameplate from average flows.

We therefore:

- Use $\text{TES}/P_{\text{full}} \approx 2.83$ as a global primary-to-useful multiple,
- Distinguish it from full multi-source KEEP/*P* (Section 7), which includes per-source ECE, CF, and GE and directly follows Eq. (1).

5. Physical Flux Conversion

Table 5.1: Primary Energy Under Different Accounting Conventions

Source	IEA TES (TW)	ECE _{phys}	Physical-Flux TES (TW)	Multiplier
Oil	6.075	—	6.075	1.0×
Coal	5.579	—	5.579	1.0×
Natural Gas	4.571	—	4.571	1.0×
Biofuels & Waste	1.776	—	1.776	1.0×
Nuclear	0.949	0.33	0.949*	1.0×
Hydropower	0.485	0.90	0.539	1.1×
Wind	0.374	0.38	0.984	2.6×
Solar PV	0.257	0.20	1.285	5.0×

Source	IEA TES (TW)	ECE _{phys}	Physical-Flux TES (TW)	Multiplier
Geothermal	0.0157	0.12	0.131	8.3×
Other	0.012	0.30	0.04	3.3×
Total	20.09	—	21.929	1.09×

* Nuclear is reported at thermal equivalent, so physical-flux TES equals reactor thermal power.

Physical-flux TES is 9% higher than IEA TES, with the difference concentrated in solar and wind. KEEP, however, is constructed from P and physical ECE, CF, and GE, and so is **independent** of whether TES is reported in IEA or physical-flux terms.

6. KEEP Calculation: Electrical Sector

6.1 Parameters

Table 6.1: Electrical Sector Parameters

Source	Generation Share f_i	ECE	CF	GE	$d_i = ECE_i \times CF_i \times GE$
Coal	0.3548	0.38	0.566	0.92	0.19795
Natural Gas	0.2207	0.48	0.410	0.92	0.18106
Hydropower	0.1459	0.90	0.422	0.92	0.34942
Nuclear	0.0910	0.33	0.793	0.92	0.24075
Wind	0.0775	0.38	0.304	0.92	0.10628
Solar PV	0.0533	0.20	0.122	0.92	0.02245
Oil	0.0258	0.38	0.254	0.92	0.08880
Bio+Waste	0.0257	0.30	0.608	0.92	0.16781
Geothermal	0.0033	0.12	0.741	0.92	0.08180
Other	0.0021	0.30	0.400	0.92	0.11040
Total	1.00000	—	—	—	—

Here d_i is the fraction of installed nameplate capacity that translates to **useful** output:

$$d_i = ECE_i \times CF_i \times GE.$$

6.2 Useful Electrical Output

We define:

$$P_{\text{elec}} = P_{\text{generation}} \times GE \times \eta_{\text{end}},$$

Nikolaj Vestorp

with:

- $P_{\text{generation}} = 3.43 \text{ TW}$,
- $GE = 0.92$,
- $\eta_{\text{end}} = 0.75$ (average end-use efficiency of electricity).

Then:

$$P_{\text{elec}} = 3.43 \times 0.92 \times 0.75 \approx 2.36 \text{ TW}.$$

This 2.36 TW is the **useful power** from electrical end-uses.

6.3 KEEP Calculation

For each source:

$$KEEP_i = \frac{f_i P_{\text{elec}}}{d_i}, \text{KEEP}_{\text{elec}} = \sum_i KEEP_i.$$

Table 6.2: Electrical Sector KEEP

Source	f_i	$f_i p$	d_i	$KEEP_i \text{ (TW)}$	KEEP Share
Coal	0.3548	0.8373	0.19795	4.2300	24.18%
Natural Gas	0.2207	0.5209	0.18106	2.8767	16.44%
Hydropower	0.1459	0.3443	0.34942	0.9854	5.63%
Nuclear	0.091	0.2148	0.24075	0.8920	5.10%
Wind	0.0775	0.1829	0.10628	1.7209	9.84%
Solar PV	0.0533	0.1258	0.02245	5.6030	32.03%
Oil	0.0258	0.0609	0.0888	0.6857	3.92%
Bio+Waste	0.0257	0.0607	0.16781	0.3614	2.07%
Geothermal	0.0033	0.0078	0.0818	0.0952	0.54%
Other	0.0021	0.0050	0.1104	0.0449	0.26%
Total	1	2.36	—	17.4953	100.00%

Result:

$$KEEP_{\text{elec}} \approx 17.49 \text{ TW}$$

$$\frac{KEEP_{\text{elec}}}{P_{\text{elec}}} \approx \frac{17.49}{2.36} \approx 7.41 \times.$$

6.4 INEC Calculation and Consistency Reconstruction

The Installed Nameplate Electrical Capacity (INEC) is calculated from average generation and capacity factor:

$$\text{INEC}_i = \frac{\bar{P}_{\text{gen},i}}{\text{CF}_i}$$

Note: GE is not included in this calculation because nameplate capacity is rated at the generator terminals, before transmission.

Table 6.3: INEC Calculation and Comparison with Reported Capacity

Source	P_{gen} (TW)	CF	Calculated INEC (GW)	Reported Capacity (GW)	Ratio
Coal	1.22	0.566	2,155	2,155	1
Natural Gas	0.7589	0.41	1,851	1,850	1.001
Hydropower	0.5018	0.422	1,189	1,188	1.001
Nuclear	0.3128	0.793	394	394	1
Wind	0.2663	0.304	876	875	1.001
Solar PV	0.1832	0.122	1,502	1,500	1.001
Oil	0.0888	0.254	350	350	1
Bio+Waste	0.0882	0.608	145	145	1
Geothermal	0.0112	0.741	15	15	1
Total	3.43	—	8,477	8,472	1.001

The calculated INEC of 8,477 GW (8.477 TW) agrees with adjusted reported capacity of 8,472 GW within 0.1%.

Important clarification: This close agreement is a **consistency reconstruction**, not independent empirical validation. The capacity factor values used in KEEP calculations were derived from the same generation and capacity data. The agreement confirms internal consistency of the parameter set but does not independently validate the framework against external measurements.

6.5 Monte Carlo Uncertainty Analysis

To quantify uncertainty in $\text{KEEP}_{\text{elec}}/P_{\text{elec}}$, we performed a Monte Carlo simulation with 100,000 iterations using Latin Hypercube Sampling.

Table 6.4: Parameter Distributions for Monte Carlo Analysis

Parameter	Base Value	Distribution	Uncertainty (σ)	Bounds
ECE_i	Per Table 3.1	Normal	Per Table 3.1	[0.05, 0.95]

Parameter	Base Value	Distribution	Uncertainty (σ)	Bounds
CF_i	Per Table 3.2	Normal	5% relative	[0.05, 0.95]
GE	0.92	Normal	0.02	[0.85, 0.98]
η_{end}	0.75	Normal	0.05	[0.60, 0.90]
f_i	Per Table 6.1	Fixed	—	—

Generation shares f_i were treated as exact values from IEA data.

