University of Applied Sciences and Arts Northwestern Switzerland
School of Engineering

member of swissuniversities

Properties and Characteristics of Alternative Renewable Fuels

- overview renewable fuels
- fuel properties & characteristics
- combustion behavior & emissions

POWERLOOP-Forum 2024

November 20th, Bern

University of Applied Sciences and Arts Northwestern Switzerland (FHNW)
Institute of Thermal and Fluid Engineering (ITFE)
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Klosterzelgstrasse 2, 5210 Windisch

Introduction

Motivation

Climate change: **CO_2 reduction** according to "Paris Agreement"

PARIS AGREEMENT

→ **GHG reduction** targets for **"large" IC engines***: adoption of fuels with significantly **lower net carbon footprint**

*Propulsion (Marine)

WIN GD

*Power plant / Combined heat & power (CHP)

INNIO JENBACHER

WÄRTSILÄ

Introduction

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Climate change: **CO_2 reduction** according to "Paris Agreement"

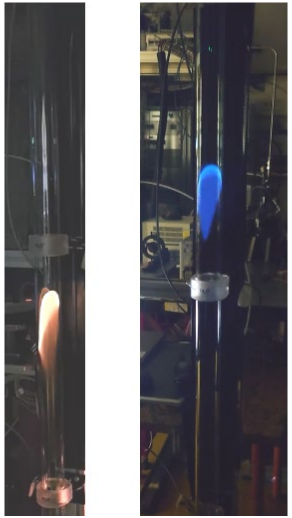
→ **GHG reduction** targets for **"large" IC engines**: adoption of fuels with significantly **lower net carbon footprint**

CH_4 / H_2 / NH_3 / CH_3OH are considered as **promising candidates**, but certain challenges require consideration

→ *production by **renewables**, handling, storage, **fuel properties**, and **combustion behavior***

Ammonia

NH_3



Methane

CH_4

Introduction

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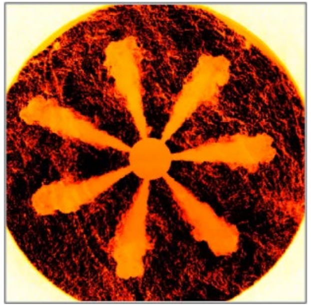
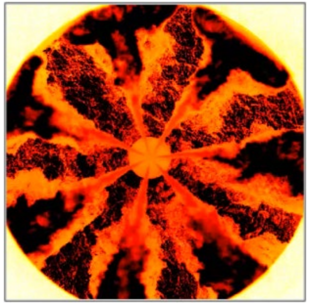
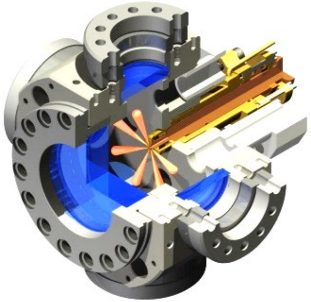
→ *production by **renewables**, handling, storage, **fuel properties**, and **combustion behaviour***

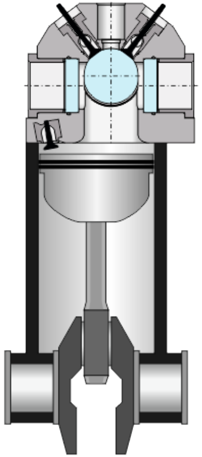
Objective: fundamental insight into **ignition** and **combustion** (performance, emissions, etc.) characteristics

