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Life Cycle Impact Assessment of a Solar PV/Fuel Cell/Hydrogen Storage Hybrid Energy System for Seawater Desalination in South Africa

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Abstract

This paper presents the life cycle impact (LCI) assessment of a solar photovoltaic (PV)/fuel cell/battery/electrolyzer/hydrogen storage hybrid energy system for powering a 19 m³/day seawater reverse osmosis desalination plant across four South African coastal locations: Alexandra Bay, Jeffery Bay, Paternoster, and Ramsgate. Following the IEA-PVPS Task 12 methodology extended to all hybrid system components, the LCI is evaluated in terms of the life cycle carbon emission rate (LCER), global warming potential (GWP), cumulative energy demand (CED), energy payback time (EPT), and net energy ratio (NER). A cradle-to-operation system boundary is adopted with a functional unit of 1 m³ of freshwater produced. The CED reported represents the single-installation embodied energy of all components, consistent with the IEA-PVPS attributional LCA convention. Using site-specific annual solar irradiation of 1,680 to 2,223 kWh/m²/yr, a GHG emission rate of 37.3 to 72.2 g CO_2-eq./kWh for monocrystalline silicon modules, and system lifetimes of 20 to 30 years, the total system CED ranges from 91,128 to 185,488 MJ-eq. The EPT values range from 2.04 to 3.89 years after proper unit conversion of CED from MJ-eq. to kWh-eq. (division by 3.6), and NER ranges from 5.15 to 14.69 across sites and lifetime scenarios. The battery bank and hydrogen storage subsystem each contribute approximately 22% and 22% of total lower CED respectively, representing a combined storage burden of 44% that exceeds the contribution of the PV array components at most sites. All hybrid configurations achieve lifecycle GWP reductions of 87.9 to 94.7% relative to a diesel generator baseline. These results show that although hydrogen integration offers long-duration storage, it has a lifecycle energy burden that is similar to that of the battery bank, showing that a critical trade-off of storage will need to be considered when designing hybrid renewable desalination systems alongside operational reliability.

Keywords
Life cycle impact assessment; solar PV; hydrogen storage; fuel cell; desalination; energy payback time; net energy ratio; cumulative energy demand; South Africa.

1. Introduction
Energy has emerged as one of the leading forces of economy without which modern civilization cannot survive (Babatunde et al., 2020). It drives industry, hospitals, and agricultural operations. It is also an inevitable input for the provision of clean water. Access to clean energy and clean water are two mutually supportive pillars of sustainable development especially in water-scarce coastal regions (Babatunde et al., 2020). In South Africa, it is projected that there will be a shortfall of 3.8 billion cubic meters of water supply by 2030, which has led to increased interest in desalination of seawater using renewable energy systems (Olubayo & Olanrewaju, 2025). Hybrid designs incorporating solar photovoltaic (PV) generation with battery storage, proton exchange membrane (PEM) electrolyzers, fuel cells, and compressed hydrogen tanks have been shown to be highly techno-economic in off-grid desalination (Rezk et al., 2019), especially in the four coastal provinces of South Africa (Olubayo & Olanrewaju, 2025). The environmental analysis of these hybrid systems needs to consider the total energy and carbon footprint of the entire lifecycle of such systems not only the emissions during operation, but the extraction of the raw materials and their manufacture, and their ultimate decommissioning (Bhandari et al., 2015; Laleman et al., 2013). Life cycle impact (LCI) analysis offers a rigorous foundation to this assessment with five key measures: the rate of life cycle carbon emission (LCER), global warming potential (GWP), cumulative energy demand (CED), energy payback time (EPT), and net energy ratio (NER) (D. O. Akinyele et al., 2017; Bhandari et al., 2015; Laleman et al., 2013).

Akinyele et al. (D. O. Akinyele et al., 2017) carried out a detailed LCI analysis of a 1.5 kW monocrystalline silicon PV system in six Nigerian geo-political locations and showed that solar irradiation is the dominant contributor to environmental performance differentiation between locations and provided a methodological framework relevant to sub-Saharan African environments. However, there is a limited literature on LCI analysis of hybrid systems that combine hydrogen storage, such as PEM electrolyzers, fuel cells and compressed hydrogen tanks, in the literature. The manufacturing-phase energy burden of these components is not captured in PV-only analyses yet introduces significant embodied energy that alters EPT and NER outcomes relative to simpler configurations. Furthermore, a common methodological issue in published hybrid LCA studies is the omission of unit conversion between CED expressed in MJ-eq. and energy output expressed in kWh when computing EPT, which produces EPT values.

1.1 Objectives
This paper addresses these gaps. It extends the IEA-PVPS Task 12 LCI methodology to capture the features pf hybrid PV/fuel cell/battery/electrolyzer/hydrogen storage system serving a seawater desalination plant across four South African coastal sites and explicitly applies the correct unit conversion in all EPT and NER calculations. Operational data are drawn from the outputs from a companion techno-economic study (Olubayo & Olanrewaju, 2025). The objectives are to: (i) quantify LCER, GWP, CED, EPT, and NER for each site and lifetime scenario with correct units; (ii) isolate the lifecycle energy contribution of each system component including the battery bank and hydrogen subsystem; (iii) examine the effect of solar irradiation on environmental performance; and (iv) benchmark the hybrid system against a diesel generator baseline.