Table 6.5: Monte Carlo Results

Statistic	$KEEP_{\text{elec}}/P_{\text{elec}}$	$KEEP_{\text{elec}}$ (TW)	P_{elec} (TW)
Base Case	7.41	17.49	2.36
Monte Carlo Mean	7.52	17.34	2.31
Monte Carlo Median	7.28	16.78	2.31
Standard Deviation	1.42	3.21	0.18
5th Percentile	5.54	12.76	2.01
95th Percentile	9.98	23.44	2.60
90% Confidence Int.	[5.5, 10.0]	[12.76, 23.44]	[2.01, 2.60]

Central result:

$$\frac{KEEP_{\text{elec}}}{P_{\text{elec}}} = 7.4 \text{ (90\% CI: [5.5, 10.0])}$$

Interpretation of the Monte Carlo. The Monte Carlo analysis should be interpreted strictly as a parameter-uncertainty analysis for the realized 2023 system, not as an exploration of alternative system designs or improved technologies. We hold the generation shares f_i and total average generation $P_{\text{generation}}$ fixed at their observed 2023 values, and treat ECE_i , CF_i , GE, and η_{end} as uncertain parameters describing that same realized year.

We also sample ECE_i and CF_i independently across technologies and do not enforce the algebraic constraint that, for fixed generation, increases in CF_i would have to be offset by corresponding changes in installed capacity. In other words, we are quantifying how uncertainty in **parameter estimates** (e.g., how efficient the average coal plant is) propagates into uncertainty in $KEEP_{\text{elec}}/P_{\text{elec}}$ conditional on the observed 2023 mix and generation, rather than re-optimizing capacity or exploring technological improvements. A fully coupled treatment of uncertainty in both parameters and system design is beyond the scope of this study.

6.6 Sensitivity Analysis

The Monte Carlo analysis reveals which parameters contribute most to uncertainty in $KEEP_{\text{elec}}/P_{\text{elec}}$:

Table 6.6: Variance Contribution by Parameter Category

Parameter Category	Variance Contribution
Solar PV (ECE, CF)	45.6%
Grid Efficiency (GE)	13.0%
Wind (ECE, CF)	12.7%
Coal (ECE, CF)	10.3%
Gas (ECE, CF)	7.4%
Other sources combined	11.0%

Key finding: solar PV parameters dominate uncertainty (~46%) because:

- Solar has the largest KEEP share (~32%) despite a small generation share (~5.3%),
- Solar's d_i (0.02245) is the smallest, making $KEEP_{\text{solar}}$ highly sensitive to parameter variations,
- Both ECE and CF for solar have significant uncertainty.
- Grid efficiency (GE) is the second-largest contributor (13.0%) because it affects all sources simultaneously – a 1% change in GE produces approximately a 1% change in the ratio.

7. Full Multi-Source KEEP and Infrastructure Burden

7.1 Full Multi-Source KEEP (Physical-Flux Basis, Illustrative)

To estimate a full multi-source $KEEP/P$ for the entire energy system, we apply Eq. (1) to all primary energy sources on a physical-flux basis:

$$KEEP_{\text{full}} = \sum_i \frac{w_i P_{\text{full}}}{d_i}, d_i = \eta_{\text{chain},i} CF_i GE,$$

where:

- P_{full} is total useful power (~7 TW),
- w_i is the fraction of total useful energy contributed by source i ($\sum_i w_i = 1$),
- $\eta_{\text{chain},i}$ combines primary-to-carrier and carrier-to-useful efficiencies for each source,
- CF_i and GE are per-source capacity factor and delivery efficiency.

We do not have a globally consistent, fully disaggregated data set of end-use flows and chain efficiencies by primary source for 2023. Instead, we construct an order-of-magnitude illustrative example using a representative physical-flux global mix (oil, coal, gas, nuclear, hydro, wind, solar, bio/other) and typical 2023-like chain efficiencies and CFs drawn from the literature. The resulting table should therefore be interpreted as illustrative only, not as a precise reconstruction of the 2023 full system.

Table 7.1: Illustrative Full Multi-Source KEEP (Physical-Flux Basis, Order of Magnitude Only)

Source	w_i	$w_i P$ (TW)	d_i	KEEP _{<i>i</i>} (TW)	Share
Oil	0.268	1.903	0.1457	13.06	27.4%
Coal	0.246	1.747	0.1540	11.34	23.8%
Natural Gas	0.269	1.910	0.2458	7.77	16.3%
Nuclear	0.032	0.227	0.2061	1.10	2.3%
Hydro	0.049	0.348	0.2979	1.17	2.4%
Wind	0.038	0.270	0.1001	2.70	5.6%
Solar PV	0.027	0.192	0.0271	7.07	14.8%
Bio/Other	0.071	0.504	0.1439	3.50	7.3%
Total	1.00	7.10	—	47.71	100%

Here P_{full} is rounded to 7.1 TW for illustration. Summing:

$$\text{KEEP}_{\text{full}} \approx 47.71 \text{ TW.}$$

Thus:

$$\frac{\text{KEEP}_{\text{full}}}{P_{\text{full}}} \approx \frac{47.71}{7.1} \approx 6.72.$$

This ≈ 6.7 is therefore presented as an **order-of-magnitude, illustrative full-system KEEP/ P** , in the sense of Eq. (1) applied to all primary sources with per-source d_i . It:

- Is higher than the $\text{TES}/P_{\text{full}} \approx 2.8$ flow multiple because it accounts for CF and GE, and
- Is somewhat lower than the electrical-only $\text{KEEP}_{\text{elec}}/P_{\text{elec}} \approx 7.4$, because non-electrical uses often have higher effective chain efficiencies and CFs.

We emphasize that a fully consistent 2023 multi-source $\text{KEEP}_{\text{full}}/P_{\text{full}}$ would require a detailed reconstruction of w_i and d_i from 2023 physical-flux TES and end-use splits, which is beyond the scope of this paper. The ≈ 47.71 TW, $\approx 6.72\times$ result here should be interpreted as illustrative and order-of-magnitude, demonstrating that plausible parameter choices yield a full-system capacity multiplier in the $7\times$ range.

7.2 Burden Ratio Definition

The infrastructure burden ratio quantifies how much more (or less) primary capture infrastructure a source requires relative to its contribution to useful output:

$$\text{Burden Ratio}_i = \frac{\text{KEEP Share}_i}{f_i},$$

where:

- $KEEP\ Share_i = \frac{KEEP_i}{KEEP_{total}}$ (electrical sector in this context),
- f_i = share of useful electrical output from source i.

Interpretation:

- $BR = 1.0$: source requires proportional infrastructure,
- $BR < 1.0$: source is infrastructure-efficient (less capacity per unit output),
- $BR > 1.0$: source is infrastructure-intensive (more capacity per unit output).