→ Initial thermodynamic investigations with "optical engine" test facilities





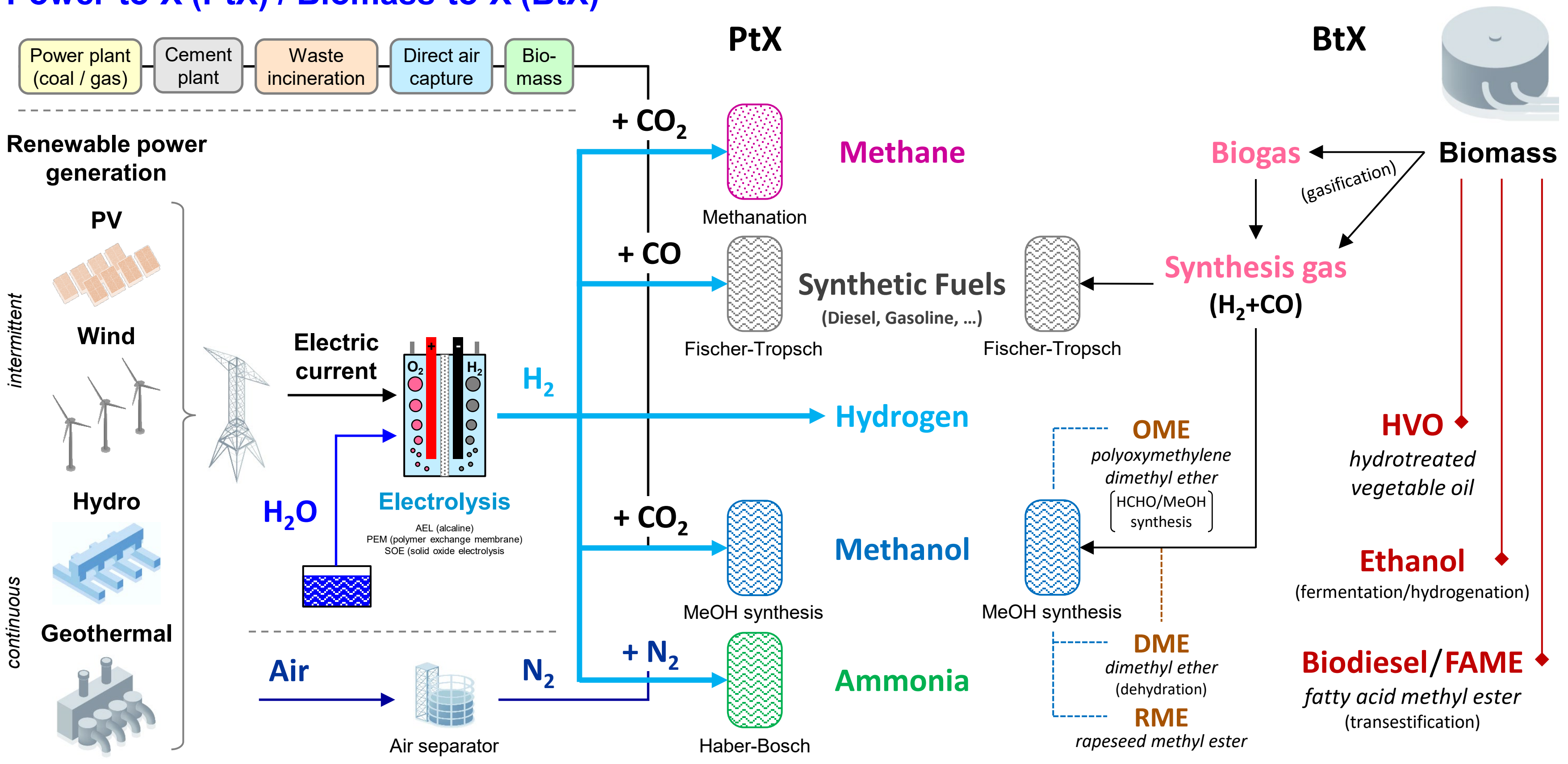




→ ICE relevant operating conditions: **pressure** / **temperature** / **flow**

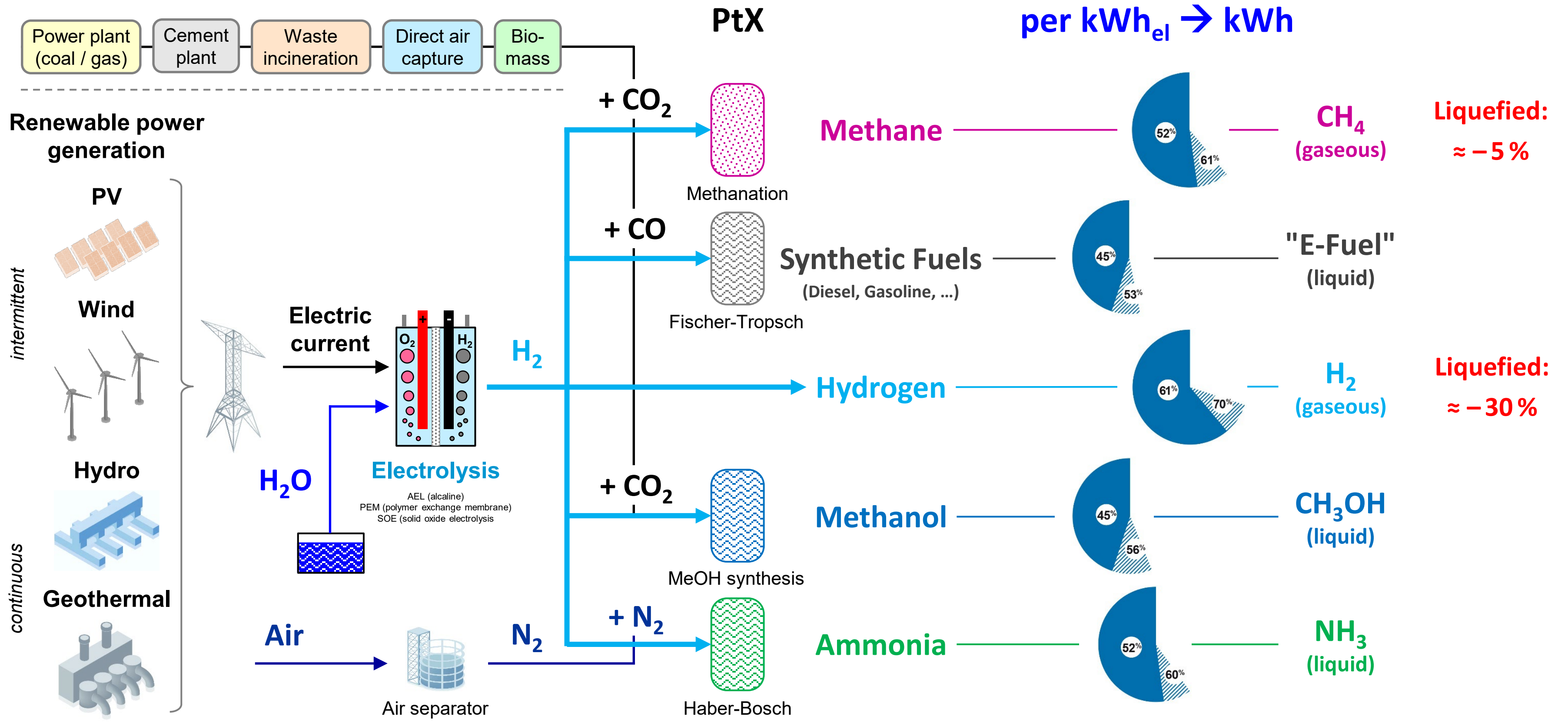
Renewable Fuels

Power-to-X (PtX) / Biomass-to-X (BtX)