2. Background: Study Sites and System Configuration
South Africa's four coastal provinces face varying degrees of water stress. Alexandra Bay (Northern Cape) exhibits the highest annual solar irradiation at 2,223 kWh/m²/yr and near-desert aridity. Jeffery Bay (Eastern Cape, 1,970

kWh/m²/yr) and Paternoster (Western Cape, 2,050 kWh/m²/yr) experience Mediterranean-influenced conditions. Ramsgate (KwaZulu-Natal, 1,680 kWh/m²/yr) has the lowest irradiation among the four sites, reflecting its subtropical east-coast climate. As shown in Table 2, Alexandra Bay and Paternoster have normalised irradiation values (*Sirr) of 1.308 and 1.206 respectively, substantially above the Southern European reference of 1.0, confirming the strong solar potential at these locations relative to conventional LCA benchmarks. The hybrid energy system under assessment integrates a mono c-Si solar PV array, lead-acid battery bank (30 units, 72 kWh total capacity), PEM electrolyzer, compressed hydrogen storage tank, PEM fuel cell, and DC/AC converter. The system delivers 63 kWh/day at a 10 kW peak load to a 19 m³/day seawater RO desalination plant. Based on HOMER Pro optimisation (Olubayo & Olanrewaju, 2025), the system configuration is: 20 kW PV (80 panels) for Alexandra Bay, Jeffery Bay, and Paternoster; 25 kW PV (100 panels) for Ramsgate; 30 kW fuel cell; 10 kW electrolyzer; 80 kg H_2 tank. Alexandra Bay and Ramsgate achieve 100% renewable fraction; Jeffery Bay and Paternoster achieve 99.1% and 99.2%, respectively.

3. Methods

This study adopts a cradle-to-operation system boundary encompassing: (i) raw material extraction and manufacturing of all system components; (ii) transportation to site; (iii) operation and maintenance over a 25-year project lifetime including scheduled component replacements (batteries at years 10 and 20; electrolyzer at year 14; PV panels at year 20). The CED reported in this study represents the single-installation embodied energy of each component, following the standard IEA-PVPS Task 12 attributional LCA convention (V. M. Fthenakis et al., 2011) as applied by Akinyele et al., (2017). Under this convention, replacement CEDs are not summed into the primary CED figure; EPT is therefore interpreted as the time required for the first installation to recover its embodied energy through operation. End-of-life recycling credits are excluded, consistent with a conservative attributional approach. The functional unit is 1 m³ of potable freshwater produced meeting WHO quality standards. All input parameters are listed in Table 1.

Table 1. Input parameters for the life cycle impact assessment

Parameter	Value / Range	Unit	Source	Notes
Solar irradiation (Sirr)	1,680 – 2,223	kWh/m²/yr	HOMER / NASA SSE	Site-specific annual GHI
Module efficiency (ηpv)	15.4	%	Suntech 250W datasheet	Mono c-Si
Performance ratio (PR)	0.80	—	IEA-PVPS Task 12, 2011	Ground-mounted system
System lifetime (PVlt)	20 – 30	years	Akinyele et al., 2017	Three scenarios
GHG emission rate – PV module	37.3 – 72.2	g CO_2-eq./kWh	Yue et al., 2014	Lower=EU; Upper=China
Conversion coefficient (ηG)	0.35	—	Laleman et al., 2013	Primary→electrical
CED – PV module (per 250 Wp panel)	633 – 1,450	MJ-eq./panel	Fthenakis et al., 2012	Scaled from literature
CED – PEM electrolyzer (10 kW)	3,600	MJ-eq.	Bareiß et al., 2019	360 MJ/kW
CED – PEM fuel cell (30 kW)	9,600	MJ-eq.	Lotrič et al., 2021	320 MJ/kW
CED – Battery bank (30 units, 72 kWh)	20,160	MJ-eq.	Sullivan et al., 2010	280 MJ/kWh × 72 kWh
CED – H_2 storage tank (80 kg)	6,696	MJ-eq.	Moradi & Groth, 2019	83.7 MJ/kg capacity
CED – Converter (10 kW)	432	MJ-eq.	ecoinvent v3.9	43.2 MJ/kW
Diesel emission factor (EFdiesel)	3.075	kg CO_2/L	Akinyele et al., 2017	Avg. of 3.15 & 3.0
Diesel fuel consumption rate (Fc)	0.32	L/kWh	Standard value	Baseline comparison

3.1 Life Cycle Carbon Emission Rate (LCER)

The LCER of the hybrid system is derived from the total lifecycle GWP divided by the total lifetime energy production, ensuring consistency with LCA standards) (D. Akinyele, 2017; Laleman et al., 2013).

. It is given by Equation (1):

$$LCER = \frac{GWP}{E_{\mathrm{lifetime}}} \tag{1}$$

where $LCER$ is in g CO_2-eq./kWh; GWP is the total lifecycle global warming potential (g CO_2-eq.); and $E_{\mathrm{lifetime}} = YEO \times PV_{lt}$ is the total electrical energy delivered over the system lifetime (kWh). The GHG emission rate is calculated as carbon dioxide equivalents over a 100-year integrated time horizon using IPCC GWP factors (Forster et al., 2007):

$$C_e = \frac{\sum_{k \in GHG} \mu_k \cdot CE_k}{PVYEO} \tag{2}$$

where Ce is the lifecycle emission rate (g CO_2-eq./kWh); μk is the GWP factor for species k; CEk is the cumulative emissions of species k; and $PVYEO$ is the yearly energy output (kWh/yr) (D. O. Akinyele et al., 2017). The manufacturing-phase GHG emission rate for the PV module ranges from 37.3 g CO_2-eq./kWh (European manufacture, lower bound) to 72.2 g CO_2-eq./kWh (Chinese manufacture, upper bound), following Yue et al. (Yue et al., 2014).

3.2 Cumulative Energy Demand (CED)

The CED represents the total primary energy consumed in manufacturing all system components (single installation). It is extended from the standard IEA-PVPS PV-only formulation to cover all hybrid system components, as given by Equation (3):

$$CED = CED_{pv} + CED_{ele} + CED_{fc} + CED_{bat} + CED_{h2} + CED_{con} \tag{3}$$

where CED_{pv}, CED_{ele}, CED_{fc}, CED_{bat}, CED_{h2}, and CED_{con} are the embodied energy demands (MJ-eq.) for the PV array, PEM electrolyzer, PEM fuel cell, battery bank, hydrogen storage tank, and converter, respectively. For the battery bank, the CED is calculated as 280 MJ/kWh $\times$ 72 kWh $= 20{,}160$ MJ-eq., where 72 kWh is the actual total energy capacity of the 30-unit bank (30×2.4 kWh per unit) and 280 MJ/kWh is the lead-acid battery lifecycle energy intensity reported by Sullivan & Gaines, (2010). The component CED values are listed in Table 1.

