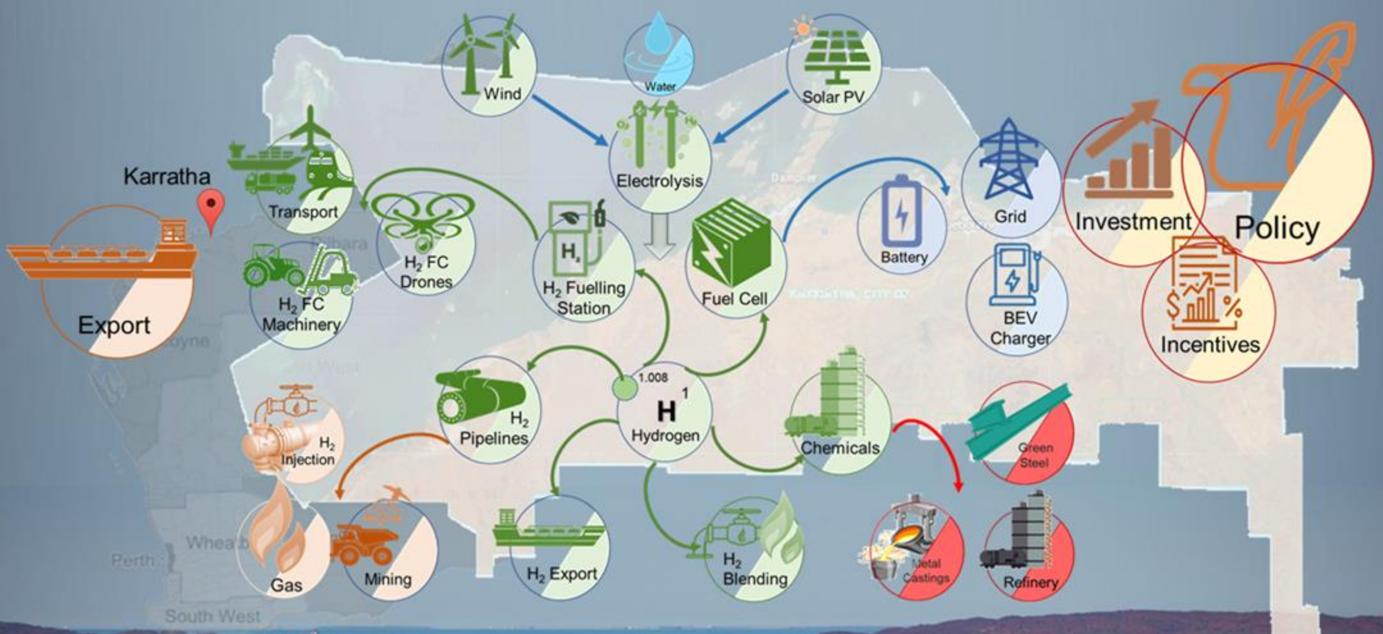
The Renewable Hydrogen Industry Hub

Seizing today's opportunities



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Executive Summary

Decarbonising the global economy to keep global warming below 1.5ºC requires a transition from fossil fuel dependence to an economy running on renewable energy. Hydrogen is a viable large-scale and long-term storage solution for the Renewable Energy (RE) challenges of variability and intermittency. Hydrogen is storable, transportable and flexibly utilisable as an energy carrier which can be used as a direct fuel, electricity generation and heat energy, as well as a primary industrial material.

Renewable hydrogen is Australia's export industry of the future and will underpin our domestic energy economy. It is emerging now, and Karratha can become a national hub of this industry. Karratha is already a massive fossil gas export hub of Australia and has the necessary infrastructure and supporting industries to transition to the hydrogen economy.

This study presents the opportunities for Karratha to transit to a National Renewable Hydrogen Hub. It identifies what competitive advantages the City has that can be leveraged to attract investment in renewable hydrogen. The Pilbara region is already considered as a promising location for renewable hydrogen and many initiatives are underway by industry, State and Federal Governments, local and international agencies including:

- The Renewable Ammonia pilot plant by Engie and Yara Pilbara.
- The 15 GW of renewable energy and up to 12 GW of renewable hydrogen by Asia Renewable Energy Hub.
- DBNGP (WA) Nominees Pty Ltd; preparing the Dampier to Bunbury natural gas pipeline for hydrogen.
- The 86 MW power station by ATCO Power in Karratha with plans to upgrade the plant to hydrogen blending or 100% hydrogen turbines.
- The key industry players in the Pilbara region, such as BHP, Fortescue, Anglo American and Hatch have established a green hydrogen consortium to tackle the mining industry's carbon emissions.

The following steps can be taken for Karratha to transition to a National Renewable Hydrogen Hub.

1. **Policy development:** A short, medium- and long-term policy framework is proposed to remove barriers and increase investment incentives. Firstly, increase community, professionals and stakeholder's awareness and engagement. Secondly, identify the low hanging fruit to develop pilot projects to enrich RD&D activities in Karratha. Finally, an investment strategy to transition Karratha to a renewable hydrogen landscape.

2. **Business investment:** There is a need for a pro-business investment environment to champion renewable hydrogen and increase the attractiveness of investments. Starting with building the community trust, support and engagement as well as establishing an investor's information and database centre (e.g. local resources, contacts, land availability, complementary industries, etc.) can attract new investment into the region. Unlocking new hydrogen utilisation pathways (i.e. more hydrogen offtakes) and increasing the renewable energy generation capacity (i.e. economy of scale hydrogen production) are the essential steps.
3. **Complementary industries:** Key industries directly involved in the hydrogen supply chain, like renewable energy (solar PV and wind) installers and after sales service providers, were identified as the starting point. The direct hydrogen industries to scale-up in parallel including RE powered water treatment, hydrogen with natural gas (NG) blending facility, hydrogen fuel cell (FC) heavy transport and fuelling stations are all vital complementary industries. Moreover, large hydrogen offtake industries like green steel and ammonia can play a key role in green commodity export. Logistic suppliers and services enhancement are needed to attract more workers into the rapidly developing renewable hydrogen industry.

4. **Strategic partnerships:** Essential strategic partners in supporting and facilitating development of renewable hydrogen in Karratha will be ATCO Gas, ATCO Power, Woodside, Apache, Rio Tinto, Pilbara Ports. DPIRD, WA, Renewable Hydrogen Unit, JTSI, WA, Water Corporation and Pilbara Development Commission. Likewise, at a Federal level COAG Energy Council, CSIRO, ARENA and Australia Hydrogen Council. In addition, academic and RD&D institutions as well as think tanks can be strategic partners to develop a hydrogen technology park in Karratha.

5. **Low hanging fruit:** A preliminary list of hydrogen pilot projects:
    a. City of Karratha Operations Centre staged conversion to 100% RE grid-connected starting with onsite hydrogen vehicle fuelling station.
    b. Karratha Airport staged conversion to 100% RE grid-connected with onsite hydrogen fuelling station.
    c. A hydrogen-based 100% RE Stand-Alone Microgrid (SAM) system within City of Karratha that can be replicated for other remote off-grid communities and mining sites.
    d. City of Karratha, by commencing the above projects has then provided the necessary facilities to be the start of WA's Hydrogen Highway to the south.
    e. The long-term multistage transitioning of Karratha region and the Dampier port to a 100% RE-hydrogen based system.

Glossary of Terms

ARENA	Australian Renewable Energy Agency
BEV	Battery Electric Vehicle
CCSU	Carbon, Capture, Storage and Utilisation
COAG	Council of Australian Governments
CSIRO	The Commonwealth Scientific and Industrial Research Organisation
DER	Distributed Energy Resources
DITR	Department of Industry, Tourism and Resources
DPIRD	Department of Primary Industries and Regional Development
EPCC	Engineering, Procurement, Construction and Commissioning
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicles
FCHEA	Fuel Cell and Hydrogen Energy Association
GHG	Greenhouse Gas
H2City	Hydrogen City
HSA	Hydrogen Society of Australia
HyESS	Hydrogen Energy Storage System
HyFC	Hydrogen Fuel Cell
HyFCV	Hydrogen Fuel Cell Vehicle
HyTP	Hydrogen Technology Park
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
JTSI	The Department of Jobs, Tourism, Science and Innovation
KIA	Kwinana Industrial Area
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
NG	Natural Gas
PD	Professional Development
PUC	Pilbara University Centre
RD&D	Research, Development and Demonstration
RE	Renewable Energy
RE-PPA	Renewable Energy Power Purchase Agreements
RESS	RE Storage System
SAM	Stand-Alone Microgrid
SWOT	Strength, Weakness, Opportunity, and Threats
The City	City of Karratha
ZEH	Zero Emission Highway

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1 Introduction

1.1 Sustainable Development – Green Recovery

Modern energy supply depends on hydrocarbon (fossil fuel) energy resources, which are increasingly conflicted and globally polluting. Our dependence on the fossil-fuelled economy, caused a significant increase in the levels of carbon dioxide (CO_2) and other GHGs in our atmosphere the results being global warming and climate change. The CO_2 now exceeds 400 ppm with global warming approaching 1.5ºC above average. Fossil fuel fluctuating prices and supplies as well as the increasing global awareness of climate change challenges have forced many countries to look for alternative energy sources. Decarbonising the energy supply by utilising alternative clean, sustainable energy is therefore essential for future energy sustainability. Transitioning Australia towards a low carbon economy and to zero emissions by 2050 [1] will require increasingly efficient energy use and renewable energy (RE) uptake.

The main challenge in transitioning towards 100% RE is the variable and intermittent nature of these resources. This requires technical adaptation and large-scale energy storage systems. The storage system will need to decouple supply and demand by shifting the generated energy on different time scales (hourly, daily and seasonally). The innovative idea of storing RE in an energy carrier such as hydrogen, which is storable, transportable, and utilizable can be the solution. Hydrogen is a viable large-scale and long-term RE storage medium as well as it has many properties that make it an excellent choice as an energy carrier. Examples are high energy density, i.e. energy content per unit weight (120-142 MJ per kg) which is equivalent to 2.79 kg of diesel, versatile forms such as liquid, gas or solid as a metal hydride; and efficient utilization and conversion.

Despite the cost, economics, and lack of government strategies; the concept of a Hydrogen-based Energy Storage Systems (HyESS) is gaining potential as a cost-effective solution for large-scale RE storage, transport and export. Hydrogen-based energy systems are leading the way towards a 100% RE economy which is called the "Hydrogen Economy" [2, 3]. Hydrogen economy refers to a system where hydrogen is the principal energy carrier.

Additionally, storing RE in the form of hydrogen which is an exportable commodity can open the gate for a new energy export industry as pure hydrogen or carriers like ammonia, methane and toluene [4]. The global hydrogen market was estimated in 2016 to be 85 million tonnes [2] and expected to rise to 304 Mtpa by 2050, including over 90 Mtpa for electricity generation [3]. The energy carried on pure hydrogen is a zero-emission energy at the use point with only water as by-product. However, hydrogen round trip associated emissions depend on how clean the energy stored in that hydrogen during the production process which is referred to as a "Guarantee of Origin" [2]. Therefore, renewable hydrogen is considered as the cleanest and most sustainable form of energy that mitigates greenhouse gas (GHG) emissions' as well as global warming.

1.2 Study Overview

This study aims to provide a succinct "Hydrogen Strategy" report for the City of Karratha. The project team (Murdoch University and Hydrogen Society of Australia) conducted interviews with the targeted industry and government stakeholders to gather data and perspectives to support the development of this study. The team has also utilised private and publicly available data sources, building on recent work undertaken by Geoscience Australia, the hydrogen industry landscape, and a comprehensive stakeholder engagement process to extract recent information. This study considers the supply chain, infrastructure, and strategic partnerships requirements to support the development of export and domestic hydrogen hub for Karratha.

In this report, unless otherwise indicated, "hydrogen" refers to "clean hydrogen" which is defined as being produced by utilising renewable energy, otherwise named green hydrogen. Hydrogen produced using fossil fuels with carbon capture and storage is referred to as blue hydrogen. The name "Pilbara" in this report refers to the greater area of the Pilbara region including Karratha and the Pilbara ports in the North-West of Western Australia.

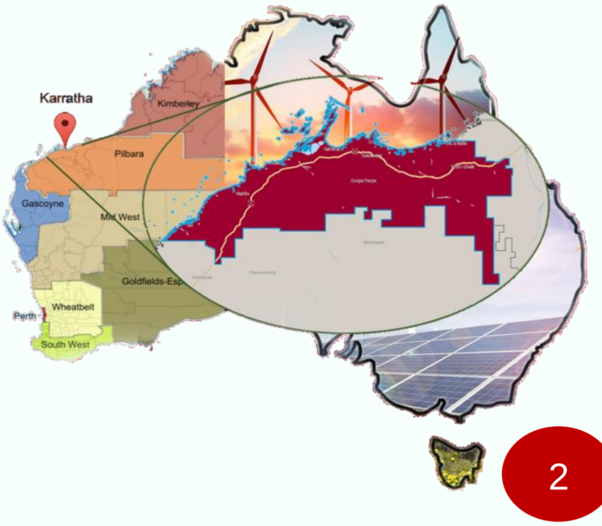
The City of Karratha (Local Government Authority) will be referred to as "The City", and the area will be referred to as Karratha onwards in this report.

1.3 Study Outcome

This report identifies opportunities and proposes strategies for the City to become the Australian renewable hydrogen hub. Hydrogen production pathways, transportation mechanisms and applications were evaluated to identify how the City of Karratha renewable hydrogen hub can be used to balance supply and demand of hydrogen. The hydrogen supply chain infrastructure (existing and required) in the City to become a renewable hydrogen hub for both export and domestic use were identified.

The competitive advantages for the City as a hydrogen hub and a gateway for the emerging renewable hydrogen industry in Western Australia (WA) were evaluated. A hydrogen policy, and strategy were proposed to raise public awareness, and activities as well as attracting investment to position Karratha strongly in the hydrogen landscape.

The low hanging fruit and the key steps have been recommended for the City to become a National Renewable Hydrogen Hub. A preliminary list of current or anticipated locations for hydrogen projects has been developed through desktop research, the project team knowledge, and the stakeholder consultation process.



2 Renewable Hydrogen: Australian Context

2.1 Hydrogen Value Chain

The hydrogen value chain comprises production pathways, storage, and utilisation as illustrated in Fig (1). Hydrogen can be produced from different pathways utilising different types of energy such as thermal, electrical, chemical, biological, photonic, etc. Hydrogen can be stored in a physical-based, material-based, and chemically based technology. Liquid hydrogen and hydrogen combined in metal hydride structures or carbon-based nanotubes (CNTs) are some of the alternatives that are currently being examined.

Box 1: Hydrogen Facts
Atomic number 1.008
Hydrogen is a flammable gas
Colourless and odourless
33 kWh = 120 MJ/kg @ LHV, 298 K
11 Nm^3 per kg of hydrogen

Box 2: What a kg of H_2 can do?
Drive FCV family car ~ 100 km
Energise full day Av. household
120 – 141 MJ Heat energy
1kg avoids 15kg CO_2-e

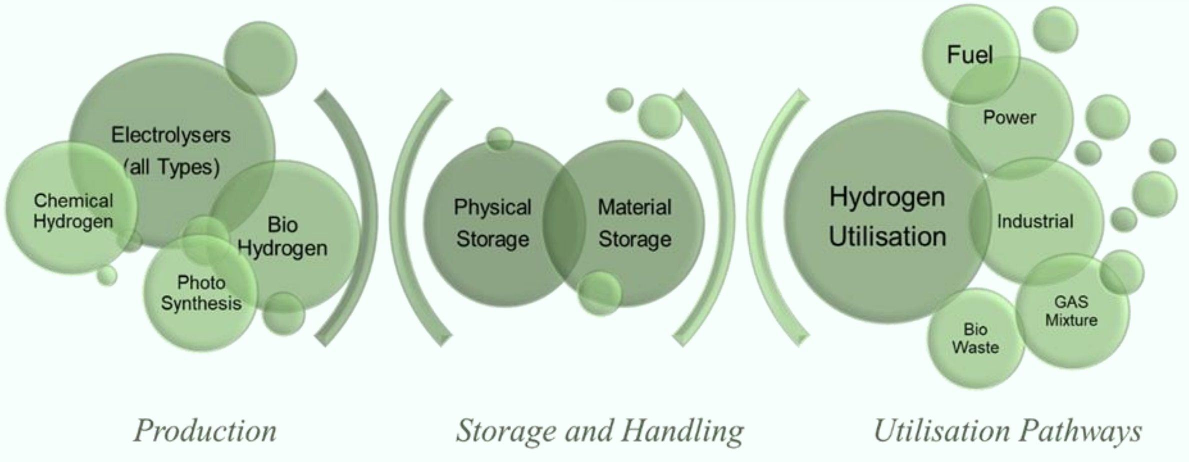


Figure (1): The hydrogen value chain

2.1.1 Why Hydrogen?

Hydrogen is seen as a solution to the problems arising from the current unsustainable fossil fuel economy. The variable and intermittent nature of RE resources such as solar and wind raise the necessity to store some of that energy when excess is available to be used later if needed. Storing the variable and intermittent RE in the form of hydrogen, is promising pathway in transitioning towards carbon-free economy [2]. This will allow a seamless transition from the conventional fossil fuel-based economy to cleaner, eco- friendly, and sustainable “Hydrogen Economy” [2].
Hydrogen can be utilised in its pure form or chemically bounded or physical admixed in a wide range of applications. Pure hydrogen utilisation creates no emissions, only water or water vapour as by-products therefore, hydrogen direct conversion (electrochemically) to electricity using fuel cell (FC) is a promising technology for electricity [2].

