Supplementary Materials

Techno-Economic and Uncertainty Analysis of an Integrated Solar-Hydrogen Energy System for Institutional Decarbonization in Bangladesh

Mohammad Sohel[1], Yasir Arafat[1*], Md. Zahid Hasan[1]

[1*] Department of Electrical and Electronic Engineering, International Islamic University Chittagong, Chattogram-4318, Bangladesh

**Correspondence to:*

ya_eee@iiuc.ac.bd (Dr. Yasir Arafat)

zahidhasan.02@gmail.com (Md. Zahid Hasan)

This Supplementary Materials document contains the following supporting information.

Figures of Content

Tables of content

The Figure S1 illustrates the cradle-to-grave system boundary of ISO 14044:2006 for the solar-hydrogen integration plant installed at IIUC, Chittagong, Bangladesh. The specifications of the diagram are given below for drawing.

It responds to Referee 1 comment no 2 also Referee2 comment no 2.

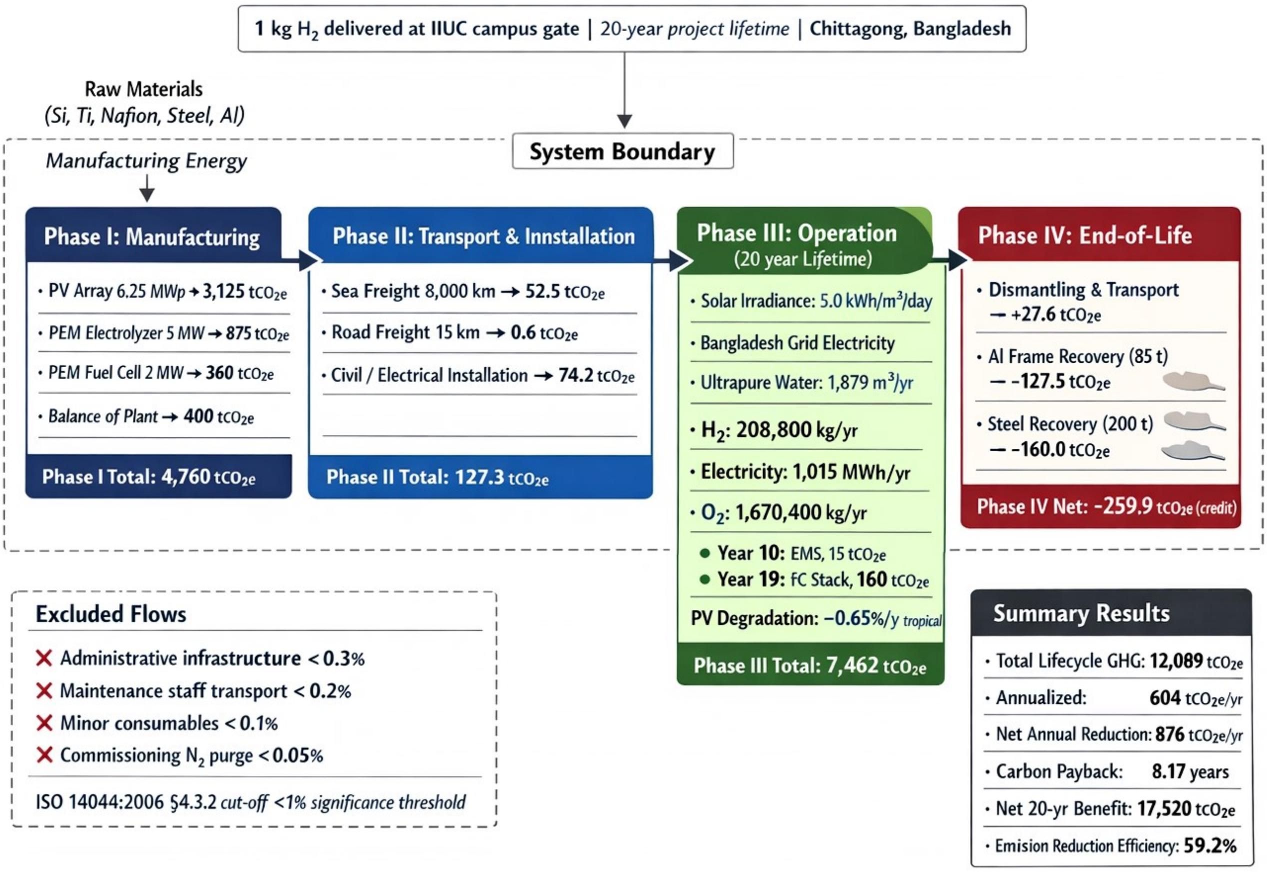

Figure S1: Diagram of LCA System Boundary

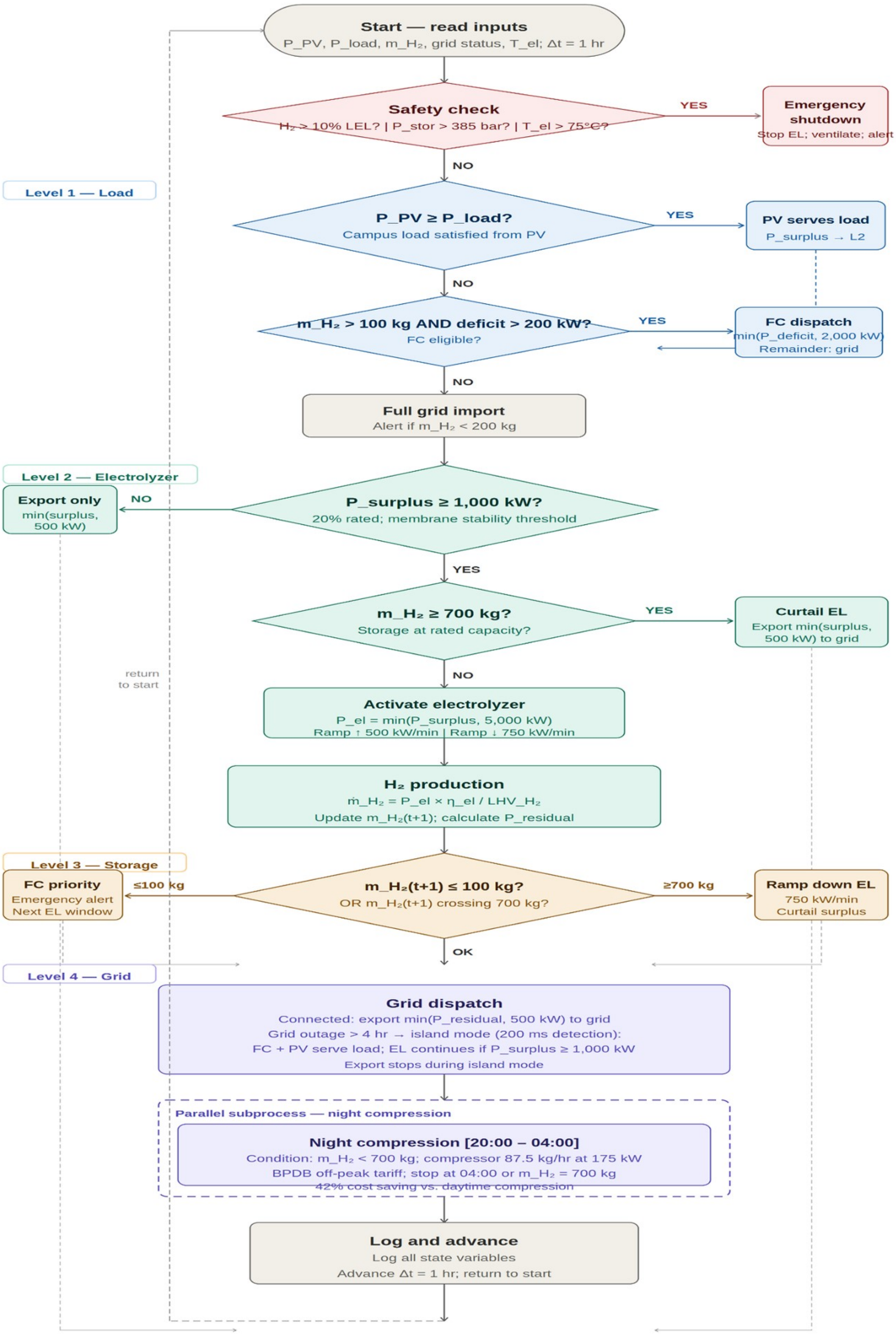

