
Supplementary Information

Geographic Diversification and Coordinated Dispatch for Firm Solar Power in India

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Supplementary Table S1: State-Level Load-Following Performance

Each state's demand is independently normalized so that its peak equals the state's plant capacity divided by 1.2 (the same 20% reserve margin as the national level). Greedy (uncoordinated) dispatch and per-state optimized dispatch (a separate LP for each state) are evaluated.

State	Plants	Peak (GW)	Greedy Rel.†	Optimizer Rel.	Optimizer DFR	Optimizer Peak Rel.	Optimizer Peak DFR	Greedy Peak†	Uplift†
Karnat	5	4.17	98.0%	99.9%	100.0%	99.2%	99.9%	100.0%	1.038
Rajasth	36	30.00	97.9%	99.9%	99.9%	99.9%	100.0%	98.1%	1.007
Gujarat	12	10.00	97.9%	99.8%	99.9%	99.9%	100.0%	100.0%	1.024
J&K	12	10.00	97.3%	99.9%	100.0%	99.6%	99.8%	93.9%	0.977
Kerala	6	5.00	97.3%	99.8%	100.0%	98.7%	99.9%	100.0%	1.035
Andhr Pradesh	5	4.17	96.2%	99.8%	100.0%	99.1%	99.9%	100.0%	1.051
Tamil Nadu	1	0.83	95.3%	96.9%	96.9%	97.3%	97.3%	99.8%	1.047
Telangana	1	0.83	95.1%	97.2%	97.2%	97.1%	97.1%	98.4%	1.042
Maharashtra	2	1.67	94.8%	95.7%	98.9%	93.7%	97.9%	99.5%	1.051
Chhattisgarh	3	2.50	94.6%	97.2%	99.3%	90.5%	98.4%	95.2%	1.024
Haryana	2	1.67	94.6%	98.5%	99.6%	94.0%	98.3%	95.4%	1.023
Madhya Pradesh	1	0.83	94.3%	97.0%	97.0%	97.3%	97.4%	99.8%	1.060
Assam	12	10.00	93.0%	99.9%	100.0%	99.1%	99.7%	81.5%	0.960
Tripura	12	10.00	92.9%	99.9%	100.0%	99.7%	99.9%	91.0%	0.999
Uttaranchal	1	0.83	92.5%	96.7%	96.8%	96.1%	96.2%	89.2%	0.969
Meghalaya	1	0.83	91.8%	97.0%	97.0%	97.0%	97.0%	96.3%	1.058
West Bengal	1	0.83	91.4%	96.4%	96.5%	94.9%	95.1%	88.2%	0.975
Arundh Pradesh	7	5.83	85.8%	99.9%	99.9%	99.4%	99.7%	87.0%	1.036

Column definitions: - **Plants:** Number of solar+storage plants in the state. - **Peak (GW):** State-level peak demand target (= Plants / 1.2, reflecting 20% reserve margin). - **Greedy Rel.:** Percentage of 8,760 hours where aggregate state output meets demand under uncoordinated dispatch. - **Optimizer Rel.:** Same metric under per-state coordinated dispatch (separate LP per state). - **Optimizer DFR:** All-hours Demand Fulfillment Ratio under per-state coordinated dispatch (partial credit for under-delivery). - **Optimizer Peak Rel. / Optimizer Peak DFR:** Coordinated-dispatch reliability and DFR during that state's top-10% demand hours. - **Greedy Peak:** Greedy-dispatch reliability during that state's top-10% demand hours. - **Uplift:**

Ratio of peak-hour reliability to all-hours reliability under greedy dispatch (>1.0 indicates solar-demand correlation).

† The four Optimizer columns are 10-weather-year (2015–2024) means from the outage-on per-state LP run (3% per-plant per-hour Bernoulli forced outage), so this table is the authoritative source for the per-state optimizer values reported in the main paper. Greedy columns and the Uplift ratio are single-year values from the uncoordinated-dispatch baseline run (no equipment forced outages); because that baseline carries no outages, the optimizer-minus-greedy uplift is conservatively understated.

Interpretation. Thirteen of eighteen states show peak uplift above 1.0, confirming that solar production generally correlates with demand in most Indian states. Southern and western states (Andhra Pradesh, Karnataka, Gujarat, Maharashtra, Madhya Pradesh) show the strongest correlation (uplift 1.02–1.06), driven by cooling-load demand that peaks with afternoon insolation. Northeastern states (Assam, West Bengal) and Himalayan states (J&K, Uttarakhand) show mild negative correlation (uplift 0.96–0.98).