Hydrogen can be used as a direct fuel for power and heat generation or blended with the natural gas for greening the gas supply [2]. Moreover, it can be an alternative zero-emission fuel to reduce GHG emissions in the transport sector. Importantly for Karratha, hydrogen can be used to produce green steel and new products [2] like green ammonia, fertilisers, methane. Green steel and ammonia are already acknowledged as the future major industries for the Pilbara region and Karratha is well-placed to lead this industry development.

Box 3: Hydrogen:

- ✓ Sustainable zero-emissions (green) energy
- ✓ Large scale of production (modular)
- ✓ Storable & transportable
- ✓ Suitable for grid & off-grid renewable energy storage
- ✓ Power regeneration FC technologies
- ✓ Direct Fuel
- ✓ Long discharge duration & 100% depth of discharge
- ✓ Integrate into the existing energy and transport systems
- ✓ Renewable hydrogen export from Australia

2.1.2 Hydrogen Production

Hydrogen cleanness was described and labelled by four main colours code: grey, brown, blue and green. The colour of hydrogen is determined by the type of energy utilised to produce that hydrogen and the emissions released in the production. Grey and brown hydrogen are the most polluting types of hydrogen, whereby hydrogen is produced from natural gas or coal, with the associated CO_2 released to atmosphere [2]. Blue hydrogen is produced similarly but with the CO_2 captured and stored or utilised which defines the Carbon Capture, Storage and Utilisation (CCSU) [2]. Green hydrogen is produced from 100% RE sources which is considered to be the cleanest (low-carbon-emissions) hydrogen energy [2]. In this study, renewable (green) hydrogen will be the main focus as it is the most clean hydrogen energy. Hence, the guarantee of origin will become a necessity to ensure the cleanness of energy stored in the hydrogen [2]. Figure (2) illustrates the existing hydrogen certification scheme.

Hydrogen can be produced by thermochemical, electrochemical, and biochemical processes [2]. Among all the available methods, electrochemical (water electrolysis) is likely to be suitable for the large-scale production of green hydrogen. The most abundant source of hydrogen is water [2]. Hydrogen can be produced from water using a process called electrolysis. The schematic diagram of the main three types of water electrolysis systems are shown in Fig. (3). This process is the most promising option for hydrogen production from RE resources. It is a mature technology and relatively efficient.

The current hydrogen production by water electrolysis utilises at least nine kg (litres) of pure (deionised and demineralised) water per kg of H_2 produced which stores 33-39 kWh of energy per kg of H_2.

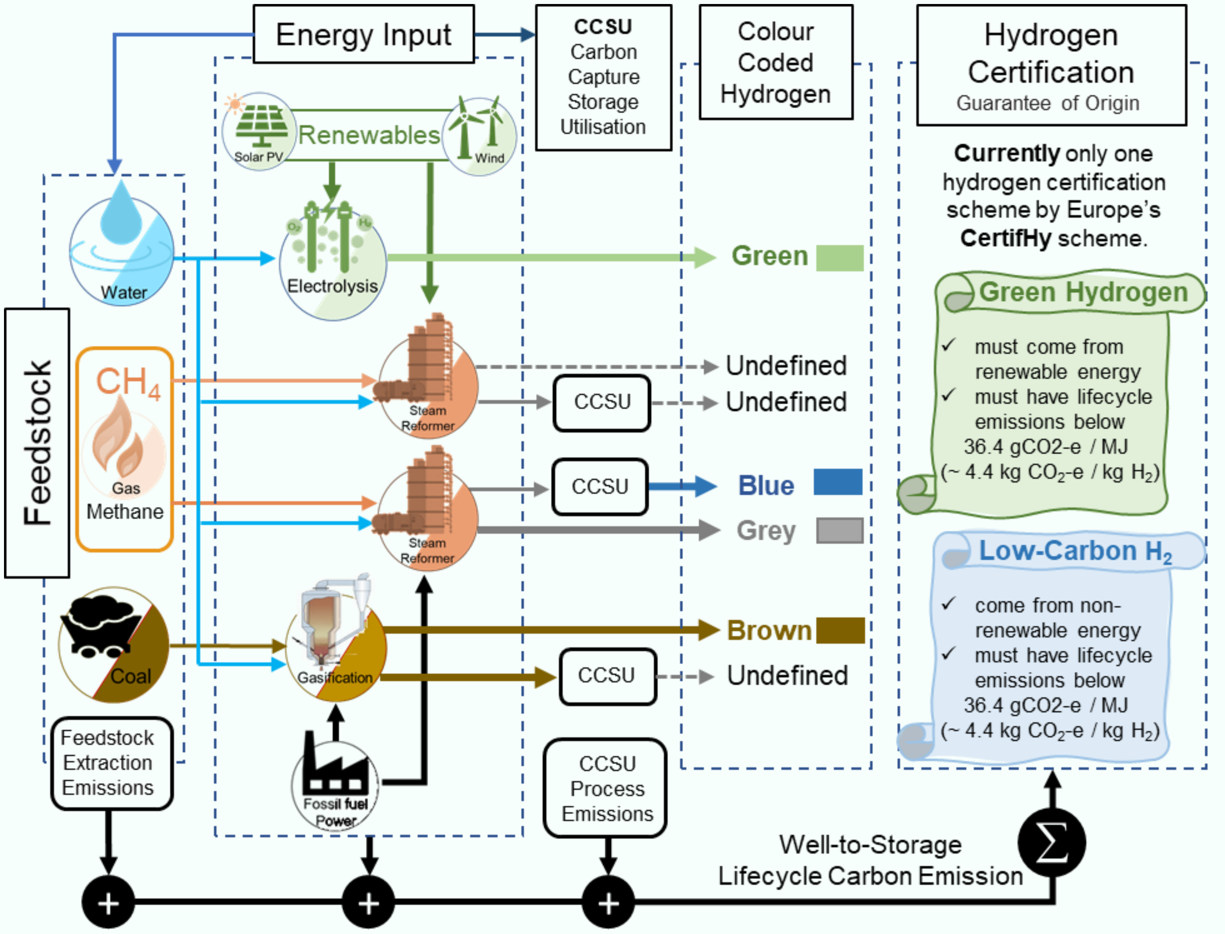


Figure (2): Hydrogen certification scheme.

The three main types of electrolysers; overall reaction, ions movement through membrane and operation temperatures are illustrated in Fig. (3).

$$\text{The overall reaction: } 2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g)$$

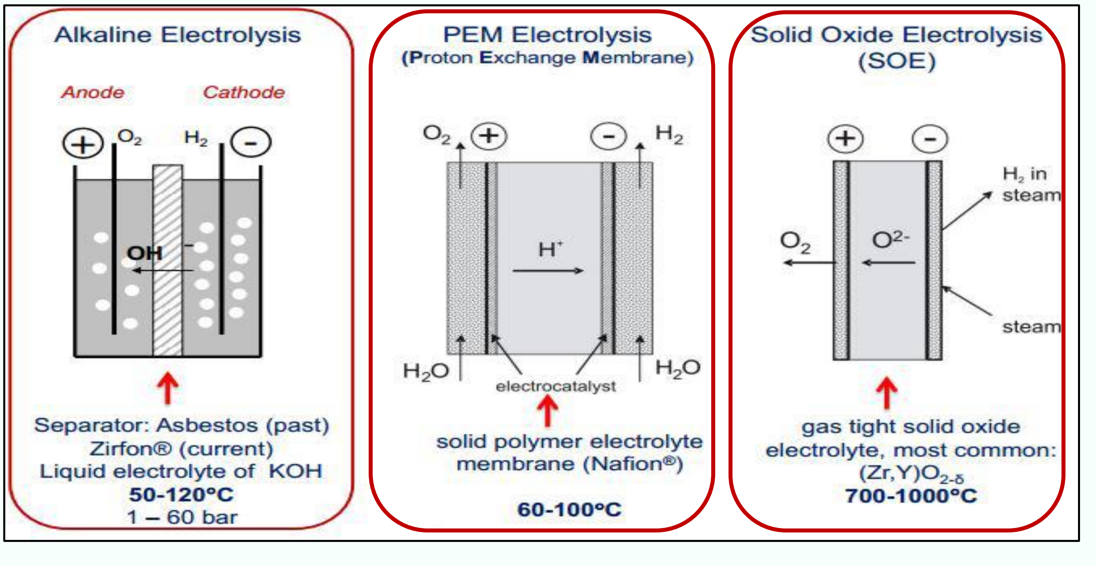


Figure (3): Types of electrolysers

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2.1.3 Hydrogen Storage

Hydrogen can be stored physically as either a gas or a liquid. Storage of hydrogen as a gas typically requires high-pressure tanks i.e. 350 – 700 bars. Storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is −252.8°C. Large cryogenic hydrogen tanks reduces the proportion of thermal insulation mass and volume with respect to hydrogen volume. Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption) [2]. Metal hydrides are an excellent material for storing hydrogen due to its abundance in nature and inexpensive. Figure (4) summarises hydrogen storage technologies.

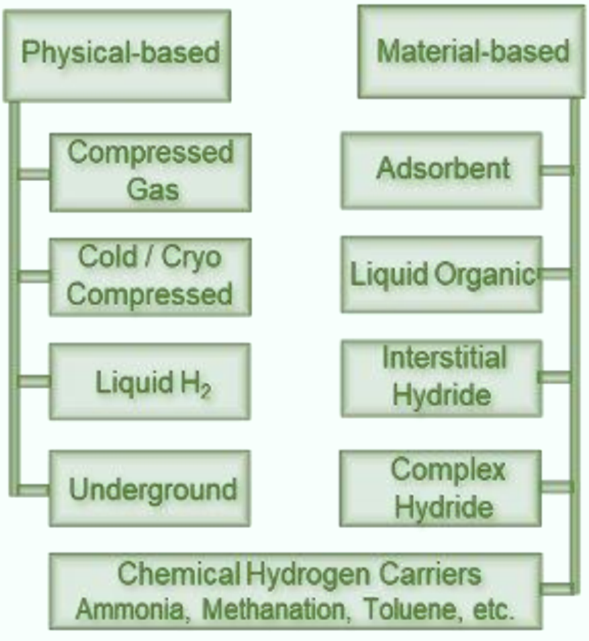


Figure (4): Hydrogen storage technologies

Hydrogen storage for vehicles and portable applications is a challenge due to low volumetric energy density. The large-scale hydrogen storage technologies are rapidly developing with the growing interest in the hydrogen export industry prospects [4]. Nevertheless, the Pilbara region is well placed to export hydrogen stored as green steel or ammonia after establishing a substantial value-add manufacturing industry at Karratha in particular.

2.1.4 Hydrogen Transport and Export

Today, hydrogen is transported from the point of production to the point of use via pipeline, over the road in cryogenic liquid tanker trucks or gaseous tube trailers, or by rail or barge. For larger quantities of hydrogen, pipeline delivery is the cheapest [2]. Hydrogen used in portable or stationary applications can be delivered by truck to a storage facility or in cylinders, like the propane used for gas grills, or in cartridges that would resemble a battery. Hydrogen used in fuel cell electric vehicles (FCEVs) is dispensed the similar way gasoline is which makes hydrogen not less or more dangerous compared to the conventional fossil fuels such as petrol and liquefied petroleum gas [2]. Drivers pull into a filling station, connect the dispenser to the vehicle, fill, disconnect, pay, and then drive away with a full tank. Refuelling an FCEV takes approximately the same amount of time as refuelling a gasoline powered car i.e. 3 - 5 minutes.

On the other hand, small-scale in-situ water electrolysers in the remote area (like regional Pilbara) may avoid the need for investing in the transport and distribution infrastructure such as cryogenic pipeline system or virtual pipeline (tube trailers trucking).

Hydrogen delivery, onsite storage, and dispensing technologies include:

- Gaseous hydrogen
- Gaseous compression
- Pipelines
- Tube trailers
- Liquid hydrogen tanks
- Novel hydrogen carriers
- On-site and bulk storage
- Dispensing hydrogen fuel to vehicles

Box 4: How Safe is Hydrogen

- Hydrogen is non-toxic
- Much lighter than air, dissipates rapidly when released, relatively safer than other spilt fuels.
- Like all fuels, has some degree of danger
- Require additional engineering controls to ensure its safe use
- Care needs to be taken to avoid metal hydrogen embrittlement

2.1.5 Hydrogen Integration and Utilisation Pathways

Hydrogen can be utilised directly for power and heat generation or used as a direct fuel for transport sector [2]. Also, hydrogen can be utilised indirectly to form new materials like ammonia, methane, ethanol, etc. Additionally, it can be used as a reduction element in metal industries like the green steel emerging industry [4].

Hence, hydrogen integration into the existing energy systems is on the verge of being unstoppable while the world inches towards using more green energy and less fossil fuel. Converting the hydrogen to other forms are usually more efficient than that of other fuels. Figure (5) shows hydrogen utilisation possibilities and pathways to integrate with or replace existing energy systems.

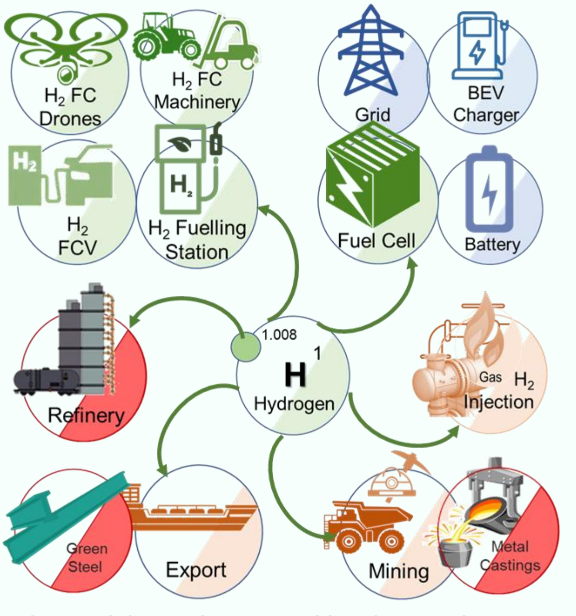


Figure (5): Hydrogen utilisation pathways

2.2 Water for Hydrogen Production

Hydrogen production by water electrolysis typically demand of approximately 15-20 litres of potable water per kg of hydrogen to produce nine litres of deionised and demineralised water depending on the design of the water treatment system [5]. The same amount of water is required for the coal gasification process, while half of the quantity is required for methane steam reforming. The energy intensity of the water treatment (purification and deionisation) depends on the source of the raw water like freshwater or seawater as well as surface or underground water [5].

Also, the water treatment technology determines the energy consumption; this energy must be included and aligned with the hydrogen production pathway for the guarantee of that hydrogen origin i.e. green, blue, grey and brown hydrogen [2].

Box 5: 1 kg of hydrogen requires at least (deionised and demineralised water)

- Electrolysis 9 L
- Coal gasification 9 L
- Methane steam reforming 4.5 L

2.3 Hydrogen Economy of Scale

Transition to hydrogen economy will be achievable only when hydrogen cost competes with other conventional fuels.
At the present time, brown and blue hydrogen can be delivered at lower cost than diesel. Green hydrogen may be approaching parity, especially if a carbon price is introduced. The hydrogen market is existing at a scale of 70 million MT/year, however 95% of the global hydrogen supply is grey and brown hydrogen at a competitive cost. The challenge is to reduce the renewable (green) hydrogen cost of production to be at a competitive level, which is only achievable by scaling up RE to the hydrogen supply chain.

The scale-up of the supply chain requires a parallel scale-up in hydrogen markets (offtakes) domestically and globally. This is only achievable by the widespread adoption of hydrogen to play a role in the economy and to reduce GHG emissions. By appropriately accounting to internalise all externalities such as carbon emissions, health, and environmental impacts will give cost advantages for green hydrogen.

