Energy & Homeland Security

The future of H2 internal combustion engines in California?

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KEY TAKE-AWAYS

Strong global H2ICE development and demonstration activity

"Over 130 OEMs are interested in, planning or running H2 engine R&D projects" (Bosch, 2022)

Small-series production underway for off-highway applications

Short time-to-market can significantly accelerate heavy-duty transport decarbonization

H2ICEs can power heavy-duty vehicles with near-zero emissions

Significantly lower raw NOx emissions possible relative to a diesel engine

Developing low-NOx H2ICEs can mitigate emissions for hard-to-electrify off-road sectors

H2ICE exhaust conditions favorable for efficient and durable after-treatment

Unknowns regarding the N_2O emission

Most H2ICEs will initially lag behind FCEV and diesel heavy-duty vehicles in terms of efficiency

Fuel-consumption parity might be achieved over time, initially ~10-20% fuel consumption penalty

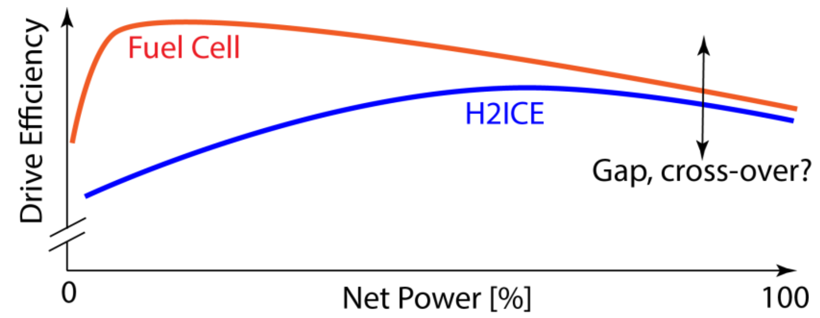
H2ICE projected to have short and long-term upfront cost advantages

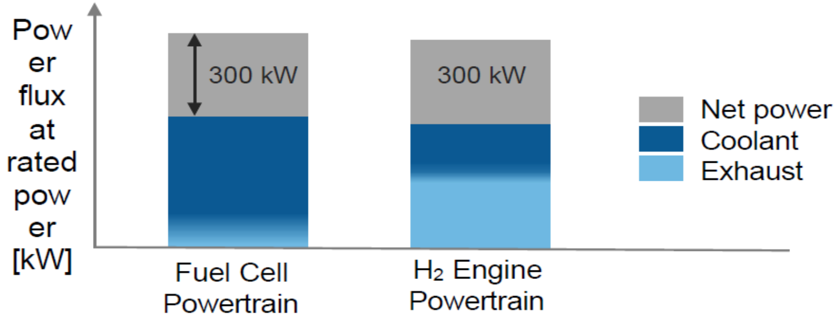
The H2ICE's potential in North America is strongly dependent on legislation

Stricter US NOx legislation will require additional development relative to global engine products

RELATIVE STRENGTHS OF H2ICE AND H2FC – TODAY'S TECHNOLOGY

Characteristic	H2ICE	H2FC
Efficiency	Good: mid – high load	**Excellent: low – mid load**
Cooling needs	**Intermediate**	High, critical for stationary and slow-moving applications
Emissions	NOx (and trace N_2O, CO_2) Low with aftertreatment	**None**
Durability	**High**	Improving with new R&D
Robustness	**High**	Sensitive to vibration
Noble metal consumption	**Low – intermediate** (after-treatment)	High
Fuel purity	**Tolerant to contaminants**	High-purity H2 required
Fuel flexibility	**Diesel/NG backup**	Can be flexible, efficiency penalty
Upfront cost	**Low**	High
Cold start	No issues	Temperature conditioning
Resale value	Depending on infrastructure	Unclear

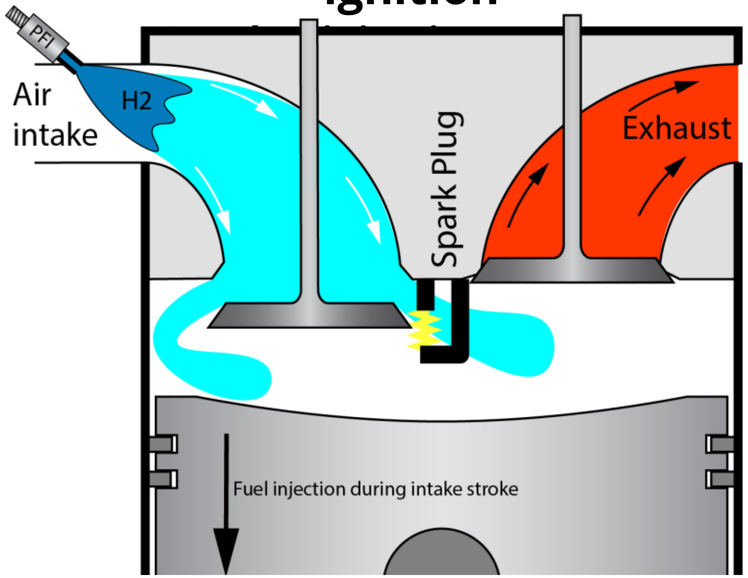




FCEV challenges and changing regulatory framework prompted several OEMs to invest into H2ICE as an alternative H2 powertrain

