Webinar on
Technical Potential of Hydrogen and GHG Emissions in its Transportation through Natural Gas Pipelines

NSERC/Cenovus/Alberta Innovates Associate Industrial Chair Program in Energy and Environmental Systems Engineering

www.energysystems.ualberta.ca

Webinar

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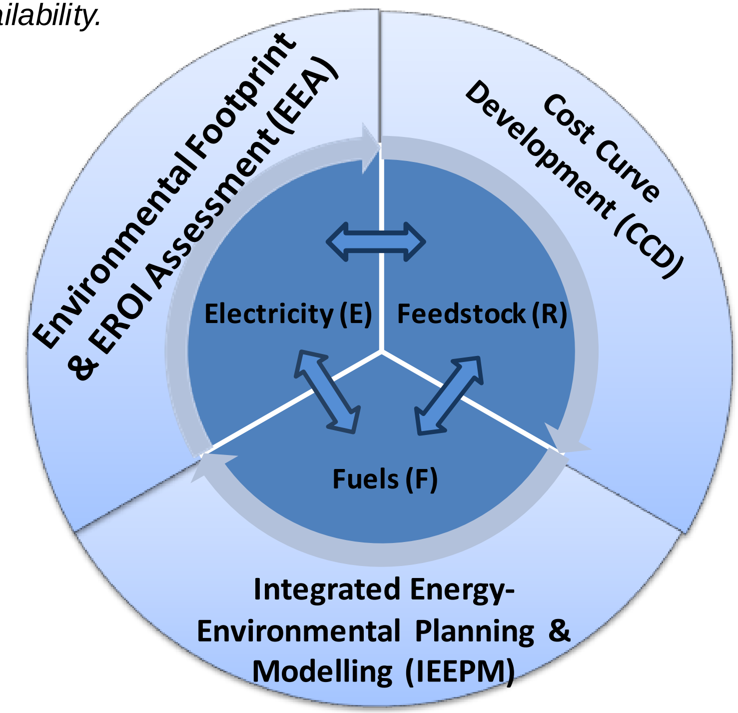
Ayodeji Okunlola, Giovanni Di Lullo, Matthew Davis, Abayomi Oni
Amit Kumar

Department of Mechanical Engineering, University of Alberta, Edmonton, Canada

Overall Structure of the NSERC IRC Program

<u>NSERC/Cenovus/Alberta Innovates Associate Industrial Chair Program in Energy and Environmental Systems Engineering</u>

Objective: To identify pathways to low carbon energy production and use considering costs, environmental impacts, and resource availability.



Cost Curve Development (CCD)	Environmental Footprint & EROI Assessment (EEA)	Integrated Energy-Environmental Planning & Modelling (IEEPM)
Understand the costs of existing and new low carbon/decarboznied energy production and use through the development of techno-economic models	Understand the GHG, water, and land footprints and energy return on investment (EROI) of different energy production and use pathways	Understand the GHG abatement cost and mitigation potential for energy pathways for a jurisdiction along with feedstock availability

Overall NSERC IRC Program

P6 - Comparative life cycle assessment of the combustion of petcoke with coal

P9 - Comparative assessment of biorefinery pathways

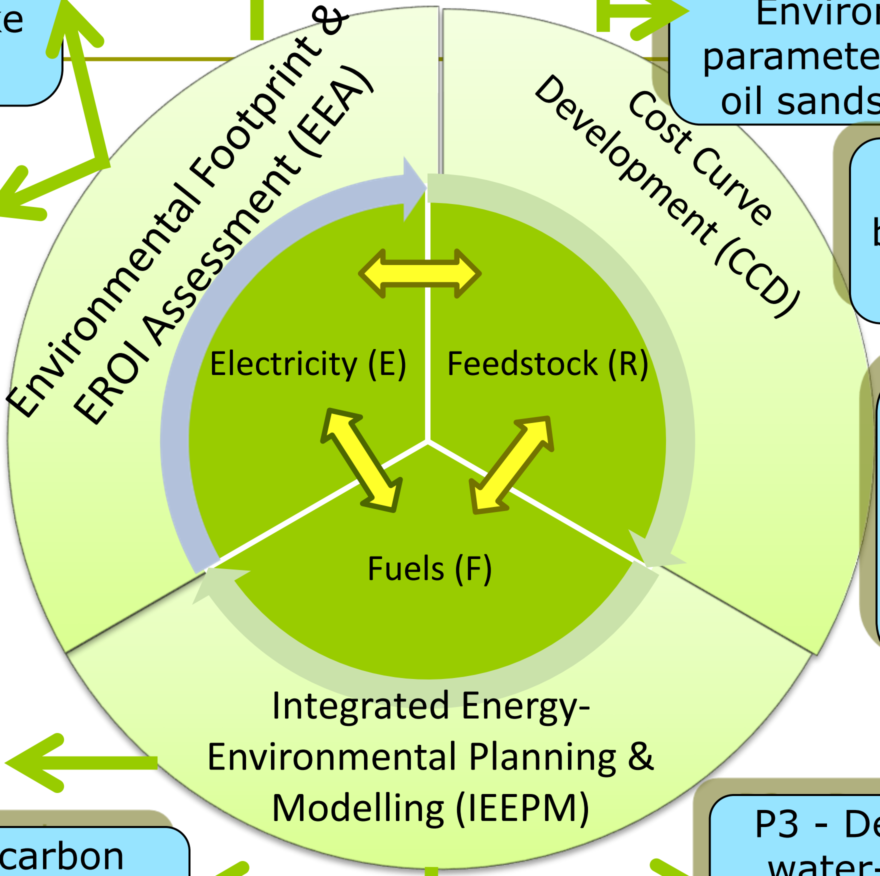
P7 - Development of Environmental and economic parameters for assessment of new oil sands extraction technologies

P5 - Assessment of energy & emissions for pipelines for conventional natural gas and crude oil in Canada

P10 - Development of a baseline model for carbon, capture, use and storage

P8 - Assessment of pathways for production & blending of renewable crude with conventional crudes & green diluents

P11 – Penetration of renewable natural gases and hydrogen in Canada's demand sectors



P1-Development of low carbon options for Canada's energy demand and supply sectors

P3 - Development of integrated water-GHG saving cost curves for the energy sector

P2 - Development of energy efficiency assessment models for GHG emission-intensive industries

P4 - Development of integrated models to determine optimal locations for waste-to-value added facilities

HYDROGEN ECONOMY STUDY: APPROACH

LITERATURE REVIEW & DATA SYNTHESIS

Comprehensive literature scan to identify hydrogen production pathways available in Canada

Literature review to identify data available, applicability to Canada, and data gaps

Conduct analyses to fill missing data requirements

Determine regional technical potentials of hydrogen production across Canada

DATA DEVELOPMENT

Life cycle assessment

g CO_2 eq per unit output
m^3 water per unit output

Techno-economic assessment

Cost metrics
$ per unit output

LONG-TERM HYDROGEN-ECONOMY MODELLING

LEAP-Canada
Long-range Energy Alternatives Planning Model

-Canada-wide by region

-Long-term (beyond 2050)

-Bottom-up energy demand and supply

-Integrated market penetration modelling

-Fully integrated energy system model

OUTPUTS

Long-term annual results per scenario

Indicators:
GHG mitigation potential, system costs, $/tonne of CO_2e abatement, market penetration of technology,

Results for:

Adopting hydrogen-based technology across demand sectors

GHG emissions mitigation potential

Economic feasibility of market penetration of hydrogen-based demand technologies

Optimize hydrogen production pathways by region

OUTLINE

Background and framework for hydrogen study

- **Motivation and overview**
- **Study framework**
- **Current hydrogen supply and demand in Canada**

Technical potential of hydrogen production

- **Natural gas**
- **Wind**
- **Solar**
- **Conclusions and future work**

FUNNEL-GHG-NGTL model and NG+H_2 mixtures (hythane)

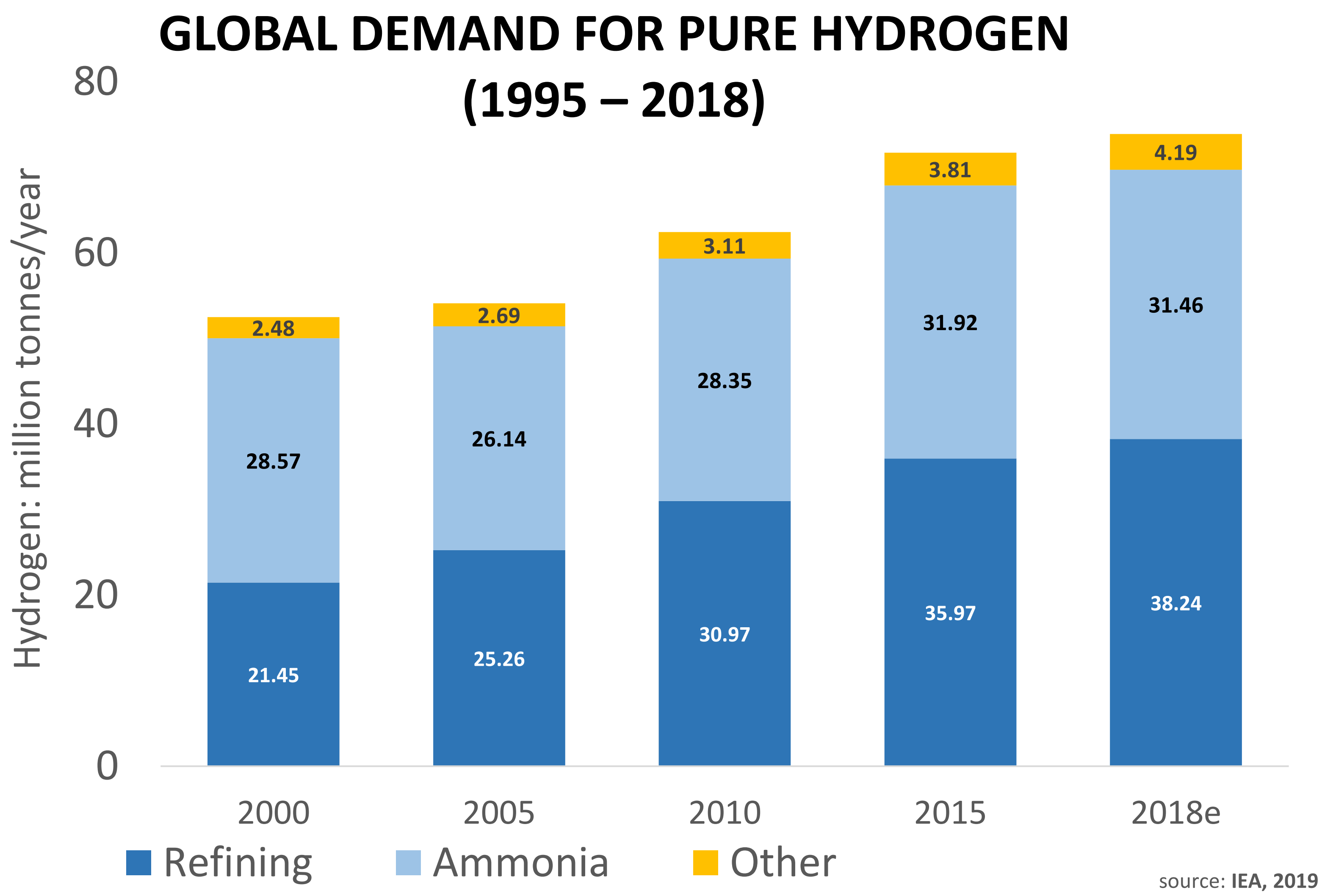
Questions (after the presentation) – Please type your question in the chat box or just indicate that you have a question to ask

BACKGROUND & FRAMEWORK FOR HYDROGEN STUDY

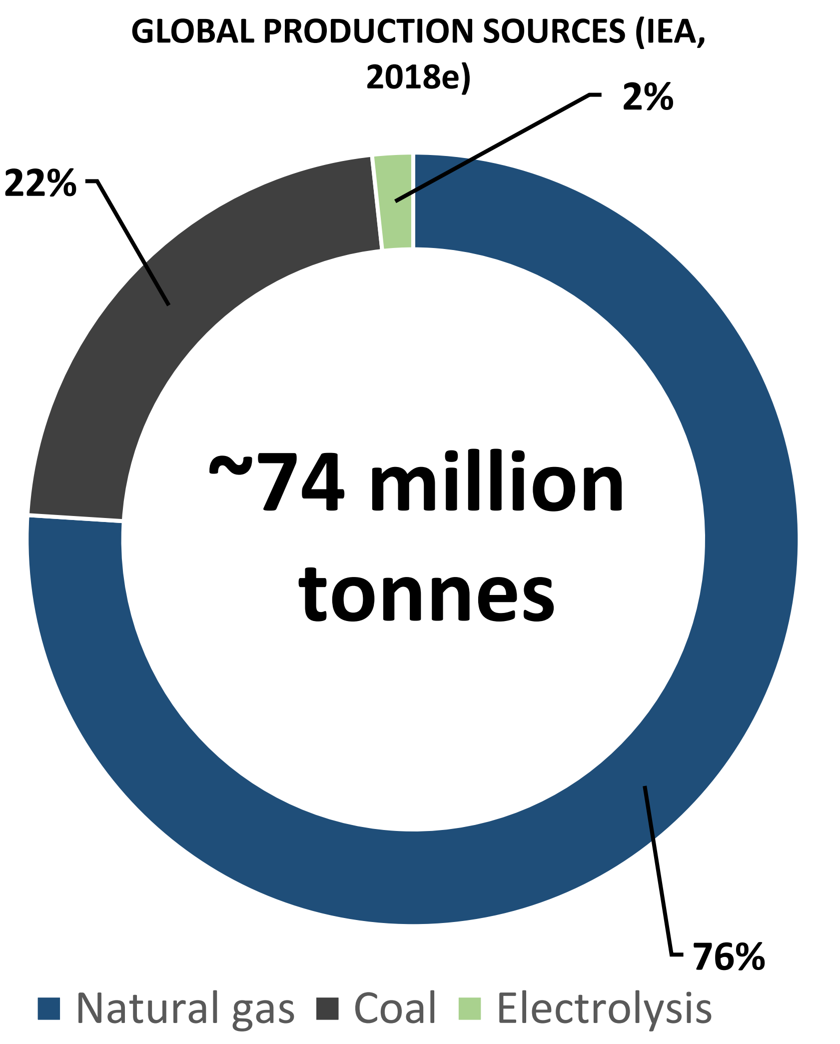
BACKGROUND: MOTIVATION & OVERVIEW

- Growing need to decarbonize the energy mix
- Need to improve the operations of variable output generators
- Hydrogen (H_2) is emerging as a major fuel and energy carrier for a transition to a low-carbon future
- First step to drive a hydrogen economy is to understand the country-wide production potential

