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A Practical Reliability Framework for Grid-Connected Hybrid Renewable Energy in Northern Iraq

Saeed Alan[1*], Yousif Kamil[1] and Abdulrazzaq maiwan[2]

1. Dept. of Environmental Science, College of Science, University of Zakho, Duhok, Iraq.
2. Dept. of Computer Science, College of Science, University of Zakho, Duhok, Iraq.

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**Corresponding author: alan.saeed@uoz.edu.krd (S. Alan)*

Abstract

The Gali Zakho Tunnel in Dohuk, Iraq, consumes 12,704.44 kWh daily. Lighting, ventilation, safety monitoring, and control systems operate continuously. Power failure constitutes a life-safety event. This study designs and optimizes a grid-connected hybrid renewable energy system (HRES) for the tunnel using HOMER Pro, operating strictly within the current grid policy of the Kurdistan Region of Iraq: a purchase tariff of $0.129/kWh, zero export credit for surplus generation, and monthly net metering with no carryover. Five configurations were evaluated against a strict zero annual capacity shortage constraint. Two met this requirement. Case-B (PV–Generator–Grid, 5,558 kW PV) is the most economical: NPC $3.28 million, COE $0.0187/kWh, and a renewable fraction of 68.5%. The standby diesel generator consumes no fuel under normal conditions and activates only if both the grid and PV fail simultaneously. Case-C (PV–Battery–Grid, 5,768 kW PV) is the most environmentally favorable: NPC $5.27 million, COE $0.0380/kWh, an 84.1% renewable fraction, and a 78.6% reduction in CO2 emissions compared to a grid-only system. A two-layer battery framework separates daily economic cycling (10.4 hours) from a locked emergency reserve of 2,954 kWh (~5.6 hours). Together, the system can sustain uninterrupted tunnel operation for approximately 16 hours without external input. Comprehensive sensitivity analyses on discount rate (0.95%–10% real), battery cost ($175–$300/kWh), and land/civil works ($0–$250,000) confirm that both configurations remain economically viable across all tested scenarios. Both configurations are fully reliable and feasible to implement today under current regulations, without awaiting policy reform.

Keywords: *HOMER Pro, Constrained grid export, Two-layer battery reliability, Critical infrastructure, Tunnel electrification, Sensitivity analysis.*

1. Introduction

Northern Iraq's Kurdistan Region possesses some of the strongest solar resources in the Middle East. Its grid, however, tells a different story. Iraq is approximately 22,000 MW short of national demand, and renewables contribute less than 1% of generation [1, 2]. The Kurdistan Regional Government is responding. The "Runaki" initiative, launched in October 2024, has already provided round-the-clock power to Erbil, Duhok, and Sulaimani, with full regional coverage targeted by the end of 2026 [3]. A separate government target aims for 31% clean energy in the public grid by the same date [4]. These commitments are supported by tangible investments. Nonetheless, the regulatory framework for distributed generation is still evolving. Solar and wind projects can connect to the grid today, but the amount of surplus power they can export is tightly capped under current policy [5]. This constraint influences every design decision in this paper.

The site is the Gali Zakho Tunnel (36°55′20″ N, 42°55′ E, Dohuk Governorate). Two parallel tunnels, each 3,604 m long, cut through the mountains of northwest Iraq, connecting the country to Turkey. The tunnel consumes 12,704.44 kWh/day at a peak demand of 670 kW. Lighting, ventilation fans, safety monitors, and control systems operate 24 hours a day with no seasonal variation and no demand flexibility [6]. There is no off-peak window. If power fails, it results in a tunnel full of vehicles losing lighting and ventilation simultaneously. Zero annual capacity shortage is the strict engineering requirement [7].

Most grid-connected HRES studies optimize for cost or renewable fraction. A few model grid export as a revenue stream [8, 9]. Very few treat export as a fixed, non-negotiable regulatory ceiling and then ask: given that ceiling, what is the optimal system? This is the current situation at Gali Zakho, and it is the gap this paper addresses.

System Sizing Strategy Under Constrained Policy. The system employs 5,768 kW of PV for a 670 kW peak demand, resulting in an 8.6:1 PV-to-load ratio. This ratio is driven by the extreme seasonal variation at this latitude. In January, PV generation drops to approximately 280 MWh/month, covering only 28% of the tunnel's monthly demand of about 1,000 MWh. In June, generation increases to approximately 1,010 MWh/month (263% of monthly demand). Under a zero-export-credit policy, summer surplus receives no financial benefit and is either stored in the battery (Case-C) or allowed to flow to the grid at zero compensation. The 8.6:1 ratio thus represents the minimum necessary to ensure adequate winter coverage. The system is optimized for load satisfaction, not export revenue. The tunnel's continuous 670 kW load drives all design decisions; excess summer generation results from winter oversizing rather than profit motives.

Three features make this study original. First, it is the first HOMER Pro optimization for critical transportation infrastructure conducted under Kurdistan's actual enforced export policy rather than an idealized net-metering assumption. Second, it introduces a two-layer battery reliability framework that separates daily economic cycling (10.4 hours) from a locked emergency reserve (minimum 35% state of charge, approximately 5.6 hours of combined backup across two units). Most HRES reliability studies do not explicitly distinguish this. For a life-safety system, this distinction is crucial. Third, the results present two entirely different configurations—one generator-backed and one battery-backed—that both achieve 100% operational reliability. Choosing between them is a values question: fuel dependence versus capital cost, emissions versus response time. This paper provides decision-makers with the data necessary to make that choice.

2. Literature review

2.1. HRES for Critical and Transportation Infrastructure

Transportation infrastructure remains underrepresented in the HRES literature [10]. Most published work focuses on residential, commercial, or rural electrification applications. A highway tunnel study in southern China combined PV, wind, diesel, and battery storage using HOMER and reported a 95.6% renewable fraction, generating over 1.1 GWh/year, with diesel contributing only 2.4% [11]. A related expressway service-area study added small hydrokinetic generation, employed a three-dimensional site evaluation method, and achieved a 97% renewable fraction at $0.22/kWh [12]. Both studies confirm that PV-heavy hybrid systems can reliably support transportation loads. Neither distinguishes the battery's economic role from an emergency reserve function; they treat storage purely as a cost-dispatch asset, which is sufficient for most facilities.