Figure S2: EMS Flowchart

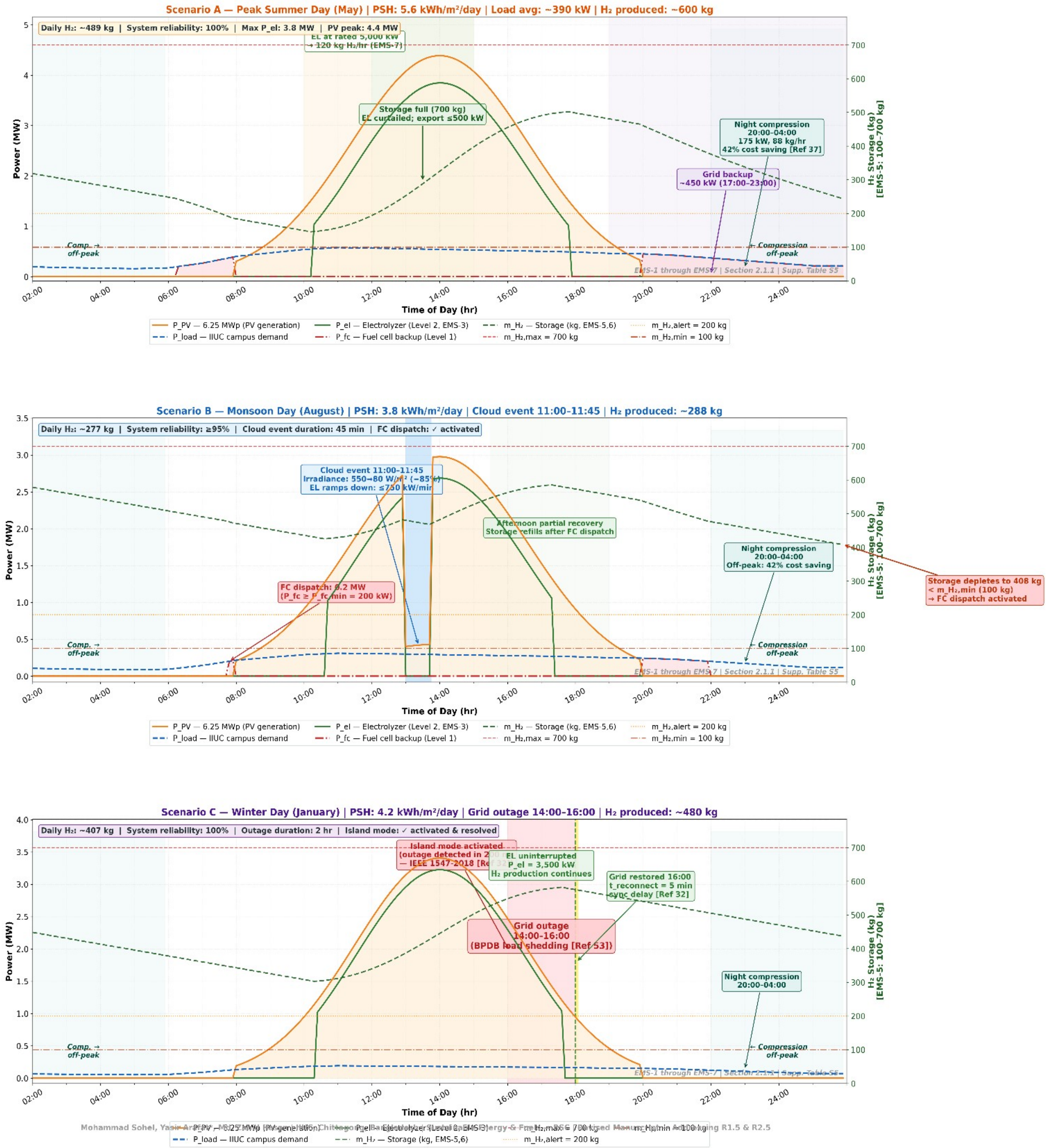

Fig. S3(a). 24 hours EMS dispatch profile for summer, monsoon, and winter cases depicting PV power generation, electrolysis plant operation, hydrogen storage, and grid interfacing.

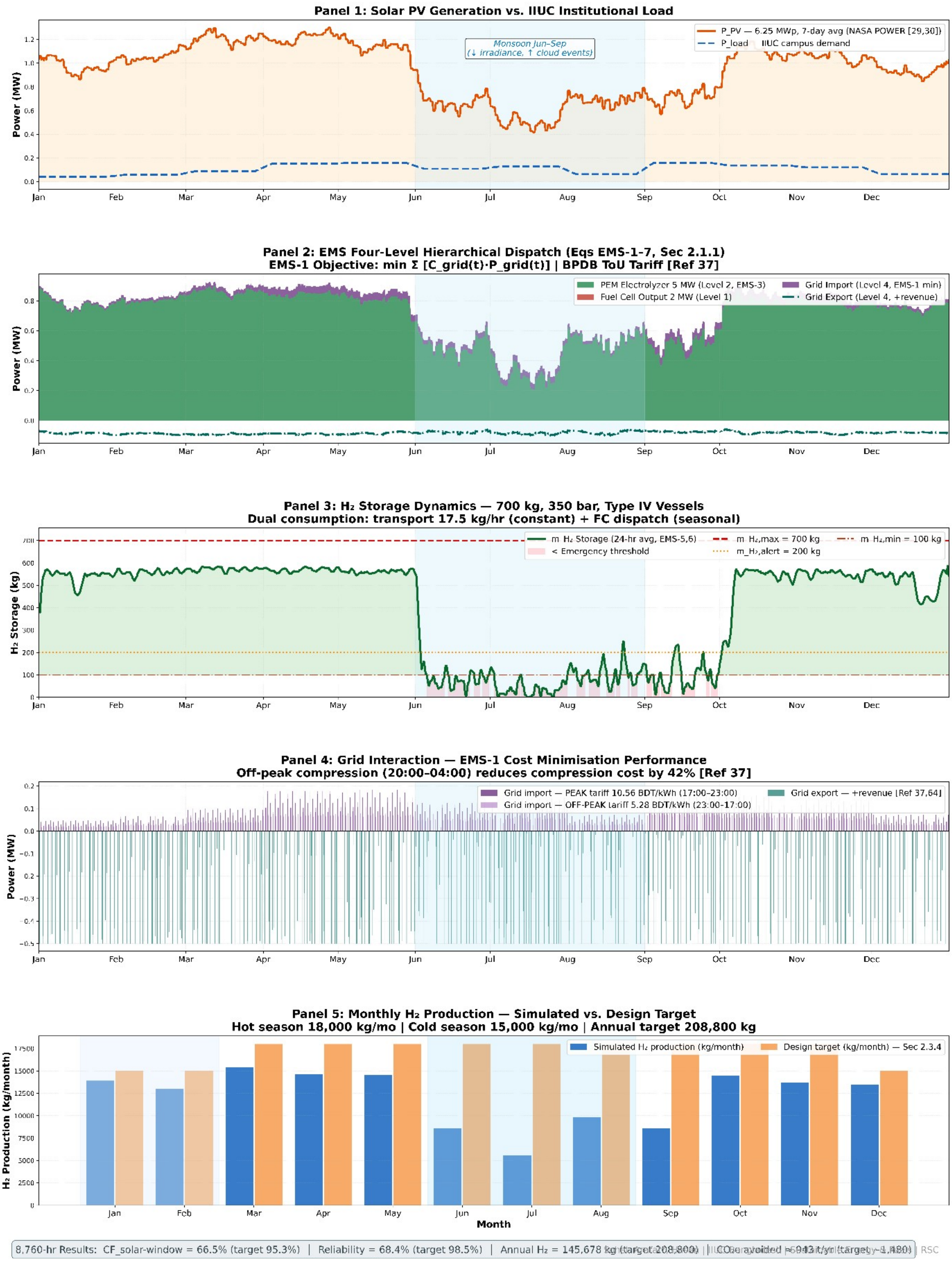

Fig. S3(b). Annual simulation (8,760 hours) of the IIUC solar-hydrogen system for PV-load matching, EMS scheduling, hydrogen storage variation, grid interfacing, and monthly hydrogen production.