Renewable Fuels

Power-to-X (PtX) efficiency



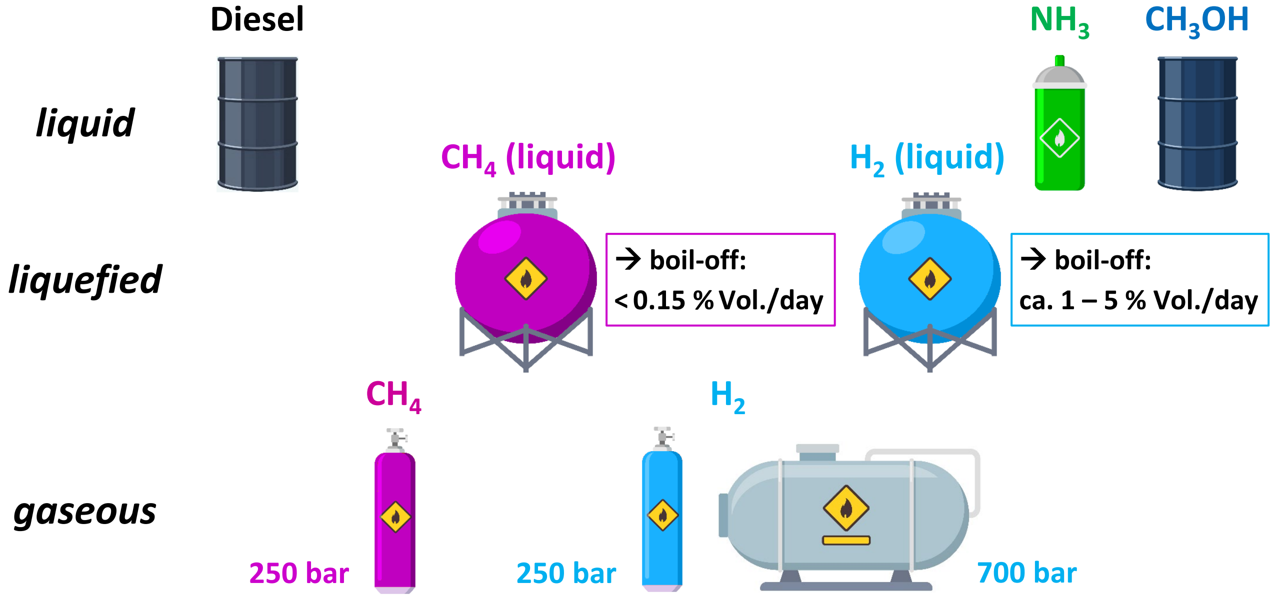
Source: Öko-Institut e.V., 2019

Fuel Properties

State / storage

Methane Hydrogen Ammonia Methanol

	Diesel	CH_4		H_2			NH_3	CH_3OH	OME 3-5	HVO	Lithium-Ion Battery	
Storage conditions:	*Liquid*	*Compressed*	*Liquid*	*Compressed*	*Compressed*	*Liquid*	*Liquid*	*Liquid*	*Liquid*	*Liquid*	current	2040
at pressure:	*Ambient*	250 bar	*Ambient*	250 bar	700 bar	*Ambient*	10.6 bar	*Ambient*	*Ambient*	*Ambient*		
at temperature:	27 °C	27 °C	-161 °C	27 °C	27 °C	-253 °C	27 °C	27 °C	27 °C	27 °C		



→

Fuel slip / unburnt

CH_4: × 28 ↑ GWP than CO_2

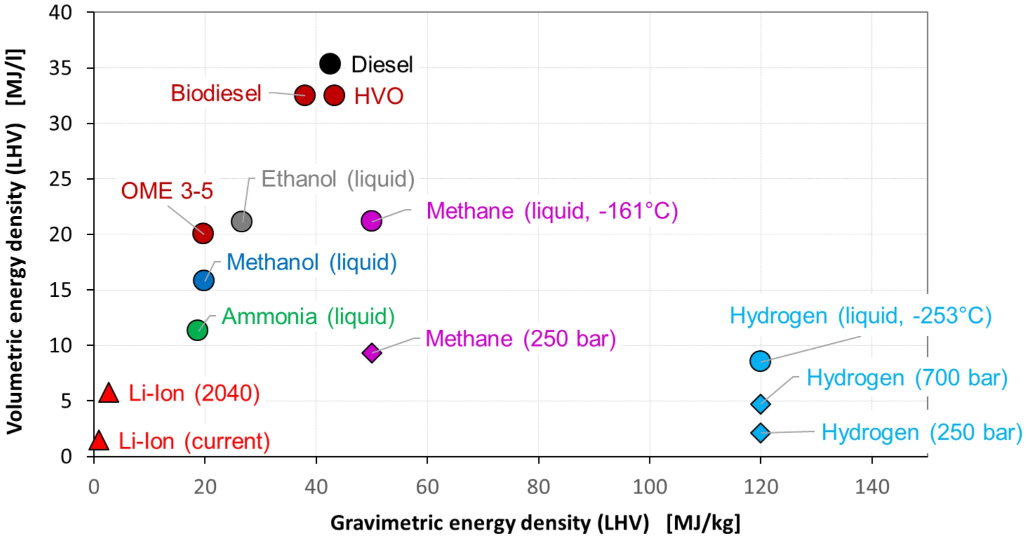
H_2: indirect GHG ↑ lifetime CH_4

Fuel Properties

Energy density

Methane Hydrogen Ammonia Methanol

	Diesel	CH_4		H_2			NH_3	CH_3OH	OME 3-5	HVO	Lithium-Ion Battery	
Storage conditions:	*Liquid*	*Compressed*	*Liquid*	*Compressed*	*Compressed*	*Liquid*	*Liquid*	*Liquid*	*Liquid*	*Liquid*	current	2040
	Ambient	250 bar	-161 °C	250 bar	700 bar	-253 °C	10.6 bar	*Ambient*	*Ambient*	*Ambient*		
Energy density:	**42.6 MJ/kg**	**50 MJ/kg**		**120 MJ/kg**			**18.8 MJ/kg**	**19.9 MJ/kg**	**19.8 MJ/kg**	**43.4 MJ/kg**	**0.9 MJ/kg**	**2.7 MJ/kg**
(Lower heating value H_u)	**37 MJ/L**	**9.3 MJ/L**	**21.15 MJ/L**	**2.1 MJ/L**	**4.69 MJ/L**	**8.5 MJ/L**	**11.3 MJ/L**	**15.78 MJ/L**	**20 MJ/L**	**32.5 MJ/L**	**1.44 MJ/L**	**5.76 MJ/L**