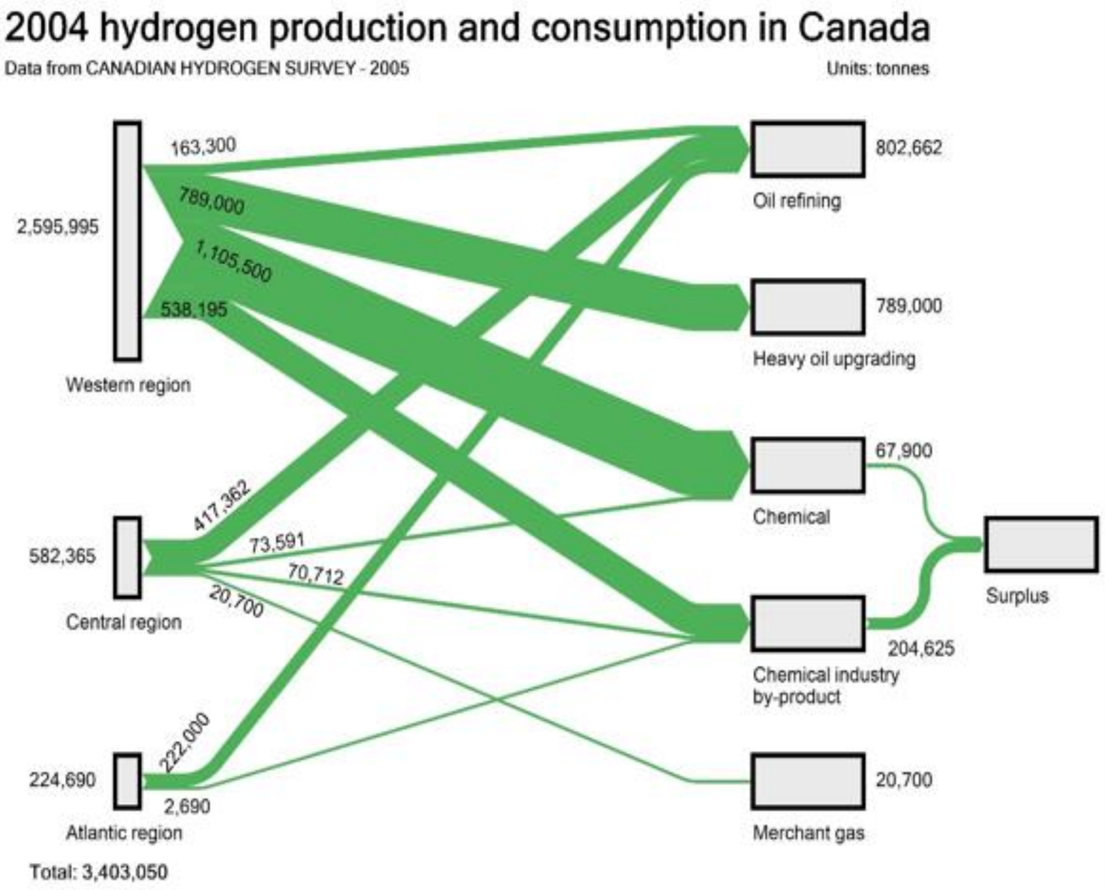
BACKGROUND: GLOBAL H_2 DEMAND AND SUPPLY

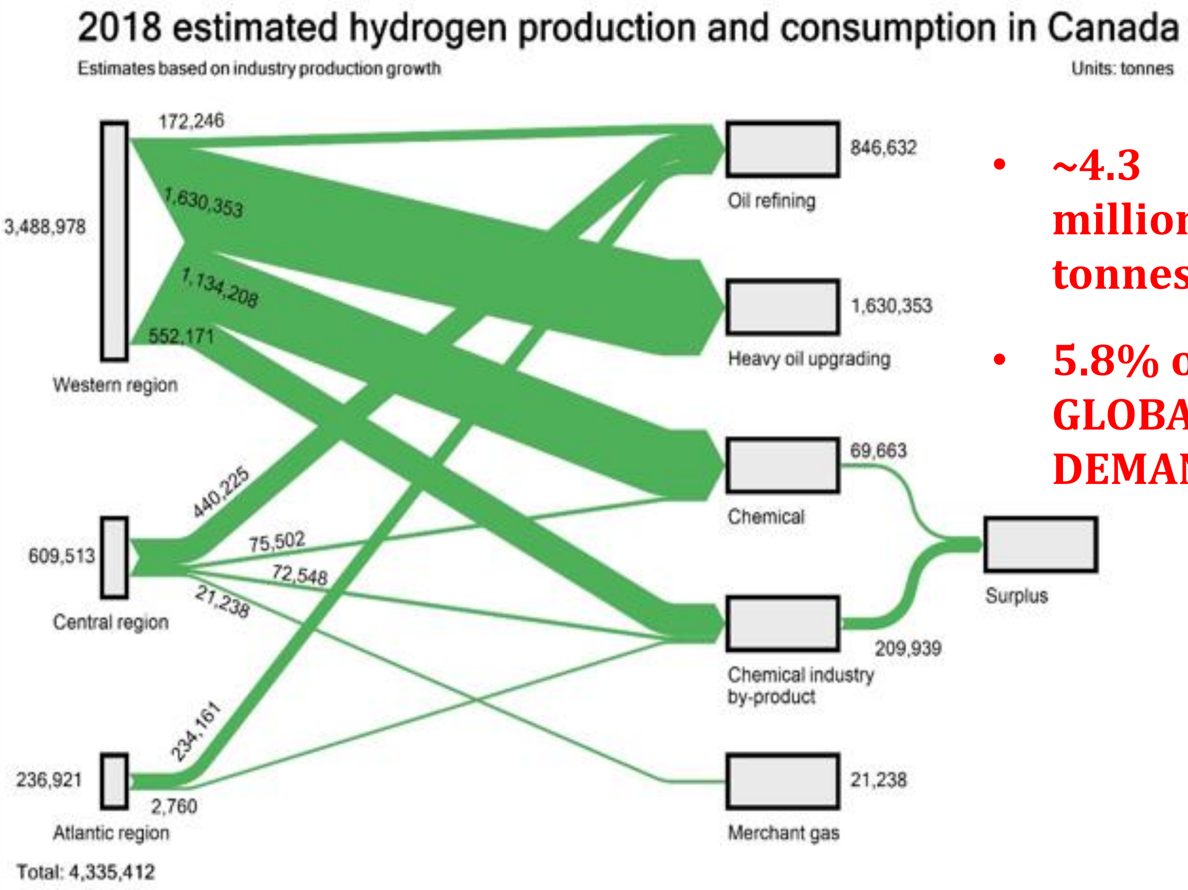


source: **IEA, 2019**



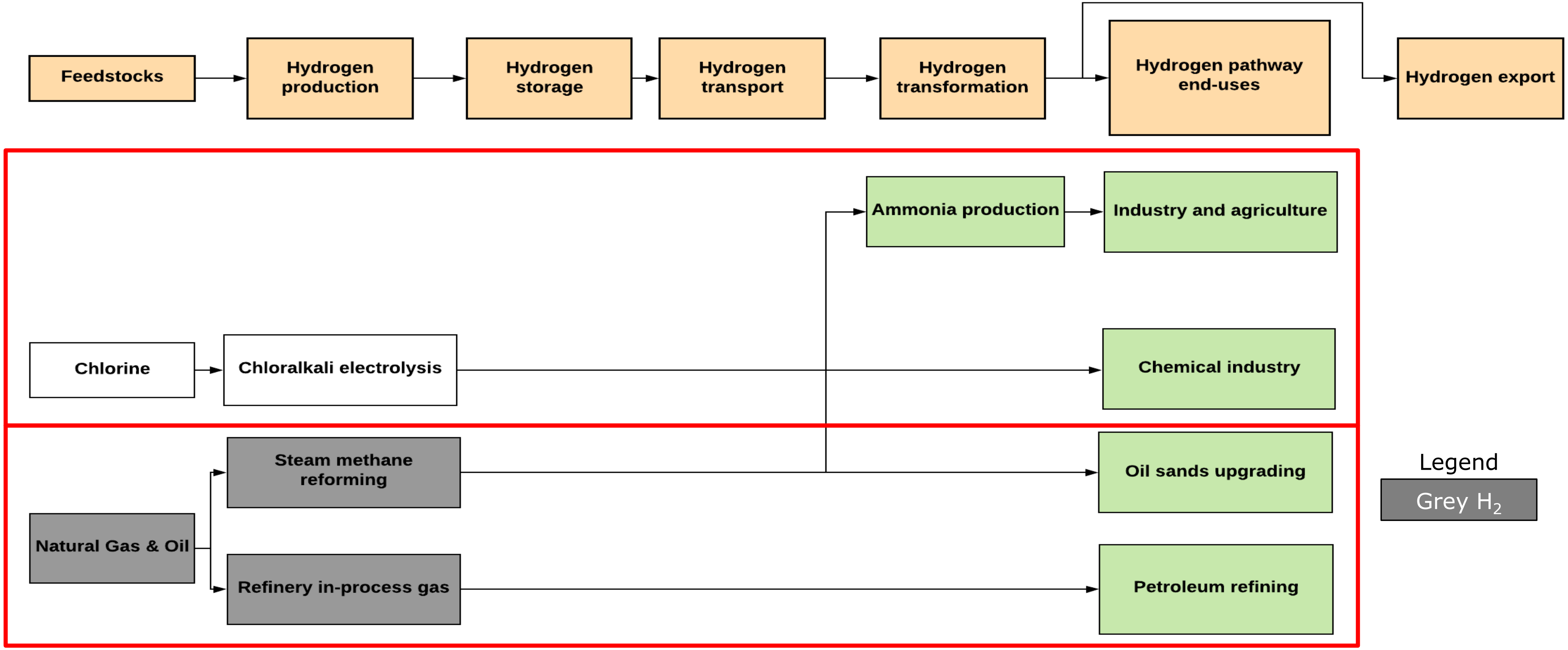
BACKGROUND:
CANADA H_2 SUPPLY AND DEMAND





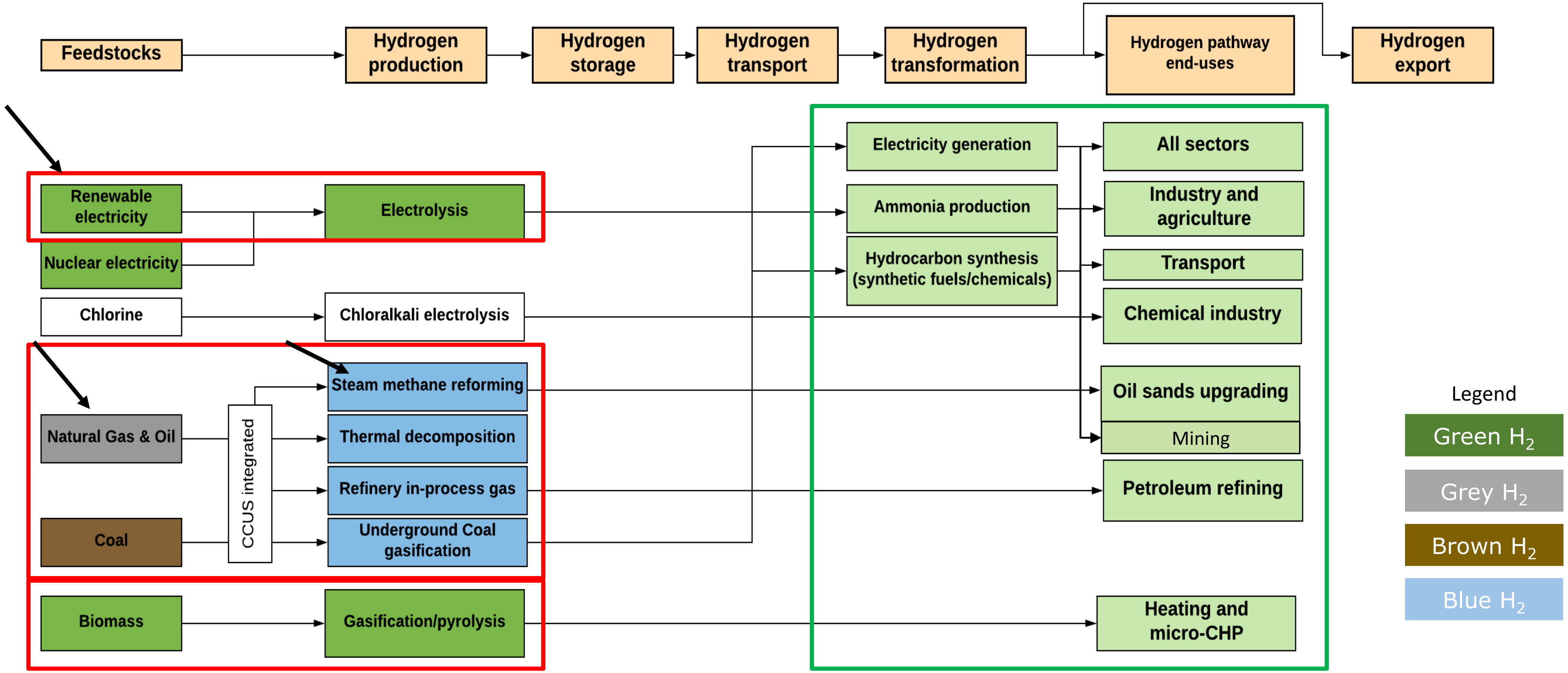
- ~4.3 million tonnes
- 5.8% of GLOBAL DEMAND

HYDROGEN ECONOMY STUDY: CURRENT HYDROGEN PATHWAYS IN CANADA



Source: Fairlie M, Potter I. Canadian Hydrogen Current Status and Future Prospects, 2004

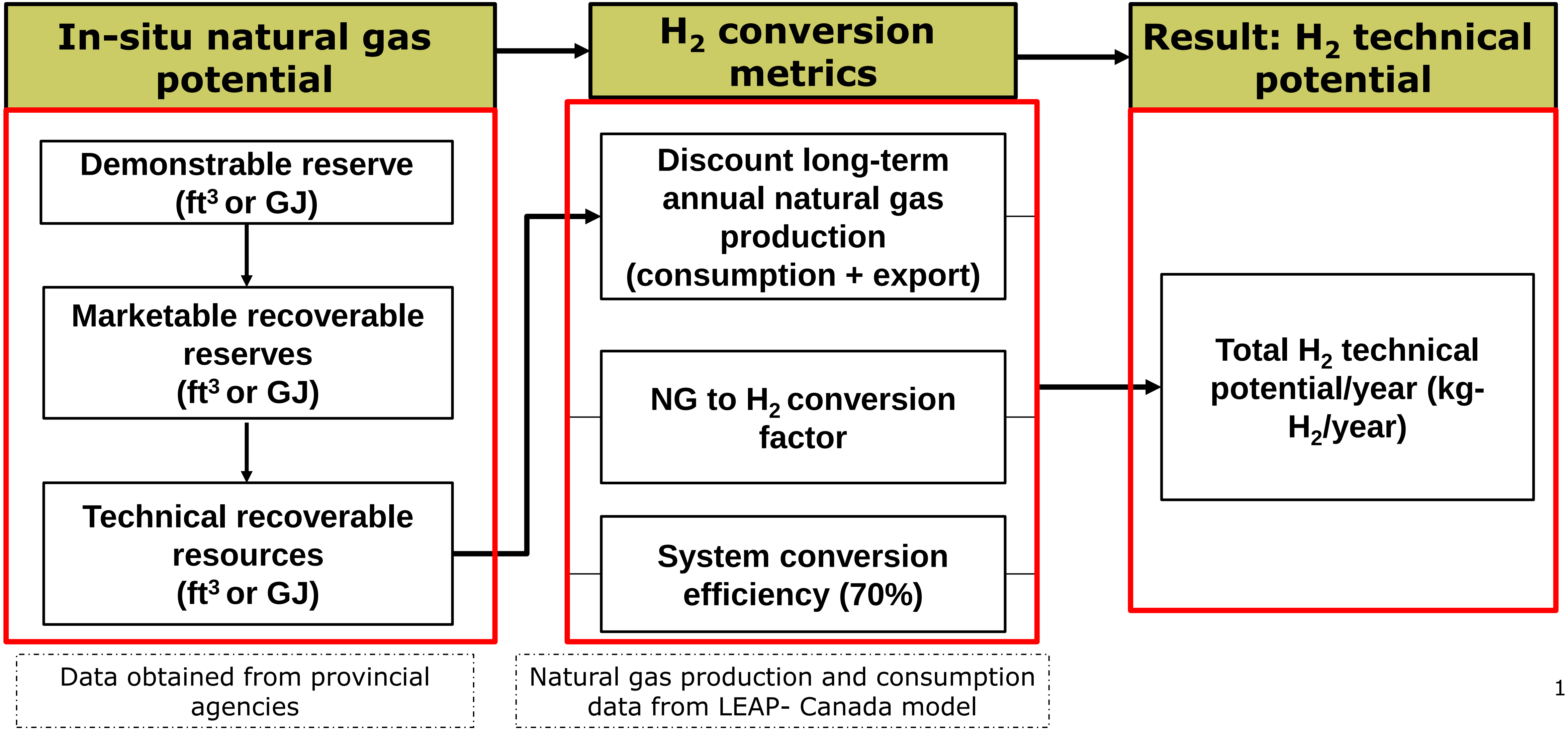
HYDROGEN ECONOMY STUDY: POTENTIAL HYDROGEN PATHWAYS IN CANADA



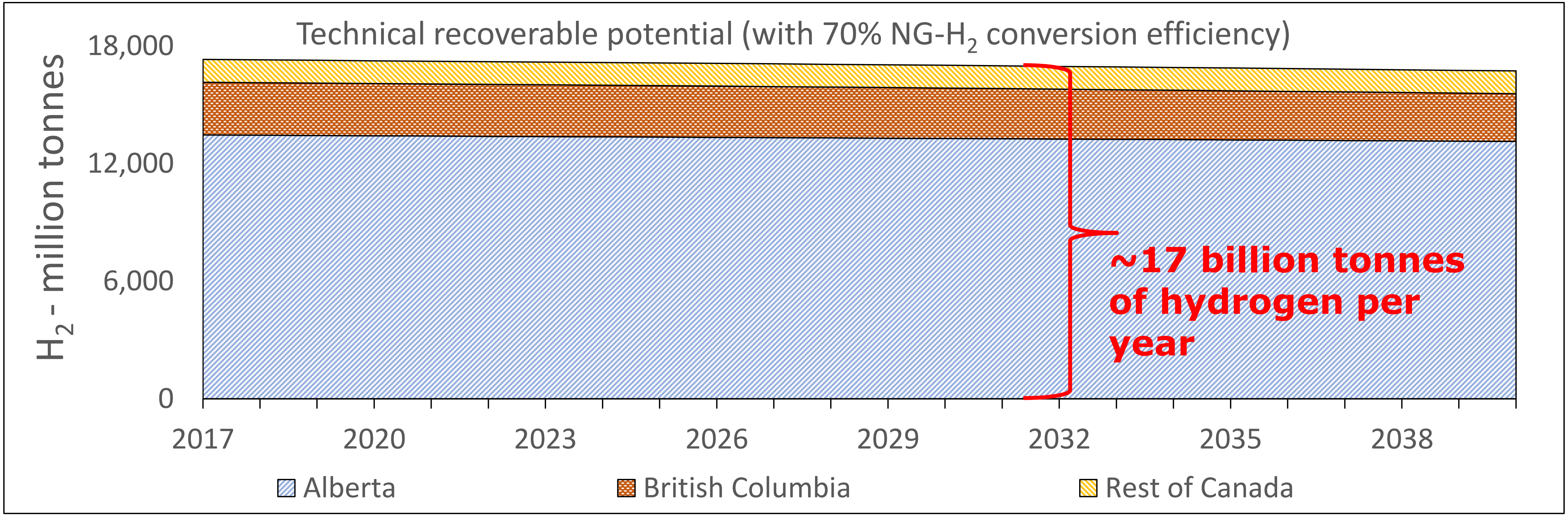
TECHNICAL POTENTIAL OF HYDROGEN PRODUCTION FROM:

NATURAL GAS (STEAM METHANE REFORMING)

METHODOLOGY:
AGGREGATED INVENTORY APPROACH



RESULT: HYDROGEN POTENTIAL FROM TECHNICAL RECOVERABLE NATURAL GAS



- **230x of current global annual hydrogen demand.**
- Provincial distribution is low: Alberta represents 78% of the technical recoverable potential.
- Influenced by the high GHG footprint and the global shift towards renewable energy-based hydrogen production.

TECHNICAL POTENTIAL OF HYDROGEN PRODUCTION FROM:

WIND-BASED ELECTRICITY (ELECTROLYTIC HYDROGEN)

WIND-BASED HYDROGEN METHODOLOGY: A THREE LEVEL SPATIAL ANALYSIS

Step 1. Location suitability analysis → **Step 2. Resource penetration zoning** → **Step 3. Wind energy to hydrogen conversion**

Step 1. Location suitability analysis	Step 2. Resource penetration zoning	Step 3. Wind energy to hydrogen conversion
Obtain locations across the country that are geographically suitable for wind farms	Analysis of high cut-off wind characteristics to suitable locations	Technical analysis calculations for hydrogen production

- GIS modelling with ArcGis and Qgis is used for the spatial analysis
- Height at 100m to focus on high potential areas
- Cut-off wind speed set at 7m/s for high velocity and high capacity factor
- Existing wind power infrastructure is negligible (< 0.1%)

WIND-BASED HYDROGEN METHODOLOGY: LOCATIONAL SUITABILITY ANALYSIS

Initial map of the country per county

OBJECTIVE

To extract suitable geographical areas far away from landmarks:

- Rivers & Coastal water
- Buildings
- Population clusters
- Streets/Avenues
- Designated places
- Highways
- Roads
- Forests
- Parks

WIND-BASED HYDROGEN METHODOLOGY: LOCATIONAL SUITABILITY ANALYSIS

Add a setback distance (from literature) for each landmark where a wind farm cannot be built

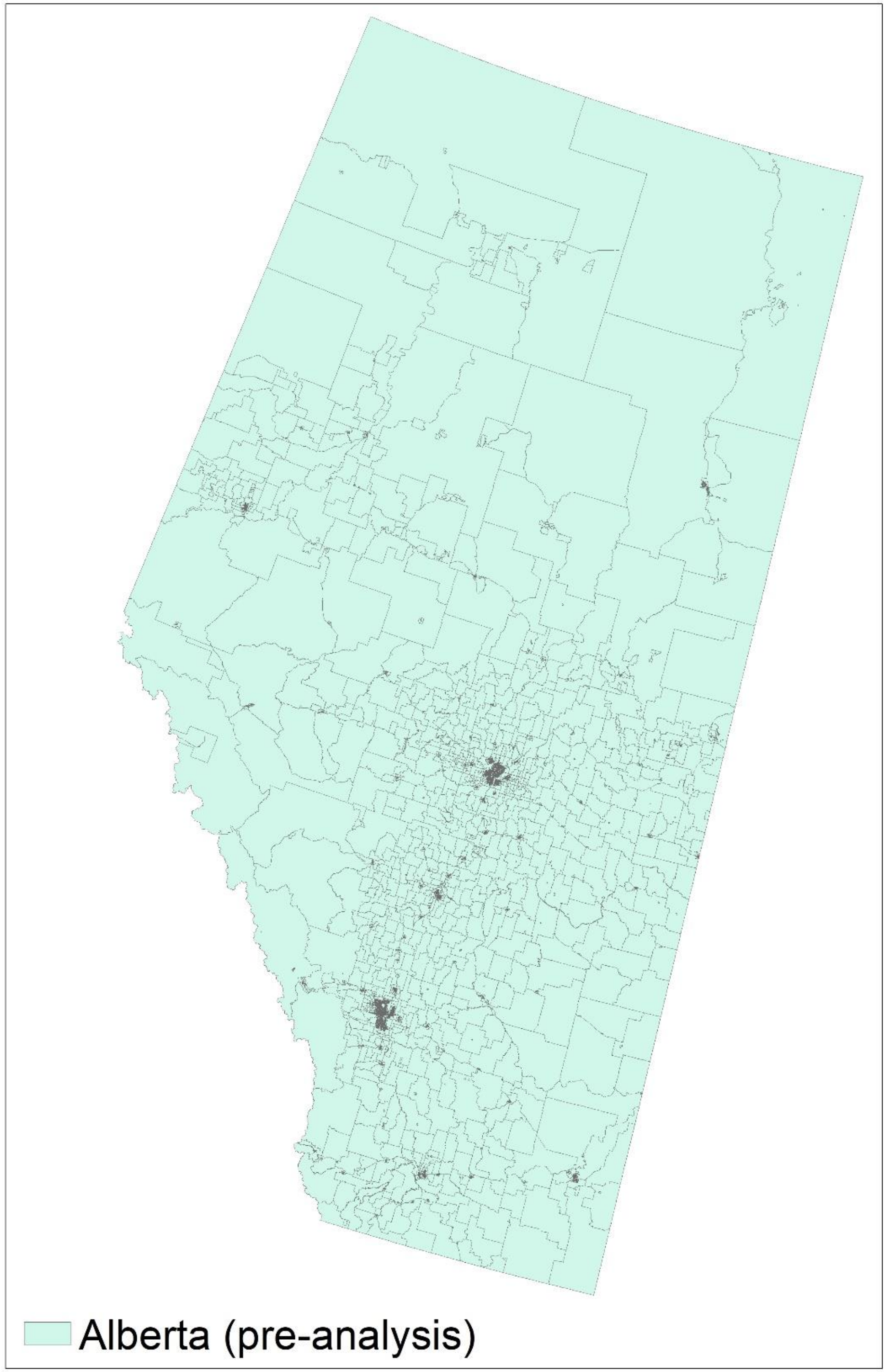
LANDMARK	SETBACK DISTANCE
Buildings	2000 meters
Population clusters	2000 meters
Streets/Avenues	5000 meters
Designated places	1000 meters
Highways	2000 meters
Roads	1000 meters
Forests	1000 meters
Rivers & Coastal waters	500 meters
Parks	150 meters

Removed all setback distances (area) for the landmarks

OUTPUT

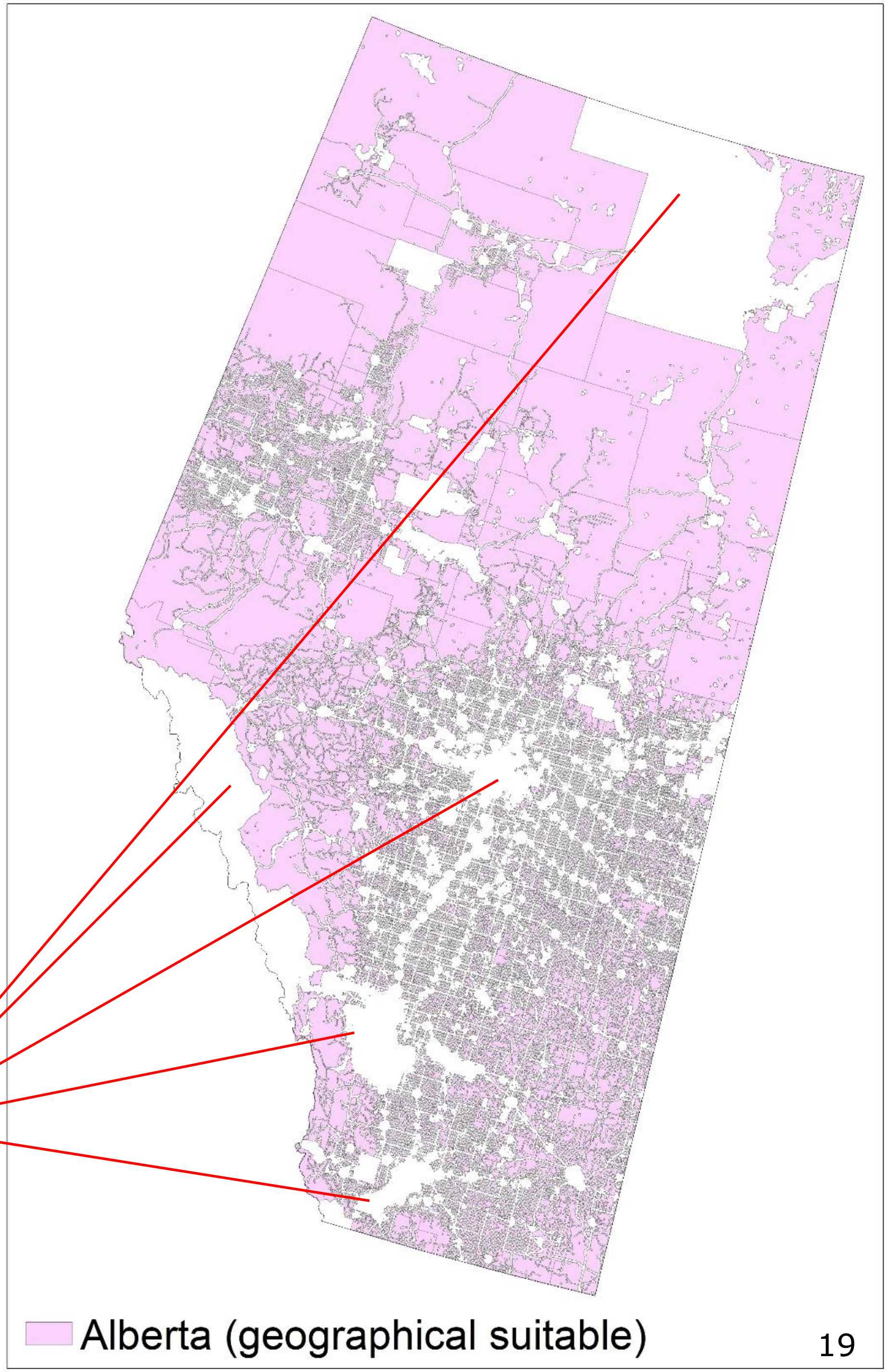
Only geographical suitable land across the country remain

