Supplementary Information

Integrated Design and Construction of a 50kW Flexible Hybrid Renewable Power Hydrogen System Testbed

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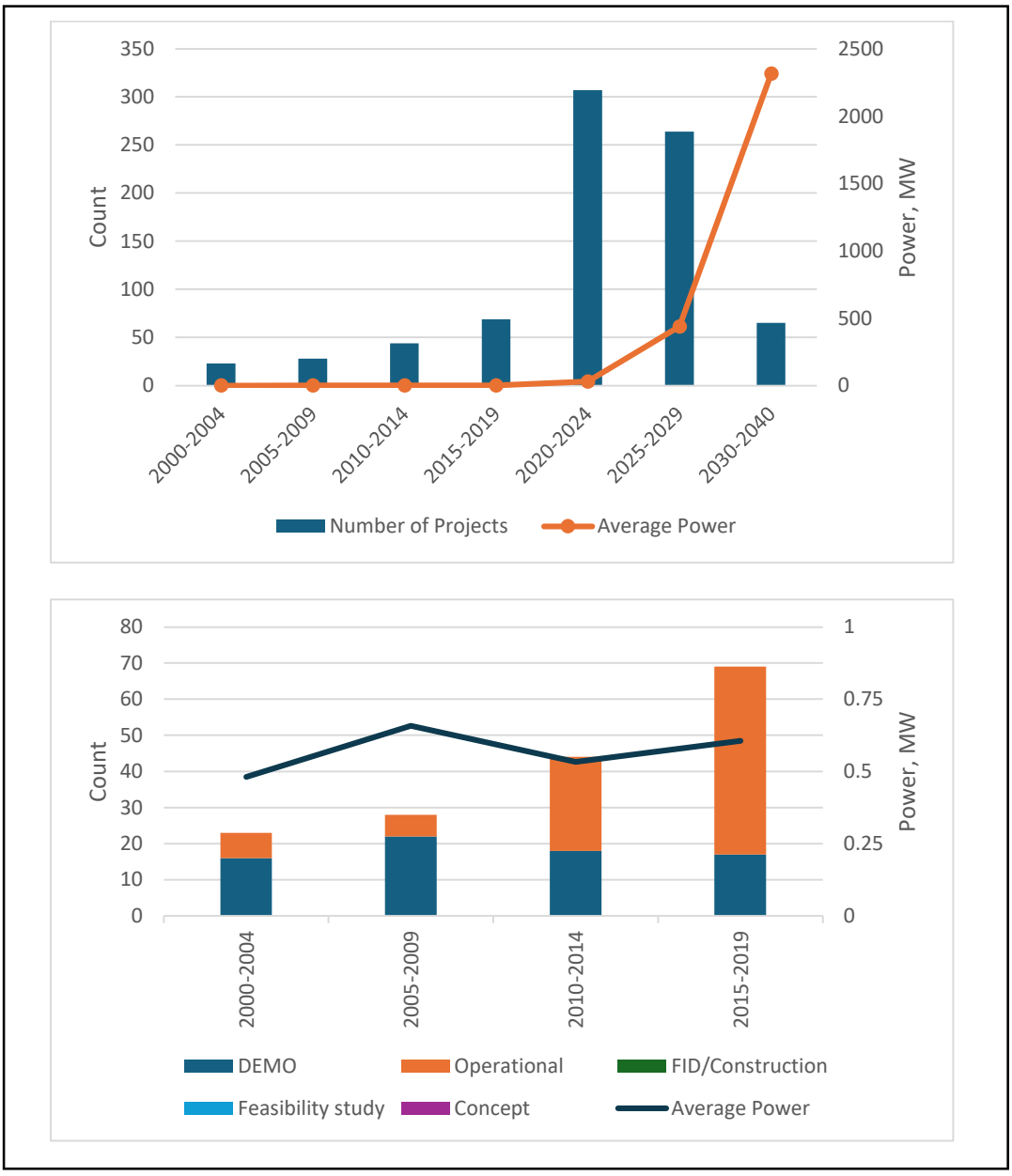
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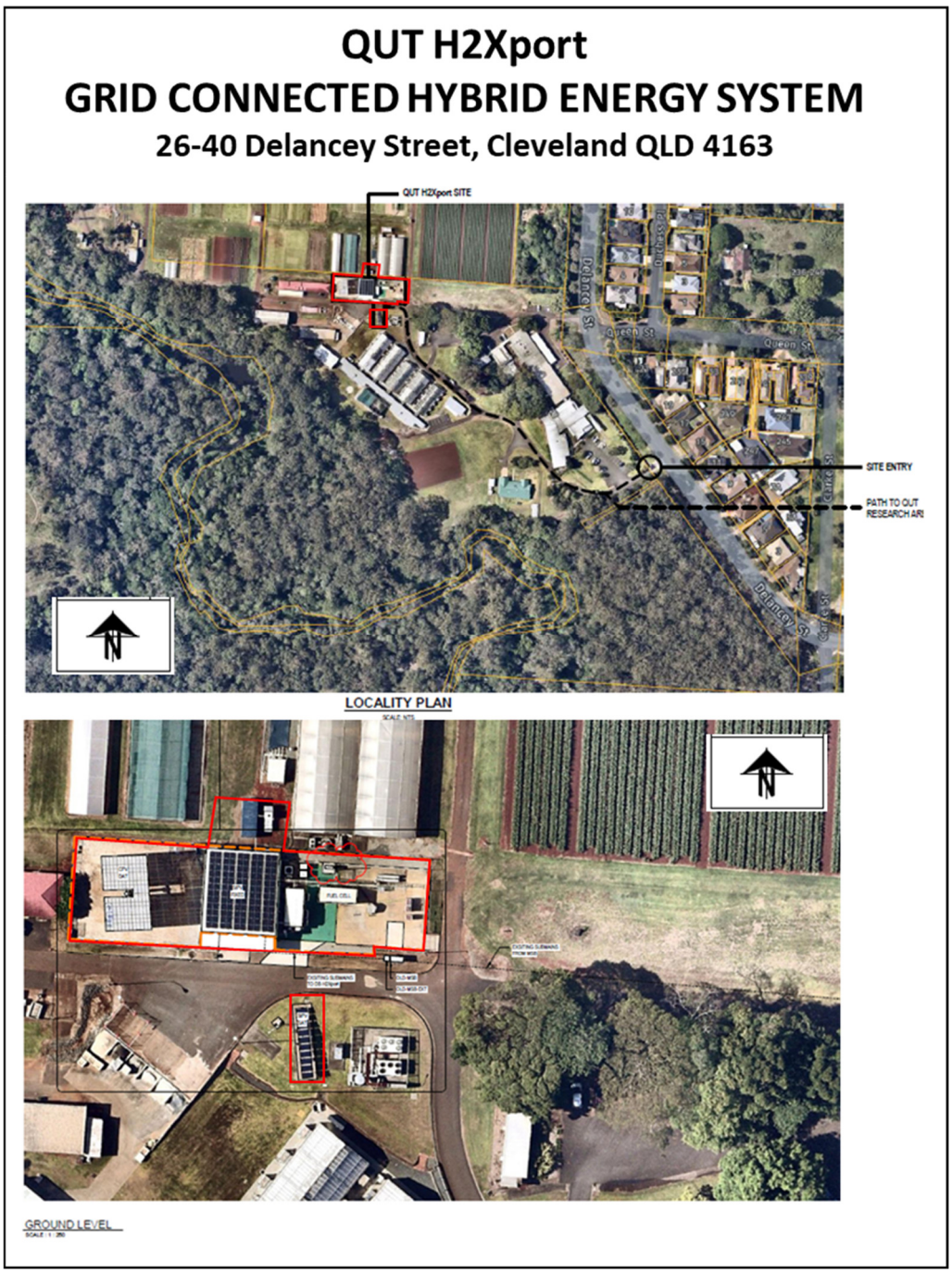
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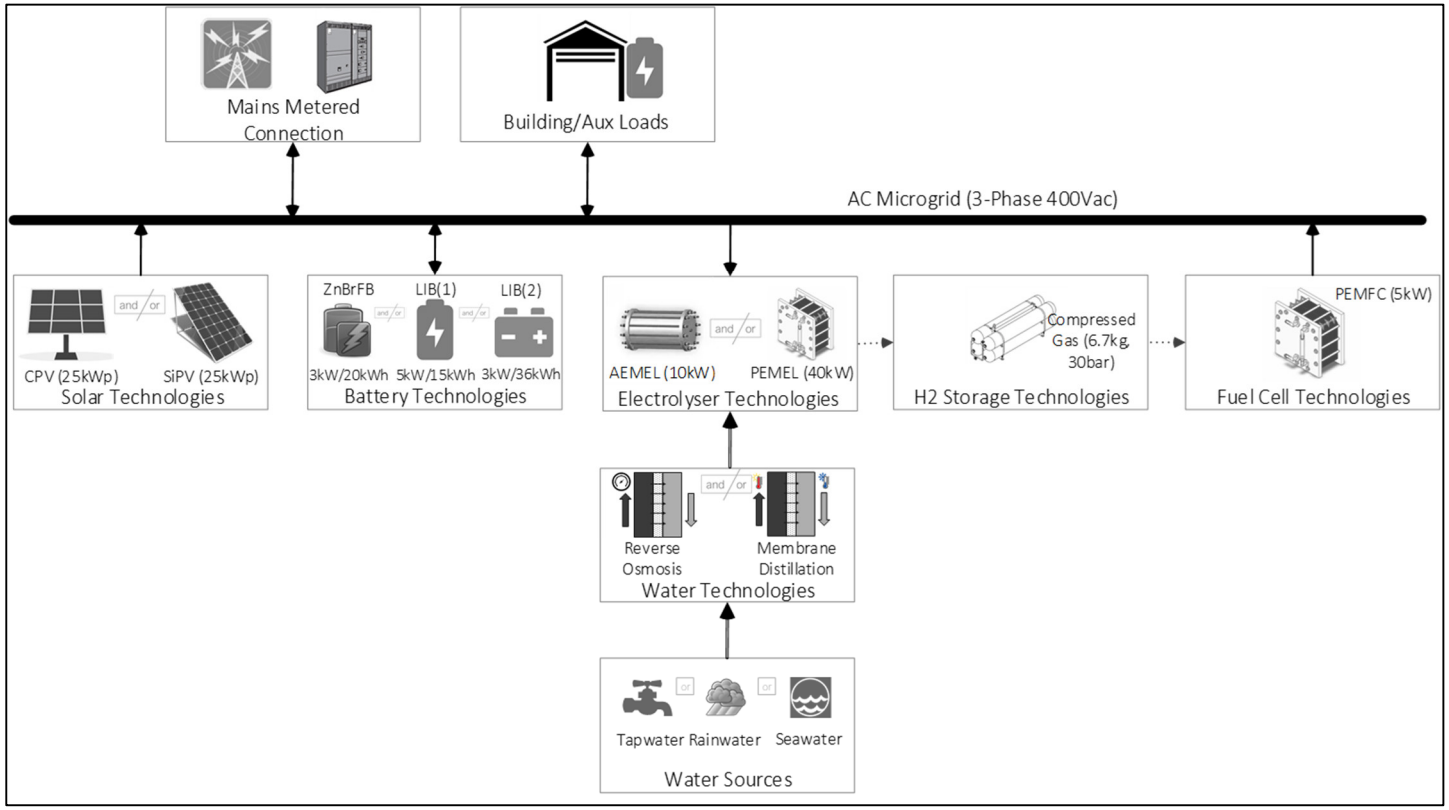
Supplementary Table S4 State of storage levels for mass and energy flows (re Schematics shown in Supplementary Figure S5).



