CLEAN HYDROGEN MISSION

Storage & Distribution Working Group

Blended hydrogen pipeline distribution workshop

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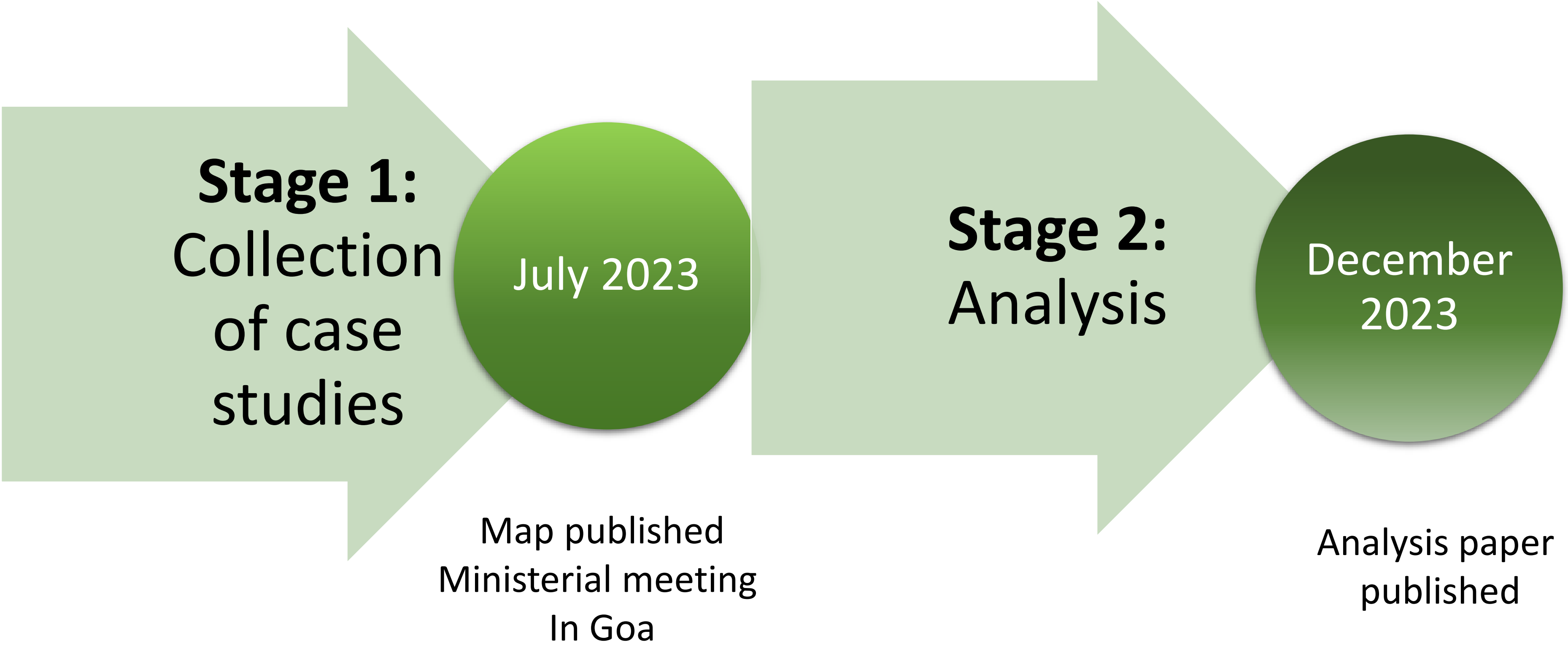
Stage 1: Collection of case studies
July 2023
Map published
Ministerial meeting
In Goa
Stage 2: Analysis
December 2023
Analysis paper
published

10 countries
45 case studies

26 demonstration projects
19 translational research projects

25 distribution focus
32 storage focus

Technology focus:
- 12 pipelines
- 10 liquid carriers
- 10 underground storage
- 5 liquid hydrogen

Workshops planned

August – blended hydrogen pipeline distribution

September – pure hydrogen pipeline distribution

October – underground storage

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Blended hydrogen pipeline transport workshop

Clean Hydrogen Mission Storage and Distribution Working Group

30 August 2023

Dampier Bunbury Pipeline | Multinet Gas Networks | Australian Gas Networks | Hydrogen Park

Acknowledgement of Country

AGIG acknowledges the Traditional Custodians of the lands upon which we live and operate, and we pay our respects to Elders past, present and emerging.

We recognise Aboriginal and Torres Strait Islander people's historical and ongoing connection to land and waters, and we embrace the spirit of reconciliation.

Our Connection to Country
By Artist Karen Briggs

Our Business

One of the largest gas infrastructure businesses in Australia

>2m
customers

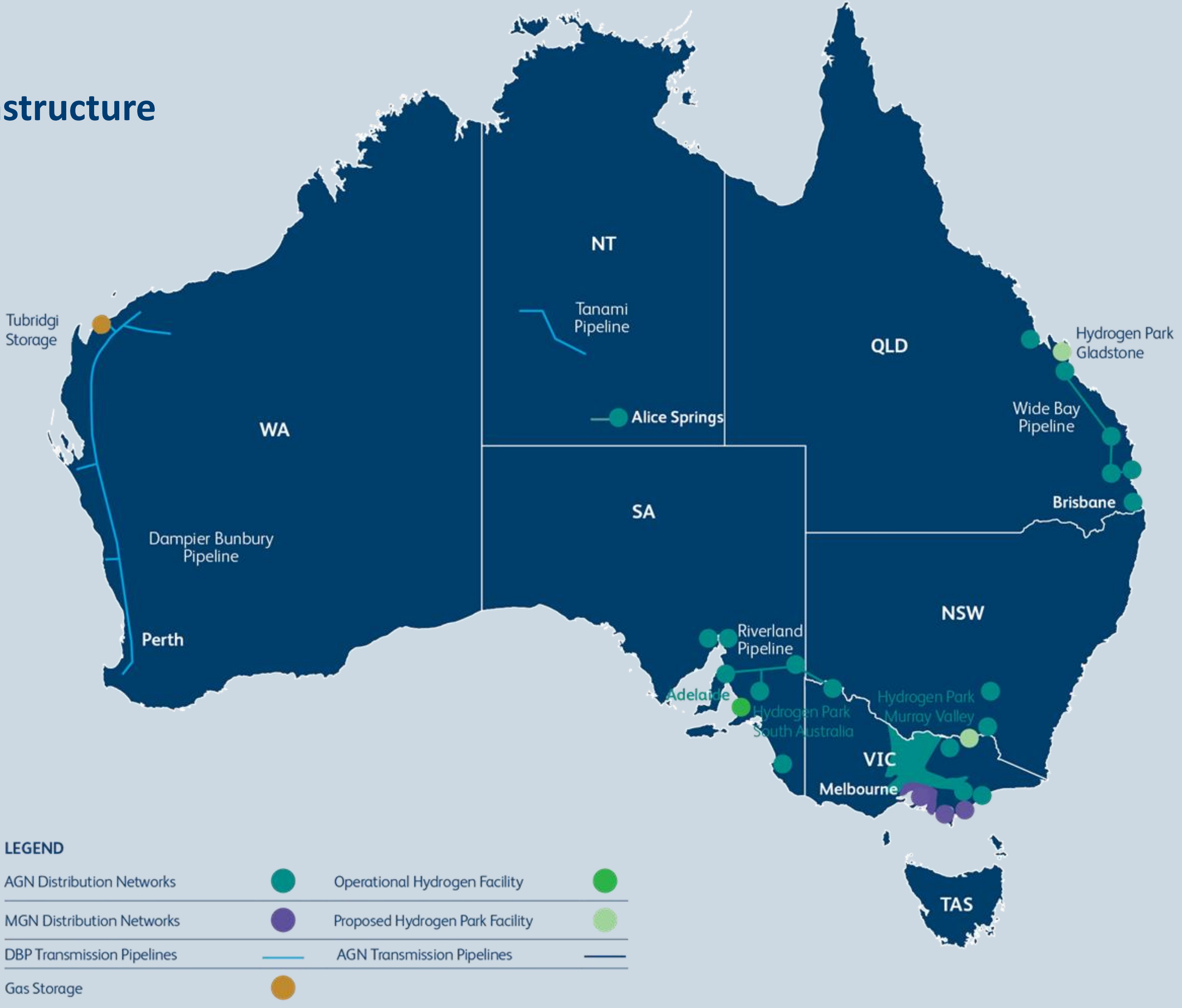
530 PJ
gas delivered

4,317 km
transmission

35,211 km
distribution

60 PJ
gas storage

1.25 MW
electrolysis



Note: Penetration rate is an estimate of the percentage of homes connected to the gas in areas served by our networks

WE ARE PROUD TO BE A PART OF THE TOP 30 BEST WORKPLACES TO GIVE BACK 2022 BROUGHT TO YOU BY GOODCOMPANY

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Our Vision

To be the leading gas infrastructure business in Australia, aiming for top quartile performance on all our targets.

Delivering for Customers

- Public safety
- Reliability
- Customer service

A Good Employer

- Health and safety
- Employee engagement
- Skills development

Sustainably Cost Efficient

- Working within industry benchmarks
- Delivering profitable growth
- Environmentally and socially responsible

Our Values

Drive our culture and how we behave and make decisions.

Trust

Respect

Perform

One Team

Our Low Carbon Vision

Delivering for customers through the transition

Our first ESG Report was released in 2022

Stretch target: Distribution networks transitioning to renewable gas by 2040

- 2020
- HyP SA online
- 2022
- Australian Hydrogen Centre studies on converting our distribution networks to 10% and 100% renewable hydrogen complete
- Interim Scope 1 and 2 emission reduction targets set
- HyP Murray Valley and HyP Gladstone achieve relevant approvals
- 2024
- HyP Murray Valley and HyP Gladstone online
- 2026
- Vic and SA's CBD distribution network Mains Replacement Program complete and renewable gas ready
- 2030
- 10% renewable gas across our distribution networks
- 2040
- **Full renewable gas conversion for our distribution networks** (2040 stretch target, and by no later than 2050)

We will set interim Scope 1 and Scope 2 emissions reductions targets for our transmission and mid-stream assets by end-2023. We will continue developing infrastructure solutions for our customers, targeting net zero Scope 1 and 2 emissions by 2050

- 2020
- Initial feasibility studies undertaken on blending hydrogen into the Dampier to Bunbury Natural Gas Pipeline
- 2022
- Ongoing feasability studies on blending hydrogen into the Dampier to Bunbury Natural Gas Pipeline
- Interim Scope 1 and 2 emission reduction targets set
- 2024
- 2026
- 2050
- **Net zero Scope 1 and 2 emissions**

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Delivering the Vision | Setting the Scene – Why?

Decarbonisation is a big challenge - we need many options

Gas (natural* and renewable) can contribute to delivering emissions reductions whilst maintaining energy affordability, security, reliability and customer choice

Deliverability	**Emissions**	**Affordability**	**Customer Choice**
Reliability and Resilience	**Efficient Electricity**	**Building Hydrogen**	**Enabling Industry**

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* Natural gas produces less carbon emissions than grid energy derived from burning coal (Australian National Greenhouse Accounts factors). Over the past 12 months, the states with the highest populations electricity grids have been largely powered by coal (Victoria 67%, New South Wales 70% and Queensland 65% coal based electricity, *Australian Energy Statistics Electricity Generation by Fuel Type*).

Our Low Carbon Vision | Delivering the Vision

Our renewable gas targets can be met by hydrogen and biomethane

To date, our focus has been on hydrogen projects due to the availability of funding and also our skill set

Regulatory

Engagement

Policy

Projects

Projects: Demonstrating renewable gas is achievable and desirable

- Hydrogen production and supply
- Hydrogen appliance demonstration
- Biomethane production and supply
- Feasibility studies on blending and conversion

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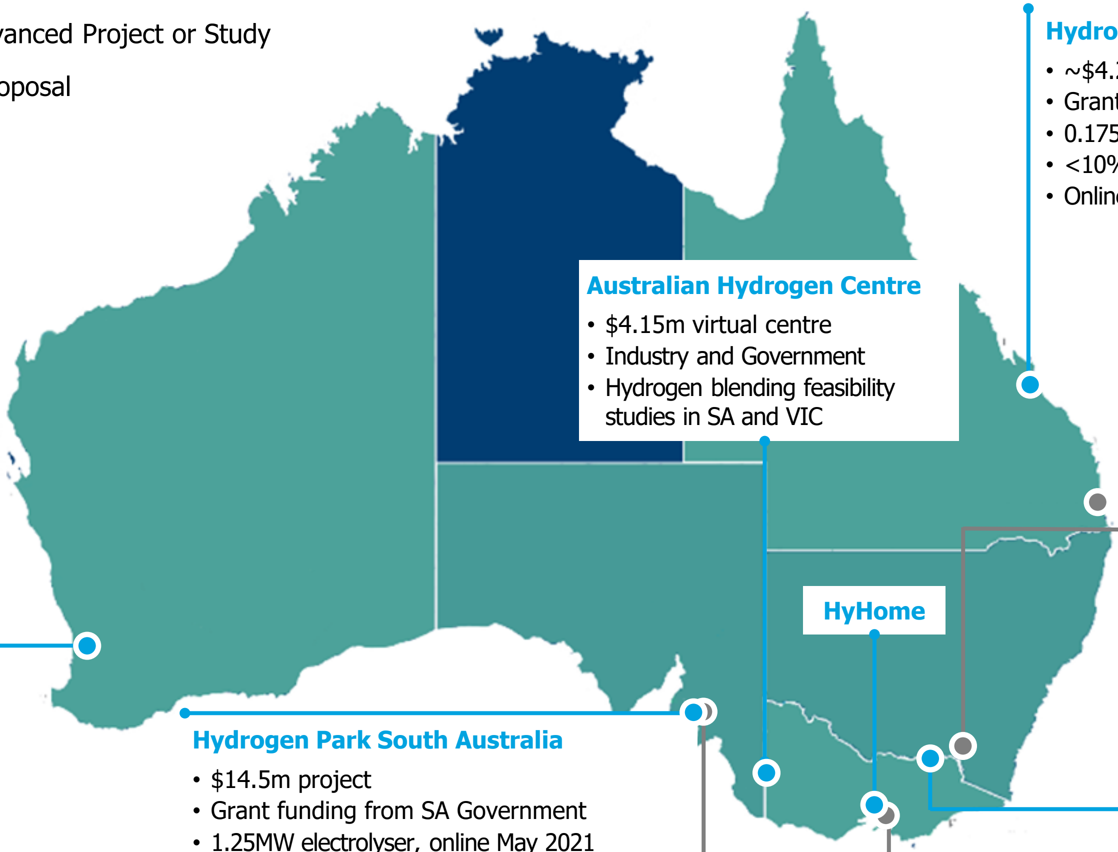
Delivering the Vision