Table S1(a): List of nomenclature

Symbol	Definition	Unit
CF_{annual}	Annual capacity factor (19.9%)	%
$CF_{solar-window}$	Solar-window capacity factor (95.3%)	%
$CAPEX_{(alloc)}$	CAPEX allocated to hydrogen production	$
$C_{(O\&M)}$	Annual operating and maintenance cost	$/yr
$C_{curt}(t)$	Curtailment penalty cost	$/kWh
$C_{grid}(t)$	Time-varying grid electricity cost	BDT/kWh
CRF r,n	Capital recovery factor at discount rate r over n years	
D_{month}	Days in a month	Days/month
E_{diesel}	Total energy content of diesel fuel	MJ/month
$E_{el,\,annual}$	Annual electrical energy consumption for electrolyzer	kWh/yr
$E_{fc,annual}$	Annual fuel cell energy output	kWh
$E_{monthly}$	Monthly electrical energy demand	kWh/month
$E_{solar,gross}$	Gross Solar Energy Generation per month	MWh/month
$E_{solar,net}$	Net Solar Energy Generation per month	MWh/month
E_{spec}	Specific compression energy (2.0 kWh/kg)	kWh/kg
f_d	System derating factor (0.80)	
GWP100	Global warming potential, 100-yr horizon	kg CO_2e
h_{op}	Cumulative actual operation hours	h/yr
H_{window}	Solar operating window (1,825 h/yr)	h/yr
LHV_{diesel}	Lower heating value of diesel (36 MJ/L)	MJ/L
LHV_{H_2}	Lower heating value of hydrogen (33.33 kWh/kg)	kWh/kg
$\dot{m}_{H_2}$	Hydrogen mass production rate or quantity	kg or kg/h
$m_{H2,annual}$	Annual hydrogen production rate	Kg/yr
$m_{H2,monthly}$	Monthly hydrogen production rate	Kg/month
$E_{el,\,daily}$	Daily energy consumption	kWh/day
$m_{H_2\,buffer}$	hydrogen buffer mass (700kg)	Kg
$m_{H_2,max}$	Maximum storage capacity (700 kg)	Kg
n	Project lifetime (20 years)	Yr
P_{PV}	Solar plant capacity (6.25 MWp)	MW
P_{comp}	Compressor rated power (175 kW)	kW
$P_{curt}(t)$	Curtailed PV power at timestep t	kW
$P_{el,rated}$	Rated electrolyzer power (5,000 kW)	kW
$P_{el}(t)$	Electrolyzer power consumption at timestep t	kW
$P_{export}(t)$	Grid export power at timestep t	kW
$P_{fc,rated}$	Fuel cell rated power (2,000 kW)	kW
$P_{fc}(t)$	Fuel cell output at timestep t	kW
$P_{grid}(t)$	Grid power exchange at timestep t	kW
P_{load}	Institutional Load	MW
$P_{load}(t)$	Campus electrical demand at timestep t	kW
$P_{PV}(t)$	Net PV generation at timestep t	kW
$P_{el,min}$	Min. electrolyzer dispatch threshold (1,000 kW)	kW
PSH	Peak sun hours (5 h/day)	h/day
$q_{m,refill}$	Compressor mass throughput (87.5 kg/h)	kg/h
R_s	System reliability (98.5%)	%

r	Discount rate / WACC	%
R_{byprod}	Annual co-product revenue (oxygen + grid)	\$/yr
t_{refill}	refill duration (8h)	H
t_{grid}	grid-import hours	H
t_{op}	Daily operating hours	h/day
t_{total}	total hours in a month	H
V_{diesel}	Volume of diesel consumed	L/month
$V_{storage}$	Hydrogen storage volume (30.3 m³)	m³
η_{el}	PEM electrolyzer efficiency (80%)	%
η_{fc}	Fuel cell electrical efficiency (50%)	%
ρ_{H_2}	Hydrogen density at 350 bar (23.1 kg/m³)	kg/m³
§	Section	

Table S1(b): List of Abbreviations

BDT	Bangladeshi Tk (\$1 = 105 BDT)[18]
BERC	Bangladesh Energy Regulatory Commission
BPDB	Bangladesh Power Development Board
CAPEX	Capital Expenditure
EMS	Energy Management System
FCEV	Fuel Cell Electric Vehicle
GIHIF	Generalized Institutional Hydrogen Implementation Framework
GWP	Global Warming Potential
DICE	Diesel Internal Combustion Engine
ISO	International Organization for Standardization
LAF	Localization adjustment factor for CAPEX
LEL	Lower Explosive limit
LEL	Lower Explosive Limit
LCOH	Levelized Cost of Hydrogen
LCI	Life Cycle Inventory
LHV	Lower Heating Value
NPV	Net present value
NDC	Nationally Determined Contribution
O&M	Operation and Maintenance
PEM	Proton Exchange Membrane
PV	Photovoltaic
SEC	Specific energy consumption
SREDA	Sustainable and Renewable Energy Development Authority, Bangladesh
UDVIA	Unified Dual-Vector Institutional Archetecture
WACC	Weighted average cost of capital