H2ICE TECHNICAL CONCEPTS DIFFERENTIATED BY FUEL INJECTION

Port-injection spark-ignition

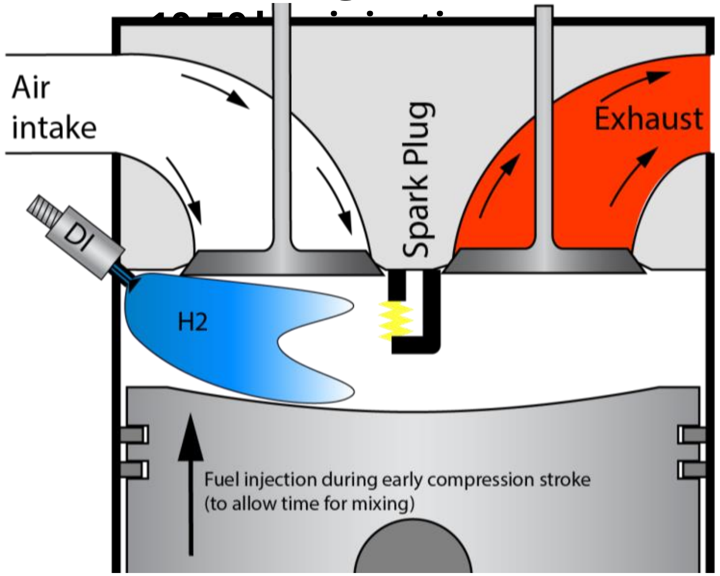


Key challenges: power density, abnormal combustion, efficiency

"Generation 1" H2ICE technology ~2025 market introduction, retrofits

- \+ Simplest system – minimal engine modification, low-cost fuel system
- \+ Typically low NOx emission
- \+ Simple to integrate with advanced ignition systems
- — Loss of power density, efficiency
- — Risks of back-fire into intake manifold, prone to pre-ignition
- — Poor transient response, extreme turbocharging requirements

Direct-injection spark-ignition



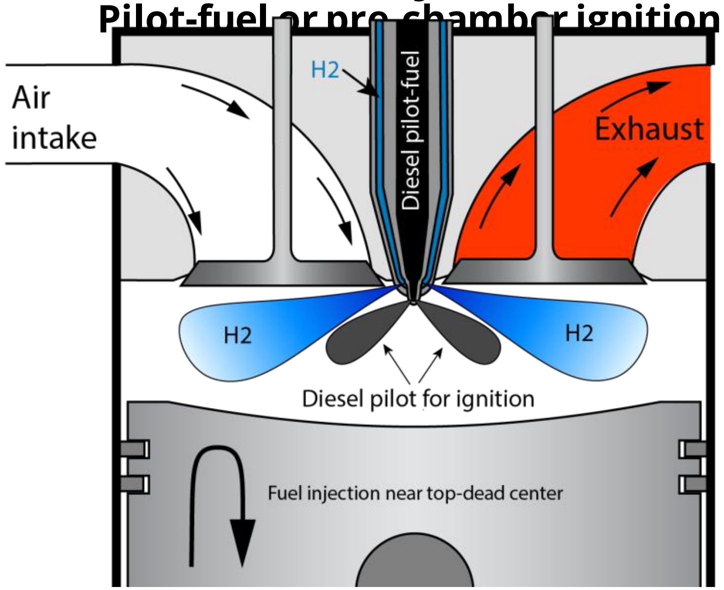
Key challenges: injection technology, abnormal combustion

"Generation 2" H2ICE technology ~2025-2030 market introduction

- \+ Higher power density, improved efficiency, transient response
- \+ Moderate engine modification required
- \+ No back-fire risk, reduced pre-ignition
- — Somewhat higher NOx emission
- — Residual pressure in "empty" tank
- — Injection system with high durability required
- — Development effort for optimization

High-pressure (100-600bar) direct-inj.

