Supplementary Information for Advancing Low-Carbon Industry Transition: Decarbonizing Industrial Captive Generation in Indonesia

Kaarthigeswaran A Gnapathy, Lucien Chen, Michael R. Davidson

November 2025

1 Nomenclature

1.1 Sets

- G – All grid generation resources (indexed by g), including existing units and candidate new builds.
- Z – Zones in the power system (indexed by z), representing distinct regional nodes.
- L – Transmission lines (paths) connecting zones (indexed by l).
- T – Time steps in the modeling horizon (indexed by t), e.g., representative hours.
- P – Representative time periods or clusters (e.g., days or weeks) in the horizon (indexed by p).
- M – Segments for price-responsive (curtailable) demand (indexed by m).
- $UC \subseteq G$ – Subset of generators that require unit commitment (thermally dispatchable units with start-up/shut-down constraints).
- $ED \subseteq G$ – Subset of generators that are economically dispatchable without commitment (e.g., renewables and other non-UC units).
- $STOR \subseteq G$ – Subset of G that are energy storage resources.
- $VRE \subseteq G$ – Subset of variable renewable energy generators (intermittent resources with time-varying availability).
- $NEW \subseteq G$ – Subset of generators that can be newly built (candidate resources).
- $OLD \subseteq G$ – Subset of generators representing existing units (initially installed).
- UC_OLD, UC_NEW, ED_OLD, ED_NEW – Further subdivisions of UC and ED into existing (OLD) and new (NEW) unit sets.
- IP – Industrial parks (indexed by p or ip), each with on-site (“captive”) generation and demand.
- IP_G – All industrial park generation resources (indexed by g when referring to an individual on-site unit).
- $IP\_UC \subseteq IP\_G$ – Industrial park generators that require unit commitment (e.g., captive coal or large CHP units).
- $IP\_ED \subseteq IP\_G$ – Industrial park generators that are dispatchable without commitment (e.g., on-site renewables, small engines).
- $IP\_STOR \subseteq IP\_G$ – Industrial park storage units (if any).
- IP_NEW, IP_OLD – Subsets of IP_G designating new candidate vs. existing on-site units (with further splits IP_UC_NEW, IP_UC_OLD, IP_ED_NEW, IP_ED_OLD analogous to grid generators).

1.2 Indices

- $g \in G$ – Index for a generation resource (grid generator).
- $l \in L$ – Index for a transmission line/path.
- $z \in Z$ – Index for a zone.
- $t \in T$ – Index for a time step (hour).
- $p \in P$ – Index for a representative period (cluster of hours).
- $m \in M$ – Index for a demand curtailment (non-served energy) segment.
- $ip \in IP$ – Index for an industrial park.

1.3 Parameters

- $D_{z,t}$ – Electricity demand in zone z at time t (MW).
- $D^{IP}_{p,t}$ – Electricity demand of industrial park p at time t (MW).
- $D^{heat}_{p,t}$ – Heat (steam) demand of industrial park p at time t (MW heat).
- w_t – Weight of time step t in the objective (hours represented by t).
- H – Number of hours in each representative period (used for wrap constraints).
- $\omega_{g,t}$ – Availability factor of generator g at time t (fraction); for VRE $0 \le \omega_{g,t} \le 1$.
- Ω_g – Maximum potential capacity for new installation of generator g (MW).
- Ω^e_g – Maximum potential energy capacity for new storage g (MWh).
- Ω_l – Maximum reinforcement capacity for transmission line l (MW).
- Cap^{ex}_g – Existing installed power capacity of generator g (MW).
- $Cap^{ex,e}_g$ – Existing energy capacity of storage g (MWh).
- Cap^{ex}_l – Existing capacity of transmission line l (MW).
- π^{inv}_g, π^{OM}_g – Annualized investment and fixed O&M cost for generator capacity ($\$/\mathrm{MW} \cdot \mathrm{yr}$).
- $\pi^{inv,e}_g$, $\pi^{OM,e}_g$ – Annualized investment and fixed O&M cost for storage energy capacity ($\$/\mathrm{MWh} \cdot \mathrm{yr}$).
- π^{inv}_l, π^{OM}_l – Annualized investment and fixed O&M cost for line capacity ($\$/\mathrm{MW} \cdot \mathrm{yr}$).
- π^{var}_g – Variable generation cost of unit g ($/MWh).
- π^{start}_g – Start-up cost for generator g per MW ($\$/\mathrm{MW} \cdot \mathrm{start}$).
- π^{NSE}_m – Cost of non-served energy for segment m ($/MWh).
- Λ_m – Maximum allowable fraction of demand that can be curtailed in segment m.
- r^+_g, r^-_g – Ramp-up and ramp-down rate limits for generator g (per unit capacity per hour).
- P^{min}_g – Minimum stable generation of unit g when on (MW).
- η^+_g, η^-_g – Charging and discharging efficiencies for storage g (fraction).
- τ^+_g, τ^-_g – Minimum up-time and minimum down-time for unit g (hours), for $g \in UC$.
- R_g – Indicator for renewable resource: $R_g = 1$ if g is renewable, else 0.