A snapshot of our most advanced projects

- Operational/Advanced Project or Study
- Earlier Stage Proposal



Hydrogen Park Gladstone
- ~$4.2m project
- Grant funding from QLD Government
- 0.175MW electrolyser
- <10% blend to >800 homes and businesses
- Online: Q1 2024

Australian Hydrogen Centre
- $4.15m virtual centre
- Industry and Government
- Hydrogen blending feasibility studies in SA and VIC

Hydrogen Park Wagga Wagga
- 10MW electrolyser
- <10% blend to >20,000 homes, businesses
- Supply to refinery and power station
- Online: 2026 (proposed)

HyHome

DBP Feasibility Study
- $0.45m project
- Grant funding from WA Government
- Technical Feasibility
- Regulatory Roadmap

Hydrogen Park South Australia
- $14.5m project
- Grant funding from SA Government
- 1.25MW electrolyser, online May 2021
- <5% blend to >700 homes, expanded to ~3,800 homes in Q1 2023
- Supply to industry via tube trailer

Biomethane Opportunity
- Biomethane supply to networks
- Feasibility work

Hydrogen Park Murray Valley
- ~$55m project
- Grant funding from ARENA
- 10MW electrolyser
- <10% blend to >40,000 homes and businesses
- Online: 2025

Edinburgh Park Biomethane
- Project seeking FID

Industry Memberships:
- Hydrogen Council
- Australian Hydrogen Council
- Bioenergy Australia
- Future Fuels Cooperative Research Centre
- SA H_2H Hydrogen Cluster
- Clean Energy Council
- Energy Transition Initiative
- Australian Pipeline and Gas Association
- Energy Networks Australia

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Hydrogen Park South Australia | Overview

SA Climate Leaders Awards 2020 Business and Industry category winner

Australian Pipelines and Gas Association Environment Award 2020

Engineers Australia Australian Engineering Excellence Award 2020

South Australian Premiers Awards Commendation 2020 Energy and Mining Innovation and Collaboration Category

Hydrogen Project of the Year 2022 Connecting Green Hydrogen MENA Future of Hydrogen Awards

South Australian Premiers Awards Winner 2022 Energy and Mining Community Engagement Category

More information on HyP SA

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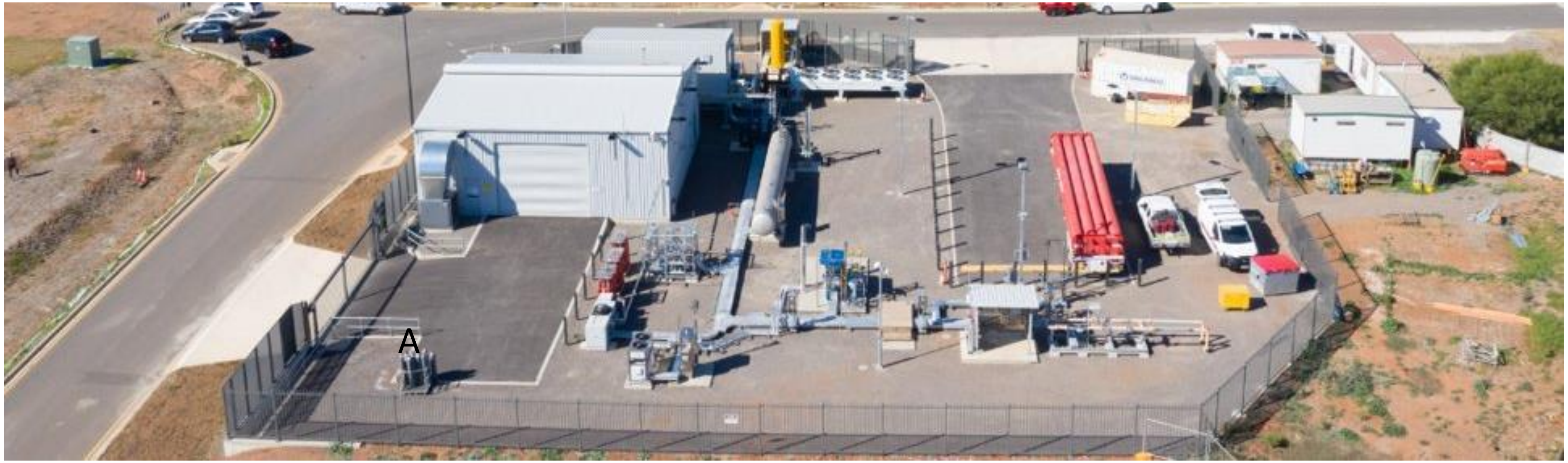


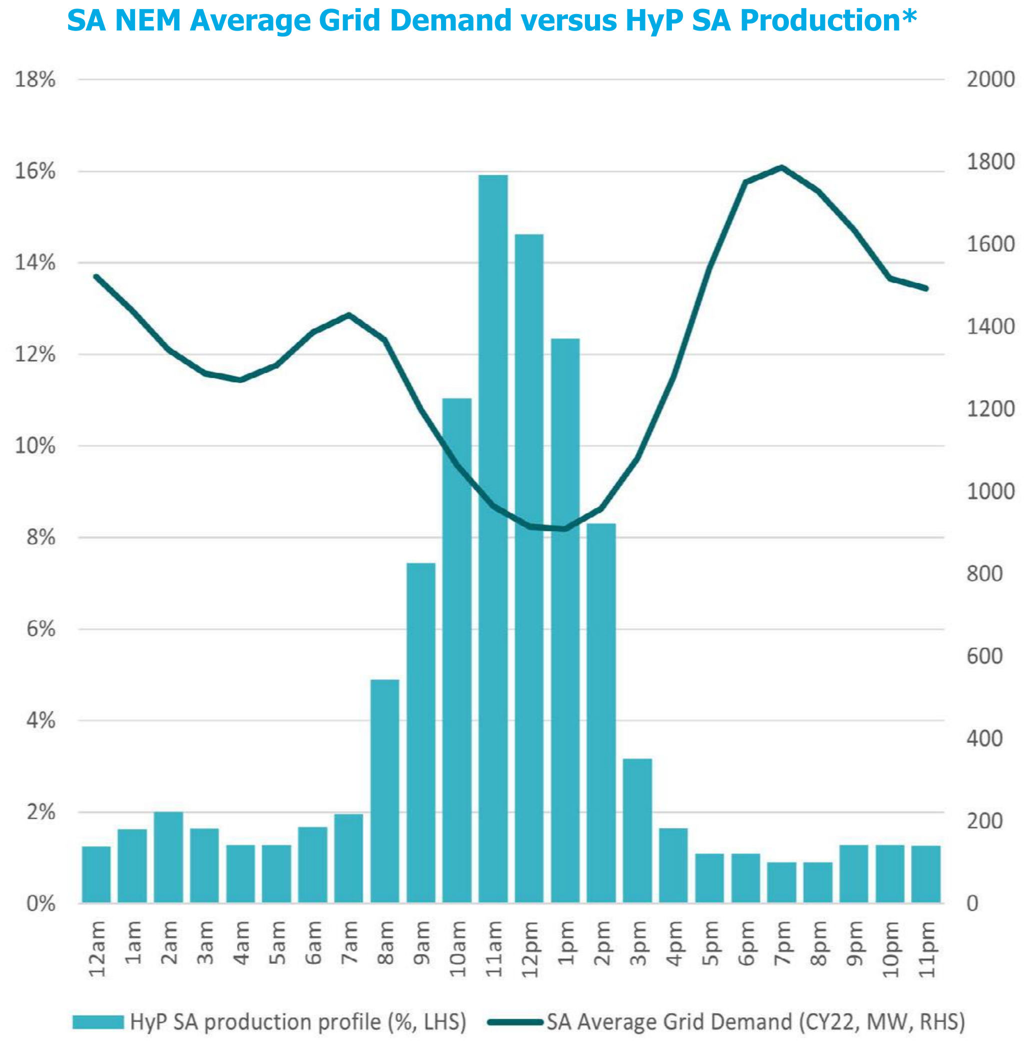
- Online May 2021, 1.25 megawatt (Australia's largest electrolyser)
- 100% renewable H_2 supply to industry via tube trailer
- Refuelling opportunities
- Up to 5% renewable H_2 blend to >700 homes*
- Expanded to ~3,800 homes, schools and businesses in 2023
- Significant engagement, >3,000 visitors to site

A $14.5m project enabled by a $4.9m grant from the South Australian Government Renewable Technology Fund

* AGIG purchases GreenPower Large Scale Generation Certificates which are surrendered as required to ensure the electricity used to produce hydrogen is renewable

Hydrogen Park South Australia | Operating Protocol

HyP SA's integrates electricity and gas networks, enabling the gas network to be used like a battery to store excess renewable energy



* AGIG engaged an independent technical advisor to provide analysis on the data captured at HyP SA between May 2021 to November 2022

- By targeting production when the electricity price is low or negative, HyP SA has minimised the price of hydrogen produced whilst demonstrating potential for electrolysis to support the electricity grid:
  - 65% of HyP SA's operational hours were between sunlight hours of 1000 to 1500 hours
  - HyP SA has captured electricity market pricing at 13% of the average wholesale cost
- This demonstrates how the scaled and efficient application of rapid demand-response hydrogen technologies could be well suited to balancing supply and demand in the South Australian electricity grid
- The National Hydrogen strategy points out that if managed well, this could lower electricity costs for consumers

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Hydrogen Park South Australia | Key Outcomes

"Glad to be involved with this project. Am learning more about blended gas and reducing carbon emissions."

"Anything which assists with the reduction of emissions is interesting to me."

Community feedback

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Hydrogen production, blending underpinning projects and policy	**ZERO** leaks caused by H_2 and uniform blending	sector coupling: excess solar, wind as gas for use	Pilot for certification, regulatory changes	New production committed in SA
Community sentiment and satisfaction	**91%** positivity on renewable gas supply	**100%** say safety has remained the same or improved	**95%** appealing-to-neutral project sentiment	**ZERO** customer issues or complaints
Increased engagement, education and knowledge sharing	Established engagement standard for other projects	TAFE SA skills and training collaboration	**3,000+** visitors: students to ambassadors	**↑31%** in awareness (24% to 55%)
Anchored hydrogen production to drive new markets	**INDUSTRY** tube trailer supply to industry from 2022	**~4,000** homes and businesses to receive blended gas in 2023	investigating refuelling	

Source: Australian Hydrogen Centre, Hydrogen Park South Australia Knowledge Sharing.

Australian Hydrogen Centre (AHC) | Overview

Regional Town Studies available

State-wide and HyP SA reports available soon

Assessing the feasibility of blending renewable hydrogen into gas distribution networks, and transitioning to 100% hydrogen networks

- **Regional Town Studies:** 10% hydrogen blending into selected regional towns in South Australia and Victoria
- **State-wide Studies:** 10% and 100% hydrogen networks of South Australia and Victoria
- **Hydrogen Park South Australia Knowledge Sharing:** Key learnings from Hydrogen Park South Australia's first year of operations (facility, gas network and community engagement)

Finds 10% and 100% hydrogen conversion of SA and Victoria gas networks is technically and economically feasible, and outlines a promising pathway forward to achieve it

Established at the end of 2019, the $4.15 million Australian Hydrogen Centre (AHC) is supported by a $1.28 million Australian Renewable Energy Agency (ARENA) grant

AHC | Network Transition

- Gas distribution networks, their components, and constituent materials are generally compatible to safely and reliably transport 100% hydrogen.
- Works to enable can be performed under normal preventative maintenance programs at a cost of ~$100 million per network. The average annual network spend in South Australia and Victoria is $200 million.
- 100% hydrogen could slightly reduce the networks overall capacity by around 13%. The network could absorb this reduction and maintain supply at historic service levels.
- Updates to safety and operating procedures and systems to reflect the differing characteristics between hydrogen and natural gas do not represent a major step-change to current procedures.

Typical polyethylene (plastic) gas mains

Australia's gas distribution networks commonly stored and transported about 50% hydrogen in 'town gas' around 50 years ago.

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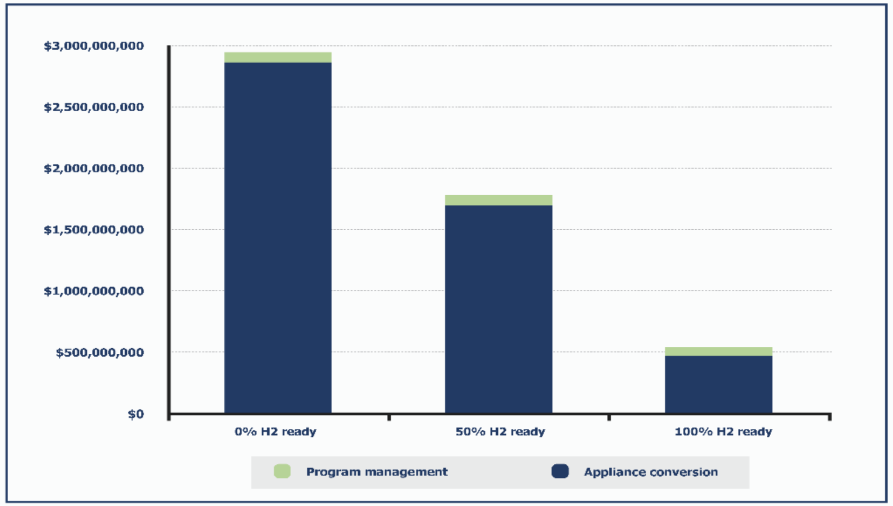
Existing appliances will not work on 100% hydrogen, ensuring 'Hydrogen Ready' appliances are mandated in Australia ensures a lower cost and less customer disruption

AHC | Appliance Pathways

- Customer fitting lines are compatible with 10% and 100% hydrogen
- Customer appliances are compatible with 10% hydrogen, with research well progressed to support ~20% hydrogen.
- A 19-step pathway to network conversion is mapped, based on lessons from the conversion from Town Gas and international experience



100% Hydrogen Cooktop installed at AGIG's HyHome, Victoria

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Summary

- One of the largest gas infrastructure businesses in Australia, with assets across the country and across the value chain
- Delivering energy for customers, today (natural gas) and tomorrow (renewable gas)
- Customers want to continue using gas into the future – they value reliability and energy security
- Our infrastructure can deliver a low-risk, low-cost and reliable transition
- Owner and operator of Australia's largest electrolyser (1.25MW at HyP SA)
- A focus on delivering projects, engaging with the community, facilitating the market through appropriate policy settings

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Image: AGIG's Dampier to Bunbury Natural Gas Pipeline, approximately 1539km of mainline pipe, 1228km of loop pipe and 300km of lateral pipe.