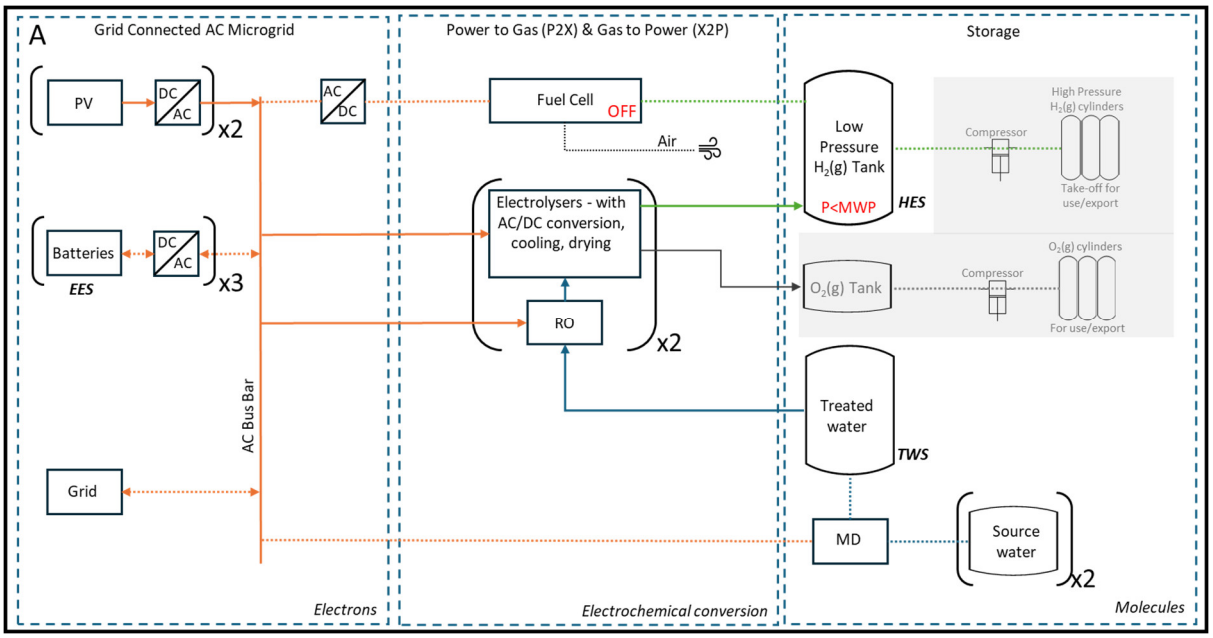
Supplementary Figure S1. Analysis of the project data in IEA database [3]. Database filtered for: known online dates (x-axis), dedicated renewables, hydrogen product while ignoring blank and 0MW$_{el}$ capacity. Upper plot between 2000-2040 and the lower plot 2000-2019, which shows hydrogen projects at the time the QUT H2Xport testbed was designed and constructed.