- $CO2Rate_g$ – CO_2 emissions rate of generator g (tCO_2/MWh).
- $CO2Start_g$ – CO_2 emitted per start per MW of unit g (tCO_2/start/MW).
- $CO2\_limit$ – Emissions cap for grid generation (tCO_2/yr).
- $CO2\_BAU$ – Baseline annual CO_2 emissions for industrial parks (tCO_2/yr).
- ξ – Renewable generation share target (fraction of total generation).
- π^{imp} – Tariff/marginal cost for grid imports to parks ($/MWh).

1.4 Decision Variables

All are continuous and non-negative unless noted.

Capacity expansion and retirement (grid). I_g (MW), D_g (MW), O_g (MW) – new, retired, and final power capacity for generator g; I_g^e (MWh), D_g^e (MWh), O_g^e (MWh) – new, retired, and final storage energy capacity; I_l (MW), D_l (MW), O_l (MW) – new, retired, and final line capacity.

Generator commitment and operation (grid). $G_{g,t}$ (MW) – generation; $u_{g,t} \in \{0,1\}$ – commitment (on/off) for $g \in UC$; $s_{g,t}, d_{g,t} \in \{0,1\}$ – start-up and shut-down; $C_{g,t}$ (MW) – storage charging; $E_{g,t}$ (MWh) – storage state of charge; $M_{z,m,t}$ (MW) – non-served energy for zone z; $F_{l,t}$ (MW) – line flow (bidirectional).

Industrial park capacity and operation. $I_g^{IP}, D_g^{IP}, O_g^{IP}$ (MW) – new, retired, and final on-site capacity; $I_g^{e,IP}, D_g^{e,IP}, O_g^{e,IP}$ (MWh) – storage energy capacity (park); $G_{g,t}^{IP}$ (MW) – on-site electric generation; $H_{g,t}$ (MW heat) – on-site heat output (CHP-capable units); $u_{g,t}^{IP}, s_{g,t}^{IP}, d_{g,t}^{IP} \in \{0,1\}$ – UC binaries for $g \in IP\_UC$; $C_{g,t}^{IP}$ (MW), $E_{g,t}^{IP}$ (MWh) – charging and SOC for park storage; $M_{p,m,t}^{E}$ (MW), $M_{p,m,t}^{H}$ (MW heat) – unserved electric and heat demand at park p; $I_{p,t}^{imp}$ (MW) – grid import to park p.

2 Constraints

2.1 Capacity Accounting

Generators (grid).

$$
\begin{aligned}
O_g &= Cap_g^{ex} - D_g, && \forall g \in ED\_OLD, && (1)\\
O_g &= I_g, && \forall g \in ED\_NEW, && (2)\\
O_g &= Cap_g^{ex} - D_g, && \forall g \in UC\_OLD, && (3)\\
O_g &= I_g, && \forall g \in UC\_NEW. && (4)
\end{aligned}
$$

Storage energy (grid).

$$
\begin{aligned}
O_g^e &= Cap_g^{ex,e} - D_g^e, && \forall g \in STOR \cap OLD, && (5)\\
O_g^e &= I_g^e, && \forall g \in STOR \cap NEW. && (6)
\end{aligned}
$$

Transmission (grid).

$$
O_l = Cap_l^{ex} - D_l + I_l, \qquad \forall l \in L. \qquad (7)
$$

Industrial parks.

$$
\begin{aligned}
O_g^{IP} &= Cap_g^{ex} - D_g^{IP}, && \forall g \in IP\_OLD, && (8)\\
O_g^{IP} &= I_g^{IP}, && \forall g \in IP\_NEW, && (9)\\
O_g^{e,IP} &= Cap_g^{ex,e} - D_g^{e,IP}, && \forall g \in IP\_STOR \cap IP\_OLD, && (10)\\
O_g^{e,IP} &= I_g^{e,IP}, && \forall g \in IP\_STOR \cap IP\_NEW. && (11)
\end{aligned}
$$

