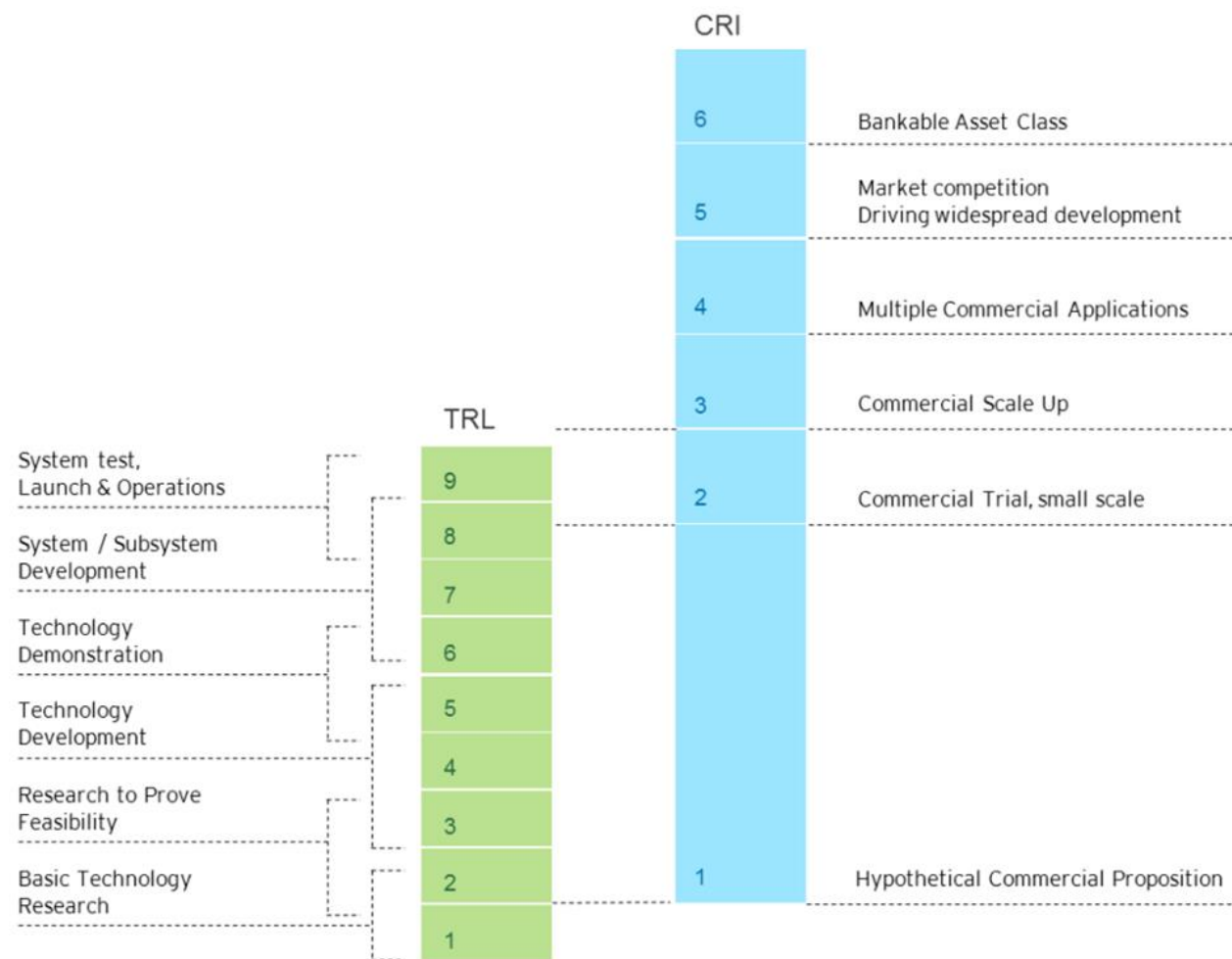


Appendix

Green Hydrogen and Derivatives Technology Assessment for the Pacific

Relationships between Technology Readiness Level (TRL) and Commercial Readiness Index (CRI)



References:

Commonwealth of Australia (Australian Renewable Energy Agency) 2014.

Technology readiness level (TRL)

TRL	Description
1	Basic principles observed and reported: Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.
2	Technology concept and/or application formulated: Applied research. Theory and scientific principles are focused on a specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.
3	Analytical and experimental critical function and/or characteristic proof of concept: Proof of concept validation. Active research and development is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.
4	Component/subsystem validation in laboratory environment: Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.
5	System/subsystem/component validation in relevant environment: Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.
6	System/subsystem model or prototyping demonstration in a relevant end-to-end environment: Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.
7	System prototyping demonstration in an operational environment: System prototyping demonstration in operational environment. System is at or near scale of the operational system with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.
8	Actual system completed and qualified through test and demonstration in an operational environment: End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed
9	Actual system proven through successful operations: Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

References:
Commonwealth of Australia (Australian Renewable Energy Agency) 2014.

