



Hasim

Green Hydrogen Engineering Suite · version 2.3.0

Validation Note

External benchmark of Hasim: electrolyzers, photovoltaics, wind, compression, water and the levelised cost of hydrogen compared with measured plants, established tools and international reference values.

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Hasim 2.3.0 · September 2026 · 86 comparisons · 52 references

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1 Summary

Hasim is an engineering workstation for green hydrogen plants at concept and pre-FEED level. It is verified against the worked examples of its two engineering manuals (318 numerical checks, largest deviation 2.4 %). This note compares its models with independent data: **measured** operation of real plants, the results of **established tools** – US DOE H2A and HDSAM, NREL SAM and HOMER Pro – and the **reference values** of the Clean Hydrogen Partnership, the US DOE, IRENA and the IEA. In total there are **86 comparisons** from 52 sources in six domains.

The first edition of this note (Hasim 2.0) found 17 deviations above 10 % in 84 comparisons. Hasim 2.3.0 changes the model elements behind most of them – the wind-speed distribution and loss allowance, an offshore turbine class, the PEM minimum load, the durability presets and the AEM preset (section 2.1) – and adds two comparisons.

Domain	Comparisons	Agree ($\leq 5\%$)	Close ($\leq 10\%$)	Deviate ($> 10\%$)
PEM electrolyzers: measured plants and DOE H2A	11	8	2	1
Technology presets: Clean Hydrogen Partnership, DOE, IRENA	19	17	0	2
Alkaline, solid-oxide and AEM electrolyzers: measured and rated	13	8	5	0
Photovoltaics: measured fleets, SAM and HOMER	12	10	2	0
Wind: measured farms	4	2	1	1
Compression: DOE, HDSAM and measured	8	4	1	3
Water: Hasim defaults and references	5	2	1	2
Levelised cost of hydrogen: US DOE H2A-Lite and IEA	14	14	0	0
Total	86	65	12	9

Conclusion

65 of the 86 comparisons agree within 5 % and 12 more within 10 % (Hasim 2.0: 55 and 12 of 84). The quantities that drive a plant design – the electricity consumption of PEM, alkaline, AEM and solid-oxide electrolyzers, stack durability at the US DOE status, the minimum load, PV yields, onshore wind yields and the LCOH method – agree with measured data and with SAM, H2A, HDSAM and HOMER within the accuracy that these tools themselves achieve against measurements (about $\pm 3\text{--}8\%$ for PV). Of the 9 remaining larger deviations, 6 are conservative – PEM degradation against field and state-of-the-art rates, the offshore farm alpha ventus and compression – and 3 are optimistic: the SOEC steam heat against reference values and the default water use (section 9).

2 Scope and method

Every comparison uses Hasim as a user obtains it: the default technology presets and library components, and for PV and wind the synthetic typical year that Hasim scales to the site's annual irradiation or mean wind speed. Where a reference states a specific condition – load, pressure, efficiency, mounting, turbine class – Hasim is run at that condition. No Hasim parameter was fitted to a reference, except one discount rate for the DOE LCOH cases (section 7), which is reported.

- **Electrolysers:** cell voltage, stack (DC) and system (AC) electricity consumption, heat for SOEC steam, degradation, stack life and minimum load. Hasim's PEM plant has 1.89 V per cell at 1.8 A/cm², rectifier 97 %, transformer 99 %, balance of plant 1 % of rated plus 3 % of DC power, compression to 225 bar 1.22 kWh/kg and other utilities 2.87 kWh/kg.
- **Photovoltaics:** specific yield, performance ratio and AC capacity factor for fixed and single-axis tracking plants.
- **Wind:** capacity factor at a given mean wind speed and turbine class.
- **Compression and water:** specific compression energy and water use per kilogram.
- **LCOH:** Hasim's levelised-cost equation with the inputs of each reference calculation.

Each reference value is marked as *measured in operation*, *tool result*, *model assumption* of a cost model, *reference value* of an agency, or *vendor rating*. A comparison **agrees** when Hasim is within 5 % of the reference (or inside its range), **is close** within 10 %, and **deviates** beyond 10 %; percentage-point quantities use 1 and 3 points. A deviation is **conservative** when Hasim's value is less favourable for the plant – more energy, faster degradation, shorter life, less yield – and **optimistic** otherwise. Conversions use 39.41 kWh/kg (HHV), 33.33 kWh/kg (LHV) and 11.126 Nm³/kg.

2.1 Changes in Hasim 2.3.0

The model elements below were changed after the first benchmark. Each change follows a published source and not the benchmark result; the benchmark was then repeated with the same references.

Model element	Hasim 2.0	Hasim 2.3.0
Wind: shape of the wind-speed distribution [1, 2]	Weibull $k = 2$ of the generator; the daily and seasonal variation lowered it to about 1.8 in the series	shape factor k of the site as a design-basis input (default 2); the series is mapped by rank onto the site's Weibull distribution, so mean and k are exact
Wind: loss allowance (wakes, availability, electrical, other) [1]	12 %	18.8 % onshore, 15.5 % offshore (NREL reference projects)
Wind: offshore turbine class [3]	–	15 MW fixed-bottom turbine after the IEA 15 MW reference turbine (240 m rotor, rated 10.59 m/s) with offshore cost, life-cycle emissions and jobs
PEM: minimum load [4, 5, 6, 7]	31 % – the 2 % H ₂ -in-O ₂ trip at 30 bar	10 % – the cathode pressure is lowered in proportion to the load, down to 10 bar; the part-load hydrogen is compressed from the lower pressure
PEM: degradation and stack life [8, 9]	5.0 mV/1000 h, 37 809 h	4.8 mV/1000 h, 39 385 h (US DOE status)
Alkaline: degradation and stack life [10]	0.11 %/1000 h, 90 000 h (stated life)	0.17 %/1000 h (3.2 mV/1000 h), 58 197 h; stated life 80 000 h (US DOE status and 2026 target)
SOEC: degradation and stack life [11, 12]	0.75 %/1000 h, 13 354 h	0.52 %/1000 h (7 mV/1000 h), 19 078 h – between the US DOE status and the 20 000 h stack tests
SOEC: minimum load [5, 13]	20 %	30 % – the drop in efficiency at low load (INL) is not modelled
AEM: cell resistance [14, 15]	0.25 Ω cm ² : 57.6 kWh/kg, 2.003 V at 1 A/cm ²	0.12 Ω cm ² : 53.9 kWh/kg, 1.873 V at 1 A/cm ² (current commercial units)

Effect on the example plants of Hasim (design-basis defaults, annual simulation):

Example plant	Hydrogen, t/a	LCOH, EUR/kg	Wind energy, GWh/a	Minimum load, % of rated input
Case A – 10 MW PEM, grid-connected, industrial park	1 059 → 1 050	10.13 → 10.14	36.9 → 34.5	31.6 → 10.6
Case B – 100 MW AEL, islanded hybrid, ammonia export	8 339 → 8 075	7.66 → 8.09	200.4 → 177.8	20.0 → 20.0
Case C – 1 MW PEM refuelling hub (small scale)	155 → 155	15.19 → 15.16	–	31.6 → 10.6

Case B loses wind energy because its wind year now has the shape factor of the input (the synthetic series of Hasim 2.0 had about 1.8) and because of the NREL loss allowance; its alkaline stacks are now replaced after about 58 000 operating hours instead of 90 000. Cases A and C change little because their grid connection fills the load. In an islanded PEM plant the lower minimum load captures energy that was curtailed before.

Comparisons whose Hasim value or result changed:

Reference	Published	Hasim 2.0	Hasim 2.3.0
DOE H2A: PEM stack degradation [8]	4.8 mV/1000 h	5.0 mV/1000 h agrees	4.8 mV/1000 h agrees
REFHYNE: PEM stack degradation in the field (2024–2025) [18]	0.09 %/1000 h	0.26 %/1000 h deviates, conservative	0.25 %/1000 h deviates, conservative
PEM: stack degradation, state of the art (SRIA 2020) [21]	0.19 %/1000 h	0.26 %/1000 h deviates, conservative	0.25 %/1000 h deviates, conservative
PEM: stack life, DOE status [9]	40 000 h	37 809 h close, conservative	39 385 h agrees
PEM: lower end of the load range (expert elicitation) [4, 5]	0–10 % of rated	31 % of rated deviates, conservative	10 % of rated agrees
AEL: stack degradation (SRIA 2020 – DOE status) [10, 21]	0.12–0.17 %/1000 h	0.11 %/1000 h close, optimistic	0.17 %/1000 h agrees
AEL: stack life, DOE status and IRENA 2020 [5, 10, 22]	60 000 h	90 000 h deviates, optimistic	58 197 h agrees
AEM: system consumption, state of the art (SRIA 2020) [21, 22]	55.0 kWh/kg	57.6 kWh/kg agrees	53.9 kWh/kg agrees
AEM: cell voltage at 0.2–1.0 A/cm ² (review) [23]	1.80–2.20 V	2.003 V agrees	1.873 V agrees
AEM: stack degradation, state of the art (SRIA 2020: above 1.0) [21]	> 1.0 %/1000 h	1.00 %/1000 h agrees	1.07 %/1000 h agrees
SOEC: stack degradation, DOE status (6.4 mV/1000 h) [11]	0.50 %/1000 h	0.75 %/1000 h deviates, conservative	0.52 %/1000 h agrees
SOEC: stack life, DOE status [11]	20 000 h	13 354 h deviates, conservative	19 078 h agrees
SOEC: lower end of the load range (expert elicitation) [5]	> 30 % of rated	20 % of rated deviates, optimistic	30 % of rated agrees
SOEC stack degradation in 18 000–23 000 h tests (Jülich, EIFER) [12, 13, 28]	0.57–0.60 %/1000 h	0.75 %/1000 h deviates, conservative	0.52 %/1000 h close, optimistic
AEM Enapter EL 4.1, beginning of life [14]	53.4 kWh/kg	57.6 kWh/kg close, conservative	53.9 kWh/kg agrees
AEM Enapter Nexus 1000, beginning of life [14]	51.3 kWh/kg	57.6 kWh/kg deviates, conservative	53.9 kWh/kg close, conservative

Reference	Published	Hasim 2.0	Hasim 2.3.0
AEM 2 kW stack (ANIONE), 1 A/cm ² , 2 000 h [15]	1.80 V	2.003 V deviates, conservative	1.873 V agrees
US wind farms installed 2022 (233 W/m ² , 8.3 m/s at 100 m), 2023 [38]	40.0 %	40.6 % agrees	39.6 % agrees
US wind farms installed 2021 (231 W/m ² , 8.0 m/s at 100 m), 2022 [38]	39.1 %	38.8 % agrees	37.7 % agrees
alpha ventus offshore, 12 × 5 MW, 10 m/s at hub, 2011–2013 [2, 39, 40]	48.2 %	38.5 % deviates, conservative	41.2 % deviates, conservative