2.2 Generator Operational Limits

Max output.

$$
\begin{aligned}
G_{g,t} &\le \omega_{g,t}\, O_g, && \forall g \in ED,\ \forall t \in T, && (12)\\
G_{g,t} &\le O_g\, u_{g,t}, && \forall g \in UC,\ \forall t \in T. && (13)
\end{aligned}
$$

Min output (UC).

$$
G_{g,t} \ge P_g^{min}\, u_{g,t}, \qquad \forall g \in UC,\ \forall t \in T. \tag{14}
$$

Industrial park generation.

$$
\begin{aligned}
G_{g,t}^{IP} &\le \omega_{g,t}\, O_g^{IP}, && \forall g \in IP\_ED,\ \forall t, && (15)\\
G_{g,t}^{IP} + H_{g,t} &\le O_g^{IP}\, u_{g,t}^{IP}, && \forall g \in IP\_UC,\ \forall t, && (16)\\
G_{g,t}^{IP} + H_{g,t} &\ge P_g^{min}\, u_{g,t}^{IP}, && \forall g \in IP\_UC,\ \forall t. && (17)
\end{aligned}
$$

2.3 Ramping

Non-UC (grid).

$$
\begin{aligned}
G_{g,t} - G_{g,t-1} &\le r_g^{+}\, O_g, && \forall g \in ED,\ \forall t \in T \setminus \{1\}, && (18)\\
G_{g,t-1} - G_{g,t} &\le r_g^{-}\, O_g, && \forall g \in ED,\ \forall t \in T \setminus \{1\}. && (19)
\end{aligned}
$$

UC (grid) with start/shut logic. For each $g \in UC$ and $t \in T \setminus \{1\}$,

$$
\begin{aligned}
G_{g,t} - G_{g,t-1} \le r_g^{+}\, Cap_g^{ex}\, (u_{g,t} - s_{g,t}) + \max\{P_g^{min},\ r_g^{+}\, Cap_g^{ex}\}\, s_{g,t}\\
- P_g^{min}\, Cap_g^{ex}\, d_{g,t}, \qquad (20)
\end{aligned}
$$

$$
\begin{aligned}
G_{g,t-1} - G_{g,t} \le r_g^{-}\, Cap_g^{ex}\, (u_{g,t} - s_{g,t}) + \max\{P_g^{min},\ r_g^{-}\, Cap_g^{ex}\}\, d_{g,t}\\
- P_g^{min}\, Cap_g^{ex}\, s_{g,t}. \qquad (21)
\end{aligned}
$$

Industrial parks. For non-UC $g \in IP\_ED$,

$$
G_{g,t}^{IP} - G_{g,t-1}^{IP} \le r_g^{+}\, O_g^{IP}, \qquad G_{g,t-1}^{IP} - G_{g,t}^{IP} \le r_g^{-}\, O_g^{IP}. \tag{22}
$$

For $g \in IP\_UC$, apply the above formulas to $G_{g,t}^{IP} + H_{g,t}$ in place of $G_{g,t}$.

2.4 Storage Operation

Charge/energy limits.

$$
\begin{aligned}
C_{g,t} &\le O_g, && \forall g \in STOR,\ \forall t, && (23)\\
E_{g,t} &\le O_g^{e}, && \forall g \in STOR,\ \forall t. && (24)
\end{aligned}
$$

Energy balance (grid). For $t \in T \setminus \{1\}$ and each $g \in STOR$,

$$E_{g,t} = E_{g,t-1} + \eta_g^+ C_{g,t} - \frac{1}{\eta_g^-} G_{g,t}, \tag{25}$$

and across representative-period boundaries (first hour t_0 of a period, last hour t_f of previous period):

$$E_{g,t_0} = E_{g,t_f} + \eta_g^+ C_{g,t_0} - \frac{1}{\eta_g^-} G_{g,t_0}. \tag{26}$$

Industrial park storage. Identical constraints for $C_{g,t}^{IP}, E_{g,t}^{IP}, G_{g,t}^{IP}$ with $g \in IP\_STOR$.

2.5 Unit Commitment

State transition.

$$u_{g,t+1} - u_{g,t} = s_{g,t+1} - d_{g,t+1}, \qquad \forall g \in UC,\ \forall t \in T_{\text{interior}}. \tag{27}$$

Identical for $u_{g,t}^{IP}$, $s_{g,t}^{IP}$, $d_{g,t}^{IP}$ for $g \in IP\_UC$.