Commercial readiness index (CRI) description

CRI	Description
6	"Bankable" grade asset class driven by same criteria as other mature energy technologies. Considered as a "Bankable" grade asset class with known standards and performance expectations. Market and technology risks not driving investment decisions. Proponent capability, pricing and other typical market forces driving uptake.
5	Market competition driving widespread deployment in context of long-term policy settings. Competition emerging across all areas of supply chain with commoditisation of key components and financial products occurring.
4	Multiple commercial applications becoming evident locally although still subsidised. Verifiable data on technical and financial performance in the public domain driving interest from variety of debt and equity sources however still requiring government support. Regulatory challenges being addressed in multiple jurisdictions.
3	Commercial scale up occurring driven by specific policy and emerging debt finance. Commercial proposition being driven by technology proponents and market segment participants – publically discoverable data driving emerging interest from finance and regulatory sectors.
2	Commercial trial: Small scale, first of a kind project funded by equity and government project support. Commercial proposition backed by evidence of verifiable data typically not in the public domain.
1	Hypothetical commercial proposition: Technically ready – commercially untested and unproven. Commercial proposition driven by technology advocates with little or no evidence of verifiable technical or financial data to substantiate claims.

References:

Commonwealth of Australia (Australian Renewable Energy Agency) 2014.

Multicriteria Analysis Framework – Production Technology

Metric	Description	Scoring
Technology maturity	Technology maturity is evaluated based on the technology readiness level (TRL) of the hydrogen and derivatives production technology	1 – TRL 1-4 2 – TRL 5-8 3 – TRL 9
PICTs infrastructure readiness	Infrastructure readiness is evaluated based on the availability of existing supporting infrastructures in PICTs required for the production technology, particularly feedstock (e.g., water, renewable electricity, and carbon source) sourcing and storage as well as product storage and distribution	1 – No necessary supporting infrastructures exist, and significant new infrastructures must be developed 2 – Most necessary supporting infrastructures exist, and the production technology can be implemented safely with several modifications 3 – All necessary supporting infrastructures exist, and the production technology can be implemented safely without any infrastructure modifications
Current economic feasibility	Current economic feasibility is evaluated based on the current levelised costs of hydrogen and derivatives production (LC) against the fossil counterparts	1 – LC > 3x fossil 2 – LC = 1.5-3x fossil 3 – LC < 1.5x fossil
Energy efficiency	Energy efficiency is evaluated based on the specific energy consumption (SEC) relative to the lower heating value (LHV) of hydrogen and derivatives	1 – SEC/LHV > 2 2 – SEC/LHV = 1.25-2 3 – SEC/LHV < 1.25
Water efficiency	Water efficiency is evaluated based on the water consumption (WC) of hydrogen and derivatives against the fossil counterparts	1 – WC > 2x fossil 2 – WC = 1.25-2x fossil 3 – WC < 1.25x fossil
Technology scalability	Technology scalability is evaluated based on the scale range of the production technology that is commercially available	1 – Scale < 1 GWh/year 2 – Scale = 1-5 GWh/year 3 – Scale > 5 GWh/year
Operation flexibility	Operation flexibility is evaluated based on the ability of the production system to operate under dynamic conditions of renewable and feedstock input as well as the possibility for automation, enabling standalone operation in remote areas	1 – Non dynamic 2 – Dynamic but requires special design or measures 3 – Inherently dynamic

Multicriteria Analysis Framework – Production Technology

Metric	Hydrogen	Ammonia	Methanol		SAF		Renewable Diesel	
			B	E	B	E	B	E
TRL	TRL: 9	TRL: 9	TRL: 9	TRL: 9	TRL: 9	TRL: 6	TRL: 9	TRL: 6
PICTs infrastructure readiness	Low	Average	High	Low	High	Low	Average	Low
Current production cost vs. fossil fuels (US\$/kg)	4 (vs. 1.7)	0.72-1.4 (vs. 0.44)	0.75 (vs. 0.5)	1.5-2.5 (vs. 0.5)	1.4 (vs. 0.8)	3.9 (vs. 0.8)	1.4 (vs. 1.1)	3.6 (vs. 1.1)
Energy efficiency (kWh _{SEC} /kWh _{LHV})	1.2-1.5	2	0.01	1.8-2.8	0.01-0.08	3.5	0.01-0.08	3.6
Water consumption vs. fossil fuels (L _{H2O} /kg)	30 (vs. 19.8)	1.6 (vs. 0.66)	>100 (vs. 0.53)	1.5 (vs. 0.6)	>100 ³ (vs. 0.53)	1.9 (vs. 0.53) ¹	120 (vs. 0.53)	1.9 (vs. 0.53) ¹
Scale (GWh/year)	>40	0.6-600	>0.65	>0.6	0.01-5	<0.1	1.5-12	<0.1
Operation flexibility	High	Average	Low	Low	Low	Average	Low	Average