Box 6: The National Hydrogen Roadmap in 2018 stated *"The development of an export industry represents a potential 'game changer' for hydrogen and the broader energy sector due to associated increases in scale."*

Box 7: The National Hydrogen Roadmap in 2018 stated *"Hydrogen technology is largely mature. Market activation is the key priority for developing an economically sustainable hydrogen industry in Australia"*

2.3.1 Large-scale Hydrogen Storage

Large-scale hydrogen storage capacity is essential for the seamless transition of the national economy to a hydrogen economy as well as plays a vital role in the hydrogen export industry globally. The existing gas pipeline network has the potential for large-scale storage of hydrogen, however, the volume of percentage of hydrogen blending with natural gas depends on the pipeline network technical properties and integrity. The size and the pressure of the gas pipeline network determine the volume of hydrogen that can be stored [6]. Storing hydrogen geologically in underground salt caverns and depleted gas fields is an emerging technology which is a promising long-term, large-scale hydrogen storage pathway. Furthermore, hydrogen can be stored chemically (i.e. hydrogen chemical carriers) via forming a new compound of hydrogen-containing materials which can be extracted when needed.

2.3.2 Hydrogen for Green Industries

The hydrogen export supply chain is still at the early development stage and bulk shipping is not commercially ready [7]. Hence, green steel, green ammonia and green fertilisers as well as many other petrochemical and metallurgical industries are promising approaches for indirect hydrogen export (green commodities export). These emerging green industries create new jobs and stimulate economic growth as well as reduce the GHG emissions.

2.4 Australia Hydrogen Industry Landscape

The hydrogen industry in Australia has gained tremendous momentum in 2018 and after the publishing of the National Hydrogen Roadmap as illustrated in Fig (6). The vision of a hydrogen economy in Australia can be traced back to the 1930s when Councillor JF Kemp from Brisbane suggested to use hydrogen from the town gas to power vehicles [8].

Figure (6): Hydrogen industry landscape

The National Hydrogen Study by ACIL Tasman and Parsons Brinckerhoff was prepared in October 2003 for the Department of Industry, Tourism and Resources (DITR) which was built on the success of the conference, “The Hydrogen Economy Challenges and Strategies for Australia” [8]. This conference was held in Broome, Western Australia, in May 2003, where experts from around the world were invited by the Australian Federal Government that cumulated in the publication of the National Hydrogen Study [8]. Since then, a tremendous amount of work has been conducted in the hydrogen industry space which cumulated into Australia’s National Hydrogen Roadmap by the CSIRO in August 2018 [9, 10]. This led to the first renewable hydrogen conference on the 31st August 2018 in Perth, WA [11] followed by the founding of National Hydrogen Strategy Taskforce by the COAG Energy Council to develop Australia’s National Hydrogen Strategy [12, 13].

ARENA recently has announced a renewable hydrogen deployment funding; the media release stated *“Australia is well placed to become a major renewable hydrogen producer and exporter. We are blessed with some of the world’s best wind and solar resources, a large sparsely populated landmass, and as a major energy and resources exporter, we are already an experienced and trusted Trading partner for countries like Japan and South Korea that will be the future hydrogen importers”* [14].

BOX 8: According to the International Energy Agency and the World Energy Council, Australia has the potential to be the world’s largest hydrogen producer.

3 Karratha Competitive Advantages

The competitive advantages of the City of Karratha in the hydrogen industry landscape have been investigated through the use of two models [15]:

- Sustainable Livelihoods Model
- Industrial Symbiosis Model

The Sustainable Livelihoods Model was created over time by the UK Department for International Development in order to determine optimum development pathways. Figure (7) shows a typical sustainable livelihoods model for the City.

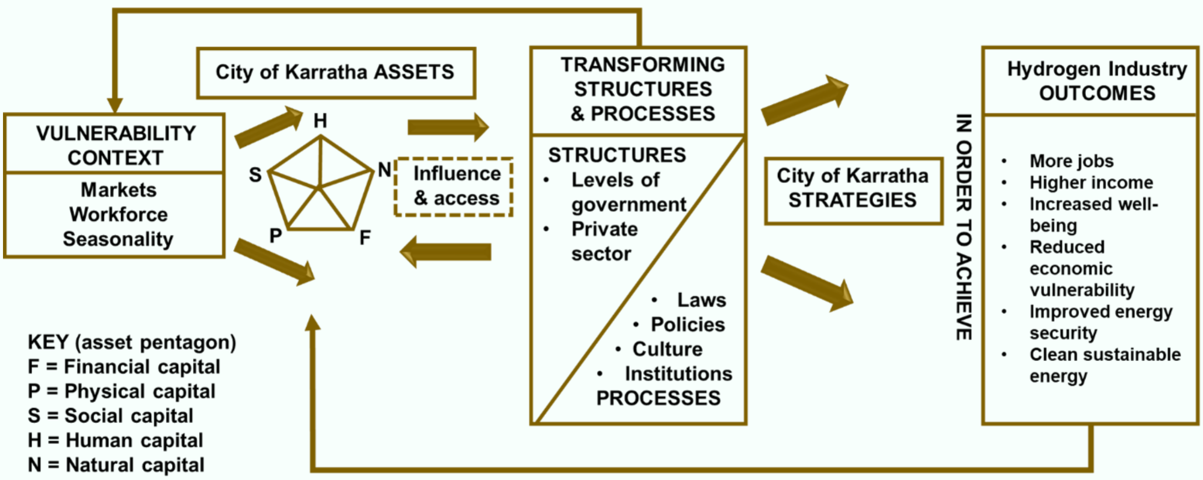


Figure (7): The Sustainable Livelihoods Model

This simplified graphical representation of the model reveals the key assets relative to the City of Karratha as follows:

- Human capital: the Karratha residential population and FIFO workers need to be boosted in the future as required for the hydrogen industry.
- Social capital: relationships of trust, reciprocity and exchange that the City of Karratha can enable to lower the costs of working productively with the hydrogen industry stakeholders.
- Natural capital: the land, water, wind, tides, and solar energy that exist in the region in abundance and that the City of Karratha can promote for hydrogen project developments.
- Physical capital: the transport and communication systems, educational facilities, shelter, water and sanitation systems, and power supply need to grow for the hydrogen industry.
- Financial capital: facilitating industry's financial services for business investment into hydrogen developments and access to State and Federal funding programs, e.g. CEFC and ARENA.

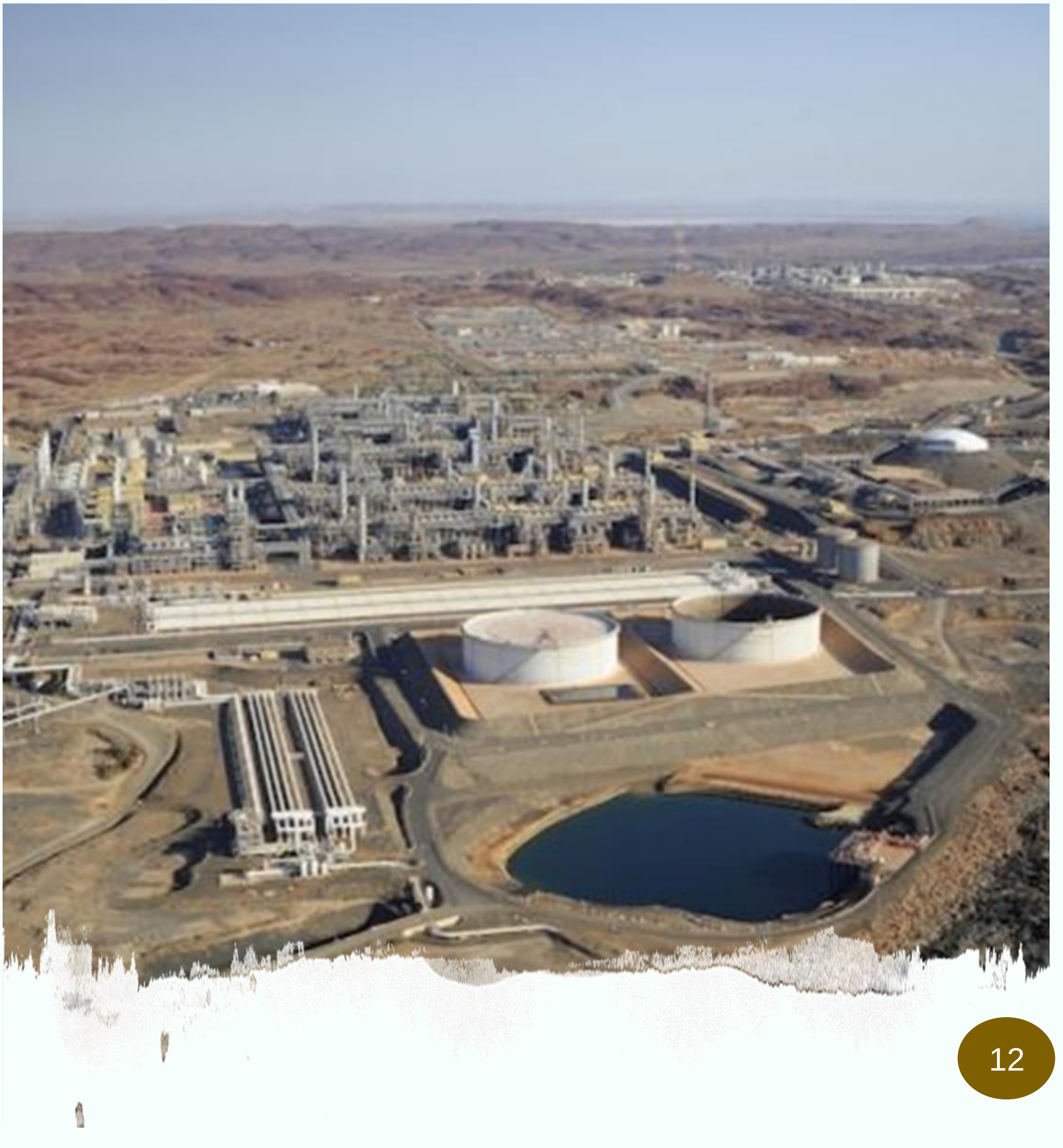
These assets are described in detail in this chapter.

Secondly, the City of Karratha competitive advantages can be described through an Industrial Ecology or Industrial Symbiosis model, which sees, “traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products” with four synergy dimensions:

1. Product and by-product
2. Skilled workforce
3. Support (complementary) industry
4. Governance

This approach has been proven at Kwinana Industrial Area (KIA) [15] over 40 years of industrial growth and can be promoted by the City of Karratha for growth of the hydrogen industry.

The following sections elaborate the competitive advantages of the City of Karratha.



3.1 Hydrogen-related Initiatives in Karratha and Regional Pilbara

A lens on the hydrogen industry landscape in the Pilbara Region reveals:

- Pilbara Renewable Ammonia: Yara has embarked on a collaboration with ENGIE in 2018 to develop a solar ammonia plant in Pilbara. The 200-hectare solar array will have a 100 MW capacity, coupled with 66 MW water electrolyser, allowing Yara to produce 80 metric tonnes of green ammonia per day, a small fraction of the site's annual capacity of 840,000 metric tonnes of fossil ammonia [16]. It is proof of concept for potential subsequent scaling to economic size.

BOX 9: Yara Pilbara Green Ammonia Fast Facts

- ✓ Currently produce 840,000 MT/year fossil Ammonia; 5% of world market & 15% of Yara trade.
- ✓ Technical Ammonium Nitrate (TAN); design capacity of 330,000 MT.
- ✓ Storage capacity is 80,000 MT of NH_3
- ✓ Exported via Dampier Port.
- ✓ Planned Green Ammonia by 2021-23 is 29,200 MT/year
- ✓ Each Kg of H_2 produces 5.6 kg NH_3
- ✓ Offsets ~ 28,678 tonne of CO_2

Therefore, the existing infrastructure in the Dampier Port represents a competitive advantage for Karratha to attract more green ammonia, fertilisers, green steel, and indirect renewable hydrogen via hydrogen carriers. Hence, Ammonia export infrastructure needs to be up scaled in parallel with the increase of green ammonia production.

- The Pilbara 15 GW RE project by Asia Renewable Energy Hub announced in 2019 to start production in 2025 [7]. This proposed project is the largest of its type to use over 7,000 square kilometres represents an enormous opportunity for Karratha [7].

- Woodside Energy announced in April 2020 [17] *"an agreement with Japanese companies JERA Inc, Marubeni Corporation and IHI Corporation to undertake a joint study examining the large-scale export of hydrogen as ammonia for use in decarbonising coal-fired power generation in Japan. As part of the recently approved study, the partners will be investigating the transition between hydrogen production processes for export: from blue hydrogen to green hydrogen."*

- A proposed $4.5 billion urea production plant in the Pilbara by Perdaman Chemicals and Fertilisers Pty Ltd, signed up in 2018 for 20 years of gas from Woodside to produce two million tonnes of urea per year. This project has the green light to move on in July 2020 which can be prospect to green hydrogen-based fertilisers in Karratha which is another opportunity for Karratha hydrogen hub [18].

- ATCO Power's 86MW power station in Karratha plans to upgrade to hydrogen blending or 100% hydrogen turbines [19]. Also, ATCO's proposal to deploy a hydrogen fuelling station is an opportunity to transit the City to use hydrogen FC vehicles to become a key player in the clean transport space [19].

- The key industry players in the Pilbara region such as BHP, Fortescue, Anglo American and Hatch have established a green hydrogen consortium to tackle the mining industry's carbon emissions [20]. These four companies will together find ways of increasing its adoption and application of clean hydrogen within the sector which can be another big opportunity for Karratha to lead the hydrogen industry development.

- A number of feasibility studies are currently underway from the WA Government-renewable hydrogen funding scheme [20] and ARENA. These studies could enable Karratha to host the emerging outcomes from feasibility studies which are expected to emerge early in 2021. These studies are conducted by [20]:

  - ATCO Gas Australia Pty Ltd; comprise 10 MW electrolyser.
  - City of Cockburn, Perth; solar hydrogen production for waste collection and light vehicle fleets.
  - DBNGP (WA) Nominees Pty Ltd; preparing the Dampier to Bunbury NG pipeline for hydrogen.
  - Energy Developments Limited; Hydrogen Enabled Hybrid Renewables for the integration of renewable hydrogen production (Remote applications).
  - Hazer Group Limited; Renewable Hydrogen Transport Hub in the City of Mandurah.
  - Murdoch University; 100% renewable energy stand-alone power system for an indigenous community in the Pilbara (Remote applications).
  - Pacific Hydro Australia Developments Pty Ltd; "Ord Hydrogen" project for hydrogen production near Kununurra utilising existing hydro generation for export, transport and remote applications.
  - BP will be supported by GHD Advisory to deliver a $4.42 million feasibility study with $1.71 million in funding from ARENA, which will investigate producing renewable hydrogen using electrolysis to assess the feasibility of building a renewable hydrogen and ammonia production facility in Geraldton, WA [21].
  - Recently announced Murchison Renewable Hydrogen Project by Siemens and Hydrogen Renewables Australia aims to produce green hydrogen for local industry and export to Asia. The project comprises up to 5,000 MW of combined wind and solar capacity [22].

BOX 10: Preparing Dampier to Bunbury NG Pipelines for hydrogen can be a huge step towards making Karratha the hydrogen energy capital of the Nation.

- On 17 August 2020, the Premier announced several successful capital works projects as part of the WA Recovery Plan [20]:

  - ATCO Gas Australia Pty Ltd has been granted $1.0 million to implement a hydrogen refueller station in Metro WA.
  - Fortescue Hydrogen Pty Ltd has been granted with $2.0 million to implement Christmas Creek Renewable Hydrogen Mobility Project in Pilbara WA.
  - Horizon Power has been granted with $1.0 million to implement Denham Hydrogen Microgrid Demonstration Project in Gascoyne WA.

3.2 Green Steel for Karratha and Regional Pilbara

Green steel uses renewable hydrogen to reduce iron ore to iron metal in-lieu of metallurgical coal [23]. The existing iron ore at economy of scale in Pilbara along with the current 660 billion dollars global market and the role that Dampier port plays in the global supply chain markets; represent a historic opportunity for Karratha to host and facilitate the emerging green steel industry. The abundant RE resources in the Pilbara region can produce renewable hydrogen at economy of scale competitive cost with the existing large-scale offtakes like green steel industry. Additionally, a scale of economy green steel industry requires large-scale hydrogen storage capacity which is available in the Pilbara region in the underground salt caverns [22]. Moreover, the green steel export can be the main motivator for more investment in renewable hydrogen [24].

BOX 11: *'Green steel'* could help make Australia a renewable energy superpower, and represents the best opportunity for exports and job creation in key regions - Ross Garnaut [24].