Logical bounds (retirement/operation link).

$$u_{g,t},\ s_{g,t},\ d_{g,t}\ \le\ \frac{O_g}{Cap_g^{ex}}, \qquad \forall g \in UC,\ \forall t; \tag{28}$$

and analogously for $g \in IP\_UC$ with O_g^{IP} in the numerator.

Minimum up/down. For $g \in UC$,

$$u_{g,t} \ge \sum_{\tau=t-\tau_g^+ +1}^{t} s_{g,\tau}, \qquad \forall t, \tag{29}$$

$$1 - u_{g,t} \ge \sum_{\tau=t-\tau_g^- +1}^{t} d_{g,\tau}, \qquad \forall t, \tag{30}$$

with the same form for $g \in IP\_UC$.

2.6 Network & Balances

Line limits.

$$-O_l \le F_{l,t} \le O_l, \qquad \forall l \in L,\ \forall t \in T. \tag{31}$$

Zonal balance (grid).

$$\sum_{g \in G_z} G_{g,t} + \sum_{m \in M} M_{z,m,t} - \sum_{g \in STOR_z} C_{g,t} - D_{z,t} - \sum_{l \in L} X_{z,l} F_{l,t} - \sum_{p \in IP_z} I_{p,t}^{imp} = 0, \quad \forall z, t. \tag{32}$$

Industrial park balances.

$$\sum_{g \in IP\_G^p} G_{g,t}^{IP} + I_{p,t}^{imp} + \sum_{m \in M^{IP}} M_{p,m,t}^{E} - \sum_{g \in IP\_STOR^p} C_{g,t}^{IP} = D_{p,t}^{IP}, \qquad \forall p, t, \tag{33}$$

$$\sum_{g \in IP\_G^{p,(\text{heat})}} H_{g,t} + \sum_{m \in M^{IP}} M_{p,m,t}^{H} = D_{p,t}^{heat}, \qquad \forall p, t. \tag{34}$$

2.7 Curtailment (NSE) Limits

$$
\begin{aligned}
&M_{z,m,t} \le \Lambda_m \, D_{z,t}, && \forall z, m, t, && (35)\\
&M^{E}_{p,m,t} \le \Lambda_m \, D^{IP}_{p,t}, && \forall p, m, t, && (36)\\
&M^{H}_{p,m,t} \le \Lambda_m \, D^{heat}_{p,t}, && \forall p, m, t. && (37)
\end{aligned}
$$

2.8 Policy Constraints

CO_2 cap (grid).

$$
\sum_{t\in T}\sum_{g\in G} w_t \, \mathit{CO2Rate}_g \, G_{g,t} + \sum_{t\in T}\sum_{g\in UC} w_t \, \mathit{CO2Start}_g \, s_{g,t} \;\le\; \mathit{CO2\_limit}. \tag{38}
$$

Industrial parks (35% reduction).

$$
\sum_{t\in T}\sum_{g\in IP\_UC} w_t \, \mathit{CO2Rate}_g \, (G^{IP}_{g,t} + H_{g,t}) + \sum_{t\in T}\sum_{g\in IP\_UC} w_t \, \mathit{CO2Start}_g \, s^{IP}_{g,t} \;\le\; 0.65 \, \mathit{CO2\_BAU}. \tag{39}
$$

Renewable share.

$$
\sum_{t\in T}\sum_{g\in G} w_t \, R_g \, G_{g,t} \;\ge\; \xi \sum_{t\in T}\sum_{z\in Z} w_t \, D_{z,t}. \tag{40}
$$

3 Objective Function

Minimize total annual cost:

$$
\begin{aligned}
\min \quad & \underbrace{\sum_{g\in G} \pi^{OM}_g \, O_g}_{\text{Fixed O\&M (grid gen)}} + \sum_{g\in ED\_NEW\cup UC\_NEW} \pi^{inv}_g \, I_g \\
& + \underbrace{\sum_{g\in STOR} \pi^{OM,e}_g \, O^e_g}_{\text{Storage fixed}} + \sum_{g\in STOR\cap NEW} \pi^{inv,e}_g \, I^e_g \\
& + \underbrace{\sum_{l\in L} \left(\pi^{OM}_l \, O_l + \pi^{inv}_l \, I_l\right)}_{\text{Transmission}} \\
& + \underbrace{\sum_{t\in T}\sum_{g\in G} w_t \, \pi^{var}_g \, G_{g,t}}_{\text{Grid variable}} + \sum_{t\in T}\sum_{g\in IP\_ED} w_t \, \pi^{var}_g \, G^{IP}_{g,t} + \sum_{t\in T}\sum_{g\in IP\_UC} w_t \, \pi^{var}_g \, (G^{IP}_{g,t} + H_{g,t}) \\
& + \underbrace{\sum_{t\in T}\sum_{z\in Z}\sum_{m\in M} w_t \, \pi^{NSE}_m \, M_{z,m,t}}_{\text{NSE (grid)}} + \sum_{t\in T}\sum_{p\in IP}\sum_{m\in M^{IP}} w_t \, \pi^{NSE}_m \, (M^E_{p,m,t} + M^H_{p,m,t}) \\
& + \underbrace{\sum_{t\in T}\sum_{g\in UC} w_t \, (\pi^{start}_g \, Cap^{ex}_g) \, s_{g,t}}_{\text{Start-ups (grid)}} + \sum_{t\in T}\sum_{g\in IP\_UC} w_t \, (\pi^{start}_g \, Cap^{ex}_g) \, s^{IP}_{g,t} \\
& + \underbrace{\sum_{t\in T}\sum_{p\in IP} w_t \, \pi^{imp} \, I^{imp}_{p,t}}_{\text{Grid imports (parks)}} .
\end{aligned}
$$

4 Scenario Definitions

Decarbonisation options and clean-energy targets define five primary scenarios.

Scenario	Grid connection	Captive renewables & storage
BAU	No	No
BAU + JETP	No	No
Grid + JETP + 35%R	Yes	No
Captive + JETP + 35%R	No	Yes
GridCaptive + JETP + 35%R	Yes	Yes

Table 1: Definitions of the scenarios used in the analysis.

Scenario	Clean-energy targets
BAU	None
BAU + JETP	JETP CO_2 cap + renewable share
Grid + JETP + 35%R	JETP CO_2 cap + renewable share + 35% emissions reduction
Captive + JETP + 35%R	Same as above
GridCaptive + JETP + 35%R	Same as above

Table 2: Definitions of the scenarios used in the analysis.

Sensitivity analyses examined higher grid import prices (21% increase) and scenarios with emissions constraints applied only to industrial power generation or with a reduced coal price of $70/ton.

Data Sources

Multiple datasets were combined to parameterise the model:

1. **Grid infrastructure and load:** PLN's *Rencana Usaha Penyediaan Tenaga Listrik* (RUPTL 2021–2030) provides current and planned generators, transmission network topology and zonal load projections.

2. **Fuel costs and new projects:** Fuel price assumptions and lists of new power plant projects were taken from the Just Energy Transition Partnership (JETP) Comprehensive Investment and Policy Plan.

3. **Renewable resource assessment:** Capacity factors for wind and solar were derived using the *geodata* package applied to ERA5 weather data, while geothermal potential was estimated using the International Heat Flow Commission's Global Heat Flow Database with kriging interpolation. Land-use restrictions from the Ministry of Environment and Forestry (KLHK) and slope constraints from USGS data were used to identify suitable sites.

4. **Industrial facilities:** Generator information for captive facilities was compiled from the Sunrise Project's Indonesian captive power database. Synthetic load profiles were constructed based on industry literature, with production growth rates of 3–5 % applied to historical trends.

5. **Time sampling:** A k-means clustering algorithm was applied to hourly load profiles to select eight representative weeks, including a peak week for resource adequacy. Each

representative week is weighted to reconstruct annual demand. The weeks that were chosen: 24, 3, 4, 45, 8, 46, 39, and 5.

6. **Zonal aggregation:** Indonesia's power system is divided into regional systems (Sumatera, Jawa-Bali, Kalimantan, Sulawesi, North Maluku, Maluku, Papua and Nusa Tenggara). Each system is subdivided into provinces serving as zones.

5 Notes

This MILP formulation covers capacity expansion with unit commitment and economic dispatch for Indonesia's grid and industrial captive generation, including transmission expansion, storage operation, demand curtailment, and policy targets (CO_2 cap, captive-emission reduction, and renewable share). Scenario toggles (e.g., grid connection for parks, captive-only operation, coal bans) are implemented by activating/deactivating sets or cost/limit parameters in the corresponding constraints.