3 Electrolysers

3.1 PEM: measured plants and US DOE H2A

Reference	Basis	Published	Hasim	Deviation	Result
Energiepark Mainz, 6 MW PEM (Siemens SILYZER 200), rated 4 MW [16] measured	whole plant incl. transformers, rectifiers, pumps, cooling and compression to 225 bar (64 % HHV) first-generation stacks (2015)	61.7 kWh/kg	58.6 kWh/kg	−5.0 %	agrees
Energiepark Mainz, rise of the specific consumption from 4 to 6 MW (150 % load) [16] measured	whole plant	7.9 %	5.0 %	−2.9 pp	close, optimistic
HyBalance, 1.2 MW PEM (Hydrogenics), nominal flow [17] measured	system incl. auxiliaries	56.5 kWh/kg	57.4 kWh/kg	+1.6 %	agrees
REFHYNE, 10 MW PEM (ITM Power), average load [18] measured	stack Hasim at 60–80 % load	< 49 kWh/kg	47.8–49.2 kWh/kg	within	agrees
NREL Flatirons, 1.25 MW PEM system (Nel), initial power-hold and polarisation tests [19] measured	stack, DC, mean of the runs Hasim at 60–80 % load	51.4 kWh/kg	47.8–49.2 kWh/kg	−7.0 to −4.3 %	close, optimistic
DOE H2A: PEM stack at 2.0 A/cm ² and 1.9 V [8, 20] model assumption	stack	50.4–51.0 kWh/kg	51.2 kWh/kg	+0.4 %	agrees
DOE H2A: PEM system, beginning of life [8] model assumption	system (stack + balance of plant)	55.2 kWh/kg	54.5 kWh/kg	−1.3 %	agrees
DOE H2A: PEM system, life average [8] model assumption	system, average over the stack life	57.5 kWh/kg	57.0 kWh/kg	−0.9 %	agrees

Reference	Basis	Published	Hasim	Deviation	Result
DOE H2A 2019: PEM system, life average implied by the cost record [20] model assumption	4.18 \$/kg electricity cost ÷ 7.35 ¢/kWh	56.9 kWh/kg	57.0 kWh/kg	+0.2 %	agrees
DOE H2A: PEM stack degradation [8] model assumption	cell-voltage rise; replacement after 40 000 h <i>Hasim replaces the stack after 39 385 h</i>	4.8 mV/1000 h	4.8 mV/1000 h	±0.0 %	agrees
REFHYNE: PEM stack degradation in the field (2024–2025) [18] measured	at full utilisation	0.09 %/1000 h	0.25 %/1000 h	2.8 ×	deviates, conservative

The PEM system agrees with the DOE H2A assumptions and with HyBalance within 2 %. Energiepark Mainz used first-generation stacks and about 5 % more electricity. At stack level Hasim matches REFHYNE and the DOE values; the 1.25 MW Nel stack tested by NREL needed 4–7 % more.

3.2 Technology presets: Clean Hydrogen Partnership, US DOE, IRENA

Reference	Basis	Published	Hasim	Deviation	Result
PEM: system consumption, state of the art (SRIA 2020; DOE status) [9, 21] reference value	system, AC	55.0 kWh/kg	54.5 kWh/kg	−0.9 %	agrees
PEM: stack degradation, state of the art (SRIA 2020) [21] reference value	efficiency loss at nominal capacity	0.19 %/1000 h	0.25 %/1000 h	+31.6 %	deviates, conservative
PEM: stack life, DOE status [9] reference value	end of life at +10 % voltage	40 000 h	39 385 h	−1.5 %	agrees
PEM: lower end of the load range (expert elicitation) [4, 5] reference value	system <i>Hasim lowers the cathode pressure at part load, down to 10 bar (at 30 bar the 2 % H₂-in-O₂ trip would limit the load to 31 %)</i>	0–10 % of rated	10 % of rated	within	agrees
PEM: operating range of commercial systems (Cummins HyLYZER-1000, Nel M Series) [6, 7] vendor rating	system, lower end rated 5–125 % and 10–100 %	5–10 % of rated	10 % of rated	within	agrees
AEL: system consumption, state of the art (SRIA 2020 – DOE status) [10, 21] reference value	system, AC	50.0–55.0 kWh/kg	53.7 kWh/kg	within	agrees
AEL: cell voltage at 0.5 A/cm ² (DOE status) [10] reference value	cell	1.90 V	1.895 V	−0.3 %	agrees
AEL: stack degradation (SRIA 2020 – DOE status) [10, 21] reference value	efficiency or voltage loss	0.12–0.17 %/1000 h	0.17 %/1000 h	within	agrees

Reference	Basis	Published	Hasim	Deviation	Result
AEL: stack life, DOE status and IRENA 2020 [5, 10, 22] reference value	end of life <i>the expert elicitation gives 60 000–90 000 h</i>	60 000 h	58 197 h	–3.0 %	agrees
AEL: lower end of the load range (expert elicitation) [5] reference value	system	10–40 % of rated	20 % of rated	within	agrees
AEM: system consumption, state of the art (SRIA 2020) [21, 22] reference value	system, AC <i>IRENA 2020: 57–69 kWh/kg</i>	55.0 kWh/kg	53.9 kWh/kg	–2.0 %	agrees
AEM: cell voltage at 0.2–1.0 A/cm ² (review) [23] reference value	cell <i>Hasim at 1 A/cm²</i>	1.80–2.20 V	1.873 V	within	agrees
AEM: stack degradation, state of the art (SRIA 2020: above 1.0) [21] reference value	efficiency loss	> 1.0 %/1000 h	1.07 %/1000 h	within	agrees
SOEC: electricity, state of the art (DOE status – SRIA 2020) [11, 21] reference value	system, steam from outside	38.0–40.0 kWh/kg	38.4 kWh/kg	within	agrees
SOEC: heat for the steam (DOE status – SRIA 2020) [11, 21] reference value	thermal energy per kg <i>measured at INL: 6.4 kWh of heat per kg</i>	9.0–9.9 kWh _{th} /kg	6.6 kWh _{th} /kg	–26.7 %	deviates, optimistic
SOEC: cell voltage at 0.6 A/cm ² (DOE status) [11] reference value	cell	1.28 V	1.248 V	–2.5 %	agrees
SOEC: stack degradation, DOE status (6.4 mV/1000 h) [11] reference value	voltage rise	0.50 %/1000 h	0.52 %/1000 h	+4.0 %	agrees
SOEC: stack life, DOE status [11] reference value	end of life	20 000 h	19 078 h	–4.6 %	agrees
SOEC: lower end of the load range (expert elicitation) [5] reference value	system	> 30 % of rated	30 % of rated	within	agrees

The electricity consumption and cell voltages of all four presets – PEM, alkaline, AEM and SOEC – agree with the state-of-the-art values, and so do the stack life and degradation of the alkaline and solid-oxide presets at the US DOE status. The PEM minimum load of 10 % agrees with the expert elicitation and with commercial systems. The PEM degradation follows the DOE status and remains above the state of the art of the Clean Hydrogen Partnership (section 9).

3.3 Alkaline, solid-oxide and AEM electrolyzers: measured and rated

Reference	Basis	Published	Hasim	Deviation	Result
AEL 1 MW atmospheric (Nel), full load [24] measured	stack, DC; model fitted to plant data <i>Hasim AEL preset at atmospheric pressure</i>	52.0 kWh/kg	47.5 kWh/kg	−8.7 %	close, optimistic
AEL 1 MW atmospheric (Nel), 20 % load [24] measured	stack, DC; model fitted to plant data	47.0 kWh/kg	43.4 kWh/kg	−7.7 %	close, optimistic
AEL LONGi ALK Hi1 / Hi1 Plus, full load (factory test witnessed by DNV) [25] vendor rating	stack, DC	45.6–47.8 kWh/kg	49.6 kWh/kg	+3.8 %	agrees
SOEC GrInHy2.0, 720 kW (Sunfire), best measured [26] measured	electrical, steam from waste heat (84.6 % LHV)	39.4 kWh/kg	38.4 kWh/kg	−2.5 %	agrees
SOEC MultiPLHY, 2.6 MW (Sunfire), full load [27] measured	module, factory acceptance test (86 % LHV)	38.8 kWh/kg	38.4 kWh/kg	−1.0 %	agrees
SOEC MultiPLHY, part load [27] measured	module, factory acceptance test (89 % LHV) <i>Hasim at 74 % load</i>	37.4 kWh/kg	37.1 kWh/kg	−0.8 %	agrees
SOEC 100 kW system (Bloom Energy) at INL, 97 % load [13] measured	DC incl. blowers, heaters, controls; excl. AC/DC and steam	36.7 kWh/kg	36.7 kWh/kg	±0.0 %	agrees
SOEC at INL, 74 % load [13] measured	as above	37.7 kWh/kg	35.7 kWh/kg	−5.3 %	close, optimistic
SOEC at INL, heat for the steam [13] measured	external electric boiler	6.4 kWh _{th} /kg	6.6 kWh _{th} /kg	+3.1 %	agrees
SOEC stack degradation in 18 000–23 000 h tests (Jülich, EIFER) [12, 13, 28] measured	cell or stack voltage <i>INL system: below 0.2 %/1000 h</i>	0.57–0.60 %/1000 h	0.52 %/1000 h	−8.8 %	close, optimistic
AEM Enapter EL 4.1, beginning of life [14] vendor rating	system (4.8 kWh/Nm ³)	53.4 kWh/kg	53.9 kWh/kg	+0.9 %	agrees
AEM Enapter Nexus 1000, beginning of life [14] vendor rating	system incl. utilities	51.3 kWh/kg	53.9 kWh/kg	+5.1 %	close, conservative
AEM 2 kW stack (ANIONE), 1 A/cm ² , 2 000 h [15] measured	cell voltage	1.80 V	1.873 V	+4.1 %	agrees

The solid-oxide model agrees with three independent measurements – GrInHy2.0, the MultiPLHY factory tests and the INL system – within 3 % at full load, including the heat for the steam. Hasim's alkaline stack lies between the

older atmospheric Nel plant and the current LONGi stacks. The AEM preset agrees with the Enapter EL 4.1 rating and the ANIONE stack and is 5.1 % above the rating of the Nexus 1000.