Pilot-fuel or pre-chamber ignition



Key challenges: High-pressure pump, NOx, fuel compression energy

"Generation 2+" technology, best efficiency Market readiness ~2025-2030

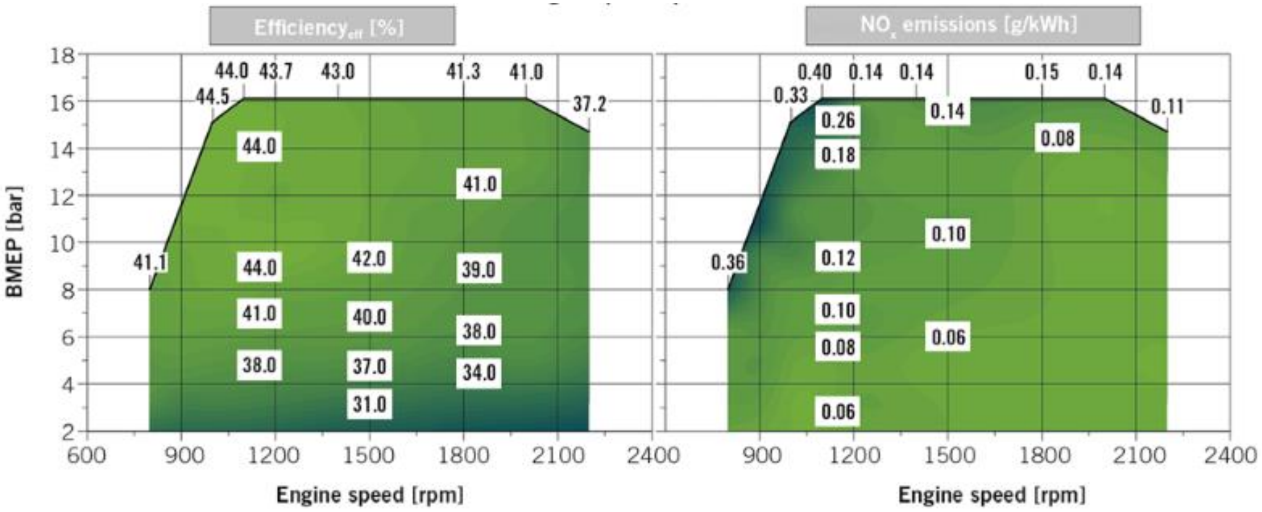
- \+ Best efficiency, power density, transient response
- \+ Reduced turbocharging req., moderate engine modification
- \+ No back-fire risk, no pre-ignition
- \+ Diesel pilot can be substituted with renewable fuels, single-fuel concepts under development
- — Higher NOx emission
- — On-board compressor required

The continued engine development will address many shortcomings of the first H2ICEs on the market

H2-ICE EFFICIENCY AND NO_X EMISSIONS

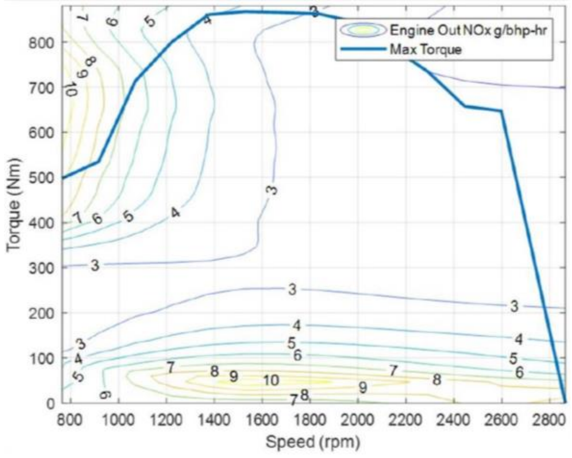
Port-injection 7.8L H2ICE efficiency and raw NOx emissions

Koch et al., MTZ worldwide, Volume 81, Issue 5, 2020



Comparable diesel engine (6.7L) raw NOx emission

Vijayagopal et al.,
SAE Technical Papers,
2022-01-1156



Efficiency of H2ICE:

- ➢ **Somewhat reduced efficiency**
  - ➢ Diesel engine efficiency: up to 50%
- ➢ **High-efficiency zones** overlap with typical engine operating range in HD applications