Quick Facts:
- 51 kg of hydrogen is consumed per tonne of steel output compared to 600 kg of Coal per tonne of steel output.
- The carbon dioxide (CO_2) emissions using current technology are 1.6 – 2.1 tonnes of CO_2 per tonne of steel cast

3.3 Renewable Energy Resources in Karratha and Regional Pilbara

Solar resources in the Pilbara region including Karratha is at the highest end of the solar radiation scale in Australia as shown in Fig. (8). Karratha experiences solar irradiation levels reaching approximately 6.33 kilowatt-hours per square metre per day on average over a year [22]. This positions Karratha well among the best RE resources for hydrogen production in Australia.

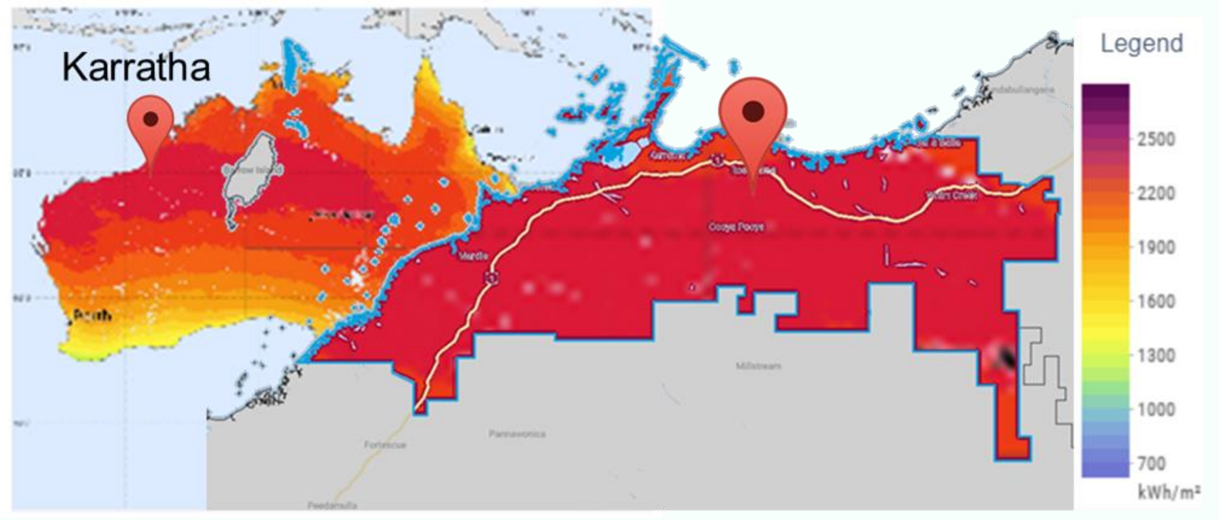


Figure (8): Solar resources in the Pilbara region
Source: Global Solar Atlas, https://globalsolaratlas.info/map

Another advantage comes from the viable wind resources which increases considerably with above ground height i.e. over a 100 metre as shown in Fig. (9). This makes the Pilbara and Karratha more suitable for large-scale wind turbines. However, Pilbara coast including Karratha experiences more cyclones than any other part of Australia, which needs special engineering attention to withstand the cyclone season; runs from mid-December to April peaking in February and March [25].

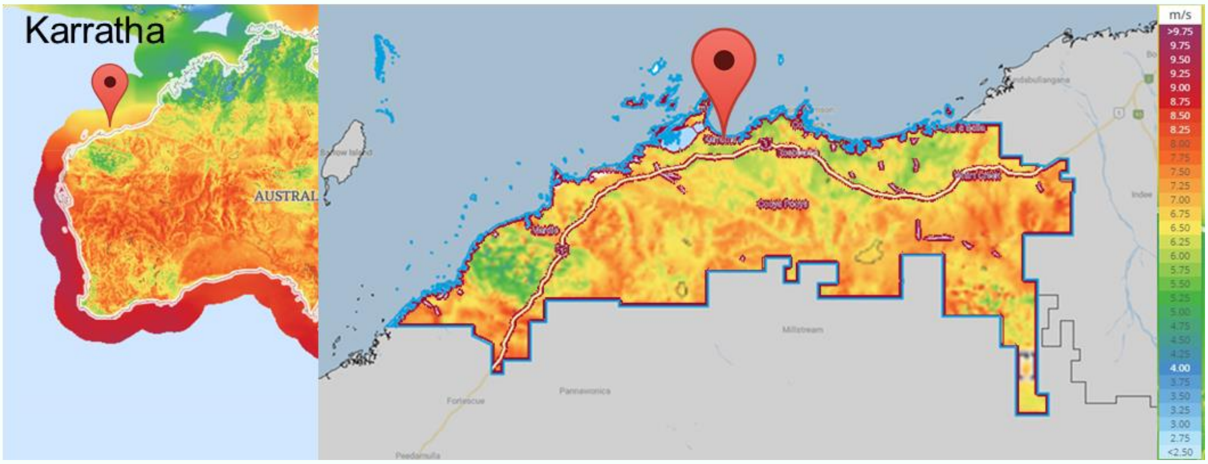


Figure (9): Wind resources in the Pilbara region
Source: Global Wind Atlas, https://globalwindatlas.info/area/Australia

3.4 Underground Hydrogen Storage

Hydrogen can be stored underground, for example, in salt caverns or depleted gas reservoirs, to be available for use as required like the common practice for natural gas storage. Further work is required to identify and characterise areas, such as salt deposits, like the Canning Basin in Pilbara region where hydrogen could be stored for future use [22]. The hydrogen study by Geoscience Australia has identified the Canning Basin as major salt deposits onshore in WA North- West i.e. Pilbara regional WA, as shown in Fig. (10) [26]. This large-scale underground hydrogen storage is vital for the prospect of pure hydrogen export industry from Australia.

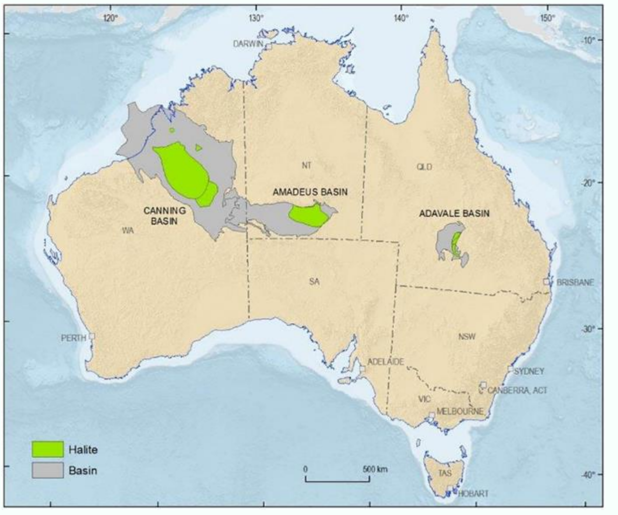


Figure (10): Salt caverns or depleted gas reservoirs for hydrogen storage
Source: https://www.ga.gov.au/scientific-topics/energy/resources/hydrogen

3.5 Water Resources in Pilbara

The WA Department of Water developed the Pilbara Regional Water Plan 2010-2030 [27]. The report explains that water use across the Pilbara is dominated by mining operations and mine dewatering discharge, which respectively account for an estimated 26% and 52% of total water use. Total water use in 2008 were estimated at 127 GL/yr. The West Pilbara water supply scheme, operated by Water Corporation, supplies the towns and port facilities of Karratha, Dampier, Roebourne, Wickham, Point Sampson and Cape Lambert. Water for the scheme comes primarily from the Harding Dam with the Millstream bore field being used when water is not available from the dam. In 2012, the Bungaroo Creek Water Reserve was added to the scheme. The water quality from these sources meets the Australian drinking water guidelines (NHMRC 2004). Recharge of the Harding Dam and Millstream borefield occurs predominantly through cyclonic events. Drinking water source protection plans exist for all Water Corporation-supplied towns [27]. The City has developed its own water management plan [28] with its holistic approach towards drinking water, surface water, groundwater and wastewater. Key areas of action were [29]:

- Planning decision-making on future planning and development proposals.
- Management and maintenance of stormwater drainage infrastructure.
- Maintenance of public open space including irrigation; and
- Advocacy for increased water conservation, efficiency and reuse and enhancement of cultural and community connections to water.

Importantly, the report notes that the resources industry has made significant advances in water efficiency. Consistent with this, Rio Tinto provides recycled water for use by the City for irrigation in Wickham and Dampier, which reduces the demand on the West Pilbara water supply scheme.

3.6 Karratha Ports

There are three existing and three proposed ports within Karratha local government authority boundaries as shown in Fig (11) [28-31]. The web-based WA Government–DPIRD-Renewable Hydrogen Information Portal [30, 31]; reveals that all the existing seaports within the Karratha boundary are suitable for renewable hydrogen export.

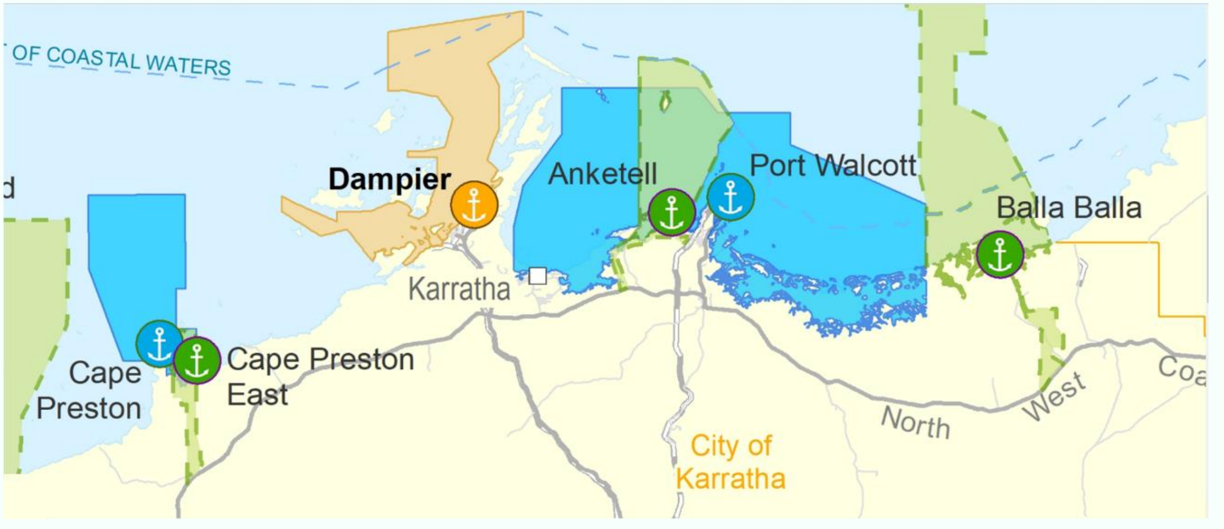


Figure (11): Existing and developing ports within Karratha boundary
Source: The web-based DPIRD renewable hydrogen information portal

Dampier Port:

The Pilbara Ports Authority [30, 31] stated “Despite being one of the youngest Western Australian ports, the Port of Dampier has been recognised as one of the world’s largest bulk export ports for most of the last 25 years”.
The Port of Dampier comprises private port terminals that facilitate the import and export of [30]:

- ✓ Iron ore
- ✓ Liquefied petroleum gas
- ✓ Liquefied natural gas
- ✓ Diesel
- ✓ Condensate
- ✓ Salt
- ✓ Ammonia
- ✓ Bulk cargo and general cargo

Box 11: DAMPIER Port Fast Facts [32]

- ➢ 2016-17 annual throughput of 668,554 anhydrous ammonia
- ➢ Throughput Tonnage (2018 - 19) is 172,995,939
- ➢ Vessels Movements (2018 - 19) 10,521
- ➢ More than 120ha of land area and 650km^2 of marine waters
- ➢ Network extends 350 kilometres inland
- ➢ 200 kilometres seaward to the oil and gas fields of the North West Shelf

3.7 Karratha: the Australian Renewable Hydrogen Hub

Karratha is a city in the Pilbara region of Western Australia, adjoining the port of Dampier. It was established in 1968 to accommodate the processing and exportation workforce of the Hamersley Iron mining company and, in the 1980s, the petroleum and liquefied natural gas operations of the North West Shelf Venture. In 2018, Karratha had an urban population of 22,205 [32]. The City's name comes from the cattle station of the same name, which derives from a word in a local Aboriginal language meaning "good country" or "soft earth". The City is the seat of government of the City of Karratha, a local government area covering the surrounding region. It covers an area of 15,882 square kilometres as shown in Fig. (12).

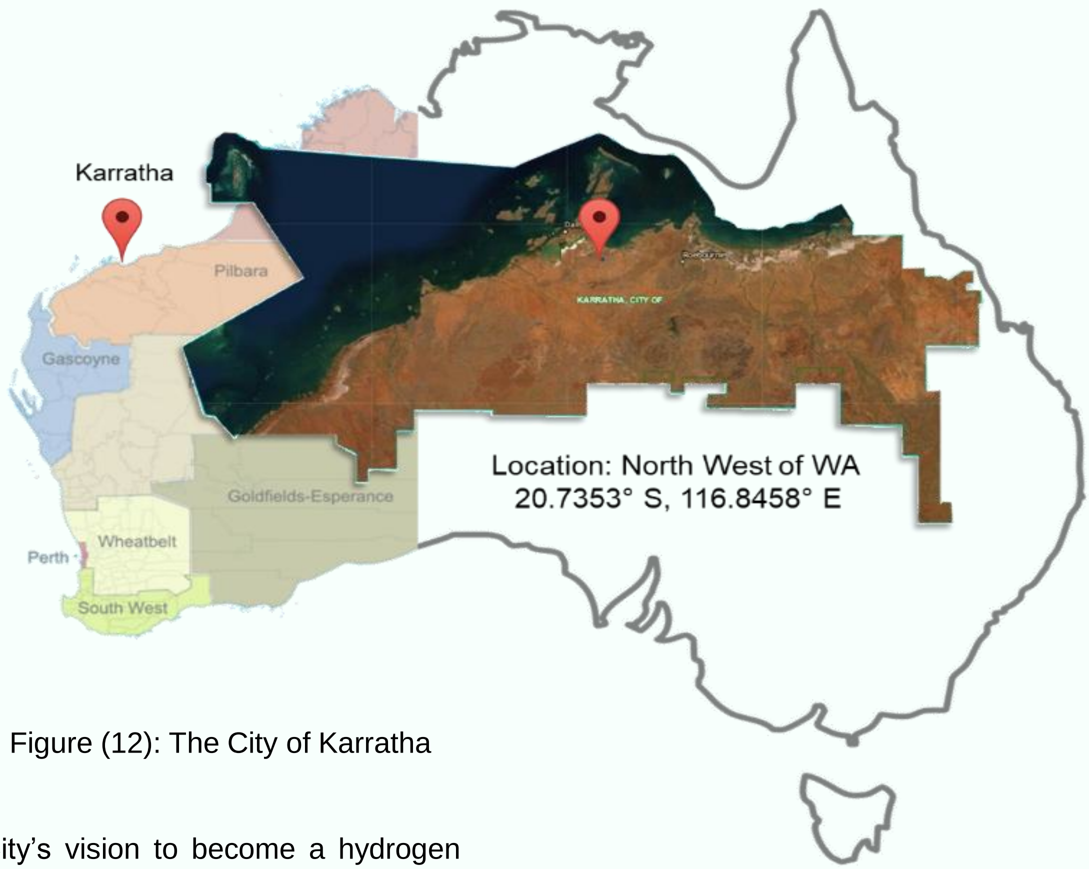


Figure (12): The City of Karratha

The City's vision to become a hydrogen hub must be aligned with the Australia's National Hydrogen Strategy by scaling-up support for pilot, trial projects and incentivise growth of hydrogen hub demonstration [32].

An overview on the hydrogen infrastructure in Karratha and Dampier port revealed that Karratha is ticking most of the hydrogen hubs' assessment criteria framework developed by Australian Hydrogen Hubs Study [5].

Box 12: Hydrogen Hubs

The Australia's National Hydrogen Strategy defines hydrogen hubs;

"Hubs are regions where various users of hydrogen across industrial, transport and energy markets are co-located."