7.3 Results

Table 7.2: Infrastructure Burden Analysis (Electrical Sector)

Source	Output Share f_i	KEEP Share	Burden Ratio	Category
Hydropower	14.59%	5.63%	0.39×	Most efficient
Nuclear	9.10%	5.10%	0.56×	Very efficient
Coal	35.48%	24.18%	0.68×	Efficient
Natural Gas	22.07%	16.44%	0.74×	Efficient
Bio+Waste	2.57%	2.07%	0.81×	Near proportional
Other	0.21%	0.26%	1.24×	Moderate burden
Wind	7.75%	9.84%	1.27×	Moderate burden
Oil	2.58%	3.92%	1.52×	High burden
Geothermal	0.33%	0.54%	1.64×	High burden
Solar PV	5.33%	32.03%	6.01×	Highest burden

Weighted sum check:

$$\sum_i f_i \cdot \text{Burden Ratio}_i = \sum_i \text{KEEP Share}_i = 1.0.$$

7.4 Infrastructure Efficiency (Inverse Burden)

An alternative framing emphasizes infrastructure efficiency rather than burden:

Table 7.3: Infrastructure Efficiency by Source

Source	Burden Ratio	Infrastructure Efficiency (1/BR)	Interpretation
Hydropower	0.39×	2.56×	~2.6× more output per unit KEEP
Nuclear	0.56×	1.79×	~1.8× more output per unit KEEP

Source	Burden Ratio	Infrastructure Efficiency (1/BR)	Interpretation
Coal	0.68×	1.47×	~1.5× more output per unit KEEP
Natural Gas	0.74×	1.35×	~1.4× more output per unit KEEP
Bio+Waste	0.81×	1.24×	Slightly more output per unit KEEP
Wind	1.27×	0.79×	~0.8× output per unit KEEP
Solar PV	6.01×	0.17×	~0.17× output per unit KEEP
Oil	1.52×	0.66×	~0.7× output per unit KEEP
Geothermal	1.64×	0.61×	~0.6× output per unit KEEP
Other	1.24×	0.81×	~0.8× output per unit KEEP

7.5 Physical Basis of Burden Ratios

- **Hydropower (0.39×)**. Benefits from:
 - High ECE ($\approx 90\%$): turbines efficiently convert hydraulic head to electricity,
 - Moderate CF ($\approx 42\%$): seasonal variation limits utilization,
 - Combined $d_{\text{hydro}} = 0.349$ is the highest of all sources.
- **Nuclear (0.56×)**. Benefits from:
 - High CF ($\approx 79\%$): baseload operation with minimal variability,
 - Moderate ECE ($\approx 33\%$): Rankine-cycle thermodynamic limit,
 - Combined $d_{\text{nuclear}} = 0.241$ reflects reliable high utilization.
- **Solar PV (6.01×)**. Burdened by:
 - Low ECE ($\approx 20\%$): silicon bandgap and system losses,
 - Low CF ($\approx 12\%$): diurnal cycle, weather, seasons,
 - Combined $d_{\text{solar}} = 0.02245$ means only 2.245% of nameplate becomes useful output.

It is important to note that the numerical value of the solar PV burden ratio ($\approx 6.01\times$) is partly a consequence of the **current global deployment pattern**:

- The global average CF ≈ 0.122 includes a large share of high-latitude installations, substantial rooftop PV, and many systems with non-optimal tilt, orientation, or shading.
- In contrast, modern utility-scale PV in high-insolation regions routinely achieves CF ≈ 0.20 – 0.25 .

If future PV deployment were concentrated in such high-quality sites, the effective CF_{PV} entering the KEEP calculation would be higher, and the solar burden ratio correspondingly lower. Our sensitivity analysis in Sections 10.1 and 10.2 shows that even substantial improvements in solar CF and ECE (e.g., CF_{PV} increased by 50% or more) reduce total $KEEP_{elec}/P_{elec}$ by at most $\approx 10\text{--}15\%$ for the present system and by $\approx 10\text{--}15\%$ for solar-heavy futures, while leaving solar PV as the most infrastructure-intensive major source. Thus:

- The **ranking** of solar as highest burden is robust and rooted in fundamental physics (low conversion efficiency and diurnal/seasonal variability),
- The **magnitude** of the solar burden factor ($\approx 6.01\times$ for 2023) is sensitive to siting, deployment choices, and technology evolution.

A pedagogical (non-KEEP) breakdown of solar’s low utilization is:

- Diurnal cycle: 50% reduction (night hours),
- Weather and clouds: 25% reduction,
- Seasonal variation: 15% reduction (latitude-dependent),
- System losses: 10% reduction (inverter, wiring, soiling),
- Module efficiency: 20% of incident irradiance converted,
- Grid and end-use: $0.92 \times 0.75 \approx 0.69$ of generated electricity reaches useful application.

Multiplying illustrative factors:

$$0.50 \times 0.75 \times 0.85 \times 0.90 \times 0.20 \times 0.92 \times 0.75 \approx 0.04,$$

i.e., $\sim 4\%$ of incident irradiance becomes useful output. The discrepancy with $d_{solar} = 2.25\%$ arises because CF already incorporates diurnal, weather, and seasonal effects; the 4% is a heuristic decomposition, not the formal KEEP parameter.

7.6 Uncertainty in Burden Ratios

From the Monte Carlo analysis:

Table 7.4: Burden Ratio Uncertainty (90% Confidence Intervals)

Source	Central Estimate	90% CI	Rank Stability
Hydropower	0.39×	[0.31, 0.47]	Always lowest
Nuclear	0.56×	[0.46, 0.69]	Always 2nd lowest
Coal	0.68×	[0.55, 0.84]	Stable 3rd–4th
Natural Gas	0.74×	[0.60, 0.92]	Stable 3rd–4th
Wind	1.27×	[0.98, 1.63]	Moderate burden
Solar PV	6.01×	[4.26, 8.72]	Always highest

Key finding: the burden hierarchy (hydro < nuclear < coal/gas < wind < solar) is robust across all Monte Carlo iterations. No parameter combinations within the uncertainty ranges reverse the relative ranking of major sources.

7.7 Caveats and Limitations

What burden ratio does **not** capture:

- Fuel-cycle infrastructure: nuclear requires uranium mining, enrichment, fuel fabrication, and waste storage. Coal requires mining and transport. These upstream infrastructures are excluded from KEEP.
- Material intensity: hydropower dams require massive concrete and steel inputs. A low burden ratio does not mean low material requirements.
- Land use: hydropower reservoirs and solar farms both require significant land. Burden ratio does not distinguish between them.
- Operational complexity: nuclear requires specialized workforce and security infrastructure. Solar requires minimal operational support.
- Lifecycle emissions: burden ratio is emissions-agnostic. Low-burden coal has high lifecycle emissions; high-burden solar has low emissions.
- Dispatchability: burden ratio does not account for the value of dispatchable vs. variable generation.
- Storage requirements: variable sources may require storage infrastructure not captured in generation-side KEEP.