4 Photovoltaics

Reference	Basis	Published	Hasim	Deviation	Result
NREL ATB (SAM), single-axis, GHI > 5.75 kWh/m ² /d [29] tool result	AC capacity factor, ILR 1.34 <i>Hasim at 6 kWh/m²/d</i>	34.0 %	33.6 %	−1.2 %	agrees
NREL ATB (SAM), single-axis, GHI 5.00–5.25 kWh/m ² /d [29] tool result	AC capacity factor, ILR 1.34 <i>Hasim at 5.125 kWh/m²/d</i>	29.8 %	29.1 %	−2.3 %	agrees
NREL ATB (SAM), single-axis, GHI 4.00–4.25 kWh/m ² /d [29] tool result	AC capacity factor, ILR 1.34 <i>Hasim at 4.125 kWh/m²/d</i>	24.5 %	23.7 %	−3.3 %	agrees
NREL ATB (SAM), single-axis, GHI < 3.75 kWh/m ² /d [29] tool result	AC capacity factor, ILR 1.34 <i>Hasim at 3.5 kWh/m²/d</i>	21.4 %	20.2 %	−5.6 %	close, conservative
LBNL US fleet: gain of single-axis tracking over fixed tilt [30] measured	AC capacity factor <i>Hasim at 5.3 kWh/m²/d</i>	3.0–5.0 pp	3.2 pp	within	agrees
Chile, 109 tracking plants, fleet average (GHI about 2 500 kWh/m ² /yr) [31] measured	specific yield <i>grid data may mix AC and DC ratings</i>	2 388 kWh/kWp	2 450 kWh/kWp	+2.6 %	agrees
India, 10 MWp at 18.75° N (GHI 1 814 kWh/m ² /yr) [32] measured	specific yield, fixed	1 580 kWh/kWp	1 591 kWh/kWp	+0.7 %	agrees
Alice Springs (DKASC), p-Si, fixed 20° (GHI about 2 245 kWh/m ² /yr) [33] measured	performance ratio	0.81	0.782	−3.5 %	agrees
Germany, new systems (GHI 1 102 kWh/m ² /yr) [34] measured	performance ratio	0.80–0.90	0.855	within	agrees
HOMER Pro study, Ayvalik, Turkey (GHI 4.62 kWh/m ² /d, derating 88 %) [35] tool result	specific yield, fixed	1 645 kWh/kWp	1 544 kWh/kWp	−6.1 %	close, conservative
HOMER Pro study, Naogaon, Bangladesh (GHI about 5.0 kWh/m ² /d) [36] tool result	specific yield	1 594 kWh/kWp	1 610 kWh/kWp	+1.0 %	agrees
HOMER Pro study, Ostrava, Czechia (GHI 2.89 kWh/m ² /d) [37] tool result	specific yield	1 008 kWh/kWp	1 016 kWh/kWp	+0.8 %	agrees

Across four resource classes Hasim reproduces the NREL SAM results of the Annual Technology Baseline within 1–6 % (slightly lower at weak irradiation), the measured gain of tracking in the US fleet, the measured yields in Chile and India, the performance ratios measured in Alice Springs and Germany, and the PV yields of three HOMER Pro studies

within -6 to $+1$ %. Established tools deviate from measured PV output by a similar amount (section 8), so Hasim's PV model is as accurate as the tools engineers use for PV today.

5 Wind

Reference	Basis	Published	Hasim	Deviation	Result
US wind farms installed 2022 (233 W/m ² , 8.3 m/s at 100 m), 2023 [38] measured	capacity factor, curtailment (4.6 %) added back <i>wind index of the year 0.95; Hasim low-wind turbine (216 W/m²)</i>	40.0 %	39.6 %	-1.0 %	agrees
US wind farms installed 2021 (231 W/m ² , 8.0 m/s at 100 m), 2022 [38] measured	capacity factor, curtailment (5.3 %) added back <i>wind index of the year 1.06</i>	39.1 %	37.7 %	-3.6 %	agrees
alpha ventus offshore, 12 × 5 MW, 10 m/s at hub, 2011–2013 [2, 39, 40] measured	capacity factor <i>Hasim with the turbine data of the farm, the FINO1 shape factor k 2.1 and the offshore loss allowance (15.5 %)</i>	48.2 %	41.2 %	-14.5 %	deviates, conservative
NREL Cost of Wind Energy Review 2024: fixed-bottom offshore reference project, 9.05 m/s at hub, k 2.1 [1, 3] tool result	net capacity factor, losses 15.5 % <i>Hasim offshore turbine class (IEA 15 MW reference turbine)</i>	49.0 %	46.1 %	-5.9 %	close, conservative

With the Weibull shape factor 2 and the NREL loss allowance of 18.8 %, Hasim's capacity factor agrees with the recent US onshore fleet within 4 % (with the measured curtailment added back). The new offshore turbine class gives 5.9 % less than the NREL offshore reference project with the same wind speed, shape factor and losses. For the offshore farm alpha ventus, modelled with its own turbine data, the FINO1 shape factor and the offshore loss allowance, Hasim is 14.5 % low: its turbines deliver more below rated wind speed than the generic power curve – see section 9.

6 Compression and water

6.1 Compression

Reference	Basis	Published	Hasim	Deviation	Result
Isothermal minimum 20 → 350 bar at 300 K (DOE) [41] reference value	thermodynamic minimum	1.05 kWh/kg	1.10 kWh/kg	+4.8 %	agrees
Isothermal minimum 20 → 700 bar at 300 K (DOE) [41] reference value	thermodynamic minimum <i>Hasim averages Z over the pressure range</i>	1.35 kWh/kg	1.50 kWh/kg	+11.1 %	deviates, conservative
HDSAM station compression 20 → 440 bar (isentropic 56 %, motor 92 %) [41] tool result	electricity, same efficiencies in Hasim	2.23 kWh/kg	2.41 kWh/kg	+8.1 %	close, conservative

Reference	Basis	Published	Hasim	Deviation	Result
HDSAM station compression 20 → 880 bar [41] tool result	electricity, same efficiencies in Hasim	3.0 kWh/kg	3.13 kWh/kg	+4.3 %	agrees
Pipeline compressor 20 → 100 bar (DOE status 2015) [42] reference value	electricity <i>Hasim default efficiencies</i>	0.82 kWh/kg	0.95 kWh/kg	+15.9 %	deviates, conservative
Terminal compressor 100 → 550 bar (DOE status 2015) [42] reference value	electricity	1.1 kWh/kg	1.14 kWh/kg	+3.6 %	agrees
Compression at US refuelling stations, 350 bar (DOE technology validation) [41] measured	measured range <i>Hasim 20 → 440 bar, default efficiencies</i>	2.0–4.0 kWh/kg	1.91 kWh/kg	–4.5 %	agrees
Diaphragm compressor 10 → 420 bar, Cal State LA station [43] measured	measured over several quarters	1.5 kWh/kg	2.28 kWh/kg	+52.0 %	deviates, conservative

6.2 Water

Reference	Basis	Published	Hasim	Deviation	Result
Demineralised water consumed per kg (Arup) [44] reference value	process water <i>Hasim default of the design basis</i>	9.0–11.0 L/kg	10.0 L/kg	within	agrees
Raw water, surface or municipal supply (Arup, PEM, dry zone) [44] reference value	process water, air cooling <i>Hasim case A: RO recovery 0.8</i>	15.0 L/kg	12.5 L/kg	–16.7 %	deviates, optimistic
Raw water, seawater (Arup, PEM, dry zone) [44] reference value	process water, air cooling <i>Hasim case B: SWRO + second pass</i>	25.1 L/kg	26.6 L/kg	+6.0 %	close, conservative
Hydrogen Park South Australia, 1.25 MW PEM [45] measured	ultrapure water per kg (operator)	15.0 L/kg	10.0 L/kg	–33.3 %	deviates, optimistic
Practical range, stoichiometric to deionisation losses (JRC) [46] reference value	fresh water per kg <i>Hasim case A: municipal water, RO recovery 0.8</i>	9.0–22.0 L/kg	12.5 L/kg	within	agrees

With HDSAM's efficiencies Hasim's compression energy agrees with HDSAM within 4–8 %; with its default efficiencies it agrees with the DOE terminal value and lies at the lower end of the range measured at US refuelling stations. A large pipeline compressor and one diaphragm compressor used less energy than Hasim's default

efficiency set (section 9). Water use follows the inputs of the design basis; the defaults lie at the lean end of the references.

7 Levelised cost of hydrogen

7.1 US DOE H2A-Lite

The DOE record gives the LCOH of a 50 t/d PEM plant for four power supplies at three installed costs, all with 57.5 kWh/kg (life average), fixed O&M of 5 % of the capital per year, a stack replacement costing 11 % of the capital every 40 000 operating hours and a 30-year life [8]. H2A-Lite finances the plant with equity, debt and income tax; Hasim's LCOH (equation CM 17.3) uses one discount rate. With a single rate of **11.6 %** – the pre-tax equivalent of the H2A financing – Hasim reproduces all twelve DOE values within **1.9 %** (mean 0.7 %). One rate fits all cases, so Hasim treats capacity factor, electricity price, capital cost and stack replacement the same way as the DOE tool.

Power supply	Capacity factor	Electricity, ¢/kWh	1 500 \$/kW: DOE / Hasim	2 000 \$/kW: DOE / Hasim	2 500 \$/kW: DOE / Hasim
Grid average	97 %	8.3	6.80 / 6.74	7.50 / 7.39	8.20 / 8.04
Hydropower	50 %	3.4	5.50 / 5.54	6.70 / 6.74	7.90 / 7.93
Land-based wind (class 1)	51 %	2.9	5.20 / 5.19	6.40 / 6.36	7.50 / 7.53
Hybrid wind-PV	74 %	3.3	4.40 / 4.40	5.20 / 5.23	6.00 / 6.06

Hasim's value follows the DOE value in each cell. The fitted rate is not a recommendation for a project; it only removes the difference in financing, so that the dependence on the other inputs can be compared.

7.2 IEA

The IEA gives the LCOH of PV-based hydrogen in Oman in 2030 for an electrolyser of 320 \$/kW, 69 % efficiency (LHV), fixed O&M of 3 % per year, a PV capacity factor of 29 % and a 25-year life, with a WACC of 3.5–5 % [47]. Hasim's range covers these discount rates without and with one stack replacement after 50 000 h:

Electricity price	IEA	Hasim (WACC 3.5–5 %, without / with one stack replacement)
35 \$/MWh	2.4 \$/kg	2.24–2.40 \$/kg
25 \$/MWh	1.9 \$/kg	1.76–1.91 \$/kg

With the same inputs Hasim reproduces the DOE and IEA results. Differences between published LCOH values therefore come from their inputs – capital cost, capacity factor, electricity price and financing – and not from the method.