The list of hydrogen hub selection criteria [4, 5, 33, 34] that Karratha ticks for export and domestic hydrogen hubs are [30, 31, 35]:

- ✓ Environmental, economic and social considerations.
- ✓ Community awareness, support and engagement in the hydrogen industry space.
- ✓ Health and safety practices in Karratha and Dampier port.
- ✓ Land availability for renewable and hydrogen industries.
- ✓ Port terminal expansion possibilities and shipping distance to target market e.g. Japan, South Korea and Singapore.
- ✓ Robust electricity grid is managed by Horizon Power with over 80 MW powerplant run by ATCO Gas Australia.
- ✓ Availability of NG and LNG infrastructure and pipelines e.g. Dampier to Bunbury.
- ✓ Existing large industrial projects which can be prospect hydrogen off-takers.
- ✓ Existing Solar PV farm e.g. 1 MW at Karratha airport.
- ✓ Potential for offshore hydrogen production e.g. offshore wind turbines.
- ✓ Existing road and railway access to the ports i.e. Hamersley & Robe River railway.
- ✓ Water availability e.g. solar powered desalination.
- ✓ Existing co-location with industrial like Yara Green Ammonia project and the Asian Renewable Energy Hub in the Pilbara (15 GW).
- ✓ Existing of underground large-scale carbon and hydrogen storage i.e. salt caverns and depleted gas fields.
- ✓ Availability construction & operation skilled workforce and potential for hydrogen skilled workers e.g. TAFE, Karratha and Pilbara Universities Centre.
- ✓ Proposed hydrogen highway starting point i.e. hydrogen fuelling station.

3.8 Existing Renewable Energy Policy

A close look at the existing policy for renewable energy in Karratha; reveals a lack of incentives, such as zero feed-in tariff which is one of the main barriers for more RE systems and projects development. This is evidenced by the case-specific design of the few solar PV systems in Karratha to cover the internal consumption with minimal export to the grid [36], as illustrated in the power consumption profiles of Karratha Airport shown in Fig. (13). This barrier raises the necessity for robust, reliable, and large capacity RE storage systems which hydrogen is the perfect candidate. Storing excess RE in the form of hydrogen can play a vital role to incentivise more solar PV systems to be integrated into the grid without altering its balance and stability. However, hydrogen offtakes are required to be identified and established in the form of power generation and direct fuel, leading to Power Purchase Agreements (PPA), in the case of grid connection.

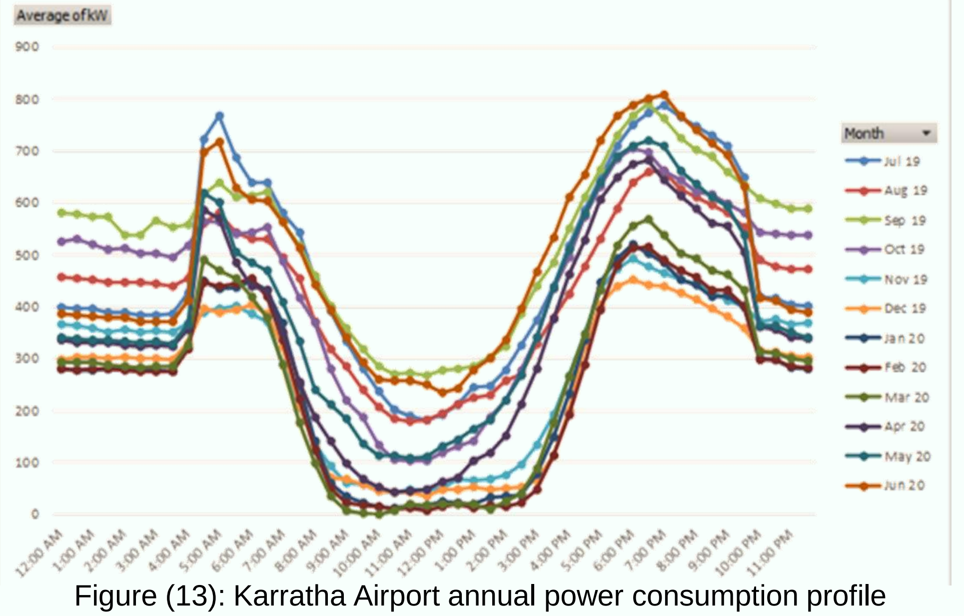


Figure (13): Karratha Airport annual power consumption profile
Source: Karratha Airport Authority

3.9 Hydrogen Markets

The industrial hydrogen (pure form) global market is estimated at 70 Mtpa in 2018, as a primary industrial material for refineries and ammonia production [2, 4]. Whilst, most of the industrial hydrogen was produced from steam reforming of fossil fuels mainly coal and methane, less than 5% of the global hydrogen production is produced from RE resources, referred to as clean or green hydrogen [2]. The global hydrogen demand is expected to rise to 304 Mtpa in 2050, including over 90 Mtpa for electricity generation [4].

The development of an export market would enable a domestic market to achieve economies of scale more rapidly than relying on a gradually evolving local market [37, 38]. Additionally, the CSIRO Roadmap argues that technological developments have reached a sufficient level of maturity that the narrative is ready to shift to 'market activation' [38].

3.9.1 *Hydrogen Domestic Markets*

The projection for hydrogen demand in Australia's domestic market is minimal. The right policy and more investments will promote potential hydrogen applications. Furthermore, developing a domestic hydrogen distribution network with safety and handling standards is a key for expanding the hydrogen domestic demand. It is essential to have both hydrogen supply chain and the end-use market grow in parallel for an optimal hydrogen value chain scale-up. However, more government support in the infrastructure sector investment is vital to avoid the chicken and egg situation.

Additionally, with no existing hydrogen export supply chain [7, 23]; it is an opportunity to scale-up the domestic demand for hydrogen which can increase the commercial readiness index for the renewable hydrogen production. Hence, the economy of scale infrastructure is ready for rapid scale-up when hydrogen export is globally established.

Box 13: Hydrogen market creation and Cost reduction drivers

- More investment
- Policy alignment
- Scale-up
- Safety and handling Standards
- Unlocking potential applications
- Industry feedstock applications
- Domestic hydrogen distribution
- Global hydrogen shipping

Box 14: Hydrogen Domestic Demand

- Can grow fast
- Lage-scale capacity
- Can be a transitioning step towards hydrogen export
- In-direct hydrogen export
- Create jobs
- Reduce GHG emissions

3.9.2 Global Market Prospects

In May 2020 ANT energy solutions [7] stated, *"The CSIRO National Hydrogen Roadmap estimated an Asian renewable hydrogen import demand of up to 3.8 million tonnes by 2030. The ACIL Allen Opportunities for Hydrogen Exports model indicated Australia could secure 10-20% of Japanese and Korean demand, with a mid-case forecast of 500,000 tonnes of hydrogen per annum by 2030."*.

Box 15: Hydrogen Export options

- Pure compressed gas H_2
- Pure liquified H_2
- Solid-state storage
- Hydrogen carriers
- Hydrogen-based products (In-direct)

It is crucial to develop a government to government international agreement to nurture industry development where Australia is an obvious supplier to Japan and South Korea who are keen purchasers of renewable hydrogen. However, renewable hydrogen in Australia is currently minimal which foreseen to reach 3,000 tonnes by 2025 with the existing initiatives [7]. Whilst, the predicted 10-20% global market share requiring 166X scale-up in renewable hydrogen production capacity [7], which represent an opportunity for Karratha to capture.
ACIL Allen [37] concluded that the value of Australian exports could surpass $10 billion by 2040. This hydrogen production capacity would require roughly 70 TWh of renewable electricity if produced via the water electrolysis [37, 38].

3.9.3 Coupling of Hydrogen Export and in Return Import

As the hydrogen export focus involves building upon the existing bilateral LNG trade relations with the Asian market like Japan, South Korea and China which are the largest LNG importers globally. The hydrogen fuelled vehicles and machinery market in Australia should grow in parallel to allow these foreign economies to export their hydrogen goods in return to maintain balance of trade, which will in turn support the development of an Australian domestic hydrogen market [5]. The Australia-Japan Memorandum of Cooperation on Energy and Minerals Cooperation signed on 16th June 2019 [5] and the letter of intent in September 2019 to collaborate with South Korea [5] can be a great opportunity for Karratha to play a key role in the emerging future energy export.

3.10 SWOT Analysis

Key strengths and opportunities with associated weaknesses and threats for the City to become a hydrogen leader in the region are presented in the Strength, Weakness, Opportunity, and Threats (SWOT) analysis as shown in Fig (14).

Figure (14): Strength, Weakness, Opportunity, and Threats (SWOT) analysis for Karratha

These can be leveraged to overcome the weaknesses and threats through the Sustainable Livelihoods Framework and the Industrial Symbiosis model.

How these assets will be harnessed are described in the strategy of the following chapter.

4 The City of Karratha Hydrogen Strategy

A hover view over Karratha landscape reveals many strengths and opportunities as well as competitive advantages in establishing a hydrogen economy. Therefore, there is a need for pro-business investment environment to capture the advantages as well as to reduce the barriers in order to become a champion for renewable hydrogen. However, the existing policy and regulatory framework have a degree of associated weakness or barriers as listed in Fig. (14) which need to be removed to attract investments.

This section maps out a strategy which the City can achieve through the following steps:

1. Developing key policies to enable the City to overcome any barriers, increase its profile and promote its brand in the renewable hydrogen market.
2. Attracting business investment into renewable hydrogen projects.
3. Networking with complementary industries that are required to support the development of the renewable hydrogen industry.
4. Proposing strategic partnerships to become Western Australia's centre for renewable hydrogen.

There is a strong desire from business and industry which could be aligned with future-focused sustainable economic development, creating jobs, and meeting environmental targets. Along with technological advancement, fact-based policymaking and an adequate policy framework are needed based on fostering knowledge to ensure the role of hydrogen in their economic growth. Moreover, the policy framework must be flexible and capable of adapting and encouraging technological change over time [32, 39-42]. Also, the developed regulatory framework requires to supports renewable energy-power purchase agreements (RE-PPA) to stimulate new RE and hydrogen business models [35].

4.1 Policy Framework and Incentives

According to the Western Australian Renewable Hydrogen Strategy, there are four strategic areas of focus for the development of the hydrogen economy in WA [43]:

- Export
- Remote applications
- Hydrogen blending in natural gas networks
- Transport

To address the above strategies, a key approach taken by the Australian government is to create Hydrogen Hubs. Based on the available resources, Karratha is well-positioned to become a Hydrogen Hub. Karratha's proximity to existing commercial energy importers in Asia means it has the potential to meet the hydrogen needs of these transitioning to hydrogen economy markets. Additionally, there are industries and mining areas that need power, and therefore, Karratha is well-positioned to supply renewable hydrogen as RE carrier and storage medium. Karratha meets all the criteria to be chosen as hydrogen hub as mentioned in the Australian Renewable Hydrogen Strategy [1, 44].

The City of Karratha needs to strengthen its renewable energy policy framework, generally via its 2019 Economic Development Strategy on investment attraction and diversification (page 28) [32]. Specifically, its strategy [32] section 2.1; “Encourage the development of renewable energy generation operations” and the Renewable Energy Development Study prepared by GHD for the City [45], are aligned with the policies needed for hydrogen industry development. This can be achieved, for example, by hosting industry expos, seeking funding for the City’s own demonstration projects and raising awareness and knowledge of the City’s staff and councillors.

4.1.1 Policy and Regulatory Aspects

To achieve this, the regulatory framework needs to be aligned with:

- Karratha Economic Development Strategy [32]
- Indigenous rights and legal considerations for any new development [29]
- National hydrogen strategy and roadmap to set targets [9]
- Australia climate policy goals and INDC
- International and domestic energy prices
- Responsive regulations to facilitate the process of obtaining permissions from the associated stakeholders
- International standardisation of technical specifications, safety, and handling
- Infrastructure use, reuse, and modification
- National incentives like carbon tax, tax breaks and subsidies

For developing a hydrogen economy, Karratha needs to develop a pathway, initially by removing regulatory barriers to hydrogen use, developing local industries and encouraging it through policies to help overcome investment barriers. A regulatory and legal framework will help to develop consistent approaches for [39]:

- Efficient supply chains and markets
- Supportive investment environment
- Robust training requirements and safety standards
- International engagement
- Skills and workforce
- Community confidence
- Innovation and R&D

Karratha's Economic Development Strategy [32] may include financial support for the development of clean hydrogen supply chains and policies to create hydrogen demand or other policies that stimulate private investment. The following approaches may be considered by the City to create a hydrogen economy:

- Develop a strategic and coordinated international outreach to focus on key markets and to harmonise standards and encourage trade and enhance international engagement.
- Establish training centres in coordination with universities and other training nodes to improve workforce skills and establish training regimes as well as develop safety standards.
- Run workshop for communities with industries to earn the community's trust and build confidence in hydrogen.
- Collaborate with research institutes and universities and provide targeted support for research and development activities, with a focus on international collaboration and City's priorities.
- Develop partnerships with the Traditional Owners to enable access to land required for solar PV generation.

4.1.2 Potential Policy Framework for the City of Karratha

Given the hydrogen industry is a new industry, the regulatory model needs to support the hydrogen industry and align with the national hydrogen strategy. In order to achieve a strong and effective hydrogen economy, the policy framework needs to focus on the opportunities and also how to remove the threats and barriers. The City could follow the following framework illustrated in Fig. (15).

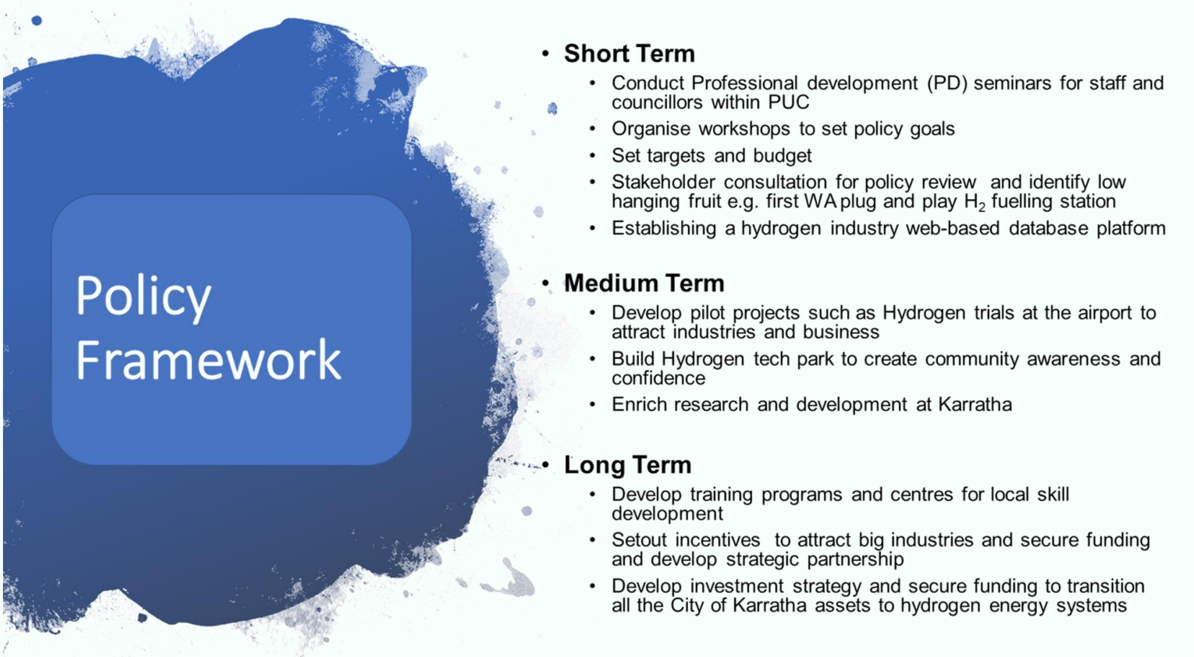


Figure (15): Policy framework for the City of Karratha

4.2 Attracting Business Investments

Australia's National Hydrogen Strategy [1] stated: *"An Australian hydrogen industry could generate about 7,600 jobs and $11 billion in GDP in 2050 with targeted global deployment; if global markets develop faster, consistent with the energy of the future scenario, estimates rise to around 17,000 jobs and $26 billion in GDP"*. This promising future for the hydrogen industry in Australia represents an opportunity for Karratha to secure a leading position at the front due to the region's suitability and Karratha's capability to do so. Hence, Karratha should act quickly to attract business and industry investors to the region. Karratha needs to focus on attracting investment in the key areas of the hydrogen industry as well as complementary industries to kick start transition to a hydrogen hub. Additionally, investment in infrastructure and skilled workforce capacity building need to be looked at from the renewable hydrogen perspectives.