ALBERTA EXAMPLE



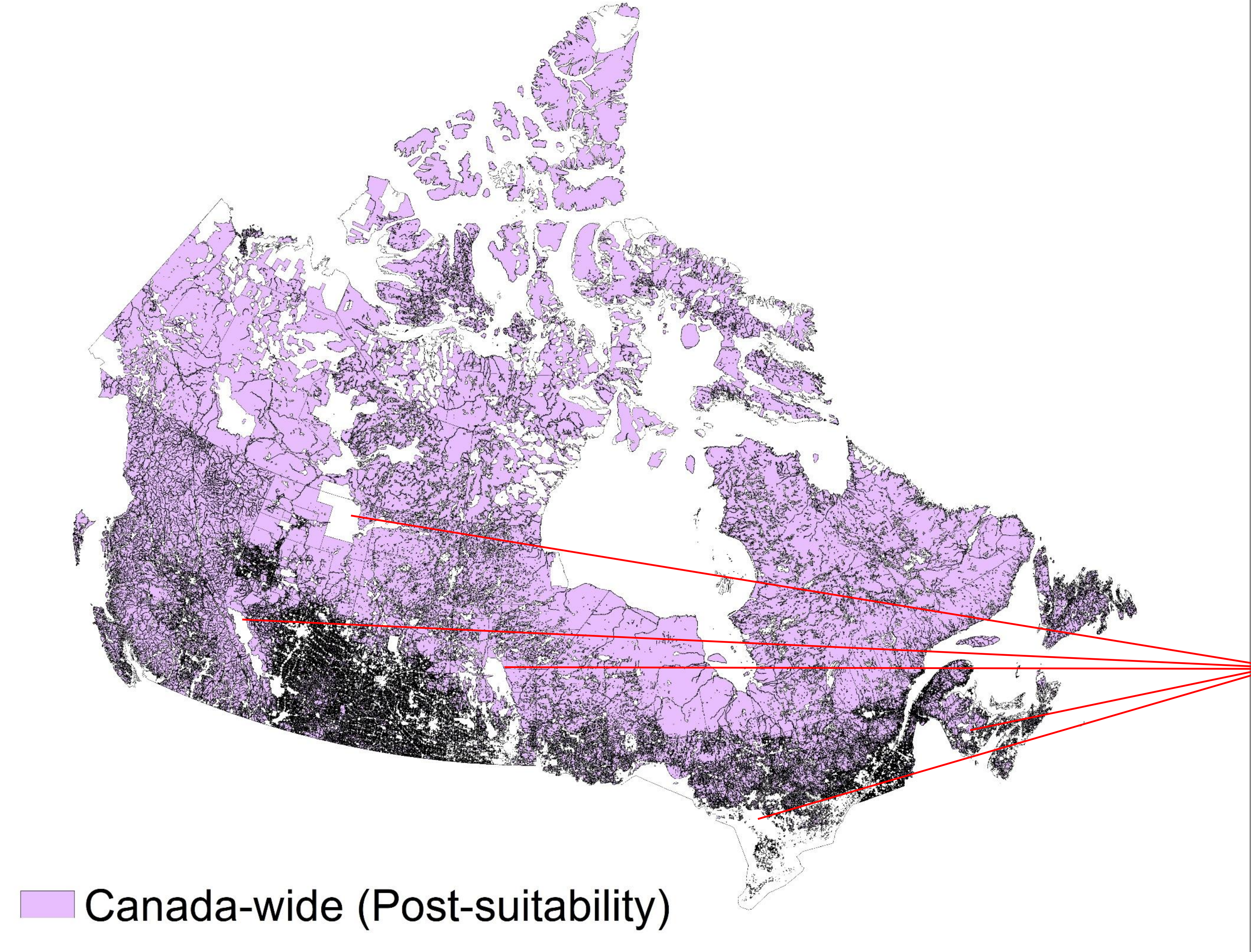
Post-suitability analysis

White spaces showing extracted unsuitable areas which contained landmarks



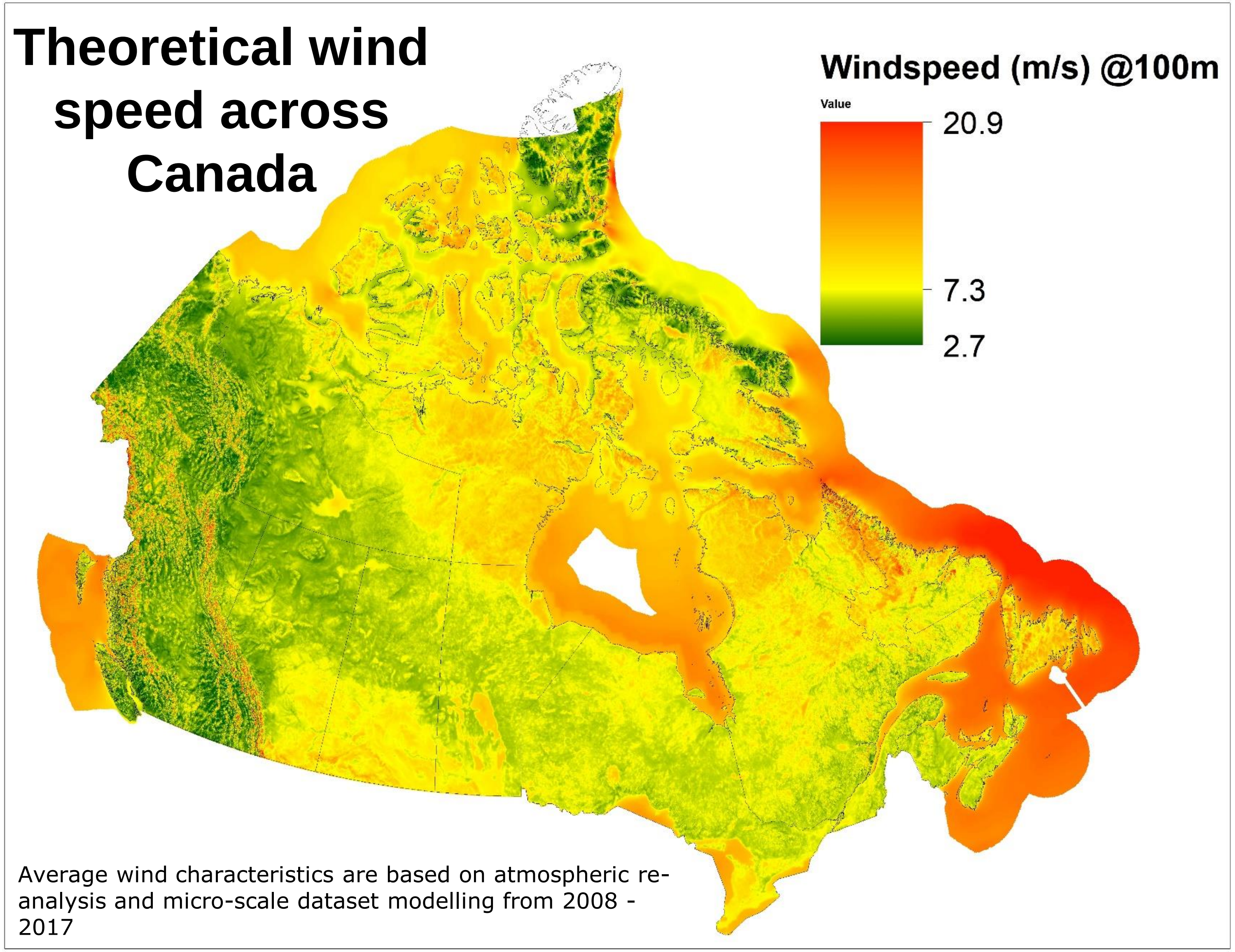
CANADA-WIDE

Post-suitability analysis



White spaces showing extracted unsuitable areas which contained landmarks

WIND-BASED HYDROGEN METHODOLOGY: WIND RESOURCE PENETRATION ZONING

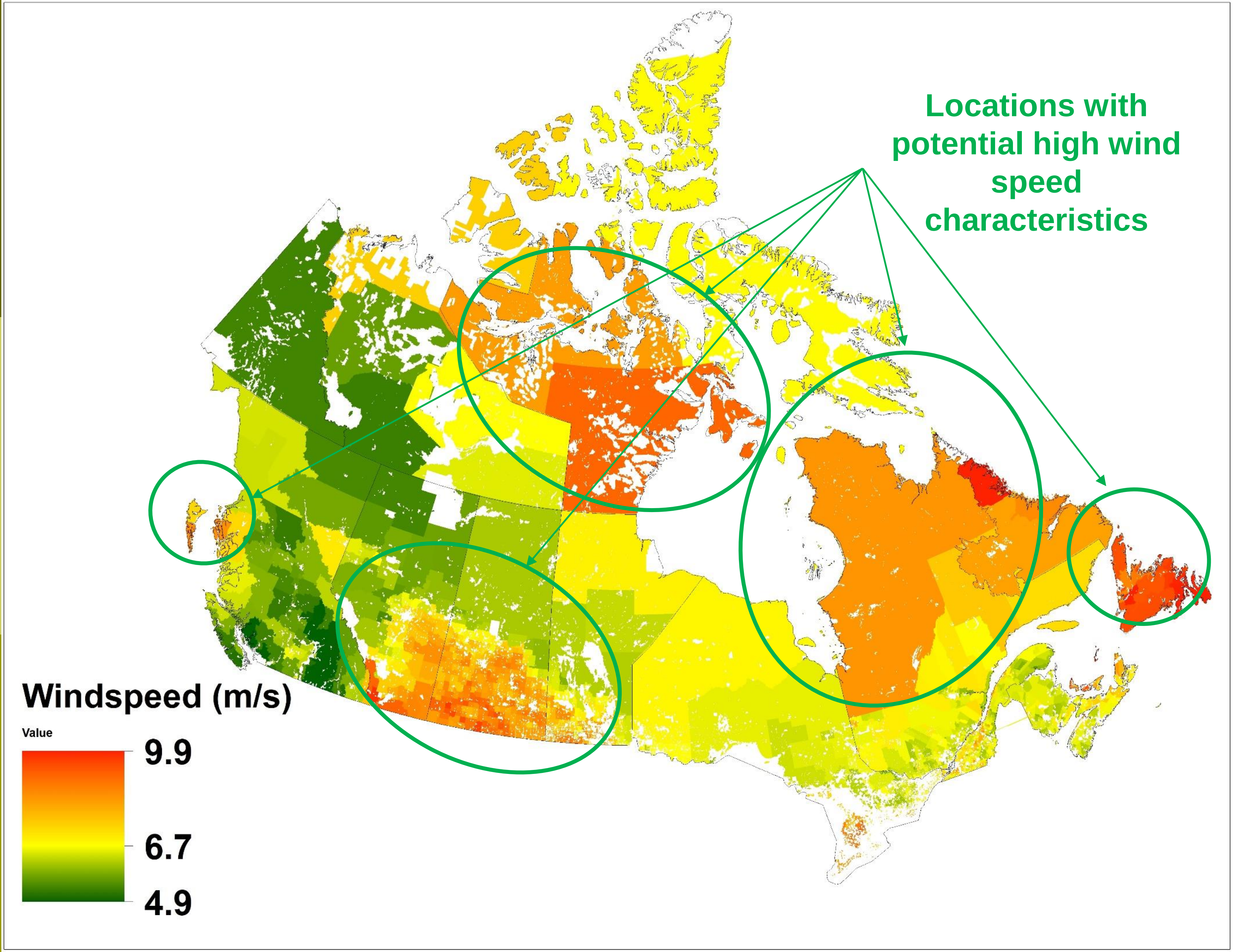


OBJECTIVES

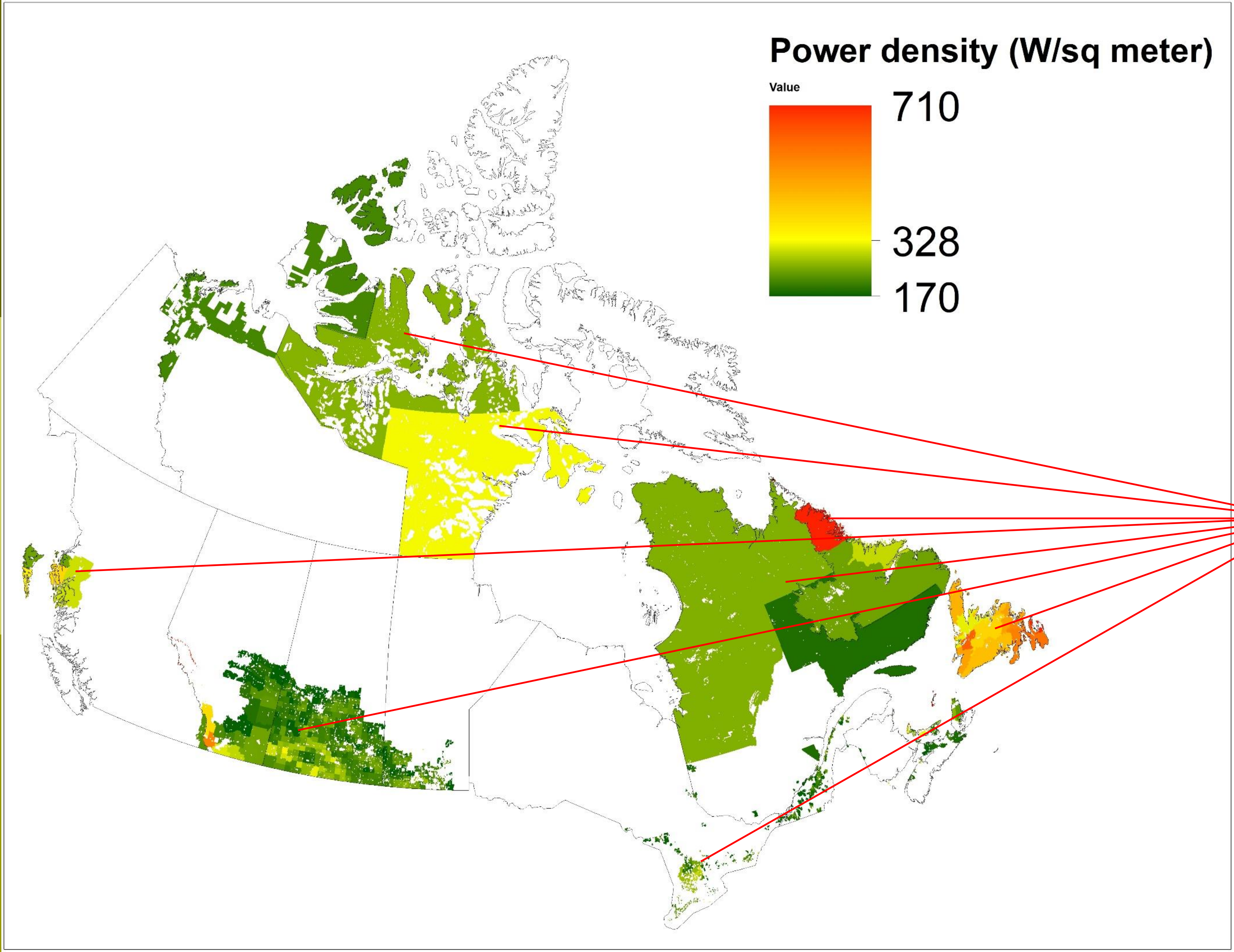
1. Zone all country-wide theoretical wind characteristics to only suitable geographical points

2. Create a layer with wind power characteristics with cut-off wind speeds $\geq$ 7m/s

1st OBJECTIVE



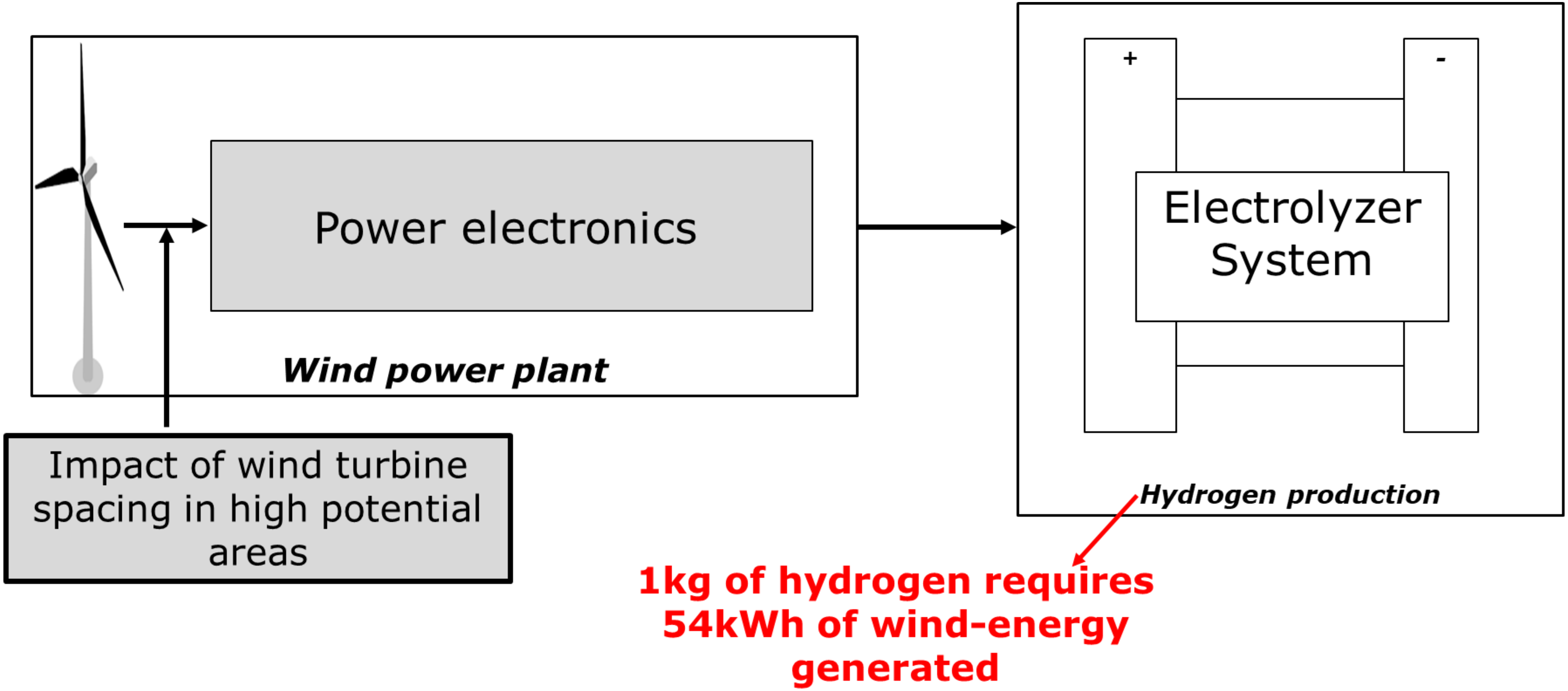
- **Windspeed analysed for Canada-wide suitable areas**
- **Onshore-wind properties only**



2nd OBJECTIVE

Suitable high potential areas with windspeed ≥ 7m/s

WIND-BASED HYDROGEN METHODOLOGY: WIND ENERGY TO HYDROGEN CONVERSION



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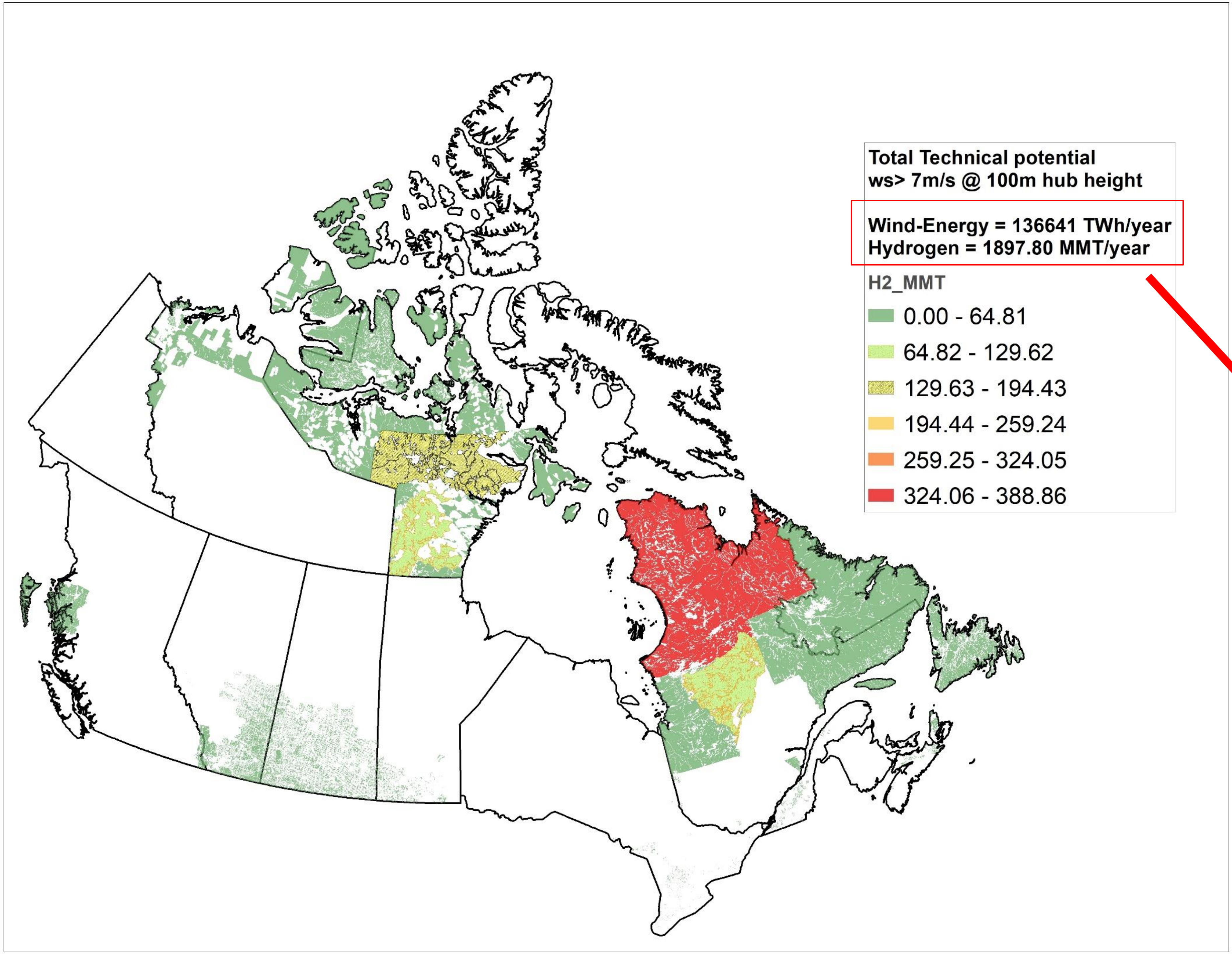
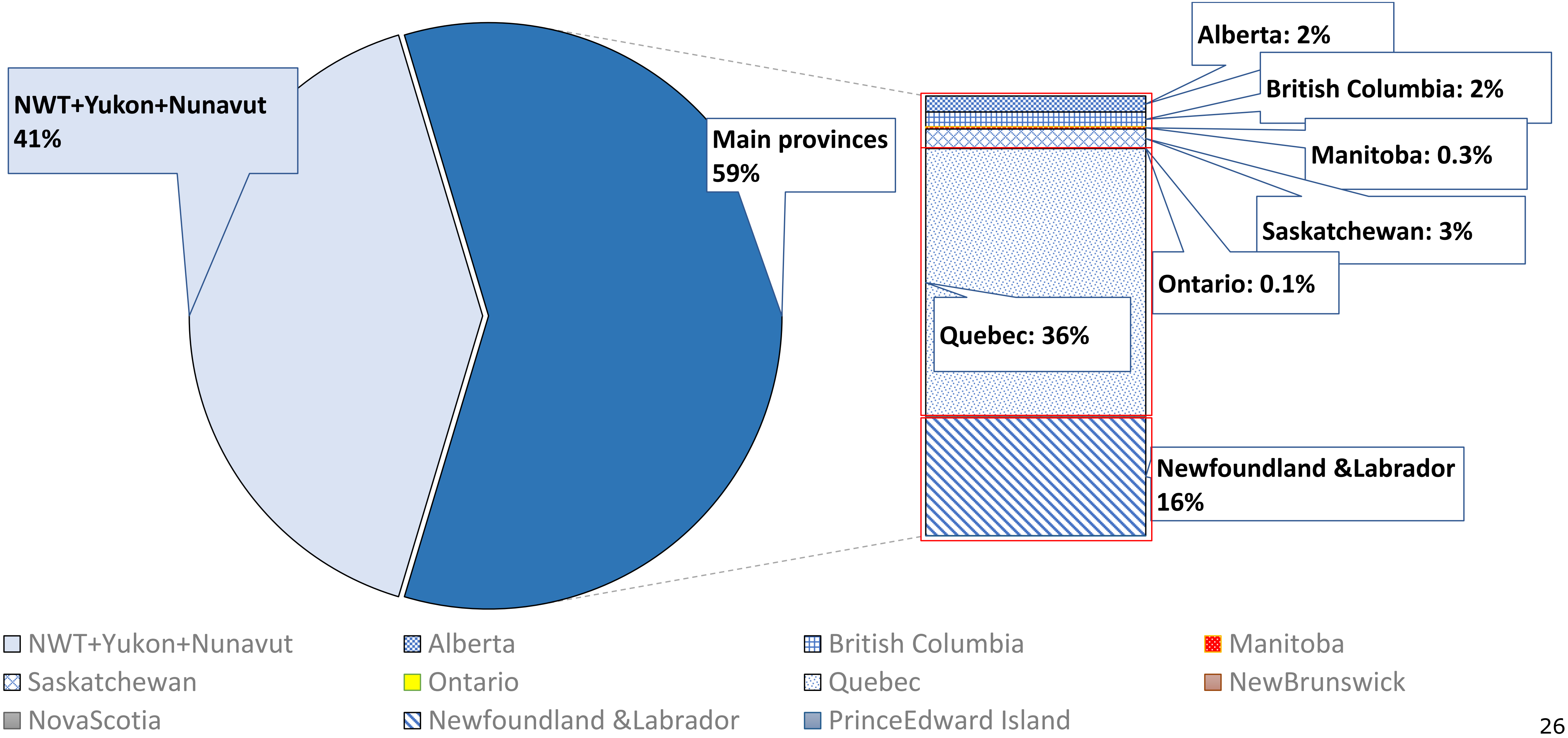