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Deutscher Verein des Gas- und Wasserfaches e.V.

DVGW

www.dvgw.de

H2-20 – Blending hydrogen in a german distribution grid

Blended hydrogen pipeline transport workshop - Clean Hydrogen Mission Storage and Distribution Working Group

Stefan Gehrmann, DVGW e.V.

Project Team: Holger Dörr (DVGW-EBI), Angela Brandes (Avacon), Martin Kronenberger und Nils Janßen (GWI)

German Association for Gas and Water (DVGW) has launched an Innovation Program on Hydrogen in 2021

Research

- H2 research program alongside complete value chain
- Virtual Hydrogen-Institut of the german energy industry

Technical Standards

- DVGW sets technical standards by law
- H2 guides with advice for practitioners on planning, construction and operation


Technischer Hinweis – Merkblatt
DVGW G 409 (M)

Products & Services

- Portfolio of product certifications
- H2-seminars
- H2-events

Communication

- Participation on political processes
- H2-marketing

www.h2-dvgw.de

Cooperation

- Cooperation + founding of community commities e.g. with german Hydrogen association
- Setting up new initiatives such as „H2-locally“

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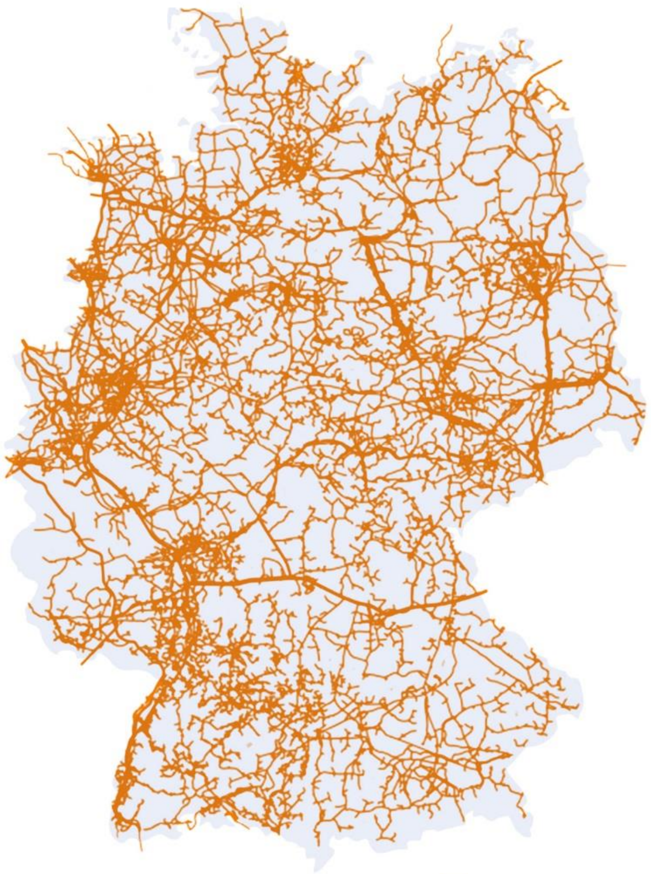
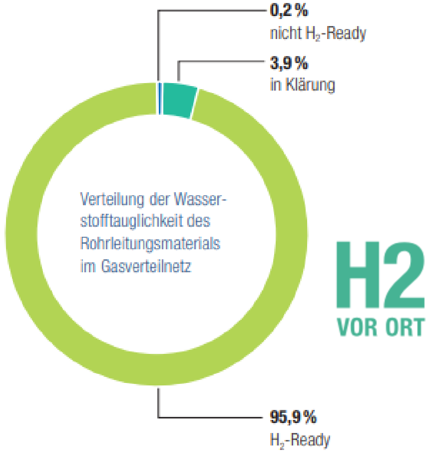
Structure of the German gas grid



	distribution grid	transmission grid
Length	> 500,000 km	> 40,000 km
Industial & commercial end users	> 1.8 million	~ 500
Household customers	~ 13 million	-
Share of energy supplied to customers	~ 80%	~ 20%

H2-readiness of piping material



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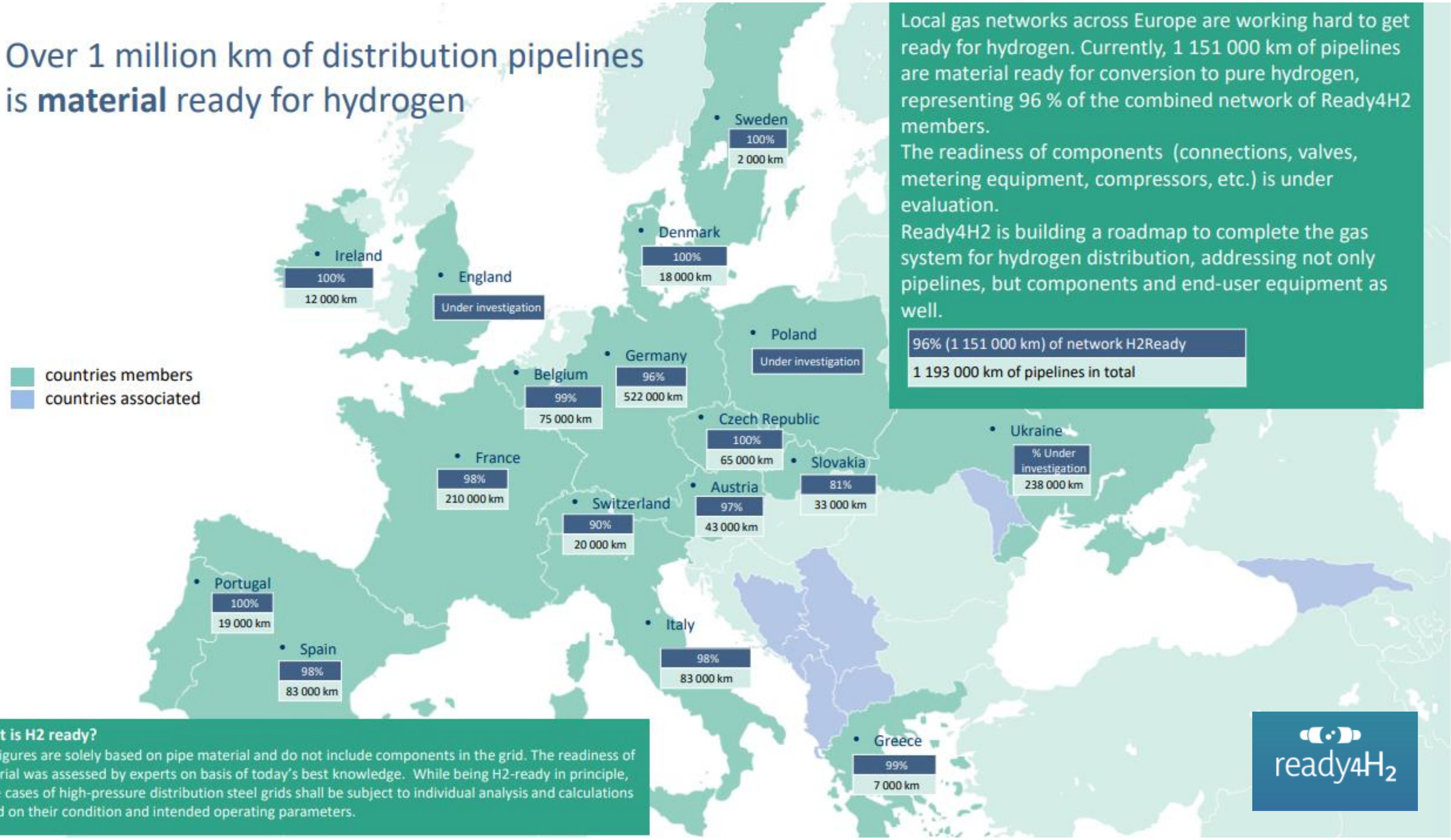
What is the European picture?

Over 1 million km of distribution pipelines is **material** ready for hydrogen



Local gas networks across Europe are working hard to get ready for hydrogen. Currently, 1 151 000 km of pipelines are material ready for conversion to pure hydrogen, representing 96 % of the combined network of Ready4H2 members.

The readiness of components (connections, valves, metering equipment, compressors, etc.) is under evaluation.

Ready4H2 is building a roadmap to complete the gas system for hydrogen distribution, addressing not only pipelines, but components and end-user equipment as well.

96% (1 151 000 km) of network H2Ready
1 193 000 km of pipelines in total

What is H2 ready?
The figures are solely based on pipe material and do not include components in the grid. The readiness of material was assessed by experts on basis of today's best knowledge. While being H2-ready in principle, some cases of high-pressure distribution steel grids shall be subject to individual analysis and calculations based on their condition and intended operating parameters.

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H2-20 – Field Test Trial in Germany

Objective of H2-20

Injection of up to 20 % by volume of hydrogen into an existing distribution grid supplying about 340 domestic and commercial customers, and deduction of recommendations for action.

Engler-Bunte-Institute (EBI)

Project Coordinator

scientific leader of the project.

Avacon Netz GmbH

Research Partner and Project funder

leader of the project from the perspective of a distribution grid operator.

GWI e. V.

Research Partner

project support testing domestic gas appliances.

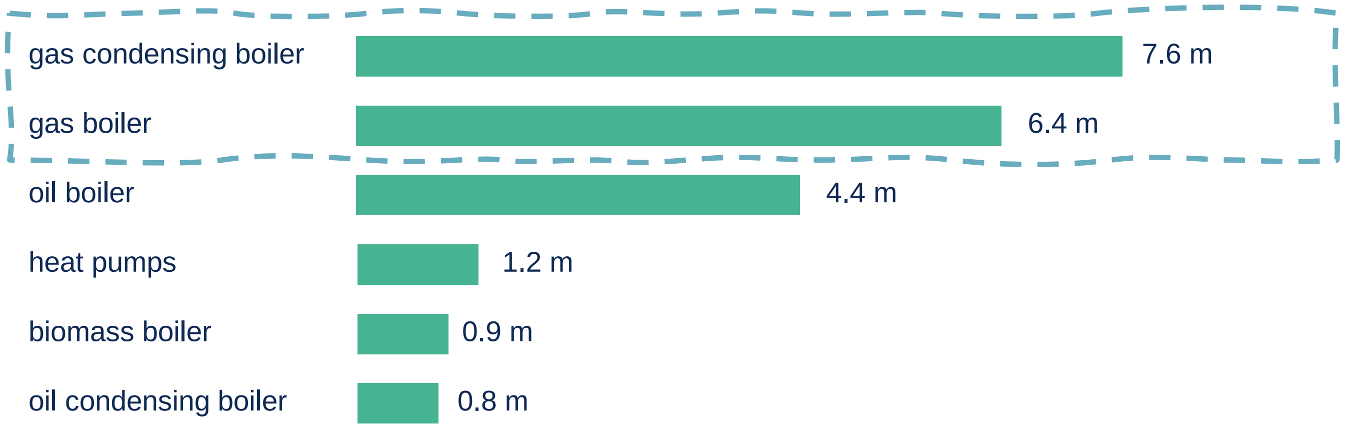
DVGW e.V.

Project Funder

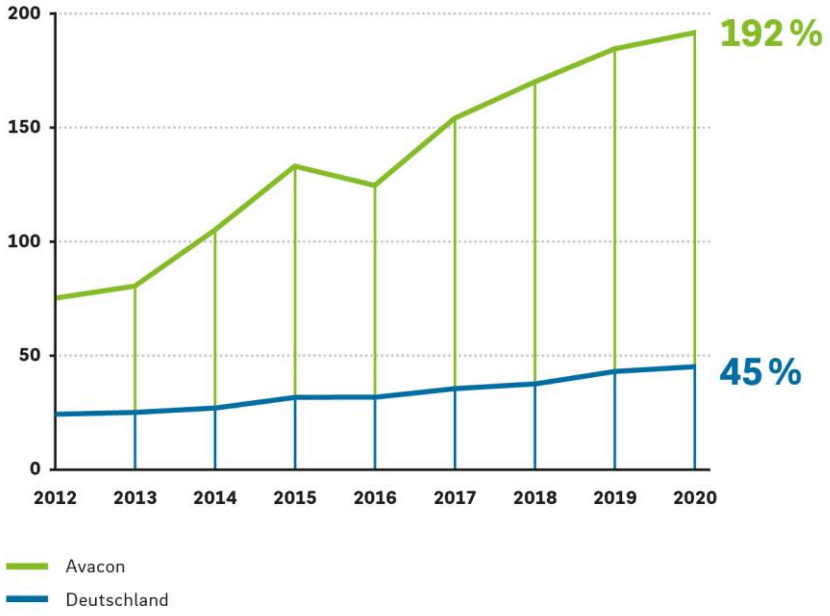
project Support as recognized standardization body for the gas industry with technical and scientific expertise.