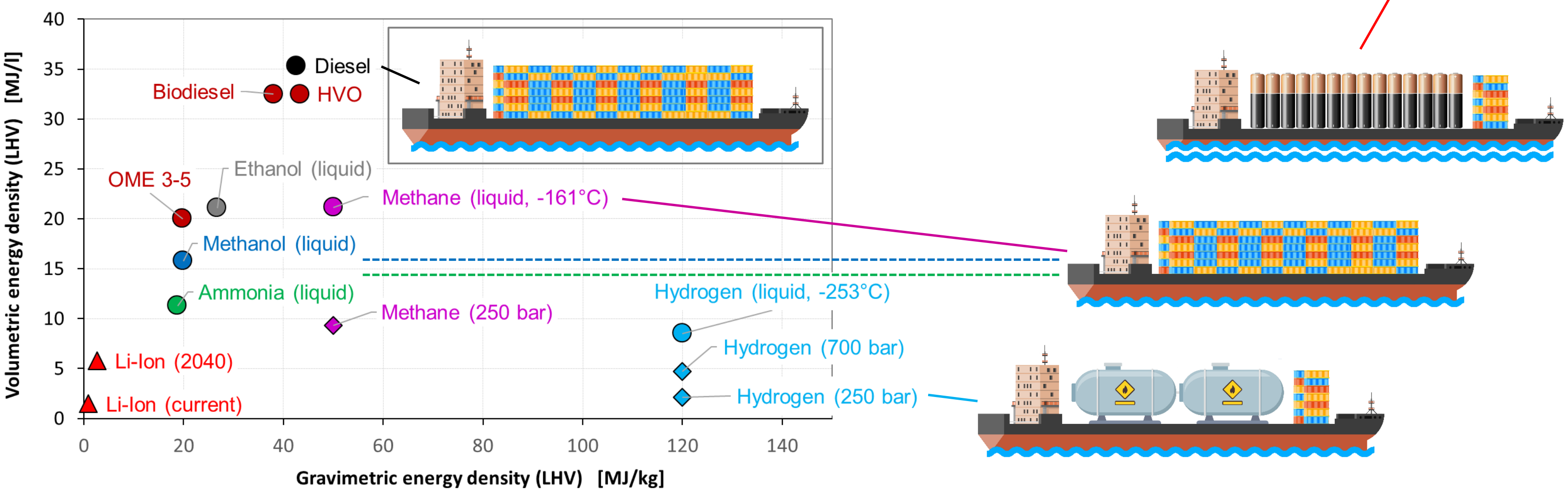
Fuel Properties

Energy density

Methane | Hydrogen | Ammonia | Methanol

	Diesel	CH_4		H_2			NH_3	CH_3OH	OME 3-5	HVO	Lithium-Ion Battery	
Storage conditions:	*Liquid*	*Compressed*	*Liquid*	*Compressed*	*Compressed*	*Liquid*	*Liquid*	*Liquid*	*Liquid*	*Liquid*	current	2040
	Ambient	250 bar	-161 °C	250 bar	700 bar	-253 °C	10.6 bar	*Ambient*	*Ambient*	*Ambient*		
Factor weight:	***compared to***	**x 0.9**	**x 0.9**	**x 0.4**	**x 0.4**	**x 0.4**	**x 2.3**	**x 1.6**	**x 2.2**	**x 1.0**	**x 24.4***	**x 8.1***
Factor volume:	***Diesel***	**x 3.5**	**x 1.6**	**x 15.7**	**x 7.0**	**x 3.9**	**x 2.9**	**x 1.6**	**x 1.7**	**x 1.0**	**x 11.5***	**x 2.9***

*** 2 × efficiency**

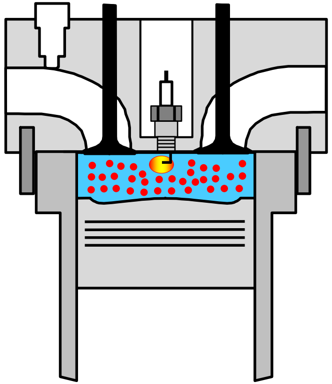


Fuel Properties

Combustion

	Diesel	Methane CH_4	Hydrogen H_2	Ammonia NH_3	Methanol CH_3OH	OME 3-5	HVO
Ignition energy	-	≈ 0.21 mJ	≈ 0.016 mJ	≈ 8 mJ	0.14 - 0.2 mJ	-	-
Lam. flame speed	0.2 - 0.25 m/s	0.38 m/s	3.5 m/s	0.07 m/s	0.4 - 0.5 m/s	0.3 m/s	0.2 m/s

CH_4 H_2



→ "influence" on "engine design" and combustion process

Fuel Properties

Combustion

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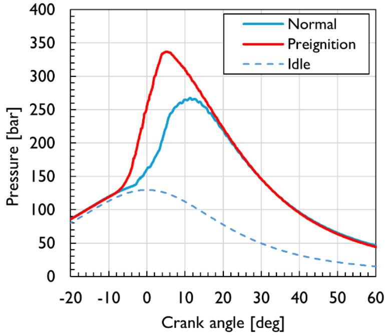
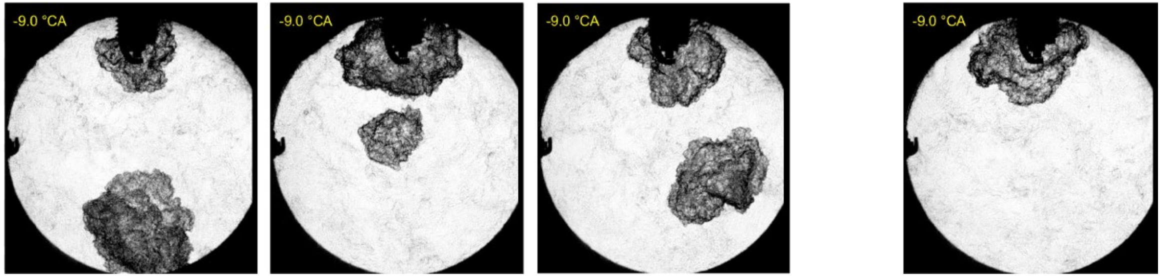
Lam. flame speed	0.2 - 0.25 m/s	0.38 m/s	3.5 m/s	0.07 m/s	0.4 - 0.5 m/s	0.3 m/s	0.2 m/s

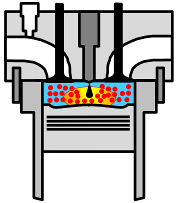
H_2

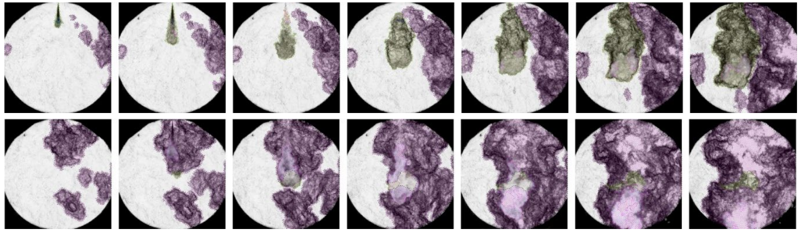




→ i.e. lubricating oil induced susceptibility to pre-ignition

CH_4/air charge



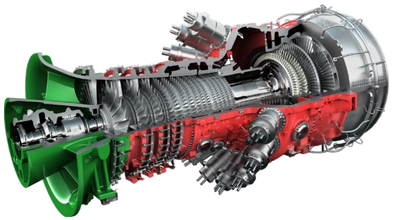


SFOE / FVV project "PREFER"
FHNW, IFS Uni Stuttgart

Combined Heat and Power Generation (CHP)