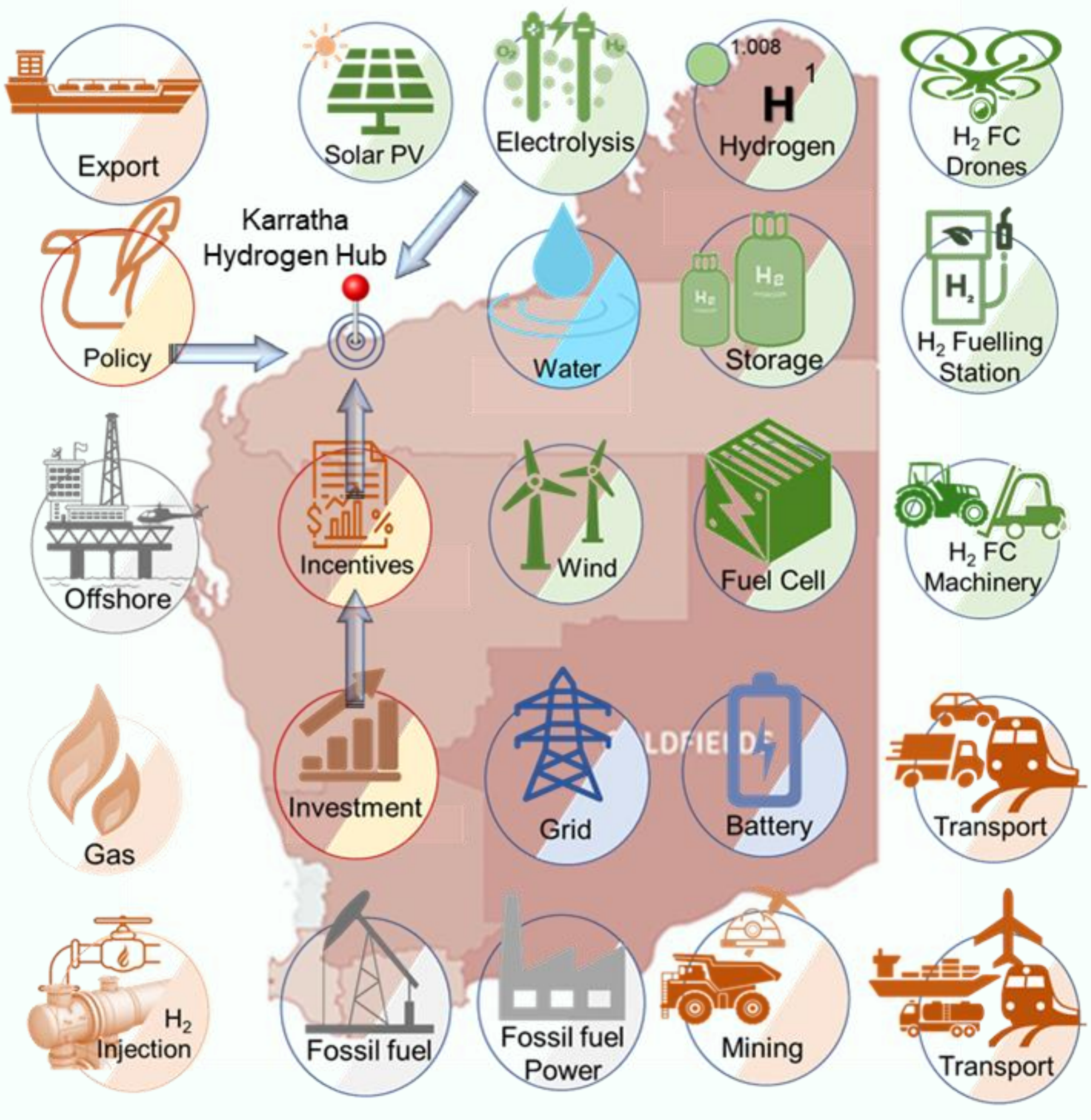
The concept of the reverse auction in attracting competitive bids has driven down the cost of solar and wind without placing an onerous burden on ACT and Victoria governments [41]. This bidding model can be adopted by the City of Karratha for developing new large-scale solar and wind farms for renewable hydrogen production.

4.2.1 Areas Needing Investment

- Renewable energy generation namely solar PV and wind turbines
- Hydrogen production plants i.e. green and blue hydrogen
- Hydrogen storage facilities i.e. compression, liquifying, material based
- Large-scale hydrogen storage utilising underground salt caverns
- Hydrogen blending into the gas pipeline network
- Upgrading gas networks to be suitable for more hydrogen blending
- Industrial hydrogen for heat
- Stand-alone hydrogen-based renewable energy powered microgrids
- Grid scale hydrogen-based energy storage systems
- Unlock new hydrogen utilisation pathways
- Hydrogen fuelling stations
- FCEV and FC powered machinery
- Hydrogen to alternative fuels industries
- Heavy transport such as trucks, trains, and ships
- Mining industries to adopt and transit to hydrogen energy
- Attract human and technological resources to support the building and deployment of hydrogen industry projects [4]
- Hydrogen certification scheme or what called guarantee of origin [12]

4.2.2 Increase the Attractiveness of Investment

- Hydrogen strategy existence
- Policy certainty and relevant regulations
- Skilled workforce availability and ability to transform or build-on
- Existing offtakes for hydrogen directly or indirectly
- Regional prospect and potential hydrogen-based green industries database
- Community trust, support, and engagement
- Preliminary land exploration and resources survey existence
- Pilot projects with a knowledge- sharing platform
- An investor's information centre with web-based platform
- RD&D facilities like "Centres of Eminence" through facilitating partnerships with key universities engaged in hydrogen research and industry support



4.2.3 Low Hanging Fruit for Karratha

The City of Karratha can act quickly and effectively to attract attention among the hydrogen industry stakeholders and become a landmark in the hydrogen landscape. This can be achieved by identifying the low hanging fruit with the most impact creation and the least capital and time requirement. For example, installing a small-scale hydrogen fuelling station, but the first in the state, with a couple of public transport buses, supported by the Australian public's perception of hydrogen as stated in the energy report published in 2018 [33]. This will position Karratha quickly and well in the hydrogen landscape nationwide. Additional opportunities exist in building on existing projects like the solar PV system in the City Operations Centre using a compact plug and play hydrogen fuelling station coupled with a few HyFCVs, may be achieved within the City's budget as well as being quick to implement. Additionally, transitioning Karratha Airport to be the first in the world to run on 100% renewable energy based on hydrogen storage system would propel Karratha to the global hydrogen landscape. Moreover, expanding small-scale projects like the first hydrogen refuelling station to be the start point for the proposed WA Hydrogen Highway (Zero emission Highway) which, if it happens, can be extended to Australia National Hydrogen Highway.

Also of importance,, Karratha's presence in some high impact public hydrogen events such as hosting an event to celebrate the "(Inter)National Hydrogen Day" on the 8th of October can make remarkable publicity. Additionally, establishing partnerships with hydrogen research centres such as universities and CSIRO-Hydrogen Industry Mission, as well as sistering the City with international H2Cities like H21 Leeds City Gate in the UK, can add another dimension to Karratha reputation in the hydrogen space. These low hanging fruit projects will transit the City of Karratha to become a Hydrogen City (H2City) which can attract strong interest globally.

4.3 Complementary Industries

During the City's transition to becoming a hydrogen hub, it is important to co-locate hydrogen generation in proximity to existing and potential energy industries and other resources-based industries [5]. By doing this, utilising existing infrastructure, industries trade-offs and sector coupling can save time and costs, as well as establishing industries' nexus way of thinking.
There are many complementary industries to be directly or indirectly involved with the hydrogen value chain. Some of these industries already exist but need to be scaled-up while other industry sectors are required to be created. Furthermore, some of these complementary industries needed to be established before large-scale hydrogen projects are implemented and other complementary industries can emerge with or after developments. Additionally, the existence of these complementary industries will reduce hydrogen production cost and investment risks, as well as ensure after commissioning services.

4.3.1 Direct Hydrogen Complementary Industries

- Solar PV farms installation and maintenance industry including associated civil and metal work. This can lead to more investment in local solar PV panels manufacturing for the big demand for many years to follow. Also, large-scale solar PV farms inspection using state-of-the-art technologies, drones and artificial intelligence is a fast-growing industry that can be a necessity for the proposed 15 GW Solar PV and Wind project in the Pilbara region [16, 46].
- Wind turbine installation and maintenance will be another key complementary industry to be investigated.
- Large electrical contracting companies which can provide Engineering, Procurement, Construction and Commissioning (EPCC) including electrical and associated civil works.
- Renewable energy powered water desalination, purification, and de-ionisation with possibility to expand to water recovery from hydrogen production and utilisation.
- Renewable energy powered wastewater and industrial wastewater treatment and recycling for hydrogen production. Furthermore, utilising the renewable oxygen associated with the hydrogen electrolysis in wastewater treatment (i.e. aeriation) is another complementary industry which can reduce the renewable hydrogen production cost.
- Hydrogen ready natural gas pipeline network and end user appliance industry.
- Economy of scale hydrogen storage facilities including underground hydrogen storage projects.
- Hydrogen trucks and trains associated with hydrogen fuelling stations industry.
- Hydrogen guarantee of origin certification scheme to certify the hydrogen to ensure how clean is any of the produced hydrogen. This is an essential industry for any pure hydrogen or hydrogen-based green industry to comply with the developing global hydrogen market regulations.

4.3.2 Direct Hydrogen Offtake Industries

- Green steel industry is a promising avenue for indirect hydrogen export embedded in a green and more valuable commodity [23, 24]. Green steel uses hydrogen to replace metallurgical carbon to reduce iron ore to iron metal [23]. This industry requires a large-scale hydrogen production as well as large-scale hydrogen transport and storage which will be coupled with most of the direct complementary industries mentioned in the previous sub-section.
- Green ammonia and fertilisers are a fast-growing industry based on replacing the brown and grey hydrogen used for conventional ammonia production with renewable hydrogen. The large-scale project for green ammonia in Yara can be a ready economy of scale offtake industry in the region. Both green ammonia and green fertilisers can indirectly export renewable hydrogen. The existing ammonia export infrastructure in Dampier port is a step ahead and another competitive advantage for Karratha.
- Many other industries can be transformed by green hydrogen to produce green commodities to reduce GHG emissions globally. These industries are all the energy-intensive manufacturing processes like aluminium, alumina, cement calcination, and glass manufacturing.
- Bio-methane upgrades, biofuels and alternative fuels based on renewable hydrogen are possible pathways for indirect hydrogen export.
- Negative carbon emission is an emerging technology based on the old concept of utilising CO_2 to chemically interact with hydrogen to produce methane gas which is called methanation. This industry is a promising pathway to export hydrogen via chemical carrier methane (CH_4). The rapidly developing technology of direct green methane production from renewable energy by the co-electrolysis process [7] can be another promising avenue for Karratha.
- Wastewater treatment by anaerobic digestion to produce methane followed by conversion to hydrogen and graphite technology developed by the WA innovative company Hazer Group .

4.3.3 Indirect Complementary Industries

There are many industries which can indirectly support the renewable hydrogen industry growth in Karratha and the greater Pilbara region. For example, it has been mentioned in the latest “start with steel” report by Grattan Institute in May 2020 [23] that shortage in labour and a skilled workforce in the Pilbara region, makes it more cost-effective to ship Iron Ore to the eastern states to produce green steel. This conclusion indicates that Karratha needs a more skilled population which requires many non-energy industries to support the economic growth in Karratha. Some examples of these industries are listed below, which align with the City Economic Development Strategy [32]:

- Logistic suppliers’ companies
- Karratha airport expansion
- Enhance community services to attract more residence
- Educational institutions and Pilbara University expansion
- Food industry and many more.

4.4 Strategic Partnerships

The strategic partnership in the hydrogen industry is vital to deliver hydrogen supply chain value and harmonise production with domestic and global markets. The knowledge-sharing and technology transfer in developing hydrogen chain value can be key of success by ensuring cost reduction, the guarantee of origin, safe handling and market creation and penetration. Furthermore, there is a necessity to establish strategic partnerships in different levels and directions such as government to government, public to public, business to business, industry to industry, and the public to private partnerships. City sistering is another form of strategic partnership for knowledge-sharing and parallel development. Moreover, the strategic partnership required for the City lay in many different industry spaces. This raises the necessity for a common platform for all the stakeholders to be able to access the database information and feed-in their contribution. Some of the nominated strategic partnerships for Karratha to establish are listed in Fig. (16). Green steel industry is a promising avenue for indirect hydrogen export embedded in a green and more valuable commodity [24]. This industry requires a large-scale hydrogen production as well as large-scale hydrogen transport and storage which will be coupled with most of the direct complementary industries mentioned in the previous sub-section.

Figure (16): Strategic partners for the City of Karratha

4.4.1 Community Awareness and Engagement

According to Lambert and Ashworth in 2018 Australian community's understanding of hydrogen is low [33]. It is important to bring all Australians along the journey, so they will have ownership in the process of this development and develop confidence in the technology. It is also important to raise awareness among the community on the potential benefits of this industry. In Karratha, there are currently 19 Native Title claims and determinations. To produce Green Hydrogen, the area needs solar RE development, which requires land access. Therefore, it is important to develop partnerships and explain socio-economic benefits for Traditional Owners. It is essential to understand how different stakeholder groups are impacted by an emergent hydrogen industry, to manage community expectations [47]. Early and adequate community engagement can remove most of the barriers of land use permissions process and environmental approvals. For example, negotiations are currently underway in Port Hedland between the Traditional Owners and a large solar farm project developer.

This report proposes for the City to create community ownership of its first hydrogen fuelling station project. This can be done by developing awareness among the community and involvement in decision-making process. Some commonly used strategies are:

- Involving community-based organisations for awareness raising. These interest groups and networks are seen as one of the credible avenues for communicating new information on hydrogen industries.
- Displays in shopping centres of the hydrogen technologies and opportunities and organise public discussions similar to information sharing in focus groups. An example would be hydrogen fuel cell cars and buses, a hydrogen BBQ, or demonstration through a "display movable house" which showcase the practical uses of hydrogen. ATCO Gas at its Jandakot depot has developed the Clean Energy Innovation Hub.
- Organise Hydrogen industry expo or an open day such as, International Hydrogen Day with industries and involve the local community young people as volunteers for that event.
- It is important to maintain a relationship with the traditional landowners and recognise the traditional custodianship. It is critical to engage them early and regularly to make sure any questions could be answered appropriately and also the engagement was respectful of their culture and ensure adequate benefits are fairly distributed.
- Choosing the "key influencers" who are respected within the Aboriginal community is very important to explore new ideas. This will ensure they are listened to and take the projects more seriously.

Therefore, to develop a successful program, the technology and message should be consistent with a long-term strategy, and the frequency of communication and engagement should also be prioritised. However, it is important to note that there is not a one size fits all and stakeholder analysis and market segmentation would be a key component of any communication strategy.

4.5 Other Considerations for Karratha

4.5.1. Karratha Hydrogen Technology Park (HyTP)

Introduce a hydrogen technology park at Karratha in the transition to become a renewable hydrogen hub. It is essential to connect with all national and regional innovation hubs and hydrogen RD&D centres such as:

- Innovation hubs e.g. ATCO clean energy hub and energy transition hub, CRC, etc.
- National Hydrogen RD&D centres e.g. Australia Hydrogen Council, CSIRO, etc.
- Hydrogen development players e.g. ARENA, KPMG, GHD, Woodside, etc.
- R&D hydrogen testing area with equipped laboratory.
- Hydrogen software, advisory systems and tools e.g. H2City Tool.
- Hydrogen innovations competitions (rewarding).
- Pilbara University Centre.

4.5.2. Karratha Hydrogen Projects Initiatives

Karratha's seamless transition to the hydrogen space should start now and develop quickly with prioritised steps to position Karratha into the hydrogen industry landscape. It is recommended to start with the low hanging fruit (hydrogen projects) for the least cost and time of implementation, as well as the foreseen impact of these projects. This report represents a start point for Karratha's renewable hydrogen strategy and planned steps to be taken and pilot projects to be implemented. Below is a list of recommended projects prioritised according to their cost and expected impact to competitively position Karratha in the hydrogen industry landscape nationally and globally.

- **First hydrogen fuelling station in WA:** The innovative idea of utilising the excess RE from the existing 85 kW solar PV system at Karratha works depot (operations centre) which is currently fed back to the grid with no incentives in return. This can be done in a very short time by installing one plug and play hydrogen small-scale fuelling station to generate renewable hydrogen-based on a 100% net RE. This fuelling station is to be associated with a hydrogen fuel cell vehicle like a HyFCV bus or city rubbish collecting truck and/or a couple of HyFCVs for the City of Karratha officials use. This project, if implemented, will create an impact among the hydrogen industry stakeholders in Australia and globally. The proposed project overview is attached in Appendix (A). Additionally, this first hydrogen fuelling station can be the first station in the proposed "Zero-Emission Highway" by the Hydrogen Society of Australia and the lead to the State and National Hydrogen Highway.

- **The first-of-its-kind hydrogen-enabled Airport:** The existing medium-scale solar PV farm (1 MW) at Karratha Airport is another attractive site for a high impact hydrogen project that can be run on 100% renewable energy based on hydrogen storage and re-generating system. This project is to be done in three stages, whereby the first stage is to utilise the existing RE generation to reduce costs, implementation time and make an impact. A conceptual overview of the proposed project is attached in Appendix (B). Additionally, implementing this project even during the first stage can lead to the next project to energise the whole City of Karratha on aggregated distributed RE resources i.e. peer to peer energy trading and virtual power plant principles.