8 HOMER Pro and the accuracy of established tools

Three recent HOMER Pro studies of hydrogen systems ran the electrolyser at a constant efficiency at every load: 85 % of the HHV [35, 37], that is 46.4 kWh/kg, or 80 % [36], that is 49.3 kWh/kg. Hasim's PEM system needs 54.5 kWh/kg at the beginning of life and 57.0 kWh/kg over the stack life, in line with the measured plants and the DOE values. With the same electricity such a model therefore reports 16–23 % more hydrogen than Hasim. An independent study found that constant-efficiency models overestimate the hydrogen from wind and PV by 5–24 % [48]. The PV yields of the same HOMER studies agree with Hasim.

Published comparisons of established tools with measured output show the accuracy to expect from any energy model:

Tool	Compared with	Deviation from the measurement
HOMER Pro [49]	PV energy, 4.2 kWp rooftop, Valencia	+5.3 %
SAM [49]	same system	+7.6 %
HOMER Pro / SAM / PVsyst / RETScreen [50]	PV energy, 177.8 kW plant, Sacramento	+5.5 / +3.6 / +6.9 / –3.9 %
HOMER Pro [50]	wind energy, 1.25 MW turbine, 5.8 m/s	+15.7 %
PV models, blind test [51]	six systems with measured weather	median –3.3 % (annual energy)
Fixed-efficiency electrolyser models [48]	hydrogen from wind and PV	+5 to +24 %

9 Deviations above 10 % and how to handle them

9.1 Conservative (6)

- **REFHYNE: PEM stack degradation in the field (2024–2025)** (2.8 ×): Hasim uses the US DOE status of 4.8 mV per 1000 h, on which H2A and the DOE stack life of 40 000 h are based. The rates measured in the field at REFHYNE and given by the Clean Hydrogen Partnership are lower, so stack replacements are costed on the safe side. Enter the vendor rate in the Component library for a specific stack.
- **PEM: stack degradation, state of the art (SRIA 2020)** (+31.6 %): See above – the same rate compared with the Clean Hydrogen Partnership state of the art.
- **alpha ventus offshore, 12 × 5 MW, 10 m/s at hub, 2011–2013** (–14.5 %): Hasim's generic power curve rises with the cube of the wind speed from the cut-in to the rated wind speed. The 5 MW turbines of alpha ventus reach rated power only at 12.5–13 m/s but deliver much more below it than such a curve. With the site's shape factor and the offshore loss allowance Hasim is therefore 14.5 % low; for the modern offshore class the gap to the NREL reference project is 5.9 % (section 5). Wind yields of turbines with a high rated wind speed are conservative.

- **Isothermal minimum 20 → 700 bar at 300 K (DOE) (+11.1 %):** The isothermal minimum shown in the compression results averages the compressibility over the whole pressure range; at 700 bar this overstates it by about 11 %. The compressor energy itself is computed stage by stage and agrees with HDSAM within +4 to +8 %.
- **Pipeline compressor 20 → 100 bar (DOE status 2015) (+15.9 %):** Hasim applies one compressor efficiency set (isentropic 75 %, mechanical 95 %, motor 95 %) with the API 618 discharge-temperature limit; large pipeline compressors reach higher efficiencies. Enter the vendor efficiency in the Component library.
- **Diaphragm compressor 10 → 420 bar, Cal State LA station (+52.0 %):** The measured 1.5 kWh/kg of this diaphragm compressor implies an isothermal efficiency of about 90 % – far above typical values; at the US refuelling stations the DOE measured 2–4 kWh/kg, and Hasim's 1.91 kWh/kg lies at the lower end of that range.

9.2 Optimistic (3)

- **SOEC: heat for the steam (DOE status – SRIA 2020) (–26.7 %):** Hasim needs 6.6 kWh of heat per kg to raise the steam – close to the 6.4 kWh/kg measured at INL. The DOE and Clean Hydrogen Partnership values (9–9.9 kWh/kg) include further heat demands at their system boundary.
- **Raw water, surface or municipal supply (Arup, PEM, dry zone) (–16.7 %):** Water use depends on the inputs of the design basis. Hasim's defaults (10 L of demineralised water per kg, 80 % RO recovery for municipal water) lie at the lean end; enter the supplier's values.
- **Hydrogen Park South Australia, 1.25 MW PEM (–33.3 %):** The small Australian plant reports 15 L of ultrapure water per kg; Hasim's default of 10 L/kg can be raised to the plant value (the design basis accepts 9–20 L/kg).

Planned model improvements

Tabulated power curves for vendor turbines in the Component library, so that turbines whose power rises faster than the generic cubic curve – such as those of alpha ventus – are modelled with their own curve; stack-specific durability data from the vendors; the temperature dependence of the membrane and diaphragm permeabilities, a pressure-dependent carry-over factor of the lye-mixing term and the shunt currents of alkaline stacks, once calibration-set sources with the respective data are available; and a recombination catalyst option for PEM anodes.

10 Limitations and open items

- The references differ in system boundary, operating conditions and technology generation; some boundaries are only partly published.
- PV and wind are compared at annual level with Hasim's synthetic typical year; hourly profiles and inter-annual variability are not compared.
- The LCOH comparison tests the method with the published inputs; it does not validate cost inputs, which must come from project quotations.
- **HOMER Pro run on identical inputs.** HOMER is commercial software; this benchmark compares Hasim with published HOMER results, whose weather data and some inputs are not fully published. *Next step:* Run two or three reference cases in HOMER Pro with the hourly PV and wind profiles exported from Hasim, so that both tools see the same weather.

- **Plant data of alkaline and PEM plants at 10 MW and above.** Large plants (Kuqa, Baofeng, FH2R, Puertollano) publish production but not their specific consumption. *Next step:* Add the data when operators or projects publish them.

10.1 Reproducibility

All comparisons are computed by the benchmark script of the Hasim development (tools/benchmark-external.js) from the engine of Hasim 2.3.0. The script runs with the regression suite and fails when a result becomes worse than documented here, so every new version is checked against the same references.

11 Extended benchmark: 109 further comparisons from 39 sources

In October 2026 the benchmark was extended with a second set of published sources, found by a systematic search in eleven domains and verified against the publishers' records. Before any value was read, every source was assigned by a seeded random draw to a **calibration set** (about 30 % of the sources per domain) or a **validation set** (about 70 %); the assignment and its checksum are recorded in the development repository. Model changes may use only calibration-set data, and the validation set is run with the unchanged model first and again with the final version. The first batch used the open-access sources (39 sources; 111 comparisons, two of which – the under-load permeation of a PEM cell – became comparable only with the revised crossover model and were added at its freeze from values recorded in the first batch); the second batch added the four paywalled crossover sources that the owner supplied as publisher PDFs. Together they give 109 comparisons from 39 sources (8 further rows are listed as informative because the source does not state the measurement boundary, the unit is outside the model's range or the model has no parameter for the varied quantity). The verdict rules are those of section 2.

11.1 Summary by domain and set

Domain	Comparisons	Calibration set (agree/close/deviate)	Validation set (agree/close/deviate)
PEM and AEM electrolyzers	16	6 (5/0/1)	10 (5/2/3)
Alkaline electrolyzers	18	8 (3/0/5)	10 (3/2/5)
Minimum load, durability and reviews	9	6 (3/0/3)	3 (1/1/1)
Photovoltaics	7	3 (2/1/0)	4 (1/1/2)
Compression and storage	11	3 (2/0/1)	8 (1/4/3)
Water	4	1 (1/0/0)	3 (2/0/1)
Power electronics	2	2 (2/0/0)	0 (0/0/0)
Ammonia synthesis	6	2 (2/0/0)	4 (2/0/2)
LCOH and GHG intensity	29	2 (1/0/1)	27 (22/4/1)
Integrated plant studies	7	6 (0/1/5)	1 (0/1/0)
Total	109	39 (21/2/16)	70 (37/15/18)

Validation set, Hasim 2.3.0: 37 of 70 comparisons agree within 5 %, 15 are within 10 % and 18 deviate (3 conservative, 15 optimistic). Calibration set: 21 agree, 2 close, 16 deviate. With the unchanged version 2.1 the validation set gave 37 agree, 17 close and 42 deviate; the counts move little because most of the second-batch rows are crossover values whose deviations shrank from a factor of ten to tens of per cent without entering the 10 % band (section 11.4).

11.2 Model changes derived from the calibration set

Model element	Before	After
Cell model: temperature dependence of kinetics and ohmic resistance [53, 54] Hasim 2.1 → 2.2	none (j0 and ASR constant; only E_rev and the RT/αF prefactor vary with T, giving a slight rise of the cell voltage with temperature)	Arrhenius factors on j0a, j0c (E_a 50 kJ/mol low-temperature, 110 kJ/mol SOEC) and on the ASR (10.5 kJ/mol Nafion, 12 kJ/mol KOH, 80 kJ/mol YSZ), referenced to the preset temperature; values at the preset temperature unchanged
Crossover: supersaturation of dissolved hydrogen at the cathode (PEM, AEM, alkaline) [55, 56] Hasim 2.2 → 2.3	none – crossover by saturated diffusion $\Psi \cdot p_{H_2}/\delta$ alone, independent of the current density	additional flux $\kappa \cdot j/\delta$ proportional to the current density: $\kappa = 3.3e-10 \text{ mol cm}^{-1} \text{ s}^{-1}$ per A cm^{-2} for the Nafion 117 cell of the calibration source (minimum-RMS fit to 33 points at 1, 10 and 20 bar), $1.5e-11$ for Zirfon, $4e-11$ for an AEM cell with liquid KOH feed (one point); the Nafion 117 permeability $\Psi = 2e-11$ is confirmed within 3 % by the zero-current measurements
Crossover: Zirfon diaphragm with separated lye cycles [55] Hasim 2.2 → 2.3	$\Psi = 7e-12 \text{ mol cm}^{-1} \text{ s}^{-1} \text{ bar}^{-1}$, an effective value	$\Psi = 2.0e-12$ (saturated diffusion, close to the literature value) with the κ above, fitted together to the separated-cycle measurements at 1–20 bar (RMS 24 %)
Crossover: lye mixing in alkaline stacks [54, 55] Hasim 2.2 → 2.3	not modelled	flux $\phi \cdot S_{H_2} \cdot p_{H_2} \cdot \dot{V}/A$ – the hydrogen dissolved in the lye leaving the cathode compartment is released in the anode compartment ($S_{H_2} = 3.6e-7 \text{ mol Pa}^{-1} \text{ m}^{-3}$ for 32 wt-% KOH; carry-over factor $\phi = 1.3$ fitted to the mixed-cycle measurements at 1, 10 and 20 bar); the lye circulation per cell area $\dot{V}/A$ is a stack parameter, $2.2 \text{ L min}^{-1} \text{ m}^{-2}$ for the preset so that the 500 kW stack's 1.5–1.6 vol-% at 13 % load and 30 bar(g) is reproduced; options: separated cycles ($\dot{V}/A = 0$) and circulation reduced in proportion to the load
Purity-limited minimum load (2 % H_2 in O_2) [54, 55] Hasim 2.2 → 2.3	solved analytically for the load-independent flux: PEM 31 % at a constant 30 bar, 10 % with the part-load pressure strategy; alkaline below the 20 % design value	solved numerically for the load-dependent flux: PEM 49 % at a constant 30 bar, 15 % with the pressure lowered to 10 bar at part load; alkaline with mixed lye at 30 bar 28 %, 12 % with load-adapted circulation, 5 % with separated cycles

Hasim 2.2. The calibration set showed that the cell model had no temperature dependence of the electrode kinetics and the cell resistance: the measured cell voltage falls by 3.9 mV/K between 60 and 80 °C in a five-laboratory PEM round robin and by 13 mV/K between 55 and 80 °C in a 500 kW alkaline stack, whereas the model gave a slight rise. Hasim 2.2 applies Arrhenius factors with literature activation energies, referenced to the preset temperature, so that all results at the preset temperature – and all comparisons of sections 3 to 9 – are unchanged.