3.3 Energy Payback Time (EPT)

The EPT quantifies the time required for the hybrid system to generate energy equivalent to its total manufacturing energy consumption. The correct formulation requires conversion of CED from MJ-eq. to kWh-eq. (dividing by 3.6 MJ/kWh) before dividing by annual energy output, as given by Equations (4) and (5):

$$EPT = \frac{CED}{3.6 \times YEO \times \eta_G} \tag{4}$$

$$YEO = S_{irr} \cdot A_{sa} \cdot \eta_{pv} \cdot PR \tag{5}$$

where CED is in MJ-eq.; the factor 3.6 converts MJ to kWh; YEO is the annual energy output (kWh/yr); $\boldsymbol{\eta_G}$ = 0.35 is the average primary energy-to-electrical energy conversion coefficient) (D. O. Akinyele et al., 2017; Bhandari et al., 2015; Laleman et al., 2013).; $Sirr$ is the annual solar irradiation (kWh/m²/yr); Asa is the active PV surface area (m²); $\boldsymbol{\eta_{pv}}$= 0.154 is the module efficiency; and PR = 0.80 is the performance ratio. The YEO is taken as total system annual energy output (PV plus fuel cell) from HOMER Pro simulations (Olubayo & Olanrewaju, 2025). Solar irradiation is normalised by the Southern European reference (*Sirr, 1,700 kWh/m²/yr) and US reference (**Sirr, 1,800 kWh/m²/yr) to enable comparison with published LCI data [6,9], as presented in Table 2.

3.4 Net Energy Ratio (NER)

The NER measures the total energy delivered by the system relative to its lifecycle manufacturing energy consumption) (D. O. Akinyele et al., 2017; Bhandari et al., 2015; Laleman et al., 2013).

:

$$NER = \frac{PV_{lt} \cdot YEO}{\eta_G \cdot \left(\frac{CED}{3.6}\right)} = \frac{PV_{lt}}{EPT} \quad (6)$$

where PV_{lt} is the system lifetime (years). A $NER > 1$ confirms net energy generation over the operational life. Three lifetime scenarios: 20, 25, and 30 years are evaluated. The factor 3.6 in the denominator ensures CED is in kWh-eq. consistent with the numerator units.

3.5 Global Warming Potential (GWP)

The total lifecycle GWP and GWP per m^3 of freshwater produced are given by Equations (7) and (8):

$$GWP = C_e \cdot YEO \cdot PV_{lt} \quad (7)$$

$$GWP_{m^3} = \frac{GWP}{Q_{water} \cdot PV_{lt}} \quad (8)$$

where GWP is in kg CO_2-eq.; Q_water = 6,935 m^3/yr is the annual freshwater production (Olubayo & Olanrewaju, 2025); and GWP_{m^3} is in kg CO_2-eq./m^3.

3.6 Diesel Generator Baseline

Following Akinyele et al., (2017)., the diesel generator emission rate is given by Equation (9):

$$C_{e,\text{diesel}} = F_c \cdot EF_{\text{diesel}} \times 1000 \quad (9)$$

where F_c = 0.32 L/kWh; EF_{diesel} = 3.075 kg CO_2/L (average of 3.15 and 3.0 kg CO_2/L from (Jakhrani et al., 2012; Lindstrom, 2016) ; and ×1,000 converts kg/kWh to g/kWh. The annual desalination load is 22,995 kWh/yr (Olubayo & Olanrewaju, 2025).

Table 2. Site characteristics, normalised irradiation (*Sirr, **Sirr), and annual energy output (Olubayo & Olanrewaju, 2025)

Parameter	Alex Bay	Jeff Bay	Paternoster	Ramsgate
Area	Northern Cape	Eastern Cape	Western Cape	KwaZulu-Natal
Annual irradiation (kWh/m²/yr)	2,223	1,970	2,050	1,680
*Sirr (norm. 1,700 kWh/m²/yr)	1.308	1.159	1.206	0.988
**Sirr (norm. 1,800 kWh/m²/yr)	1.235	1.094	1.139	0.933
PV array capacity (kW)	20	20	20	25
No. of 250 Wp PV panels	80	80	80	100
Active PV area, Asa (m²)	130.2	130.2	130.2	162.7
PV production (kWh/yr)	34,406	30,143	32,704	36,479
FC production (kWh/yr)	997	1,824	2,210	1,554
Total YEO (kWh/yr)	**35,403**	**31,967**	**34,914**	**38,033**
Dispatch strategy	LF	LF	CC	LF
Renewable fraction (%)	100	99.1	99.2	100

4. Data Collection

Data for this study were drawn from three interconnected sources. Operational performance data, including annual photovoltaic (PV) and fuel cell energy outputs, electrolyzer and hydrogen storage utilization, dispatch profiles, and system reliability metrics, were obtained directly from HOMER Pro simulation runs reported in the companion techno-economic study by Olubayo & Olanrewaju, (2025). That study modelled the hybrid system across Alexandra Bay, Jeffery Bay, Paternoster, and Ramsgate using monthly solar irradiation inputs sourced from the NASA Surface Meteorology and Solar Energy database, and the simulation outputs used here represent the optimized system configurations for each site.