H2-20 – Motivation

Stock of central heat generators for heating systems in Germany



Renewable share of electricity



→ reduction of CO_2 emissions in the heating sector
→ reaching climate goals

→ harnessing the surplus of renewable electricity

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H2-20 – Timeline

01.08.2019 until 31.07.2023

April 2019
Network selection and assessment

Since November 2019
Communication with local authorities, installation contractors, chimney sweeps and the general public

From October 2020
Data acquisition of customer appliances with testing on site

Up to February 2021 (2/2021)
Inspection of distribution system components

Safety analyses and assessments

Decision

Up to October 2021
Construction of hydrogen injection plant

22.11.-20.12.2021 – 10 vol-%

02.02.-02.03.2022 – 15 vol-%

23.03.-20.04.2022 – 20 vol-%

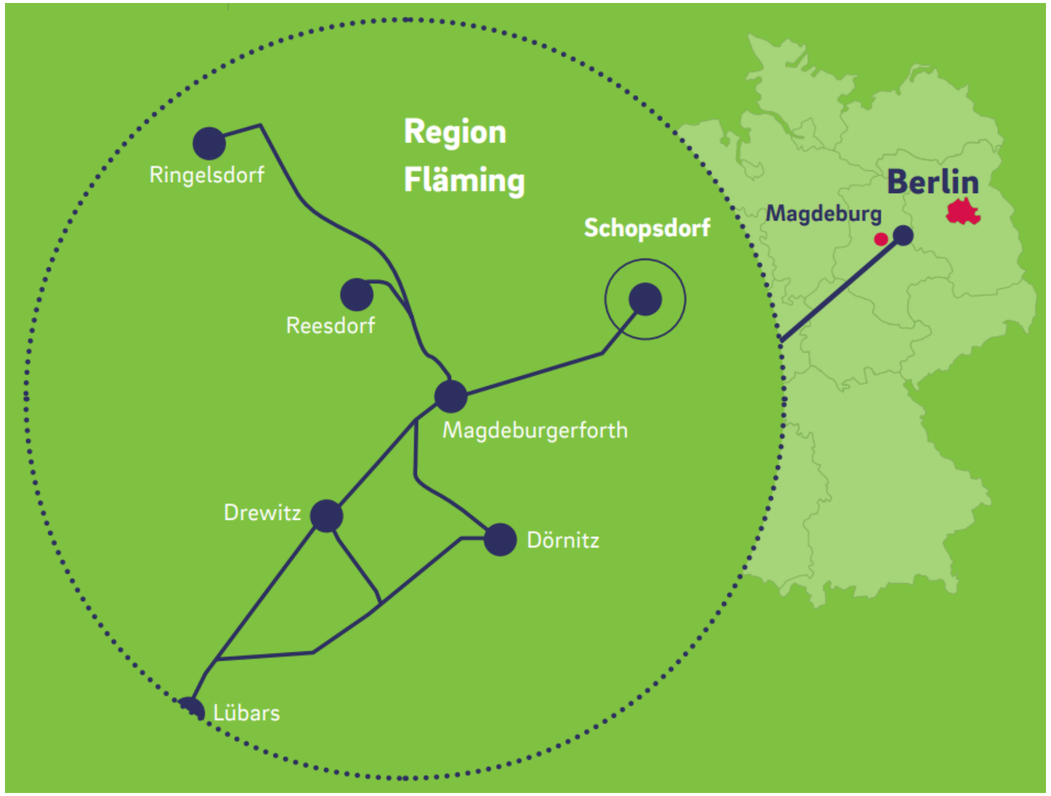
Step-by-step increase in hydrogen addition

Up to first quarter of 2023 – dynamic 0-20 vol-%
dynamic H_2 injection

Joint assessment of existing appliances and system components by the project team together with the manufacturers

H2-20 – Network selection

- single side feed
- pipeline length of 35 km with ~350 appliances
- no CNG filling station and no sensitive industrial customers
- year of construction 1994
- representative distribution of applicances



Source: Avacon Netz GmbH

H2-20 – Testing of customers appliances before injection

Gas installations: every installation is checked! Combustion tests with NG or G 222 are correlated with gas quality – setting! Short interview about pecularities etc.

visual inspection of gas installation, recording of many data: appliance manufacturer, type, age, piping

Leakage rate measurement

Testing of appliance with NG, G 222 (23 vol-% H_2 in CH_4), NG always in **full** and – if available – **partial** load

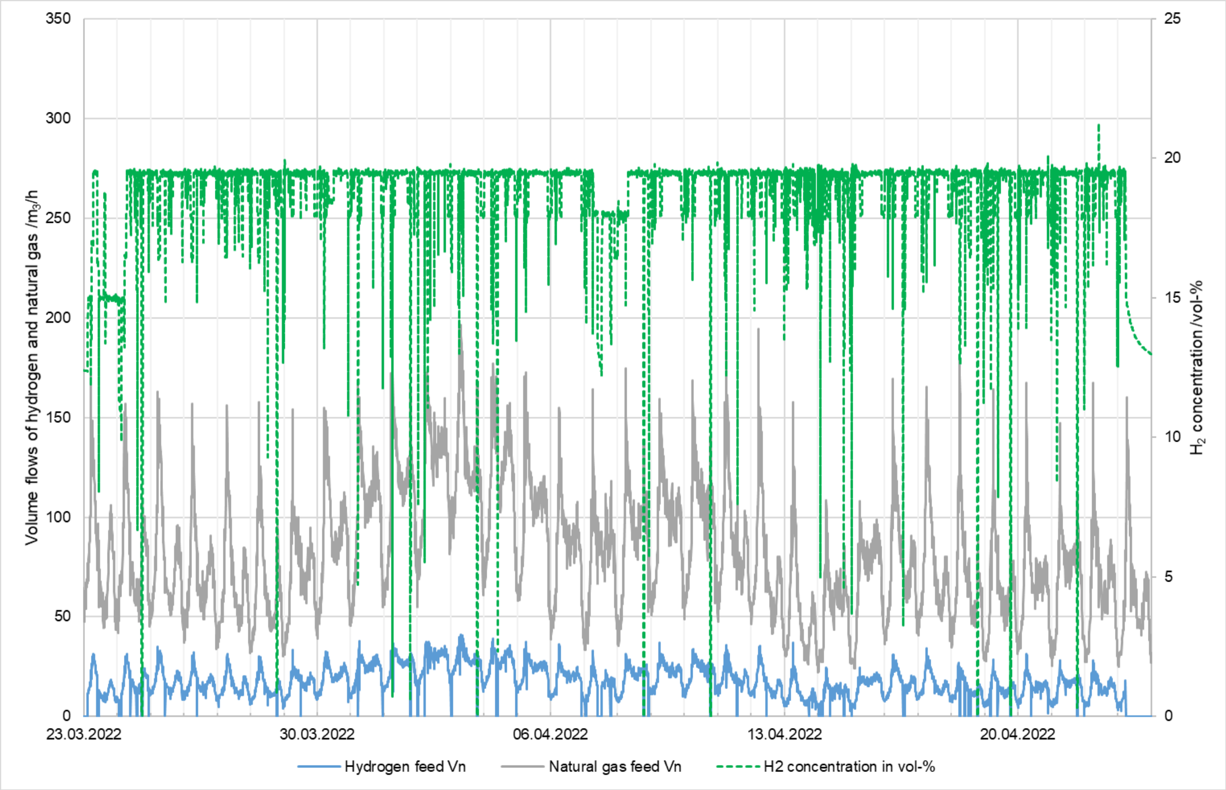
Appliances are measured as found **without any adjustment**!

5 older appliances were exchanged for lab testing
5 appliances were exchanged by customers (moderninzation)
17 pecularities were fixed

H2-20 – H2 injection plant

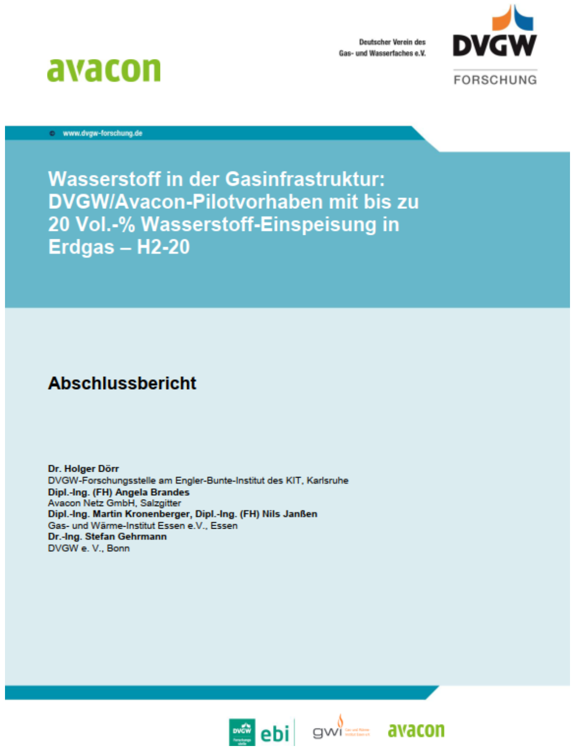
Source: Avacon Netz GmbH

H2-20 – Some results



reliable hydrogen supply during injection phases

H2-20 – Some results


Deutscher Verein des Gas- und Wasserfaches e.V.
FORSCHUNG
www.dvgw-forschung.de

Wasserstoff in der Gasinfrastruktur: DVGW/Avacon-Pilotvorhaben mit bis zu 20 Vol.-% Wasserstoff-Einspeisung in Erdgas – H2-20

Abschlussbericht

Dr. Holger Dörr
DVGW-Forschungsstelle am Engler-Bunte-Institut des KIT, Karlsruhe
Dipl.-Ing. (FH) Angela Brandes
Avacon Netz GmbH, Salzgitter
Dipl.-Ing. Martin Kronenberger, Dipl.-Ing. (FH) Nils Janßen
Gas- und Wärme-Institut Essen e.V., Essen
Dr.-Ing. Stefan Gehrmann
DVGW e. V., Bonn

~ **300 extensive spot checks** were carried out during the injection phases

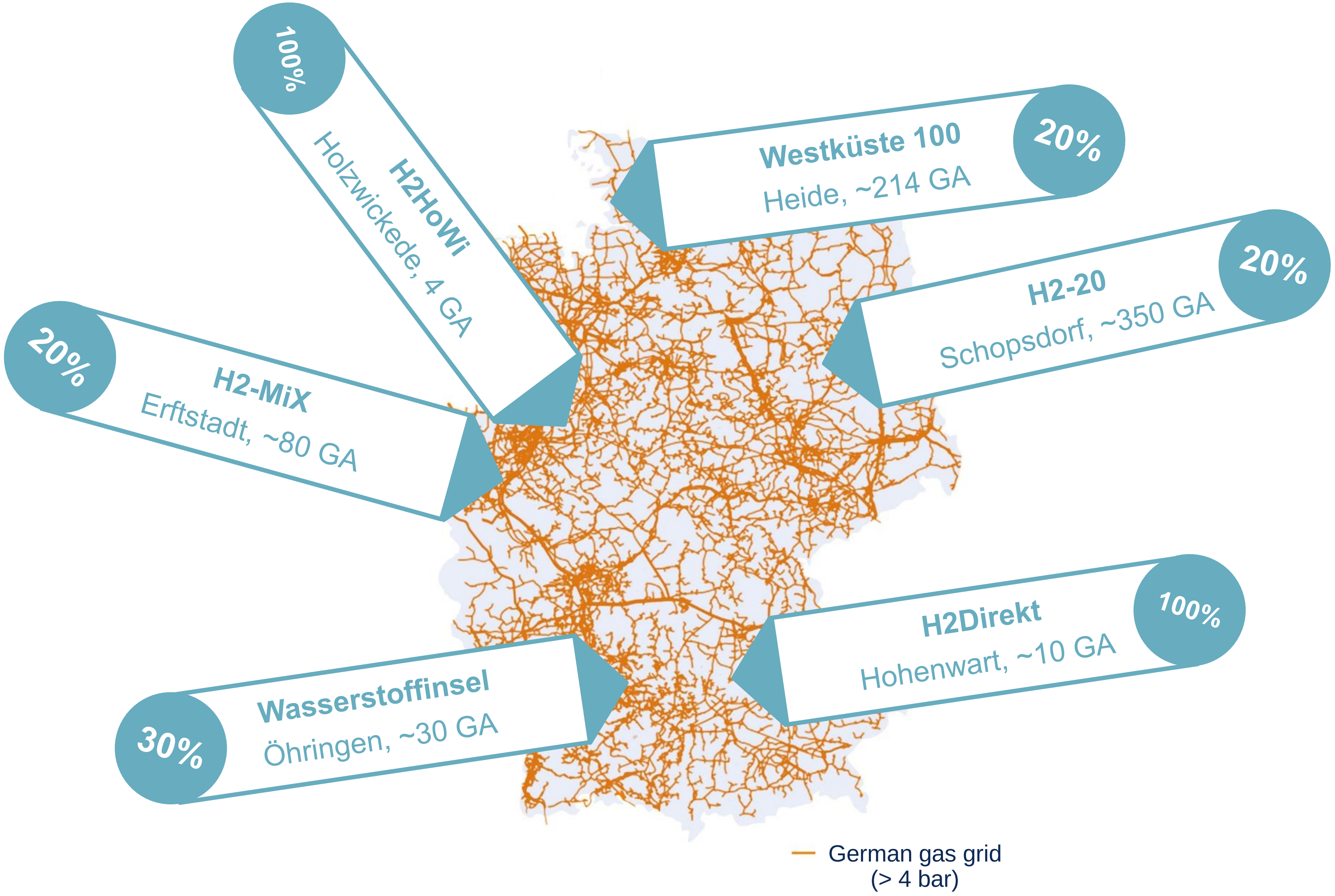
→ **no hydrogen induced safety issues were detected!**

only one case (0,28 %!) of an old appliance a thermoacoustic effect was recorded **without any safety** relevance

Final report to be published soon with more detailed information and results on e.g. safety concept, initial inspection and spot checks, NOx and CO emissions, …

Injection of 20 % hydrogen by volume into an existing distribution grid successfully proven! Flexible way to integrate renewable H_2!

We are not alone…



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Any questions?

Now or later…

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Technology and Innovationmanagement
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www.dvgw.de/forschung

WHEN TRUST MATTERS

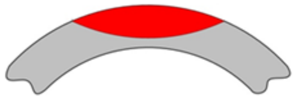
Testing approach for characterizing fracture and fatigue properties of line pipe steels in hydrogen environment.