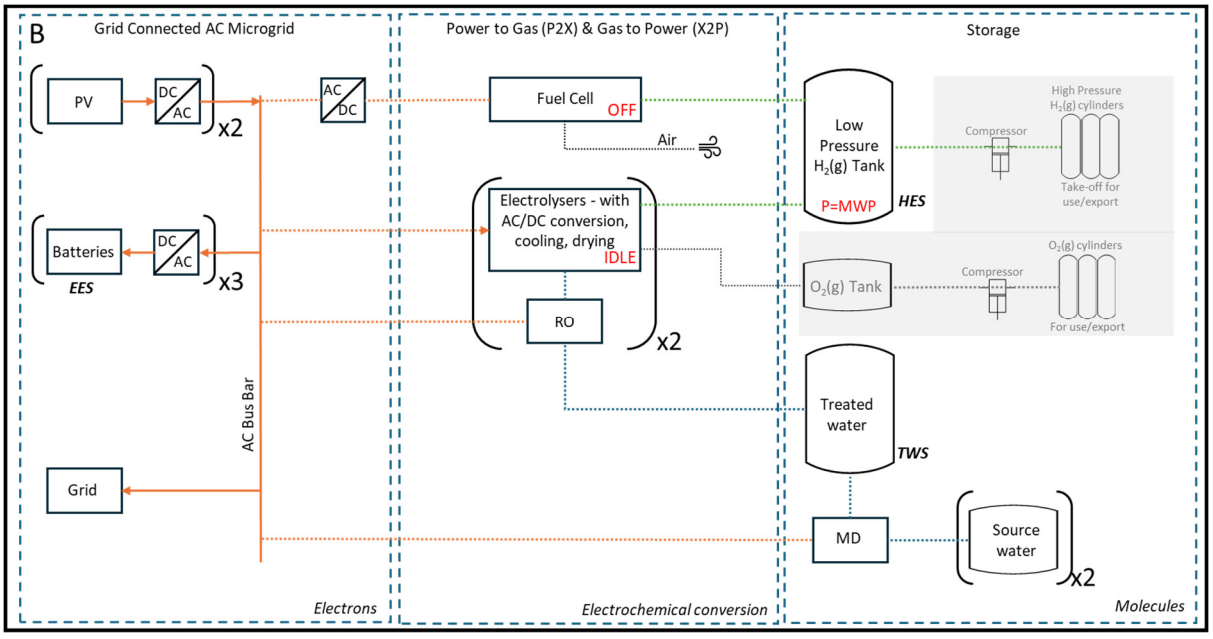


Supplementary Figure S2. Map view of QUT H2Xport HRPH site is a leased area within red outline located at Queensland Department of Agriculture and Fisheries (DAF) Redlands Research Facility, 26-40 Delancey Street, Cleveland, Queensland 4163, Australia (Coordinates: -27.526811, 153.249487).