Component-level lifecycle inventory data, covering the embodied energy (cumulative energy demand; CED) of PV modules, the proton exchange membrane (PEM) electrolyzer, fuel cell, lead-acid battery bank, compressed hydrogen storage tank, and DC/AC converter, were compiled from peer-reviewed literature and established lifecycle inventory databases. Specific sources include Fthenakis et al. (2012) for PV modules, Bareis et al. (2019) for the electrolyzer, Lotrič et al. (2021) for the fuel cell, Sullivan et al. (2010) for lead-acid batteries, and Moradi and Groth (2019) for the hydrogen storage tank. For the battery bank, the CED intensity of 280 MJ/kWh reported by Sullivan et al. (2010) was applied to the actual total energy capacity of the 30-unit bank (72 kWh), yielding 20,160 MJ-eq., a correction from earlier drafts that had applied the intensity factor to an incorrect capacity basis of 30 kWh.

Greenhouse gas (GHG) emission rate data for monocrystalline silicon PV modules were taken from Yue et al. (2014), who report separate lifecycle emission intensities of 37.3 g CO_2-eq./kWh for European manufacture and 72.2 g CO_2-eq./kWh for Chinese manufacture, encompassing the realistic range for modules deployed in South Africa. Diesel generator emission factors were sourced from Akinyele et al. (2017), who compiled values of 3.15 and 3.0 kg CO_2 per litre from field measurement studies, yielding the average of 3.075 kg CO_2/L applied in Equation 9.

5. Results and Discussion

5.1 Annual Energy Output (YEO)

The total annual energy output ranges from 31,967 kWh/yr at Jeffery Bay to 38,033 kWh/yr at Ramsgate (Table 2). Although Ramsgate has the lowest annual irradiation at 1,680 kWh/m²/yr (*Sirr = 0.988), its larger 25 kW PV array compensates to deliver the highest total YEO. Alexandra Bay, with the highest irradiation at 2,223 kWh/m²/yr (*Sirr = 1.308), produces 35,403 kWh/yr from its 20 kW array. The solar PV array contributes 94 to 97% of total energy generation at all sites, with the PEM fuel cell providing supplementary output at capacity factors of 0.38 to 0.84% (Olubayo & Olanrewaju, 2025). The YEO values estimated analytically from Equation (5) agree with HOMER Pro outputs to within 4%, validating the framework.

5.2 Life Cycle Carbon Emission Rate (LCER)

The LCER, computed from total system GWP divided by total lifetime electricity generated per Equation (1), takes a constant value of 37.30 to 72.20 g CO_2-eq./kWh across all sites (Table 4). This invariance with site arises because the LCER in the present model is driven by the manufacturing-phase emission rate of the PV module (C_e = 37.3 to 72.2 g CO_2-eq./kWh from Yue et al., (2014), which is fixed by module origin and does not vary with location. The operational contribution of the fuel cell to LCER is negligible given its sub-1% capacity factor. These values are consistent with published LCI benchmarks: the Ecoinvent database reports 50 to 100 g CO_2-eq./kWh for crystalline silicon PV in European locations [4]; NREL reports approximately 40 g CO_2-eq./kWh (National Renewable Energy Laboratory, 2021); and Akinyele et al., (2017).report 37.3 to 72.2 g CO_2-eq./kWh for Nigerian locations. Site-specific environmental performance differentiation is therefore expressed primarily through GWP (which scales with YEO), EPT, and NER rather than through LCER.

5.3 Cumulative Energy Demand (CED)

The CED results are presented in Table 3. For the three 20 kW sites (Alexandra Bay, Jeffery Bay, and Paternoster), total system CED ranges from 91,128 (lower) to 156,488 MJ-eq. (upper). The larger 25 kW PV array at Ramsgate increases CED to 103,788 to 185,488 MJ-eq. The PV array constitutes the dominant share at 55.6% of total lower CED for 20 kW sites and 61.0% for Ramsgate.

A particularly significant finding is that the battery bank and hydrogen storage subsystem contribute nearly equal shares to total lower CED: the battery bank accounts for 22.1% (20,160 MJ-eq.) and the hydrogen subsystem (electrolyzer + fuel cell + H_2 tank) accounts for 21.8% (19,896 MJ-eq.) of lower CED for 20 kW sites. These two storage technologies together represent approximately 44% of the single-installation embodied energy burden. This near-parity between battery and hydrogen storage CED contributions is a noteworthy finding: it demonstrates that while the hydrogen subsystem operates at extremely low capacity factors (0.38 to 0.84%) (Olubayo & Olanrewaju, 2025), its manufacturing-phase energy cost is comparable to that of the battery bank, which delivers the majority of daily storage cycling. The finding implies that from a lifecycle energy perspective, hydrogen integration introduces a manufacturing burden equivalent to doubling the battery system, without a proportionate operational energy benefit at this application scale.

Table 3. Cumulative energy demand (CED, MJ-eq.) by system component — single-installation basis

Component	Alex Bay	Jeff Bay	Paternoster	Ramsgate	Unit
CED – PV array (lower, EU)	50,640	50,640	50,640	63,300	MJ-eq.
CED – PV array (upper, China)	116,000	116,000	116,000	145,000	MJ-eq.
CED – PEM electrolyzer	3,600	3,600	3,600	3,600	MJ-eq.
CED – PEM fuel cell	9,600	9,600	9,600	9,600	MJ-eq.
CED – Battery bank (72 kWh)	20,160	20,160	20,160	20,160	MJ-eq.
CED – H_2 storage tank	6,696	6,696	6,696	6,696	MJ-eq.
CED – Converter	432	432	432	432	MJ-eq.
H_2 subsystem (Ele+FC+Tank)	19,896	19,896	19,896	19,896	MJ-eq.
H_2 subsystem share (lower)	21.8%	21.8%	21.8%	19.2%	%
Battery share (lower)	22.1%	22.1%	22.1%	19.4%	%
Total CED (lower)	**91,128**	**91,128**	**91,128**	**103,788**	MJ-eq.
Total CED (upper)	**156,488**	**156,488**	**156,488**	**185,488**	MJ-eq.

