Supplementary Note S4—Worked Zone Case: Methods, Equations, and Reproducible Workbook

Purpose

This note provides the exact inputs, equations, and computation steps used to generate the screening results presented in Section 4 of the manuscript. This example operationalizes the manuscript's covenant (ELCC-anchored tranches + PCC-service auditables), with standards references consolidated in the paper's Appendix.

Inputs

Table A1 summarizes the parameterization for a mature grid; Table A2 lists the emerging markets and developing economies (EMDEs) variant. Table A3 consolidates the main outcomes for the mature and EMDE cases—ELCC target and delivery (with ΔELCC), PCC obligations/delivery, and normalized costs—so that readers can view the decision metrics at a glance alongside the detailed inputs and equations provided in this note.

Table S1—Inputs (Mature grid)

Parameter	Symbol	Value	Unit/Notes
Compute load	P_comp	200	MW
FFR coefficient	f_FFR	0.15	MW per MW of compute
PCC power factor floor	PF_min	0.98	dimensionless
ELCC quota (policy band; central default)	α	[0.6, 0.8]; central = 0.7	fraction per MW compute
BESS duration	H	4	hours
BESS CAPEX	CAPEX_BESS_kWh	250	$/kWh
BESS life	n_BESS	12	years
BESS WACC	i_BESS	0.08	decimal
BESS FOM	FOM_BESS_kWyr	8	$/kW-yr
BESS ELCC credit	ELCCfrac_BESS	0.65	fraction of kW
Geothermal CAPEX	CAPEX_GEO_kW	4000	$/kW
Geothermal life	n_GEO	25	years
Geothermal WACC	i_GEO	0.08	decimal
Geothermal FOM	FOM_GEO_kWyr	110	$/kW-yr
Geothermal ELCC credit	ELCCfrac_GEO	0.90	fraction of kW
Ancillary adder (FFR+VAR)	Adder_kWyr	25	$/kW-yr on compute

BESS power (design variable)	P_BESS	230	MW; user-set
Geothermal power (design variable)	P_geo	35	MW; user-set or backfilled

Table S2—Inputs (EMDE variant)

Parameter	Symbol	Value	Unit/Notes
Compute load	P_comp	25	MW
FFR coefficient	f_FFR	0.15	MW per MW of compute
PCC power factor floor	PF_min	0.98	dimensionless
ELCC quota (policy band; central default)	α	[0.8, 1.0]; central = 0.9	fraction per MW compute
BESS duration	H	4	hours
BESS CAPEX	CAPEX_BESS_kWh	250	$/kWh
BESS life	n_BESS	12	years
BESS WACC (blended)	i_BESS	0.06	decimal (blended)
BESS FOM	FOM_BESS_kWyr	8	$/kW-yr
BESS ELCC credit	ELCCfrac_BESS	0.65	fraction of kW
Geothermal CAPEX	CAPEX_GEO_kW	4000	$/kW
Geothermal life	n_GEO	25	years
Geothermal WACC	i_GEO	0.08	decimal
Geothermal FOM	FOM_GEO_kWyr	110	$/kW-yr
Geothermal ELCC credit	ELCCfrac_GEO	0.90	fraction of kW
Ancillary adder (FFR+VAR)	Adder_kWyr	25	$/kW-yr on compute
BESS power (design variable)	P_BESS	30	MW; user-set
Geothermal power (design variable)	P_geo	0	MW; SSA variant uses DR
Demand Response power	P_DR	6	MW
Demand Response ELCC credit	ELCCfrac_DR	0.50	fraction of kW
Demand Response cost	Cost_DR_kWyr	40	$/kW-yr

Table S3—Case-study outcomes (mature vs EMDE)

Metric	Mature system	EMDE system
Compute load (MW)	200	25
FFR requirement (MW)	30	3.75

FFR delivered (MW)	30	3.75
Reactive headroom (MVAr)	40.612	5.076
ELCC target (MW)	140	22.5
ELCC delivered (MW)	140	22.5
ΔELCC (delivered − target) (MW)	0	0
ELCC from BESS (MW)	108.5	19.5
ELCC from DR (MW)	—	3
ELCC from geothermal (MW)	31.5	—
BESS power (MW)	166.92	30
BESS energy (MWh)	667.69	120
Total annual cost (USD/yr)	40,450,274.20	4,058,310.88
$/compute-kW-yr	202.25	162.33
$/ELCC-kW-yr	288.93	180.37
LOLE relative to 0.1 day·yr^{-1}	Held at target *(by construction under α)*	Held at target *(by construction under α)*

Notes:

- Values are taken from the MatureGrid and SSA worksheets of the accompanying workbook. Normalized cost entries are computed as total annual cost divided by compute kW ($/compute-kW-yr) and by ELCC kW ($/ELCC-kW-yr).
- Geothermal ELCC in the mature case is implied as *(ELCC target − ELCC to be met by BESS)*.
- Reactive headroom reflects PFmin = 0.98.