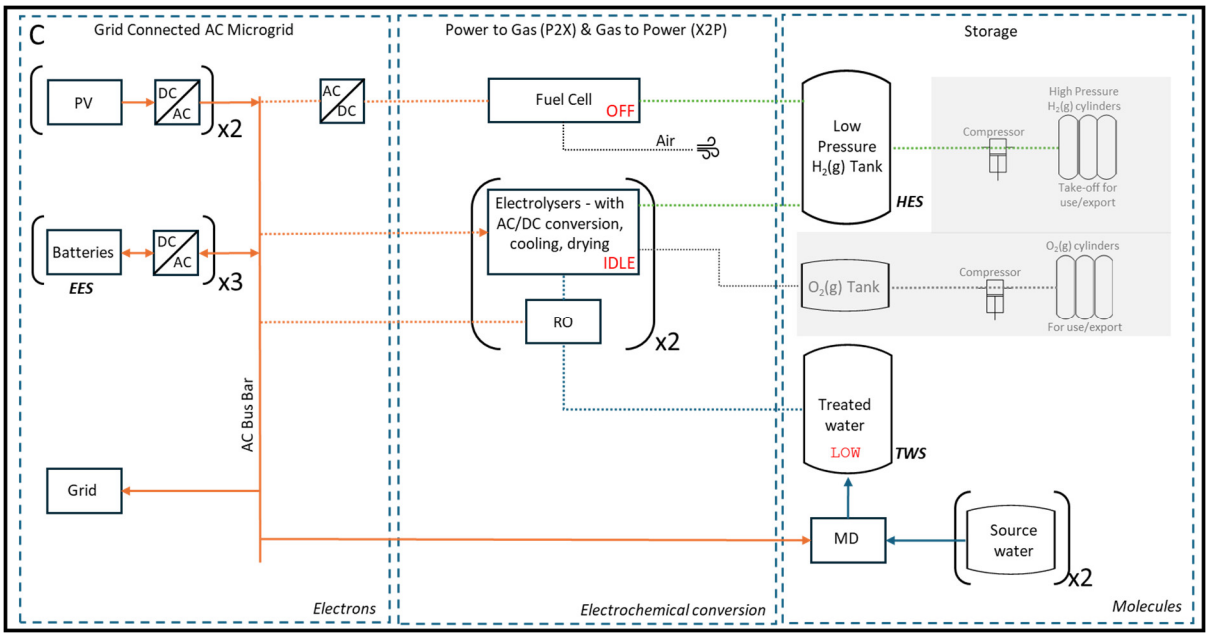
Supplementary Figure S3. Schematic of the Flexible HRPH Testbed Facility. Details of technologies are in Table 1. The testbed has flexibility to produce renewable hydrogen by selecting one of up to 72 possible daytime and 15 nighttime configurations based on desired combinations/permutations of solar, battery and electrolyser technologies.

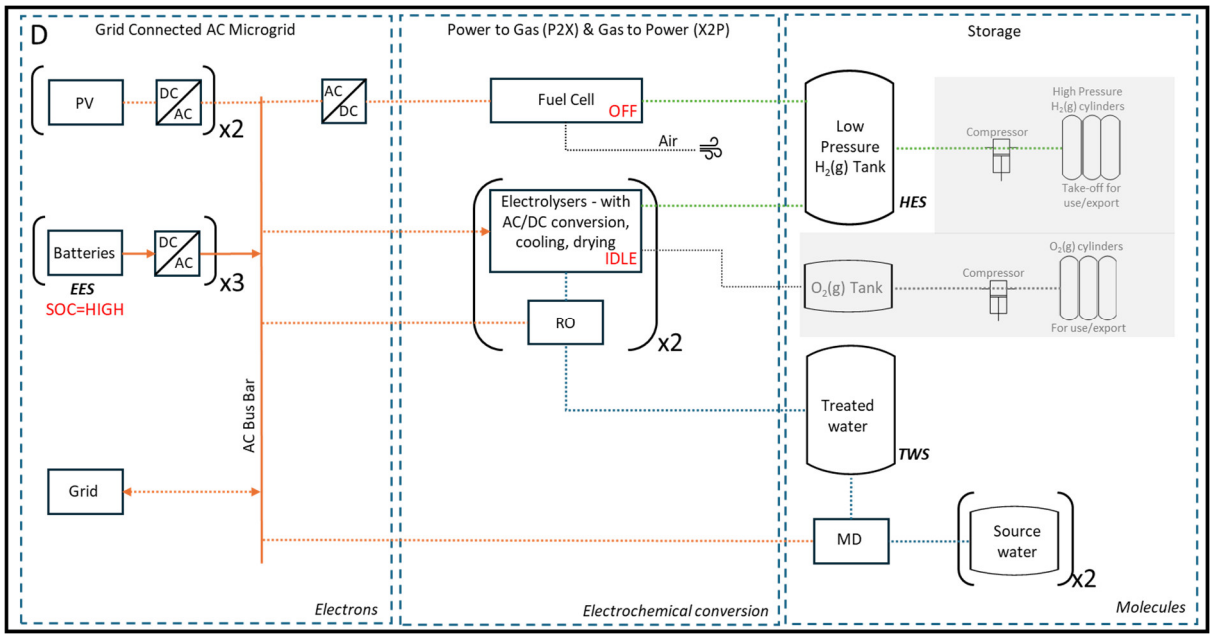




Supplementary Figure S4.
Figure 4(A-B) Schematic of energy and mass flows. Orange arrows: power. Blue arrows: water. Green arrows: hydrogen. The xN multipliers indicate the number of different technologies connected. Arrows depict direction of flow. Lines with no arrows indicate connected but no flow. Solid lines mean primary mass/energy flow and dashed lines indicates low flow conditions at minimum demand (e.g. at electrolyser minimum power or fuel cell minimum power).
(A) Full solar insolation when HES is not full; that is, electrolyser(s) are producing hydrogen

(B) Full solar insolation when HES is full; electrolyser(s) are not producing hydrogen