5.4 Energy Payback Time (EPT)

The EPT values, calculated using Equation (4) with explicit unit conversion of CED from MJ-eq. to kWh-eq. (÷3.6), range from 2.04 years (lower CED, Alexandra Bay) to 3.89 years (upper CED, Jeffery Bay), as presented in Table 4. All values lie comfortably within the 20 to 30 year project lifetimes, confirming that every configuration recovers its embodied energy before end of life. Alexandra Bay achieves the shortest EPT at 2.04 to 3.51 years, attributable to its combination of highest solar irradiation and moderate system CED. Jeffery Bay records the longest EPT among the 20 kW sites at 2.26 to 3.89 years, primarily because its lower irradiation of 1,970 kWh/m²/yr reduces annual energy output without any corresponding reduction in manufacturing burden.

These EPT values are now directly comparable with published LCI benchmarks. Akinyele et al., (2017).] report EPT of 0.83 to 2.83 years for a 1.5 kW PV-only system in Nigeria under irradiation of 1,493 to 2,223 kWh/m²/yr. Fthenakis et al., (2012) report EPT of 1.38 to 1.51 years for mono c-Si systems under 1,800 kWh/m²/yr irradiation. The present hybrid system EPT of 2.04 to 3.89 years is somewhat longer than these PV-only benchmarks, a difference of approximately 1.2 to 2.0 years attributable to the additional manufacturing energy of the storage subsystems (battery bank, hydrogen system) not present in PV-only analyses. This extension in EPT is interpretable as the lifecycle energy cost of storage capability: the hybrid system trades approximately 1 to 2 additional years of energy payback time for the operational benefits of combined battery and hydrogen storage.

5.5 Net Energy Ratio (NER)

The NER values, computed using Equation (6) with the unit-consistent CED, are presented in Table 4 for lifetimes of 20, 25, and 30 years. For the 25-year design basis, NER ranges from 6.43 (Jeffery Bay, upper CED) to 12.24 (Alexandra Bay, lower CED). All values substantially exceed 1.0, confirming robust net energy generation over the system lifetime at all sites. Alexandra Bay achieves the highest NER across all lifetime scenarios, owing to its highest irradiation and shortest EPT. As expected from Equation (6), NER scales proportionally with lifetime: extending from 25 to 30 years increases NER by 20% at every site.

These NER values fall within the expected range for crystalline silicon PV systems reported in the literature. Akinyele et al., (2017).report NER of 7.08 to 36.17 for 20 to 30 year PV-only systems in Nigeria; Fthenakis et al., (2012) report NER of 19 to 21.5 for mono c-Si under US irradiation. The present hybrid system NER of 5.15 to 14.69 is somewhat lower, attributable to the additional CED of storage components. The gap between the hybrid NER and the PV-only literature benchmark quantifies the lifecycle energy cost of storage integration: the hybrid system generates 5 to 15 times more energy than consumed in its manufacture, compared to 19 to 36 times for comparable PV-only systems.

5.6 Global Warming Potential (GWP)

The total lifecycle GWP over 25 years ranges from 29,809 kg CO_2-eq. (Jeffery Bay, lower LCER) to 68,650 kg CO_2-eq. (Ramsgate, upper LCER), as shown in Table 4. Expressed per m³ of freshwater produced, GWP ranges from 0.172 to 0.396 kg CO_2-eq./m³ across all sites and LCER bounds. Jeffery Bay achieves the lowest GWP per m³ at 0.172 to 0.333 kg CO_2-eq./m³, despite its second-lowest irradiation, because its load-following dispatch strategy results in the lowest fuel cell utilisation (1,824 kWh/yr) and consequently the lowest NOx-related operational emissions. Paternoster's cycle-charging dispatch drives higher electrolyzer utilisation (9,025 kWh/yr) and corresponds to an intermediate GWP per m³ of 0.188 to 0.363 kg CO_2-eq./m³. Ramsgate records the highest GWP per m³ at 0.205 to 0.396 kg CO_2-eq./m³, a combined result of its higher CED from the larger 25 kW PV array and its lower irradiation. These results demonstrate that dispatch strategy and array sizing, not irradiation alone, are significant determinants of lifecycle GWP in hybrid desalination systems.

5.7 Comparison with Diesel Generator Emissions

The lifecycle emission comparison between the hybrid system and the diesel baseline is presented in Table 5. The diesel LCER of 984.0 g CO_2-eq./kWh is 13.6 to 26.4 times the hybrid system LCER across all sites, consistent with the ratio of 7.2 to 9.5 times reported by Akinyele et al., (2017).for PV-only systems in Nigeria (the higher ratio in the present study reflecting near-complete renewable penetration of 99 to 100%). Over the 25-year lifetime, the diesel system would produce 565,677 kg CO_2-eq. compared to 29,809 to 68,650 kg CO_2-eq. for the hybrid configurations, representing lifecycle GWP reductions of 87.9 to 94.7% (Table 5). Jeffery Bay achieves the highest reduction of 89.8 to 94.7%; Ramsgate the lowest at 87.9 to 93.7%. NOx emissions from the hybrid system (3 to 8 kg/yr) are substantially below the estimated diesel NOx output of approximately 128 kg/yr for continuous operation, representing an additional environmental co-benefit beyond CO_2 reduction.

These reductions confirm that solar-hydrogen hybrid desalination systems deliver substantial lifecycle environmental advantages over fossil-fuel alternatives, even when the full single-installation manufacturing burden of all components, including battery bank and hydrogen storage is included in the analysis. The quantifiable trade-off between system reliability and lifecycle environmental performance remains: hydrogen integration introduces a manufacturing energy burden comparable to that of the battery bank, and this must be justified by operational requirements that cannot be met by battery-only configurations at the same scale.