6 Additional results

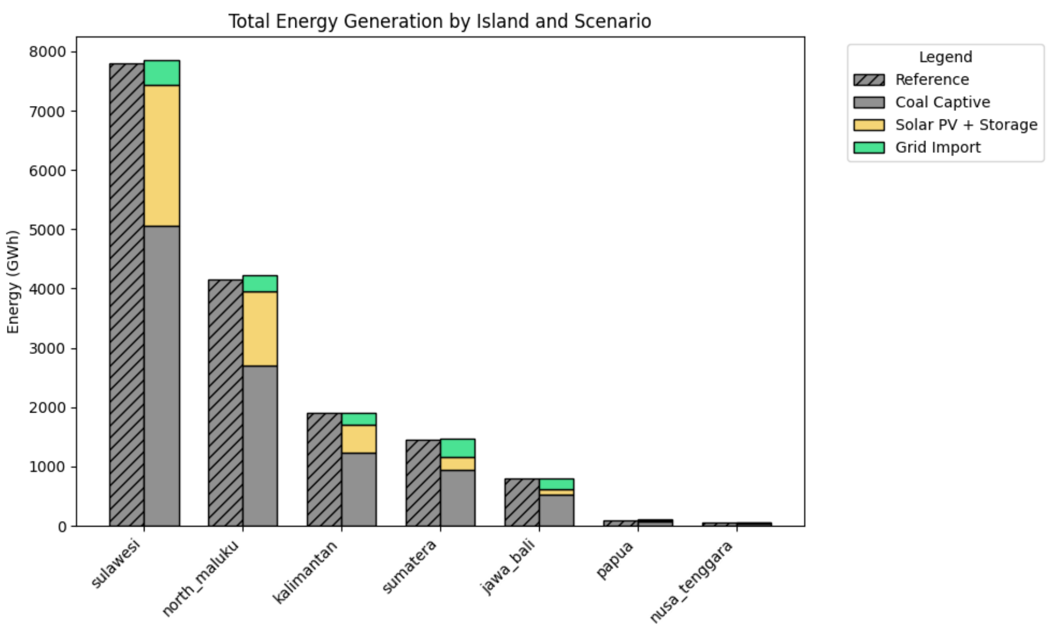

Figure 1: Generation by island systems for *GridCaptive* scenario.

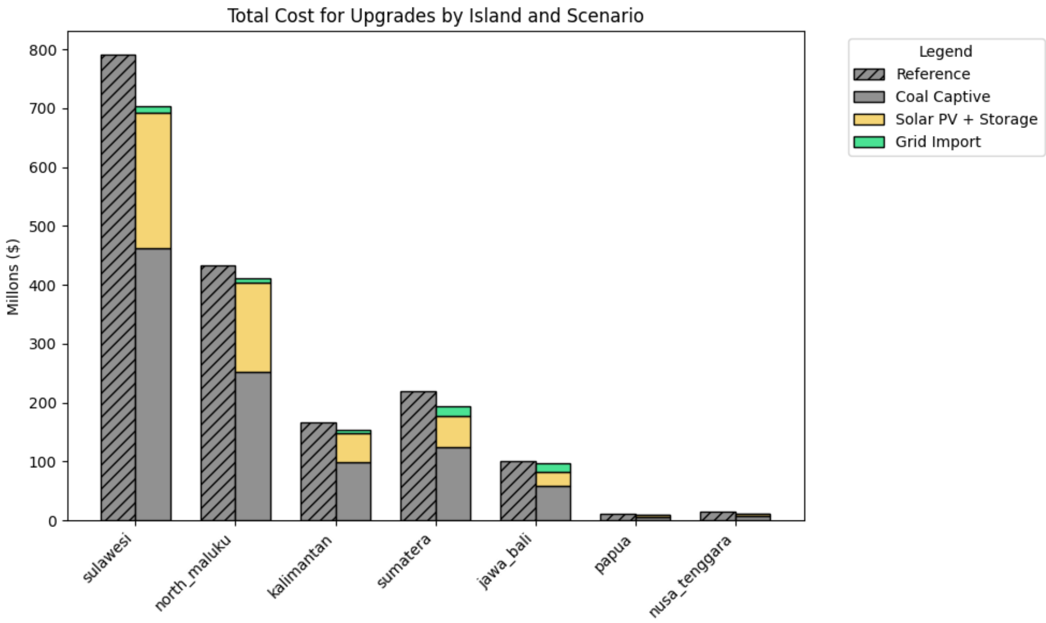

Figure 2: Cost by island systems for *GridCaptive* scenario.