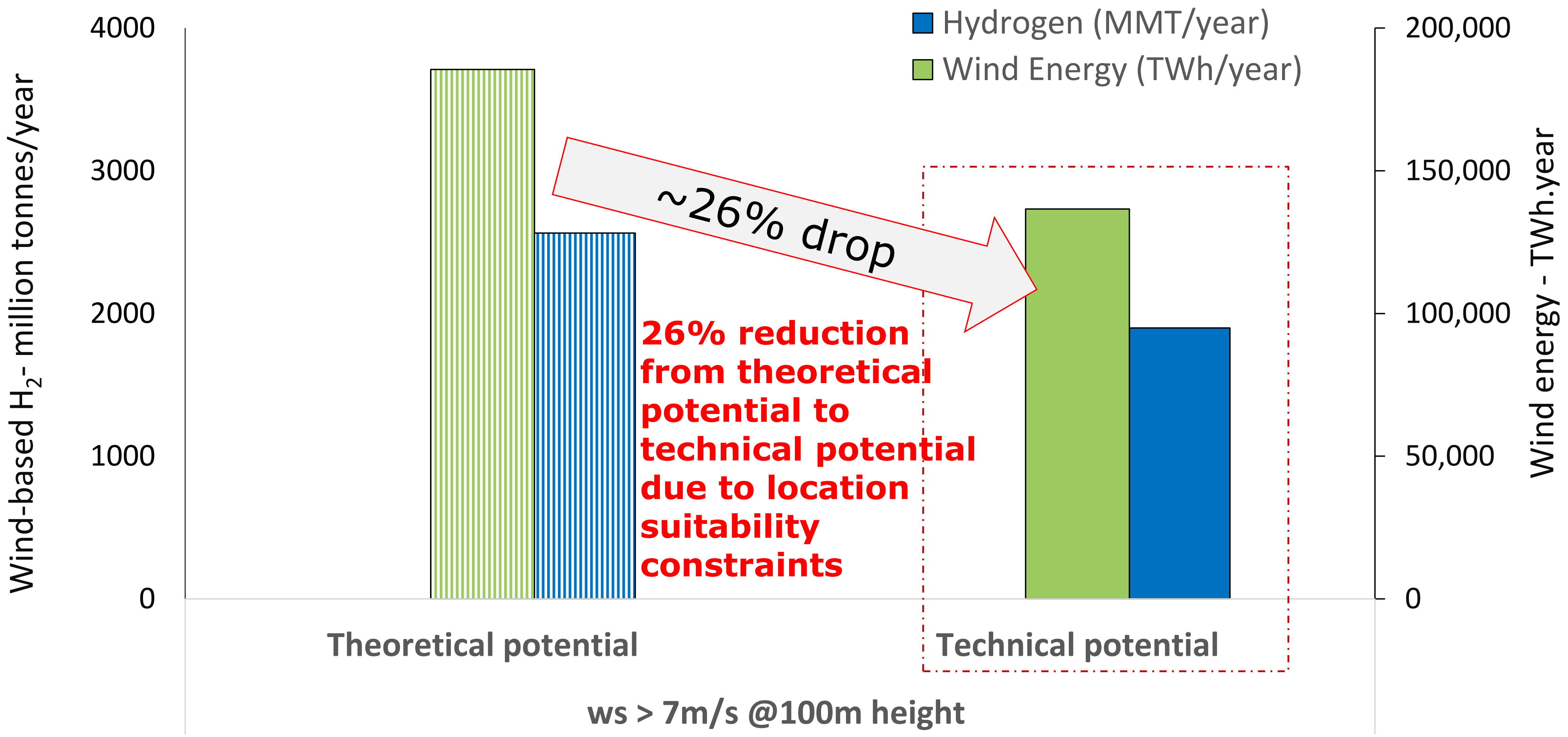
~1.9 billion tonnes of hydrogen per year

Sufficient to meet 2500% of current global annual hydrogen demand

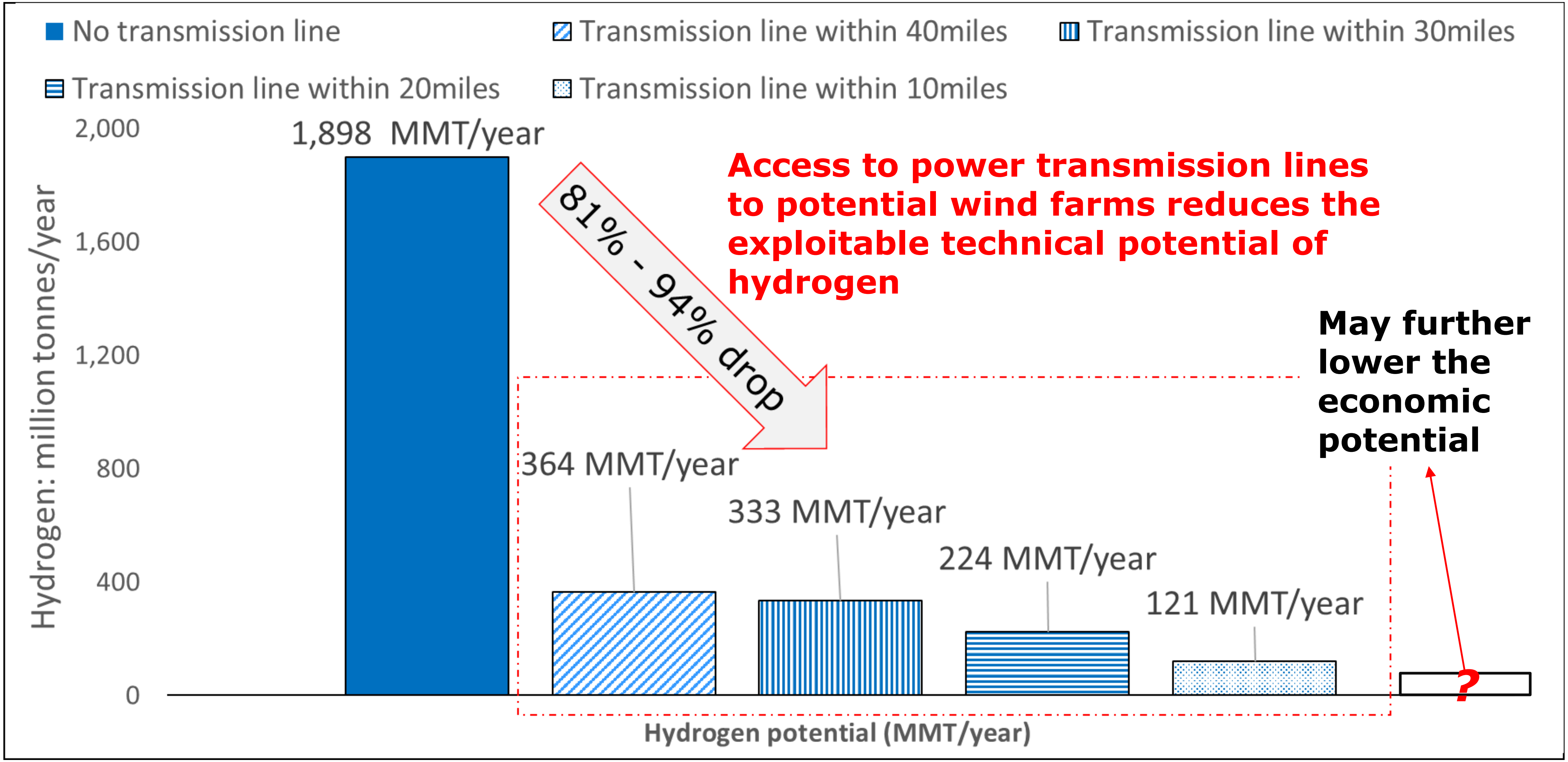
HYDROGEN POTENTIAL FROM WIND-BASED ELECTRICITY: PROVINCIAL SPREAD



HYDROGEN POTENTIAL FROM WIND-BASED ELECTRICITY: THEORETICAL VS TECHNICAL



HYDROGEN POTENTIAL FROM WIND-BASED ELECTRICITY: TRANSMISSION LINE ACCESS



TECHNICAL POTENTIAL OF HYDROGEN PRODUCTION FROM:

SOLAR-BASED ELECTRICITY (ELECTROLYTIC HYDROGEN)

SOLAR-BASED HYDROGEN METHODOLOGY: A THREE LEVEL SPATIAL ANALYSIS

Step 1. Location suitability analysis →

Identify locations across the country that are geographically suitable for solar-farms

Step 2. Resource penetration zoning →

Analysis of high cut-off solar characteristics to suitable locations

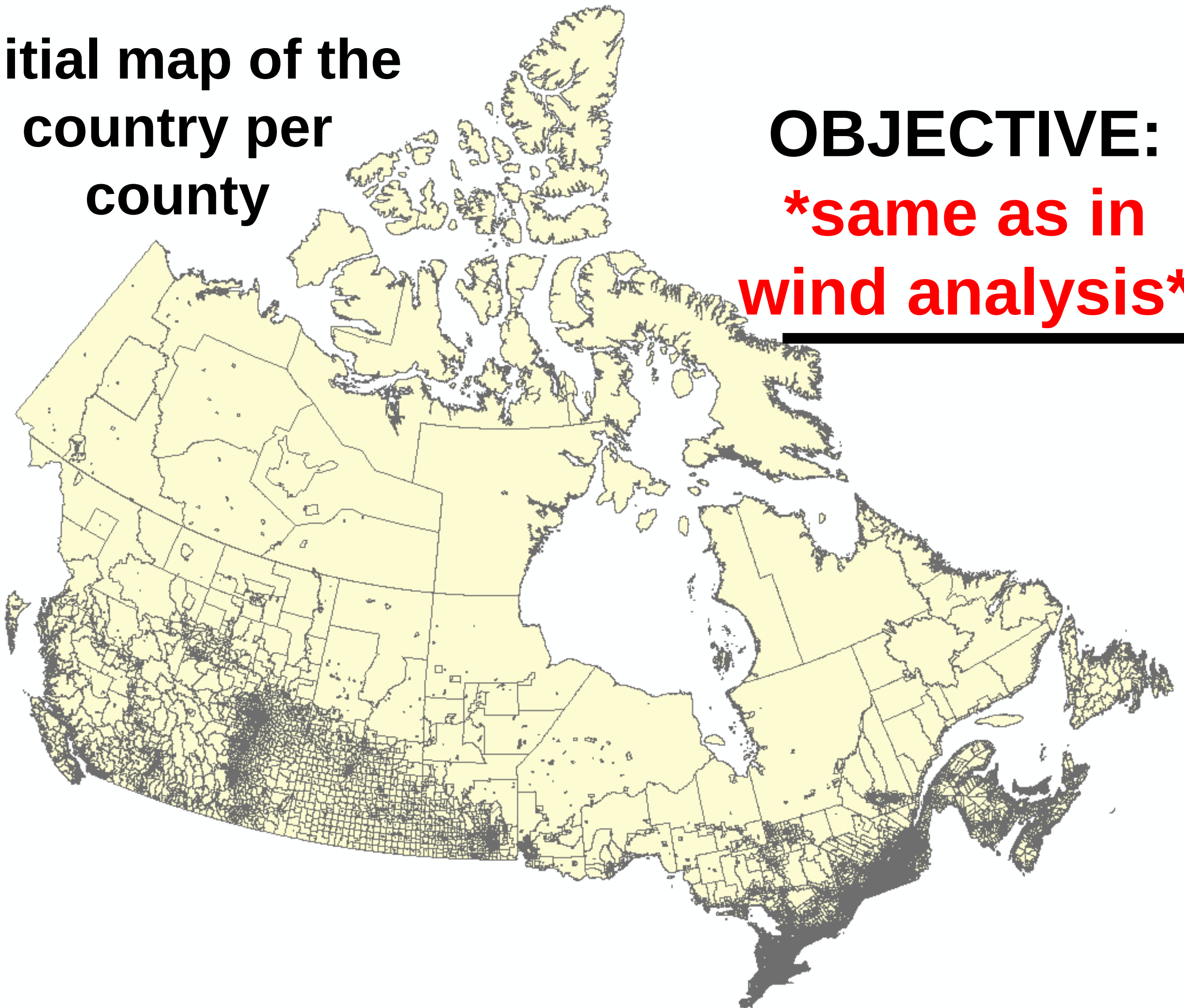
Step 3. Solar energy to hydrogen conversion

Technical analysis calculations for hydrogen production

- The Global tilted irradiation (kWh/m^2) is used: GTI incorporates better ground reflection.
- High solar photovoltaic yield (output) cut-off set at 1400kWh/kW
- Dataset does not cover the northern regions
- No Rooftop-solar: building footprint area < 0.1% of suitable area

SOLAR-BASED HYDROGEN METHODOLOGY: LOCATIONAL SUITABILITY ANALYSIS

Initial map of the country per county



OBJECTIVE:
same as in wind analysis

To extract suitable geographical areas far away from landmarks:

- Rivers & Coastal water
- Buildings
- Population clusters
- Streets/Avenues
- Designated places
- Highways
- Roads
- Forests
- Parks

SOLAR-BASED HYDROGEN METHODOLOGY: LOCATIONAL SUITABILITY ANALYSIS

Add a setback distance (from literature) for each landmark where a solar farm cannot be built

same as in wind analysis

LANDMARK	SETBACK DISTANCE
Buildings	2000 meters
Population clusters	2000 meters
Streets/Avenues	5000 meters
Designated places	1000 meters
Highways	2000 meters
Roads	1000 meters
Forests	1000 meters
Rivers & Coastal waters	500 meters
Parks	150 meters