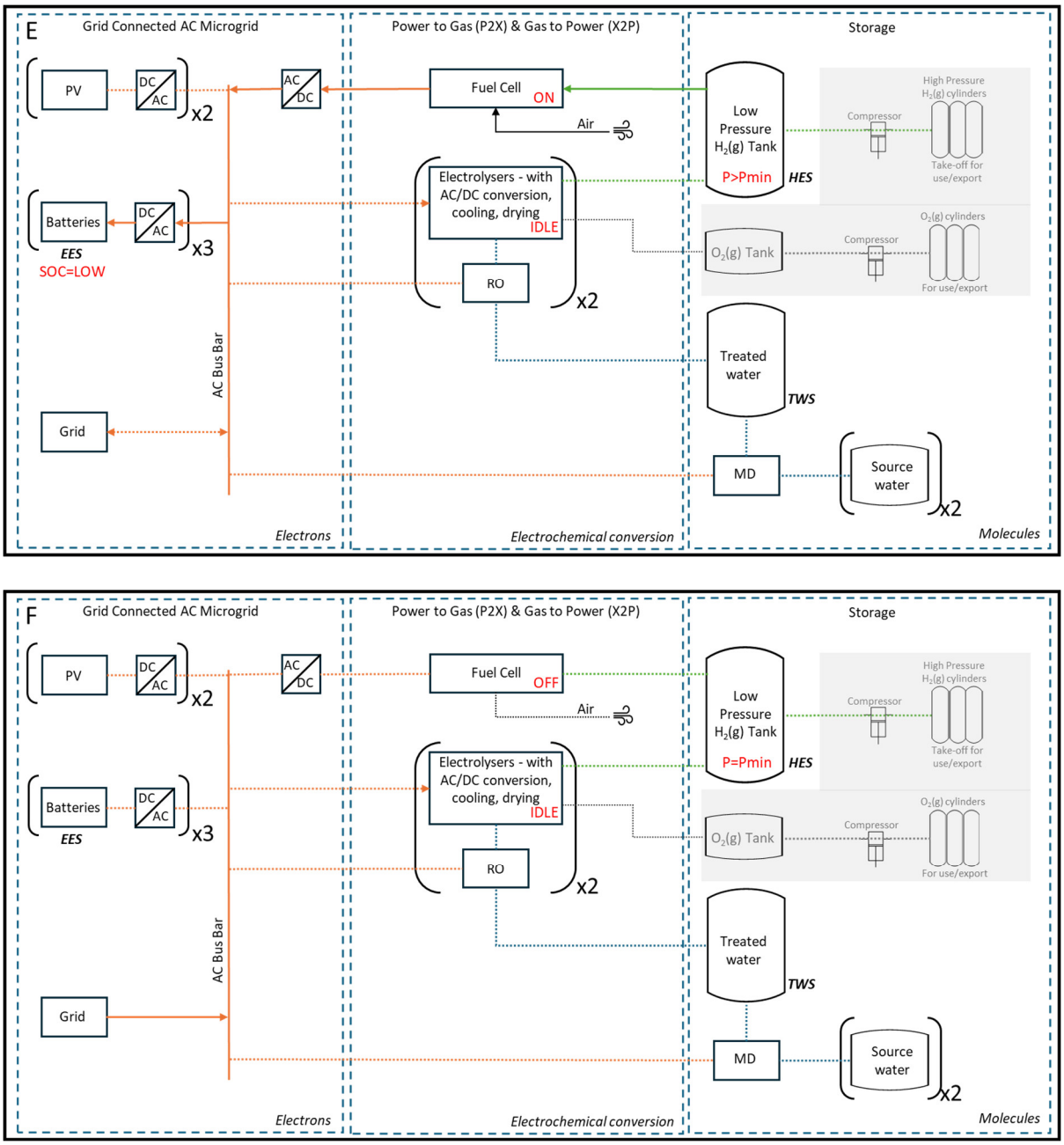




Supplementary Figure S4(C-D) Schematic of energy and mass flows. Orange arrows: power. Blue arrows: water. Green arrows: hydrogen. The xN multipliers indicate the number of different technologies connected. Arrows depict direction of flow. Lines with no arrows indicate connected but no flow. Solid lines mean primary mass/energy flow and dashed lines means low flow conditions at minimum demand (e.g. at electrolyser minimum power or fuel cell minimum power).

(C) When the treated water tank is low and can be filled by MD operation with solar insolation high, thus requiring electrolysers not to produce hydrogen.

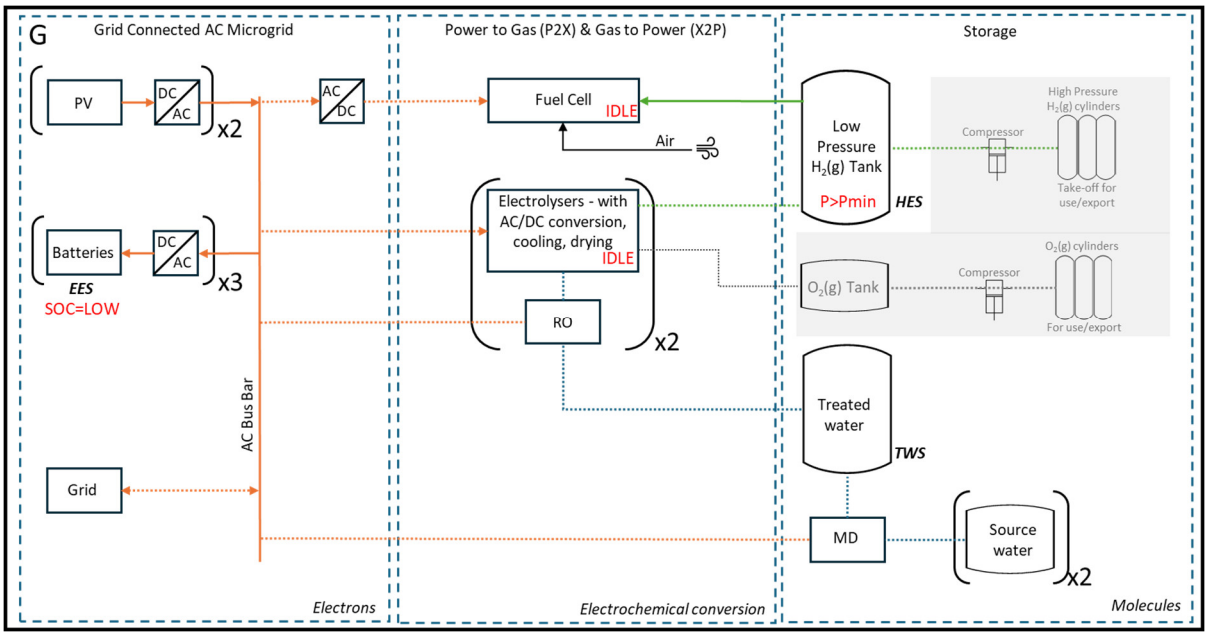
(D) No solar insolation and Energy Storage Sysytem has high SOC.