Methodological Approach

PCC-level service obligations:

- Fast Frequency Response (FFR):

$$FFR_required = f_FFR \cdot P_comp$$

- Reactive headroom (power-factor floor):

$$Q_required = tan(acos(PF_min)) \cdot P_comp = sqrt(1/PF_min\text{^}2 - 1) \cdot P_comp$$

- Adequacy quota (screening approximation to hold LOLE at target):

$$ELCC_target = \alpha \cdot P_comp$$

- Credited ELCC by resource and total:

$$ELCC_BESS = ELCCfrac_BESS \cdot P_BESS$$

$$ELCC_GEO = ELCCfrac_GEO \cdot P_geo$$

$$ELCC_DR = ELCCfrac_DR \cdot P_DR$$

$$ELCC_total = ELCC_BESS + ELCC_GEO\ (+ ELCC_DR)$$

- Storage energy sizing and CAPEX (BESS):

$$E_BESS\ (kWh)\ =\ 1000\ \cdot\ H\ \cdot\ P_BESS$$

$$CAPEX_BESS\ (\$)\ =\ CAPEX_BESS_kWh\ \cdot\ E_BESS$$

- Capital recovery and annualized cost:

$$CRF(i,n)\ =\ i(1+i)\text{^}n\ /\ ((1+i)\text{^}n\ -\ 1)$$

$$AnnualizedCost\ =\ CRF\ \cdot\ CAPEX\ +\ FOM\ \cdot\ (kW)$$

- Normalization metrics.

$$\$/kW\cdot yr\ (compute)\ =\ TotalAnnualCost\ /\ (1000\ \cdot\ P_comp)$$

$$\$/ELCC-kW\cdot yr\ =\ TotalAnnualCost\ /\ (1000\ \cdot\ ELCC_total)$$

- Backfill rule when ELCC_total < ELCC_target:

Add firm-clean capacity

P_add = (ELCC_target − ELCC_total) / κ_Firm

and recompute annual costs; adequacy then passes by construction.

Ancillary service adder

A compute-side ancillary services adder of $25/kW-yr is applied uniformly to P_comp in both scenarios, covering FFR and VAR provisioning at the PCC in addition to technology-specific CAPEX and FOM. the adder covers PCC-bound FFR/VAR provisioning overhead (telemetry, controls, filters, protection upgrades), and that no double-counting occurs in BESS/Geo line items.

Telemetry Value-of-Information (VoI) Module

Telemetry sampling resolution Δt is treated as a design variable and evaluate it using a Value-of-Information (VoI) criterion. For each candidate Δt, the decision loss is computed as follows:

$$L(\Delta t) = \lambda\left[Penalty_{miss}\left(1-TPR(\Delta t)\right) + Penalty_{false}FPR(\Delta t)\right] + max\{0, \sigma(\Delta t) - \sigma(\Delta t_0)\}\cdot \upsilon$$

The first part of the equation refers to enforcement misclassification and the second to an optional model-loss proxy. The telemetry cost is:

$$C(\Delta t) = CAPEX_{ann} + OPEX_{storage} + OPEX_{cyber}$$

The VoI of moving from a baseline Δt_0 to Δt is:

$$VoI(\Delta t_0 \rightarrow \Delta t) = [L(\Delta t_0) - L(\Delta t)] - [C(\Delta t) - C(\Delta t_0)]$$

Positive VoI recommends tighter sampling. Sheet Telemetry_VoI in the workbook implements these equations with editable inputs (Δt, cost components, event rate λ, TPR/FPR, penalties, and optional σ, υ). Baseline selection is controlled by the Baseline flag column (default: 1 s). Decision output is provided per candidate Δt as Upgrade/No Upgrade alongside the net VoI in $/yr. Linkages to the case study are via the cost-normalization and compliance-audit parameters.

Computation Workflow

Step 1: Compute FFR_required and Q_required from Table A inputs.

Step 2: Compute ELCC_target via α·P_comp.

Step 3: With design choices P_BESS (and optionally P_geo, P_DR), compute credited ELCC by resource and ELCC_total.

Step 4: If needed, back-solve P_geo_required to meet ELCC_target.

Step 5: Compute E_BESS, CRF for BESS/Geo, and annualized costs.

Step 6: Sum annualized costs (optionally add the FFR+VAR adder on compute MW).

Step 7: Report normalized costs per kW of compute and per ELCC-kW.

Excel Sheet



Covenant_CaseStudy_
Workbook_v2.xlsx