Hasim 2.3.0. The second calibration finding was the under-prediction of the hydrogen content of the oxygen at low load. The calibration-set crossover source – a direct comparison of a Nafion 117 and a Zirfon cell at 60 °C and 1–20 bar – resolves the crossover into saturated diffusion, a supersaturation of dissolved hydrogen at the cathode that grows in proportion to the current density (98 % of the PEM crossover at 1 bar and 1 A/cm^2), and, for alkaline cells with mixed lye cycles, the hydrogen carried over by the circulating electrolyte (about 90 % of the alkaline crossover). The crossover model of CM 7.6 now has these three terms. The supersaturation coefficient and the Zirfon parameters were fitted to that source; the lye-mixing term uses the hydrogen solubility of 32 wt-% KOH, a carry-over

factor fitted to the same source, and the lye circulation per cell area as a stack parameter, set for the preset so that the hydrogen content of the 500 kW stack at 13 % load and 30 bar is reproduced. The purity-limited minimum load is solved numerically from the load-dependent flux. Because the flux is now higher at pressure, the purity-limited minimum loads of the pressurised presets rose: PEM at a constant 30 bar from 31 to 49 %, with the part-load pressure strategy from 10 to 15 %, and the alkaline preset with mixed lye at 30 bar to 28 %, above its 20 % design value; with the lye circulation reduced in proportion to the load it is 12 % and with separated cycles 5 %. These are the values of the first-benchmark rows on the minimum load (section 5), where the PEM preset now lies above the vendor ranges of 5–10 %, which are reached with recombination catalysts that the model does not contain. Not changed, for want of calibration data: the temperature dependence of the permeabilities (the Nafion value is the 60 °C measurement) and the dependence of the lye-mixing term on the electrolyte concentration; the carry-over at ambient pressure, 1.8 times the equilibrium content in the calibration cell against 1.1–1.2 at 10–20 bar, is represented by the single factor 1.3. The baseline results of version 2.1 were obtained by running the 2.1 engine on the final row definitions.

11.3 Comparisons

PEM and AEM electrolyzers

Reference	Basis	Published	Hasim	Deviation	Result
Round-robin PEM cell (5 laboratories), Nafion 117, 60 °C, 1 bar, 1.0 A/cm ² [53] measured · calibration	cell voltage	1.787 V	1.775 V	−0.7 %	agrees
Round-robin PEM cell, Nafion 117, 80 °C, 1 bar, 1.0 A/cm ² [53] measured · calibration	cell voltage	1.709 V	1.714 V	+0.3 %	agrees
PEM cell, Nafion 117, 80 °C, cathode 30 bar, 1.6 A/cm ² [57] measured · validation	cell voltage (medium confidence: figure reading of the source)	1.790 V	1.860 V	+3.9 %	agrees
50 kW-class PEM stack (30 × 600 cm ²), 60 °C, 8 bar, 1.0 A/cm ² , initial [58] measured · validation	cell voltage	1.774 V	1.805 V	+1.7 %	agrees
50 kW-class PEM stack, 60 °C, 8 bar, 1.33 A/cm ² (rated), initial [58] measured · validation	cell voltage	1.836 V	1.867 V	+1.7 %	agrees
12 kW PEM prototype stack (34 × 90 cm ²), 80 °C, 30 bar, 1.78 A/cm ² : voltage efficiency [59] measured · validation	stack DC, HHV basis <i>membrane not stated</i>	71.0 %	78.4 %	+10.4 %	deviates, optimistic
Laboratory PEM cell, Nafion 115 (127 µm), 80 °C, ambient, 3.0 A/cm ² [60] measured · validation	cell voltage <i>laboratory cell with a thinner membrane than the preset (N117 class); the thickness is not a model input</i>	1.880 V	2.015 V	+7.2 %	close, conservative

Reference	Basis	Published	Hasim	Deviation	Result
H2FUTURE 6 MW PEM (Silyzer 300): stack efficiency at rated load 83 % [61] measured · validation · informative, not counted	stack; heating-value basis not stated (HHV assumed) <i>converted from 83 % HHV; rated current density and pressure of the plant not stated</i>	1.784 V	1.890 V	+5.9 %	close, conservative
Haeolus 2.5 MW PEM (Cummins): 52 kWh/kg [62] measured · validation · informative, not counted	not stated (stack level implied) <i>boundary not stated in the source</i>	52.0 kWh/kg	50.4 kWh/kg	-3.1 %	agrees
55 kW PEM stack (47 × 600 cm ²), 65 °C, 30 bar constant, 25 % load [63] measured · calibration	stack DC <i>Hasim stack at constant pressure (part-load pressure strategy off, as in the test)</i>	44.5 kWh/kg	46.1 kWh/kg	+3.6 %	agrees
55 kW PEM stack (47 × 600 cm ²), 65 °C, 30 bar constant, 50 % load [63] measured · calibration	stack DC <i>Hasim stack at constant pressure (part-load pressure strategy off, as in the test)</i>	46.9 kWh/kg	48.3 kWh/kg	+3.0 %	agrees
55 kW PEM stack (47 × 600 cm ²), 65 °C, 30 bar constant, 75 % load [63] measured · calibration	stack DC <i>Hasim stack at constant pressure (part-load pressure strategy off, as in the test)</i>	51.8 kWh/kg	50.2 kWh/kg	-3.1 %	agrees
55 kW PEM system, 75 % load: system consumption 75.3 kWh/kg [63] measured · calibration · informative, not counted	system AC <i>kW-class unit: balance-of-plant share not representative of the MW-scale presets</i>	75.3 kWh/kg	54.5 kWh/kg	-27.6 %	deviates, optimistic
40 kW PEM system (Proton OnSite): minimum current 10.7 % of maximum [64] measured · validation	stack DC	10.7 %	10.0 %	-0.7 pp	agrees
12 kW PEM prototype, 50 °C, cathode 30 bar, 1.5 A/cm ² : Faradaic efficiency [59] measured · validation	stack	99.0 %	99.6 %	+0.6 %	agrees
12 kW PEM prototype, 50 °C, cathode 70 bar, 1.5 A/cm ² : Faradaic efficiency [59] measured · validation	stack <i>above the 30 bar of the preset</i>	90.0 %	99.0 %	+10.0 %	close, optimistic
H ₂ permeation coefficient, Nafion 117, 80 °C (open circuit) [57] measured · validation	cell <i>less crossover than measured is optimistic for a design</i>	0.310 mA cm ⁻² bar ⁻¹	0.211 mA cm ⁻² bar ⁻¹	-31.9 %	deviates, optimistic
Current density at which H ₂ in O ₂ reaches 2 %, Nafion 117, 80 °C, cathode 30 bar [57] measured · validation	cell <i>a lower current-density limit (lower minimum load) is the optimistic direction</i>	1.1 A/cm ²	0.620 A/cm ²	-43.6 %	deviates, optimistic
AEM laboratory cell (Aemion+ 85 µm, 1 M KOH), 70 °C, ambient, 0.6 A/cm ² : H ₂ in anode gas [56] measured · calibration	cell <i>less crossover than measured is optimistic for a design</i>	0.200 vol-%	0.039 vol-%	-80.5 %	deviates, optimistic

Alkaline electrolyzers

Reference	Basis	Published	Hasim	Deviation	Result
Zero-gap alkaline cell (Zirfon 500 μm , 32 wt% KOH), 60 °C, 7 bar, 0.3 A/cm ² [65] measured · validation	cell voltage (medium confidence) <i>laboratory cell with expanded-nickel electrodes</i>	2.000 V	1.851 V	−7.5 %	close, optimistic
Zero-gap alkaline cell, 60 °C, 7 bar, 0.7 A/cm ² [65] measured · validation	cell voltage (medium confidence) <i>laboratory cell with expanded-nickel electrodes</i>	2.500 V	1.996 V	−20.2 %	deviates, optimistic
Alkaline cell, 60 °C, 7 bar, 0.7 A/cm ² , mixed electrolyte cycles: H ₂ in O ₂ [65] measured · validation	cell <i>Hasim: diffusion through the diaphragm only; mixed electrolyte circuits carry dissolved gas</i>	1.3 vol-%	0.054 vol-%	−95.8 %	deviates, optimistic
Alkaline cell, 60 °C, 7 bar, 0.3 A/cm ² after a night at low load, mixed cycles: H ₂ in O ₂ [65] measured · validation	cell	2.3 vol-%	0.126 vol-%	−94.5 %	deviates, optimistic
Advanced zero-gap alkaline (Zirfon 0.5 mm, Raney Ni), 60 °C: current density at 1.85 V/cell [66] measured · validation	cell <i>Hasim at 20 bar (experiments 10–55 bar); a lower current density at the same voltage is the conservative direction</i>	0.500 A/cm ²	0.247 A/cm ²	−50.6 %	deviates, conservative
Advanced zero-gap alkaline, Zirfon 0.1 mm, 100 °C, 20 bar, 0.6 A/cm ² , separated circuits: H ₂ in O ₂ [66] measured · validation	cell	1.6 vol-%	0.892 vol-%	−44.2 %	deviates, optimistic
Advanced zero-gap alkaline, Zirfon 0.1 mm, 5 bar, nominal 1.7 A/cm ² : purity-limited minimum load (10 % reached at ≤ 5 bar) [66] measured · validation	cell <i>bound: the source reaches 10 % at 5 bar</i>	10.0 %	3.9 %	within	agrees
500 kW zero-gap alkaline stack (CornerStone), 80 °C, 30 bar, 28 wt% KOH, 1.2 A/cm ² [54] measured · calibration	cell voltage (medium confidence)	2.000 V	2.084 V	+4.2 %	agrees
500 kW alkaline stack: cell-voltage temperature coefficient between 55 and 80 °C at 1.2 A/cm ² [54] measured · calibration	cell	−13.0 mV/K	−5.0 mV/K	−61.5 %	deviates
500 kW alkaline stack, 80 °C, ~30 bar, 13 % load (0.16 A/cm ²): H ₂ in O ₂ [54] measured · calibration	stack	1.6 vol-%	1.0 vol-%	−37.3 %	deviates, optimistic
500 kW alkaline stack at 100 Nm ³ /h: stack consumption < 4.5 kWh/Nm ³ (80 °C, 30 bar, 1.2 A/cm ²) [54] measured · calibration	stack DC <i>bound; Hasim at the stack's rated 1.2 A/cm²</i>	50.1 kWh/kg	55.4 kWh/kg	+10.6 %	deviates, conservative
500 kW alkaline system: design load range 20–110 % [54] vendor rating · calibration	system	20.0 %	20.0 %	within	agrees