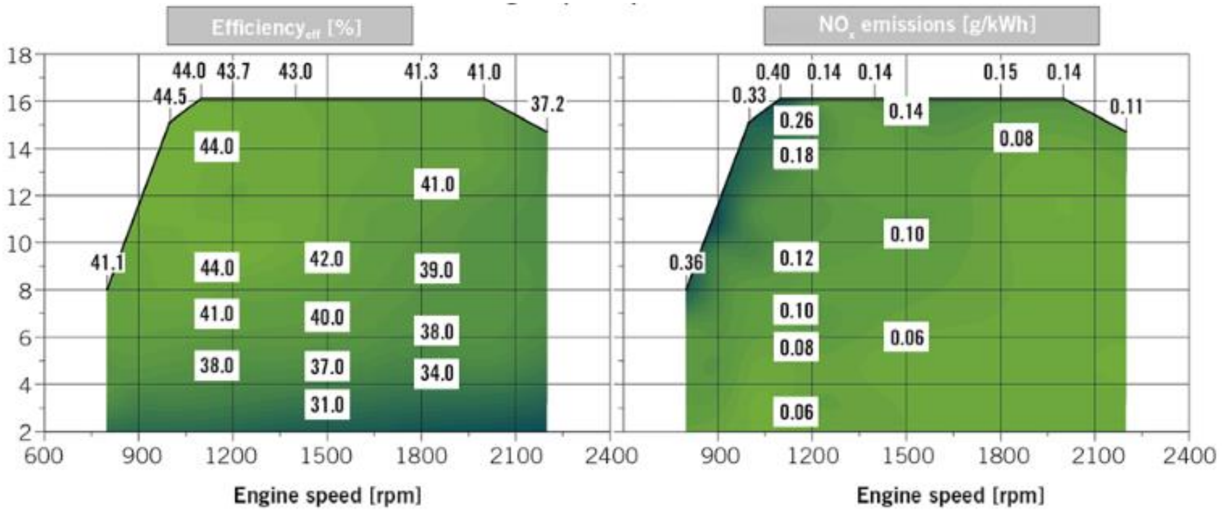
NOx emissions:

- ➢ **>10X reduction in raw NOx** emission vs. typical diesel engine
  - ➢ H2ICE can fulfill current EURO6 legislation with no after-treatment
- ➢ **Very low idle NOx emission**
- ➢ After-treatment will be needed for **EPA2027/EURO7**

TRADEOFF BETWEEN EFFICIENCY, COST AND RAW NO_X EMISSION

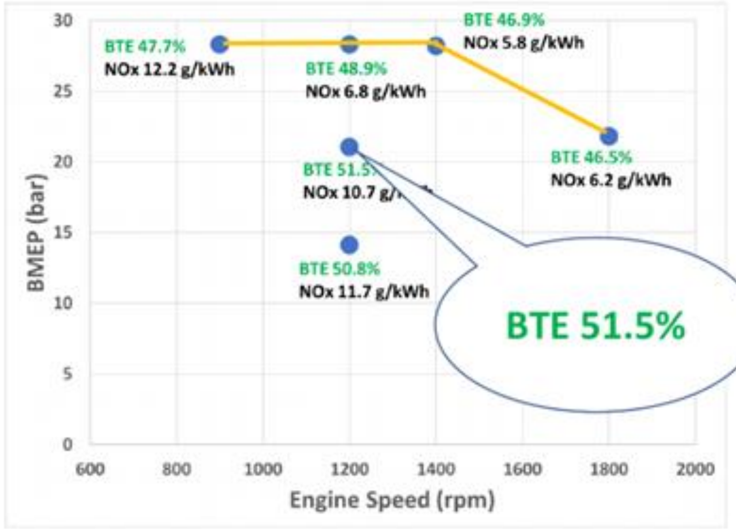
Port-injection 7.8L H2ICE efficiency and raw NOx emissions

Koch et al., MTZ worldwide, Volume 81, Issue 5, 2020



Premixed combustion, spark ignition

High-Pressure Direct-Injection H2ICE 13L HD engine efficiency and NOx emission



Mumford et al., H2 Expo presentation, 2023

Diffusion combustion

Low raw NOx emission
Lower after-treatment needs
Lower upfront cost
Lower efficiency