For critical infrastructure, that approach is inadequate. A grid-connected hybrid system serving a hospital and school complex in Rangpur, Bangladesh, reached a 78.1% renewable fraction at $0.0445/kWh under a real-time tariff [13]. Healthcare feasibility work in Yemen reported renewable coverage near 90–100% at a competitive cost [14]. These studies optimize reliability alongside cost and emissions, but none frame the analysis around a strict constraint where any shortage event constitutes a safety incident. Such framing fundamentally alters the engineering approach.

In Iraq, HRES research is rapidly expanding. An off-grid PV–diesel–battery system for Kut, Iraq, achieved a COE of $0.492/kWh and reduced CO_2 emissions by 72% compared to diesel-only operation [15]. A date molasses factory in Iraq combining PV, biogas, fuel cell, and battery reduced emissions by 99.98% against a diesel baseline at $0.0978/kWh [16]. Alshamri et al.

developed an on-off-grid strategy tested across 15 Iraqi sites, deliberately avoiding battery discharge while the grid is connected, which extended battery life and reduced payback from 20.1 years to 7.8 at one location [17]. Aziz et al. designed a Baghdad residential PV–battery system with a HOMER–MATLAB forecast-based dispatch strategy that outperformed conventional load-following and cycle-charging under frequent, unscheduled outages [18-20]. Recent work on remote communities across Iraq compared five HRES configurations, consistently finding PV/wind/battery/diesel combinations to outperform alternatives in cost, output, and emissions [21]. None of these studies treat zero shortage as a binding constraint or explain mechanistically how a system achieves it.

2.2. Grid-connected HRES and constrained export

Grid connection improves HRES economics in almost every published study [22, 23]. The mechanism is straightforward: the grid substitutes for batteries as a form of storage, reducing capital costs. A Tekirdağ industrial facility in Turkey reduced LCOE from $0.120/kWh (grid-only) to $0.0837/kWh using PV, wind, and grid interconnection with no battery required [24]. A university campus in Lucknow, India, achieved $0.0404/kWh with a roughly six-year payback [25]. A PV-wind system on Tumbatu Island, Zanzibar, was deployed to correct chronic voltage drops on a 33 kV line, improving voltage from 29.6 kV to 31.23 kV at peak demand while reducing LCOE by 21% [26].

The export side of grid connection is critically important when sell-back is unrestricted. Studies in Egypt, Canada, and Bangladesh all show that even modest sell-back tariffs significantly influence project economics [27-29]. A Pakistani study of three remote villages found that grid-connected, net-metered configurations could drive NPC negative: the system becomes a revenue source [30]. A Bangladeshi university residence exported nearly 160,000 kWh/year under unrestricted net metering [31], and a Saskatchewan irrigation study found that a sellback rate as low as $0.01/kWh kept a hybrid system cheaper than a grid-only baseline [32].

These results are compelling. They make a strong case for policy reform. However, none of these models consider what happens when the export ceiling is set by regulation rather than by economics. That is precisely the situation at Gali Zakho today. The Kurdistan Region currently caps the amount of surplus power a distributed generator can push onto the grid. This is a strict regulatory boundary, not a pricing variable that the system can optimize around. Designing within that boundary distinguishes this study from nearly all previous grid-connected HRES literature.

2.3. Dispatch strategy and reliability in HRES

Standard HRES reliability metrics (loss of power supply probability, deficiency of power supply probability, capacity shortage fraction) rank configurations well. They do not explain how a configuration achieves its reliability score [33]. A generator that fires up on demand and a battery with a locked emergency reserve can post identical zero-shortage scores, even though they represent completely different engineering propositions in terms of fuel logistics, emissions, and response time.

Dispatch-strategy research reinforces this point. Novel dispatch modes for off-grid wind–diesel–battery–desalination systems outperformed conventional load-following and cycle-charging in both cost and renewable fraction [34]. A MATLAB-linked dispatch strategy for a Saudi off-grid PV–wind–diesel–battery system achieved a 100% renewable fraction with near-zero unmet load, again outperforming standard dispatch logic [35]. These studies confirm that dispatch approach materially affects both economic and reliability outcomes. None of them, however, separate the battery's function into distinct layers and then ask which layer performs the reliability work.

For a tunnel, that question is the entire point. This paper builds a mechanistic reliability framework that answers it directly: which backup mechanism delivers zero shortage, when does each layer activate, how long does it hold, and what does choosing one over the other cost in fuel, emissions, and response time.

2.4. Wind resource screening

The annual average wind speed at the tunnel site is 4.25 m/s, measured on-site at a mountain-top location above the tunnel. This speed is below the viable threshold for commercial wind turbines (minimum approximately 5.5 m/s for a capacity factor exceeding 15%). In the initial HOMER screening, wind turbines contributed less than 0.03% of total generation at a disproportionate capital cost. Therefore, wind generation is excluded from the recommended configurations. All feasibility analyses and recommended cases are optimized for PV plus storage only. This finding is consistent with similar semi-arid mountain sites in the broader MENA region [7].

2.5. Summary of reviewed studies

Table 1 summarizes the most relevant studies reviewed. The proposed study row shows where this work fits and what no prior study has done.

Research gap: Three gaps emerge from Table 1. First, no published HRES study models a grid-export limit as an actual, currently enforced regulatory constraint; all grid-connected studies either assume unrestricted net metering or treat export price as an optimization variable. Second, no study separates battery storage into economic cycling and emergency-reserve layers for life-safety infrastructure. Third, no study of critical transportation infrastructure imposes zero shortage as a hard constraint rather than one objective among several. This paper addresses all three.