Removed all setback distances (area) for the landmarks

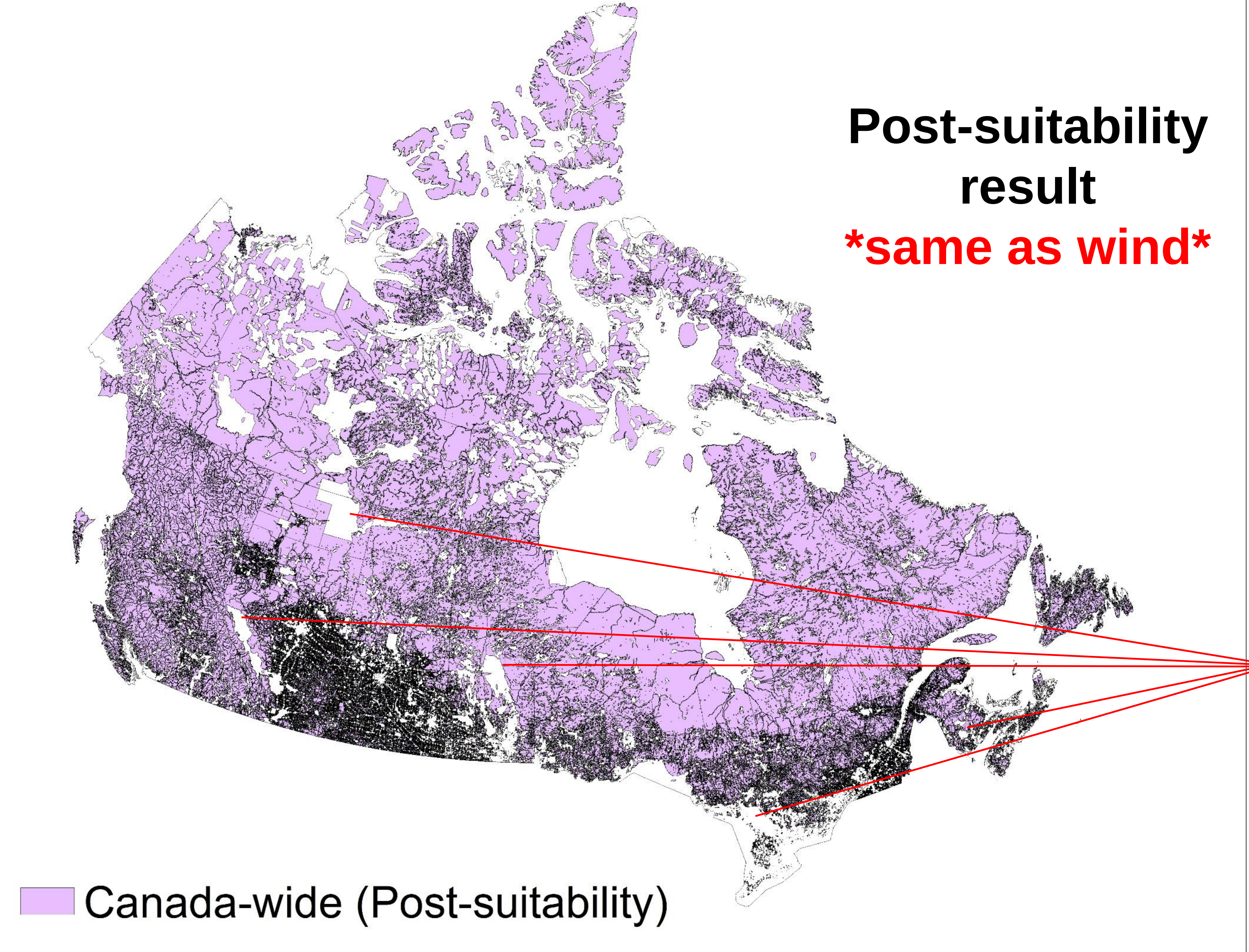
OUTPUT

Only geographical suitable land areas across the country remain

CANADA-WIDE

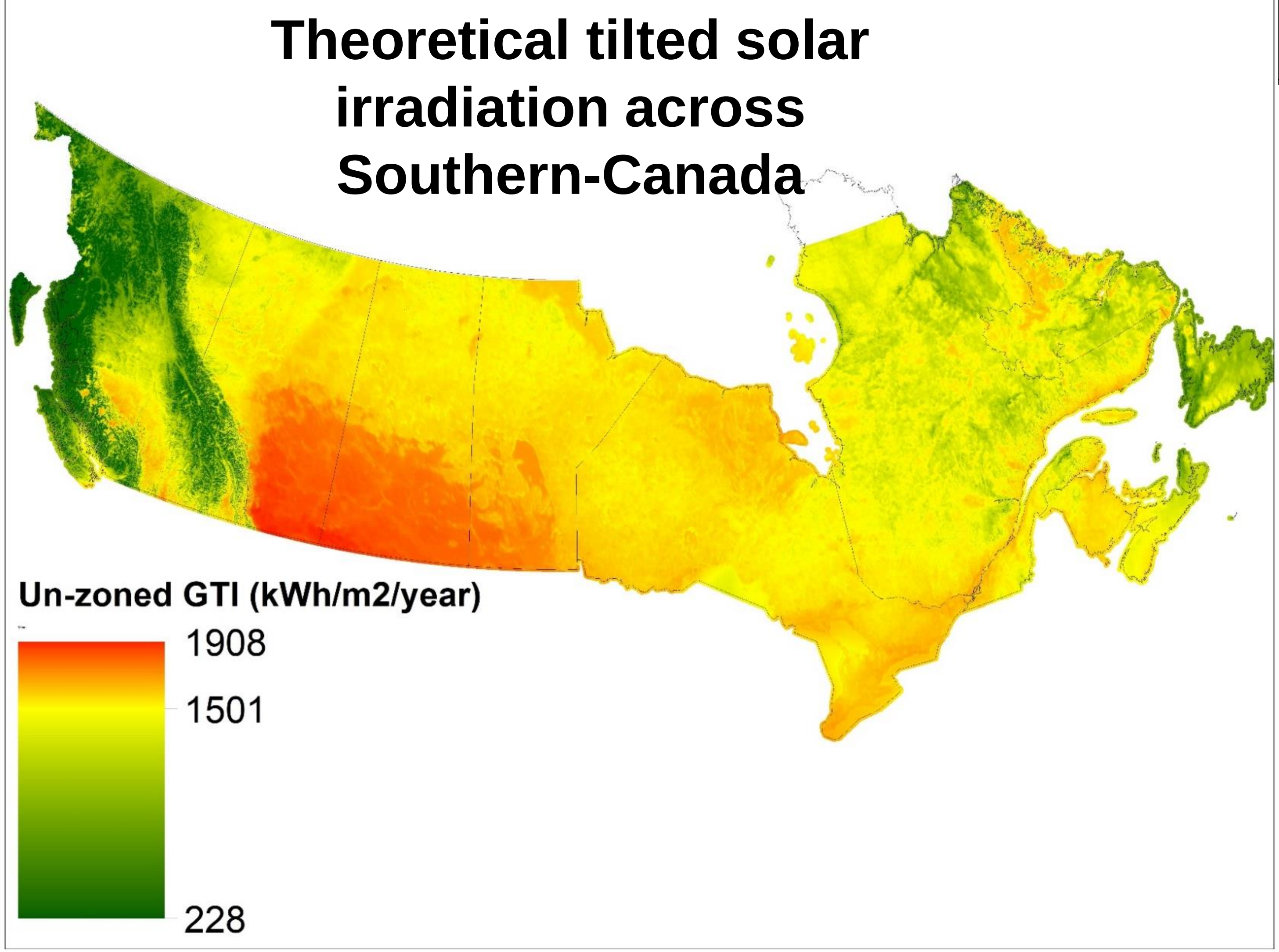
Post-suitability result

same as wind



White spaces showing extracted unsuitable areas which contained landmarks

SOLAR-BASED HYDROGEN METHODOLOGY: SOLAR RESOURCE PENETRATION ZONING

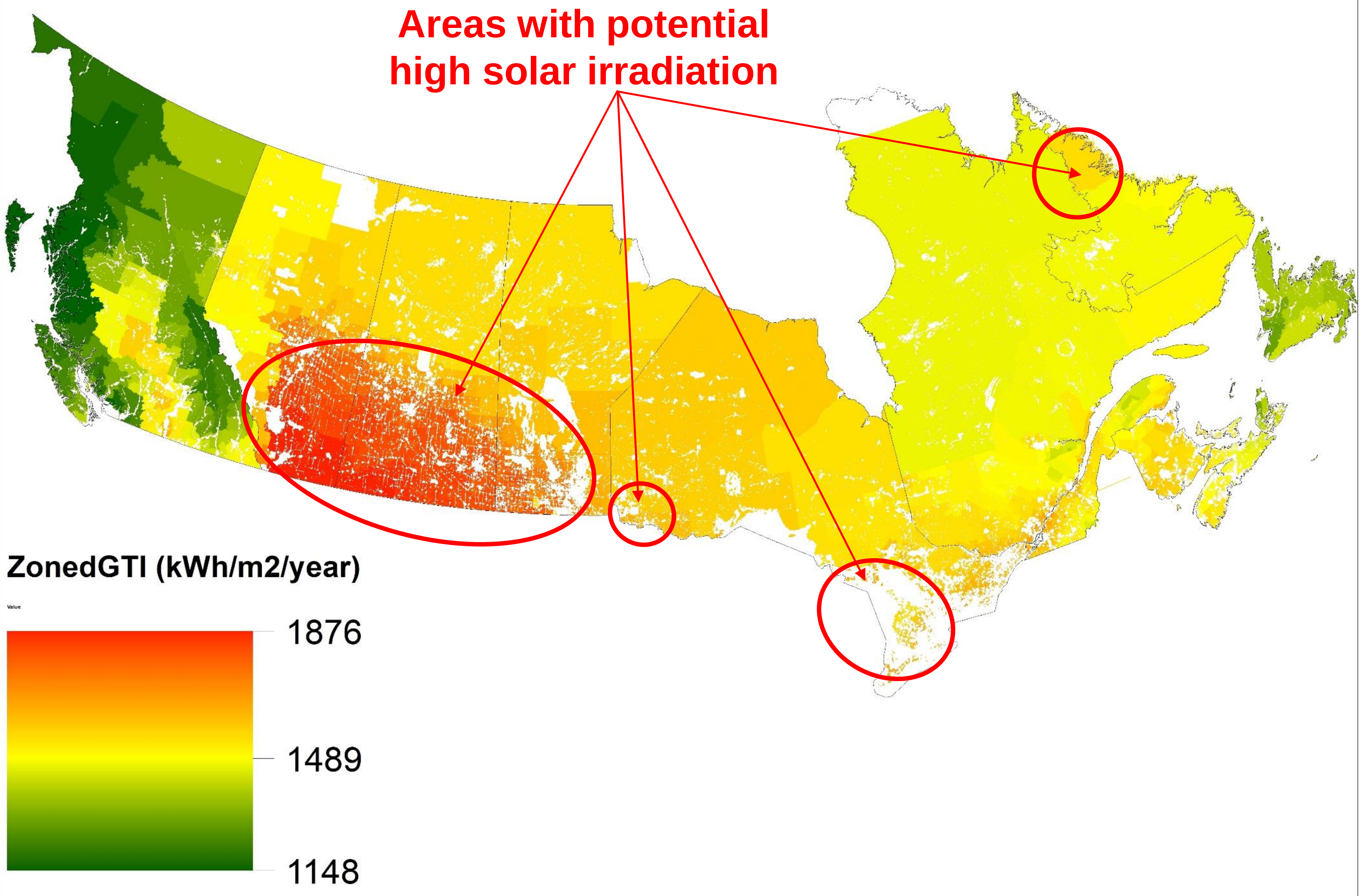


OBJECTIVES

1. Zone all country-wide theoretical solar irradiation characteristics to only suitable geographical points

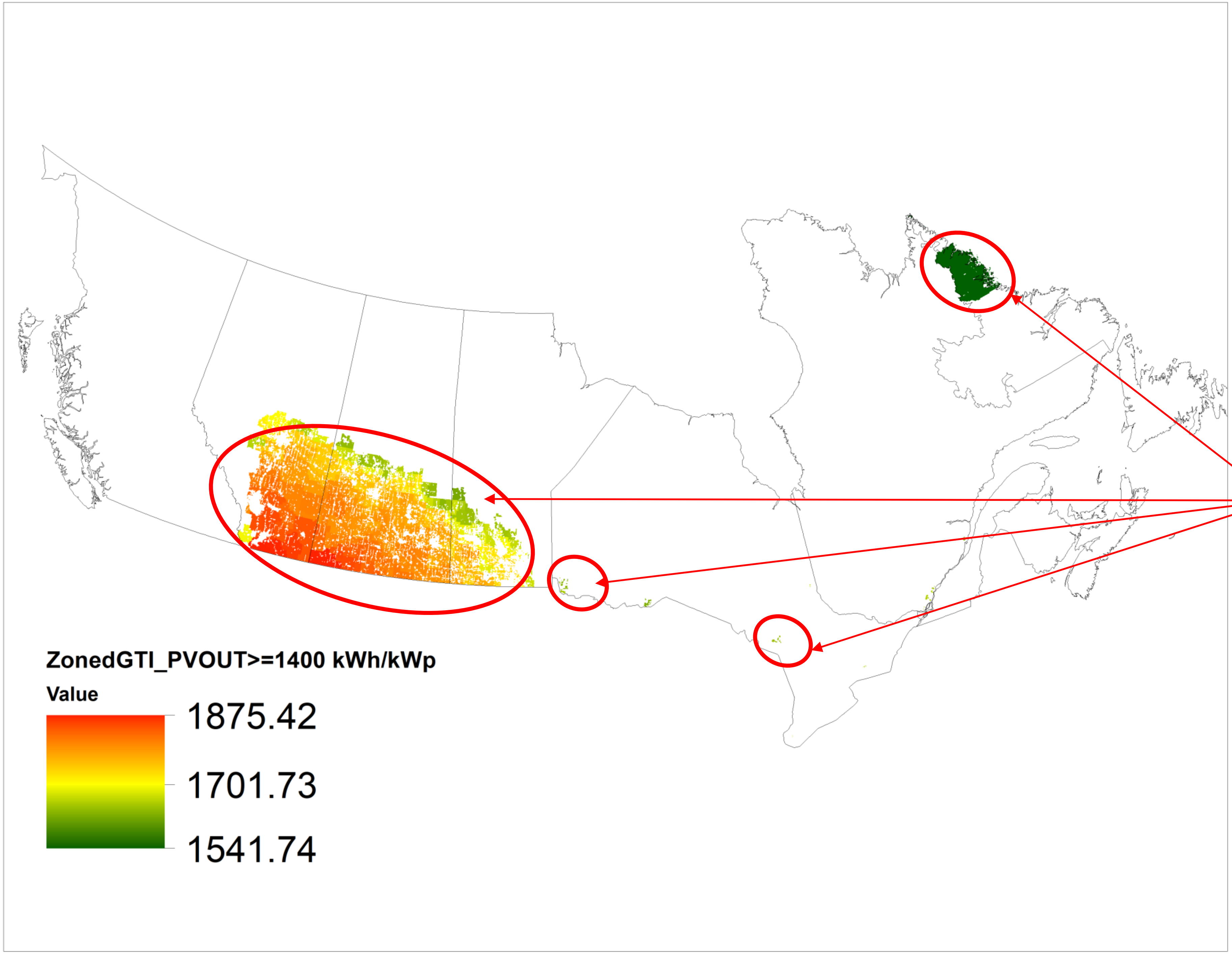
2. Create a layer with solar power characteristics with cut-off solarPV yield ≥ 1400kWh/kW

1st OBJECTIVE



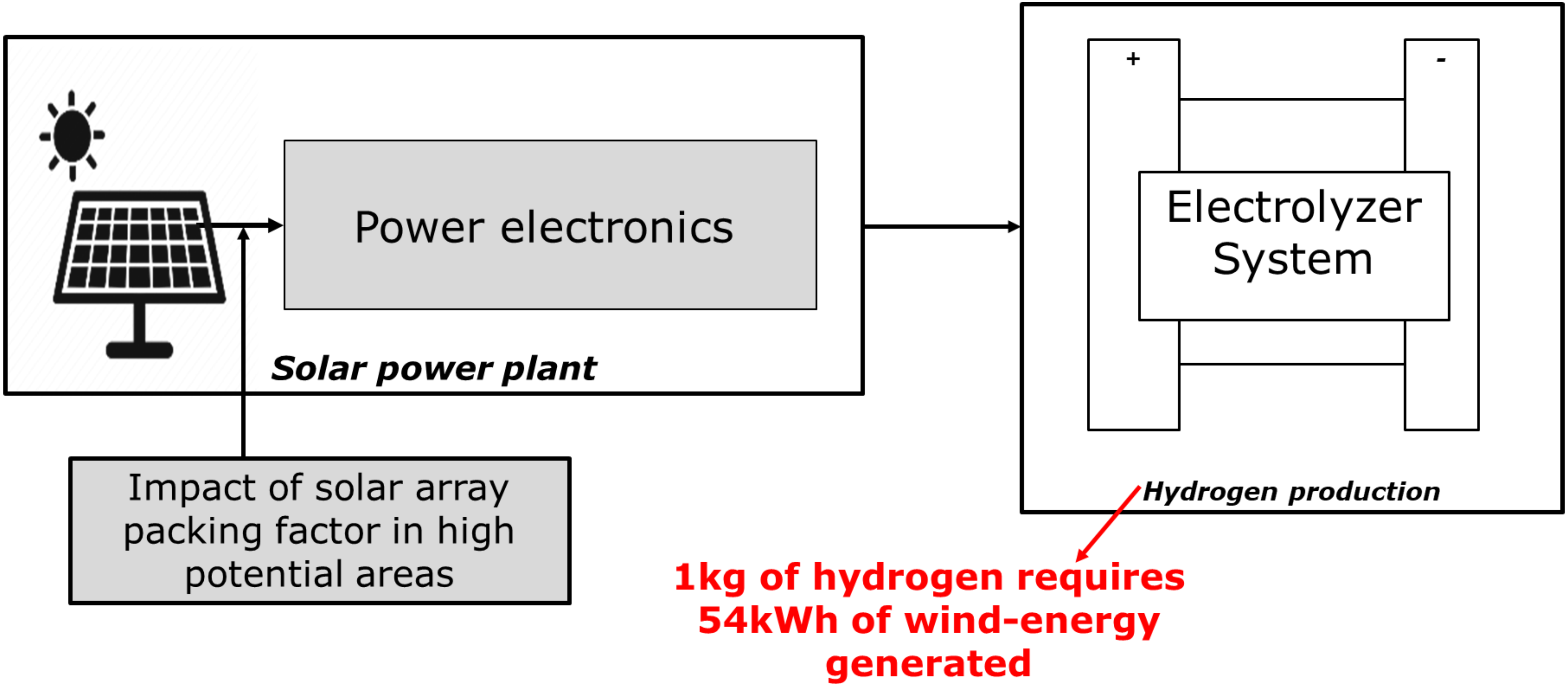
- **Tilted solar irradiation analysed for Canada-wide suitable areas**

2nd OBJECTIVE



High solar irradiation with solarPV yield ≥ 1400kWh/kW

SOLAR-BASED HYDROGEN METHODOLOGY: SOLAR ENERGY TO HYDROGEN CONVERSION



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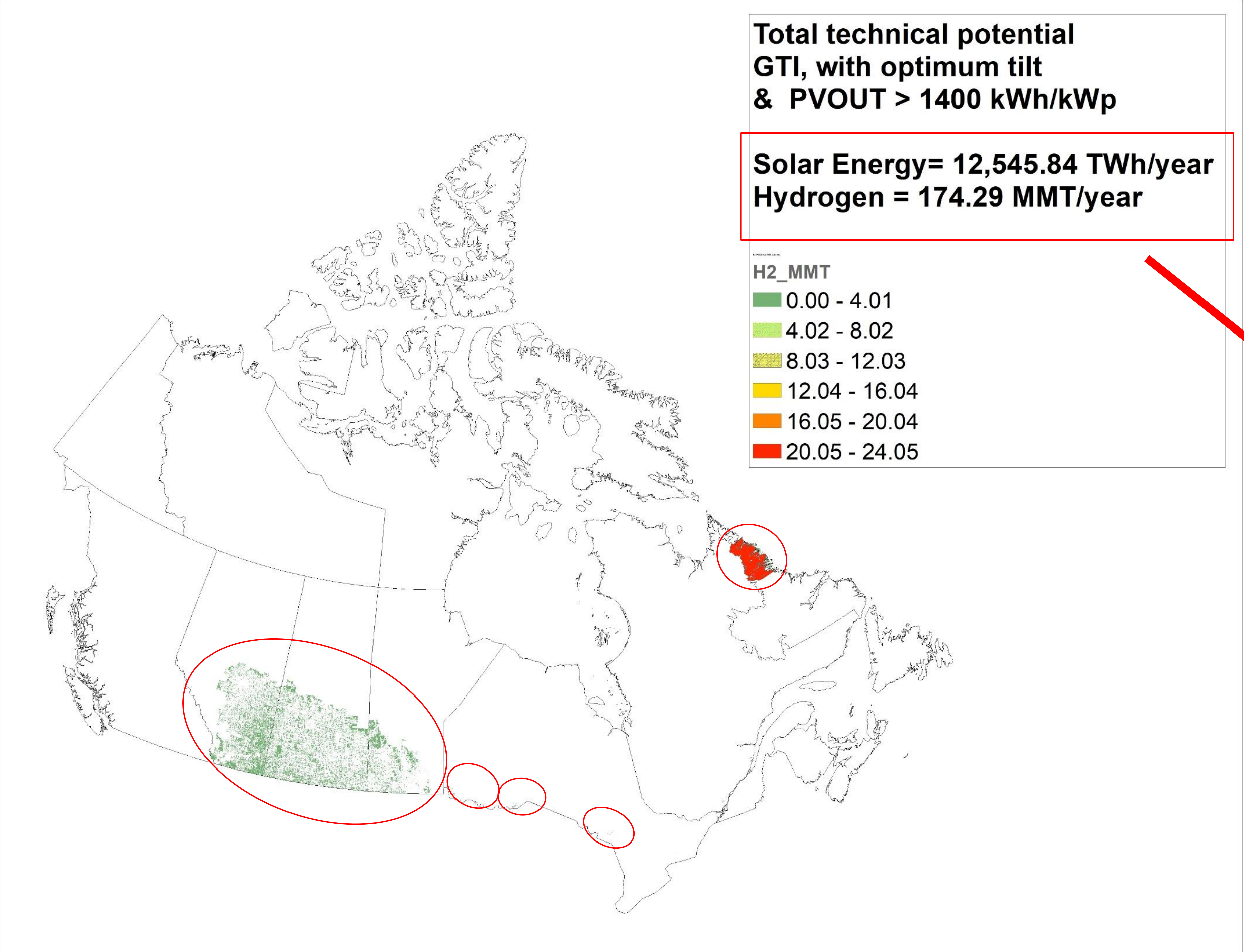
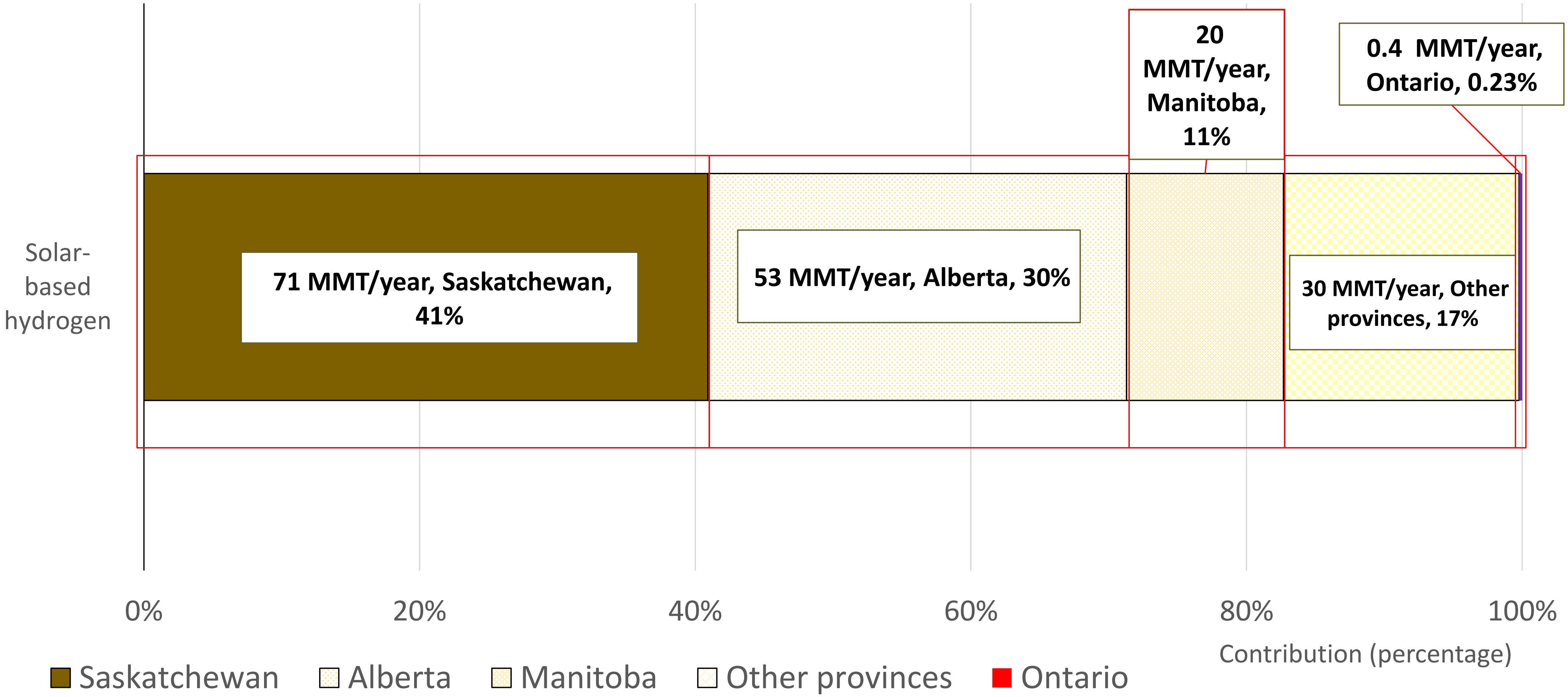