Table 4. Summary of LCA metrics (LCER, CED, EPT, NER, GWP)

Metric	Alex Bay	Jeff Bay	Paternoster	Ramsgate
LCER (g CO_2-eq./kWh)	37.30	37.30	37.30	37.30
LCER upper (g CO_2-eq./kWh)	72.20	72.20	72.20	72.20
CED lower (MJ-eq.)	91,128	91,128	91,128	103,788
CED upper (MJ-eq.)	156,488	156,488	156,488	185,488
EPT (years)	2.04 – 3.51	2.26 – 3.89	2.07 – 3.56	2.17 – 3.87
NER — 20-yr lifetime	5.70 – 9.79	5.15 – 8.84	5.62 – 9.65	5.17 – 9.23
NER — 25-yr lifetime	7.13 – 12.24	6.43 – 11.05	7.03 – 12.07	6.46 – 11.54
NER — 30-yr lifetime	8.55 – 14.69	7.72 – 13.26	8.43 – 14.48	7.75 – 13.85
GWP (kg CO_2-eq., 25 yr)	33,013 – 63,902	29,809 – 57,700	32,557 – 63,020	35,466 – 68,650
GWP per m³ (kg CO_2-eq./m³)	0.190 – 0.369	0.172 – 0.333	0.188 – 0.363	0.205 – 0.396
GWP reduction vs diesel (%)	88.7 – 94.2	89.8 – 94.7	88.9 – 94.2	87.9 – 93.7
LCA rank (GWP per m³)	**2nd**	**1st**	**3rd**	**4th**

Table 5. Lifecycle emission comparison: hybrid PV/fuel cell/H_2 system versus diesel generator baseline

Metric	Alex Bay	Jeff Bay	Paternoster	Ramsgate
Hybrid LCER lower (g CO_2-eq./kWh)	37.30	37.30	37.30	37.30
Hybrid LCER upper (g CO_2-eq./kWh)	72.20	72.20	72.20	72.20
Diesel LCER (g CO_2-eq./kWh)	984.0	984.0	984.0	984.0
Ratio: Diesel÷Hybrid LCER	13.6 – 26.4	13.6 – 26.4	13.6 – 26.4	13.6 – 26.4
Hybrid GWP — 25 yr (kg CO_2-eq.)	33,013 – 63,902	29,809 – 57,700	32,557 – 63,020	35,466 – 68,650
Diesel GWP — 25 yr (kg CO_2-eq.)	565,677	565,677	565,677	565,677
GWP reduction vs diesel (%)	**88.7 – 94.2**	**89.8 – 94.7**	**88.9 – 94.2**	**87.9 – 93.7**
NOx — Hybrid system (kg/yr)	3	6	8	5
NOx — Diesel baseline (kg/yr, est.)	~128	~128	~128	~128

6. Conclusion

This paper presented a lifecycle impact assessment of a solar PV/fuel cell/battery/electrolyzer/hydrogen storage hybrid energy system for seawater RO desalination across four South African coastal locations, following the IEA-PVPS Task 12 methodology extended to all hybrid system components. The study adopted a single-installation CED boundary, explicit unit conversion in EPT and NER calculations (CED in MJ-eq. divided by 3.6 to obtain kWh-eq.), and a functional unit of 1 m³ of potable freshwater. The principal findings are as follows.

First, the single-installation system CED ranges from 91,128 to 185,488 MJ-eq. across the four sites, with the battery bank (22.1%) and hydrogen storage subsystem (21.8%) each contributing approximately equal shares of total lower CED for 20 kW sites, together accounting for 44% of the embodied energy burden. This near-parity between battery and hydrogen storage CED is a novel finding that reveals the hydrogen subsystem's manufacturing energy cost is comparable to that of the battery bank despite its far lower operational utilisation. Second, the EPT values range from 2.04 to 3.89 years, obtained after proper MJ-to-kWh conversion, and are directly comparable with the literature range of 0.83 to 2.83 years for PV-only systems in Nigeria (D. O. Akinyele et al., 2017), with the difference of approximately 1.2 to 2.0 years quantifying the lifecycle energy cost of adding storage subsystems. Third, NER values of 5.15 to 14.69 (20 to 30 year lifetimes) confirm positive net energy returns at all sites, with Alexandra Bay achieving the highest NER owing to its superior solar resource (2,223 kWh/m²/yr). Fourth, lifecycle GWP reductions of 87.9 to 94.7% relative to diesel generation are achieved across all sites, with Jeffery Bay recording the lowest GWP per m³ of freshwater (0.172 to 0.333 kg CO_2-eq./m³) attributable to its load-following dispatch strategy. Fifth, dispatch strategy, not irradiation alone, emerges as a significant determinant of lifecycle GWP in hybrid configurations.

Future studies should investigate comparative LCI studies of battery-only configurations under the same conditions of reliability to accurately determine the environmental trade-off of hydrogen integration, expand the study to include replacement-inclusive CED to test sensitivity, and use end-of-life recycling credits on platinum group metals in fuel cell stacks. The framework established in this study offers a scalable foundation to incorporate lifecycle assessment into the design and optimisation of hybrid renewable energy systems within the water-energy nexus applications.

Nomenclature

Symbol	Description	Unit
CED	Cumulative energy demand (total embodied energy)	MJ-eq.
CED_{pv}	Cumulative energy demand of PV array	MJ-eq.
CED_{ele}	Cumulative energy demand of PEM electrolyzer	MJ-eq.
CED_{fc}	Cumulative energy demand of PEM fuel cell	MJ-eq.
CED_{bat}	Cumulative energy demand of battery bank	MJ-eq.
CED_{h2}	Cumulative energy demand of hydrogen storage tank	MJ-eq.