Gas/steam turbines, IC engines

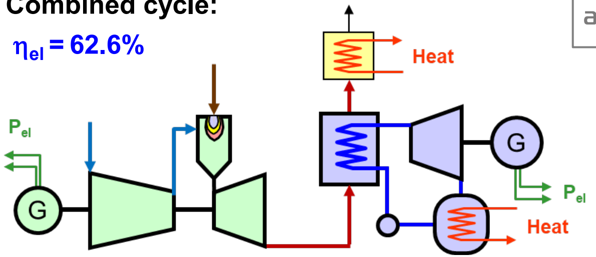
Ansaldo GT36



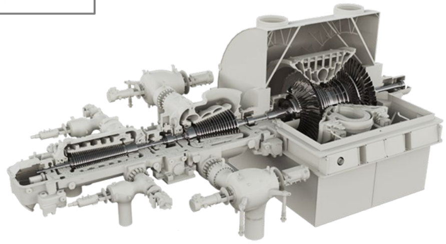
P = 78 – 560 MW η = 43%

Combined cycle:

η_{el} **= 62.6%**

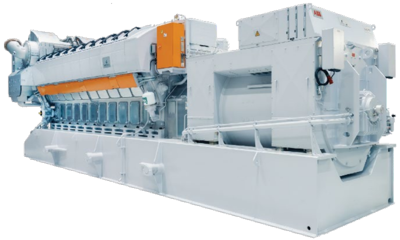


P = 120 – 800 MW



Power generation / Combined Heat & Power (CHP)

P$_{el}$ = 11.4 – 11.8 MW η_{el} **= 50.2%**



Wärtsilä 31DF **multi-fuel** engine

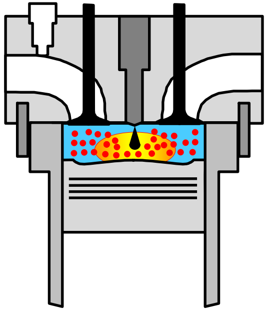
η_{el} **= 52.1%**   **P$_{el}$ = 10.4 – 12.8 MW**

Wärtsilä 31SG **gas** engine

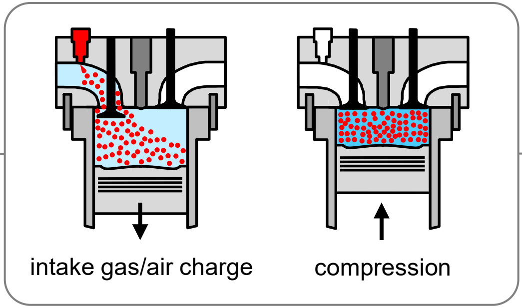
Large IC Engines

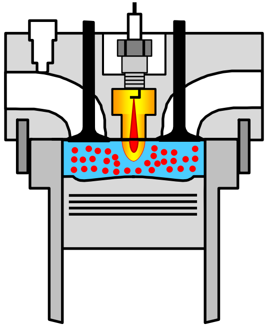
Gas engine (ignition) concepts

"Otto" principle (premixed)



Ignition by pilot-fuel spray

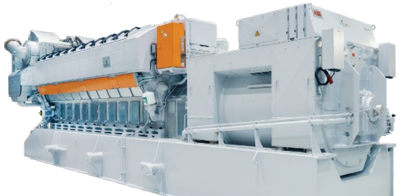




Ignition by pre-chamber jet

Power generation / Combined Heat & Power (CHP)

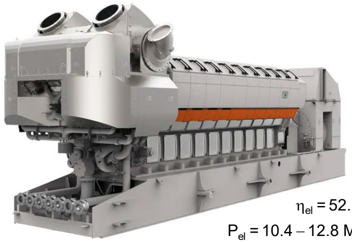
Natural gas, Biogas, E-Methane
Diesel, LFO / Biodiesel, HVO



$\eta_{el} = 50.2\%$
$P_{el} = 11.4 – 11.8$ MW

Wärtsilä 31DF **multi-fuel** engine

Natural gas, Biogas, E-Methane
25% H_2-blends / pure H_2 (2026)

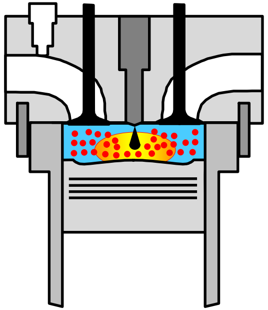


$\eta_{el} = 52.1\%$
$P_{el} = 10.4 – 12.8$ MW

Wärtsilä 31SG **gas** engine

Ammonia (NH_3) vs. Methane (CH_4)