- **A 100% RE hybrid battery-hydrogen system for stand-alone microgrids (SAM):** This project can be a very attractive for governments and investors, as well as the mining industry. There is an ongoing funded feasibility study for a similar project in principle in the Pilbara region which will share the outcome around mid-year 2021. Karratha can build on that feasibility study and propose a similar system for one of Karratha's off-grid sites. The proposed project overview is attached in Appendix (C). Additionally, implementing this project can be an investment attractive to be replicated in stand-alone mining sites.

- **First fuelling station for the Zero Emissions Highway:** Karratha can be well-positioned in the hydrogen FCEV and BEV landscape by being the first to take action and implement the first fuelling station for the Zero Emission Highway. This is a project for heavy transport across WA. It is intended to run from 2020-2028 (8 years), building 80 hydrogen refuelling and EV charging facilities for a budget of about $500 million. The Hydrogen Highway is a subproject of the Zero Emission Highway and was initiated by Innovate Australia and now being led by the Hydrogen Society of Australia.
  The Hydrogen Highway describes roads equipped with hydrogen refuelling stations, allowing the use of hydrogen FCEVs. WA's Hydrogen Highway will focus on heavy transport, helping to introduce zero-emission transport, lower cost of fuel, and eventually, a secure fuel supply, eliminating the need for importing diesel. Two routes from Perth to Karratha were proposed. The range of most zero emission trucks is 600-1000km. Hence, setting up stations every 400km is required to accommodate FCEV trucks and give transport companies confidence in the viability of the route. Karratha should facilitate the development of a Karratha hydrogen refuelling and commercial scale electric recharging station. In addition, it should facilitate the development of refuelling stations along the routes leading to Karratha. The proposed project overview is attached in Appendix (D).

- **Transition Dampier Port to 100% RE hybrid system:** By implementing the first stage of this proposed multistage 100% RE-based hybrid hydrogen storage system project which can be the biggest project in Australia and globally, will position Karratha and Dampier port well in the global hydrogen landscape. Despite, there being many similar (in concept) proposals around the world, for example, Los Angeles port, Long Island port, and Qingdao ports, but still an opportunity for Karratha to be the first to act. This project can include the City of Karratha in the 100% RE plan as Karratha load is a small portion of Dampier port and interconnected to the same power grid. The proposed project overview is attached in Appendix (E).

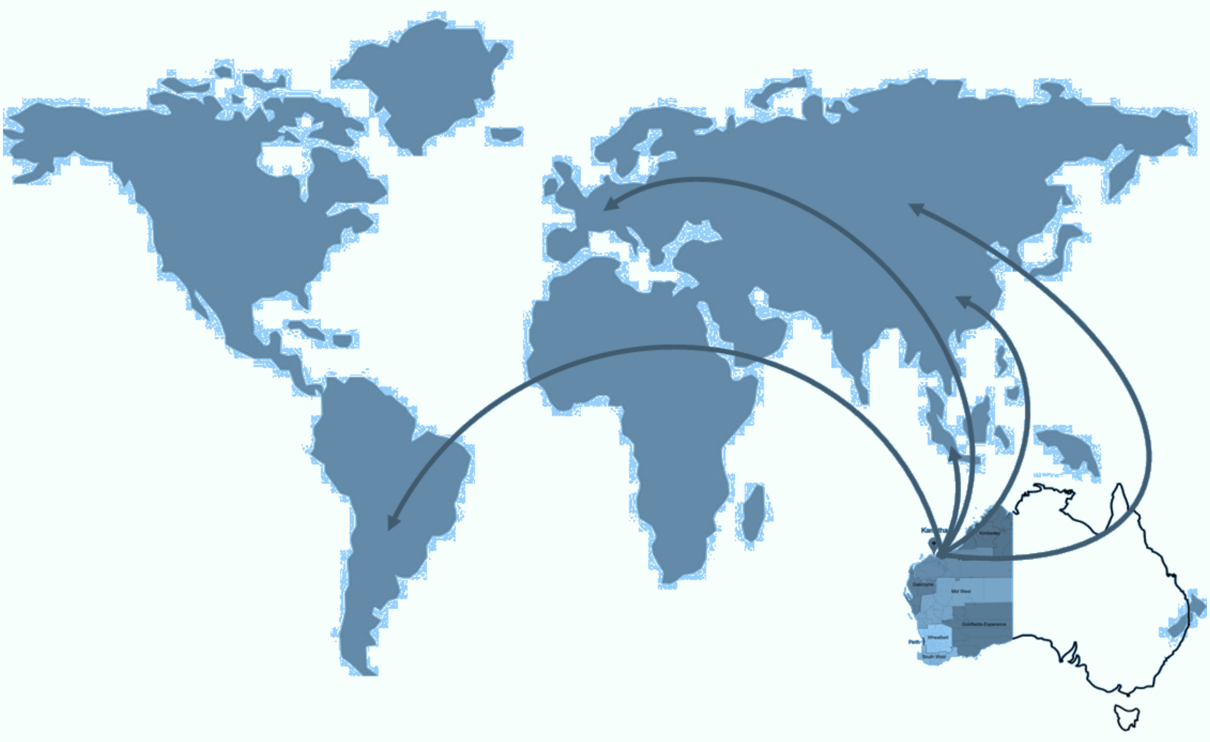
4.5.3 Engage with Global Hydrogen Players

A list of recommendations for Karratha to engage globally to play a role in the hydrogen industry development and the existing landscape is:

- Sister with International Hydrogen Cities e.g.
  - ➢ South Korea wants to build three hydrogen-powered cities by 2022.
  - ➢ H21 Leeds City Gate, UK

- International engagement globally, e.g. IEA hydrogen, hydrogen Europe, US-FCHEA, hydrogen council, IPHE, etc.

- Host international hydrogen events and conferences e.g. organise an international hydrogen conference in Karratha as a follow-up to the Broome 2003 conference.



5 The Hydrogen Strategy: Summary

Summarised hydrogen strategy for the City of Karratha to become a renewable hydrogen hub.

Short Term

- Conduct PD seminars for staff and councillors within PUC
- Organise workshops to set policy goals
- Set targets and budget
- Stakeholder consultation for policy review and identify low hanging fruit e.g. first WA H2 fuelling station
- Establish a hydrogen industry online database

Medium Term

- Develop pilot projects such as Hydrogen trials at the airport to attract industries
- Build Hydrogen tech park to create community awareness and confidence
- Enrich research and development at Karratha

Long Term

- Develop training programs for local skill development
- Setout incentives to attract big industries and secure funding and develop strategic partnerships
- Develop investment strategy and secure funding to transition all City of Karratha assets to hydrogen energy systems

Governmental agencies

- COAG Energy Council- Hydrogen Working Group
- CSIRO-Hydrogen Industry Mission
- ARENA-Hydrogen
- WA Government-JTSI, WA's Renewable H2 Unit
- WA Water Corp.
- Pilbara Development Commission
- Regional Development Australia Pilbara

Industrial partners

- Australia H2 Council & NERA Hydrogen Cluster
- Horizon Power, ATCO, Yara, Woodside, etc.
- Oil and Gas e.g. Woodside, Chevron and Apache
- Energy OEM suppliers e.g. Siemens, nel, etc.
- Mining e.g. Rio Tinto
- EPCC and consultancy e.g. GHD, Advisian, Worley
- Western Roads Federation

RD&D and educational institutions

- Universities, PUC and TAFE
- CSIRO, Innovation hubs

Create supportive policy and regulatory framework

Develop strategic partnerships

City of Karratha

Renewable Hydrogen Hub

Attract investment

More complementary Industries

Our Competitive Advantages

Attract investment

- Positive council attitude
- Hydrogen strategy existence
- Policy certainty
- Skilled workforce availability
- Existing offtake for hydrogen
- Community trust
- Preliminary land exploration
- Resources survey
- Land suitability survey
- Pilot projects
- An investor's information centre
- RD&D facilities
- JTSI Fellowship program
- JTSI credentials development

Our Competitive Advantages

- Supportive proactive council
- Pro-business & industry environment
- Skilled workforce diversity
- Significant solar energy resources
- Land and water resources availability
- Seaports and airport
- Existing fossil gas processing
- Export infrastructure
- Proposed ports
- Proximity to energy importer markets

More complementary Industries

- Solar PV installers
- Electrical large contracting companies
- RE powered water purification
- RE powered wastewater treatment
- Hydrogen ready NG pipeline network
- Hydrogen storage facilities
- Hydrogen FC heavy transport i.e. trucks and trains
- Hydrogen guarantee of origin certifiers
- Establishment of direct hydrogen offtake agreements e.g. green stall, green ammonia, alumina, glass, etc.
- Establishment of indirect complementary industries e.g. logistics

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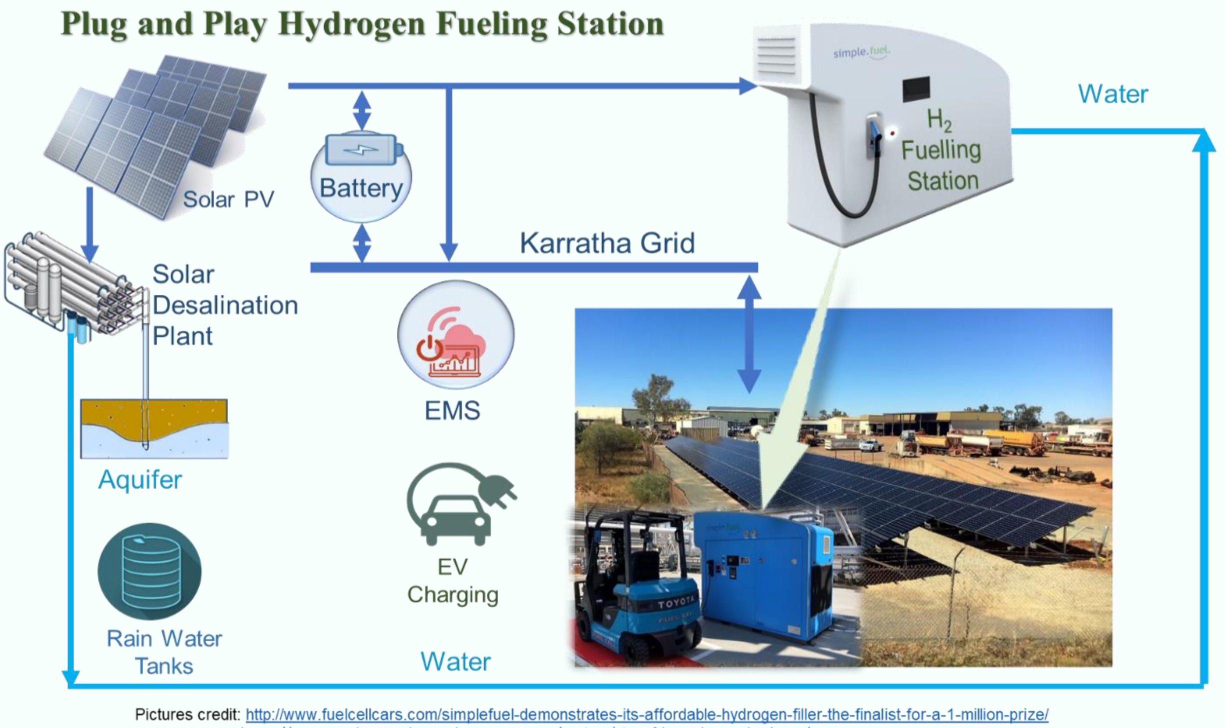
Appendix (A): First Hydrogen Fuelling Station in WA

The City of Karratha Operations Centre has an 85 kW ground-mounted solar PV with a battery system to cover part of the power consumption for the depot operations with an approximate generation of 175.7 MWh per annum [48]. The solar PV system is connected to the grid to export excess power if any, especially during the weekends or when the Depot is not fully operational.

This is a low hanging fruit for the City of Karratha to act immediately to install a small hydrogen fuelling station in the works depot and lease a few HyFCVs such as one HyFC forklift, one FC- SUV servicing vehicle and a HyFC truck. This first hydrogen fuelling station in Western Australia can create tremendous publicity and attract a lot of attention towards Karratha as an emerging renewable hydrogen hub.

The proposed fuelling station is a plug and play piece of equipment which can be installed by an electrician into a wall socket. The principle of net RE to be used for the fuelling station to operate 24 hours utilising the energy directly generated from the solar PV system in the works depot and import from the grid some of the exported excess power. This makes the hydrogen fuel net-zero emission fuel i.e. net renewable hydrogen. Figure (A1) illustrates the interoperability of the system and the hydrogen fuelling station integration into the existing RE system in Karratha's works depot. This plug and play hydrogen fuelling station has an electrolyser coupled with a 5 kg of hydrogen storage cylinders and a fuelling compressor to the two international standards of 350 bar and 700 bar for small and heavy HyFCVs. However, the proposed Simple Fuel from PDC in Fig. (A1) is an example of this type of plug and play hydrogen fuelling station which can be purchased from many other OEM vendors around the world.



Pictures credit: http://www.fuelcellcars.com/simplefuel-demonstrates-its-affordable-hydrogen-filler-the-finalist-for-a-1-million-prize/
https://www.perdamanadvancedenergy.com.au/project/city-of-karratha-works-depot/

Figure (A1): Plug and play hydrogen fuelling station for the City of Karratha Operations Centre

Appendix (B): A 100% RE Hybrid Battery-Hydrogen System for Stand-Alone Microgrid (SAM)

A 100% renewable energy hydrogen-based stand-alone microgrid (SAM) system can be developed by robust RE hybrid battery-hydrogen storage systems to stabilize the variable and intermittent renewable energy resources. This system is proposed for remote off-grid stand- alone microgrids for both the urban and rural communities as well as off-grid farming villages, cattle stations, and mining sites. A recently published paper has introduced a techno-economic assessment and evaluation with a proposed model and system simulation [48]. This study revealed that the hybrid battery-hydrogen based storage system is the most cost-effective solution to transit from diesel-powered SAM to a 100% RE SAM systems.
The feasibility study of this system is underway by the Murdoch Hydrogen Team which expected to be published in the middle of next year (2021). It can be implemented on a selected site within Karratha boundaries to be a pioneer pilot project which leading the way of many replications around the Pilbara region, WA, Australia and globally.

The proposed model is shown in Fig (B1).

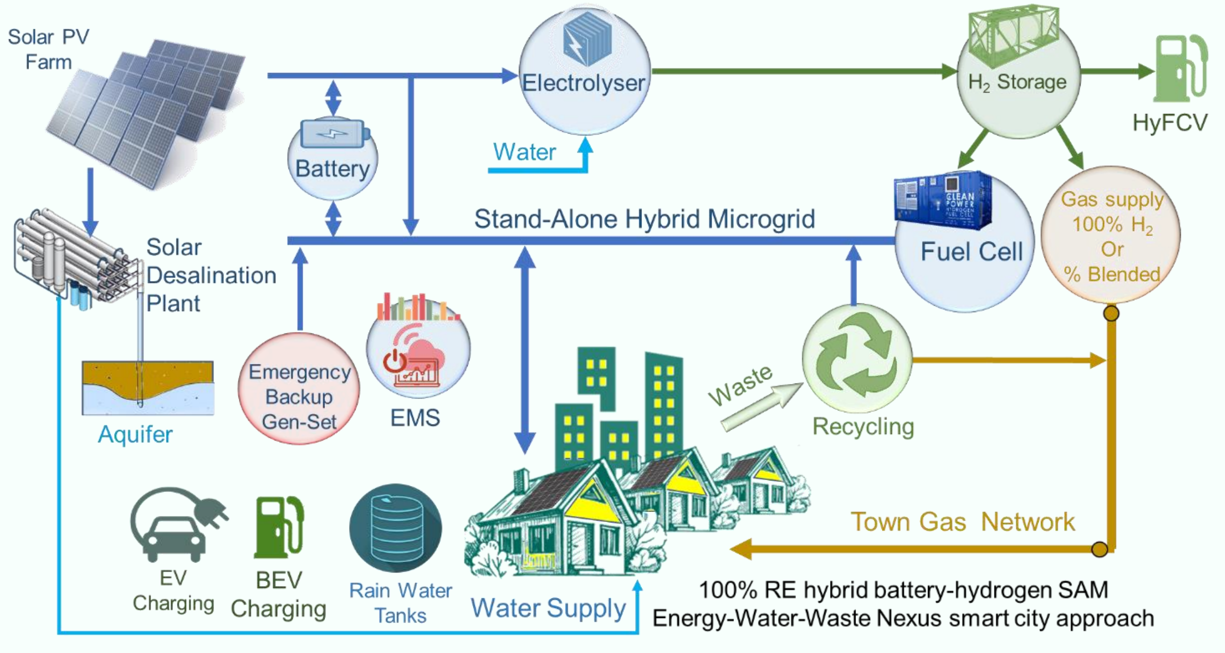


Figure (B1): Proposed 100% RE hybrid battery-hydrogen SAM system model

Appendix (C): Hydrogen-Based Energy System for Karratha Airport

Proposed model

The aim of developing renewable hybrid microgrid for Karratha Airport is to diversify the renewable energy storage for secure, reliable, and eco-friendly energy supply and zero-emission transport. The proposed system comprises solar PV-RE generation (exist) and Hydrogen-based energy storage system, as shown in Figure (C1).