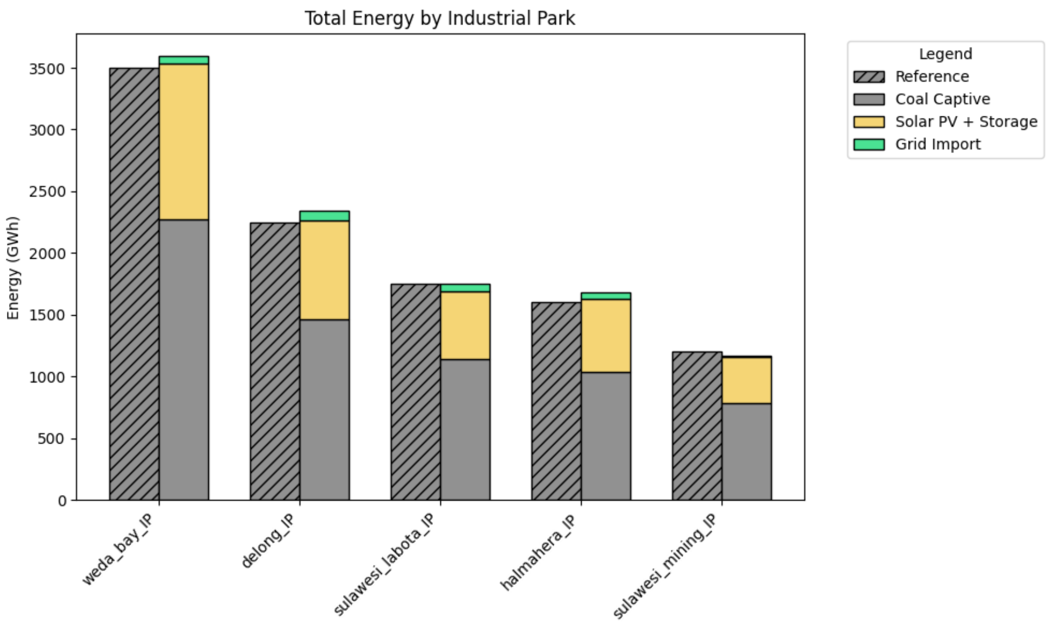

Figure 3: Generation for top 5 industrial parks for *GridCaptive* scenario.

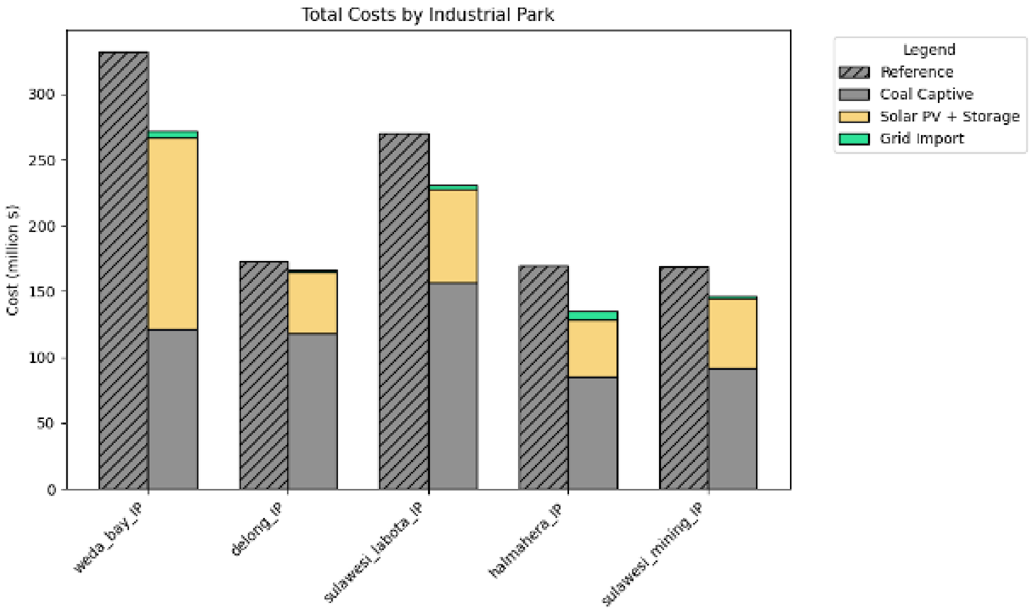

Figure 4: Cost for top 5 industrial parks for *GridCaptive* scenario.