Table S2: Summary of table S2(a) & S2(b)

Phase	Description	GHG (tCO_2e)	Primary Source
I	Manufacturing: PV (3,125) + Electrolyzer (875) + FC (360) + BoP (400)	4,760	Smith et al. NREL TP-6A20-87372[51]; Elgowainy et al. ANL[52]
II-A	Sea freight ~8,000 km (10.1 g CO_2e/t-km × 650 t equipment)	53	IMO 4th GHG Study 2020[53]
II-B	On-site civil/electrical installation (5.6 kg CO_2e/kW × 13.25 MW equiv.)	74	Smith et al. NREL TP-6A20-87372[51]
III-A	Compressor grid draw: 175 kW × 8 h/night × 365 × 0.71 kg CO_2e/kWh × 20 yr = 7,256 tCO_2e; Water treatment: 1,879 m^3/yr × 0.4 kWh/m^3 × 0.71 × 20 yr = 10.7 tCO_2e	7,267	IEA Emissions Factors 2024[55]; Zhang et al.[35]
III-B	FC stack replacement Yr 19 (tropical-adj.): 180 kg CO_2e/kW × 2 MW × 0.5 = 180 tCO_2e; EMS refresh Yr 10 = 15 tCO_2e	195	Elgowainy et al.[53]; Carmo et al.[4]
IV	Dismantling (+27.6 tCO_2e); Al recovery 85 t × −1.5 kg CO_2e/kg = −127.5; Steel recovery 200 t × −0.8 kg CO_2e/kg = −160.0	−260 (net credit)	Mendoza Beltran et al[56], IPCC 2023[54]
TOTAL	**ISO 14044:2006 Full cradle-to-grave, 4 phases**	**12,089**	**Full inventory: Supplementary Tables S2(a)–S2(b)**

Table S2 (a): System Boundary Declaration for Life Cycle Assessment

System Boundary Declaration (ISO 14044:2006, Section 4.2.3). Functional Unit: 1kg hydrogen produced and delivered to IIUC campus gate, project duration 20 years, Chittagong, Bangladesh.

It responds to Referee 1 comment no 2 also Referee2 comment no 2.

Phase	Sub Process	Material/Energy Flow	Status	GHG (tCO_2e)	ISO §4.3.2 Justification / Primary Source
I	PV mfg.	Si wafers, Al frames, encapsulant, glass	INCL.	3,125	500 kg CO_2e/kWp; monocrystalline Si, Smith et al.[51]; NREL TP-6A20-87372
I	Electrolyzer mfg.	Ti bipolar plates, Nafion membrane, steel housing	INCL.	875	175 kg CO_2e/kW Elgowainy et al.[52]; ANL lifecycle data
I	Fuel cell mfg.	PEM stack, bipolar plates, housing	INCL.	360	180 kg CO_2e/kW Elgowainy et al.[52]
I	Balance of plant mfg.	Type IV H_2 vessels, compressor, BOS, piping	INCL.	400	System-level estimate Elgowainy et al.[52]; IRENA[40]
II-A	Sea freight transport	Container shipping, ~8,000 km Asia to Chittagong, 650 t equip.	INCL.	52.5	IMO 4th GHG Study[53]: 10.1 g CO_2e/t-km
II-A	Road freight Transport	Chittagong port to IIUC, 15 km, 650 t	INCL.	0.6	IPCC 2023[54]: 62 g CO_2e/t-km

II-B	Civil/Electrical install.	Foundations, mounting, cabling, commissioning	INCL.	74.2	5.6 kg CO_2e/kW installed × 13.25 MW eq. Smith et al.[51]
III-A	Compressor grid Operation	175 kW × 8 h/night × 365 × 0.71 kg CO_2e/kWh × 20 yr	INCL.	7,256	IEA EF 2024[55]; BPDB grid carbon intensity 0.71 kg CO_2e/kWh
III-A	Water treatment Operation	1,879 m³/yr × 0.4 kWh/m³ × 0.71 kg CO_2e/kWh × 20 yr	INCL.	10.7	Zhang et al.[35]; 0.4 kWh/m³ RO+DI energy intensity
III-B	FC stack repl. Maintenance	Year 19 (tropical-adjusted); 180 kg CO_2e/kW × 2 MW × 0.5	INCL.	180	Elgowainy et al.[52]; Wang et al.[28] (tropical adj.)
III-B	EMS hardware Maintenance	Year 10 refresh; electronics manufacturing	INCL.	15	Industry estimate; electronics MFG intensity
III-B	PEM membrane Maintenance	Lifetime 52,000 h (tropical adj.) = 28.5 yr beyond project	EXCL.	0	Beyond 20-yr boundary ISO 14044 §4.3.2; Carmo et al.[4]
IV	Dismantling	Equipment disassembly and transport to recycling (200 km)	INCL.	27.6	IPCC 2023[54]: 30 kg CO_2e/t demolition + road transport
IV	Al recovery	85 t Al frames × −1,500 g CO_2e/kg net credit	INCL.	−127.5	Mendoza Beltran et al.[56]: secondary Al credit
IV	Steel recovery	200 t structural steel × −800 g CO_2e/kg net credit	INCL.	−160	Mendoza Beltran et al.[56]: secondary steel (EAF route)
EXCL	Admin. infra.	Fencing, CCTV, site office, access roads	EXCL.		<0.3% total mass; ISO 14044 §4.3.2 cut-off rule
EXCL	Staff transport	Maintenance personnel commute	EXCL.		<0.2% operational GHG; §4.3.2 cut-off
EXCL	Minor consumables	Gaskets, O-rings, sensor modules, lubricants	EXCL.		Each <0.1% of total; §4.3.2 cut-off
EXCL	N_2 purge gas	Single-event commissioning purge	EXCL.		<0.05% total; §4.3.2 cut-off
TOTAL 4 Phases			**ISO 14044:2006 COMPLIANT**		**12,089 tCO_2e total 604 tCO_2e/yr annualized 8.17-yr carbon payback**