Hydrogen fuelling stations and EV fast-charging stations are essential to ensure zero-emission energy and transport in Karratha Airport. Also, installing the hydrogen fuelling station at the Airport can be integrated with the proposed zero-emission (hydrogen) highway from Perth to Karratha and with the inevitable transition towards the zero-emission economy, i.e. Hydrogen Economy.

Implementation

Three stages of application have been proposed for Karratha Airport Authority to seamlessly transit to a 100% RE zero-emission self-sufficient smart Airport, as illustrated in Figure (C1). Whilst, each stage is modularly designed to be gradually expanded in the transit according to the planned timeline and supply/demand scheme. A feasibility study must be conducted to prove our preliminary techno-economic evaluation, which has been led to this proposal.

Stage (1)

The proposed system for stage (1) is to facilitate 50% of Karratha Airport's average load. This system comprises a sufficient RE capacity, e.g. increase the existing 1 MW to 3 MW solar PV farm coupled with 2 MW capacity of electrolysis system, adequate compressed Hydrogen storage tanks, and a 1 MW FC capacity. The Hydrogen fuelling station with an EV fast- charging facility will complete the zero-emission picture. Hence, this proposal has been based on converting a few buses and servicing vehicles to EV and hydrogen FCEV.

Stage (2) and (3)

Depending on evaluating the stage (1), the next step is to expand the RE generation to the maximum Airport capacity for solar PV farms and the Distributed Energy Resources (DER) within the Airport boundary. Furthermore, expanding the hydrogen round trip system accordingly.

Following stage (2), stage (3) is to expand beyond the Airport boundaries to import RE from the DER over the utility grid with expanding the Airport renewable hydrogen production capacity. The produced hydrogen can be stored as compressed gas, injected into the gas pipelines, or in the developing solid-state hydrogen storage technologies.

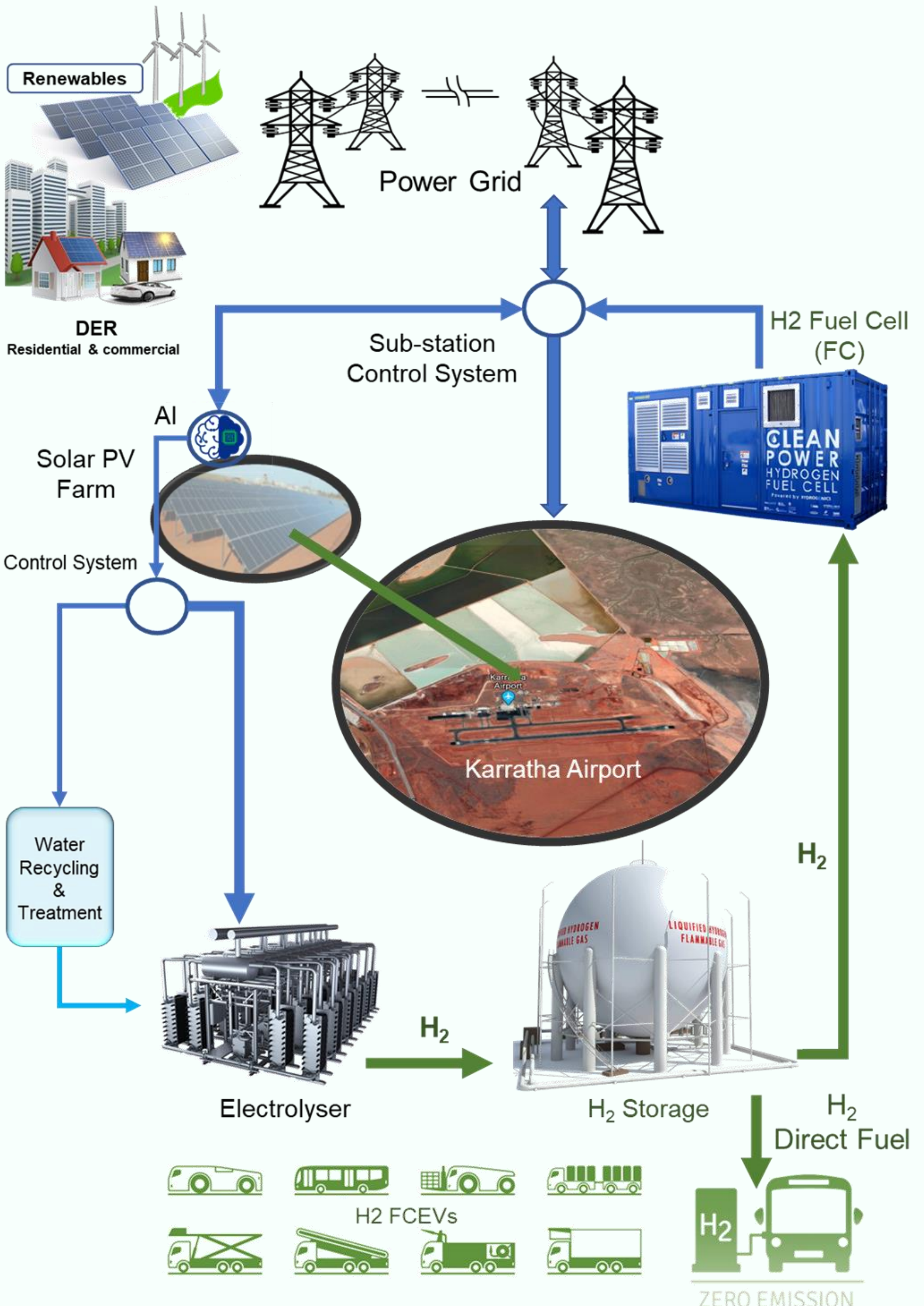


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Figure (C1): Proposed Hydrogen-Based Energy System for Karratha Airport

Appendix (D): Zero Emission Highway

Background

Western Australia (WA) is rapidly approaching a systemic challenge in powering its state transportation system. WA consumes 25% of Australia's diesel with heavy transport being the largest consumer. Heavy diesel transport vehicles require long range and long up-times. The commercial transportation sector is critical to WA's economy and communities.

The Australian Bureau of Statistics (ABS) has shown that WA had the highest tonne-kilometres for intrastate road freight movements in Australia (33,746 million) [49]. Australia's fuel security is at risk, with average storage supplies well below the international standard of 90 days. An increased drive for decarbonisation of fuel supplies will continue to pressure on Australia's large GHG emitters to find zero-emissions alternatives.

In the words of Western Roads Cam Dumesny:

"Western Australia is critically reliant on road transport to provide the logistics required to support its economic and when needed, security activities. As the peak body for the state's transport industry, we have identified the need to migrate our risk by diversifying from our singular reliance on diesel fuel. Therefore, we are passionately behind the concept of the zero- emissions highway as the means of establishing the infrastructure required to enable us to deliver on our risk and mitigation strategy."

Zero Emission Highway (ZEH) is a project for heavy transport across Western Australia (WA). It is envisages building 80 hydrogen refuelling and EV charging facilities, at an estimated cost of about $500 million. It will focus on heavy transport, helping to introduce zero-emission transport, lower cost of fuel, and eventually, a secure fuel supply, eliminating the need for importing diesel. Although there is some consensus [50] that battery electric vehicles (BEV) will be the choice for city transport and small vehicles, and that hydrogen will fuel heavy long-distance vehicles. The concept of the zero-emissions highway does not pick a winner and accommodates refuelling both. It will evolve as the technologies evolve. The ZEH was initiated by Innovate Australia and now being led by the Hydrogen Society of Australia.

Phase 1 ZEH

Phase 1 for the ZEH is for the establishment of four hydrogen refuelling stations along National Route 1 between Perth and Karratha (1500 km). And a further four stations along State Route 95 between Perth and Karratha/Port Hedland (1600 km). See Figure D1. Perth to Karratha (National Route 1) had an average of 233 trucks per day in 2019, and State Route 95 to Port Hedland has 1065 Trucks per day [51]. The minimum number of stations along the route is dependent on the range of trucks that will use it. Currently the range of trucks under development vary from about 600 to 1200 km range. Hence two refuelling stations between Perth and Karratha is the minimum to attract FCEV trucks to have confidence in the viability of the route.

The vision is for three of the remote stations to be designed as stand-alone microgrids to enable onsite production of energy, in particular, energy from RE sources and hydrogen. The stand-alone system will ensure fuel security for these remote areas, as well as create local jobs.

City of Karratha Role

The City can facilitate the development of the ZEH and place Karratha at the centre. Key steps:

- Engagement with local governments along the route of ZEH between Perth and Karratha.
- Engage with State Government.
- Facilitate collaboration between local and state authorities, trucking companies, resource companies, local businesses, and those currently developing hydrogen production facilities and those involved with refuelling stations.
- Plan the development of the Karratha hydrogen refuelling station.

Most of the significant players in Pilbara resources industries have hydrogen development options in development. It is likely they will see the advantage of linking their projects with the Karratha and state transport developments.

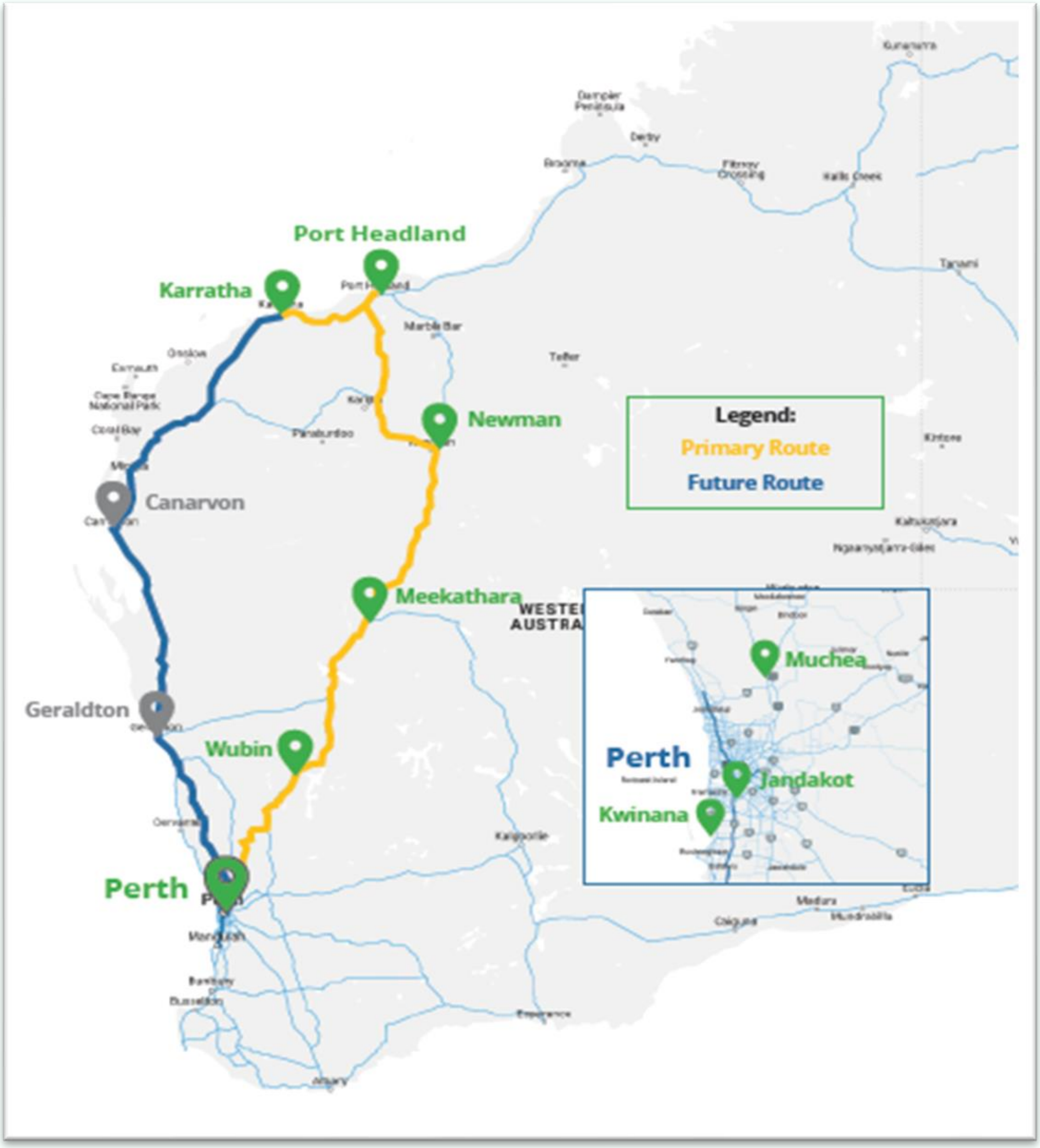

Figure (D1): Proposed routes for Zero-Emission Highway

Appendix (E): Karratha and Dampier Port Transition to 100% RE

Karratha, including the Airport and Dampier Port with all other Karratha and Pilbara Ports can be transit to 100% RE system utilising hydrogen as a backbone for the interconnected energy system using smart cities and Energy-Water-Waste nexus way of thinking. This is a transition to the future hydrogen economy which makes Karratha the Australian Hydrogen Hub. Fig. (E1) illustrate Karratha position in the future hydrogen landscape.

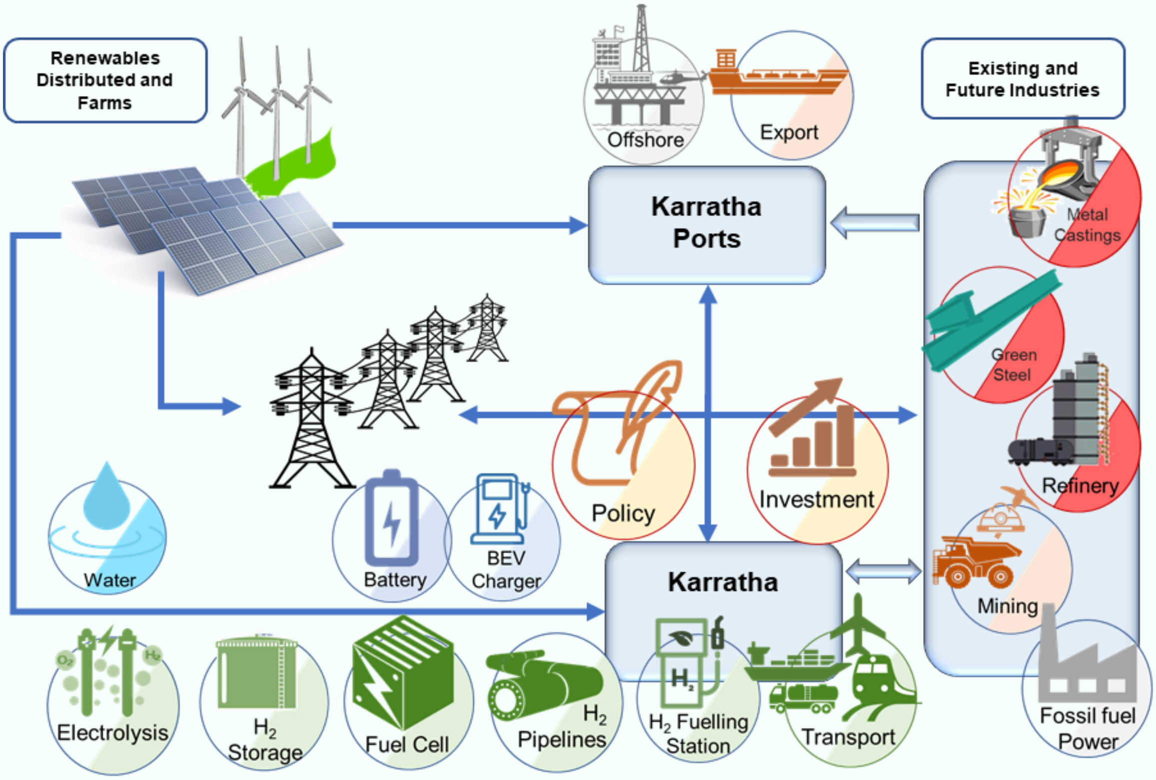

Figure (E1): The big vision of future Karratha as a renewable hydrogen hub

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