~174 million tonnes of hydrogen per year

Sufficient to meet 236% of current global annual hydrogen demand

HYDROGEN POTENTIAL FROM SOLAR-BASED ELECTRICITY: PROVINCIAL SPREAD



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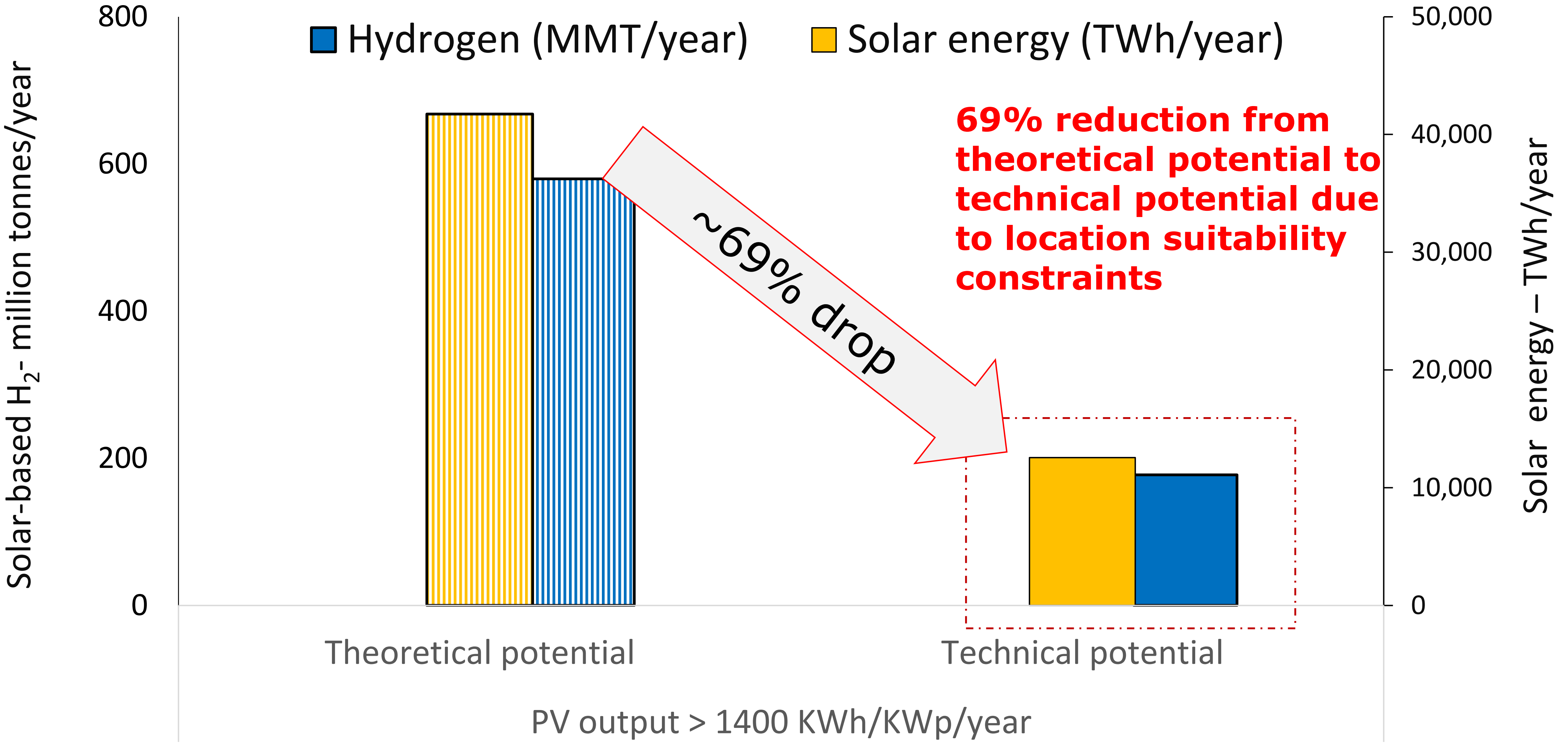
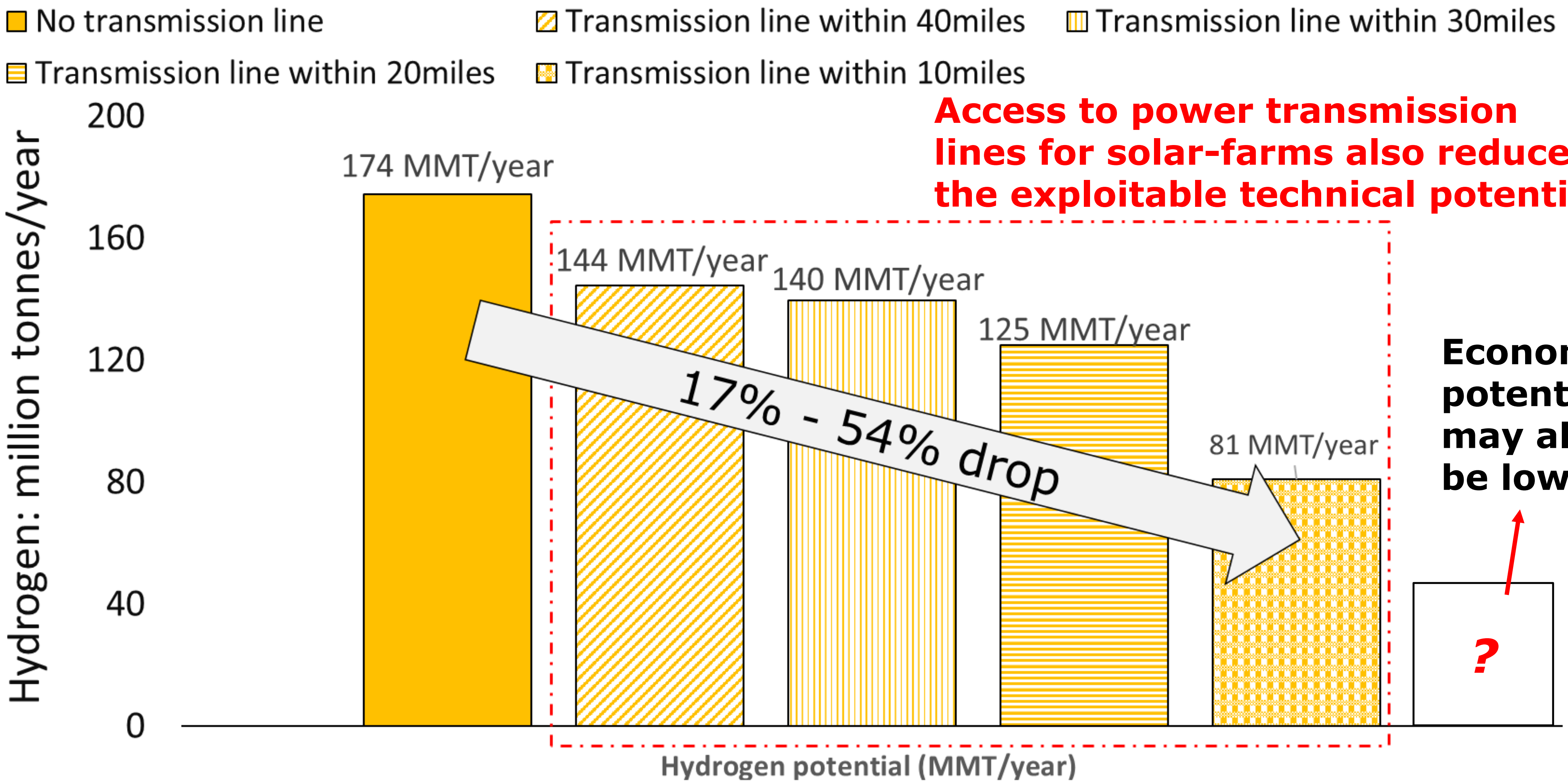


HYDROGEN POTENTIAL FROM SOLAR-BASED ELECTRICITY: TRANSMISSION LINE ACCESS



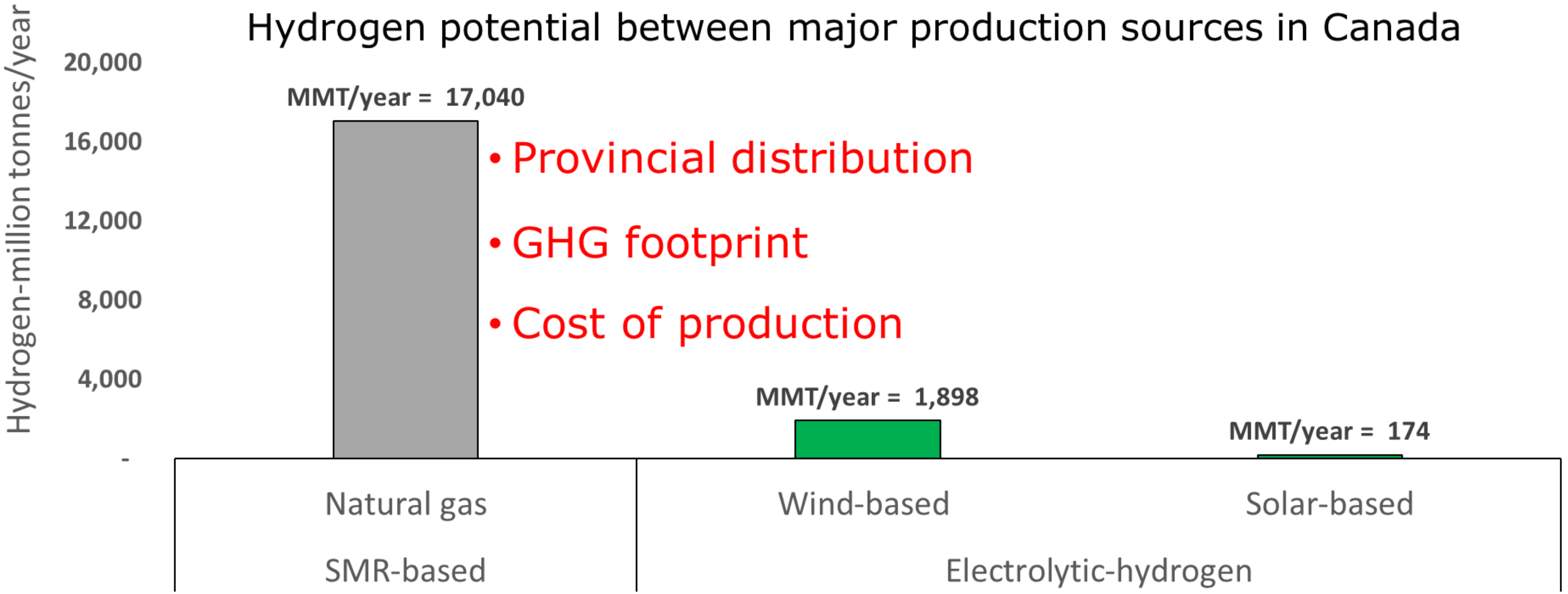
Access to power transmission lines for solar-farms also reduces the exploitable technical potential

Economic potential may also be lowered

TECHNICAL POTENTIAL OF HYDROGEN PRODUCTION: KEY OBSERVATIONS & FUTURE WORK

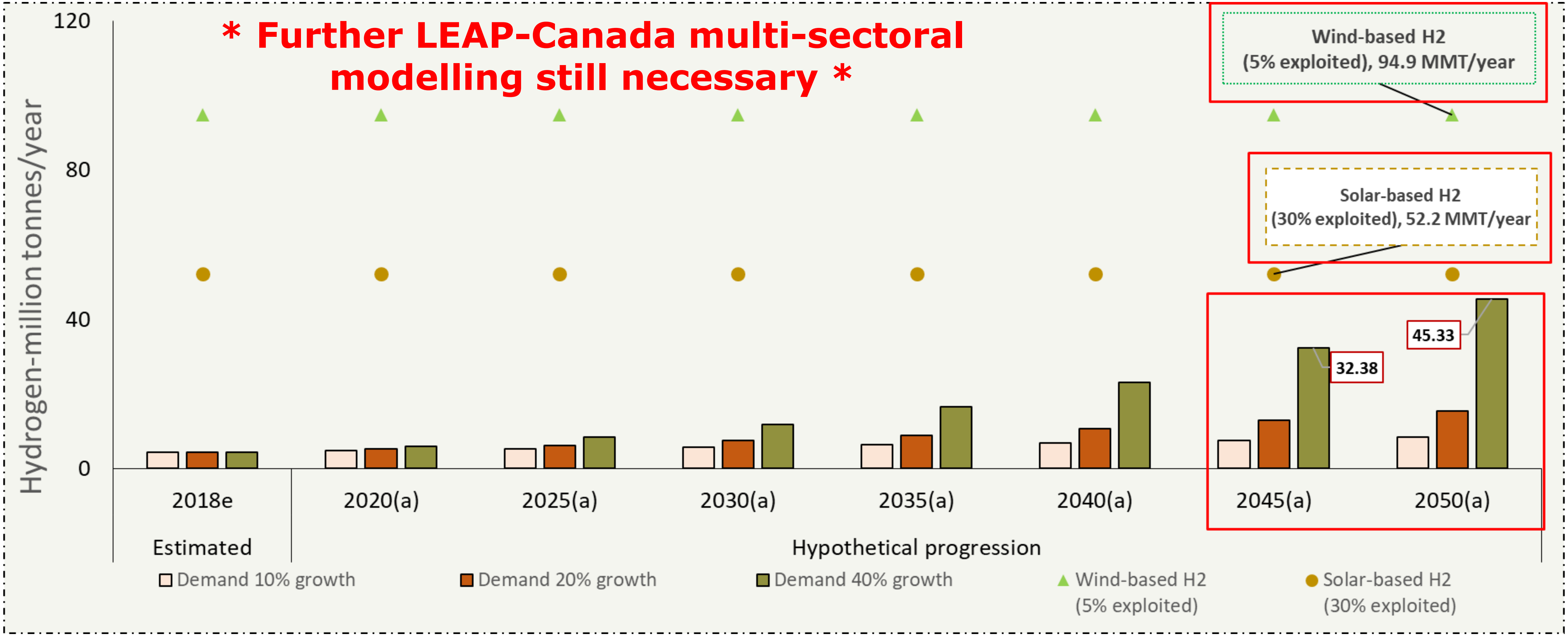
KEY OBSERVATION: HYDROGEN TECHNICAL POTENTIAL

- Hydrogen technical potential from resource-level natural gas is ~ 9x greater than from cleaner RE-based production.



KEY OBSERVATION: HYDROGEN POTENTIAL FROM WIND & SOLAR-BASED ELECTRICITY

- ~5-30% of feasible hydrogen technical potential from wind and solar-based electricity can meet long-term country-wide demand.



FUTURE WORK

- Constraint analysis for electrolytic hydrogen:
  - Access to water bodies (rivers or lakes)
  - Access Natural gas pipeline
- Quantify the hydrogen production potential from other production pathways.
- Techno-economic analysis for multi-sectoral hydrogen diffusion with LEAP-Canada.
- LEAP-Canada modelling of long-term GHG abatement potential and abatement cost for hydrogen.

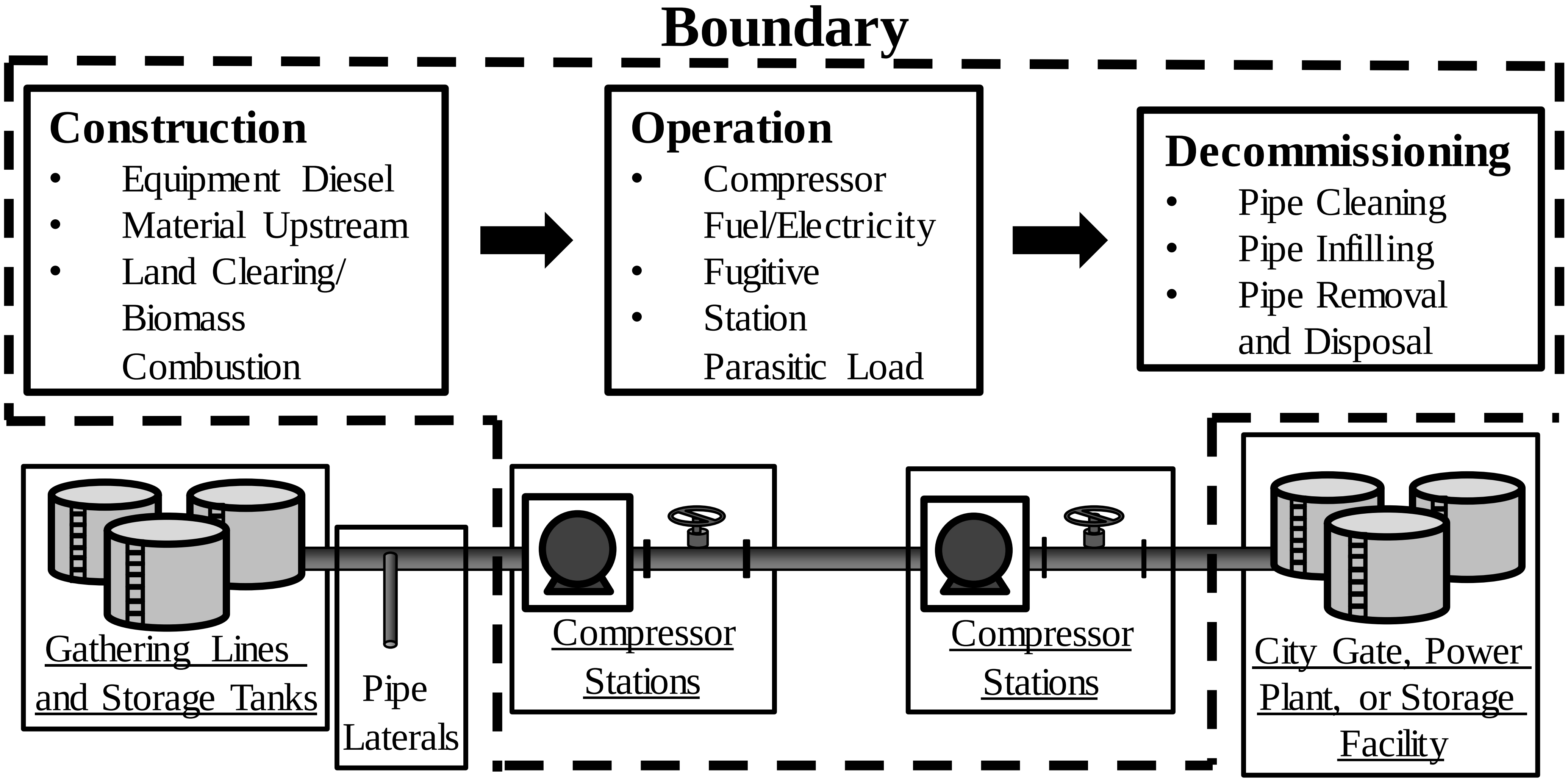
GHG Emissions in Transporting Hydrogen through Natural Gas Pipelines: Hythane

FUNNEL-GHG-NGTL MODEL AND NG+H_2 MIXTURES (HYTHANE)

BACKGROUND

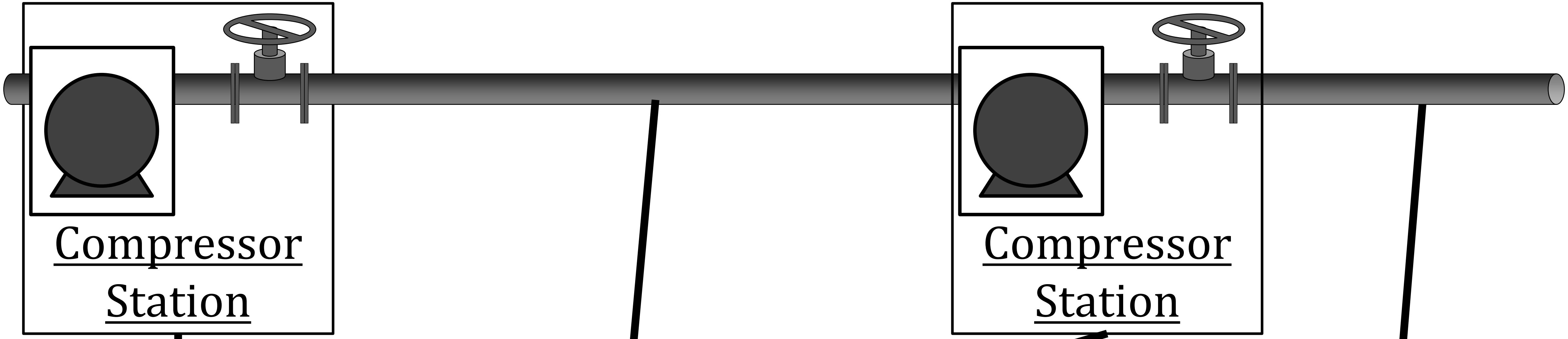
- NG demand is expected to increase by 40% from 2015 to 2040
- Pipeline proposals are being presented to the federal government
- Transportation stage contributes
  - 8-40% of pre-combustion emissions
  - Up to 8% of well-to-combustion (WTC) emissions
- Current literature results are high level and not pipeline-specific
  - Uses aggregated data or a high-level analysis with limited scope
- Gaps to Address:
  - The developed model will determine pipeline-specific emissions and be able to investigate the effects of key project alternatives
  - Investigate potential of "greening" NG with H_2

FUNNEL-GHG-NGTL MODEL OVERVIEW: BOUNDARY



Giovanni Di Lullo, Abayomi Olufemi Oni, Eskinder Gemechu, Amit Kumar, Developing a greenhouse gas life cycle assessment framework for natural gas transmission pipelines, *Journal of Natural Gas Science & Engineering*, vol. 75, pp. 103-136, Jan. 2020

FUNNEL-GHG-NGTL MODEL OVERVIEW: TEMPLATE LAYOUT



Compressor Parameters	Units	User Input	Model Input
Inlet Pressure	MPa	7	6.775
Outlet (To Pipeline) Pressure	MPa	9.93	9.93
Flowrate	m3/hr	4,245,833	4,234,574
Cooler Pressure Drop	%	0.75%	
Scrubber Pressure Drop	MPa	0.2	
Facility Piping Pressure Drop	MPa	0.05	
Max CR		N/A	
# Stages		1	1
CR			1.47
Flowrate Change (+) enters pipe	m3/hr	0	
Fuel taken from pipeline?	Yes/No	Yes	
Interstage Cooler Outlet Temp	C	40	
Polytropic Efficiency		78%	
Compressor Mechanical Efficiency		98%	
Max / Total Power	kW/station	52,800	32,920
Turb Eff. (pipe gas used) or Grid ele	% or g/kWh	0.35	
Fuel Consumption	m3/hr		11,260
Electricity Consumption	kWh/hr		0
Compressor Type /Fugitive Methan	gCH4/hr	Cent.	1.06E+05

Pipe Section Parameters	Units	User Input	Model Input
Inlet Pressure	MPa	9.93	9.93
Outlet Pressure	MPa	Solve	7.43
Flowrate	m3/hr	4,234,574	4,234,574
Inner Diameter/Gas Outlet Temp	mm/K	1219.0	299.89
Parallel?		No	FALSE
Parallel Diameter	mm		0
Parallel flowrate guess	%		0
Length	km	87.0	
Absolute Roughness	m	1.00E-05	
ΔElevation (+ uphill)	m	307	
Pipeline Efficiency		95%	
Gas Inlet Temperature	K	313.15	
Ground Temperature	K	283	
Gas Viscosity	cp		1.44E-02
Max Velocity	m/s	10-13m/s	12.70
Average Pressure drop	kPa/km	aim for 15-35	28.78
Pipe Thickness / Steel Volume	mm/m3	20.0	6,773
Pipe Volume	m3		101,535

Compressor Parameters	Units	User Input	Model Input
Inlet Pressure	MPa	7.43	7.201054845
Outlet (To Pipeline) Pressure	MPa	9.93	9.93
Flowrate	m3/hr	4,234,574	4,225,150
Cooler Pressure Drop	%	0.75%	
Scrubber Pressure Drop	MPa	0.2	
Facility Piping Pressure Drop	MPa	0.05	
Max CR		N/A	
# Stages		1	1
CR			1.38
Flowrate Change (+) enters pipe	m3/hr	0	
Fuel taken from pipeline?	Yes/No	Yes	
Interstage Cooler Outlet Temp	C	40	
Polytropic Efficiency		78%	
Compressor Mechanical Efficiency		98%	
Total Power	kW/station	52,800	27,257
Turb Eff. (pipe gas used) or Grid ele	% or g/kWh	0.35	
Fuel Consumption	m3/hr		9,423
Electricity Consumption	kWh/hr		0
Compressor Type /Fugitive Methan	gCH4/hr	Cent.	1.06E+05

Pipe Section Parameters	Units	User Input	Model Input
Inlet Pressure	MPa	9.93	9.93
Outlet Pressure	MPa	Solve	7.27
Flowrate	m3/hr	4,225,150	4,225,150
Inner Diameter/Gas Outlet Temp	mm/K	1219.0	299.01
Parallel?		No	FALSE
Parallel Diameter	mm		0
Parallel flowrate guess	%		0
Length	km	98.0	
Absolute Roughness	m	1.00E-05	
ΔElevation (+ uphill)	m	100	
Pipeline Efficiency		95%	
Gas Inlet Temperature	K	313.15	
Ground Temperature	K	283	
Gas Viscosity	cp		1.44E-02
Max Velocity	m/s	10-13m/s	12.98
Average Pressure drop	kPa/km	aim for 15-35	27.18
Pipe Thickness / Steel Volume	mm/m3	20.0	7,629
Pipe Volume	m3		114,373