Table 1. Summary of relevant HRES studies and comparison with the proposed study

Location, Application, Ref.	Grid Status	Key Components	LCOE ($/kWh)	RF (%)	Key Finding / Gap
Southern China, highway tunnel [11]	Off-grid	PV + Wind + Diesel + Battery	0.176	95.6	Tunnel HRES; no emergency-reserve battery logic
Southern China, expressway [12]	Off-grid	PV + Wind + Hydro + Diesel + Battery	0.220	97	3D site evaluation; same gap on battery role
Rangpur, Bangladesh, health/education [36]	Grid-connected	PV + Diesel + Battery	0.0445	78.1	Real-time tariff modeling; no export cap
Iraq, date molasses factory [16]	Off-grid	PV + Biogas + Fuel Cell + Battery	0.0978	~100	99.98% CO_2 cut.
15 sites, Iraq, residential [17]	On-off-grid	PV + Wind + Battery	—	—	Battery-life strategy; payback 20.1→7.8 yrs
Baghdad, Iraq, residential [37]	Grid-connected	PV + Battery + Grid	0.142	54.2	Forecast dispatch; outperforms LF and CC
Tekirdağ, Turkey, industrial [24]	Grid-connected	PV + Wind + Grid	0.0837	68.8	Grid as virtual storage; no battery needed
Lucknow, India, university [25]	Grid-connected	PV + Grid	0.0404	59.7	Lowest LCOE in reviewed set
Zanzibar, island grid [26]	Grid-connected	PV + Wind + Grid	0.090	—	Voltage correction; 21% LCOE reduction
Saskatchewan, Canada, irrigation [38]	Grid-connected	PV + Wind + Grid	0.0154	91.3	$0.01/kWh sellback still beats grid-only
Balochistan, Pakistan, villages [30]	Grid + net metering	PV + Wind + Diesel + Battery	−0.004 to −0.007	—	Unrestricted net metering drives NPC negative
Bangladesh, university residence [39]	Grid + net metering	PV + Wind + Biogas + Battery	0.0339	85	159,354 kWh/yr exported; unrestricted export
Proposed study Gali Zakho Tunnel, Iraq	Grid-connected, export-limited (current KRG policy)	PV + Battery/Generator + Grid	0.0187 / 0.0380	68.5 / 84.1	First HRES under actual Kurdistan export cap; two-layer battery reliability framework; dual-winner result

3. Study site, data, and system design

3.1. Study area

The Gali Zakho Tunnel is located in the mountains of northwest Iraq, Dohuk Governorate (36°55′20″ N, 42°55′ E). Two parallel tunnels, each 3,604 m long and 12.4 m wide, facilitate Iraq–Turkey trade traffic around the clock. Lighting, ventilation fans, safety monitors, and office systems all operate continuously. There is no off-peak window and no load flexibility.

Figure 1: Tunnel photograph and geographical location

3.2. Meteorological and load data

Solar radiation and temperature data were obtained from the NASA POWER database (July 2024 – June 2025) [40]. Wind speed was measured on-site by the authors at a mountain-top location above the tunnel for the same twelve months. Table 2 presents the full statistical breakdown.

The solar resource is strong but seasonal: 1.67 kWh/m²/day in January and 8.10 kWh/m²/day in June (CV = 45.77%). Wind speed averages 4.25 m/s with low variability (CV = 12.00%). At that wind speed, turbines incur additional costs without proportionate generation benefits, consistent with similar semi-arid mountain sites in the broader MENA literature [7]. The tunnel load averages 529.35 kW and varies minimally across seasons (CV = 12.27%). This stability is expected given the infrastructure operates the same equipment every hour of every day. Load data were obtained from the General Electricity Directorate of Dohuk [41].

Table 2. Statistical characteristics of meteorological and load data

Parameter (Unit)	Mean	Min (Month)	Max (Month)	Std. Dev.	CV (%)	SV (%)
Solar Radiation (kWh/m²/day)	4.82	1.67 (Jan)	8.10 (Jun)	2.21	45.77	133.4
Clearness Index (–)	0.487	0.166 (Jan)	0.870 (Jun)	0.238	48.87	144.9
Wind Speed (m/s)	4.25	3.45 (Nov)	5.14 (Jun)	0.51	12.00	39.8
Temperature (°C)	21.36	8.06 (Jan)	36.23 (Jul)	11.06	51.78	131.5
Load Demand (kW)	529.35	400 (Dec)	670 (Sep)	64.9	12.27	51.0

3.3. Grid tariff and net metering policy

The system operates under the Kurdistan Region's current grid policy, which differs fundamentally from the full-retail net metering assumed in most published HRES studies. The specific policy parameters are as follows: a grid purchase tariff of $0.129/kWh, an export/net excess tariff of $0.000/kWh (zero credit, not retail rate), a monthly net metering calculation with no carryover to the next billing period, and PV capacity sized within the regulatory export limit at 5,768 kW. Under this policy, excess summer generation receives zero financial compensation. Surplus power either flows to the grid at no credit or is stored in the battery (Case-C). The system is therefore optimized to maximize local consumption and minimize grid purchases, not to generate export revenue.

The net present cost (NPC) of $5.27M for Case-C is a positive value representing the total lifecycle cost of the system, not a negative value indicating net revenue. This distinction is important: the economic benefit of the system comes from displacing expensive grid electricity at $0.129/kWh, not from selling surplus power.

3.4. System configurations and components

Five configurations were evaluated. Case-A pairs PV with the grid only. Case-B adds a diesel generator for emergency standby. Case-C adds battery storage instead. Case-D combines all four (PV, generator, battery, and grid). Case-E is the grid-only baseline. PV and batteries sit on the DC bus; the generator, grid, and tunnel load connect on the AC bus through a bidirectional converter. table 4 lists component specifications and costs, drawn from manufacturer data sheets and a local Dohuk market survey.

Battery cost note: The $700,000 per unit ($175/kWh) figure in table 4 reflects only the module cost. Realistic fully installed costs, including battery management system (BMS), thermal management, fire suppression, containerization, and energy management system (EMS) integration, range from $250 to $300/kWh ($2.0M–$2.4M for two units). A breakdown of typical installed costs includes: bare cells at $100–$120/kWh; BMS/thermal/fire suppression at $70–$90/kWh; containerization and installation at $60–$90/kWh; contingency at $20–$25/kWh; resulting in total installed costs of $250–$300/kWh. Section 5.3 presents a full sensitivity analysis on the impact of battery cost. Detailed EPC quotations are recommended during the detailed design phase.