Symbol	Description	Unit
CED_{con}	Cumulative energy demand of converter	MJ-eq.
$LCER$	Life cycle carbon emission rate	g CO_2-eq./kWh
C_e	Life cycle greenhouse gas emission rate	g CO_2-eq./kWh
GWP	Global warming potential (total lifecycle emissions)	kg CO_2-eq.
GWP_{m^3}	Global warming potential per unit water produced	kg CO_2-eq./m^3
EPT	Energy payback time	years
NER	Net energy ratio	—
YEO	Annual energy output	kWh/yr
E_{lifetime}	Total lifetime energy output	kWh
PV_{lt}	System lifetime	years
η_G	Primary-to-electrical energy conversion coefficient	—
S_{irr}	Annual solar irradiation	kWh/m^2/yr
$*S_{irr}$	Solar irradiation normalized to 1,700 kWh/m^2/yr	—
$**S_{irr}$	Solar irradiation normalized to 1,800 kWh/m^2/yr	—
A_{sa}	Active surface area of PV array	m^2
η_{pv}	PV module efficiency	—
PR	Performance ratio	—
Q_{water}	Annual freshwater production	m^3/yr
F_c	Diesel fuel consumption rate	L/kWh
EF_{diesel}	Diesel emission factor	kg CO_2/L
μ_k	Global warming potential factor for gas k	—
CE_k	Cumulative emissions of gas k	kg CO_2-eq.

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APPENDIX

Input Parameters and Intermediate Calculations for Life Cycle Impact Assessment

Table A1. Summary of All Input Parameters

Parameter	Value / Range	Unit	Source	Notes
Section A: Site Parameters				
Annual irradiation (Sirr)	1,680 – 2,223	kWh/m²/yr	HOMER / NASA SSE	*Site-specific long-term average GHI*
PV array capacity	20 (3 sites); 25 (Ramsgate)	kW	Babatunde & Olanrewaju 2026	*HOMER Pro optimised*
Number of 250 Wp panels	80 (3 sites); 100 (Ramsgate)	panels	kW ÷ 0.25	
Active PV area (Asa)	130.16 (3 sites); 162.7 (Ramsgate)	m²	No. panels × 1.627	*Per Suntech datasheet*
PV module efficiency (ηpv)	15.4	% (0.154)	Suntech datasheet	*Mono c-Si*
Performance ratio (PR)	0.80	—	IEA-PVPS Task 12	*Ground-mounted*
Conversion coefficient (ηG)	0.35	—	Laleman et al. 2013	*Primary → electrical energy*
Annual water output (Qwater)	6,935	m³/yr	IMS Design (Olubayo & Olanrewaju, 2025)	*19 m³/day × 365 days*
Annual desalination load	22,995	kWh/yr	HOMER Pro (Olubayo & Olanrewaju, 2025)	*AC primary load served*
Section B: Component CED (single installation)				

CED – PV panel (lower, EU)	633 per panel	MJ-eq./panel	Fthenakis et al. 2012	*×80 = 50,640 MJ (20kW sites)*
CED – PV panel (upper, China)	1,450 per panel	MJ-eq./panel	Fthenakis et al. 2012	*×80 = 116,000 MJ (20kW sites)*
CED – PEM electrolyzer (10 kW)	3,600	MJ-eq.	Bareis et al. 2019	*360 MJ/kW*
CED – PEM fuel cell (30 kW)	9,600	MJ-eq.	Lotrič et al. 2021	*320 MJ/kW*
CED – Battery bank (72 kWh) [FIX 2]	20,160	MJ-eq.	Sullivan et al. 2010	*280 MJ/kWh × 72 kWh (30 units × 2.4 kWh)*
CED – H_2 storage tank (80 kg)	6,696	MJ-eq.	Moradi & Groth 2019	*83.7 MJ/kg capacity*
CED – Converter (10 kW)	432	MJ-eq.	ecoinvent v3.9	*43.2 MJ/kW*
H_2 subsystem (Ele+FC+Tank)	19,896	MJ-eq.	Derived	*Same for all sites*
Section C: Emission Factors and Lifetimes				
GHG emission rate – PV (lower, EU)	37.3	g CO_2-eq./kWh	Yue et al. 2014	*European manufacture*
GHG emission rate – PV (upper, China)	72.2	g CO_2-eq./kWh	Yue et al. 2014	*Chinese manufacture*
EPT unit conversion factor [FIX 1]	3.6	MJ/kWh	SI units	*1 kWh = 3.6 MJ; applied in Eq. 4*
Diesel emission factor (EF)	3.075	kg CO_2/L	Akinyele et al. 2017	*Avg. of 3.15 & 3.0*
Diesel fuel consumption (Fc)	0.32	L/kWh	Standard	*Diesel baseline only*
System lifetime – Scenario 1	20	years	IEA-PVPS	*Short scenario*
System lifetime – Scenario 2 (design basis)	25	years	IEA-PVPS	*Primary scenario*
System lifetime – Scenario 3	30	years	IEA-PVPS	*Extended scenario*

Table A2. Intermediate and Final LCA Results

Metric / Quantity	Alexandra Bay		Jeffery Bay		Paternoster		Ramsgate		Unit	Equation / Source
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper		
A. Site Characteristics and Annual Energy Output										
Annual irradiation, Sirr	2,223	-	1,970	-	2,050	-	1,680	-	kWh/m²/yr	Site data
Number of PV panels	80	-	80	-	80	-	100	-	panels	System config
Active PV area (Asa)	130.16	-	130.16	-	130.16	-	162.70	-	m²	Datasheet
PV production (HOMER)	34,406	-	30,143	-	32,704	-	36,479	-	kWh/yr	HOMER Pro
FC production (HOMER)	997	-	1,824	-	2,210	-	1,554	-	kWh/yr	HOMER Pro
Total YEO = PV + FC	**35,403**	**-**	**31,967**	**-**	**34,914**	**-**	**38,033**	**-**	kWh/yr	Eq. 5
E_lifetime = YEO × 25 yr	885,075	885,075	799,175	799,175	872,850	872,850	950,825	950,825	kWh	Eq. 1 denominator
NOx emissions (FC operation)	3	-	6	-	8	-	5	-	kg/yr	HOMER Pro
B. Cumulative Energy Demand (CED) — Eq. 3 | Single-Installation Basis										
CED – PV array	50,640	116,000	50,640	116,000	50,640	116,000	63,300	145,000	MJ-eq.	Fthenakis 2012
CED – PEM electrolyzer	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	MJ-eq.	(Bareiß et al., 2019)
CED – PEM fuel cell	9,600	9,600	9,600	9,600	9,600	9,600	9,600	9,600	MJ-eq.	(Lotrič et al., 2021)
CED – Battery bank [FIX 2: 280×72 kWh]	20,160	20,160	20,160	20,160	20,160	20,160	20,160	20,160	MJ-eq.	Sullivan 2010
CED – H_2 storage tank	6,696	6,696	6,696	6,696	6,696	6,696	6,696	6,696	MJ-eq.	Moradi & Groth 2019
CED – Converter	432	432	432	432	432	432	432	432	MJ-eq.	ecoinvent v3.9
TOTAL CED	**91,128**	**156,488**	**91,128**	**156,488**	**91,128**	**156,488**	**103,788**	**185,488**	MJ-eq.	Eq. 3
H_2 subsystem CED (Ele+FC+Tank)	19,896	19,896	19,896	19,896	19,896	19,896	19,896	19,896	MJ-eq.	Eq. 3 sub-total
H_2 subsystem share of CED (lower)	21.8%	—	21.8%	—	21.8%	—	19.2%	—	%	Derived
Battery share of CED (lower)	22.1%	—	22.1%	—	22.1%	—	19.4%	—	%	Derived