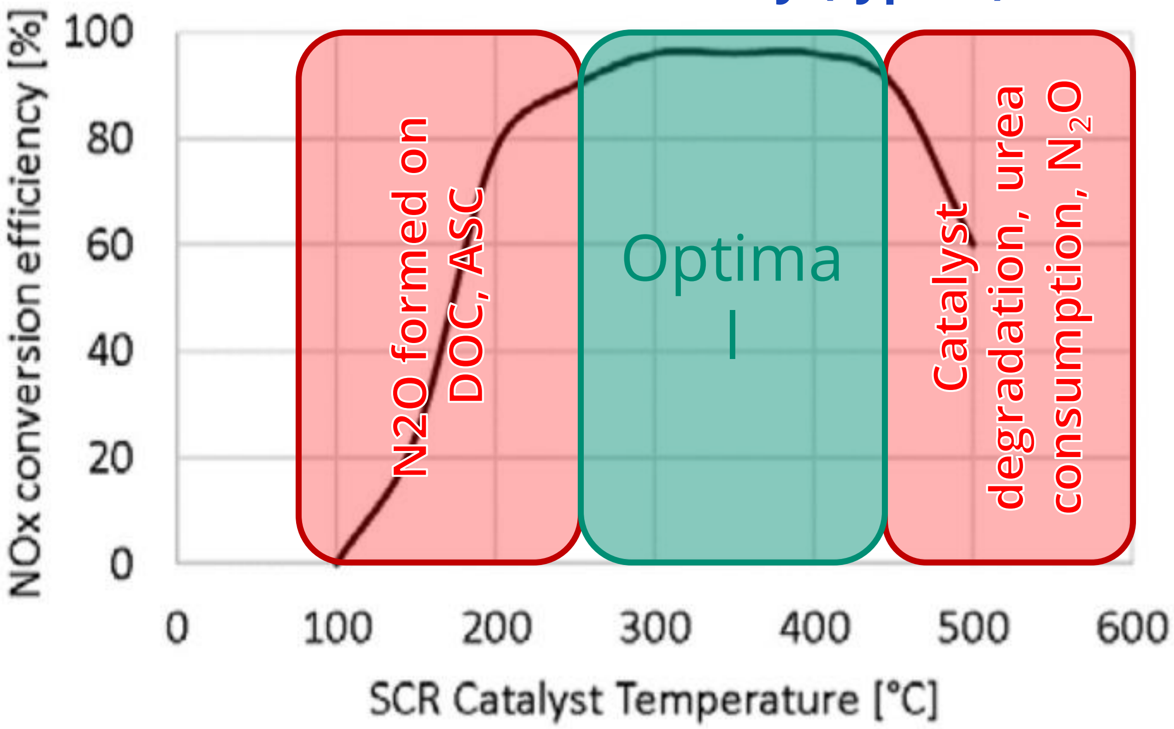
Trade-off

Very-high efficiency
High raw NOx emission
Increased after-treatment required
Higher cost (AT, fuel system)

The tradeoffs will likely be alleviated with maturing of H2ICE technology.
Lower or equal tailpipe NOx to diesel engine expected for all technologies.

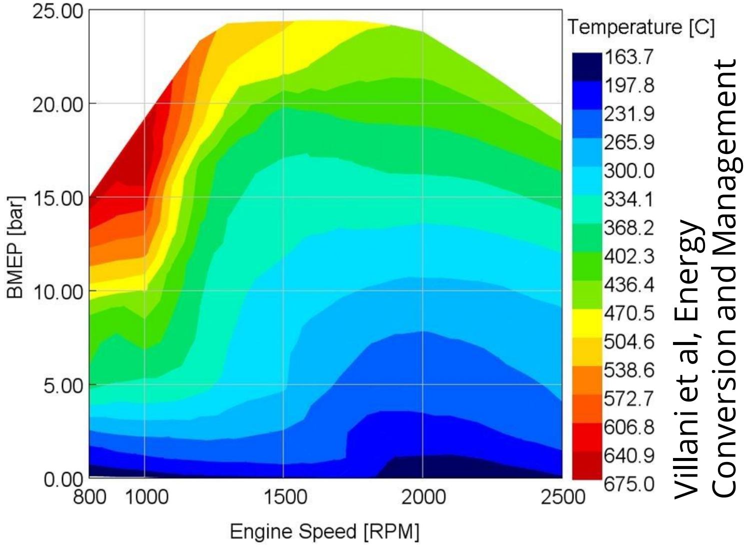
IS H2ICE WELL SUITED FOR EXISTING AFTER-TREATMENT TECH.? PERFORMANCE OF SELECTIVE CATALYTIC REDUCTION OF NO_X?

Temperature dependence of SCR conversion efficiency (typical)



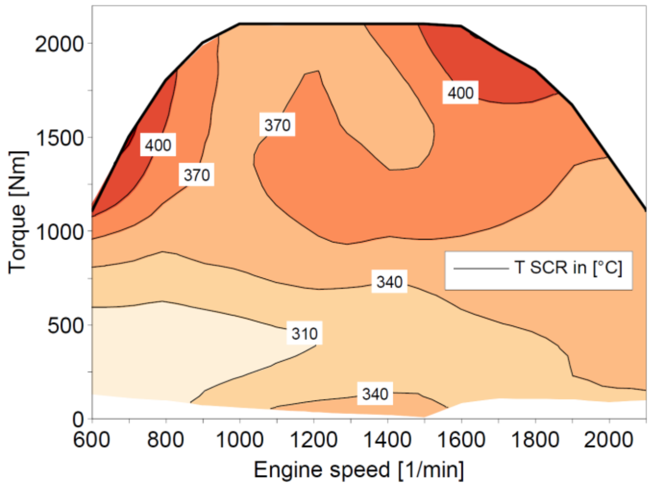
Gosala et al, IJER 19, 2018

Generic diesel engine exh. temperature map



Villani et al, Energy Conversion and Management 187, 2019

HD H2ICE SCR temperature map



Schumacher et al, Presentation at 2023 KIT H2ICE conference

Current understanding suggests that urea-SCR will be well-suited, efficient and durable for H2ICE De-NOx