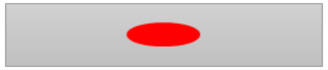
Ashwini Chandra
Senior Engineer
DNV, USA

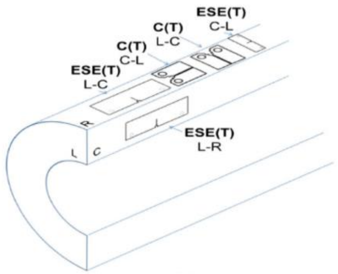
30th August 2023

Introduction

- The hydrogen economy envisions the use of hydrogen as an energy carrier for reducing carbon emissions.
- An economically viable option to transport this hydrogen is utilizing existing natural gas infrastructure.
- It is important to understand testing approaches as well as their limitations in considering the effects H_2
  - Fracture mechanics is a commonly used approach





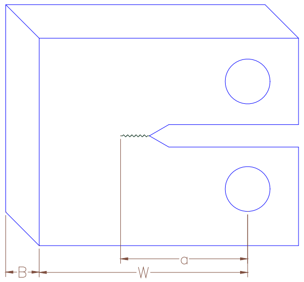


$$K = Y\sigma\sqrt{\pi * a}$$

Stress Intensity Factor

Stress

Crack Length



Fatigue Crack Growth Rate (FCGR) Effect of % Hydrogen Blend

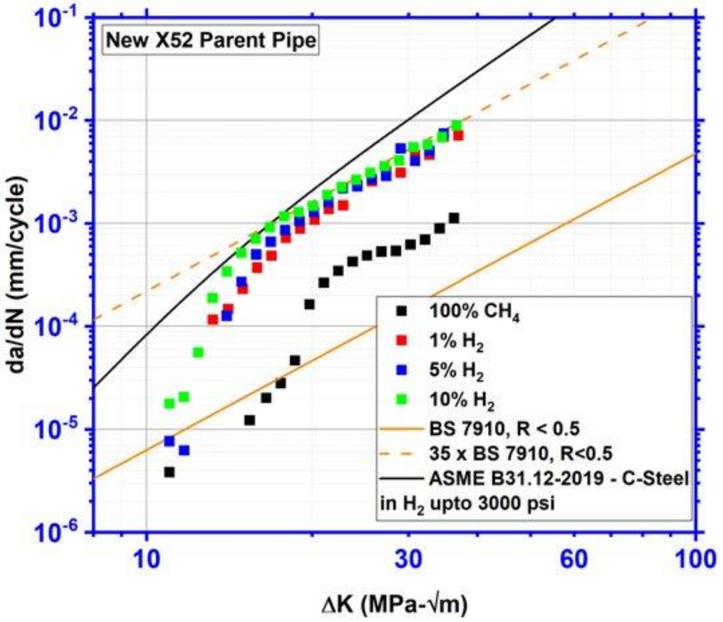
Previous research is predominantly under high pp H_2 relative to anticipated application.
1800 psi @ 10% molar blend yields partial pressure of 180 psi

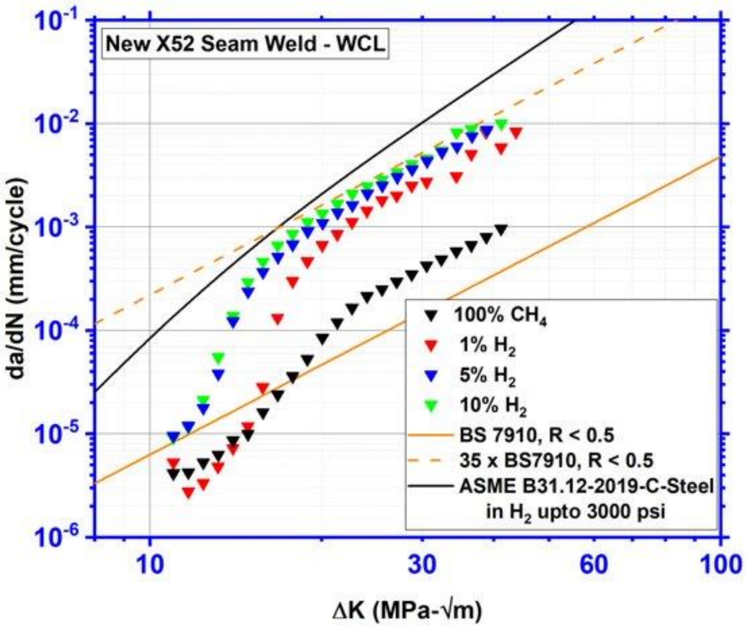
Environment

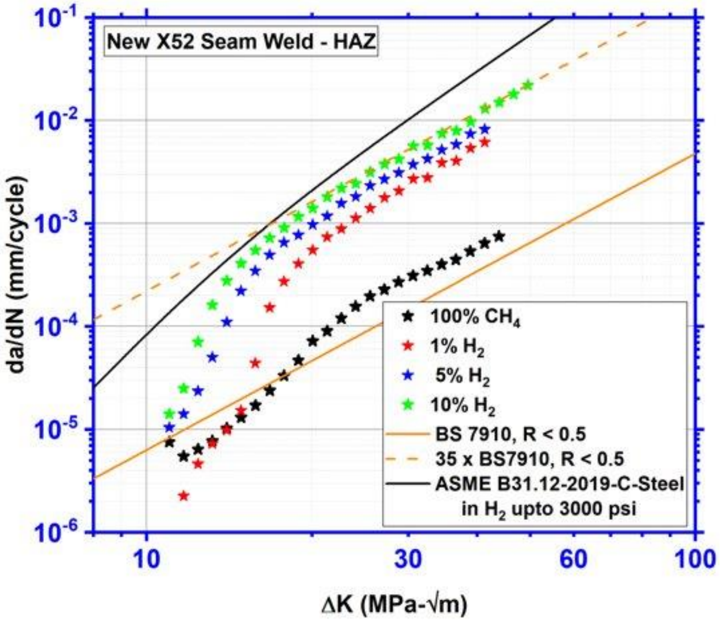
- Total Pressure – 1800 psia (12.4 MPa)
- Effect of hydrogen blends studied using the following
  - 100% CH_4 (baseline)
  - 1 mole% H_2 balance CH_4 (pp H_2 - 0.12 MPa)
  - 5 mole% H_2 balance CH_4 (pp H_2 - 0.62 MPa)
  - 10 mole% H_2 balance CH_4 (pp H_2 - 1.24 MPa)

Fatigue Loading Parameter

- Paris Curve Parameters – Increasing ΔK method, R – 0.3, $\Delta K_{initial}$ – 11 MPa-√m, f – 0.1 Hz



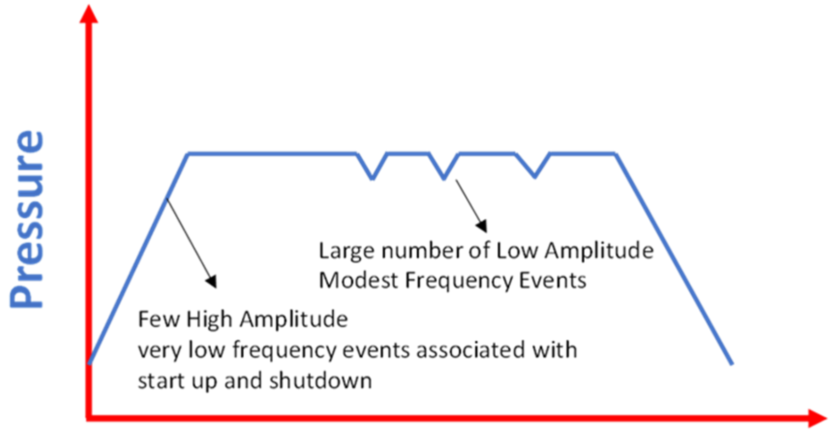


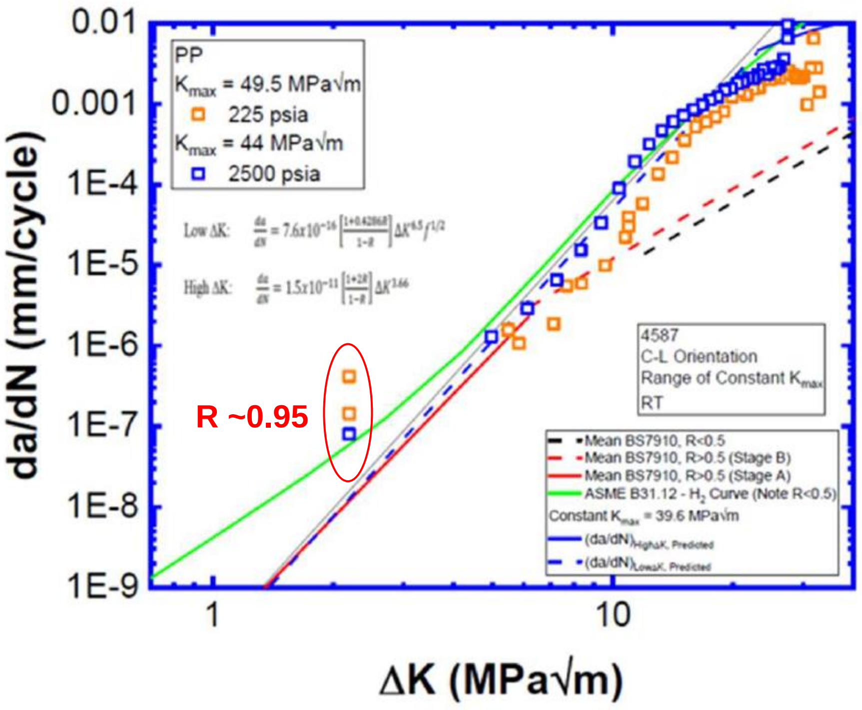


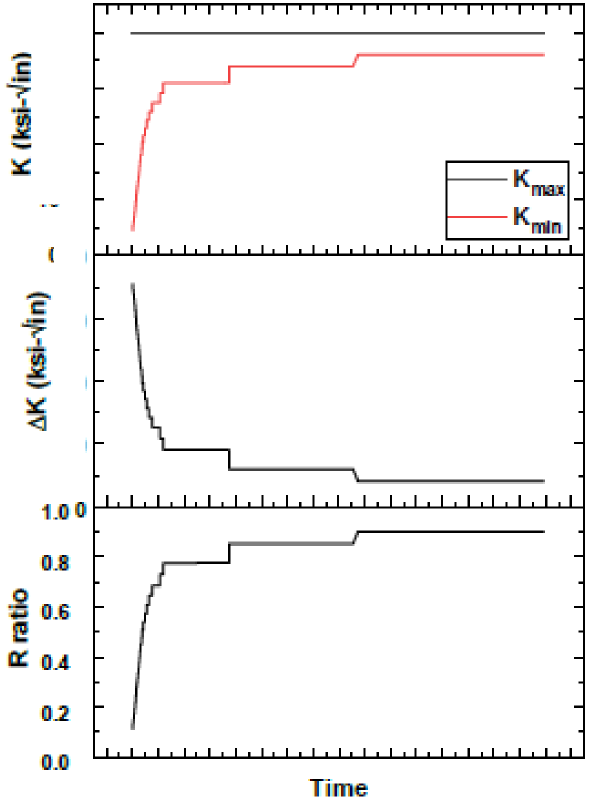
Chandra, A. et al., PVP 2023-106091

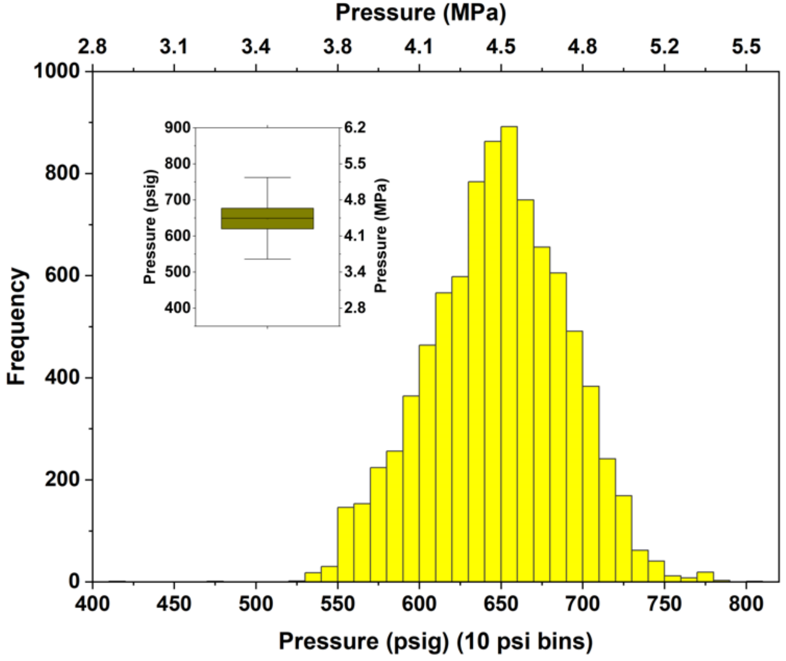
Fatigue Crack Growth Rate (FCGR) Effect of R ratio

- Most natural gas pipelines operate under many high R ratio pressure cycles with few low R ratio pressure cycles.
  - B31.12 FCGR equation valid for R-ratio < 0.5
- R-ratio is shown to have a measured effect on FCGR









Bezensek,B. et al., PVP2023-105972

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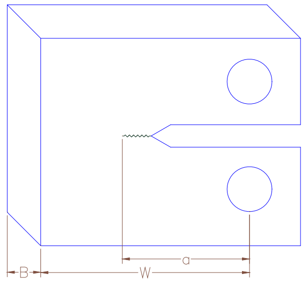
Fracture Toughness Characterization - Effect of Test Method/Parameters



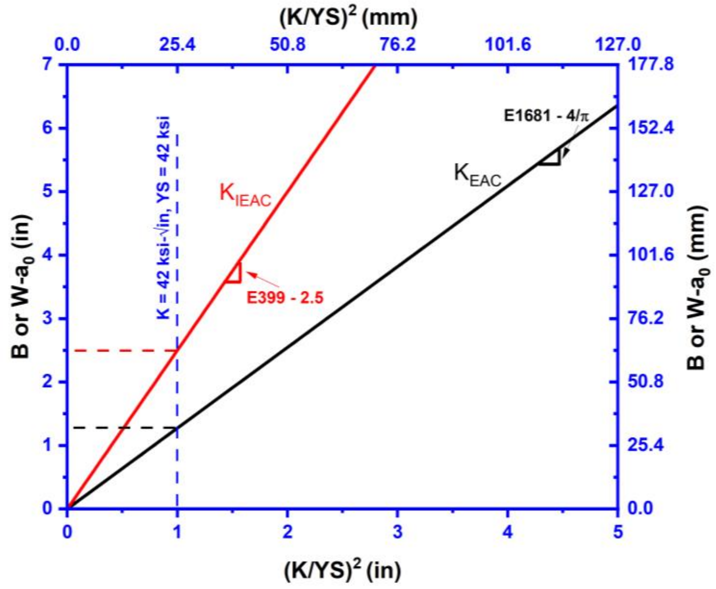
- ASME B31.12 – 2019 provides guidelines on qualifying pipe and weld material for H_2 service.
  - Refers to Article KD-10 of ASME BPVC Section VIII Div 3 which guides the user to evaluate using ASTM E1681
- ASTM E1681 evaluates toughness via constant load/displacement
- Size restrictions are based on stress intensity factors for environmentally assisted cracking (EAC)

$$B, a_o, W - a_o \geq 2.5 \left(\frac{\mathrm{K}_{\mathrm{IEAC}}}{YS}\right)^2 \qquad W - a_o \geq \left(\frac{4}{\pi}\right)\left(\frac{\mathrm{K}_{\mathrm{EAC}}}{YS}\right)^2$$

- Pressure vessels applications typically have larger thicknesses and higher yield strengths that satisfy these requirements
- Line pipe may not meet the size requirements given the thin walls and lower yield strengths
- May not yield conservative results as they're constant load/displacement yields $K_{th\text{-}a}$ values.