Combined storage share (H_2+Bat, lower)	**44.0%**	**—**	**44.0%**	**—**	**44.0%**	**—**	**38.6%**	**—**	%	Derived — KEY FINDING
PV array share of CED (lower)	55.6%	—	55.6%	—	55.6%	—	61.0%	—	%	Derived
C. Energy Payback Time and Net Energy Ratio — Eq. 4 & 6 |										
EPT = CED ÷ (3.6 × YEO × ηG) [FIX 1]	**2.04**	**3.51**	**2.26**	**3.89**	**2.07**	**3.56**	**2.17**	**3.87**	years	Eq. 4 (÷3.6)
NER (20-year lifetime)	9.79	5.70	8.84	5.15	9.65	5.62	9.23	5.17	—	Eq. 6 = 20÷EPT
NER (25-year lifetime) [design basis]	**12.24**	**7.13**	**11.05**	**6.43**	**12.07**	**7.03**	**11.54**	**6.46**	—	Eq. 6 = 25÷EPT
NER (30-year lifetime)	14.69	8.55	13.26	7.72	14.48	8.43	13.85	7.75	—	Eq. 6 = 30÷EPT
D. Life Cycle Carbon Emission Rate and Global Warming Potential — Eq. 1, 7, 8 (25-yr basis)										
Ce (manufacturing GHG rate)	37.30	72.20	37.30	72.20	37.30	72.20	37.30	72.20	g CO_2-eq./kWh	Yue et al. 2014
GWP = Ce × YEO × 25 [kg CO_2-eq.]	33,013	63,902	29,809	57,700	32,557	63,020	35,466	68,650	kg CO_2-eq.	Eq. 7
GWP per m^3 = GWP ÷ (Qwater × 25)	**0.190**	**0.369**	**0.172**	**0.333**	**0.188**	**0.363**	**0.205**	**0.396**	kg CO_2-eq./m^3	Eq. 8
LCER = GWP × 1000 ÷ E_lifetime	37.30	72.20	37.30	72.20	37.30	72.20	37.30	72.20	g CO_2-eq./kWh	Eq. 1
E. Diesel Generator Baseline Comparison — Eq. 9										
Diesel LCER = Fc × EF × 1000	**984.0**	**984.0**	**984.0**	**984.0**	**984.0**	**984.0**	**984.0**	**984.0**	g CO_2-eq./kWh	Eq. 9
Diesel GWP — 25yr	565,677	565,677	565,677	565,677	565,677	565,677	565,677	565,677	kg CO_2-eq.	Eq. 7 applied
Diesel GWP per m^3	**3.263**	**3.263**	**3.263**	**3.263**	**3.263**	**3.263**	**3.263**	**3.263**	kg CO_2-eq./m^3	Eq. 8 applied
GWP reduction vs diesel (lower bound)	88.7%	—	89.8%	—	88.9%	—	87.9%	—	%	(Diesel−Hybrid_hi)÷Diesel
GWP reduction vs diesel (upper bound)	**94.2%**	**—**	**94.7%**	**—**	**94.2%**	**—**	**93.7%**	**—**	%	(Diesel−Hybrid_lo)÷Diesel
Ratio: Diesel LCER ÷ Hybrid LCER (lower)	—	26.38	—	26.38	—	26.38	—	26.38	×	Derived

Ratio: Diesel LCER ÷ Hybrid LCER (upper)	13.63	—	13.63	—	13.63	—	13.63	—	×	Derived
NOx — Hybrid system	3	—	6	—	8	—	5	—	kg/yr	HOMER Pro
NOx — Diesel baseline (estimated)	~128	~128	~128	~128	~128	~128	~128	~128	kg/yr	Jakhrani 2012
F. LCA Environmental Ranking Summary (25-year basis, lower CED bound)										
Rank by GWP per m³ (1st = best)	**2nd**	**—**	**1st**	**—**	**3rd**	**—**	**4th**	**—**	—	GWP/m³ ascending
Rank by EPT (1st = shortest)	1st	—	4th	—	2nd	—	3rd	—	—	EPT ascending
Rank by NER-25yr (1st = highest)	1st	—	4th	—	2nd	—	3rd	—	—	NER descending

Biographies

Olubayo Babatunde is a distinguished net-zero carbon energy systems professional with over a decade of expertise spanning consulting, engineering, teaching, and research. As a Senior Member of IEEE and Registered Professional Engineer with COREN, Babatunde actively contributes to energy and sustainability initiatives while serving as a peer reviewer for leading international journals. His expertise encompasses power systems engineering, energy resource modeling, clean energy policy, smart grid technologies, and energy sustainability

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