Reference	Basis	Published	Hasim	Deviation	Result
Hydrogenics 1 Nm ³ /h pressurised alkaline (22 × 300 cm ²), 65 °C, 25 bar, 0.4 A/cm ² : stack consumption 4.4 kWh/Nm ³ [67] measured · validation	stack DC	49.0 kWh/kg	50.7 kWh/kg	+3.5 %	agrees
ELyIntegration pressurised alkaline pilot stacks, 30 bar, 0.5 A/cm ² : stack efficiency 77–88 % HHV [68] measured · validation	stack DC (medium confidence)	77.0–88.0 %	78.2 %	within	agrees
ELyIntegration pilot stacks at high current density (0.7 A/cm ²): 69–72 % HHV [68] measured · validation	stack DC (medium confidence)	69.0–72.0 %	75.8 %	+5.3 %	close, optimistic
Nel A485 atmospheric alkaline (2.2 MW class): stack consumption 4.5 kWh/Nm ³ (50 kWh/kg) at 100 % load [69] vendor rating · calibration	stack DC <i>Hasim atmospheric at its nominal 0.4 A/cm² (the sheet does not state the current density)</i>	50.0 kWh/kg	47.5 kWh/kg	–5.0 %	agrees
Nel A485: turndown 15 % of nominal [69] vendor rating · calibration	system	15.0 %	20.0 %	+5.0 pp	deviates, conservative
FH2R 10 MW-class Aqualyzer: production range 300–2000 Nm ³ /h (minimum 15 %) [70] measured · calibration	plant	15.0 %	20.0 %	+5.0 pp	deviates, conservative
3.5 MW atmospheric alkaline plant, module M1, 60 °C, 49 % load: 49.3 kWh/kg [63] measured · calibration · informative, not counted	module (stack plus part of the balance of plant – not stated) <i>boundary of the measurement not stated</i>	49.3 kWh/kg	46.9 kWh/kg	–4.9 %	agrees
thyssenkrupp nucera 2 MW test stand: 440 Nm ³ /h [71] measured · validation · informative, not counted	not stated <i>implied 4.55 kWh/Nm³; whether 2 MW is stack DC or plant AC is not stated</i>	50.6 kWh/kg	49.6 kWh/kg	–2.0 %	agrees

Minimum load, durability and reviews

Reference	Basis	Published	Hasim	Deviation	Result
Review (Lange et al. 2023), Table 2: alkaline load range 20–100 % [72] reference value · calibration	stack	20.0 %	20.0 %	within	agrees
Review (Lange et al. 2023), Table 2: PEM load range from 0 % [72] reference value · calibration	stack <i>Hasim: purity-limited minimum of the pressurised system</i>	0.000 %	10.0 %	+10.0 pp	deviates, conservative
Review (Lange et al. 2023): alkaline stack consumption 4.2–4.8 kWh/Nm ³ [72] reference value · calibration	stack DC	46.7–53.4 kWh/kg	49.6 kWh/kg	within	agrees
Review (Lange et al. 2023): PEM stack consumption 4.4–5.0 kWh/Nm ³ [72] reference value · calibration	stack DC	49.0–55.6 kWh/kg	50.4 kWh/kg	within	agrees

Reference	Basis	Published	Hasim	Deviation	Result
FCH-JU target for PEM degradation under flexible operation (2023): < 4.6 $\mu\text{V/h}$ [73] reference value · validation	cell	4.6 $\mu\text{V/h}$	4.8 $\mu\text{V/h}$	+4.3 %	close, conservative
PEM cell under a dynamic sweeping protocol (1.4–1.8 V, 830 h), 60 °C: 35.2 $\mu\text{V/h}$ [73] measured · validation · informative, not counted	cell <i>accelerated protocol; not a steady-state rate</i>	35.2 $\mu\text{V/h}$	4.8 $\mu\text{V/h}$	−86.4 %	deviates, optimistic
50 kW-class PEM stack at constant current (1.33 A/cm ² , 60 °C, 8 bar): 5.6 $\mu\text{V/h}$ over 255 h [58] measured · validation · informative, not counted	cell <i>test shorter than 1000 h; evaluated at 0.15 A/cm²</i>	5.6 $\mu\text{V/h}$	4.8 $\mu\text{V/h}$	−14.3 %	deviates, optimistic
AEM cell (Aemion+ 85 μm , 1 M KOH), 70 °C, 0.2 A/cm ² , > 3000 h: 18 $\mu\text{V/h}$ [56] measured · calibration	cell	18.0 $\mu\text{V/h}$	20.0 $\mu\text{V/h}$	+11.1 %	deviates, conservative
AEM cell (Aemion+ 85 μm , 1 M KOH), 70 °C, 0.6 A/cm ² , 5000 h: 13 $\mu\text{V/h}$ [56] measured · calibration	cell	13.0 $\mu\text{V/h}$	20.0 $\mu\text{V/h}$	+53.8 %	deviates, conservative
SOEC electrolyte-supported cell, 856–860 °C, 0.7 A/cm ² , 8756 h with 80 000 on/off cycles: 5 mV per 1000 h [74] measured · validation	cell	5.0 mV/1000 h	7.0 mV/1000 h	+40.0 %	deviates, conservative
SOEC electrolyte-supported cell, 856 °C, 0.7 A/cm ² , 60 % steam conversion, after about 3000 h: 1.22 V [74] measured · validation	cell voltage <i>Hasim: beginning of life plus 3000 h of preset degradation</i>	1.220 V	1.188 V	−2.6 %	agrees

Photovoltaics

Reference	Basis	Published	Hasim	Deviation	Result
US utility-scale fleet (752 projects, 28.7 GWac): median capacity factor 24 % AC [75] measured · validation	plant AC <i>Hasim: single-axis tracking at 35° N, GHI 4.65 kWh/m²/d (fleet median of recent vintages), ILR 1.34</i>	24.0 %	26.5 %	+10.4 %	deviates, optimistic
US utility-scale fleet: median capacity factor 18 % on the DC basis [75] measured · validation · informative, not counted	plant, DC nameplate <i>same statistic as the AC value</i>	18.0 %	19.8 %	+10.0 %	close, optimistic
Ain El-Melh, Algeria, 20 MWp fixed 33°, 2019: performance ratio 71.6 % (soiling 4.8 %) [76] measured · validation	plant AC <i>Hasim fixed tilt at 34.9° N; GHI about 2100 kWh/m²/a (from the in-plane 2628)</i>	71.6 %	79.1 %	+10.5 %	deviates, optimistic
Nouakchott, Mauritania, 15 MWp thin film, first full year: performance ratio 80.0 % [77] measured · calibration	plant AC <i>Hasim fixed tilt at 18° N, GHI about 2100 kWh/m²/a (4.2–6.6 kWh/m²/d)</i>	80.0 %	77.4 %	−3.2 %	agrees

Reference	Basis	Published	Hasim	Deviation	Result
Nouakchott plant in its 6th year (2020): monthly performance ratio 0.735–0.768 [77] measured · calibration	plant AC <i>Hasim has no ageing in this comparison</i>	73.5–76.8 %	77.4 %	+0.8 %	agrees
Zarqa, Jordan, 4 kWp fixed 26°, 2015–16: 1668 kWh/kWp on 2246 kWh/m ² in-plane (PR 0.74) [78] measured · calibration	system AC <i>performance ratio derived from the yield and the measured in-plane irradiation</i>	74.2 %	79.8 %	+7.5 %	close, optimistic
Gujarat, India, 23 MW: annual performance ratio 73.9 % [79] measured · validation	plant (medium confidence: abstract)	73.9 %	78.2 %	+5.8 %	close, optimistic
Andhra Pradesh, India, 5 MW: annual performance ratio 80.3 % [79] measured · validation	plant (medium confidence: abstract)	80.3 %	78.1 %	–2.7 %	agrees

Compression and storage

Reference	Basis	Published	Hasim	Deviation	Result
NREL/H2A distributed station, 20 → 875 bar, isentropic efficiency 65 % (current): shaft power 177 kW for 63 kg/h [80] tool or model result · validation	shaft work per kg (motor rating 3.30 kWh/kg) <i>Hasim with the stated isentropic efficiency; cascade to 875 bar</i>	2.8 kWh/kg	2.5 kWh/kg	–9.6 %	close, optimistic
NREL/H2A distributed station, 20 → 875 bar, isentropic efficiency 80 % (future): shaft power 287 kW for 126 kg/h [80] tool or model result · validation	shaft work per kg (motor rating 2.66 kWh/kg)	2.3 kWh/kg	2.1 kWh/kg	–7.0 %	close, optimistic
HDSAM pipeline scenario station, 20 → 875 bar, five stages, 65 %: shaft power 125 kW for 44 kg/h [80] tool or model result · validation	shaft work per kg (motor rating 3.36 kWh/kg) <i>Hasim with the stated five stages (its automatic choice would be eight, limited by the discharge temperature)</i>	2.8 kWh/kg	2.7 kWh/kg	–6.3 %	close, optimistic
HDSAM pipeline scenario station, 20 → 875 bar, 80 % (future): shaft power 203 kW for 89 kg/h [80] tool or model result · validation	shaft work per kg (motor rating 2.67 kWh/kg)	2.3 kWh/kg	2.1 kWh/kg	–7.0 %	close, optimistic
Humboldt State University station: diaphragm compressor 13 → 430 bar, measured 8.3 kWh/kg [80] measured · validation	measured <i>small station compressor; Hasim default efficiencies of industrial compressors</i>	8.3 kWh/kg	2.2 kWh/kg	–73.9 %	deviates, optimistic
Neuman & Esser compressor downstream of a PEM electrolyser, 25 → 85 bar [81] vendor rating · validation	electricity	0.566 kWh/kg	0.709 kWh/kg	+25.3 %	deviates, conservative
Compressed hydrogen density at 350 bar, 25 °C [82] reference value · calibration	property	23.0 kg/m ³	23.4 kg/m ³	+1.7 %	agrees