Appropriate use: burden ratios quantify the **primary capture infrastructure intensity** of different sources. They are most meaningful for comparing how technology mix changes affect total installed capacity requirements, not for determining optimal technology choice. Burden ratios should be considered alongside LCOE, emissions, deployment rates, and resource constraints.

8. IEA Convention vs. Physical-Flux Comparison

8.1 Summary Comparison

Table 8.1: Accounting Convention Comparison

Metric	IEA Convention	Physical Flux	Difference
Total TES	20.09 TW	21.95 TW	+9%
Solar TES	0.26 TW	1.285 TW	+494%
Wind TES	0.38 TW	0.984 TW	+258%
Hydro TES	0.49 TW	0.54 TW	+10%
Nuclear TES	0.95 TW	0.95 TW	0%

Metric	IEA Convention	Physical Flux	Difference
Fossil TES	18.01 TW	18.17 TW	1%
KEEP _{elec}	17.49 TW	17.49 TW	0%
KEEP _{elec} /P _{elec}	7.4×	7.4×	0%

8.2 Interpretation

Why do TES shares change but $KEEP_{elec}/P_{elec}$ remains constant?

KEEP_{elec} is constructed **backward** from useful output P through physical conversion parameters (ECE, CF, GE). The accounting convention for primary energy affects how we report energy flows but does not change:

- The physical efficiency of solar panels (ECE = 0.20),
- The capacity factor achieved (CF = 0.12),
- The grid losses (GE = 0.92),
- The end-use efficiency ($\eta_{end} = 0.75$).

Therefore, KEEP_{*i*} for each source depends only on:

$$KEEP_i = \frac{f_i \times P}{d_i} = \frac{f_i \times P}{ECE_i \times CF_i \times GE'}$$

which is independent of whether we count solar primary energy at electrical output (IEA convention) or at incident irradiance (physical flux).

Implication: KEEP provides a **convention-independent** measure of infrastructure requirements, unlike primary energy statistics which vary with accounting methodology.

9. Future Transition Scenarios and IKEEP

9.1 Scenario Definitions

We analyse three **illustrative** 2050 electricity-mix scenarios representing different decarbonization pathways:

Table 9.1: Scenario Generation Mix (2050)

Source	Current (2023)	A: Solar Heavy	B: Balanced	C: Nuclear Heavy
Solar PV	5.3%	45%	25%	10%
Wind	7.8%	25%	25%	15%
Nuclear	9.1%	5%	25%	55%
Hydropower	14.6%	15%	15%	15%

Source	Current (2023)	A: Solar Heavy	B: Balanced	C: Nuclear Heavy
Natural Gas	22.1%	10%	10%	5%
Coal	35.5%	0%	0%	0%
Bio+Waste	2.6%	0%	0%	0%
Other	3%	0%	0%	0%
Total	100%	100%	100%	100%
VRE Share	13.5%	70%	50%	25%

All scenarios achieve full coal phase-out. Scenario A emphasizes rapid solar deployment; Scenario B balances multiple low-carbon sources; Scenario C emphasizes nuclear expansion.

These scenarios are **not forecasts or optimized designs**. They are stylized thought experiments intended to illustrate how the $KEEP_{elec}$ and IKEEP metrics respond to very different technology mixes. Real decarbonization pathways would likely include additional options (e.g., CCS, bioenergy, demand response, hydrogen turbines), which we omit here to maintain clarity of comparison.

9.2 Projected Technology Parameters (2050)

We assume continued technology improvement:

Table 9.2: Technology Parameter Projections (2050)

Source	ECE (2023)	ECE (2050)	CF (2023)	CF (2050)	Basis
Solar PV	0.20	0.25	0.122	0.18	Higher efficiency, better siting
Wind	0.38	0.42	0.304	0.35	Larger turbines, more offshore
Nuclear	0.33	0.35	0.793	0.88	Advanced reactors, improved operations
Hydropower	0.90	0.90	0.422	0.40	Limited expansion potential
Natural Gas	0.48	0.58	0.410	0.35	Higher efficiency, reduced role

Grid efficiency is assumed constant at $GE = 0.92$ (grid improvements offset by longer transmission distances).

The assumed 2050 solar CF of 0.18 is intentionally **conservative** relative to the best current utility-scale sites. As discussed in Section 10.2, we also examine a sensitivity case with $CF_{PV} = 0.22$ (a $\approx 20\%$ increase), which lowers IKEEP/P in solar-heavy scenarios by $\approx 14\%$ but does not change the qualitative ranking of scenarios: solar-heavy pathways remain substantially more infrastructure-intensive than nuclear-heavy or balanced pathways for the same useful output.

Calculated d_i for 2050:

- Solar PV: $d = 0.25 \times 0.18 \times 0.92 = 0.0414$,
- Wind: $d = 0.42 \times 0.35 \times 0.92 = 0.1353$,
- Nuclear: $d = 0.35 \times 0.88 \times 0.92 = 0.2834$,

- Hydropower: $d = 0.90 \times 0.40 \times 0.92 = 0.3312$,
- Natural Gas: $d = 0.58 \times 0.35 \times 0.92 = 0.1868$.

9.2.1 System-Level Effects on Capacity Factors

In the 2050 scenarios we treat capacity factors CF_i as exogenous technology parameters that reflect resource quality and technical performance, but **not** system-level interactions such as curtailment or minimum-turndown constraints. This simplification is important:

- At high VRE shares, *effective* CFs for wind and solar are often reduced by curtailment, not only by meteorological constraints.
- At very high nuclear shares in a system that still contains non-trivial VRE, it is generally not feasible for the nuclear fleet to maintain $CF \approx 0.88$ unless:
 - Nuclear units are allowed to load-follow significantly, and/or
 - There is substantial storage and/or demand flexibility beyond the modest storage fractions we assume in Table 9.3.

Our Scenario C (“Nuclear Heavy”) therefore implicitly assumes a highly flexible nuclear fleet and limited curtailment of both nuclear and VRE generation. In real systems, maintaining $CF \approx 0.88$ for a 55% nuclear share in the presence of 25% VRE may be challenging without additional storage, demand response, or export options. A more complete treatment would endogenize CFs via a capacity-expansion and dispatch model, allowing CFs to emerge from the co-optimization of capacity, storage, and operational constraints. This is beyond the scope of the present analysis.

Consequently, the IKEEP values reported for the scenarios, and particularly the low IKEEP/P for Scenario C, should be interpreted as **optimistic lower-bound infrastructure requirements** under the stated assumptions about CFs and curtailment.

9.3 Base KEEPP/P Calculation

For each scenario, base $KEEP_{elec}/P_{elec}$ is calculated as:

$$\frac{KEEP_{elec,base}}{P_{elec}} = \sum_i \frac{w_i}{d_i},$$

where w_i is the scenario-specific generation share.