Unknowns about water vapor impact on SCR De-NOx and H2+aging impact on N_2O formation in SCR

N_2O FROM H2ICE NEEDS TO BE EFFECTIVELY MITIGATED

N_2O is primarily formed in the exhaust after-treatment system
Two mechanisms of N_2O formation are relevant for H2ICE

H_2 reaction with NO over noble metal catalyst

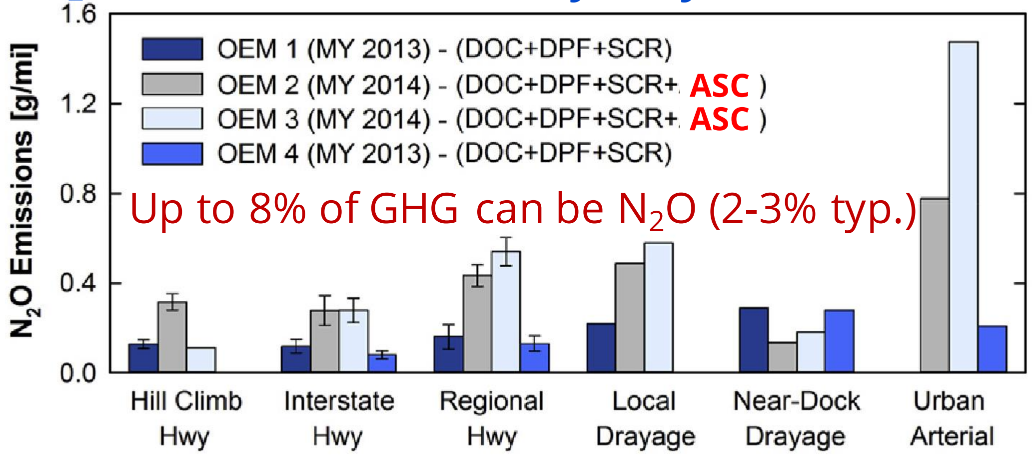
- $2NO + H_2 \rightarrow N_2O + H_2O$
- Diesel Oxidation Cat. and Ammonia Slip Cat contain Pt/Pd as catalysts
- Low-temperature pathway (150-250°C)
- A cold start issue, catalyst warm-up important

NH_3 oxidation, non-selective reduction in SCR

- A range of reactions occurring on SCR
- Ammonia oxidation on ASC is a key source
- Some N_2O may be formed across the entire SCR temperature range
- More NOx and more urea dosing increase N_2O

N_2O is also a challenge for diesel vehicles equipped with SCR

N_2O emissions from heavy-duty diesel trucks FTIR



Quiros et al., Atmospheric Environment 168, 2017

Lower raw NOx emission, option to remove the ASC from after-treatment, and favorable exhaust temperature will likely significantly reduce H2ICE N_2O emission relative to diesel engines.

<u>H2ICE N_2O GWP <1% GWP of diesel expected</u>

H2-ICE MINOR AND NON-REGULATED EMISSIONS NITROUS OXIDE, HYDROGEN, AMMONIA, CO_2, CO, PARTICULATES

Carbon Dioxide (CO_2)

Total CO2 emission for H2ICE is low (~0.5-2 g/kWh)

Engine oil

- Consumption: 0.2-0.5 g/kWh
- CO_2 emission: 0.6-1.5 g/kWh
- Trend: Higher than diesel

Urea for SCR

- 0.58g CO_2 produced per gram of reduced NOx
- Trend: <0.5 g_{CO2}/kWh

Ammonia

- Some NH_3 slips through catalyst
- Tradeoff with N_2O production on ASC
- Trend: much less than diesel (less NOx)

Hydrogen (3x GWP of CO_2)

- <0.5 – 3 g/kWh slip typically observed
- Can be mitigated by DOC (N_2O tradeoff)
- GWP of slipped H2 <1.5% of diesel GWP

Carbon monoxide, hydrocarbons, particulates

Main source: Engine lubricating oil

Carbon monoxide

- Very low (~0.1 g/kWh) based on literature data
- Well below legislated limit

Hydrocarbons

- Open data suggests emission level of ~0.05-0.1g/kWh
- Near the EPA2027 limit, DOC might be reqd. for compliance