Giovanni Di Lullo, Abayomi Olufemi Oni, Eskinder Gemechu, Amit Kumar, Developing a greenhouse gas life cycle assessment framework for natural gas transmission pipelines, *Journal of Natural Gas Science & Engineering*, vol. 75, pp. 103-136, Jan. 2020

FUNNEL-GHG-NGTL MODEL OVERVIEW: CALCULATIONS

- Governed by compressible gas flow
- Custom Excel functions allow iterative calculations
  - Z factor using Peng-Robinson equation of state
  - Pipe friction factors
  - Outlet temperature, pressure, and parallel flowrates
    - Approximates expansion cooling

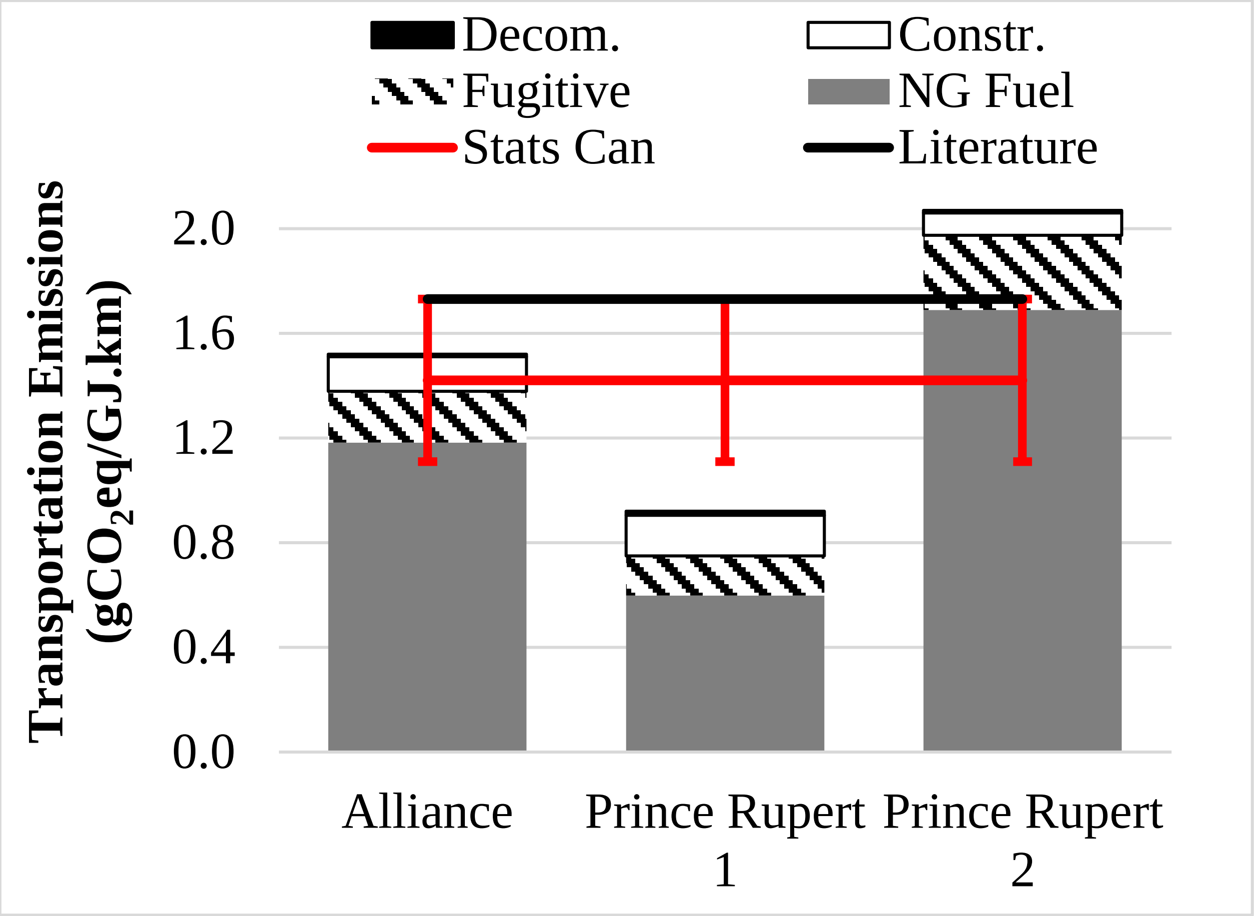
FUNNEL-GHG-NGTL MODEL OVERVIEW: PIPELINES ASSESSED

Specification	Alliance Pipeline (Built)	Prince Rupert Mainline (Planned)
Composition	Rich NG	Conventional NG
Route	3,000 km, BC/AB to Chicago, 1,361 km assessed	878 km, Hudson's Hope to Prince Rupert
Capacity (million m^3/d)	47.2 – 52	56.6 (Phase 1) 101.9 (Phase 2)
Max Allowable Operating Pressure (MAOP)	12 MPa	9.9 MPa
Diameter	914 mm / 36"	1219 mm / 48"

FUNNEL-GHG-NGTL BASE CASE RESULTS: EMISSION INTENSITY

- NG fuel: 65-82%
- Fugitive: 13-16%
- Construction: 4-17%
- Decommission <2%

- StatsCan and literature are NG comb. only



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FUNNEL-GHG-NGTL BASE CASE RESULTS: VALIDATION CHECKS

- Fugitives take up less than 0.005% of gas volume

Pipeline	V_{avg} (m/s)	ΔP_{avg} (kPa/km)	Comp Power Use
Typical	**10-13**	**15-35**	**N/A**
Alliance	**6.6**	16.8	72%
Prince Rupert 1	**4.8**	**5.5**	52%
Prince Rupert 2	**9.0**	18.7	54%

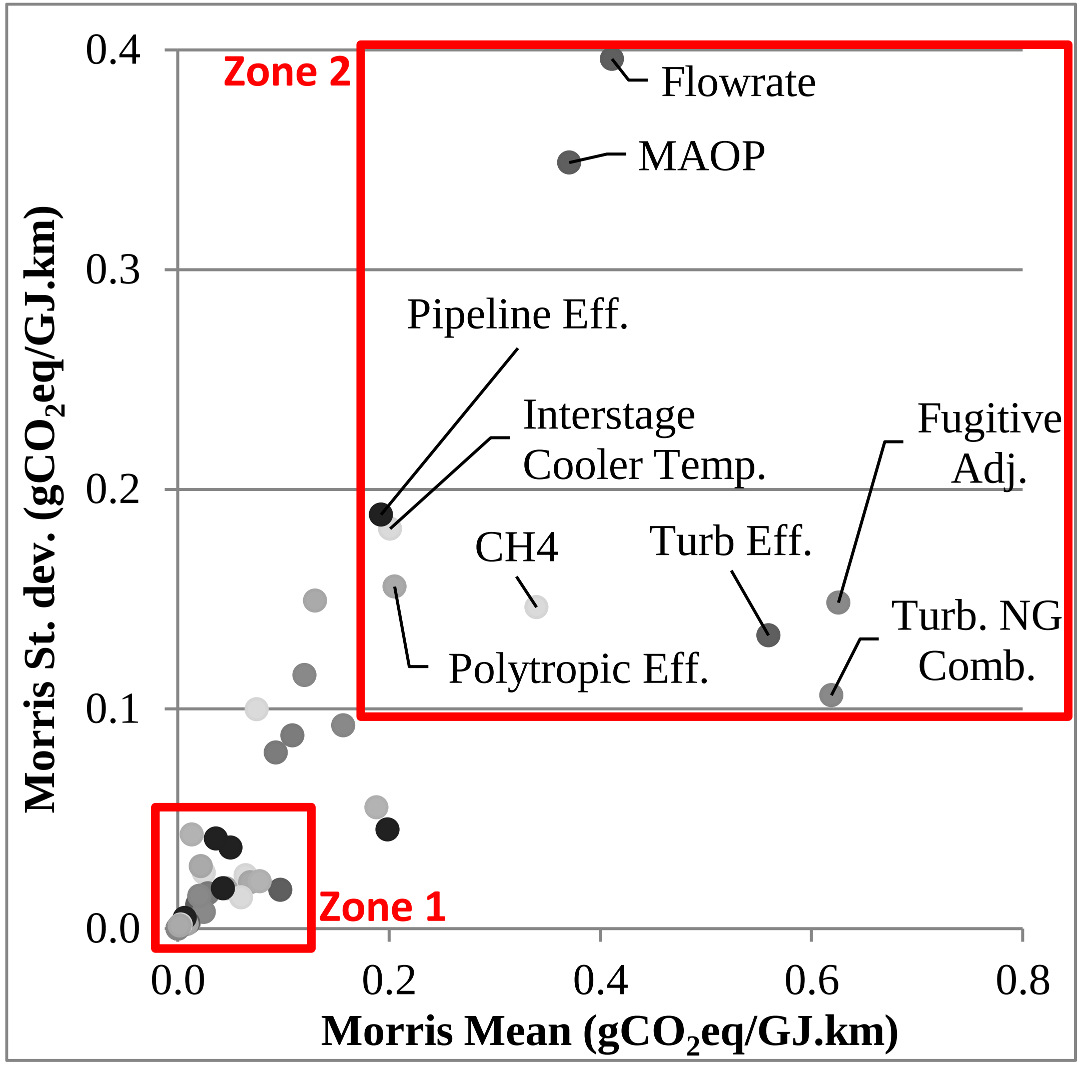
FUNNEL-GHG-NGTL BASE CASE RESULTS: VALIDATION PROCESS MODEL

- Compressor power is accurate within 1%

- Pipeline pressure drop is accurate within 4%
  - Variation due to different friction factor equations used
    - We include pipeline efficiency term to account for uncertainty in results

FUNNEL-GHG-NGTL MORRIS PARAMETER SCREENING: ALLIANCE

- Requires simple min/max ranges for each parameter
- Base case ~1.5gCO_2eq/GJ.km
- 9/55 (16%) sensitive inputs



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INJECTING H_2 INTO NG PIPELINE: KEY CONCERNS

- How to calculate Hythane properties?
- How much H_2 can pipeline handle?
- How will pipeline operation change?

H_2 PROPERTIES

- Update to more complex solver that can handle H_2 blends
  - Can calculate gas properties from composition
  - Up to 27% H_2
- Updated viscosity calculations for improved accuracy
  - Accurate ~1% for P<7MPa
  - Pipeline pressure up to 12 MPa
  - No data for higher pressure H_2 mixtures

H_2 VS. NG PROPERTIES

Energy Density	H_2	NG	
Mass Energy Density (MJ/**kg**)	**121**	**49.3**	NG **0.4** x H_2
Std. Volume Energy Density (MJ/**m³**)	**10.2**	**36.9**	NG **3.6** x H_2
12 MPa Volume Energy Density (MJ/**m³**)	**1137.9**	**5893.6**	NG **5.2** x H_2

$H_2 > CH_4$ Energy by Mass
$H_2 < CH_4$ Energy by Volume

H_2 LIMITS IN NG PIPELINES

- Limited System Adaptions: <6% H_2
- End Use Appliances: 10-15% H_2
  - 0% H_2 for poorly calibrated equipment
- Technically Possible: 5%-15% H_2
  - Europe grids allow 0.01% to 12% H_2
- Minimal Change in Risk of Ignition and Severity of Explosion: <20% H_2
- H_2 Cracking: <50% H_2

Will Examine 0-15% H_2

PIPELINE OPERATION: WHAT IS EQUIVALENT FLOW?

- Alliance Pipeline Base Case Flow:
  - Std. Volumetric Flow= 1.85 million m3/hr
  - Mass Flow = 1.41 million kg/hr
  - Pipeline Energy Capacity = 18.5 GW
- Composition affects:
  - Density
  - LHV
  - Viscosity
  - Compressibility

Density (kg/m3)

LHV (MJ/m3)

HYTHANE EXPANDED SCOPE

CCS (Optional)

↑

H_2 SMR

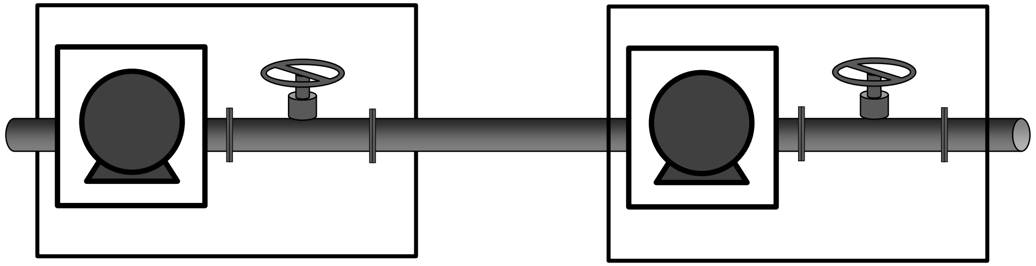
↑

NG Extraction and Processing

Weighted Average Blending

→

Transmission Pipeline



Affected by Complex Blending

→

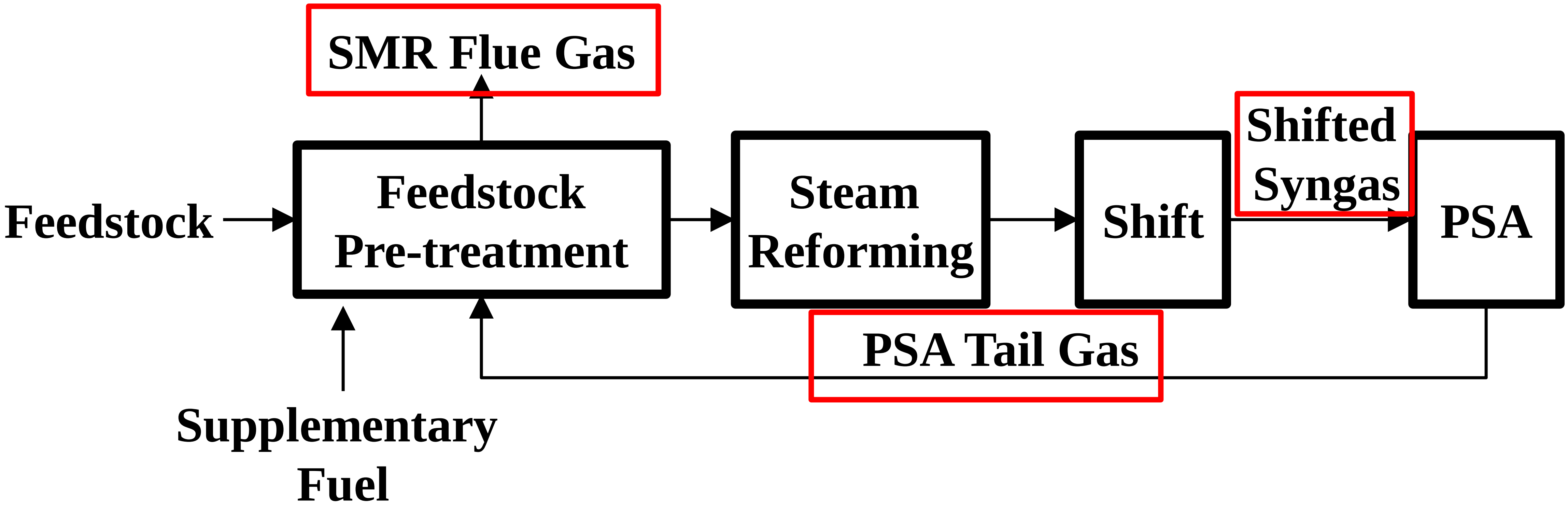
Distribution

→

NG Combustion

Calculated for Blend

H_2 STEAM METHANE REFORMING (SMR)



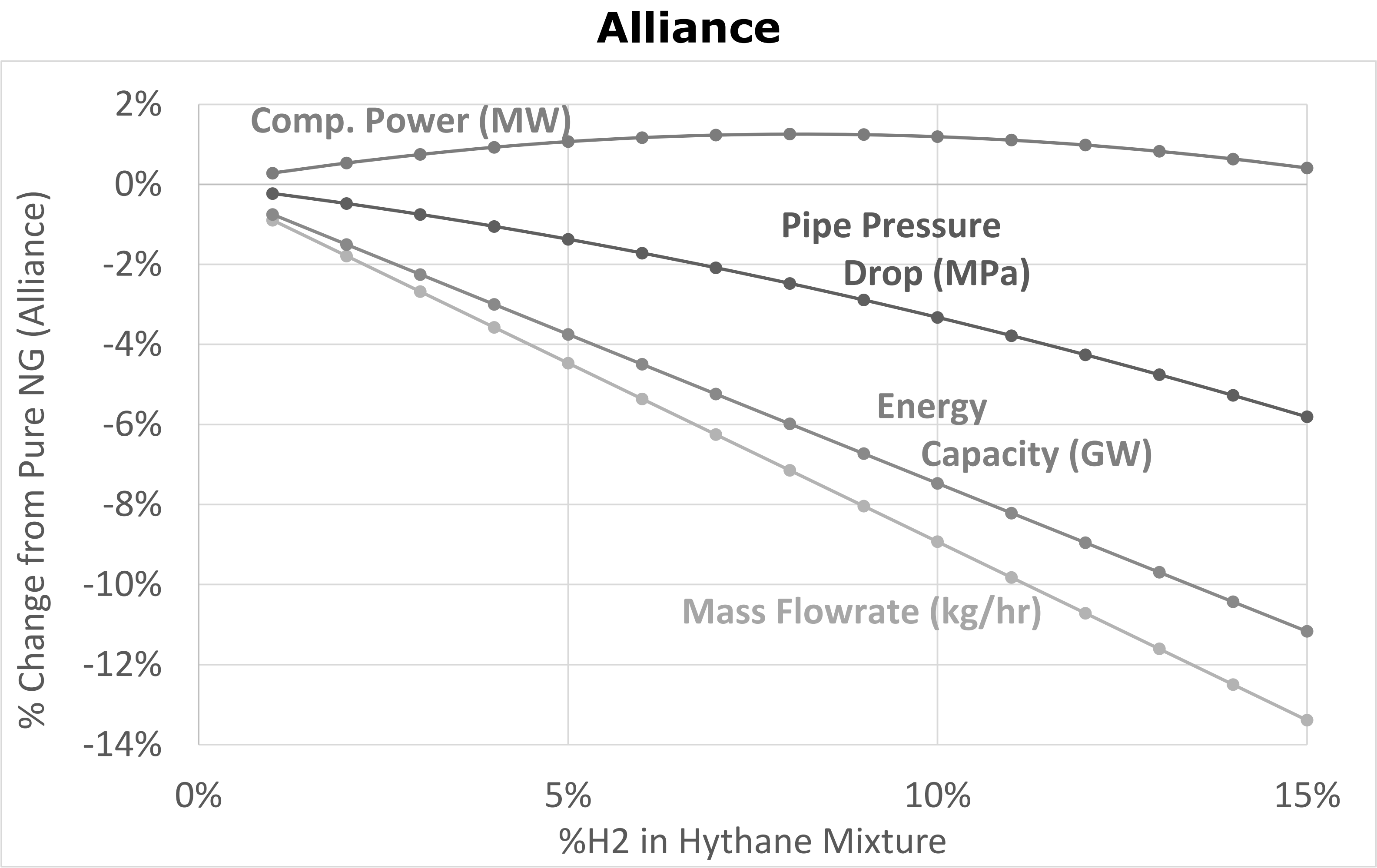
H_2 AFFECT ON NATURAL GAS FUGITIVES

- H_2 3x leaks faster than CH_4 by volume
  - By mass ~ CH_4 leaks 2.6x faster than H_2
- GWP with feedback
  - CH_4: 34 gCO_2eq/gCH_4
  - H_2: 4.8 gCO_2eq/gH_2
- Overall fugitives from CH_4 18.3x worse than H_2