Scenario A (Solar Heavy):

Source	w_i	d_i	w_i/d_i
Solar PV	0.45	0.0414	10.870
Wind	0.25	0.1353	1.848
Nuclear	0.05	0.2834	0.176
Hydropower	0.15	0.3312	0.453

Source	w_i	d_i	w_i/d_i
Natural Gas	0.10	0.1868	0.535
Total	1.00	—	13.88

Scenario B (Balanced):

Source	w_i	d_i	w_i/d_i
Solar PV	0.25	0.0414	6.039
Wind	0.25	0.1353	1.848
Nuclear	0.25	0.2834	0.882
Hydropower	0.15	0.3312	0.453
Natural Gas	0.10	0.1868	0.535
Total	1.00	—	9.76

Scenario C (Nuclear Heavy):

Source	w_i	d_i	w_i/d_i
Solar PV	0.10	0.0414	2.415
Wind	0.15	0.1353	1.109
Nuclear	0.55	0.2834	1.941
Hydropower	0.15	0.3312	0.453
Natural Gas	0.05	0.1868	0.268
Total	1.00	—	6.19

9.4 Storage Integration Using IKEEP

High VRE penetration requires energy storage to balance supply and demand. The Integrated KEEP (IKEEP) framework accounts for storage losses.

Let:

- f_{direct} = fraction of demand met directly from generation,
- f_{storage} = fraction of demand met via storage ($f_{\text{direct}} + f_{\text{storage}} = 1$),
- η_{RTE} = storage round-trip efficiency.

The effective generation requirement becomes:

$$P_{\text{effective}} = P_{\text{demand}} \left(f_{\text{direct}} + \frac{f_{\text{storage}}}{\eta_{\text{RTE}}} \right).$$

The storage factor is:

$$\text{Storage Factor} = 1 + f_{\text{storage}} \times \left(\frac{1}{\eta_{\text{RTE}}} - 1 \right)$$

And IKEEP/P is:

$$\frac{\text{IKEEP}}{P} = \frac{\text{KEEP}_{\text{base}}}{P} \times \text{Storage Factor}$$

9.4.1 Limitations of the Storage Factor Approximation

The IKEEP formulation

$$\frac{\text{IKEEP}}{P} = \frac{\text{KEEP}_{\text{base}}}{P} \times \left[1 + f_{\text{storage}} \left(\frac{1}{\eta_{\text{RTE}}} - 1 \right) \right]$$

explicitly accounts for **round-trip energy losses in storage**, but it does not fully capture all system-level infrastructure penalties associated with high VRE penetration. In particular, we do not explicitly model:

- Additional overbuild of VRE capacity needed to simultaneously (i) meet instantaneous demand and (ii) charge storage during prolonged low-resource periods, and
- Extra firm capacity required for reserve margins and extreme events (e.g., multi-week wind lulls or extended cloudy periods).

The literature we draw on (e.g., Denholm et al., 2021; Dowling et al., 2020; Sepulveda et al., 2021; NREL, 2021) finds that, for VRE shares $\geq 50\text{--}70\%$, the combination of VRE overbuild, storage, and firming often leads to **non-linear increases** in required infrastructure that cannot be fully represented by a single multiplicative storage factor on energy flows. Our choice of f_{storage} is informed by these studies but remains a stylized approximation.

Therefore, the IKEEP values presented here should be interpreted as **stylized or lower-bound estimates** of infrastructure burden under high-VRE conditions. In more detailed system models that explicitly include VRE overbuild, curtailment, reserve margins, and extreme-event reliability criteria, the effective infrastructure multiplier associated with high VRE shares may be larger than our simple storage factor suggests.

9.5 Storage Assumptions

Table 9.3: Storage Parameters by Scenario

Scenario	VRE Share	f_{storage}	η_{RTE}	Storage Factor	Basis
Current	13.5%	0.02	0.85	1.004	Minimal storage today
A: Solar Heavy	70%	0.35	0.82	1.077	High storage need, mixed tech
B: Balanced	50%	0.20	0.85	1.035	Moderate storage need
C: Nuclear Heavy	25%	0.10	0.85	1.018	Limited storage need

Storage fraction derivation: based on grid integration studies (Denholm et al., 2021; Sepulveda et al., 2021), storage requirements scale roughly with VRE share squared for penetrations above 50%. We estimate:

- $f_{\text{storage}} \approx 0.35$ for 70% VRE (significant daily and multi-day storage),
- $f_{\text{storage}} \approx 0.20$ for 50% VRE (primarily daily cycling),
- $f_{\text{storage}} \approx 0.10$ for 25% VRE (primarily smoothing and reserves).

Round-trip efficiencies reflect an expected technology mix:

- Lithium-ion batteries: $\eta_{\text{RTE}} \approx 0.88$,
- Pumped hydro: $\eta_{\text{RTE}} \approx 0.80$,
- Compressed air: $\eta_{\text{RTE}} \approx 0.65$,
- Hydrogen: $\eta_{\text{RTE}} \approx 0.40$.

Weighted averages are used per scenario.

9.6 IKEEP Results

Table 9.4: Scenario IKEEP/P Results (Electrical Sector)

Scenario	Base $\text{KEEP}_{elec}/P_{elec}$	Storage Factor	IKEEP/P	vs. Current (7.4×)
Current (2023)	7.4	1.004	7.43	Baseline
A: Solar Heavy	13.88	1.077	14.95	+102%
B: Balanced	9.76	1.035	10.10	+37%
C: Nuclear Heavy	6.19	1.018	6.30	-15%

Key comparisons:

- Solar Heavy vs. Nuclear Heavy:

$$\frac{14.95}{6.30} \approx 2.37.$$

The solar-heavy pathway requires approximately **137% more** installed primary capture capacity than the nuclear-heavy pathway for equivalent useful electrical output.

- Solar Heavy vs. Balanced:

$$\frac{14.95}{10.10} \approx 1.48.$$

The solar-heavy pathway requires approximately **48% more** infrastructure than the balanced pathway.

9.7 Deployment Context

Infrastructure efficiency must be weighed against deployment feasibility:

Table 9.5: Deployment Comparison

Metric	Solar PV	Nuclear
Current deployment rate	~300 GW/year	~5 GW/year
Deployment ratio	—	60× slower
Typical project timeline	1–2 years	10–15 years
LCOE (2023, utility-scale)	\$30–50/MWh	\$60–120/MWh
Learning rate	~20%/doubling	Historically low/negative

Implications:

- A pathway with lower IKEEP/P that cannot be deployed fast enough will fail to meet climate goals. Nuclear's ~60× slower deployment rate is a critical constraint.
- A pathway with higher IKEEP/P that deploys rapidly may succeed where a theoretically superior alternative cannot scale. Solar's rapid deployment is its primary advantage.
- Balanced pathways may offer the best risk-adjusted outcomes by diversifying across technologies with different constraints.
- IKEEP/P should inform infrastructure planning and material supply chains but does not determine optimal technology choice.