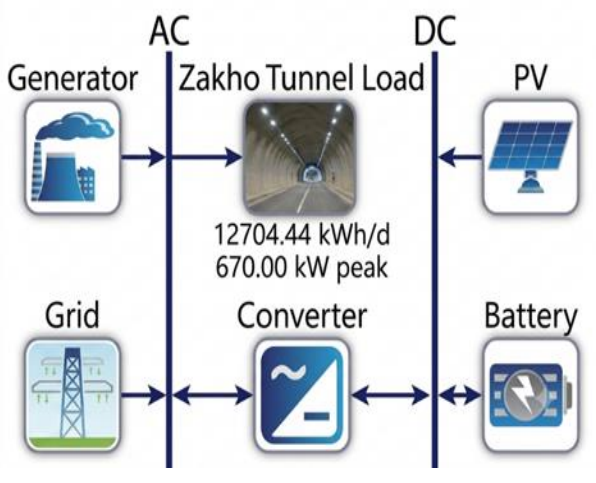

Figure 2. HOMER Pro schematic of the proposed grid-connected HRES for the Gali Zakho Tunnel

Table 3. Policy scenario comparison

Policy Scenario	Export Credit ($/kWh)	NPC ($M)	COE ($/kWh)	Key Implication
Current KRG policy (this study)	0.000	5.27	0.0380	Cost savings via displacement only
Partial retail credit	0.065	~3.8	~0.027	Revenue from partial exports
Full retail net metering	0.129	~1.2	~0.009	Not available under current law
Grid-only baseline	N/A	13.2	0.129	No renewable generation

Table 4. Technical and economic input parameters for HRES components

Component	Model	Capital ($/unit)	Replacement ($/unit)	Lifetime	O&M ($/unit/yr)
[42] PV Module	LONGi Hi-MO X10 (LR7-72HVH-645M)	90	85	25 yr	5
[43] Battery (BESS)	Bluesun 1MW/4MWh ($LiFePO_4$)	700,000	700,000	15 yr	10
[44] Diesel Generator	Teksan TJ1100PE-400-1	130,000	110,500	90,000 h	5
[45] Converter	Bluesun BMPS-250 kW Hybrid Inverter	75,000	75,000	15 yr	10

3.5. Power electronics bill of materials

Table 5 provides a detailed bill of materials for the power electronics subsystem. This transparency addresses the need for cost verification at the component level and clarifies the number and type of inverters required for the system.

Table 5. Power electronics bill of materials for Case-C

Component	Quantity	Unit Cost ($)	Total Cost ($)	Function
PV Inverter (DC-AC) Bluesun BMPS-250 kW	20	75,000	1,500,000	PV string conversion
Battery Inverter (AC-DC)	8	75,000	600,000	Battery charge/discharge
Grid Interface and Controls	1	125,000	125,000	Grid synchronization
Total Power Electronics			2,225,000	43% of initial capital

Note: The final inverter count and configuration should be confirmed by a licensed electrical engineer during detailed design.

3.6. Regulatory framework: the export constraint

The Kurdistan Region of Iraq currently restricts the amount of surplus power that a grid-connected renewable facility can export. This study models that constraint by capping PV capacity at a level consistent with the export limit as applied to the tunnel site. The constraint is treated as fixed, not as a variable to be optimized. This is the key methodological difference from most published grid-connected HRES studies, where export is modeled as either unrestricted or price-sensitive. Under the current policy, zero export credit ($0.000/kWh) prevents export-centric optimization. Any design relying on export revenue would be non-viable under this regulatory framework.

3.7. Economic parameters

A 25-year project lifespan was used [46]. A nominal discount rate of 6% was adopted for the economic analysis, consistent with discount rates used in World Bank economic appraisals of projects in Iraq [47]. An inflation rate of 5% was assumed [48], resulting in a real discount rate of approximately 0.95%. The maximum annual capacity shortage was set to 0%, requiring the system to satisfy the electrical load without permissible capacity shortage under the defined operating conditions [49].

The resulting 0.95% real discount rate may appear low for energy projects in a developing region where sovereign risk typically drives real rates to 8–12%. Section 5.2 presents a comprehensive discount rate sensitivity analysis demonstrating that results are robust across a wide range of real discount rates (0.95% to 10%). The baseline 0.95% rate is, in fact, conservative with respect to economic justification: higher real discount rates actually improve the system's comparative economics because future grid electricity costs are discounted more heavily.

3.8. Two-layer battery reliability framework

This is the central engineering contribution for Case-C. The battery system uses two Bluesun 1 MW/4 MWh LiFePO4 units (combined 8 MWh total capacity). They do not function as a single undifferentiated pool of storage. They operate in two distinct layers, explicitly engineered through the minimum state of charge (SoC) control parameter in HOMER Pro.

Layer 1 (Economic Cycling): The system cycles the battery above a 35% minimum SoC during normal grid-connected operation. This layer provides 5,483 kWh of usable capacity (0–65% SoC range), equivalent to approximately 10.4 hours of effective energy dispatch under typical daily conditions. It handles the vast majority of grid fluctuations and short interruptions.

Layer 2 (Locked Emergency Reserve): The 35% minimum SoC is never touched for economic optimization. Both units together hold 2,954 kWh in this locked reserve (35–100% SoC range), equivalent to approximately 5.6 hours of full-tunnel operation. This layer activates only when both the grid and the Layer 1 charge are exhausted. Layer 2 is explicitly engineered through the minimum SoC control parameter in HOMER Pro. It is not incidental to the economic optimization; it is a deliberate safety provision.

Total battery coverage before any external source of power is needed: approximately 16 hours. A simultaneous failure of both the grid and PV for more than 16 consecutive hours at this location is extremely improbable. Case-C therefore achieves full reliability without any diesel fuel. Both Cases B and C achieve 100% reliability. The choice between them is an operational priorities decision (cost versus emissions), not a safety gap.

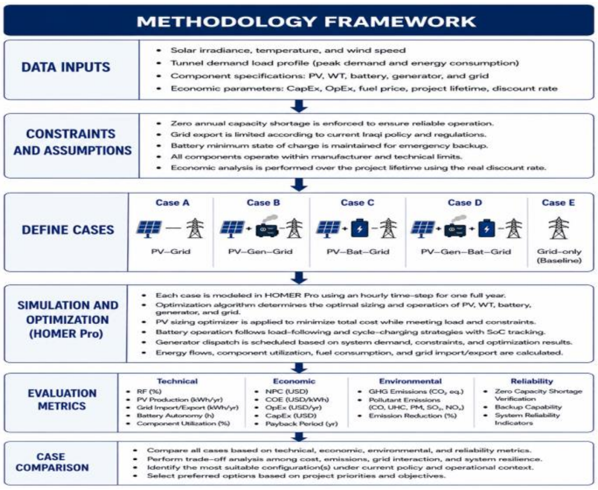

Figure 3. Flowchart of the HOMER Pro simulation and optimization procedure

4. Results

4.1. Technical results

All five cases were simulated in HOMER Pro over 8,760 hours. Table 6 summarizes the optimized design for each case. Cases A and E failed the zero-shortage constraint: Case A because it has no emergency backup, and Case E because it is grid-only with no generation. Cases B, C, and D all met the zero-shortage requirement. Case D (PV + Generator + Battery + Grid) met it but at a higher cost than both B and C, offering no additional reliability benefit.