- Distribution emissions due only to fugitives

Adding H2 will ↑ H2 emissions but ↓ CH4 emissions
Overall, ↓ Fugitive emissions

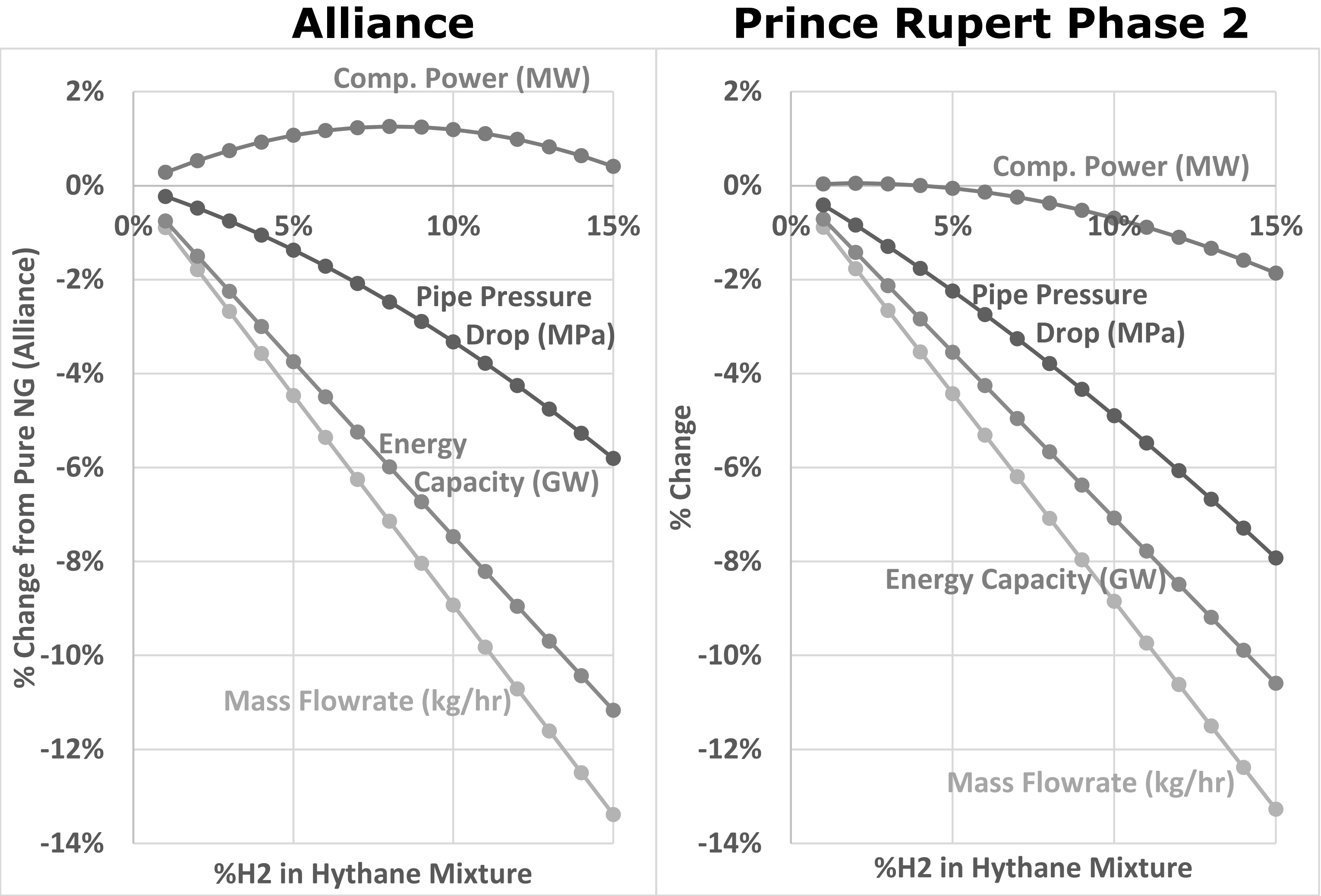
IMPACT OF H_2 ON PIPELINE OPERATION: CONSTANT VOLUMETRIC FLOWRATE



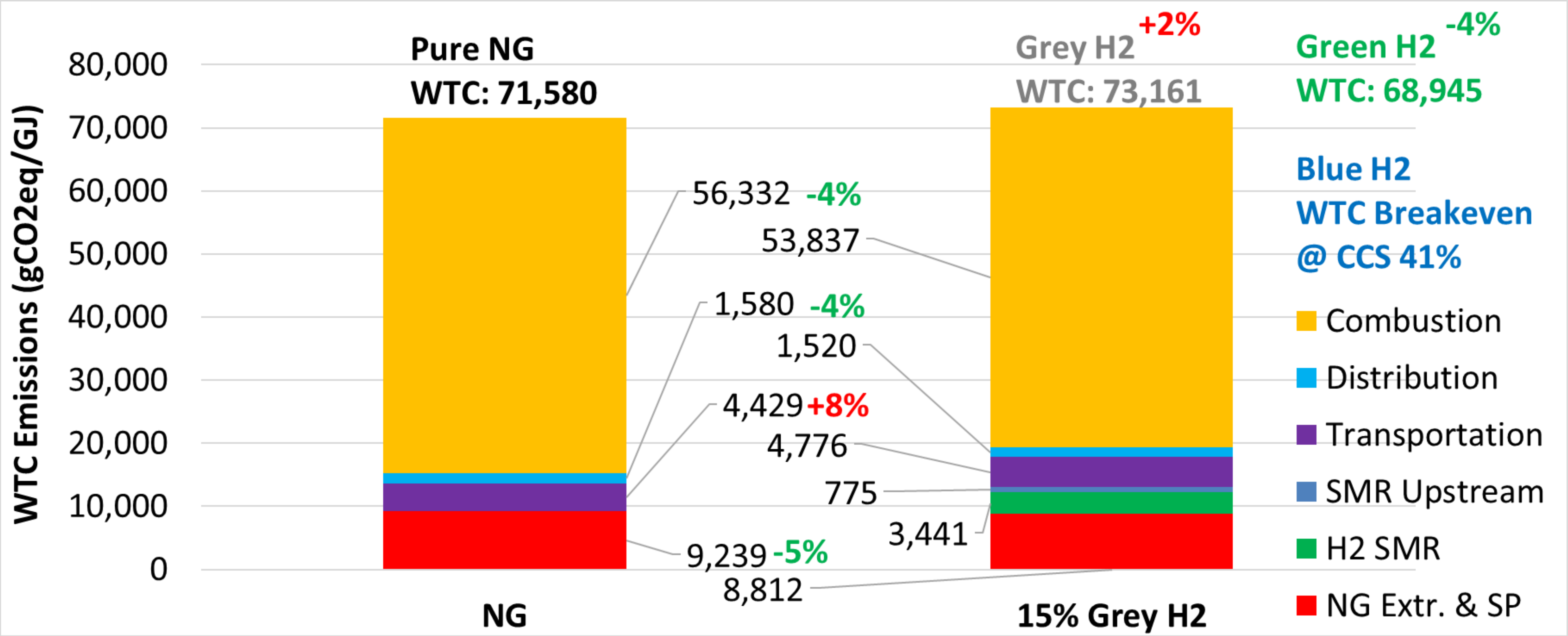
- Compressor Power
  - Multiple nonlinear affects
    - Temperature
    - Molecular Weight
    - Density
    - Heat Capacity Ratio
    - Compressor Ratio

Energy Shortage may occur
NG -> 37MJ/m^3
85%NG, 15%H_2 -> 33 MJ/m^3

IMPACT OF H_2 ON PIPELINE OPERATION: CONSTANT VOLUMETRIC FLOWRATE



WELL-TO-COMBUSTION (WTC) EMISSION BREAKDOWN



CC RATE AFFECT ON WTC EMISSIONS

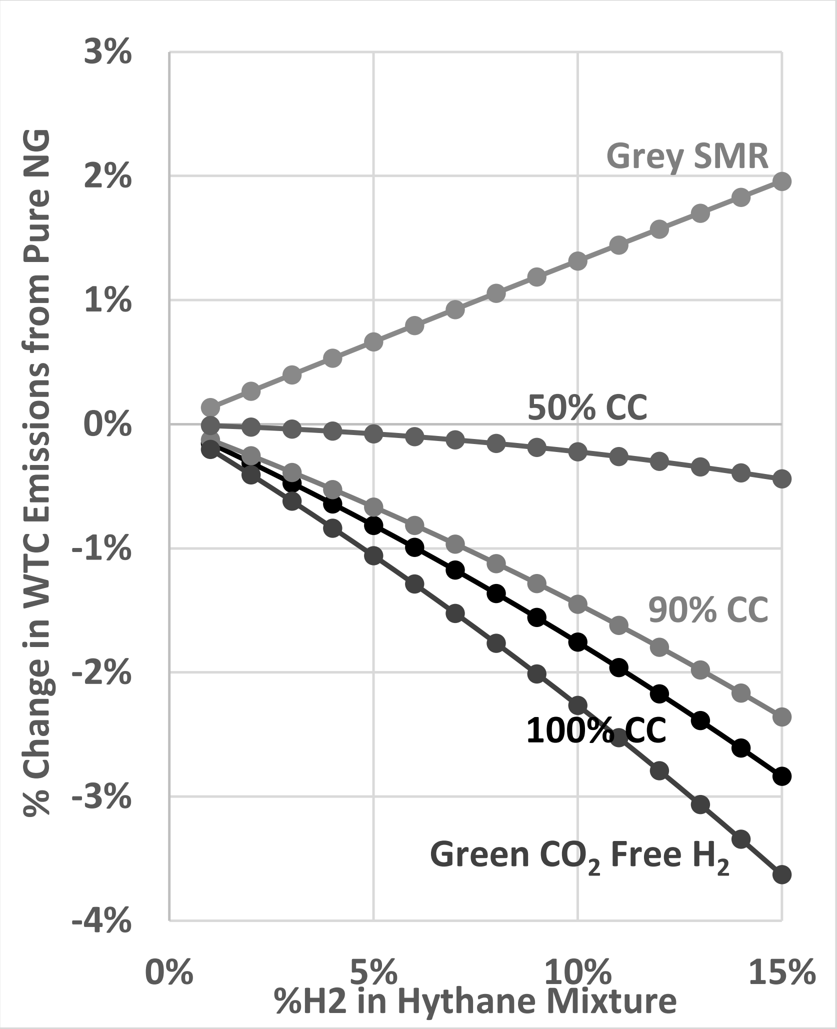
- WTC Breakeven ~30%
  - Depends on:
    - Transport distance
    - Pipeline pressure
    - Compressor spacing
    - $\%H_2$

Transportation Emissions (Transport distance, Pipeline pressure, Compressor spacing)

Fugitive & Transportation Emissions ($\%H_2$)

- 100% CC cannot capture SMR upstream emissions

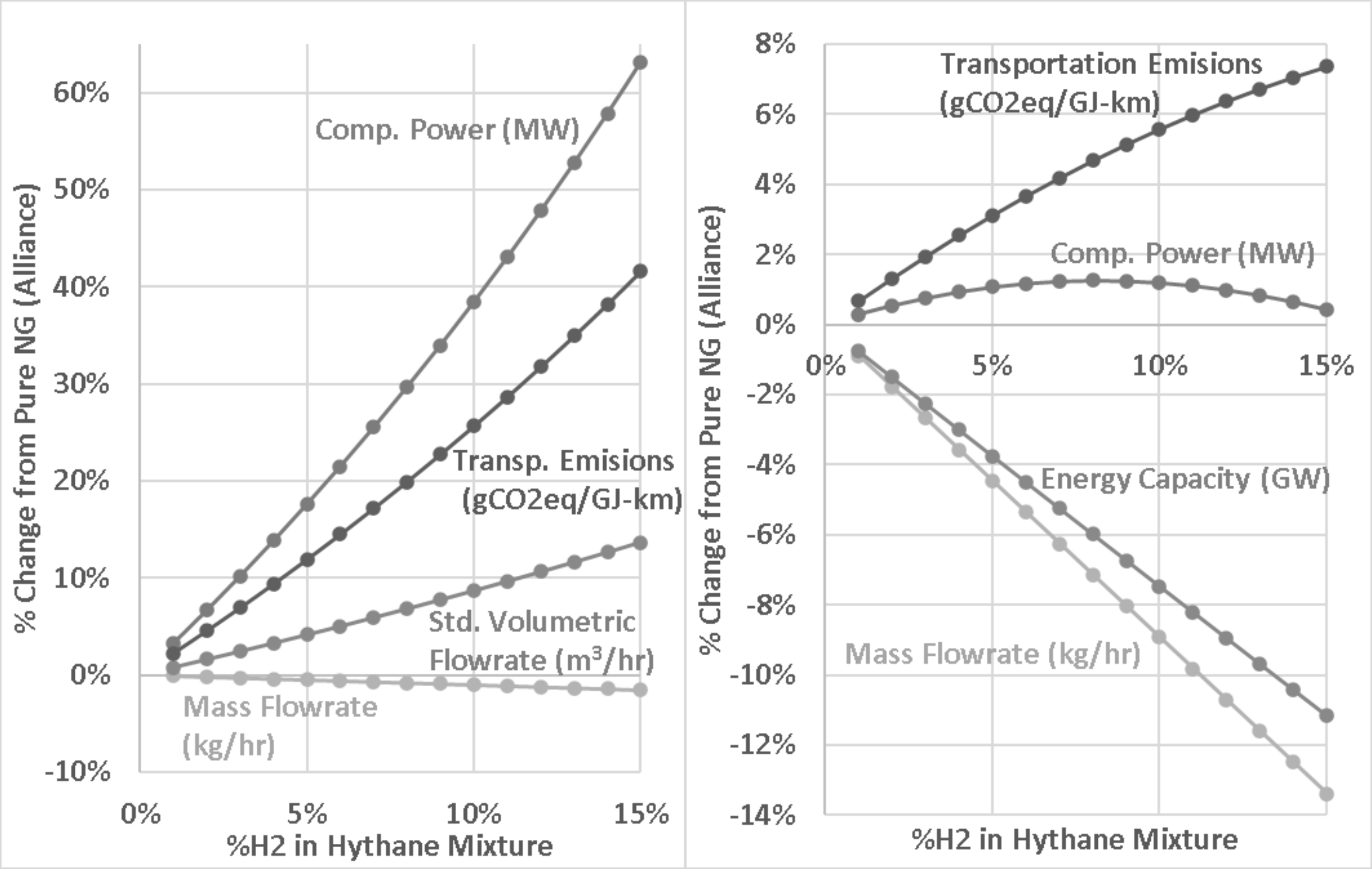
Moderate Carbon Capture Required to Justify Blue H_2



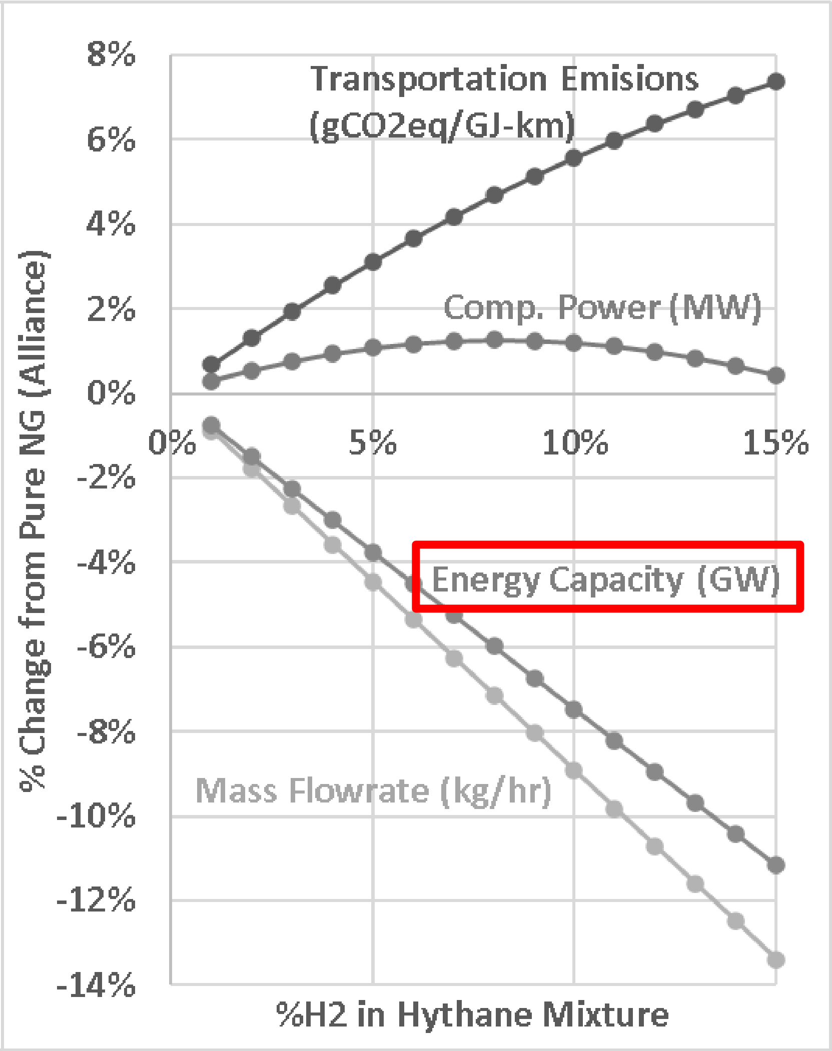
HOLDING ENERGY CAPACITY CONSTANT: ALLIANCE

- **Achieving Constant Energy Capacity Will Be Difficult**
- **Significant Investment Maybe Needed**

Constant Energy Capacity | **Previous Constant Volumetric Flowrate**



CONSTANT VOLUMETRIC FLOWRATE: IMPACT ON END USER



- Typical Energy Usage
  - HEV ~0.7kg H_2/day
  - Canadian residential ~105GJ NG/yr.
- Alliance Base Case:
  - 5.71 million Residential Users
- Alliance 0%->15% H_2, constant volumetric flow
  - +810,000 HEV
  - -856,000 residential users

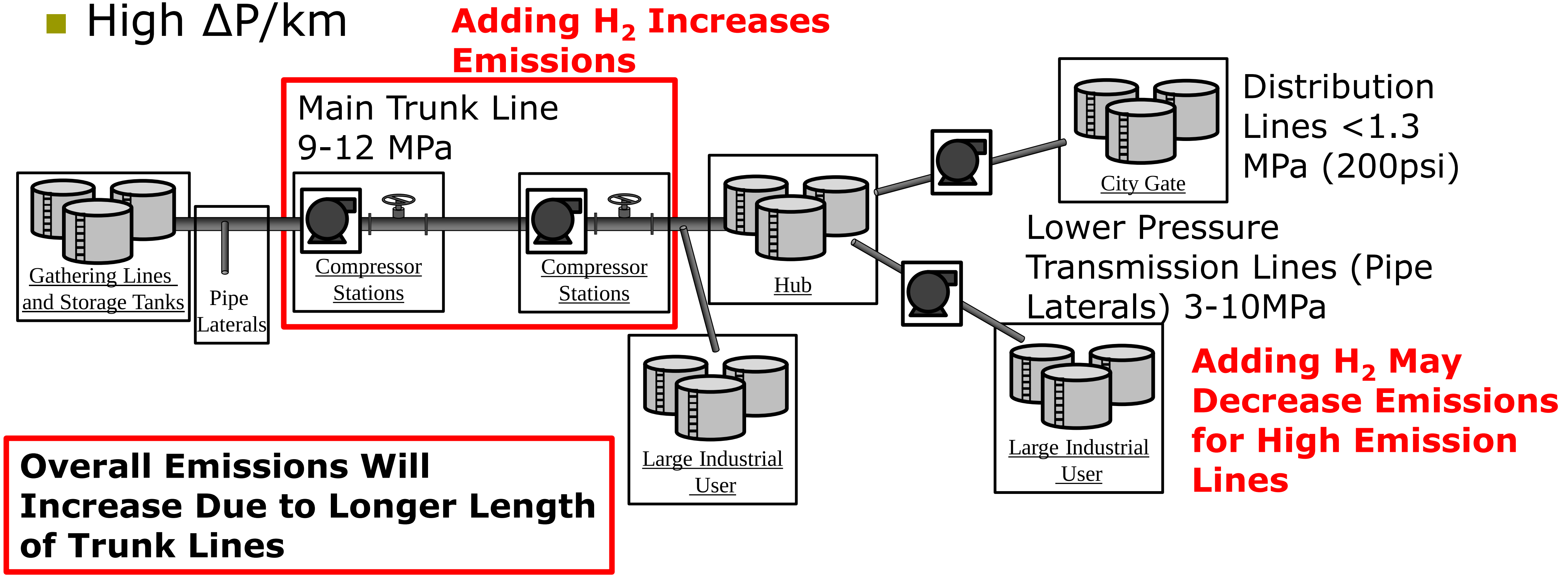
  Recover H_2 for HEV

  OR
  - -621,000 residential users

  Combust Hythane Directly

DOWNSTREAM TRANSMISSION LINES

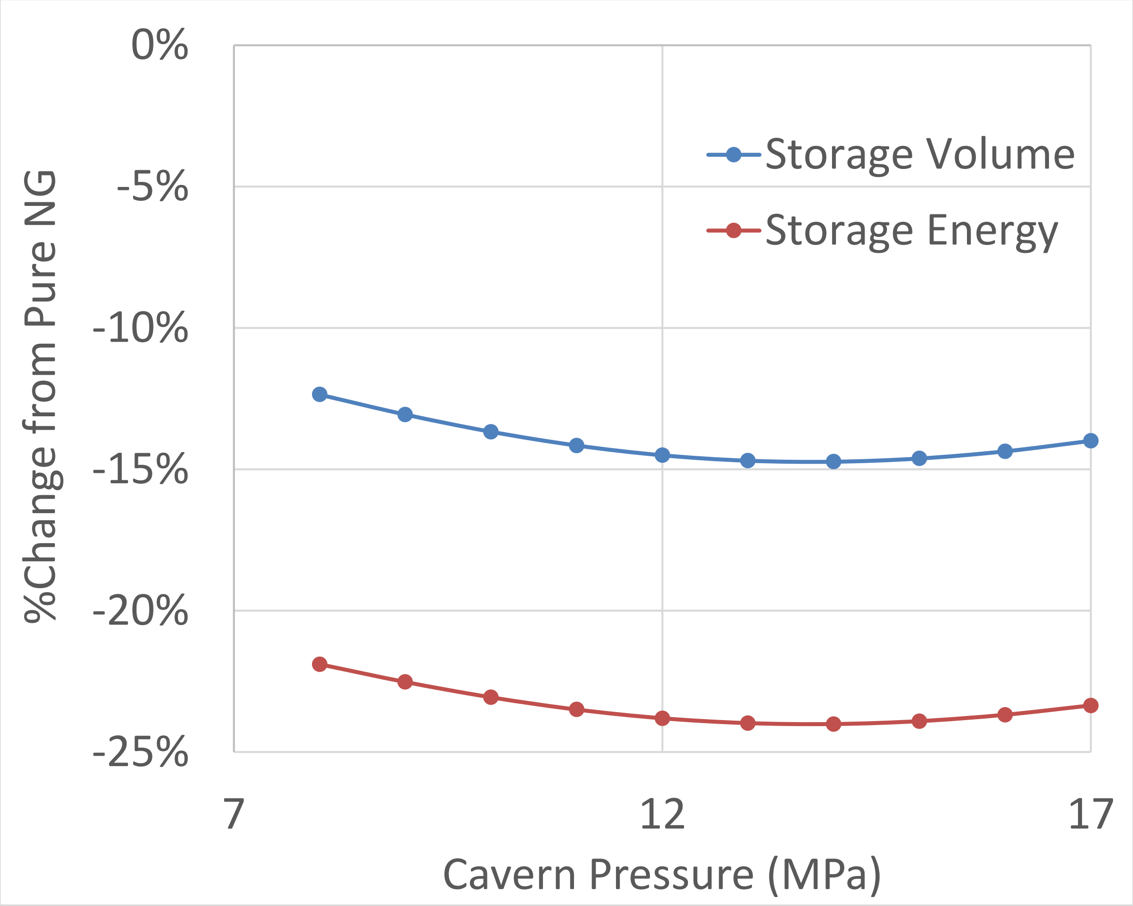
- Transport emissions may decrease if pipeline has:
  - High CR
  - High ΔP/km



LINE PACK AND STORAGE

- Line Pack for 100 km Alliance pipe section
  - 0%H_2->15%H_2
    - Volume: -8.3%
    - Energy Content: -18.0%

Salt Cavern
Min 7 MPa Pressure



WELL-TO-COMBUSTION EMISSIONS H_2 BLEND

- At 15% H_2 Blend
  - Reduces Pipeline Energy Capacity by 11% and Storage by 24%
    - NG demand is expected to increase by 40% from 2015 to 2040
  - Without CCS **(Grey)**
    - Increases WTC Emissions by 2%
  - With CCS **(Blue)**
    - Reduces WTC Emissions by 3%
    - Adds additional CCS Costs
  - With Zero Emission H_2 **(Green)**
    - Decreases WTC Emissions by 4%

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Canada

THANK YOU/QUESTIONS

For further information:

Amit Kumar, Prof.

NSERC/Cenovus/Alberta Innovates Industrial Research Chair in Energy and Environmental Systems Engineering

Cenovus Energy Endowed Chair in Environmental Engineering

Deputy Director – Future Energy Systems

Department of Mechanical Engineering, University of Alberta

E-mail: **Amit.Kumar@ualberta.ca**

Website: **www.energysystems.ualberta.ca**