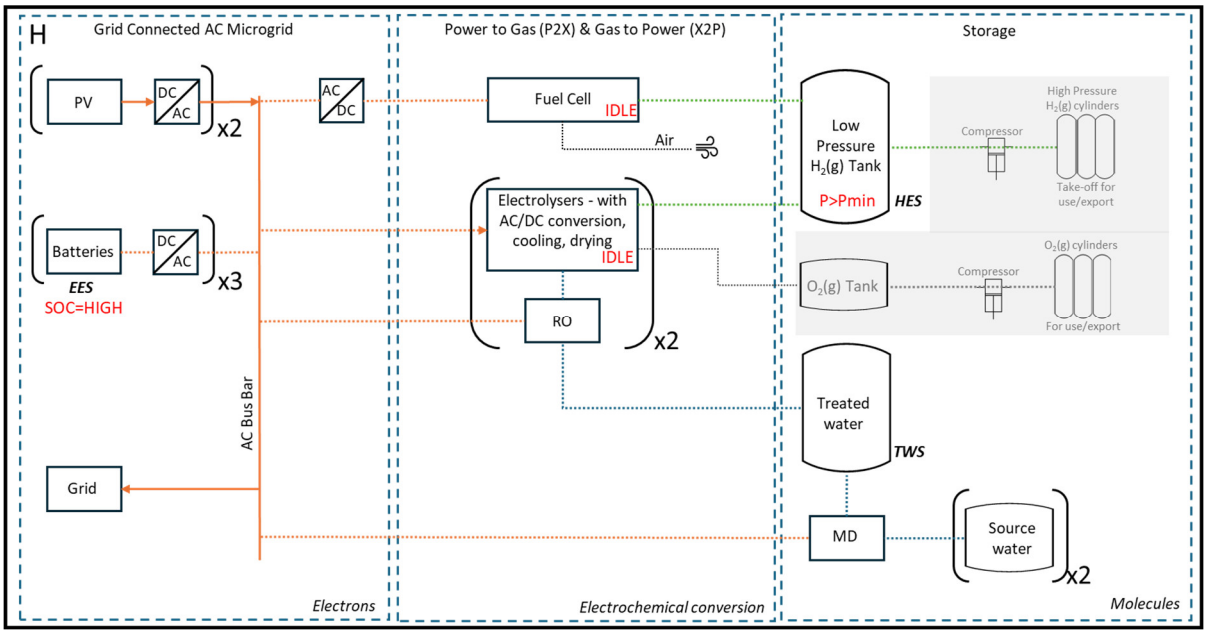


Supplementary Figure S4(E-F) Schematic of energy and mass flows. Orange arrows: power. Blue arrows: water. Green arrows: hydrogen. The xN multipliers indicate the number of different technologies connected. Arrows depict direction of flow. Lines with no arrows indicate connected but no flow. Solid lines mean primary mass/energy flow and dashed lines means low flow conditions at minimum demand (e.g. at electrolyser minimum power or fuel cell minimum power).

(E) No solar insolation and ESS with no or low SOC and the HES is above the pressure level for FC to operate.

(F) No solar insolation and ESS with no or low SOC and the HES is below the pressure level for FC to operate





Supplementary Figure S4(G-H) Schematic of energy and mass flows. Orange arrows: power. Blue arrows: water. Green arrows: hydrogen. The xN multipliers indicate the number of different technologies connected. Arrows depict direction of flow. Lines with no arrows indicate connected but no flow. Solid lines mean primary mass/energy flow and dashed lines means low flow conditions at minimum demand (e.g. at electrolyser minimum power or fuel cell minimum power).

(G) Low solar insolation with low ESS SOC

(H) Low solar insolation with maximum ESS SOC

Supplementary Figure S4(A-H) Description.

The energy and mass flow of the HRPH testbed is schematically shown in Supplementary Figure S4 for different time periods of high (A, B, C), no (D, E, F) and low (G, H) solar insolation representing full daytime sun, overnight and twilight (dawn and dusk) or cloud cover periods, respectively.

When there are full sun conditions (A) the renewable power from the solar arrays is distributed *via* solar inverters with Maximum Power Point Tracking (MPPT) to the microgrid switchboard busbar. When that power level is above the level required by the electrolyser(s) to generate hydrogen then either one or both electrolysers are

switched from a standby/idle low power state to produce hydrogen. The hydrogen production from the electrolyser(s) may be at full rated power or at a turn down power level to balance the available generated renewable power and loads so that no mains electricity is imported. The available solar power will also be distributed to connected critical auxiliary loads. The external grid acts to balance any instantaneous mismatch in total electrolyser and auxiliary load power level and generated renewable power available on the AC microgrid busbar. The fuel cell is off and consumes no hydrogen during the day. The hydrogen generated by electrolyser(s) is stored in the 30bar buffer tank.

If the HES becomes full reaching 30bar maximum working pressure (Fig. S4B), the electrolyser(s) have an internal automated process to turn off electrolyser hydrogen production and the electrolyser power demand will fall to a minimum base load level. Excess solar power charges EES or is exported to mains.

If the level of treated water (TWS) is low, the electrolysers identify a low water pressure and automatically switch to a standby/idle state where no hydrogen is produced, and the available solar power can be used to operate the MD plant to fill the TWS (Fig. S4C).

When there is no solar insolation (Fig. S4D), overnight or during very heavy cloud cover in daytimes, there is not enough solar power generated to power the HRPH testbed from renewables. All equipment is either off or in a low power state standby/idle with no hydrogen production. The low power level required by the electrolyser and auxiliary loads in the testbed (~ 2kW) is provided from the batteries that are programmed to discharge power to the AC microgrid using the hybrid inverter functionality.

If the batteries become depleted (Fig. S4E) the FC is switched on and regenerates renewable power to the AC microgrid busbar *via* consumption of renewable hydrogen from the HES. This state can continue until the HES reaches its minimum pressure level (Fig. S4F) set by the hydrogen pressure required for the FC operation when the FC is switched off. The combined energy storage in EES (~ 60kWh when full) and HES (equivalent to 120kWhe of regenerated power via the fuel cell) can sustain a low power condition for up to 3 days. Thereafter, the HRPH testbed can be powered from mains power.