Fracture Toughness Characterization - Effect of Test Method/Parameters

- Example:
  - X42 pipe validating a toughness of 42 ksi√in requires a thickness of 1.3 in or 2.5 in (plane strain)
- Increasing rated toughness further will further increase the required thickness
- Instead of using E1681, ASTM E1820 may be used to calculate K_{th} based on J-integrals
- For ASTM E1820 method, applied K - rate is an important variable to capture effects of hydrogen



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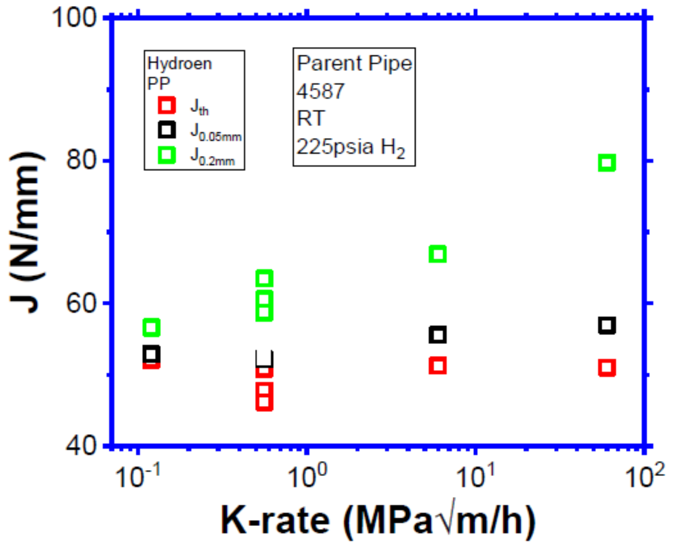

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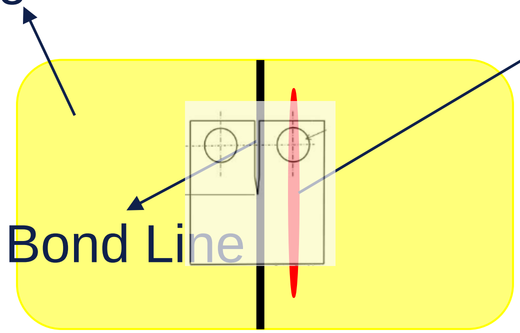
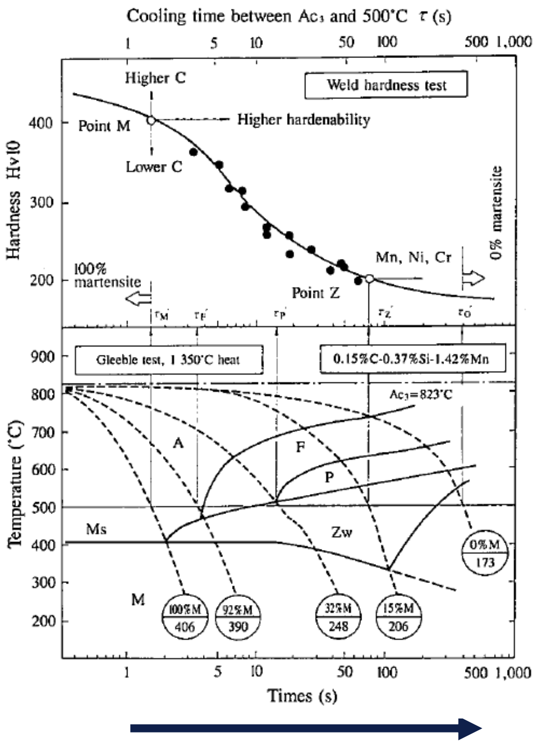
Fracture Toughness Characterization - Vintage LF ERW Welds (Ongoing JIP)

Vintage X46



Hard Spots formed due to a combination of high C_{eq} and cooling rates

- Characterize hard spot
  - Microstructure of hard spot → % martensite
  - Identify the hardness of the hard spot



- **Challenge is to identify the hard spots as well as locate a notch in the appropriate locations**
  - Gleeble simulation
    - Develop large scale sample with appropriate % martensite
    - Confirm the hardness level
    - Development of large sample to test different hardness

- **Approach to create microstructures associated with hard spots at large scale so as to evaluate susceptibility to H embrittlement**

Thank you

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DNV

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- Co authors – Ashwini Chandra, Shane Finneran
- Ramgopal Thodla

Determining Steel Weld Qualification and Performance for Hydrogen Pipelines

August 30th, 2023

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National Institute of Standards and Technology

Boulder, CO 80305 USA

Project overview: Determining Steel Weld Qualification and Performance for Hydrogen Pipelines

- Purpose: Review current codes and standards for gaps in knowledge in weld qualification requirements and provide:
  1. Weld qualification for **new** pipeline assets, including seam, girth, and repair welds
  2. Evaluate performance for **modern** steel grades
  3. Provide assessment parameters for evaluating integrity of **modern** assets

- Objectives:
  1. Characterize fatigue and fracture properties of welds and HAZs compared to base metals in hydrogen and natural gas
  2. Contribute to possible modifications of pipeline codes
  3. Evaluate performance with respect to existing regulations under 49 CFR Part 192

Microstructure-based understanding of H-effects on welds

Survey of pipe microstructures from industry partners

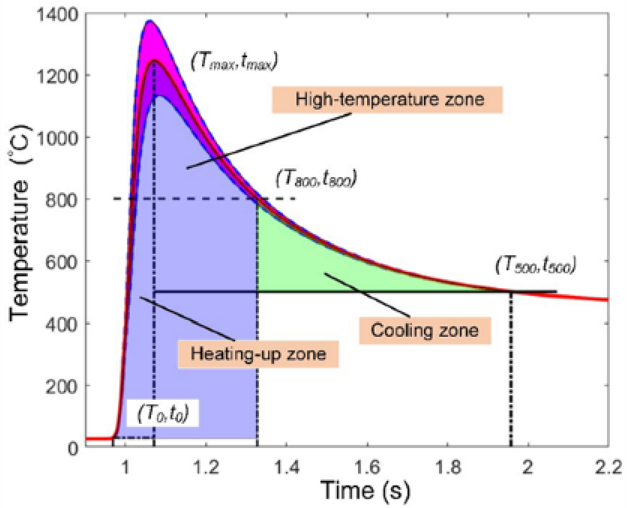
- X65, thin-walled, GMAW
- X65, thin-walled, SAW
- X70, X65 thick-walled
- X42, X65, X70 HFI Welds
- X100, thick-walled
- **Soliciting other materials of interest**

Systematic study of weld filler materials from ASME B31.12

- X65
  - AWS A5.5
  - AWS A5.18
  - AWS A5.28
  - Exploratory fillers

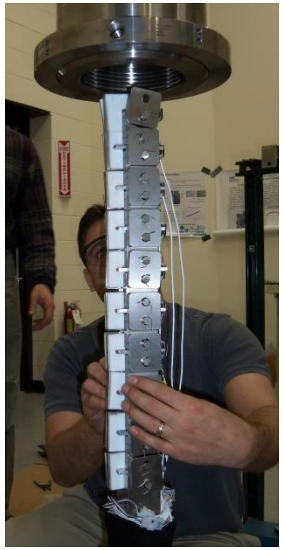
Systematic study of heat treatments

- X65



Measurement Capabilities

Load Frame 1	100 kN, 22 kip		
Load Frame 2	250 kN, 55 kip		
Pressure Vessel 1	138 MPa, 20,000 psi	0.55 ft^3, 1.5 liters	4" x 7.5"
Pressure Vessel 2	34 MPa, 5000 psi	0.341 ft^3, 9.6 liters	5" x 32"
Room Temperature			
Test control	tensile, 10^{-6} strain rate	fatigue, 0.01 - 10 Hz	

Laboratory started 2007

Test Types

Tensile
Fatigue Crack Growth Rate
Fracture Toughness
Fully-Reversed Strain-Life
Charpy

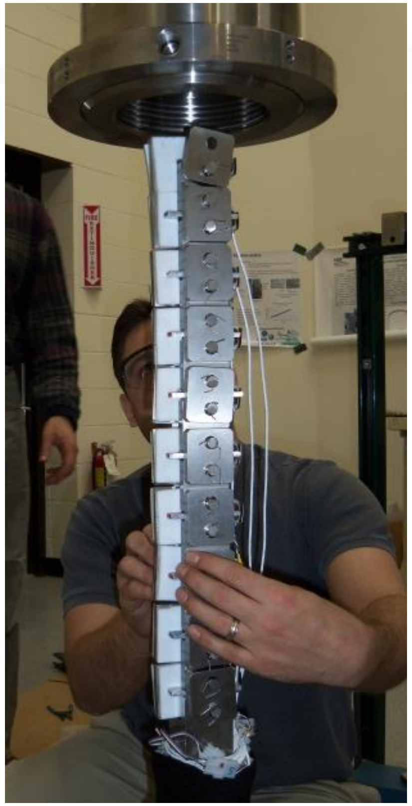
Material Types

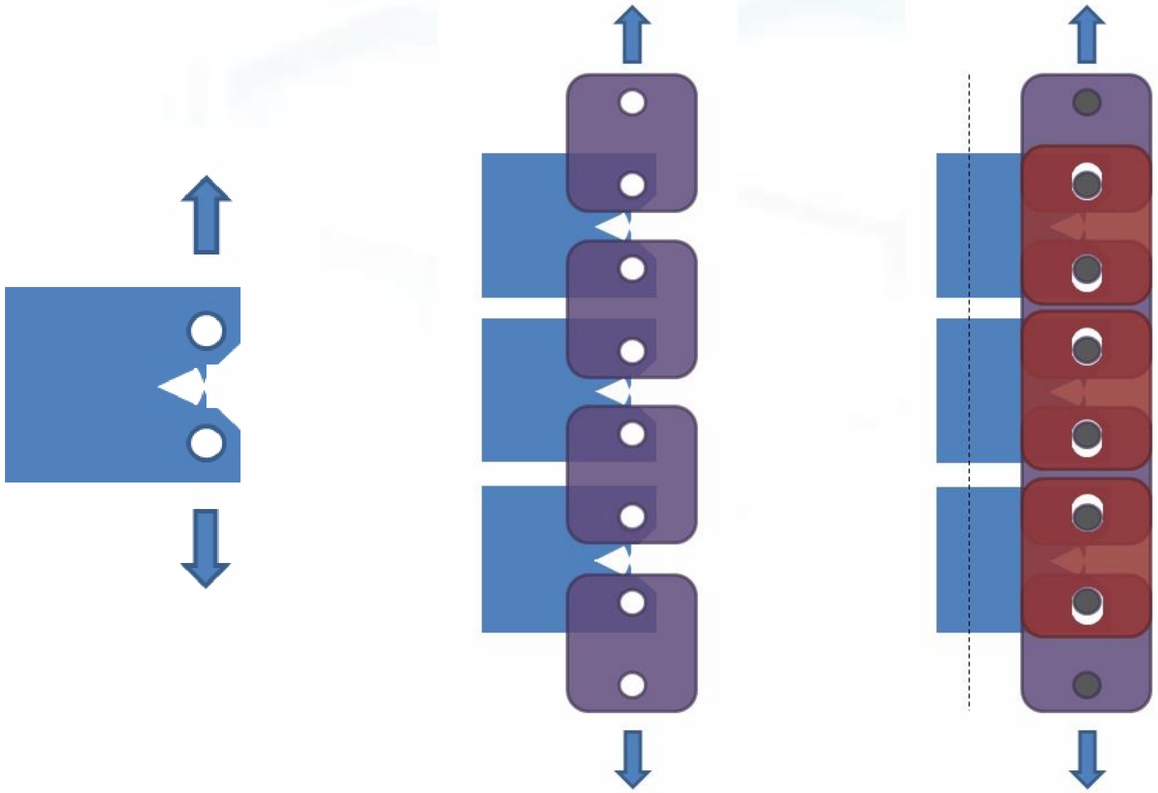
Pipeline steels
Associated welds
Associated Heat-Affected-Zones
Pressure Vessel Steels (gas cylinders
Quench and temper 25CrMo4
Austenitic stainless steels

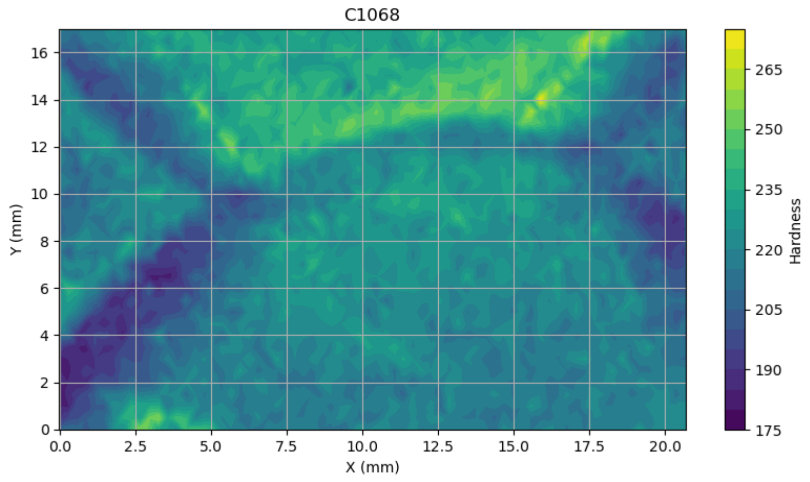
Measurement Capabilities

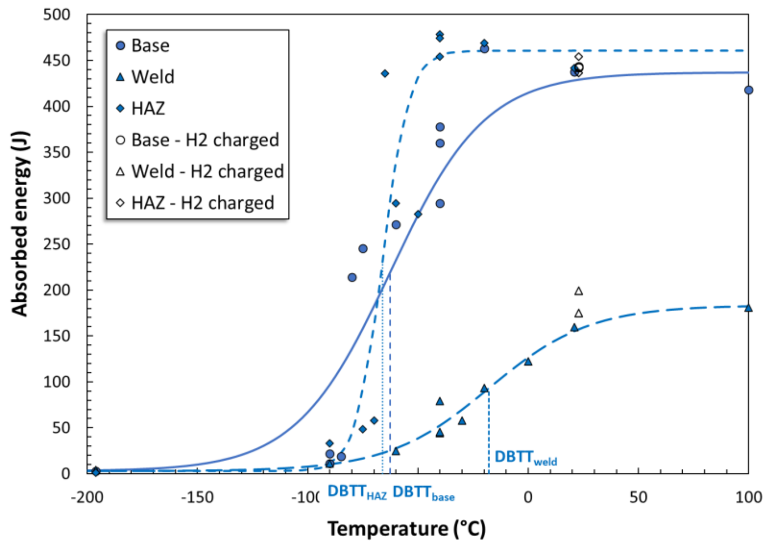
- Multiple-specimen fatigue

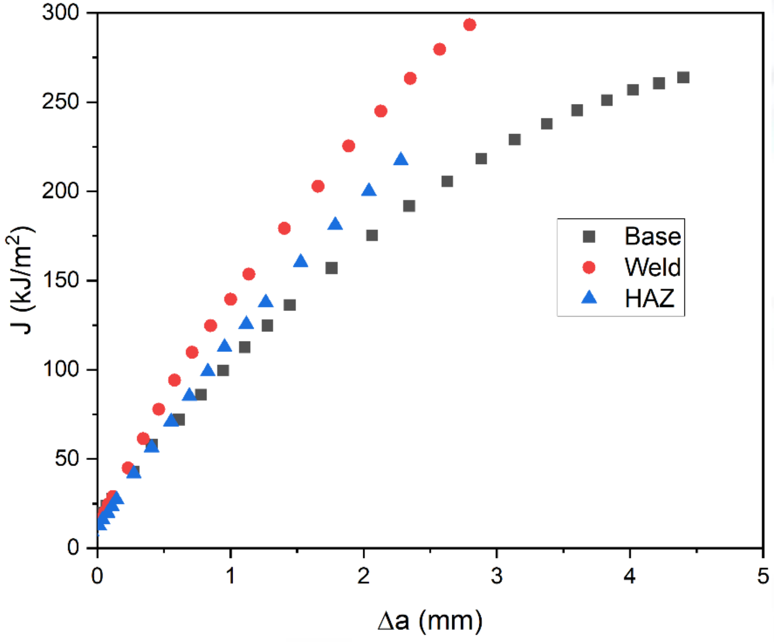
- Typical fatigue test 5M cycles > 8 weeks
  - Time
  - Hydrogen
- Problem worse for welds where crack initiation is delayed
- Multi-specimen chain allows:
  - Large data sets
  - All specimens in chain exposed to exact same environment



