Hasim

Green Hydrogen Engineering Suite · version 2.1.0

Validation Note

External benchmark of Hasim: electrolysers, 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 2.1.0 · September 2026 · 86 comparisons · 52 references

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 2.1.0 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 (≤ 5 %)	Close (≤ 10 %)	Deviate (> 10 %)
PEM electrolysers: 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 electrolysers: 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 electrolysers, 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 ±3–8 % 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 2.1.0

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 2.1.0
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 cm²: 57.6 kWh/kg, 2.003 V at 1 A/cm²	0.12 Ω cm²: 53.9 kWh/kg, 1.873 V at 1 A/cm² (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 2.1.0
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/cm² (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 2.1.0
AEM 2 kW stack (ANIONE), 1 A/cm², 2 000 h [15]	1.80 V	2.003 V deviates, conservative	1.873 V agrees
US wind farms installed 2022 (233 W/m², 8.3 m/s at 100 m), 2023 [38]	40.0 %	40.6 % agrees	39.6 % agrees
US wind farms installed 2021 (231 W/m², 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 stack (Nel), PV and wind profiles [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/cm² 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 *Hasim replaces the stack after 39 385 h*	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 *Hasim lowers the cathode pressure at part load, down to 10 bar (at 30 bar the 2 % H_2-in-O_2 trip would limit the load to 31 %)*	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/cm² (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 *the expert elicitation gives 60 000–90 000 h*	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 *IRENA 2020: 57–69 kWh/kg*	55.0 kWh/kg	53.9 kWh/kg	−2.0 %	agrees
AEM: cell voltage at 0.2–1.0 A/cm² (review) [23] reference value	cell *Hasim at 1 A/cm²*	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 *measured at INL: 6.4 kWh of heat per kg*	9.0–9.9 kWh_{th}/kg	6.6 kWh_{th}/kg	−26.7 %	deviates, optimistic
SOEC: cell voltage at 0.6 A/cm² (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 electrolysers: 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 *Hasim AEL preset at atmospheric pressure*	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) *Hasim at 74 % load*	37.4 kWh/kg	37.1 kWh/kg	−0.8 %	agrees
SOEC 2 × 100 kW (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 *INL systems: below 0.2 %/1000 h*	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 systems – 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/m²/d [29] tool result	AC capacity factor, ILR 1.34 *Hasim at 6 kWh/m²/d*	34.0 %	33.6 %	−1.2 %	agrees
NREL ATB (SAM), single-axis, GHI 5.00–5.25 kWh/m²/d [29] tool result	AC capacity factor, ILR 1.34 *Hasim at 5.125 kWh/m²/d*	29.8 %	29.1 %	−2.3 %	agrees
NREL ATB (SAM), single-axis, GHI 4.00–4.25 kWh/m²/d [29] tool result	AC capacity factor, ILR 1.34 *Hasim at 4.125 kWh/m²/d*	24.5 %	23.7 %	−3.3 %	agrees
NREL ATB (SAM), single-axis, GHI < 3.75 kWh/m²/d [29] tool result	AC capacity factor, ILR 1.34 *Hasim at 3.5 kWh/m²/d*	21.4 %	20.2 %	−5.6 %	close, conservative
LBNL US fleet: gain of single-axis tracking over fixed tilt [30] measured	AC capacity factor *Hasim at 5.3 kWh/m²/d*	3.0–5.0 pp	3.2 pp	within	agrees
Chile, 109 tracking plants, fleet average (GHI about 2 500 kWh/m²/yr) [31] measured	specific yield *grid data may mix AC and DC ratings*	2 388 kWh/kWp	2 450 kWh/kWp	+2.6 %	agrees
India, 10 MWp at 18.75° N (GHI 1 814 kWh/m²/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/m²/yr) [33] measured	performance ratio	0.81	0.782	−3.5 %	agrees
Germany, new systems (GHI 1 102 kWh/m²/yr) [34] measured	performance ratio	0.80–0.90	0.855	within	agrees
HOMER Pro study, Ayvalık, Turkey (GHI 4.62 kWh/m²/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/m²/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/m²/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/m², 8.3 m/s at 100 m), 2023 [38] measured	capacity factor, curtailment (4.6 %) added back *wind index of the year 0.95; Hasim low-wind turbine (216 W/m²)*	40.0 %	39.6 %	−1.0 %	agrees
US wind farms installed 2021 (231 W/m², 8.0 m/s at 100 m), 2022 [38] measured	capacity factor, curtailment (5.3 %) added back *wind index of the year 1.06*	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 *Hasim with the turbine data of the farm, the FINO1 shape factor k 2.1 and the offshore loss allowance (15.5 %)*	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 % *Hasim offshore turbine class (IEA 15 MW reference turbine)*	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 *Hasim averages Z over the pressure range*	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 *Hasim default efficiencies*	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 *Hasim 20 → 440 bar, default efficiencies*	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 *Hasim default of the design basis*	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 *Hasim case A: RO recovery 0.8*	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 *Hasim case B: SWRO + second pass*	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 *Hasim case A: municipal water, RO recovery 0.8*	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

The three HOMER Pro studies that publish complete inputs and results [35, 36, 37] all ran the electrolyser at a constant 46.4 kWh/kg (85 % HHV at every load). 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 HOMER therefore reports about 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; and stack-specific durability data from the vendors.

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 2.1.0. 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.

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