References:

1. Global Alliance Powerfuels. 2021. Water Consumption of Powerfuels.
2. Ghavam, S. et al. 2021. The life cycle environmental impacts of a novel sustainable ammonia production process from food waste and brown water. *Journal of Cleaner Production* 320, 128776. DOI: 10.1016/j.jclepro.2021.128776.
3. Rulli, M. C. et al. 2021. “The Nexus: Water Land Biofuels”. Roadmap to 2050: The Land-Water-Energy Nexus of Biofuels.
4. Casale. Methanol Process M3000. <https://www.casale.ch/new-plants/methanol-new-plants/methanol-process-m3000>.

Multicriteria Analysis Framework – End Use Applications

Metric	Description	Scoring
Technology maturity	Technology maturity is evaluated based on the technology readiness level (TRL) of the hydrogen and derivatives end use applications	1 – TRL 1-4 2 – TRL 5-8 3 – TRL 9
PICTs infrastructure readiness	Infrastructure readiness is evaluated based on the availability of existing supporting infrastructures in PICTs required for the end-use applications such as distribution, storage, and engine/appliance compatibility	1 – No distribution and storage infrastructures exist, and significant new engine/appliance must be developed to enable the end-use technology implementation 2 – Distribution and storage infrastructures exist but the product can only be implemented with engine/appliance modification 3 – Distribution and storage infrastructures exist, and the product can be implemented without engine/appliance modification
Current economic feasibility	Current economic feasibility is evaluated based on the current delivered cost of hydrogen and derivatives end use applications against the fossil counterparts	1 – Cost > 3x fossil 2 – Cost = 1.5-3x fossil 3 – Cost < 1.5x fossil
Fossil displacement potential	Fossil displacement potential is evaluated based on GJ of fossil fuel displaced by GJ of hydrogen and derivatives considering the efficiency of the end use technologies	1 – $GJ_{\text{fossil}}/GJ_{\text{hydrogen/derivatives}} < 1$ 2 – $GJ_{\text{fossil}}/GJ_{\text{hydrogen/derivatives}} = 1-1.5$ 3 – $GJ_{\text{fossil}}/GJ_{\text{hydrogen/derivatives}} > 1.5$
Opportunity scale in PICTs	Opportunity scale in PICTs is evaluated based on the potential for the hydrogen and derivatives to replace the applications of fossil counterparts in various sectors such as power storage, road transportation, maritime transportation, and aviation	1 – Scale < 3 TWh 2 – Scale = 3-5 TWh 3 – Scale > 5 TWh
Life cycle emission reduction	Total life cycle emission reduction is evaluated based on how much the total life cycle emission reduction potential compared to the fossil counterparts in reduction percentage	1 – Emission reduction < 50% 2 – Emission reduction = 50-90% 3 – Emission reduction > 90%

Multicriteria Analysis Framework – End Use Applications

Metric	Hydrogen		Ammonia			Methanol			SAF	Renewable Diesel	
	Power Storage	Road Fuel	Power Storage	Maritime Fuel	Fertiliser	Power Storage	Road Fuel	Maritime Fuel	Aviation Fuel	Road Fuel	Maritime Fuel
TRL	TRL: 9	TRL: 9	TRL: 6	TRL: 6	TRL: 9	TRL: 9	TRL: 9	TRL: 9	TRL: 9	TRL: 9	TRL: 9
PICTs infrastructure readiness	1	1	1	2	3	2	2	2	3	3	3
Delivered cost vs. fossil fuels (US\$/kWh for power storage, US\$/km for road fuel and aviation fuel, US\$/year for maritime fuel, and US\$/kg for fertiliser)	0.3 (vs. 0.08)	0.8 (vs. 0.3)	0.13 (vs. 0.08)	17k (vs. 3.2k)	04 (vs. 0.38)	0.15 (vs. 0.08)	B: 0.15 E: 0.4 (vs. 0.3)	B: 4k E: 26k (vs. 3.2k)	B: 7 E: 20 (vs. 4)	B: 0.5 E: 1.5 (vs. 0.3)	B: 4.5k E: 40k (vs. 3.2k)
Fossil displacement potential (GW _{fossil} /GW _{H2} or derivatives)	1.4-2	2-2.2	2.2-2.8	1.7	1	1.4-2	1.7	1.4	1	1	1
Opportunity scale in PICTs (TWh)	2.2	1.9	2.2	1.01	Small	2.2	11.9	1.01	7.8	11.9	1.01
Life cycle emission reduction (%)	85-90%	76-80%	90%	90-95%	85%	B: 95%, E: 99%	B: 95% E: 99%	B: 85% E: 99%	B: 85% E: 99%	B: 85% E: 99%	B: 85% E: 99%