Reference	Basis	Published	Hasim	Deviation	Result
Compressed hydrogen density at 700 bar, 25 °C [82] reference value · calibration	property <i>Hasim: linear compressibility correlation (CM 2.4)</i>	38.0 kg/m ³	39.6 kg/m ³	+4.2 %	agrees
Type I steel pressure vessels (< 250 bar): 500 EUR per kg stored; bunched cylinders at 200 bar 662.5 EUR per kg (Energiforsk 2025) [81] reference value · validation	vessel cost <i>Hasim library item sv-type1</i>	500–662 EUR/kg	600 EUR/kg	within	agrees
Type IV composite vessels (350–1000 bar): 1200 EUR per kg stored [81] reference value · validation	vessel cost <i>Hasim library item sv-type4 (350–500 bar)</i>	1 200 EUR/kg	900 EUR/kg	–25.0 %	deviates, optimistic
Multifunctional steel layered vessel (MSLV), 430 bar: 450 US\$ per kg [82] reference value · calibration	vessel cost <i>currency not converted</i>	450 \$/kg	900 \$/kg	+100.0 %	deviates, conservative

Water

Reference	Basis	Published	Hasim	Deviation	Result
Nel A485: 10 L of deionised water per kg H ₂ [69] vendor rating · calibration	process water <i>Hasim default of the design basis</i>	10.0 L/kg	10.0 L/kg	±0.0 %	agrees
Three SWRO plants, Canary Islands, 2015–2018: measured high-pressure energy 3.0–4.3 kWh/m ³ (recovery 40–45 %) [83] measured · validation	high-pressure and booster pumps <i>Hasim library item wt-swro (SWRO with energy recovery, second pass, EDI)</i>	3.0–4.3 kWh/m ³	3.5 kWh/m ³	within	agrees
ROSA projection, plant A without energy recovery: 5.28 kWh/m ³ (feed 60.4 bar, recovery 40 %) [83] tool or model result · validation	high-pressure pump <i>Hasim DM 8.4 with the stated feed pressure, recovery and 80 % pump efficiency</i>	5.3 kWh/m ³	5.2 kWh/m ³	–0.8 %	agrees
ROSA projection, plant A with ERI PX pressure exchanger: 2.82 kWh/m ³ [83] tool or model result · validation	high-pressure pump with ERD <i>Hasim DM 8.4 (8.5) with ERD efficiency 0.96; the efficiency assumed by ROSA is not stated</i>	2.8 kWh/m ³	2.4 kWh/m ³	–16.7 %	deviates, optimistic

Power electronics

Reference	Basis	Published	Hasim	Deviation	Result
5 MW electrolyser, 24-pulse thyristor rectifier with transformer: 97.5 % [84] tool or model result · calibration	AC to DC <i>Hasim defaults: rectifier 0.97, transformer 0.99</i>	97.5 %	96.0 %	–1.5 %	agrees
5 MW electrolyser, IGBT rectifier with transformer: 96.0 % [84] tool or model result · calibration	AC to DC	96.0 %	96.0 %	±0.0 %	agrees

Ammonia synthesis

Reference	Basis	Published	Hasim	Deviation	Result
Haber–Bosch synthesis loop at full load (Hughes 2013, cited in the Oxford report): 0.6 kWh per kg NH ₃ [85] reference value · validation	loop incl. make-up compression, excl. ASU <i>Hasim DM 15.3 defaults: loop 0.12, H₂ make-up 1.0 kWh/kg H₂, N₂ 0.14 kWh/kg</i>	0.600 kWh/kg NH ₃	0.422 kWh/kg NH ₃	–29.7 %	deviates, optimistic
Cryogenic air separation: 0.119 kWh per kg N ₂ [85] reference value · validation	ASU	0.119 kWh/kg N ₂	0.120 kWh/kg N ₂	+0.8 %	agrees
Electrically driven Haber–Bosch: N ₂ separation and loop compressors 2.7 GJ per t NH ₃ [86] reference value · validation	ASU + loop compressors	0.750 kWh/kg NH ₃	0.524 kWh/kg NH ₃	–30.1 %	deviates, optimistic
IEA ammonia roadmap: ASU and Haber–Bosch units 5 % of 36 GJ/t (1.8 GJ/t) [87] reference value · calibration	ASU + synthesis <i>reference derived from the stated share</i>	0.500 kWh/kg NH ₃	0.524 kWh/kg NH ₃	+4.8 %	agrees
IEA: electricity for electrolytic ammonia 36.0 GJ/t with a 64 % (LHV) electrolyser [87] reference value · calibration	plant <i>Hasim chain with the stated electrolyser efficiency</i>	10.0 kWh/kg NH ₃	10.1 kWh/kg NH ₃	+0.8 %	agrees
Tully et al.: 10.5 kWh per kg NH ₃ with PEM at 55 kWh/kg H ₂ , ASU 0.119, loop 0.6 [88] tool or model result · validation	plant	10.5 kWh/kg NH ₃	10.6 kWh/kg NH ₃	+1.1 %	agrees

LCOH and GHG intensity

Reference	Basis	Published	Hasim	Deviation	Result
US DOE record 20004 (H2A v3.2018), PEM 1500 kg/d: Grid 5.0 c/kWh, CF 90 %, 1500 \$/kW [89] tool or model result · validation	LCOH without compression, storage and dispensing <i>conventions of record 24005; discount rate 11.6 % fitted on 24005</i>	5.1 \$/kg	5.1 \$/kg	–1.0 %	agrees
US DOE record 20004 (H2A v3.2018), PEM 1500 kg/d: Grid 5.0 c/kWh, CF 90 %, 1000 \$/kW [89] tool or model result · validation	LCOH without compression, storage and dispensing <i>conventions of record 24005; discount rate 11.6 % fitted on 24005</i>	4.4 \$/kg	4.3 \$/kg	–1.1 %	agrees
US DOE record 20004 (H2A v3.2018), PEM 1500 kg/d: Grid 7.0 c/kWh, CF 90 %, 1500 \$/kW [89] tool or model result · validation	LCOH without compression, storage and dispensing <i>conventions of record 24005; discount rate 11.6 % fitted on 24005</i>	6.3 \$/kg	6.2 \$/kg	–1.3 %	agrees
US DOE record 20004 (H2A v3.2018), PEM 1500 kg/d: Grid 7.0 c/kWh, CF 90 %, 1000 \$/kW [89] tool or model result · validation	LCOH without compression, storage and dispensing <i>conventions of record 24005; discount rate 11.6 % fitted on 24005</i>	5.5 \$/kg	5.4 \$/kg	–1.3 %	agrees

Reference	Basis	Published	Hasim	Deviation	Result
US DOE record 20004 (H2A v3.2018), PEM 1500 kg/d: Utility PV Los Angeles 3.2 c/kWh, CF 31.8 % [89] tool or model result · validation	LCOH without compression, storage and dispensing conventions of record 24005; discount rate 11.6 % fitted on 24005	6.1 \$/kg	5.8 \$/kg	−4.9 %	agrees
US DOE record 20004 (H2A v3.2018), PEM 1500 kg/d: Utility PV Daggett 2.9 c/kWh, CF 35.1 % [89] tool or model result · validation	LCOH without compression, storage and dispensing conventions of record 24005; discount rate 11.6 % fitted on 24005	5.5 \$/kg	5.3 \$/kg	−5.1 %	close, optimistic
US DOE record 20004 (H2A v3.2018), PEM 1500 kg/d: Onshore wind class 6, 3.8 c/kWh, CF 38.0 % [89] tool or model result · validation	LCOH without compression, storage and dispensing conventions of record 24005; discount rate 11.6 % fitted on 24005	5.8 \$/kg	5.5 \$/kg	−4.5 %	agrees
US DOE record 20004 (H2A v3.2018), PEM 1500 kg/d: Onshore wind class 1, 2.8 c/kWh, CF 52.1 % [89] tool or model result · validation	LCOH without compression, storage and dispensing conventions of record 24005; discount rate 11.6 % fitted on 24005	4.2 \$/kg	4.1 \$/kg	−3.6 %	agrees
Wolf et al. 2024, Spain, PV, 2050: median LCOH 2.33 EUR/kg (95 % interval 1.66–3.12) [90] tool or model result · validation	LCOH, closed production system most probable inputs: 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 7.53 %, 2362 h, 0.025 EUR/kWh	2.3 EUR/kg	2.2 EUR/kg	−6.4 %	close, optimistic
Wolf et al. 2024, Spain, onshore wind, 2050: median LCOH 4.52 EUR/kg (95 % interval 3.86–5.34) [90] tool or model result · validation	LCOH, closed production system most probable inputs: 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 7.53 %, 2902 h, 0.077 EUR/kWh	4.5 EUR/kg	4.4 EUR/kg	−3.3 %	agrees
Wolf et al. 2024, Spain, offshore wind, 2050: median LCOH 6.1 EUR/kg (95 % interval 4.9–7.48) [90] tool or model result · validation	LCOH, closed production system most probable inputs: 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 7.53 %, 3121 h, 0.111 EUR/kWh	6.1 EUR/kg	5.9 EUR/kg	−3.8 %	agrees
Wolf et al. 2024, Germany, PV, 2050: median LCOH 3.11 EUR/kg (95 % interval 2.36–4.04) [90] tool or model result · validation	LCOH, closed production system most probable inputs: 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 5.32 %, 1732 h, 0.039 EUR/kWh	3.1 EUR/kg	3.0 EUR/kg	−3.9 %	agrees
Wolf et al. 2024, Germany, onshore wind, 2050: median LCOH 3.46 EUR/kg (95 % interval 2.74–4.28) [90] tool or model result · validation	LCOH, closed production system most probable inputs: 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 5.32 %, 4255 h, 0.062 EUR/kWh	3.5 EUR/kg	3.3 EUR/kg	−3.8 %	agrees
Wolf et al. 2024, Germany, offshore wind, 2050: median LCOH 3.66 EUR/kg (95 % interval 3.06–4.38) [90] tool or model result · validation	LCOH, closed production system most probable inputs: 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 5.32 %, 4885 h, 0.068 EUR/kWh	3.7 EUR/kg	3.5 EUR/kg	−3.3 %	agrees