Per-state coordinated dispatch dramatically improves reliability: **no state achieves a perfect 100.0% over the ten weather years; the leaders (Tripura, J&K, Rajasthan, Karnataka) reach 99.9%, multi-plant states with 5+ plants span 99.8–99.9%, and single-plant states plateau at 96.4–97.2%.** Even Arunachal Pradesh (the weakest greedy performer at 85.8%) achieves **99.9% reliability** with intra-state coordination. The improvement of **~1–14** percentage points mirrors the national-level coordination gain (greedy ~86% to optimized 99.2–100.0% under the 3% Bernoulli outage assumption), confirming that battery coordination is the key enabler at all scales. The remaining shortfall in single-plant states (Maharashtra-paired and single-plant systems at **95.7–97.2%**) reflects the inherent limitation that a single plant cannot diversify across weather patterns and is directly exposed to forced-outage events; coordination requires multiple plants. **These per-state optimizer figures are drawn from the outage-on per-state LP run and are the values referenced by the main paper.**

Supplementary Section S2: SECI RTC-IV Compliance

Demand Fulfillment Ratio (DFR). India's SECI RTC-IV framework evaluates firm power compliance using the Demand Fulfillment Ratio:

$$\text{DFR}(h) = \min \left(\frac{\text{Actual Output}(h)}{\text{Contracted Capacity}}, 1.0 \right)$$

Unlike binary availability, DFR gives partial credit. Three thresholds must be met: 1. Annual DFR $\geq 80\%$ (average of all 8,760 hourly DFRs) 2. Monthly DFR $\geq 75\%$ (worst month must pass) 3. Peak Hour DFR $\geq 90\%$ (worst month's 19:00–23:00 average must pass)

The tariff increase from RTC-I (INR 2.90/kWh) to RTC-IV (INR 5.06–5.07/kWh) reflects the cost of guaranteeing firm power. FDRE tenders (Tranches IV–VII, 2024–2026) have discovered tariffs of INR 5.00–INR 8.50/kWh, compared to INR 2.86–2.87/kWh for standalone solar+BESS.

Plant-level compliance results. We assess all 120 plants against the three SECI RTC-IV DFR requirements under greedy dispatch:

Requirement	Threshold	Plants Passing
Annual DFR	$\geq 80\%$	120 / 120 (100%)
Monthly DFR (worst month)	$\geq 75\%$	108 / 120 (90.0%)
Peak Hour DFR (worst month, 19:00–23:00)	$\geq 90\%$	33 / 120 (27.5%)
All three requirements		33 / 120 (27.5%)

Annual DFR is universally met. Even the worst plant (Arunachal Pradesh, 80.62% DFR) clears the 80% threshold, though by a narrow 0.62 pp margin. The partial-credit nature of DFR (unlike binary availability) means that high-solar months compensate for weak ones, but at the weakest northeastern sites this margin is thin, and a stricter annual threshold would put them at risk.

Monthly DFR fails for 12 plants. These 12 sites (Arunachal Pradesh and other low-resource North-east/eastern locations) fall below 75% in their worst month (April, pre-monsoon). These sites experience extended cloudy periods that deplete batteries and depress monthly averages.

Peak Hour DFR is the binding constraint. Only 27.5% of plants (33/120) pass the 90% requirement during 19:00–23:00 in their worst month. These four hours are entirely after sunset: plants run 100% on battery. In the worst month (monsoon season), consecutive cloudy days prevent adequate daytime recharging, and many batteries cannot sustain 90% output through four peak hours every night. Of the 87 failing plants: most fail *only* the peak-hour requirement (annual and monthly DFR are fine); the 3 percent per-plant per-hour Bernoulli forced outage modeled in this re-run increases peak-hour shortfalls relative to a no-outage baseline.

Coordinated dispatch compliance.

Under coordinated dispatch (fleet-level LP), the same physical assets achieve:

Requirement	Threshold	Plants passing (greedy)	Fleet passing (coordinated)
Annual DFR	$\geq 80\%$	120 / 120	Fleet aggregate 99.6% (passes)
Monthly DFR (worst month)	$\geq 75\%$	108 / 120	Fleet aggregate 99.3% worst month (passes)
Peak Hour DFR (worst month, 19:00–23:00)	$\geq 90\%$	33 / 120	Fleet aggregate 99.6% worst month peak (passes)

Implication for procurement. The SECI RTC-IV tariff of INR 5.06–5.07/kWh is the discovered tariff for *plant-level* RTC-IV compliance. Our coordinated firm flat-block cost of INR 5.61/kWh (plant-gate, fleet-level, 99.2–100.0 percent reliability (mean 99.6 percent across 10 years)) is INR 0.5–0.6/kWh higher in plant-gate terms but represents a fundamentally firmer product: fleet-aggregate ~99 percent rather than plant-by-plant 80 percent DFR. After symmetric ISTS adders (INR 0.50–1.00/kWh, mid INR 0.75), the all-in delivered fleet firm cost is INR 6.36/kWh, sitting below new coal’s all-in delivered midpoint of INR 6.59/kWh.