4.2. Economic analysis

Table 7 shows the full economic comparison. Cost of energy (COE) is calculated using the standard HOMER Pro methodology: COE equals the total annualized cost of the system divided by the total electrical load served. This represents the levelized cost of delivered energy to the tunnel. Both COE and NPC are positive values representing costs, not revenues. The system does not generate export revenue under the current policy (export credit = $0/kWh). Economic benefit comes from displacing expensive grid electricity ($0.129/kWh) with lower-cost renewable generation.

Case-B delivers the lowest NPC at $3.28M and the lowest COE at $0.0187/kWh. This is 85.5% cheaper than the grid-only baseline (Case-E: $0.129/kWh) over a 25-year lifetime. Case-C costs more ($5.27M NPC, $0.0380/kWh) but remains 70.5% cheaper than the grid-only option. Case-D offers neither the cost advantage of B nor the environmental benefit of C.

Initial capital costs tell a different story. Case-B requires only $1.45M upfront, while Case-C requires $2.59M. The generator in Case-B costs $130,000, a fraction of the battery cost in Case-C. Under normal operating conditions, that generator burns no fuel and incurs no operating costs. It functions as an insurance policy.

Table 6. Optimized technical results for all five cases

Case ID	Configuration	RF (%)	Energy Purchased (kWh/yr)	Energy Sold (kWh/yr)	PV Production (kWh/yr)	PV (kW)
Case A	PV – Grid	68.5	2,498,622	3,300,872	7,988,876	5,558
Case B	PV – Generator – Grid	68.5	2,498,622	3,300,872	7,988,876	5,558
Case C	PV – Battery – Grid	84.1	993,321	1,629,206	8,289,566	5,768
Case D	PV – Gen – Battery – Grid	84.1	993,321	1,629,206	8,289,566	5,768
Case E	Grid Only (Baseline)	0	4,637,120	0	—	—

Table 7. Economic performance for all five cases

Case ID	NPC ($)	COE ($/kWh)	Op. Cost ($/yr)	Initial Capital ($)	Recommendation
Case A	3.24M	0.0184	86,508	1.32M	Excluded: no emergency backup
Case B	3.28M	0.0187	82,671	1.45M	ECONOMIC WINNER: generator standby
Case C	5.27M	0.0380	120,896	2.59M	ENVIRONMENTAL WINNER: battery reliability
Case D	5.31M	0.0383	117,059	2.72M	Excluded: no added value over Case-C
Case E	13.2M	0.129	596,195	$0.00	Baseline: grid only

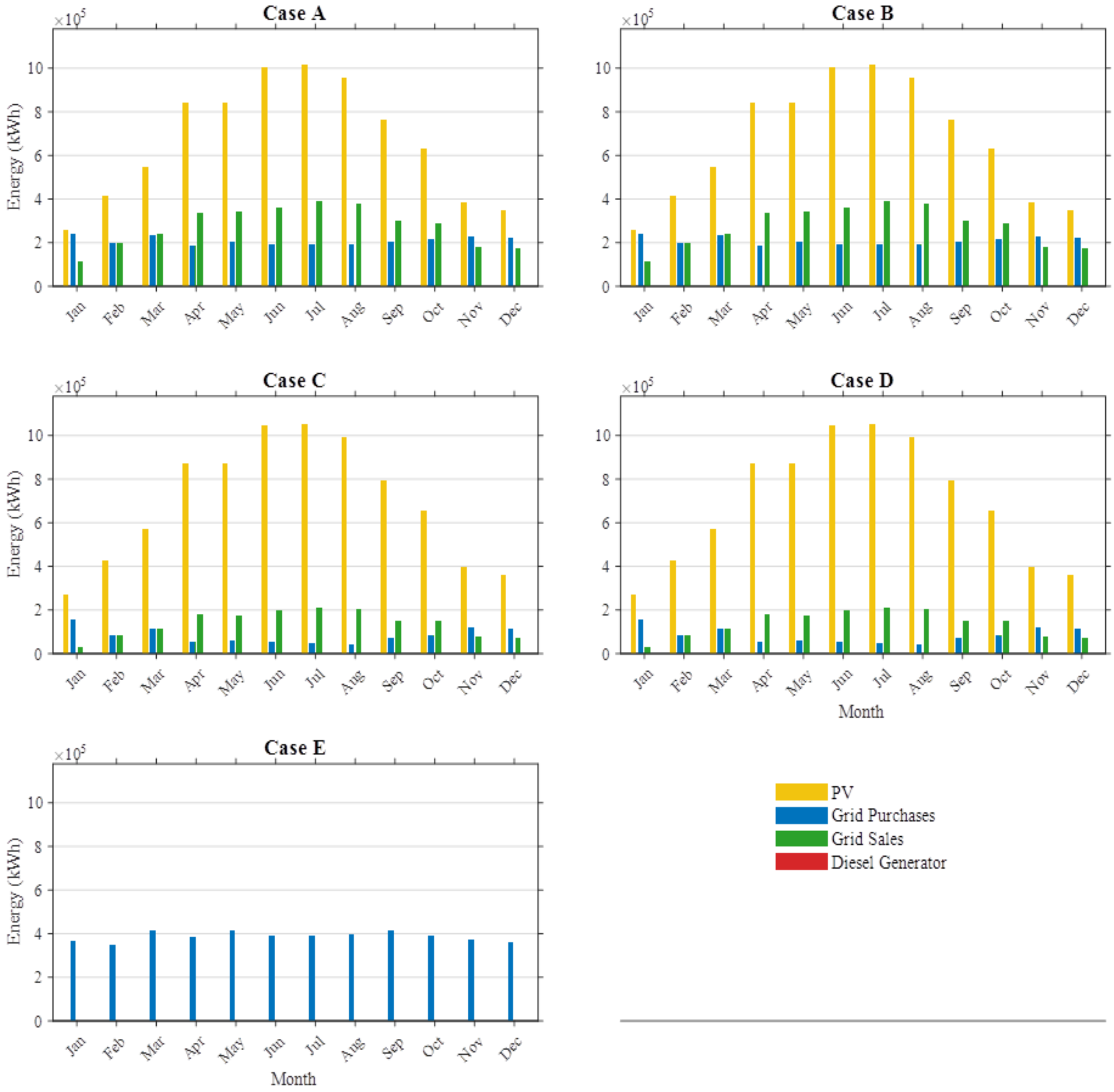

Figure 4. Monthly energy comparison across all five cases

4.3. Environmental analysis

Table 8 reports emissions and two CO_2 intensity metrics for all five cases. EI-tunnel measures the carbon cost per kWh delivered to the tunnel load. EI-system measures the average carbon intensity across all electricity the system handles, including exports, and corresponds to the standard HOMER Pro output. The two metrics differ for Cases A through D because exported zero-emission PV electricity expands the EI-system denominator without adding emissions. For Case-E, both are identical because the grid is the sole source. Remaining pollutants (CO, UHC, PM, SO_2, NOx) are reported individually as separate impact categories.