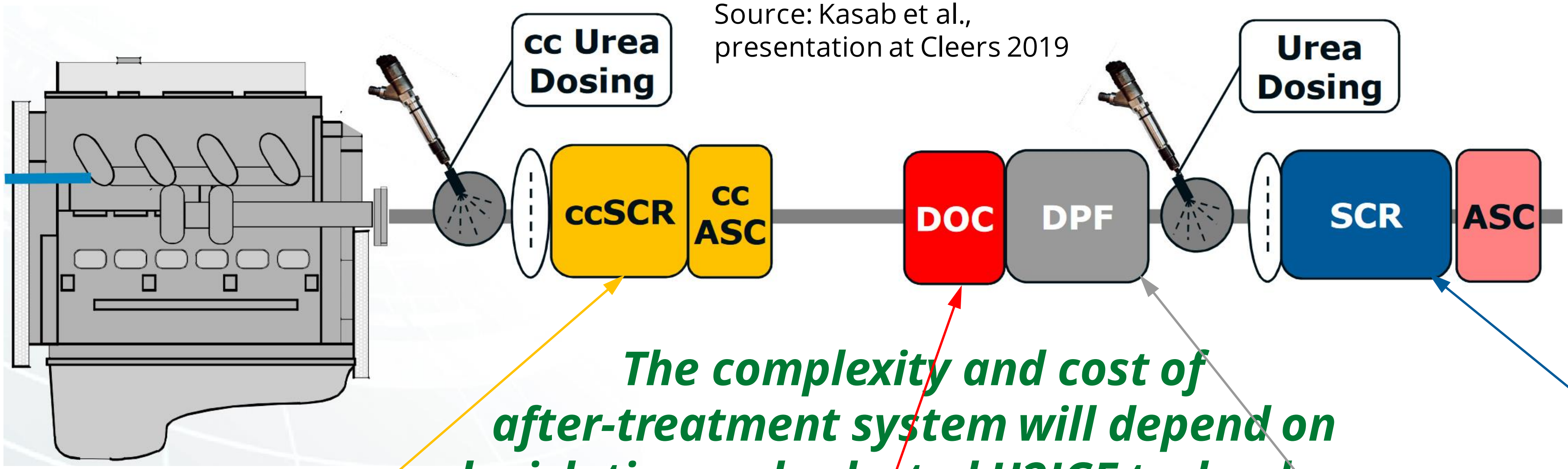
Particulates

- Particulate mass well below legislated limits
- Moderate particulate number – DPF might be reqd. for Euro7

H2ICE will emit significantly less pollutants and GHG that a diesel engine

AFTER-TREATMENT CONSIDERATIONS
SIGNIFICANT AFTER-TREATMENT SIMPLIFICATION POTENTIAL

Proposed EPA27/EURO7 heavy-duty diesel after-treatment configuration



Source: Kasab et al., presentation at Cleers 2019

The complexity and cost of after-treatment system will depend on legislation and selected H2ICE technology

Ammonia slip catalyst

Not needed in engines with very low raw NOx
A source of N_2O
Needed if targeting ultra-low NOx emission with higher urea dosing

Selective Catalytic Red.

Necessary for EPA27
Impact of water on catalyst deactivation not fully understood
High De-NOx efficiency demonstrated in lab.
Optimized SCR composition may be needed to minimize N_2O

Close-coupled SCR + Ammonia-slip catalyst

Likely not needed, H2ICE exhaust temperature is sufficiently high

Diesel oxidation catalyst (Pt+Pd)

If present, it will further reduce H_2, CO and HC
May become a source of N_2O during cold-start
Can likely be omitted

Particulate filter

May be needed for PN legislation
Not needed for PM legislation

UNPRECEDENTED R&D WAVE ON H2ICE LEGISLATION IS KEY DRIVER

World-wide OEM investment into H2ICE

- Heavy-Duty
- Off-road
- Power gen

2020 - present

A few thoughts on H2ICE market in US and CA

H2ICEs are developed as a global product for worldwide market

Unique US NOx standards will require additional investment relative to the global engine product

Financial incentives or H2ICE credits toward ZEV sales quotas might be needed to attract the initial OEM and customer investment (TCO aspect)

What about the non-zero NOx emissions?