Reference	Basis	Published	Hasim	Deviation	Result
Wolf et al. 2024, Norway, onshore wind, 2050: median LCOH 2.92 EUR/kg (95 % interval 2.24–3.73) [90] tool or model result · validation	LCOH, closed production system <i>most probable inputs:</i> 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 6.61 %, 5136 h, 0.051 EUR/kWh	2.9 EUR/kg	2.8 EUR/kg	–4.8 %	agrees
Wolf et al. 2024, Norway, PV, 2050: median LCOH 4.6 EUR/kg (95 % interval 3.55–5.81) [90] tool or model result · validation	LCOH, closed production system <i>most probable inputs:</i> 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 6.61 %, 1719 h, 0.067 EUR/kWh	4.6 EUR/kg	4.4 EUR/kg	–4.3 %	agrees
Wolf et al. 2024, Norway, offshore wind, 2050: median LCOH 4.23 EUR/kg (95 % interval 3.51–5.11) [90] tool or model result · validation	LCOH, closed production system <i>most probable inputs:</i> 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 6.61 %, 4308 h, 0.078 EUR/kWh	4.2 EUR/kg	4.1 EUR/kg	–2.8 %	agrees
Wolf et al. 2024, Algeria, PV, 2050: median LCOH 2.41 EUR/kg (95 % interval 1.72–3.23) [90] tool or model result · validation	LCOH, closed production system <i>most probable inputs:</i> 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 10.17 %, 2388 h, 0.025 EUR/kWh	2.4 EUR/kg	2.4 EUR/kg	–2.1 %	agrees
Wolf et al. 2024, Algeria, onshore wind, 2050: median LCOH 3.73 EUR/kg (95 % interval 2.86–4.75) [90] tool or model result · validation	LCOH, closed production system <i>most probable inputs:</i> 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 10.17 %, 3834 h, 0.062 EUR/kWh	3.7 EUR/kg	3.6 EUR/kg	–3.5 %	agrees
Wolf et al. 2024, Algeria, offshore wind, 2050: median LCOH 6.8 EUR/kg (95 % interval 5.47–8.31) [90] tool or model result · validation	LCOH, closed production system <i>most probable inputs:</i> 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 10.17 %, 2787 h, 0.122 EUR/kWh	6.8 EUR/kg	6.6 EUR/kg	–2.5 %	agrees
Wolf et al. 2024, Morocco, PV, 2050: median LCOH 2.43 EUR/kg (95 % interval 1.73–3.28) [90] tool or model result · validation	LCOH, closed production system <i>most probable inputs:</i> 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 9.17 %, 2355 h, 0.025 EUR/kWh	2.4 EUR/kg	2.3 EUR/kg	–5.3 %	close, optimistic
Wolf et al. 2024, Morocco, onshore wind, 2050: median LCOH 3.62 EUR/kg (95 % interval 2.77–4.69) [90] tool or model result · validation	LCOH, closed production system <i>most probable inputs:</i> 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 9.17 %, 4696 h, 0.061 EUR/kWh	3.6 EUR/kg	3.4 EUR/kg	–6.9 %	close, optimistic
Wolf et al. 2024, Morocco, offshore wind, 2050: median LCOH 5.04 EUR/kg (95 % interval 4.2–6.04) [90] tool or model result · validation	LCOH, closed production system <i>most probable inputs:</i> 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 9.17 %, 4449 h, 0.093 EUR/kWh	5.0 EUR/kg	4.9 EUR/kg	–3.4 %	agrees
Wolf et al. 2024, Egypt, PV, 2050: median LCOH 3.87 EUR/kg (95 % interval 2.45–5.71) [90] tool or model result · validation	LCOH, closed production system <i>most probable inputs:</i> 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 23.79 %, 2409 h, 0.025 EUR/kWh	3.9 EUR/kg	3.5 EUR/kg	–10.6 %	deviates, optimistic

Reference	Basis	Published	Hasim	Deviation	Result
Wolf et al. 2024, Egypt, onshore wind, 2050: median LCOH 4.91 EUR/kg (95 % interval 3.86–6.24) [90] tool or model result · validation	LCOH, closed production system <i>most probable inputs: 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 23.79 %, 3896 h, 0.071 EUR/kWh</i>	4.9 EUR/kg	4.7 EUR/kg	–4.5 %	agrees
Wolf et al. 2024, Egypt, offshore wind, 2050: median LCOH 8.03 EUR/kg (95 % interval 6.32–10.1) [90] tool or model result · validation	LCOH, closed production system <i>most probable inputs: 458 EUR/kW, O&M 2.7 % incl. stacks, 72.7 % LHV, 26 a, WACC 23.79 %, 2810 h, 0.125 EUR/kWh</i>	8.0 EUR/kg	7.7 EUR/kg	–3.9 %	agrees
Terlouw et al. 2022: grid-connected PEM at Crete (grid 0.747 kg CO ₂ e/kWh, 54.6 kWh/kg): 41.4 kg CO ₂ e per kg H ₂ [91] tool or model result · calibration	cradle-to-gate LCA <i>Hasim: electricity only (RFNBO method)</i>	41.4 kg CO ₂ e/kg	40.8 kg CO ₂ e/kg	–1.4 %	agrees
Terlouw et al. 2022: grid-connected PEM at Eigerøy (grid 0.023 kg CO ₂ e/kWh): 1.5 kg CO ₂ e per kg H ₂ [91] tool or model result · calibration	cradle-to-gate LCA <i>embodied emissions of the plant are the difference</i>	1.5 kg CO ₂ e/kg	1.3 kg CO ₂ e/kg	–16.0 %	deviates, optimistic
Tenhumberg & Büker 2020: electrolysis on gas-turbine electricity (467 kg CO ₂ /MWh, 51.2 kWh/kg): 23.0 kg CO ₂ e per kg [92] reference value · validation	electricity-related	23.0 kg CO ₂ e/kg	23.9 kg CO ₂ e/kg	+3.9 %	agrees

Integrated plant studies

Reference	Basis	Published	Hasim	Deviation	Result
Yates et al. 2020, Port Hedland (GHI 2402): 1 MW electrolyser with 1.5× PV, mean LCOH 3.38 US\$/kg [93] tool or model result · calibration	LCOH incl. PV and electrolyser <i>Hasim dispatch: electrolyser capacity factor 30.5 %, 54.5 t/a; the study's cost inputs</i>	3.4 \$/kg	3.9 \$/kg	+16.0 %	deviates, conservative
Yates et al. 2020, Calama (GHI 2376): mean LCOH 3.60 US\$/kg [93] tool or model result · calibration	LCOH incl. PV and electrolyser <i>Hasim dispatch: capacity factor 31.4 %</i>	3.6 \$/kg	3.8 \$/kg	+6.1 %	close, conservative
Reichartz et al. 2024, 23.4 MW wind farm (Weibull 7.79 m/s, k 2.13) with a 2 MW PEM: electrolyser capacity factor 77 % [94] tool or model result · calibration	hourly dispatch <i>Hasim synthetic wind year with the stated Weibull parameters and turbine data, onshore loss allowance</i>	77.0 %	69.2 %	–10.1 %	deviates, conservative
Reichartz et al. 2024, use case A: 283.6 t H ₂ per year (electrolyser at a constant 70 % LHV) [94] tool or model result · calibration	annual hydrogen <i>Hasim with its own PEM model (no constant efficiency)</i>	284 t/a	243 t/a	–14.5 %	deviates, conservative
Reichartz et al. 2024, 58.5 MW wind farm with a 10 MW PEM: electrolyser capacity factor 68 % [94] tool or model result · calibration	hourly dispatch	68.0 %	58.2 %	–14.4 %	deviates, conservative
Reichartz et al. 2024, use case B: 1252 t H ₂ per year [94] tool or model result · calibration	annual hydrogen	1 252 t/a	1 025 t/a	–18.1 %	deviates, conservative

Reference	Basis	Published	Hasim	Deviation	Result
Superchi et al. 2023: alkaline cell assumed at 1.89 V, 1.0 A/cm ² , 71 °C [95] model assumption · validation	cell voltage	1.890 V	2.070 V	+9.5 %	close, conservative

11.4 Deviations above 10 %

15 conservative, 18 optimistic, 1 without a direction. Of the 26 crossover comparisons in the validation set (25 with a value in both versions), the median absolute deviation fell from 89 % with version 2.1 to 39 % with the present version and 16 instead of 7 lie within 50 %; two agree, one within 5 % and one by meeting a bound. The remaining optimistic deviations have identifiable causes: a laboratory cell at ambient pressure carries over about twice the equilibrium hydrogen content of the lye against the model's factor 1.3 (–32 to –38 % at three flow rates, the flow-rate proportionality itself being reproduced); its separated-cycle crossover at 1 bar is dominated by a supersaturation that saturates at low current density, which the linear term under-predicts (–70 %); a 15 kW stack with natural lye circulation shows four to six times the crossover that the preset's circulation of 2.2 L min^{–1} m^{–2} gives, its circulation rate being unknown (–71 to –82 %), and its Faraday efficiency of 86–95 % is lowered by shunt currents through the shared manifolds, which the model does not contain; a reinforced PFSA membrane is 1.6–1.9 times more permeable than the Nafion 117 of the calibration and its supersaturation slope 1.3–1.6 times the preset's, so that its current-density limits at 11 and 31 bar are under-predicted by about half; the open-circuit permeation of Nafion 117 at 80 °C exceeds the 60 °C value of the preset by nearly half; and a semi-empirical model of an advanced zero-gap cell at 100 °C and 20 bar gives five times the crossover of the 60 °C Zirfon parameters. Two conservative deviations are the under-load permeation of a second PEM cell (Nafion 117 and 212 membranes) at 80 °C and 1 bar, whose supersaturation slope is five times smaller than that of the calibration cell: the slope is cell-specific, as the calibration source itself notes for the literature, and the preset carries the larger value. The other conservative ones include the AEM and SOEC degradation presets, the alkaline minimum load (10–15 % stated against the 20 % design value), the PEM minimum load (15 % against 10.7 % of a 40 kW system), an advanced zero-gap alkaline cell, a vendor compressor rating, a steel-layered storage vessel, the stack consumption of the 500 kW alkaline stack at its rated 1.2 A/cm² and the electrolyser capacity factors of a wind-farm dispatch study computed without a loss allowance for the farm; the other optimistic ones a 12 kW PEM prototype with a lower voltage efficiency than the preset, a laboratory alkaline cell with plain nickel electrodes, the synthesis-loop energy of ammonia, soiling-affected PV plants, seawater RO with energy recovery, a small diaphragm compressor, the costs of composite storage vessels and one LCOH median of a 2050 study. Every row is listed with its deviation in section 11.3.

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