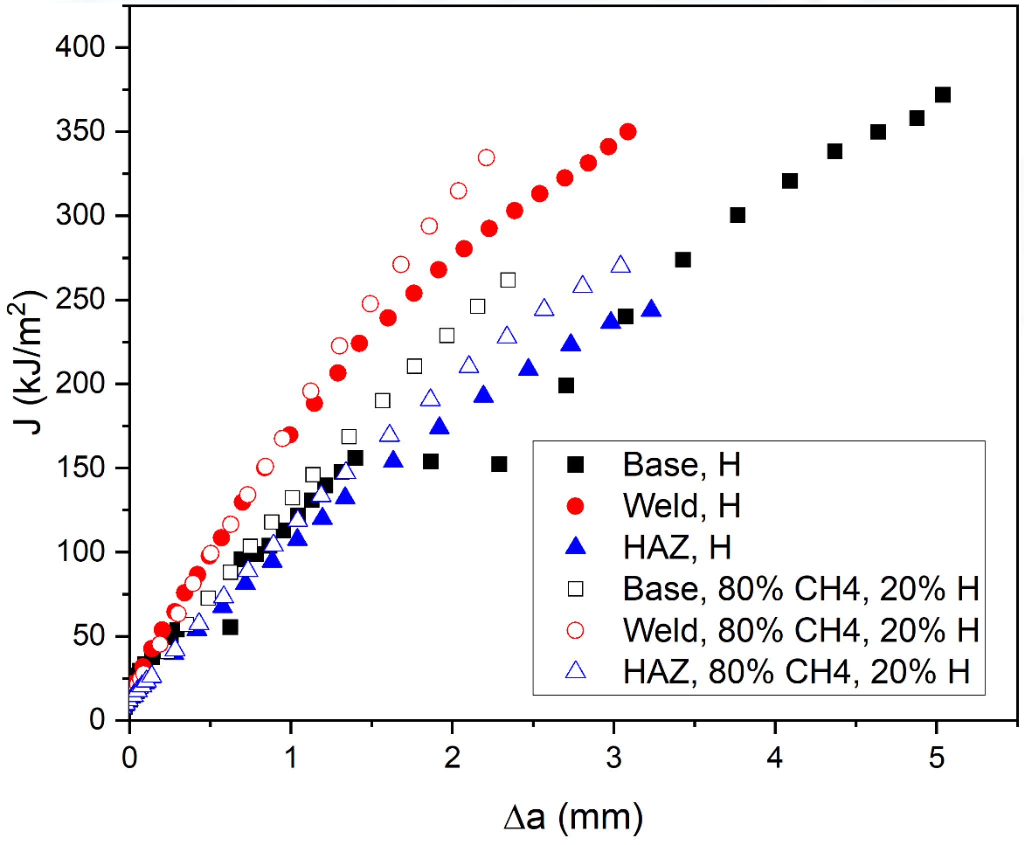


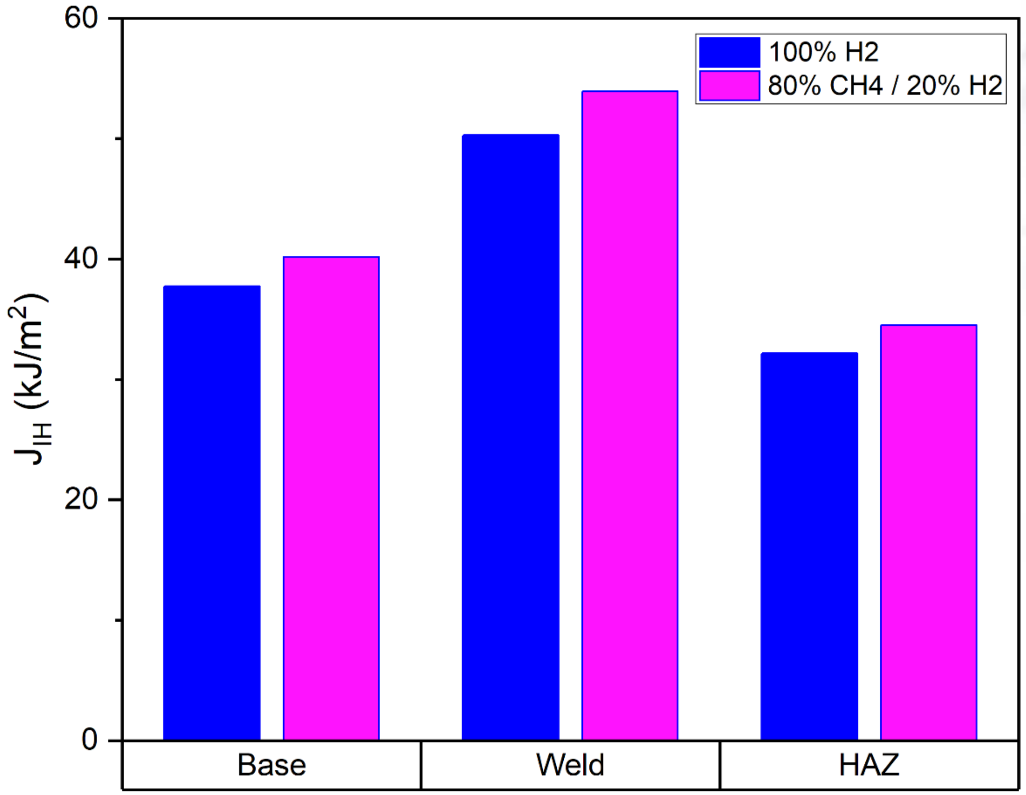

C1068
Y (mm)
X (mm)
Hardness
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
0
2
4
6
8
10
12
14
16
175
190
205
220
235
250
265


Base
Weld
HAZ
Base - H2 charged
Weld - H2 charged
HAZ - H2 charged
Absorbed energy (J)
Temperature (°C)
DBTT HAZ
DBTT base
DBTT weld
-200
-150
0
50
100
0
50
100
150
200
250
300
350
400
450
500


Base
Weld
HAZ
J (kJ/m2)
Δa (mm)
0
1
2
3
4
5
0
50
100
150
200
250
300

Blended Gas (100% H_2 compared to 80% CH_4 /20% H_2)





Hydrogen Pipeline Safety Team at NIST-Boulder

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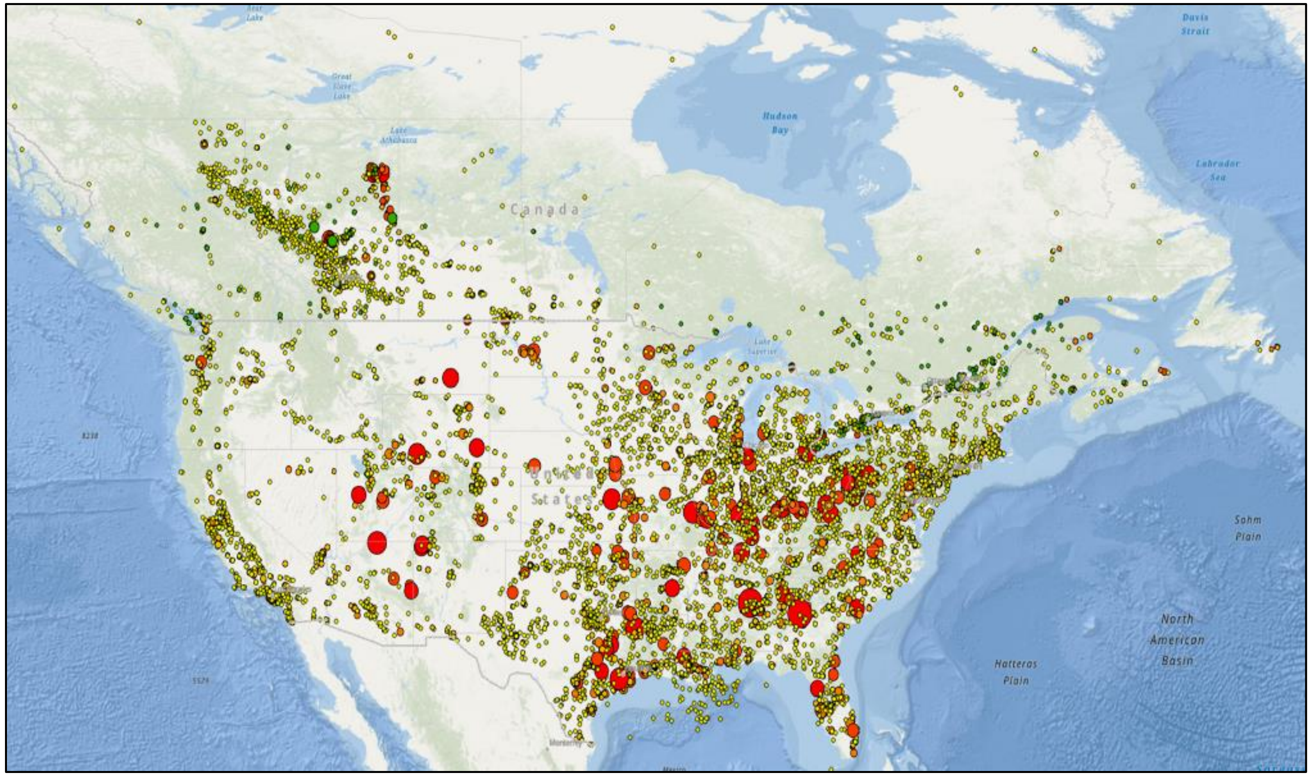
Modeling, TEA, and LCA of CCUS-H_2 Production, Purification, and Transportation (Blue-H_2)

K. Atkinson and R. Symonds
CanmetENERGY, Natural Resources Canada (NRCan)

How do we achieve net-zero CO_2 emissions?

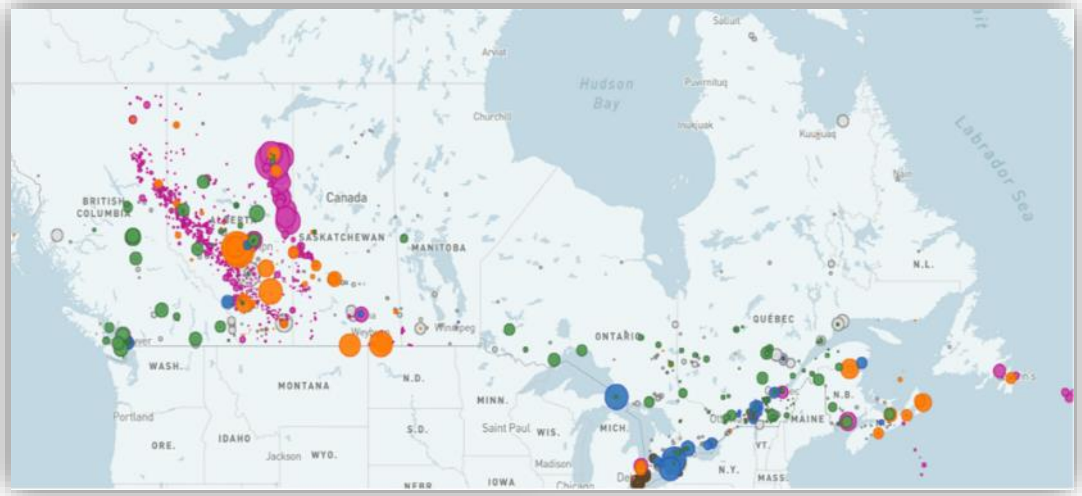
- The management of carbon dioxide emissions through **CCUS**, in combination with other strategies, **is critical** in meeting net-zero emissions targets
- Given the **complexity** of the entire CO_2 value chain, from emitting sites to storage locations, and the **diversity** of situations across Canada, decision-makers must have access to **unbiased scientific analysis of carbon management pathways**



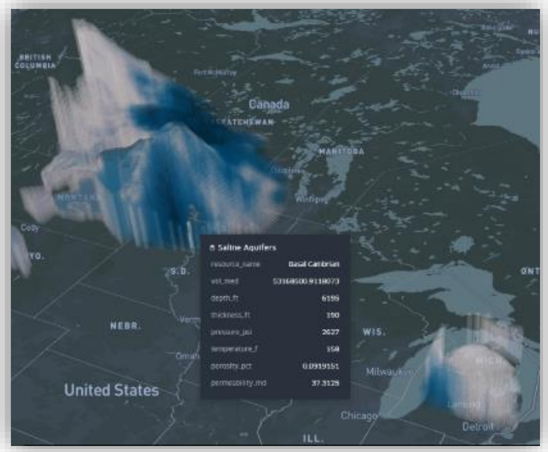
All major CO_2 emitters in Canada (2020) and USA (2013)
Coloured and sized by emission rate and source (largest emitter 22 Mt CO_2/year)

How do we achieve net-zero CO_2 emissions in Canada?