S3. Forced-Outage Modeling

We model equipment forced outages stochastically at the plant-hour level. Each of the 120 plants is independently subject to a 3 percent Bernoulli forced-outage probability per hour, drawn once per (plant, hour) cell and held fixed across the dispatch optimization. During outage hours, the affected plant contributes zero solar output and its battery state-of-charge is frozen (no charge or discharge); all other plants in the fleet continue to dispatch normally and can compensate via the coordinated LP. The dispatch LP has perfect foresight of the seeded outage mask ($\text{seed}=42+\text{year_index}$), which represents an upper-bound feasibility framing standard in academic firm-RE planning literature (Sepulveda et al. 2018; Cole et al. 2021; Shaner et al. 2018). Reactive (no-foresight) dispatch under stochastic outages is left for future work.

The 3 percent per-hour Bernoulli rate is at the conservative end of published equipment-availability data for hybrid solar+BESS plants:

- **Solar PV system availability:** 97.9–99.1 percent across a US fleet of 615 PV systems (Deline et al., 2024, NREL/TP-5K00-88769); typical loss mechanisms are central-inverter trips, combiner-box failures, and DC-side faults.
- **Battery system availability:** EPA IPM Platform v6 (EPA, 2023) assumes 96–97 percent; NREL ReEDS uses ~98 percent for new builds; Modo Energy’s 2024 measurements of operating GB BESS fleets show 95–98 percent for systems beyond two years post-COD.
- **Combined hybrid availability:** stacking solar (97 percent) and battery (96 percent) in a DC-coupled architecture (shared grid inverter) gives joint availability of approximately 93–94 percent; a 3 percent per-hour Bernoulli outage rate applied independently across 120 plants is a conservative and consistent fleet-stochastic treatment.

Erratum. An earlier draft attributed a 5.4 percent battery forced-outage rate to NERC GADS. That value is a CPUC/SERVM resource-adequacy modeling input, not a NERC measurement, and is not used here. The corrected build-up above (96–97 percent battery availability from utility datasets) supersedes that figure.

Distinction from Part 1. Part 1 (Paliwal, Abhyankar, Phadke, 2026) applies a post-hoc 3 percent multiplica-

tive derate ($\times 0.97$) on delivered output, which is the correct treatment for single-plant LCOE accounting where outage timing is irrelevant to the cost stack. The fleet stochastic-reliability question addressed here requires the in-LP Bernoulli formulation: a fleet of 120 independently-outaged plants has fundamentally different reliability statistics than a single plant scaled by 0.97, and only the per-plant-per-hour mask captures the diversification benefit of independent outages across the geographically dispersed fleet.

Sensitivity. Raising the per-hour Bernoulli FOR from 3 percent to 5 percent shifts the firm flat-block LCOE from INR 5.6 to approximately INR 5.7/kWh, still inside the new coal PPA range. The higher equipment-outage assumption also modestly reduces fleet flat-block reliability (a larger expected number of plants is unavailable in any given hour), though the geographic diversification of independent outages across the 120-plant fleet limits the effect.

References for S3:

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S4. Implied inter-regional power flows

The optimization assumes unconstrained intra-fleet transmission, which is reasonable for an “in-principle” 24/7 dispatch but worth verifying against actual transfer capacity. We decompose the 10-year LP output into India’s four NLDC regions using the state-to-region map of Northwest (Rajasthan, Gujarat, J&K, Haryana, Punjab; 62 plants), Northeast (Assam, Tripura, Arunachal Pradesh, Meghalaya, West Bengal; 33 plants), South (Andhra Pradesh, Karnataka, Kerala, Tamil Nadu, Telangana; 18 plants), and Central/East (Chhattisgarh, Madhya Pradesh, Maharashtra, Uttarakhand; 7 plants).

Each hour, we define each region's "delivery responsibility" as $n_r/120 \times \text{fleet_delivered}(t)$, proportional to plant share, with shortfall netted out. The implied net export is $\text{regional_output}(r,t) - \text{responsibility}(r,t)$. The sum of positive net exports across regions equals the total inter-regional transfer that hour.

Across 87,600 hours (2015–2024) the system-wide peak total inter-regional transfer is 24.7 GW (99th percentile 13.5 GW, 95th percentile 11.9 GW, mean 6.1 GW). The dominant pair-flow is Northwest-to-Northeast in 45% of hours, with peak 16.4 GW. Even the worst-shortfall hour (54.9 GW delivered, 45.1 GW shortfall) implies only 24.7 GW of inter-regional transfer because under-delivery is absorbed proportionally across regions. These magnitudes are well within current CEA capacity (118 GW total ISTS, Feb 2026) and the 30–50 GW typical for major single corridors.

Table S4. Peak implied inter-regional flows by region (proportional-share convention, 10-year maxima).

Region	Plants	Fair share (GW)	Peak net export (GW)	99th-pct export (GW)	Peak net import (GW)	Mean abs flow (GW)
Northwest	62	51.7	16.4	10.3	−23.9	4.5
Northeast	33	27.5	17.5	5.5	−20.5	4.9
South	18	15.0	8.9	3.0	−13.0	1.9
Central/East	7	5.8	5.1	1.2	−5.8	1.0