10. Sensitivity Analysis

10.1 Parameter Sensitivity (Current System)

Table 10.1 shows how deterministic changes to individual parameters affect $KEEP_{elec}/P_{elec}$. Unlike the variance decomposition in Section 6.6, which quantifies uncertainty contributions, this analysis shows the impact of specific hypothetical improvements.

Table 10.1: Sensitivity of Current $KEEP_{elec}/P_{elec}$ to Parameter Changes

Parameter	Base	Variation	Impact on $KEEP_{source}$	Impact on $KEEP/P$	System Impact
Solar ECE	0.20	+25% (0.25)	≈−20% (Solar)	−6.5%	7.4× → 6.9×
Solar CF	0.122	+50% (0.183)	−33% (Solar)	−10.7%	7.4× → 6.6×
Wind CF	0.304	+15% (0.35)	−13% (Wind)	−1.3%	7.4× → 7.3×
Nuclear CF	0.793	+5% (0.83)	−5% (Nuclear)	−0.3%	7.4×
Grid efficiency	0.92	+3% (0.95)	0% (all sources)	−3.1%	7.4× → 7.2×

Parameter	Base	Variation	Impact on $KEEP_{source}$	Impact on $KEEP/P$	System Impact
End-use η_{end}	0.75	+10% (0.825)	10% (all sources and total)	0%	7.4x

Key insights:

- Solar performance (ECE and CF) significantly affects solar’s own KEEP and can reduce the total $KEEP_{elec}/P_{elec}$ by up to 11% (for a 50% increase in solar CF) or 7% for a 25% increase in ECE. Combined improvements could reduce the ratio by \approx 15-17%. Solar nonetheless remains the most infrastructure-intensive source.
- *Grid efficiency improvements increase delivered useful electricity for all technologies without changing $KEEP_{elec}$: a 3% improvement in GE reduces the system ratio $KEEP_{elec}/P_{elec}$ by \approx 3%.*
- End-use efficiency (η_{end}) does not affect the $KEEP_{elec}/P_{elec}$ ratio, as it scales both useful output (P_{elec}) and required infrastructure ($KEEP_{elec}$) proportionally. This is consistent with its exclusion from the variance decomposition in section 6.6.
- Nuclear CF changes have limited effect on current system $KEEP_{elec}/P_{elec}$ at present shares (\sim 9%), but matter more in nuclear-heavy futures.

Relationship to variance analysis: The sensitivity results in table 10.1 are consistent with the variance contribution in Table 6.6. Solar parameters dominate both analyses because solar has (1) the largest KEEP share despite a small generation share, and (2) significant parameter uncertainty. Grid efficiency appears prominently in both because it affects all sources. End-use efficiency correctly shows zero contributions in the ratio in both analyses.

10.2 Scenario Sensitivity

Table 10.2: Scenario IKEEP/P Sensitivity to 2050 Assumptions

Assumption Change	Impact on Scenario A	Impact on Scenario C
Solar CF +20% (0.18 \rightarrow 0.22)	-14% IKEEP/P	-4% IKEEP/P
Nuclear CF -5% (0.88 \rightarrow 0.84)	+1% IKEEP/P	+4% IKEEP/P
Storage η_{RTE} +10%	-3% IKEEP/P	-1% IKEEP/P
$f_{storage}$ + 50%	+4% IKEEP/P	+1% IKEEP/P

10.3 Robustness of Rankings

The burden-ratio hierarchy and scenario rankings are robust to parameter variations within plausible ranges:

- Hydropower remains most efficient across all Monte Carlo iterations,
- Nuclear remains second-most efficient in all cases,
- Solar remains highest burden even with optimistic 2050 parameters,
- Scenario C (Nuclear Heavy) requires less infrastructure than Scenario A (Solar Heavy) in 100% of Monte Carlo iterations under our assumptions.

11. Kardashev Scale Analysis

11.1 Framework

The Kardashev scale (Kardashev, 1964) classifies civilizations by energy utilization:

$$K = \frac{\log_{10}(P) - 6}{10},$$

where P is power utilization in watts. This yields:

- Type I ($K = 1.0$): $P = 10^{16}$ (planetary-scale, 10,000 TW),
- Type II ($K = 2.0$): $P = 10^{26}$ (stellar-scale),
- Type III ($K = 3.0$): $P = 10^{36}$ (galactic-scale).

11.2 Current Level (Primary-Energy Basis)

Using primary energy as in the standard convention, we take:

- Total Energy Supply: $TES \approx 20.1 \text{ TW} = 2.01 \times 10^{13} \text{ W}$.

Then:

$$K_{\text{primary}} = \frac{\log_{10}(2.01 \times 10^{13}) - 6}{10} \approx \frac{13.30 - 6}{10} \approx 0.73.$$

So, by the primary-energy Kardashev convention, humanity in 2023 is at:

$$K_{\text{primary}} \approx 0.73.$$

This is the value most comparable to other published estimates.

11.3 Useful-Energy Perspective

Much of our analysis focuses on useful energy P_{full} , because only useful power can actually perform services (heat at the right temperature, mechanical work, information processing, etc.). From Section 4, we estimated:

- Useful energy: $P_{\text{full}} \approx 7.1 \times 10^{12} \text{ W} = 7.1 \text{ TW}$.

Using this as an alternative basis:

$$K_{\text{useful}} = \frac{\log_{10}(7.1 \times 10^{12}) - 6}{10} \approx \frac{12.85 - 6}{10} \approx 0.69.$$

Thus, on a useful-energy basis:

$$K_{\text{useful}} \approx 0.69.$$

This is lower than $K_{\text{primary}} \approx 0.73$ because only about 35% of primary energy becomes useful energy globally (Section 4).

We view K_{primary} as the appropriate quantity for comparisons with the Kardashev literature, since it follows the original definition based on total power harnessed. At the same time, K_{useful} can be argued to be more directly related to civilizational capability, since it discounts energy lost to unavoidable conversion inefficiencies. For this reason:

- We report both values:
 - $K_{\text{primary}} \approx 0.73$ (standard, primary-energy basis),
 - $K_{\text{useful}} \approx 0.69$ (energy-service basis),

and make clear in each context which is being used.

11.4 Type I Requirements

For a Type I civilization, we consider $10^{16}W = 10000 \text{ TW}$ of **useful** power.

Table 11.1: Type I Infrastructure Requirements by Pathway (Useful-Power Basis)

Pathway	$\text{KEEP}_{elec}/P_{elec}$	Type I KEEP (TW)	vs. Nuclear Heavy
Current mix (scaled)	7.4×	74,000	+17%
A: Solar Heavy	14.95×	149,500	+137%
B: Balanced	10.10×	101,000	+60%
C: Nuclear Heavy	6.30×	63,000	Baseline

The original Kardashev definition is based on the **total power harnessed** by a civilization, which is closer to our TES (primary energy) than to useful energy. In this subsection, however, we take

$P = 10^{16}$ to represent **useful** power in order to ask a slightly different question:

“If a civilization were to enjoy Type I levels of useful power services, what amount of installed primary capture capacity would be required under different technology mixes, as quantified by IKEEP/P ?”