Premixed pilot fuel ignited dual-fuel combustion



Ignition by pilot-fuel spray

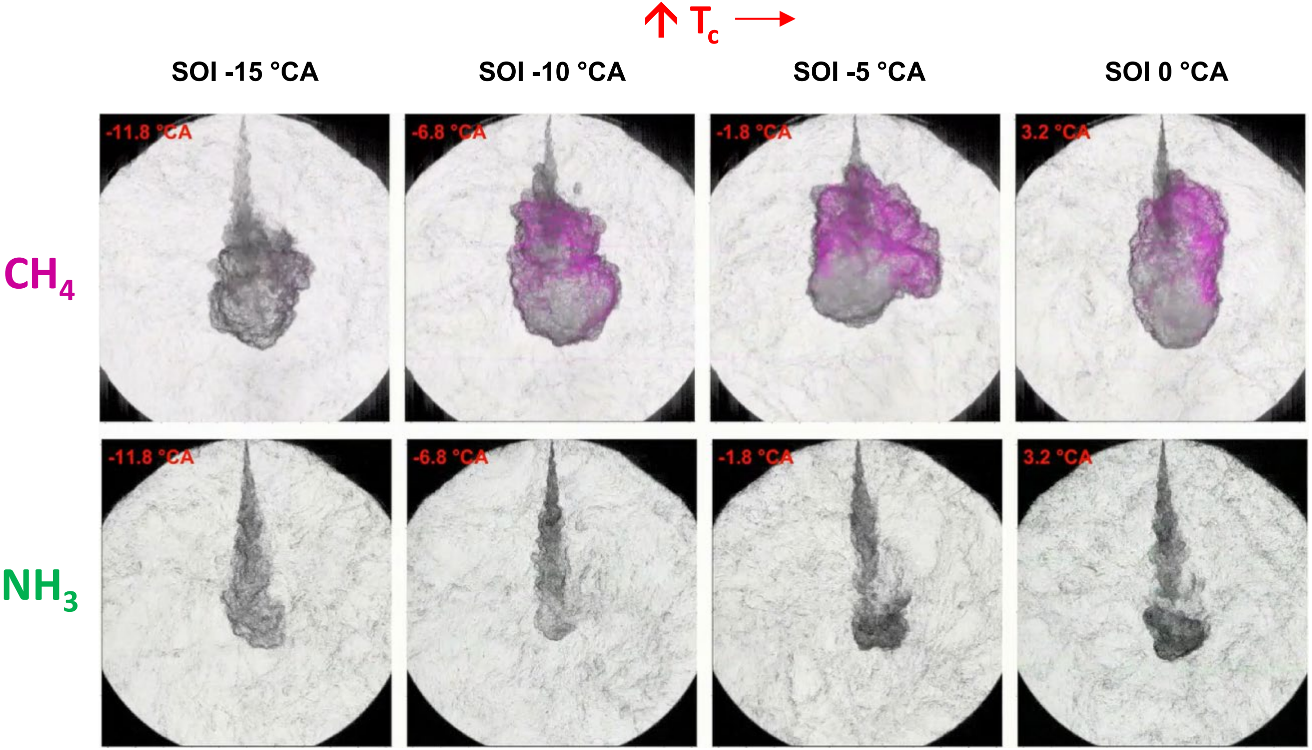
Investigations

→ Ignition delay (location)

→ Flame propagation

→ Heat release

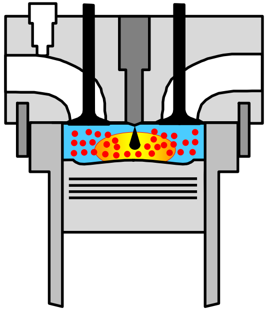
→ Cyclic stability (COV)



Simultaneous Schlieren / OH* chemiluminescence

Ammonia (NH_3) vs. Methane (CH_4)

Premixed pilot fuel ignited dual-fuel combustion



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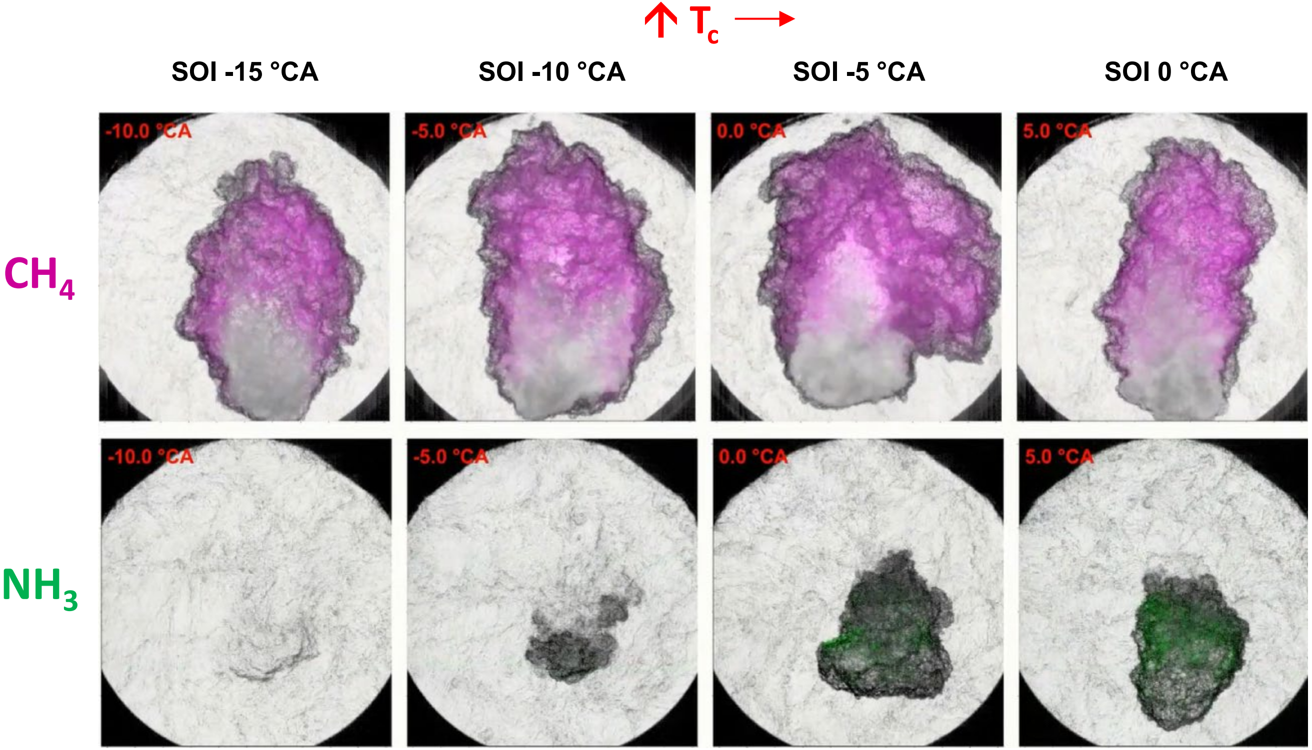
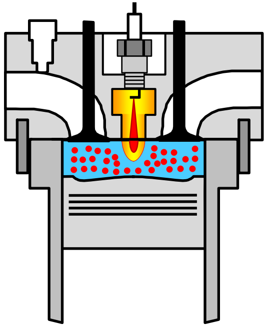


Simultaneous Schlieren / OH* chemiluminescence

Ammonia (NH_3)

Pre-chamber fuel variation



Ignition by pre-chamber jet

Investigations

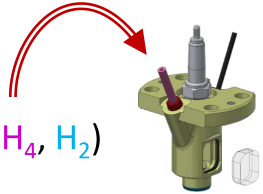
→ Ignition delay (location)