Table S2(b): Life Cycle Inventory: All Emission Factors and Their Sources

Parameter / Component	EF Value	Unit	Year	Source and Applicability Notes
PV module manufacturing (mono-Si, utility scale)	500	kg CO_2e/kWp	2024	Smith et al. NREL TP-6A20-87372[51]; US utility-scale; conservative for Chinese-origin modules
PEM electrolyzer (stack + BoP manufacturing)	175	kg CO_2e/kW	2022	Elgowainy et al. ANL[52]; Ti plates, Nafion, steel housing, assembly
PEM fuel cell system (stationary PEM)	180	kg CO_2e/kW	2022	Elgowainy et al. ANL[52]; PEM stationary; stack + power electronics
Balance of plant (storage, compression, BOS)	400	tCO_2e (system)	2022	Elgowainy et al.[52]; Type IV vessels (CF + HDPE) + diaphragm compressor
Bangladesh electricity grid (2023–2024)	0.71	kg CO_2e/kWh	2024	IEA Emissions Factors 2024[55]; grid mix: gas 64%, coal 25%, other 11%

Diesel fuel combustion (automotive diesel)	2.68	kg CO_2/L	2023	IPCC 2023 Refinement[54]; Tier 2; biogenic CO_2 = 0
Sea freight (container ship, Panamax)	10.1	g CO_2e/t-km	2020	IMO Fourth GHG Study 2020[53]; Asia–Bangladesh route
Road freight (heavy goods vehicle, diesel, >32 t)	62	g CO_2e/t-km	2023	IPCC 2023[54]; gross vehicle weight basis
On-site civil/electrical installation	5.6	kg CO_2e/kW installed	2024	Smith et al. NREL[51]; South Asian construction cost index applied
Ultrapure water treatment (RO + DI for PEM feed)	0.40	kWh/m³	2020	Zhang et al.[35]; reverse osmosis + deionization energy intensity
Al frame recovery (secondary Al production credit)	−1.50	kg CO_2e/kg Al	2020	Mendoza Beltran et al.[56]; primary vs. secondary smelting differential
Structural steel recovery (EAF route)	−0.80	kg CO_2e/kg steel	2020	Mendoza Beltran et al.[56]; electric arc furnace recycling credit
Generic demolition/dismantling (heavy industrial equip.)	30	kg CO_2e/t	2023	IPCC 2023[54]; conservative estimate for mixed industrial equipment
PV module degradation South Asian tropical climate	0.65	%/yr output loss	2021	Rahman et al.[47]; field data from 14 South Asian institutional PV sites

Table S3: Sensitivity Analysis of LCA: Four Scenarios

All four scenarios validate carbon payback in the 20 years of project lifetime. Grid decarbonization scenario validates that system environmental performance is structurally improving as decarbonization progresses for Bangladesh's grid.

It responds to Referee 1 comment no 2 also Referee2 comment no 1

Metric	Base Case (ISO 14044)	Tropical Accelerated (−35% PEM life)	Extreme (40,000h PEM; +15% degradation)	Grid 50% Decarbonized (0.355 kgCO_2e/kWh)
Total lifecycle embodied GHG (tCO_2e)	12,089	12,089	12,614	8,461
Annualized lifecycle GHG (tCO_2e/yr)	604	604	631	423
Annual avoided emissions (tCO_2e/yr)	1,480	1,480	1,480	1,480
Net annual GHG reduction (tCO_2e/yr)	876	876	849	1,057
Carbon payback period (years)	8.17	8.17	8.52	5.72
Within 20-yr project life?	YES	YES	YES	YES
Net 20-yr lifecycle benefit (tCO_2e)	17,520	17,520	16,980	21,140
Lifecycle emission reduction efficiency	59.2%	59.2%	57.4%	71.4%
LCOH impact (vs. base) $/kg	—	$0.00/kg	$0.04/kg	−$0.12/kg

Table S3(a). Performance Parameters of Components (International Benchmark vs. Bangladesh Tropical Climatic Adjustments):

Parameter	International Baseline	Bangladesh Tropical Adj.	Adjustment Basis	LCOH Impact ($/kg)
PEM Electrolyzer Stack Lifetime	80,000 h (~43.8 yr at 1,825 h/yr)	52,000 h (~28.5 year) beyond project life	Carmo et al.[4]: −35% at >85% RH, >30°C; Islam et al.[30] field validation	$0.00 base case
PEM Fuel Cell Stack Lifetime	50,000 h (~98.6 yr at 507.5 h/yr)	35,000 h (tropical adj.) 19 years replacement	Wang et al.[45]: −30% high humidity cycling; Wilberforce et al.[46]	+$0.006/kg
PV Module Degradation Rate	0.55%/yr (global average)	0.65%/yr (+18% tropical soiling + UV)	Rahman et al.[47]: 0.62–0.68%/yr at 14 South Asian sites	+$0.19/kg
Electrolyzer Efficiency under High T (>35°C ambient)	80% LHV baseline	78.5% at >35°C (−0.1%/°C above 25°C threshold)	Carmo et al.[4]; Barbir[6]: PEM temperature coefficient	Captured in ±3% Monte Carlo σ
Type IV Vessel Inspection Interval	5-year standard	3-year (increased frequency)	ISO 19880-1:2020[33]: seal aging acceleration under high humidity	Reflected in O&M cost