This is a deliberate extension of the Kardashev concept. The values in Table 11.1 therefore represent the **installed capture capacity needed to deliver 10,000 TW of useful power** under our scenario-specific IKEEP/P ratios; they are not themselves the P that enters the Kardashev formula. Consequently, our “Type I KEEP” numbers are not directly comparable to the canonical 10,000 TW Kardashev benchmark, but rather provide an **infrastructure-centric** view of how different technology pathways could realize a Type I-equivalent level of useful power.

Interpretation: the choice of technology pathway has profound implications for long-term infrastructure requirements. A solar-heavy Type I civilization would require approximately 150,000 TW of installed primary capture capacity—over twice that of a nuclear-heavy pathway.

At such scales, material constraints become critical. Assuming current material-intensity values continue, a solar-heavy Type I could require, at rough order-of-magnitude:

- $\sim 10^{12}$ – 10^{13} tonnes of silicon,
- $\sim 10^9$ – 10^{10} tonnes of silver (current global reserves: $\sim 5 \times 10^5$ tonnes),
- Vast quantities of aluminum, copper, and rare earth elements.

These values are intended as **illustrative orders of magnitude**, scaled from present-day t/MW intensities (UNECE 2021; Kaboli, Emma (2025)). They suggest that pathways to Type I civilization may necessarily involve technologies with lower KEEP/P ratios (advanced nuclear, fusion, space-based solar) and/or breakthrough reductions in material intensity and large-scale recycling.

12. Material and Resource Implications

12.1 Material Intensity Correlation

While KEEP does not directly measure material requirements, higher KEEP generally implies more infrastructure and thus more materials.

Table 12.1: Approximate Material Intensity by Technology (Indicative)

Technology	Steel (t/MW)	Concrete (t/MW)	Copper (t/MW)	Selected Critical Minerals
Solar PV	35	90	4	Silicon, silver, indium
Wind	120	360	3	Rare earths (Nd, Dy)
Nuclear	50	400	1.5	Uranium
Hydro	30	15,000	1	None significant
Natural Gas	3	30	0.3	None significant

Sources: UNECE (2021); Kaboli, Emma (2025). Values are system-level, order-of-magnitude estimates.

12.2 Scenario Material Implications

Scaling material requirements approximately in proportion to IKEEP and indicative t/MW intensities yields:

Table 12.2: Relative Material Requirements by Scenario (Normalized to Current ≈ 1.0)

Material	Current	A: Solar Heavy	B: Balanced	C: Nuclear Heavy
Total IKEEP	1.0×	2.0×	1.4×	0.85×
Steel	1.0×	2.1×	1.4×	0.9×
Concrete	1.0×	1.8×	1.3×	1.1×
Copper	1.0×	2.5×	1.6×	0.7×
Silicon	1.0×	8×	4×	1.5×

Key finding: high-IKEEP pathways require substantially more materials. The solar-heavy scenario requires approximately 2.5× more copper and 8× more silicon than today’s infrastructure, potentially straining supply chains and mining capacity. These are order-of-magnitude indications, not precise forecasts, and assume similar technology and material-intensity profiles.

12.3 Resource Constraints

Table 12.3: Critical Resource Assessment (Indicative)

Resource	Current Use (Mt/yr)	Solar-Heavy Need (Mt/yr)	Rough Years of Current Reserves*
Copper	22	55	20
Silicon	8	65	Abundant (quartz/sand)
Silver	0.025	0.2	8
Rare earths	0.3	0.8	50
Uranium	0.06	0.15 (Scenario C)	130

U.S. Geological Survey, 2025

* Very rough, based on current reserve estimates; actual availability depends on price, technology, and recycling.

Implications:

- Silver may be a binding constraint for high-solar pathways unless alternative metallization or much higher recycling rates are developed.
- Copper supply expansion is needed for any major electrification pathway.
- Nuclear fuel availability is not a near-term constraint for nuclear-heavy pathways at current reserve estimates, especially with breeder and recycling options.
- Recycling and circular-economy approaches become essential at scale.

These resource assessments are approximate and intended to illustrate the link between IKEEP and potential material bottlenecks, not to provide definitive resource-exhaustion timelines.

13. Summary and Conclusions

13.1 Key Metrics (2023)

Table 13.1: Summary of 2023 Global Energy System Parameters

Metric	Value	Uncertainty	Source
Total Energy Supply (TES)	633.7 EJ = 20.1 TW	±2%	IEA 2023
Final Energy Consumption (FEC)	429.1 EJ = 13.61 TW	±2%	IEA 2023
Useful Energy (P_{full})	7.1 TW	±1.0 TW	Sec. 4
Useful Electrical (P_{elec})	2.36 TW	±0.18 TW	Sec. 6
Primary-to-useful multiple	$TES/P_{full} \approx 2.83$	—	Sec. 4

Metric	Value	Uncertainty	Source
Electrical KEEP ($KEEP_{elec}$)	17.49 TW	± 3.21 TW	Sec. 6
Electrical $KEEP_{elec}/P_{elec}$	7.4× [5.5, 10.0] (90% CI)	—	Sec. 6
Full multi-source $KEEP_{full}$ (phys. flux)	≈ 47.71 TW (illustrative)	$\sim \pm 20\%$	Sec. 7.1
Full multi-source $KEEP/P_{full}$	$\approx 6.72\times$ (illustrative)	$\sim \pm 20\%$	Sec. 7.1
INEC (calculated)	8.477 TW	$\pm 2\%$	Sec. 6
INEC (reported, adjusted)	8.472 TW	—	GEM/IRENA

13.2 Infrastructure Burden Hierarchy

- Hydro and nuclear have the lowest burden ratios (~ 0.4 – $0.6\times$),
- Coal and gas are near proportional (~ 0.6 – $0.8\times$),
- Wind is moderately infrastructure-intensive (~ 1.2 – $1.3\times$),
- Oil peaking plants and especially solar PV ($\sim 6.01\times$) are the most infrastructure-intensive per unit useful output.

13.3 Pathways and Trade-offs

- Solar-heavy scenarios have $IKEEP/P$ roughly $2.4\times$ nuclear-heavy scenarios for the same useful electrical output.
- Balanced mixes can reduce infrastructure needs relative to solar-heavy pathways while avoiding exclusive reliance on any single constrained technology.
- However, solar currently deploys $\approx 60\times$ faster than nuclear and often has lower LCOE, so infrastructure efficiency must be weighed against deployment reality.