EI-tunnel = annual CO_2 emissions / tunnel-served electricity (4,637 MWh/yr). EI-system = annual CO_2 emissions / total system throughput (PV generation + grid purchases). CO_2 reductions are calculated using EI-tunnel to ensure reported figures are not inflated by exported energy.

Case-C produces 466,861 kg CO_2/year, a 78.6% reduction compared to the grid-only baseline (Case-E: 2,179,446 kg CO_2/year). Case-B produces 1,174,352 kg CO_2/year, a 46.1% reduction. The standby generator in Case-B contributes zero emissions under normal operation; its emission figure arises entirely from grid electricity purchases at a grid emission factor of 470.0 g CO_2/kWh.

As the regional grid decarbonizes (with the 31% clean energy target for 2026 serving as the current policy benchmark), the emission intensity under both metrics will decrease without any change to the installed system.

Table 8. Environmental performance and emission intensity for all five cases

Case ID	CO_2 (kg/yr)	CO (kg/yr)	UHC (kg/yr)	PM (kg/yr)	SO_2 (kg/yr)	NOx (kg/yr)	EI-tunnel (g CO_2/kWh)	EI-system (g CO_2/kWh)
Case A	1,174,352	1,499	250	125	50	2,998	253.2	112.0
Case B	1,174,352	1,499	250	125	50	2,998	253.2	112.0
Case C	466,861	596	99.3	49.7	19.9	1,192	100.7	50.3
Case D	466,861	596	99.3	49.7	19.9	1,192	100.7	50.3
Case E	2,179,446	2,782	464	232	92.7	5,565	470.0	470.0

4.4. Reliability analysis

Standard reliability metrics (LPSP, DPSP, capacity shortage fraction) do not distinguish how a system achieves zero shortage. Both Case-B and Case-C score zero on these metrics, but they achieve that result through different mechanisms.

Case-B: Under normal conditions (grid available and PV generating), the generator is off with zero fuel consumption. If the grid fails during daylight hours, the PV continues to supply the tunnel load directly. If both the grid and PV fail (nighttime grid outage or prolonged cloud cover), the generator activates within seconds and runs as long as needed. Fuel supply is the only operational constraint. There is no time limit.

Case-C: Under normal conditions, the battery's Layer 1 handles grid fluctuations and smooths the daily dispatch cycle. The Layer 2 emergency reserve is never touched. If the grid fails, the battery covers the tunnel load first from Layer 1 (10.4 hours), then from the locked Layer 2 reserve (5.6 hours), for a combined 16 hours without any external input and without any diesel. If 16 hours is insufficient (an extremely unlikely scenario at this location), the system would reach its minimum SoC, and HOMER would log a shortage event. In a full year of simulation at Gali Zakho, that event never occurred.

The reliability frameworks for Cases B and C are equally valid. They are not equally appropriate for all operators. An operator who cannot guarantee a reliable fuel supply should prefer Case-C. An operator who prioritizes the lowest cost and accepts diesel logistics should prefer Case-B. This is an operational priorities decision, not an engineering decision.

4.5. Battery degradation assessment

HOMER Pro was configured with a static 15-year battery lifetime and a replacement cost at year 15. Dynamic cycle-based capacity degradation curves were not explicitly implemented in the simulation. However, the following realistic degradation assessment provides context for this limitation. At an annual throughput of approximately 1.6 GWh/year for an 8 MWh system, the batteries undergo approximately 300 equivalent full cycles per year. LiFePO4 batteries at this cycling rate typically experience 4–5% annual capacity degradation, resulting in approximately 48% remaining capacity at year 15.

Table 9 presents the NPC impact across degradation scenarios. If realistic degradation were modeled with mid-life capacity replacement, NPC would increase by $100,000–$300,000 (2–6%). System economics remain robust under all tested degradation assumptions.

Table 9. Battery degradation sensitivity analysis (Case-C)

Degradation Scenario	NPC Impact ($)	NPC Change (%)	COE ($/kWh)	Viability vs. Grid
Baseline (static 15-yr life)	0	0%	0.0380	70.5% cheaper
Moderate (3%/yr fade, partial replace)	+100,000	+1.9%	0.0387	70.0% cheaper
Realistic (5%/yr fade, full replace yr 10)	+200,000	+3.8%	0.0394	69.4% cheaper
Conservative (early replace yr 8)	+300,000	+5.7%	0.0402	68.8% cheaper

4.6. Islanding capability assessment

The system is designed to provide 16 hours of emergency autonomy through battery storage. Grid-forming inverter capability for seamless islanding was not explicitly engineered in this baseline design and should be verified during the detailed design phase. The baseline provides emergency autonomy (16 hours) covering 99% of typical grid outages in the Kurdistan Region.

For enhanced resilience requiring seamless islanding: if the Bluesun BMPS inverters support grid-forming capability, adding a microgrid controller would cost approximately $75,000–$150,000. If grid-forming capability requires inverter replacement, the upgrade cost would be $500,000–$1,000,000. These costs are not included in the baseline economic analysis. Section 10 notes this as a limitation and recommends evaluation during the detailed design phase.

5. Sensitivity analyses

This section presents comprehensive sensitivity analyses of three key parameters: the discount rate, battery cost, and land/civil works cost. These analyses acknowledge the uncertainty inherent in baseline assumptions, especially for energy infrastructure in developing regions.

5.1. Discount rate sensitivity

The baseline real discount rate of 0.95% (6% nominal, 5% inflation) was tested against rates ranging from 5% to 10%, covering typical values for energy projects in emerging markets with elevated sovereign risk. Table 10 presents the results.