→ Flame propagation

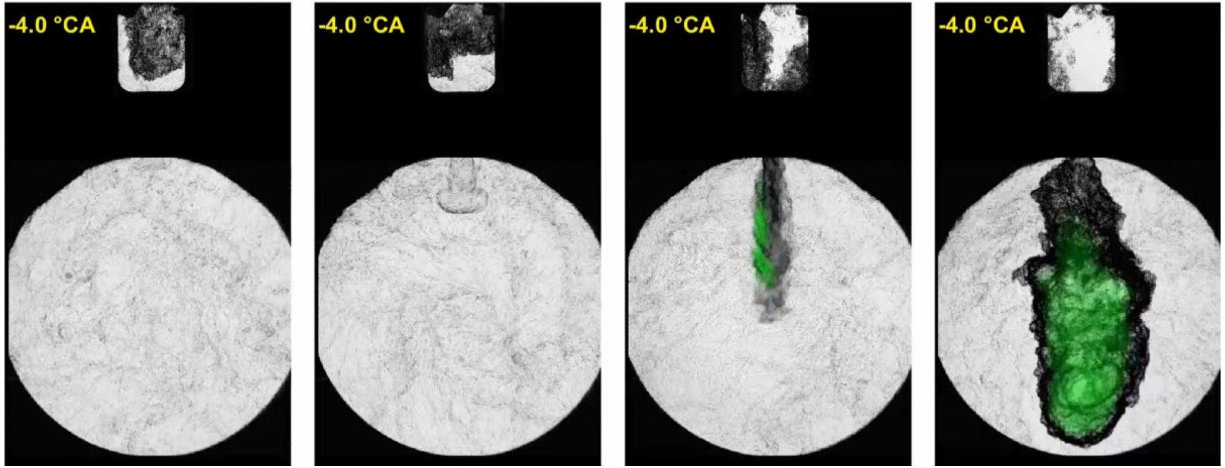
→ Heat release

→ Cyclic stability (COV)

→ **pre-chamber**: actively filled by **other fuels** (NH_3, CH_4, H_2) to achieve **stoichiometric conditions** ($\lambda_{PC} \approx 1.0$)



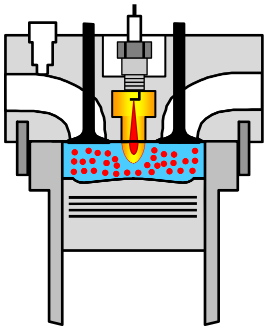
NH_3 addition | **CH_4 addition** | **H_2 addition**



→ **main chamber**: premixed **ammonia (NH_3)/air** charge ($\lambda = 1.2$)

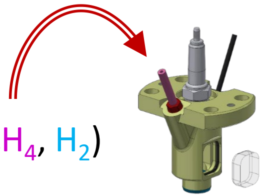
Ammonia (NH_3)

Pre-chamber fuel variation

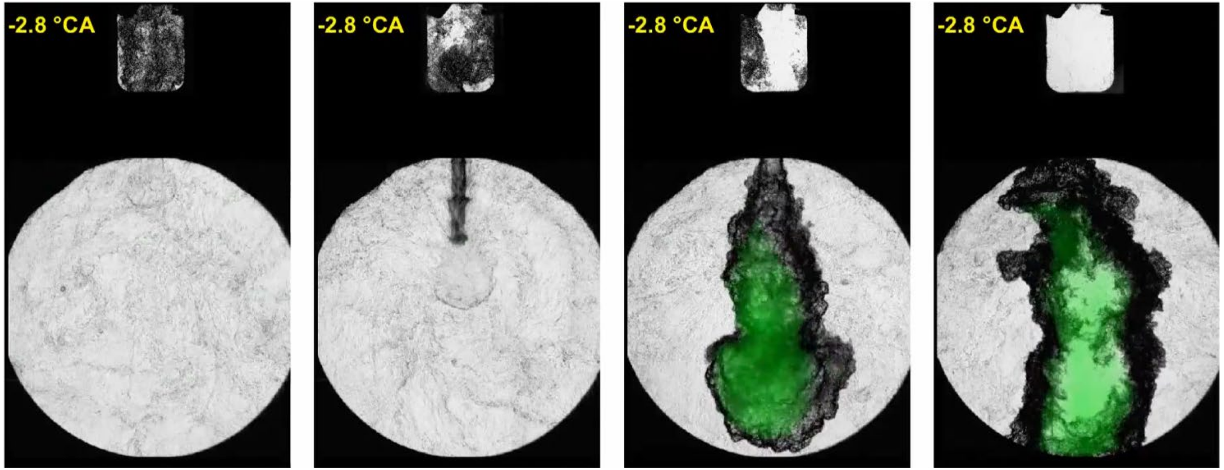


Ignition by pre-chamber jet

→ **pre-chamber**: actively filled by **other fuels** (NH_3, CH_4, H_2) to achieve **stoichiometric conditions** ($\lambda_{PC} \approx 1.0$)



NH_3 addition | **CH_4 addition** | **H_2 addition**



→ **main chamber**: premixed **ammonia (NH_3)/air** charge ($\lambda = 1.2$)

Investigations

→ Ignition delay (location)

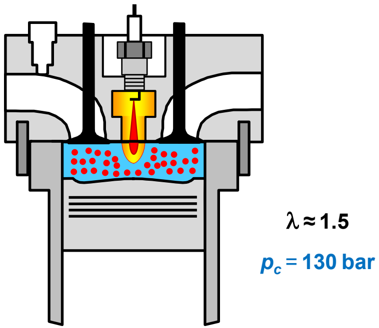
→ Flame propagation

→ Heat release

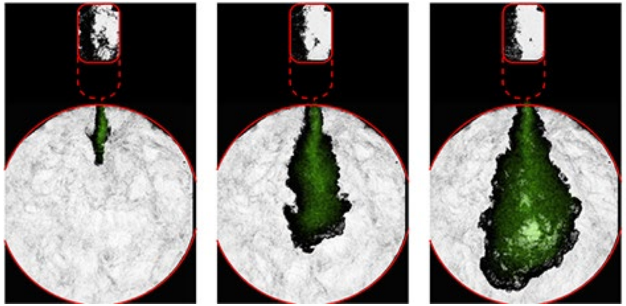
→ Cyclic stability (COV)

Ammonia (NH_3)