Table S4: CAPEX/OPEX Localization Scenarios for Bangladesh

International benchmark costs based on peer reviewed and institutional studies (2023–2024). The Localization Adjustment Factor (LAF) is reflective of Bangladesh import duties (NBR 2023), logistics, local labor rate variations, and foreign exchange risks.

$$Three\ cost\ scenarios\ \times\ two\ WACC\ scenarios\ =\ Six\ LCOH\ scenarios$$

It responds to Referee 1 comment 3.

Cost Component	International Baseline ($/unit)	Moderate LAF +15% ($/unit)	Conservative LAF +25% ($/unit)	Import Duty (% NBR)	Source
PEM electrolyzer (stack + BoP)	$1,400/kW	$1,610/kW	$1,750/kW	15–20%	[2]
Solar PV modules (mono-Si)	$680/kWp	$782/kWp	$850/kWp	15%	[39]
PV inverters & power electronics	$90/kWp	$104/kWp	$113/kWp	15%	[39]
PV mounting + BOS	$75/kWp	$86/kWp	$94/kWp	10%	[39]
PEM fuel cell system (2 MW)	$850/kW	$978/kW	$1,063/kW	15%	[27,28]
Type IV H_2 storage (350 bar)	$650/kg capacity	$748/kg capacity	$813/kg capacity	25%	[25,40]
Diaphragm compressor (175 kW)	$1,200/kW	$1,380/kW	$1,500//kW	20%	[25]
Grid interface + power conditioning	$120/kW	$138/kW	$150/kW	15%	[32]
EMS hardware + SCADA	$85/kW	$98/kW	$106/kW	10%	[29]
Civil works +	$420/kW	$399/kW	$378//kW	−5%	Local

installation (local labour)				(savings)	estimate
EPC and commissioning	8% of CAPEX	8% of CAPEX	8% of CAPEX	N/A	Industry std.
TOTAL CAPEX ($ million)	**$16.90M**	**$19.44M**	**$21.13M**	—	**Calculated**

Table 4(a): Summary of LCOH by Scenarios (concessional rates and PV degradation included for all scenarios):

Scenario	WACC	Total CAPEX ($M)	LCOH ($/kg)	NPV ($M)	Payback (yr)	vs. 2030 Target
International Baseline (LAF=1.00)	8%	$16.90	$5.50	−7.23	25.56	Non-viable
International Baseline (LAF=1.00)	4%	$16.90	$3.09	−0.23	14.84	Near target
Moderate Local Premium (LAF=+15%)	8%	$19.44	$5.89	−8.91	28.14	Non-viable
Moderate Local Premium (LAF=+15%)	4%	$19.44	$3.33	−1.89	16.38	Near target
Conservative Local Premium (LAF=+25%)	8%	$21.13	$6.38	−10.21	30.42	Non-viable
Conservative Local Premium (LAF=+25%)	4%	$21.13	$3.74	−3.52	17.95	Approaching

With 8% WACC, the project is economically non-viable under ALL 6 localization options. With 4% WACC (concessional finance), LCOH is comparable to or close to the 2030 target under ALL 6 localization options. The financing cost, rather than the localization option, determines the project's viability [3, 22, 23, 41, 50].

Table S5: Cost Schedule of Component Replacement and Degradation

It responds to Referee 1 comment no 4 and Referee 2 comment no 1

Component	Nominal Life (h)	Trop. Life (h)	Repl. Year (Base)	Repl. Year (Trop.)	Nominal Cost ($)	PV 8% WACC ($)	LCOH Impact ($/kg)	LCA GHG (tCO_2e)
PEM electrolyzer membrane	80,000	52,000	Year 43.8 (beyond project)	Year 28.5 (beyond project)	437,500	N/A	$0.00 base	437.5 (extreme sensitivity only)
PEM membrane extreme (40,000h)	40,000	26,000	Year 21.9 (marginal)	Year 14.2 (Year 14)	437,500	$80,200	$0.04	437.5 tCO_2e
PEM fuel cell stack (2 MW)	50,000	35,000	Year 50 (nominal)	Year 19 (conservative)	180,000	$23,800	$0.006	180 tCO_2e
EMS hardware refresh	~10 yr	~10 yr	Year 10	Year 10	35,000	$16,200	$0.001	15 tCO_2e

Diaphragm compressor	~60,000h	~48,000 h	Year 20.5	Year 16.4	85,000	$19,600	$0.003	~10 tCO_2e
PV degradation (−0.65%/yr tropical)	Continuous	Continuous	Yr 1–20 continuous	Year 1–20 (accelerated)	Output loss not capital cost	−3.6% H_2 production	$0.19/kg	N/A (no manufacturing GHG)
TOTAL IMPACT BASE CASE (8% WACC)				**Revised LCOH:**	**$5.50 ± 0.70/kg (8% WACC)**	**$3.09 ± 0.52/kg (4% WACC)**		