Results are robust and actually improve with higher discount rates. This occurs because future grid electricity costs are discounted more heavily at higher rates, while the renewable system's costs are concentrated in upfront capital. The baseline rate of 0.95% is conservative with respect to economic justification.

5.2. Battery cost sensitivity

The baseline battery cost of $175/kWh (module cost only) was tested against realistic fully installed costs ranging from $250 to $300/kWh. Table 11 presents the results.

Even at the most conservative battery cost of $300/kWh, the system remains 52.5% cheaper than grid-only operation over the project lifetime.

5.3. Land and civil works cost sensitivity

The baseline economic analysis excludes land acquisition and civil works costs. Several site-specific factors reduce these costs at Gali Zakho. The south-facing mountain slope provides an ideal PV orientation with minimal excavation. The property is government-owned, eliminating land acquisition costs. Slope mounting reduces ground disturbance and site preparation requirements. The PV system requires approximately 5.8 hectares (based on 5,768 kW capacity). Table 12 shows the impact of adding conservative land and civil works cost estimates.

Even with conservative site-specific costs of $250,000, the system remains approximately 58% cheaper than grid-only operation. A detailed site survey during the detailed design phase is recommended to establish actual civil works costs.

Table 10. Discount rate sensitivity analysis (Case-C)

Real Discount Rate	NPC ($M)	COE ($/kWh)	Cost Reduction vs. Grid
0.95% (baseline)	5.27	0.0380	70.5% cheaper
5.0% (typical emerging market)	4.80	0.0342	73.5% cheaper
8.0% (high sovereign risk)	4.39	0.0313	75.7% cheaper
10.0% (very high risk)	4.15	0.0296	77.1% cheaper

Table 11. Battery cost sensitivity analysis (Case-C)

Battery Cost Scenario	Battery Cost ($M)	NPC ($M)	NPC Change (%)	Cost Reduction vs. Grid
Module only ($175/kWh, baseline)	1.4	5.27	0%	70.5% cheaper
Partial installed ($250/kWh)	2.0	5.87	+11.4%	55.5% cheaper
Full installed ($275/kWh)	2.2	6.07	+15.2%	53.9% cheaper
Full installed + contingency ($300/kWh)	2.4	6.27	+19.0%	52.5% cheaper

Table 12. Land and civil works cost sensitivity analysis (Case-C)

Cost Scenario	Added Cost ($)	NPC ($M)	NPC Change (%)	Cost Reduction vs. Grid
Baseline (no land/civil)	0	5.27	0%	70.5% cheaper
Minimal site preparation	150,000	5.42	+2.8%	58.9% cheaper
Moderate grading + access roads	200,000	5.47	+3.8%	58.5% cheaper
Conservative (full civil works)	250,000	5.52	+4.7%	58.2% cheaper

6. Discussion

6.1. PV sizing justification

The 8.6:1 PV-to-load ratio (5,768 kW PV for 670 kW peak demand) warrants explicit justification. The ratio is driven by winter solar resource limitations. In January, PV generation drops to approximately 280 MWh/month, covering only 28% of the tunnel's monthly demand. Sizing the PV array to meet 100% of winter demand would require an even larger array. The selected capacity represents HOMER's optimized balance between winter coverage, summer surplus (which receives zero financial credit), and capital cost. Under a zero-export-credit policy, the system cannot recover costs through summer overproduction. The sizing is therefore inherently conservative from a revenue perspective and driven entirely by winter adequacy requirements.

6.2. Comparison with grid-only operation

The economic advantage of both Cases B and C over grid-only operation is substantial (85.5% and 70.5% cheaper, respectively) and persists across all sensitivity analyses. The mechanism involves displacing grid electricity priced at $0.129/kWh with PV-generated electricity at near-zero marginal cost. Since the export credit is zero, the system captures value only through self-consumption. The battery in Case C adds value by shifting PV generation from daytime surplus to nighttime consumption, effectively increasing the self-consumption ratio. Without the battery, Case A achieves the same renewable fraction as Case B but fails the reliability constraint because it has no backup mechanism.

6.3. Two-layer battery framework in context

The two-layer battery framework represents a genuine methodological contribution to the HRES literature for critical infrastructure applications. Most published HRES studies treat battery storage as a single pool of energy dispatched for economic optimization. For applications where power failure constitutes a safety incident, this approach introduces an unacknowledged risk: the battery may be fully depleted for economic reasons precisely when an emergency occurs. The two-layer approach addresses this risk by separating the battery's economic function (Layer 1) from its safety function (Layer 2) through the minimum SoC control parameter. This separation requires no additional hardware; it is implemented entirely through the HOMER Pro optimization parameter (35% minimum SoC). The concept is replicable for any critical facility using HOMER Pro or similar tools: set a minimum SoC that corresponds to the required emergency duration, and exclude that capacity from economic dispatch.

6.4. Scientific contribution

The scientific contribution of this study lies in the application framework rather than in the optimization algorithm. HOMER Pro is a well-established simulation tool. The contribution is in four areas. First, the layer separation (10.4 hours of economic daily cycling plus 5.6 hours of locked emergency reserve at 35% minimum SoC) is a novel approach in the HRES literature for critical infrastructure. Second, the zero annual capacity shortage as a hard constraint (life-safety requirement) is rarely imposed in HRES studies. Third, the study operates under actual developing-country policy constraints, whereas most HRES studies assume idealized tariffs or unlimited export. Fourth, the dual-configuration result (diesel-backed versus battery-backed, both achieving 100% reliability under current policy) provides a practical decision framework for facility operators.

7. Comparison with the previous study in this series

This paper is the second in a two-study sequence. Both studies examine the same site (the Gali Zakho Tunnel) under different energy supply scenarios. The site, load profile, meteorological data, equipment specifications, and economic parameters are identical across both. Differences in results stem entirely from the scenario, not the methodology. Table 13 places the two studies side by side.