When solar insolation is moderate to low, at dawn, dusk, or moderate cloud cover during the day, then the electrolysers are ramped down to no longer produce hydrogen and the low power demand is provided from the available solar power with excess solar power used to charge the batteries (Fig. S4G). If the EES has low SOC and it is dusk, the FC may be switched to idle in readiness for turning on to charge batteries from regenerated power and then reverting to mass/energy flow schematic E. If the batteries have full state of charge when solar insolation is low the excess solar power is exported to the mains grid (Fig. S4H) in which case the FC remains off as the mass/energy flow reverts to schematic D at dusk.

See also Supplementary Table S4.

Supplementary Table S1: Hydrogen R&D Testbeds.

This table shows a list of other research HRPH testbeds that may be relevant to this work with a focus on testbeds capable of testing multiple electrolysers and/or multiple hybrid energy management configurations. The list is not an exhaustive survey due to the rapid pace of the hydrogen industry and different reporting status for many projects in a rapidly transforming field. Testbeds located with electrolyser and/or fuel cell original equipment developers or manufacturers are not included. Commercial/industrial scale production plants are not included.

HRPH Testbed	Key features/capabilities	Comparison to this work (H2Xport HRPH)
Wind2H2 project [1-3]	A grid connected RPH testbed consisting of multiple electrolysers with different power input configurations. The objectives of the Wind2H2 project included demonstration, providing operating experience, investigation of energy management and use of energy storage for variable renewable electricity sources.	A similar testbed to this work with wind as the primary RE source rather than CPV and SiPV.
CSIRO's Centre for Hybrid Energy Systems (CHES), Clayton, Australia [4] Sourced from https://www.csiro.au/en/research/technology-space/energy/ches	Capable of (i) "Rapid prototyping of hybrid energy systems in different configurations" (ii) "test and evaluate any electrolysis hydrogen generation system and fuel cell" (iii) "demonstration projects involving renewable energy systems, with variable load profiles for specific locations, and emerging energy conversion / storage technologies"	Similar capabilities to the H2Xport testbed in this work. Does not include CPV and SiPV comparison nor membrane distillation treatment of seawater
Sir Samuel Griffith Centre in Griffith University. Brisbane, Australia opened in 2013 [5]. Sir Samuel Griffith Centre | Green Building Council of Australia (gbca.org.au)	376 kW solar PV array mounted on the building, 1 MWh lithium-ion battery bank, 160 kW alkaline electrolyser, 120 kg hydrogen metal hydride storage, and two 30 kW PEM fuel cells. The Sir Samuel Griffith Centre is a grid connected hybrid system with the capability to operate independently of the grid with the hydrogen energy storage capable of supporting the building electrical loads for 2 MWh consumption over several days.	Although one of the first "Hydrogen Living labs" this HRPH system has a fixed energy management system with single technology (one type SiPV, one type LiB, single electrolyser).
KETH Kiwana Energy Transformation Hub https://www.keth.com.au/research/	Industrial scale research including (i) "High level of instrumentation for detailed monitoring and analysis." (ii) "Provision for future research modules to be added to the facility". (iii) "Tie-in points to enable both full-flow and slipstream connections to research equipment".	In early stages of development
FEITH Future Energy Innovation and Training Hub https://www.stanwell.com/our-news/media/new-energy-innovation-training-centre-to-accelerate-queenslands-energy-transformation-2/	A MW Industrial scale innovation HRPH testbed for benchmarking hydrogen production technologies	In early stages of development
Translational Energy Research Centre (TERC) in the Energy Institute, Sheffield University, England [6]. TERC – Translational Energy Research Centre	TERC is "a unique, national pilot-scale facility for R&D into low- and zero-carbon energy solutions, and is one of the largest and best-equipped facilities of its kind in Europe" Includes electrolyser testbed, carbon capture and conversion to renewable liquid fuels with certification testing of SAF.	The facility has a mixture of standalone equipment and some technologies.
Research Accelerator Demonstration Building - University of Nottingham, England Hydrogen Systems Test Bed Hydrogen Systems Test Bed - ERA Energy Research Accelerator	The Hydrogen Systems Test Bed is a flexible test facility for developing different hydrogen components relating to generation, storage and use. The facility includes a 1MWh hydrogen store that enables testing to systems up to 100 kW in scale. The facilities are developing novel materials such as a AB2 metal hydride alloy with high energy density.	The facility is part of a national network of installations dedicated to solving and accelerating energy solutions (Energy Research Accelerator).
Renewable Energy Integration Demonstrator (REID) on Semakau Island, Singapore	REID is a "R3D (Research, Development, Demonstration and Deployment) platform" with	A unique system integration with seven interconnected microgrids allowing energy

Renewable Energy Integration Demonstrator - Singapore | Energy Research Institute @ NTU | NTU Singapore	multiple connected power microgrids integrated with standalone hydrogen systems.	sharing. Multiple industry compounds test stand-alone hydrogen equipment connected to the common solar field and microgrids.
GreenLab. DTU Energy Conversion at Technical University of Denmark (DTU), Denmark: https://www.dtu.dk/english/news/all-news/new-test-facility-for-testing-sustainable-fuels?id=49efd407-add6-4d38-bc21-db78e24d00ea	500kW scale research Power-to-X testbed for marine, aircraft transport sustainable fuels. Includes electrolysis, solar, wind, batteries.	Unknown if individual technologies are an integrated system or the level of plug-and-play.
University of California, Irvine (UCI), USA: http://www.nfcrc.uci.edu/Overview.html	UCI's National Fuel Cell Research Center has a testbed system for renewable hydrogen research, including pilot plants that integrate renewable power sources and electrolysers.	Unknown if individual technologies are an integrated system or the level of plug-and-play.

Supplementary Table S2: Inverter List for H2Xport Project

Fixed inverters approved by Energex as per Single Line Diagram. Inverters are connected to the microgrid via 400Vac 3-phase 3~NPE 400/230 except for EL-08 connected via 240Vac single phase.