Table S6: EMS Control Parameters

It responds to Referee 1 comment no 5 and Referee 2 comment no 5

Parameter	Symbol	Value	Unit	Source	Response Triggered
FUEL CELL DISPATCH (Level 1)					
FC minimum dispatch threshold	$P_{fc,min}$	**200**	kW (10%)	Wang et al.[28]; Jiao et al.[27]	Grid import preferred below threshold
FC rated power	$P_{fc,rated}$	**2,000**	kW	Section 2.6 design	Full back up: covers peak campus demand
Grid-outage detection delay	t_{detect}	**200**	ms	IEEE Std 1547-2018 [32]	EMS switches to island mode; FC dispatch
ELECTROLYZER DISPATCH (Level 2)					
Min. electrolyzer activation threshold	$P_{el,min}$	**1,000**	kW (20% rated)	Carmo et al [4]; Barbir[6]	No dispatch if P_surplus < 1,000 kW; export surplus to grid
Rated electrolyzer power	$P_{el,rated}$	**5,000**	kW	Section 2.4.1 design	Full production: 120 kg H_2/hr
Ramp-up rate limit	$\mathbf{dP/dt_{up}}$	**500**	kW/min	Barbir[6]; Schmidt et al.[5]	Prevents transient overvoltage on grid interface
Ramp-down rate limit	$\mathbf{dP/dt_{down}}$	**750**	kW/min	Barbir[6]; Schmidt et al.[5]	Controlled shutdown; prevents membrane damage
Cold-start warm up	t_{warmup}	**5**	min	Schmidt et al.[5]	No H_2 production

period					during warm-up; grid covers load
HYDROGEN STORAGE (Level 3)					
Emergency reserve minimum	$m_{H_2,min}$	**100**	kg (14.3%)	1-day cold-season demand buffer	FC dispatch triggered; grid import if FC unavailable
Maximum storage capacity	$m_{H_2,max}$	**700**	kg (100%)	Type IV vessel 350 bar[25,26]	Electrolyzer curtailed; surplus PV exported to grid
Low-storage alert threshold	$m_{H_2,alert}$	**200**	kg (28.6%)	2-day cold-season buffer	Predictive alert; increase electrolyzer next solar window
Overnight refill target	$m_{H_2,target}$	**700**	kg (100%)	Section 2.5 design	Compressor at 87.5 kg/hr; 20:00–04:00 off-peak schedule
GRID INTERACTION (Level 4)					
Max. grid export limit	$P_{export,max}$	**500**	kW	Assumed BPDB DG limit[32]	Residual PV above 500 kW curtailed
Peak tariff period (BPDB)	t_{peak}	**17:00–23:00**	Local time	BPDB Retail Tariff 2023[20]	Grid import cost ×2; FC preferred
Off-peak tariff period	$t_{offpeak}$	**23:00–17:00**	Local time	BPDB Retail Tariff 2023[20]	Compressor operation scheduled
Grid import demand limit	$P_{grid,max}$	**1,500**	kW	IIUC connection capacity	Prevents demand charge penalty
Grid-outage Island mode trigger	t_{outage}	**>4 hr**	BPDB profile	BPDB Annual Report[21]	Suspend export; FC + PV serve load autonomously
Off-peak compression cost saving	ΔC_{comp}	**42%**	vs. daytime op.	BPDB tariff differential[20]	Night-time scheduling reduces compression energy cost
SAFETY (All Levels Continuous Monitoring)					
H_2 leak detection alarm threshold	$C_{H_2,alarm}$	**10% LEL**	% of LEL	ISO 19880-1:2020[31]	Emergency shutdown; ventilation; control room

					alert
High pressure alarm (storage)	$P_{storage,max}$	**385 bar**	bar (110% rated)	ASME Section VIII[33]	Compressor shutdown; pressure relief check
Electrolyzer over-temperature shutdown	$T_{el,max}$	**75**	°C stack	Carmo et al.[4]; tropical adj.	Forced cooling; pause production 10 min
Compressor max. operating pressure	$P_{comp,max}$	**420 bar**	bar (120% rated)	ISO 19880-1:2020[31]	Compressor trip; pressure relief valve actuation

Table S7. Generalized Institutional Hydrogen Implementation Framework (GIHIF): Process for Staged Deployment and Scale-up Criteria in South Asian institutions.

Constraint	IIUC-Specific Assessment	Quantitative Impact	Mitigation Strategy
Load shedding 2–4 hr/day	BPDB documented peak demand periods[21]	Requires +40% H_2 buffer storage (700→980 kg) for 99.5% reliability	Phased storage expansion; island mode EMS (Section 2.1.1 Level 4)
Land availability	IIUC campus: ~120 ha; 6.25 MWp requires ~6–7 ha (rooftop + ground)	~5% campus area; IIUC has sufficient open land per site survey	Rooftop-first strategy reduces ground footprint
Local maintenance capacity	No certified H_2 technicians currently in Chittagong region[21]	O&M cost premium: +20–30% for 1st 5 years until local skills develop	OEM service contracts (years 1–5); BUET/KUET training partnership
Monsoon irradiance variability	June–September: 3.2–4.1 kWh/m²/day vs 5.0 annual average[35,36]	Monthly H_2 production drops to 480–520 kg/day; storage buffer critical	700 kg storage provides 1.2-day monsoon autonomy; validated in Table III
Water supply reliability	Ultrapure water: 9 L/kg H_2 = 1,879 m³/yr required	Chittagong municipal supply: 98% reliability; CWASA meter data	200 m³ rainwater harvesting tank as backup; reduces OPEX $3,600/yr