Modern H2ICE NOx emission is lower than when using BEV charged from present CA grid
(0.15g/kWh[1] marginal mix grid NOx emission)

Synergies with off-road H2ICE development will have spill-over benefits for mitigating off-road NOx emission
(eqv. to ~50% of on-road emissions)

[1]EPA AVERT 2022 [2]CEPAM2019v1.03 projections

CONCLUSIONS

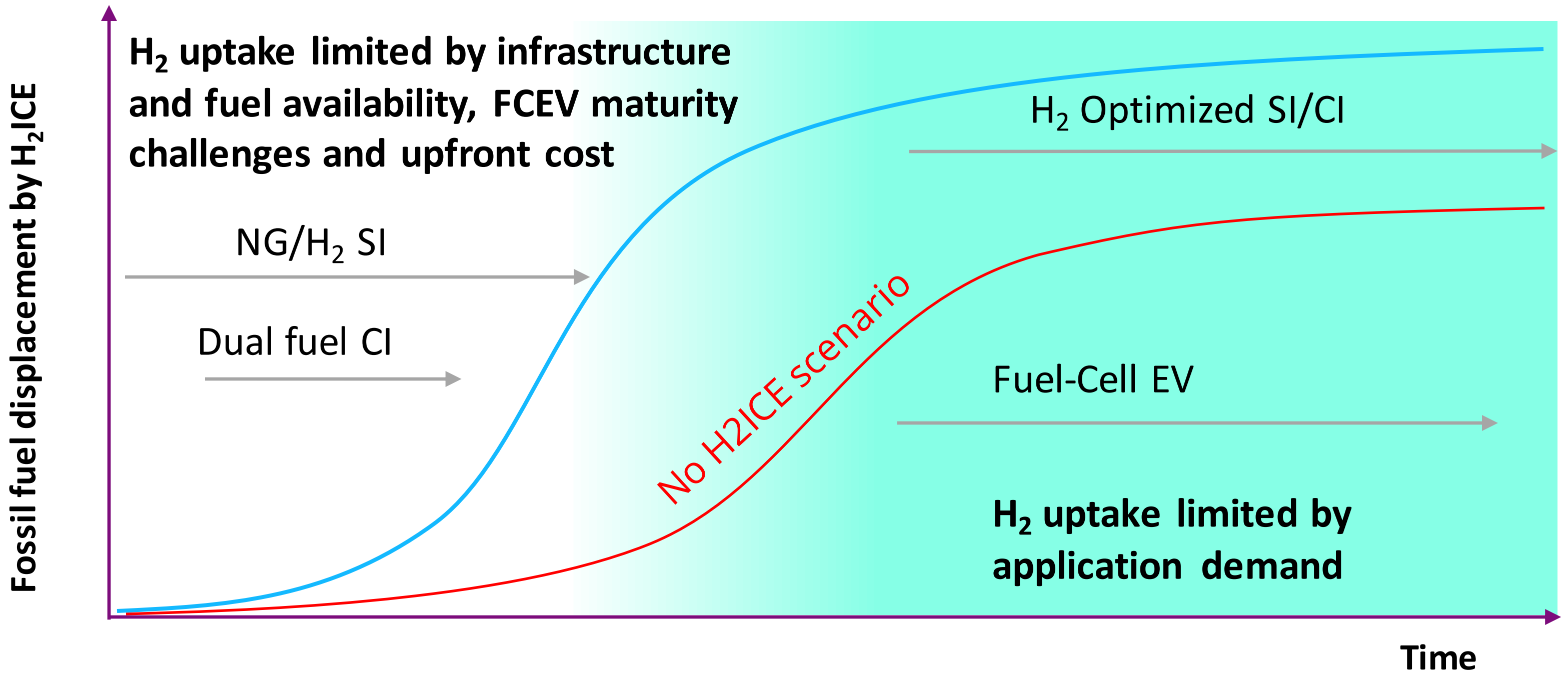
H2ICEs are a viable low-emissions technology in heavy-duty transportation

- H2ICE equipped with modern exhaust after-treatment will result in very low tailpipe pollutant and GHG emissions
- Further after-treatment improvement should be targeted to minimize N_2O formation
- First-generation H2ICE's will have an efficiency/cost/emissions tradeoff
- The efficiency gap vs. diesel and FCEV will reduce with continued development
- >95% GHG reduction at tailpipe vs. diesel is possible even with worse-case assumptions

Legislation will determine the viability of H2ICE in North America

- CO2 reduction and sales mandates (ZEV) likely the main driver for early H2ICE adopters
- Additional development needed to make global market H2ICEs EPA/CARB2027 compliant
- Long-term viability of H2ICE primarily driven by H2 cost

H2ICE CAN SPEED DECARBONIZATION & INFRASTRUCTURE DEVELOPMENT



Early adopters

Fuel flexibility: (NG/H_2 blends, low-purity H_2, backup diesel operation

Retrofits: key to decarbonizing the existing fleet

Incentives: Gov. ZEV credit, upfront cost

Full H_2 economy

Robustness/TCO:
H_2 penetration into applications challenging for H_2-FCEV

Key H2-ICE advantages in time

H2ICEs provide for a smooth, continuous transition as H_2 supply and infrastructure develops and the existing fleet turns over