INVERTER	MAKE/MODEL	POWER	VDC
IES01	FRONIUS/ ECO 27.0-3-S	27kW	580 - 1000
IES02	FRONIUS/SYMO 3.0-3-M	3kW	150 - 1000
IES03	FRONIUS/SYMO 20.0-3-M	20kW	200 - 1000
IES04, IES05, IES06, IES07	DEYE/SUN-8K-SG04LP3-AU	8kW	48
IES08	DEYE/SUN-5K-SG04LP1-AU	5kW	48

Supplementary Table S3: Instrumentation and Fittings List for H2Xport Project

Instrumentation listing. Panels assembled by Swagelock. All fittings and piping SS316. Longer piping lengths between panels and container/demountable orbital welded. All fittings Swagelock

INSTRUMENT	MAKE/MODEL	Ex Markings/ Certificate Number
Pressure transmitter	WIKA IS-3-0-2271-1ZZ-BBMNDZZ-GTA3ZZZ-UAZ AI-1	Ex ia IIC T4/T5/T6 Ga/Gb and Ex ia IIC/IIB T4 Gb IECEx TSA 16.0004X and EPS 21 ATEX 1036X
Pressure Gauge	Swagelock 100mm PGI-100S-JG4000-LAR1 Range: 0 – 4000kPa, Glycerine Filled PGI-100S-JG1600-LAR1 Range: 0 - 1600kPa, Glycerine Filled	
Humidity and Dew-Point Sensor	Michell Instruments EA2-IS-TX-B1-C1-D1 Easidew I.S. G1/2" BSP Connection, -100 to +20 0 Cdp Output range, HDPE guard (<10um), 4-20 mA,	Ex ia IIC T4 Ga Tamb -20 to 70°C IECEx BAS 06.0090X
Temperature transmitter	INOR Process AB IPAQ C330X TYPE K EXIA TO SUIT SS-TT-S8 1/2" THERMOWELL TEE	Ex ia IIC T6..T4 Ga IECEx KIWA 16.0016X
Flow Meter	Krone H250/RR/M40/ESK-Ex	Ex ia IIC T6..T2 Gb IECEx PTB 11.0069X

FITTING	MAKE/MODEL	Part Number
Regulator	1/2" RHPS MIP: 35 bar, Control Range: 0-9 bar	LRSN4-02-2-VTV
Hand Valve	1/2" AFS Ball Valve	S-AFSS8
Double block & bleed valve		SS-V2NBM8-F8-11486
Needle Valve	1/2" Needle Valve	S-1KS8
Control Valve	1/2" AFS Ball Valve with actuator	SS-AFSS8-A30C4
Relief Valve	1/2" R4 Series	SS-R4S8-SETB
Relief Valve	1/2" Proportional	CS-SS-R4S8-SETB
Check Valves	1/2" CH Series Check Valve	SS-CHS8-1 SS-8C-1

Supplementary Table S4: State of storage levels for the mass and energy flow schematics shown in Supplementary Figure S4.

n.c indicates not critical. EES is Electron Energy Storage (Batteries), HES is Hydrogen Energy Storage (30bar Tank), TWS is Treated Water Storage, EL are Electrolysers, FC is the Fuel Cell and MD is the Membrane Distillation system.

Note 1: If EES is at maximum the excess solar is exported to mains.

Note 2: EES can be charged if there is excess solar and EES SOC is low. Or EES can be discharged if more renewable power is needed and EES SOC is high.

Note 3: HES level is not critical during this low solar condition but if HES level is near minimum, then when dusk becomes night the fuel cell cannot operate to charge batteries and reverts to mass/energy flow in schematic E with larger amount of mains power used rather than reverting to that in schematic D when fuel cell can be operated.

Note 4: HES level is not critical during this low solar condition but (i) if at dawn the HES level is ideally low to allow electrolysers to switch on and reverting to mass/energy flow in schematic A and (ii) if at dusk the HES level is ideally high to allow fuel cell to switch on if reverting to mass/energy flow in schematic D.

SCHEMA IN FIGURE 5	LEVEL OF SOLAR INSOL'N	EES SOC	HES LEVEL	TWS LEVEL	EL	FC	MD	PRIMARY MASS/ENERGY FLOWS
A	FULL	Note 1	LOW	HIGH	ON	OFF	OFF	Solar power to Electrolyser to Produce Hydrogen to HES.
B		Note 1	FULL	n.c.	IDLE	OFF	OFF	Excess Solar charges ESS or is exported to mains because Electrolyser automatically stops producing hydrogen when HES is full.
H		Note 2	n.c.	LOW	IDLE	OFF	ON	Solar power to operate MD plant to fill WTS. Any excess solar charges batteries or exported.
C	NONE	HIGH	n.c.	n.c.	IDLE	OFF	OFF	Stored renewable energy in ESS provides low power demand overnight
D		LOW	Above MIN	n.c.	IDLE	ON	OFF	FC produces regenerated power from HES to charge batteries and provide low power demands overnight
E		LOW	AT MIN	n.c.	IDLE	OFF	OFF	Grid provides low power demand when no renewable energy stored in ESS or HES
F	LOW	LOW	Note 3	n.c.	IDLE	IDLE	OFF	Low levels of solar power provides low power demand and any excess charges ESS
G		MAX	Note 4	n.c.	IDLE	OFF	OFF	Low levels of solar power provides low power demand and any excess is exported

Supplementary References

1. Harrison, K.W., Martin, G.D., Ramsden, T.G., Kramer, W.E., Novachek, F.J., *The Wind-to-Hydrogen Project: Operational Experience, Performance Testing, and Systems Integration*, National Renewable Energy Laboratory, Golden CO USA, 2009.
2. *Renewable Electrolysis Integrated System Development and Testing*, National Renewable Energy Laboratory **2011** pp. 23 https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review11/pd031_harrison_2011_o.pdf?sfvrsn=9ef6f578_1 (Accessed on 20 March, 2024.)
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6. *Translational Energy Research Centre* University of Sheffield https://terc.ac.uk/ (Accessed on 12 February 2024).