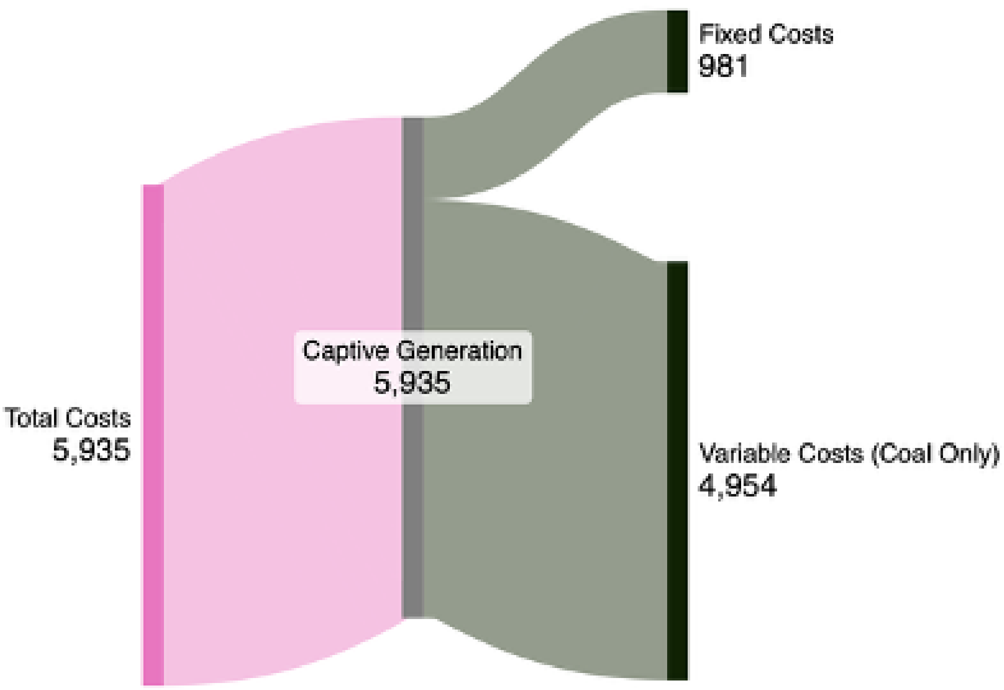

Figure 5: Industrial park cost breakdown for *BAU* scenario.

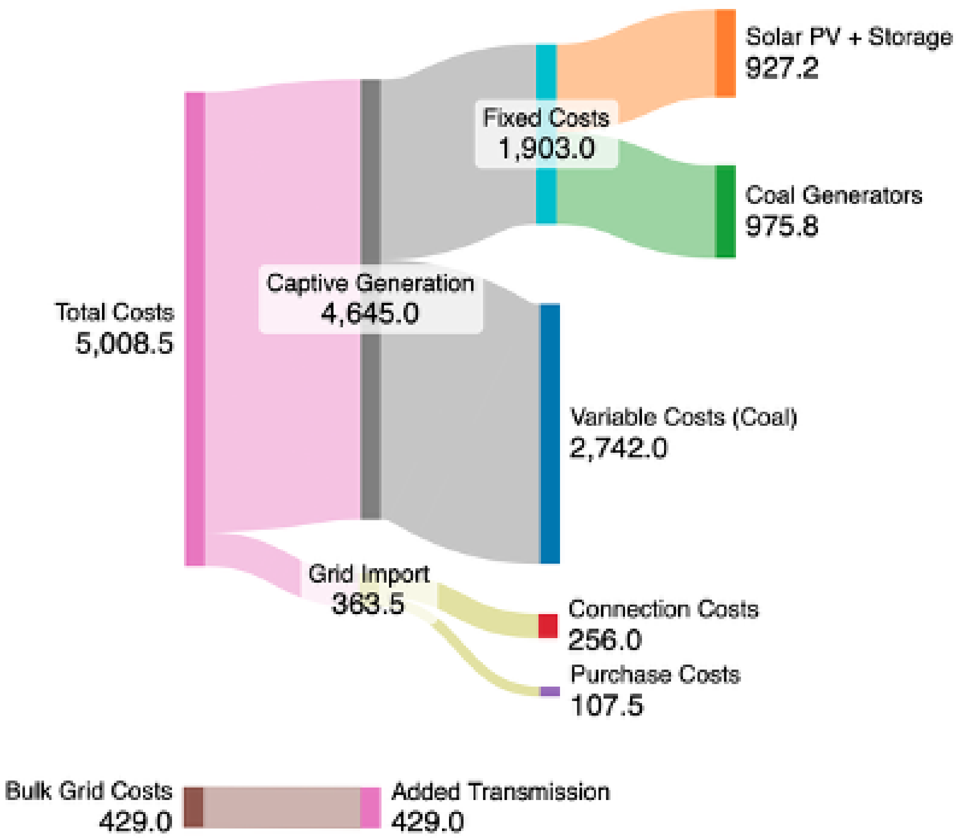

Figure 6: Industrial park cost breakdown for *GridCaptive* scenario.