- Researchers at NRCan are developing CCUS planning tools to **solve and coordinate the CCUS part of the puzzle**
- CO_2 capture from fossil, process, and biogenic sources
- **Fuel switching from natural gas to H_2 with CO_2 capture**
- CO_2 storage prospectivity
  - Geological reservoirs
  - Mineralization (e.g., tailings)
- CO_2 transportation
- CCUS and **H_2 hubs and clusters**
- Extensive external collaboration with industry, governments, and universities



Major CO_2 emitters in Canada by emission type and rate



Saline aquifers in Canada

H_2 and CCUS Hubs and Clusters

Major CO_2 emitter clusters in Canada; >0.5 Mt CO_2/year clusters

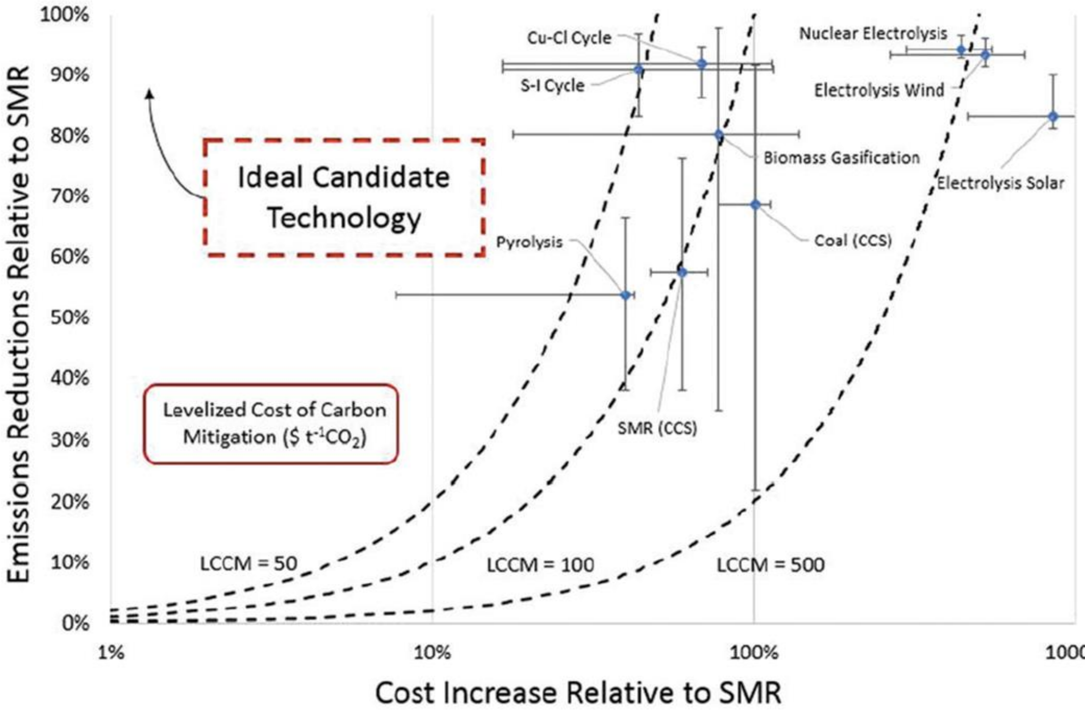
- Clustering CO_2 emitters lets us see where the big infrastructure will begin, including:
  - Where H_2 is currently produced
  - Where H_2 is and will be consumed
- Several clusters are co-located with potential CO_2 storage geology:
  - H_2 producers and end-users in the Oil & Gas and Iron & Steel sectors (Alberta and S. Ontario)
- Deployment requires more rigorous analysis than hub & cluster concepts can provide

Key Research Questions

- What is the **best approach for blue-H_2 production technology development** for each industrial sector/H_2 end-user in Canada considering both **lowest-cost pathways** and **environmental impacts**?
- What is the **ideal H_2 and CO_2 transportation mode(s) and network** linking producer and end-user locations across Canada considering existing rights-of-way, topography, population density, areas of concern, obstacles, etc.?
- Where are the **most suitable H_2-hubs across Canada** based on current and future end-use locations relative to production sources?

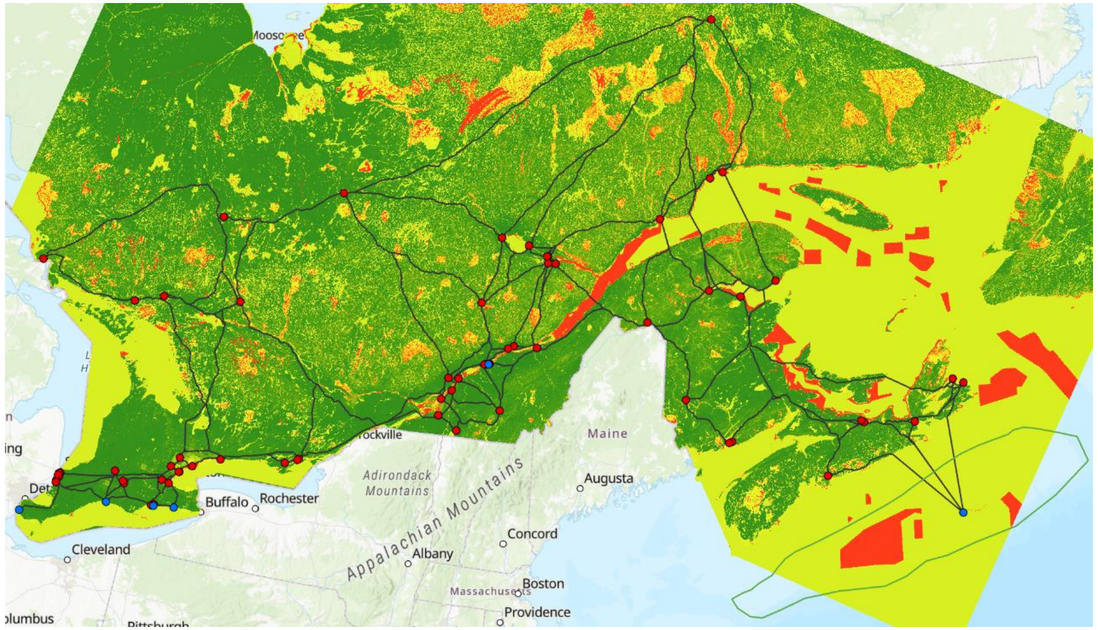
Key Project Objectives

1. Determine the **lowest cost and lowest environmental impact pathways** for blue-H_2 production, purification, and transportation considering various local factors
   - Process simulation, TEA, and LCA methods, in combination with machine learning algorithms, to achieve this objective
   - The assessments will take regional factors and industry specific requirements into consideration
2. Provide **policymakers and H_2 producers/end-users** with **standardized** TEA and LCA metrics, potential H_2-hubs, and a comparative suite of low emission options to facilitate technology adoption
   - Scenario-based supply and demand models will be developed for several key H_2-hubs across Canada



Network Modeling and Optimization

- Using outputs from TEAs to determine the **total cost of H_2 production and transportation** across Canada for both current and future H_2 end-users
- Link to the National CCUS Assessment Framework (NCAF)
  - High-throughput CO_2 pipelines connect the provinces' major emitters to CO_2 storage locations in southwest Ontario and very large CO_2 storage reservoirs in NS and NL
  - Medium facilities are connected to pipelines *via* ship & truck
- Considering **multiple H_2 transport phases**
  - Compressed, liquefied, and ammonia
  - Multi-modal transport linked with scenario-based **supply and demand models**
- **H_2 for transportation sector** on the 400 series highways
  - Centralized vs. decentralized

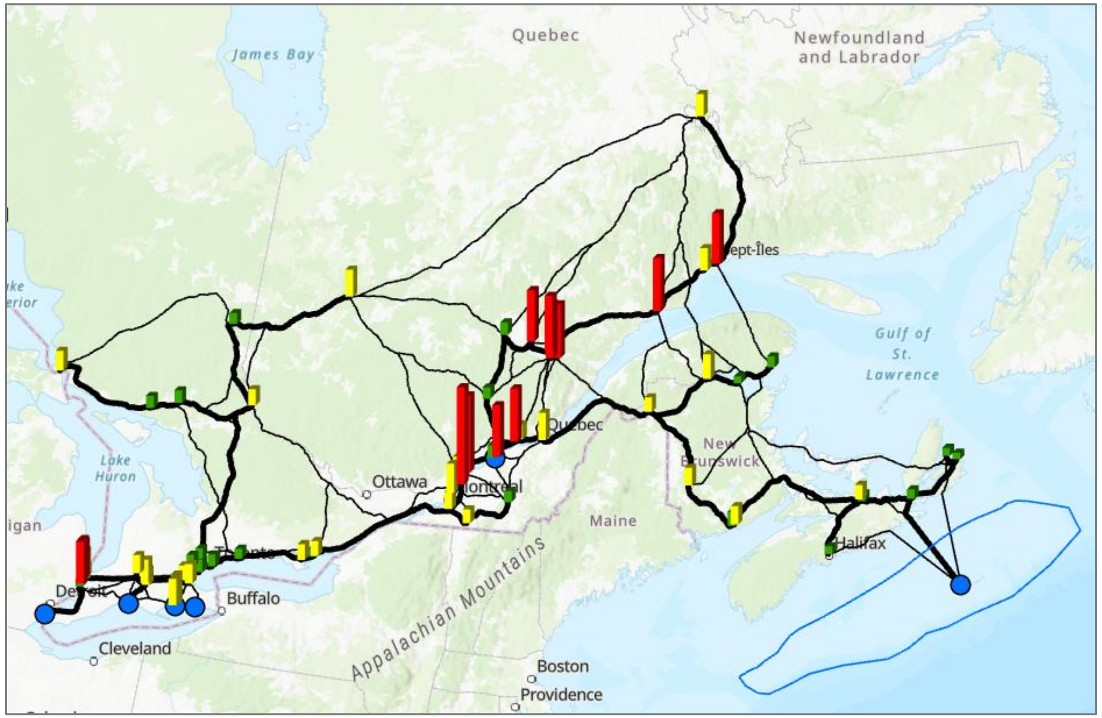


Candidate CO_2 pipeline network following **lowest-cost paths**

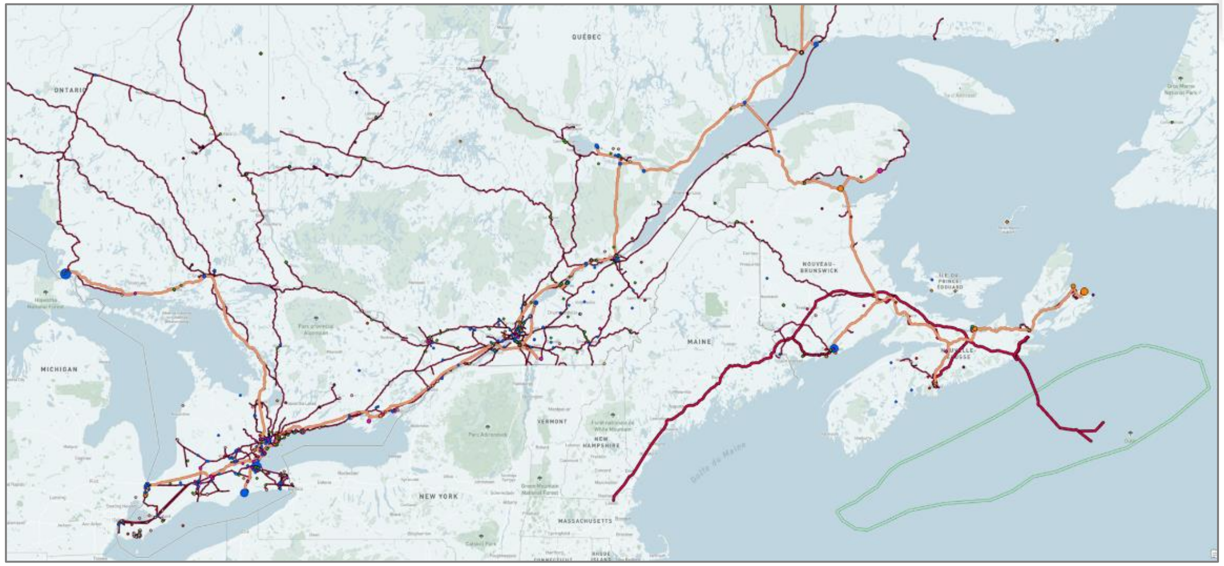
Resolution: grid region in squares of 200m x 200m

Parameters considered: population, rivers, lakes and ocean, protected areas, First Nations territories, slope of land, power line and railway rights-of-way, border with United States

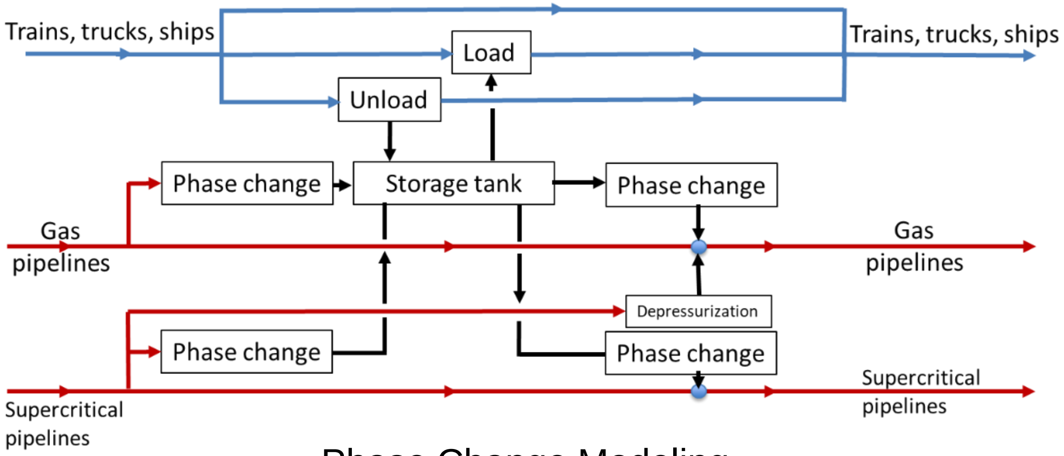
Network Modeling and Optimization



Optimized Transport Network with Cost of CO_2 Capture



Multi-modal Optimization – Source to Sink



Phase Change Modeling

Current Status

- Project officially underway as of April 1st, 2023
- Engaging with other federal departments as well as provincial governments, industrial stakeholders, and Indigenous Nations to determine critical model inputs and outputs
- Applying preliminary learning from the National CCUS Assessment Framework to guide early stages of H_2 production technology model development and network modelling approach
- Working with major companies in all industrial sectors:
  - Iron & steel, cement, oil & gas, pulp & paper, power generation, metallurgy/smelting, gas and solids transport, etc.
  - Task-share agreements with individual companies to complete case studies on options for attaining net-zero, including fuel-switching

Thank you!

CONTACT

Modeling, TEA, and LCA of CCUS-H_2 Production, Purification, and Transportation (Blue-H_2)

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CanmetENERGY
Energy Efficiency and Technology Sector (EETS)
Natural Resources Canada (NRCan)

Workshops planned

27th September – pure hydrogen pipeline distribution

25th October – underground storage