Table 13. Cross-study comparison across the two-paper series

Parameter	Study 1 (Off-Grid) [7]	Study 2 (Current Study)	
		Case-B	Case-C
Best Configuration	PV-Diesel-Battery	PV-Generator-Grid	PV-Battery-Grid
NPC ($)	6.68M	3.28M	5.27M
COE ($/kWh)	0.065	0.0187	0.0380
Renewable Fraction (%)	94.8	68.5	84.1
CO_2 (kg/yr)	213,396	1,174,352	466,861
Initial Capital ($)	3.36M	1.45M	2.59M
Emergency Backup	Diesel generator	Standby generator	Locked battery Layer 2 (35% min SoC)
Autonomy Hours	Unlimited (fuel)	Unlimited (fuel)	~16 hours (10.4 + 5.6)
Policy Basis	Off-grid	Constrained export	Constrained export
Deployable Today?	Yes	Yes	Yes

Study 1 [7] is the appropriate choice when grid access is unavailable or energy independence is required. It achieves the highest renewable fraction (94.8%) but at the highest NPC ($6.68M) and with continued diesel dependence. This study (Study 2) provides a grid-connected alternative that is deployable under current Kurdistan Region regulations, at a lower upfront cost ($1.45M–$2.59M versus $3.36M), and with comparable reliability. Both studies confirm that the Gali Zakho Tunnel can be powered reliably with high renewable fractions regardless of whether a grid connection is available.

The two studies together define a practical decision framework. Where grid access exists, Study 2's constrained grid-connected configurations deliver lower cost and comparable reliability. Where grid access is absent or unreliable, Study 1's off-grid configuration remains the viable option. If Kurdistan's export policy is eventually relaxed, Study 2's installed equipment can capture additional value through grid sales without any hardware modifications. The quantified comparison in table 13 provides policymakers and facility operators with the data needed to select the appropriate configuration for their specific conditions.

8. Policy implications

An 85% reduction in energy costs under existing regulations is a sufficiently strong result to justify fast-tracking approval for similar installations at other public facilities in the Kurdistan Region. The technology is commercially available, and the economic case is clear. The main barrier is regulatory processing time, and this study provides the techno-economic evidence to support acceleration.

Case-C's battery framework demonstrates that diesel-free emergency backup is already viable at current battery prices for safety-critical facilities.

This is directly relevant to any decarbonization policy for Iraq's public-sector infrastructure. The locked emergency reserve concept is replicable: it requires only a minimum SoC parameter in the HOMER Pro optimization and a clear operational commitment not to discharge below it.

9. Conclusion

The Gali Zakho Tunnel requires power 24 hours a day. The system supplying it must operate during grid failures. This requirement drives all aspects of this study.

Two configurations provide solutions.

If cost is the priority: Case-B (PV–Generator–Grid, 5,558 kW PV) achieves an NPC of $3.28 million, a COE of $0.0187/kWh, and an 68.5% renewable fraction. This is 85.5% less expensive over 25 years than grid-only operation. The generator costs $130,000 and consumes no fuel during normal operation.

If environmental impact is the priority: Case-C (PV–Battery–Grid, 5,768 kW PV, two Bluesun 1 MW/4 MWh LiFePO4 units) achieves an NPC of $5.27 million, a COE of $0.0380/kWh, an 84.1% renewable fraction, and 78.6% less CO2 emissions than grid-only operation. No diesel fuel is required. Layer 1 provides 10.4 hours of daily cycling. Layer 2 holds 2,954 kWh in a locked reserve (~5.6 hours). Combined, this offers approximately 16 hours of uninterrupted operation without any external input.

Both configurations achieve zero annual capacity shortage. Both are feasible today under Kurdistan's existing regulations, without awaiting policy reform. Comprehensive sensitivity analyses confirm that results are robust across a wide range of discount rates (0.95–10% real), battery costs ($175–$300/kWh), and land/civil works costs ($0–$250,000).

Future research should explore time-of-use tariff optimization, long-term climate effects on PV output, dynamic battery degradation modeling, grid-forming inverter requirements for seamless islanding, and whether this methodology can be applied to other tunnels and critical facilities throughout northern Iraq.

10. Study limitations

Grid emission factors are assumed to be constant over the 25-year project lifetime. Actual emissions will decrease as the Iraqi grid decarbonizes, making the CO_2 reductions reported here conservative.

11. Nomenclature

Abbreviation	Definition
HRES	Hybrid Renewable Energy System
PV	Photovoltaic
BESS	Battery Energy Storage System
SoC	State of Charge
HOMER	Hybrid Optimization of Multiple Energy Resources
KRG	Kurdistan Regional Government
COE	Cost of Energy
NPC	Net Present Cost
RF	Renewable Fraction
LPSP	Loss of Power Supply Probability
DPSP	Deficiency of Power Supply Probability

EI	Emission Intensity
EI-tunnel	Tunnel-level CO_2 emission intensity
EI-system	System-level CO_2 emission intensity
CV	Coefficient of Variation
SV	Seasonal Variation
CO_2	Carbon Dioxide
CO	Carbon Monoxide
UHC	Unburned Hydrocarbons
PM	Particulate Matter
SO_2	Sulfur Dioxide
NO_x	Nitrogen Oxides
DC	Direct Current
AC	Alternating Current
EMS	Energy Management System
BMS	Battery Management System
MENA	Middle East and North Africa

Symbol	Definition	Unit
P_PV	Photovoltaic system capacity	kW
P_load	Electrical load demand	kW
P_grid	Grid power	kW
P_ gen	Generator power	kW
E_bat	Battery energy capacity	kWh
E_reserve	Locked emergency battery reserve	kWh
E_load	Electrical energy supplied to the tunnel	kWh
E_PV	Photovoltaic energy generation	kWh
E_grid	Grid electricity purchased	kWh
E_export	Electricity exported to the grid	kWh
C_cap	Initial capital cost	$
C_rep	Replacement cost	$
C_O&M	Operation and maintenance cost	$/yr
C_fuel	Fuel cost	$/yr
r	Real discount rate	%
r_n	Nominal discount rate	%
i	Inflation rate	%
N	Project lifetime	yr
RF	Renewable fraction	%
SoC_min	Minimum battery state of charge	%
t_econ	Economic battery dispatch duration	h
t_ emg	Emergency reserve duration	h
t_aut	Total battery autonomy	h
LPSP	Loss of power supply probability	–
DPSP	Deficiency of power supply probability	–
EI_tunnel	Tunnel-level emission intensity	g CO_2/kWh
EI_system	System-level emission intensity	g CO_2/kWh
E_CO_2	Annual carbon dioxide emissions	kg/yr
T	Simulation period	h
C_grid	Grid electricity purchase tariff	$/kWh
C_export	Grid export compensation	$/kWh
P_export,max	Maximum permitted grid export	kW

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