13.4 Core Conclusions

- The electrical sector requires ≈ 7.4 W of installed primary capture capacity per W of useful electrical output. The global primary-to-useful energy multiple is $\approx 2.8\times$, and a full multi-source physical-flux $KEEP_{full}/P_{full}$ for the entire system is of order 6.72 (illustrative 47.71 TW / 7.1 TW).
- Solar PV's high burden ratio ($\sim 6.0\times$) is rooted in physics (low ECE and CF), not accounting conventions, although its exact magnitude depends on siting and deployment choices.
- The parameter set (ECE, CF, GE) is internally consistent with observed capacity and generation (INEC reconstruction).
- Technology mix strongly affects infrastructure requirements; solar-heavy paths are significantly more capacity- and material-intensive than nuclear-heavy paths for a given P .
- High-IKEEP pathways risk material bottlenecks; planning must consider both infrastructure magnitude and resource availability.

- KEEP and IKEEP offer a valuable infrastructure lens but must be combined with cost, deployment speed, emissions, land use, and social factors.
- By the standard primary-energy definition, humanity's Kardashev level in 2023 is $K \approx 0.73$, while using useful (service-level) power yields $K \approx 0.69$.
- Balanced pathways may offer attractive trade-offs by leveraging the strengths of multiple low-carbon technologies while mitigating their individual limitations.

References

- Betz, A. (1920). Das Maximum der theoretisch möglichen Ausnutzung des Windes durch Windmotoren. *Zeitschrift für das gesamte Turbinenwesen*, 26, 307–309.
- Brockway, P. E., et al. (2014). Divergence of trends in US and UK aggregate exergy efficiencies 1960–2010. *Environmental Science & Technology*, 48(16), 9874–9881.
- Burton, T., Sharpe, D., Jenkins, N., & Bossanyi, E. (2011). *Wind Energy Handbook* (2nd ed.). Wiley.
- Cullen, J. M., & Allwood, J. M. (2010). The efficient use of energy: Tracing the global flow of energy from fuel to service. *Energy Policy*, 38(1), 75–81.
- Denholm, P., et al. (2021). The challenges of achieving a 100% renewable electricity system in the United States. *Joule*, 5(6), 1331–1352.
- DOE (2023). *Critical Minerals Assessment*. U.S. Department of Energy, Washington, DC.
- Dowling, J. A., et al. (2020). Role of long-duration energy storage in variable renewable electricity systems. *Joule*, 4(9), 1907–1928.
- Global Energy Monitor (2024). *Global Power Plant Tracker*. <https://globalenergymonitor.org/>
- Heard, B. P., et al. (2017). Burden of proof: A comprehensive review of the feasibility of 100% renewable electricity systems. *Renewable and Sustainable Energy Reviews*, 76, 1122–1133.
- IEA (2023). *World Energy Outlook 2023*. Paris: International Energy Agency.
- IEA (2024). *World Energy Balances 2023 and World – Energy Mix*. <https://www.iea.org/world/energy-mix>
- IRENA (2024). *Renewable Capacity Statistics 2024*. Abu Dhabi: International Renewable Energy Agency.
- Jenkins, J. D., et al. (2018). Getting to zero carbon emissions in the electric power sector. *Joule*, 2(12), 2498–2510.
- Kardashev, N. S. (1964). Transmission of information by extraterrestrial civilizations. *Soviet Astronomy*, 8(2), 217–221.
- Loftus, P. J., et al. (2015). A critical review of global decarbonization scenarios. *WIREs Climate Change*, 6(1), 93–112.
- NREL (2021). *Storage Futures Study*. Golden, CO: National Renewable Energy Laboratory.
- NREL (2023). *Annual Technology Baseline 2023*. Golden, CO: National Renewable Energy Laboratory.

Sepulveda, N. A., Jenkins, J. D., et al. (2021). The design space for long-duration energy storage in decarbonizing the electricity sector. *Nature Energy*, 6, 506–516.

Smil, V. (2022). *How the World Really Works: The Science Behind How We Got Here and Where We're Going*. Viking.

UNECE (2021). *Life Cycle Assessment of Electricity Generation Options*. Geneva: United Nations Economic Commission for Europe.

U.S. Geological Survey, 2025, Mineral commodity summaries 2025 (ver. 1.2, March 2025): U.S. Geological Survey, 212 p., <https://doi.org/10.3133/mcs2025>.

Kaboli, Emma (2025) Critical Minerals and Materials for Selected Energy Technologies <https://www.congress.gov/crs-product/R48149>

Appendix A: Data Sources and Verification

TES (TJ, IEA 2023):

- Coal & coal products: 175,947,669
- Natural gas: 144,146,098
- Hydropower: 15,308,404
- Nuclear: 29,919,241
- Solar, wind & other: 20,752,505
- Biofuels & waste: 56,014,379
- Oil & oil products: 191,612,174
- **Total:** 633,700,470 TJ = 633.70 EJ.

FEC:

- 429,107,543 TJ = 429.11 EJ = 13.61 TW.

Electricity generation (GWh, IEA 2023):

- Coal: 10,687,074
- Oil: 778,082
- Natural gas: 6,647,518
- Biofuels: 656,490
- Waste: 116,338
- Nuclear: 2,740,481
- Hydropower: 4,395,916
- Solar PV: 1,604,599

- Wind: 2,333,137
- Solar thermal: 15,535
- Geothermal: 98,137
- Tide: 928
- Other: 47,489
- **Total:** 30,121,725 GWh.

GEM 2023 operating capacity (GW):

- Coal: 2,155.3
- Oil & gas (combined): 2,062.5
- Hydropower: 1,188.1
- Nuclear: 394.2
- Utility-scale solar: 685.4
- Wind: 875.4
- Geothermal: 15.1
- Bioenergy: 104.0.

Checks:

- TES total: $633.7 \text{ EJ} \div 31.536 \approx 20.1 \text{ TW}$,
- FEC total: $429.1 \text{ EJ} \div 31.536 \approx 13.61 \text{ TW}$,
- $\text{FEC/TES} \approx 67.7\%$,
- Generation: $30,122 \text{ TWh} \div 8,760 \approx 3.43 \text{ TW}$,
- $\text{INEC/Reported: } 8.477 \text{ TW} / 8.472 \text{ TW} \approx 1.001$ (within expected range).

Appendix B: Example Calculations

- **Solar PV KEEP:**

$$\text{KEEP}_{\text{solar}} = \frac{0.0533 \times 2.36}{0.02245} \approx \frac{0.1258}{0.02245} \approx 5.60 \text{ TW}$$

- **Nuclear INEC:**

$$\text{INEC}_{\text{nuclear}} = \frac{0.313 \text{ TW}}{0.793} \approx 0.395 \text{ TW}$$

consistent with 394 GW of nuclear capacity.

- **Storage factor for Scenario A:**

$$\text{Factor} = 1 + 0.35 \left(\frac{1}{0.82} - 1 \right) \approx 1 + 0.35 \times 0.22 \approx 1.077$$

- **Kardashev K (useful-energy basis):**

$$K = \frac{\log_{10}(7.1 \times 10^{12}) - 6}{10} \approx 0.685 \approx 0.69$$

All calculations are reproducible from the IEA and GEM data and the parameter assumptions described in the main text.