Pure ammonia investigations



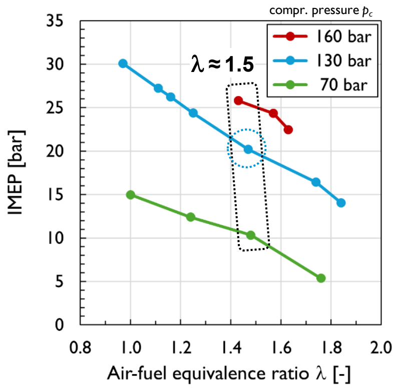
Ignition by pre-chamber jet

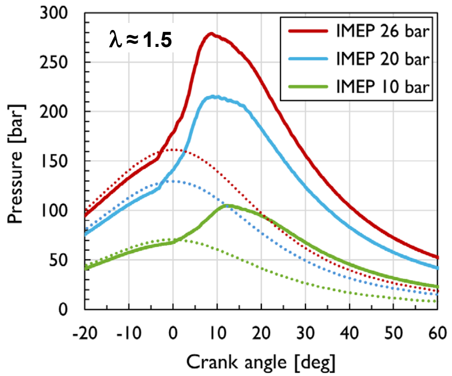


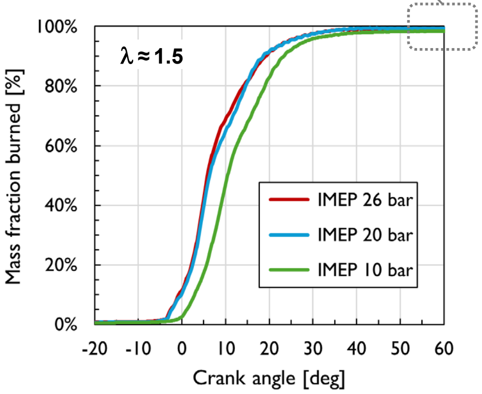
SFOE project "CREDO"
WinGD *(co-financing)*
FHNW, WinGD, CFS

WIN GD
combustion and flow solutions

N_2O: × 298 ↑ GWP than CO_2

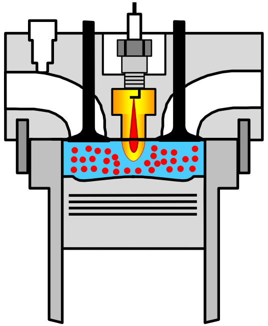




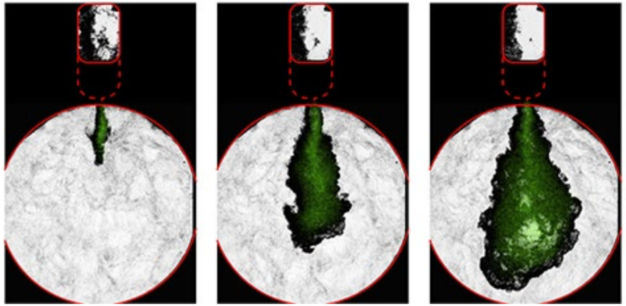


Ammonia (NH_3)

N_2O emissions



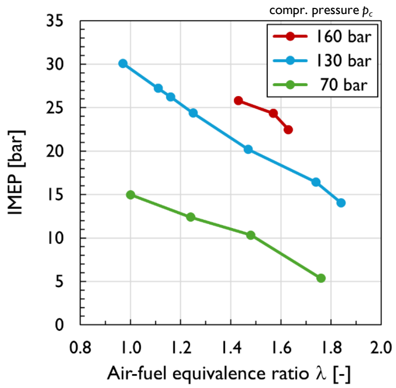
Ignition by pre-chamber jet

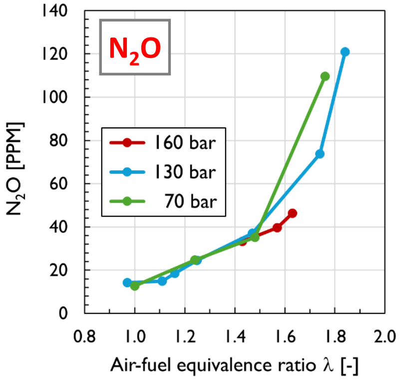


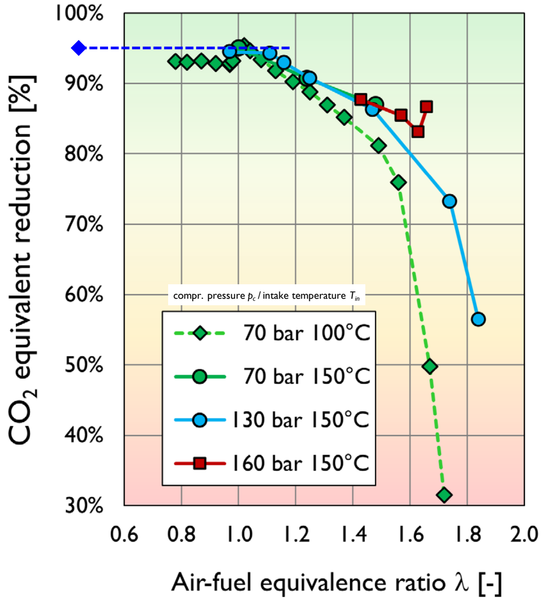
SFOE / FVV project "N2Ooff"
PSI, FHNW

→ NO_X / N_2O exhaust gas catalyst

N_2O: × 298 ↑ GWP than CO_2

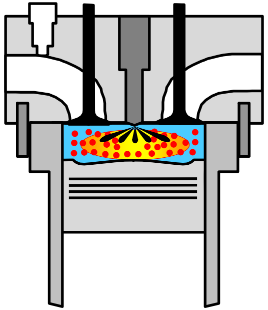






Methanol (CH_3OH)

CI combustion process



"E-Methanol Diesel"

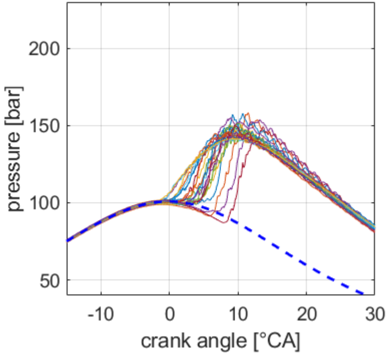
New Holland FR920 Corn chopper
FPT Vector20: **4095 Nm, 670 kW**

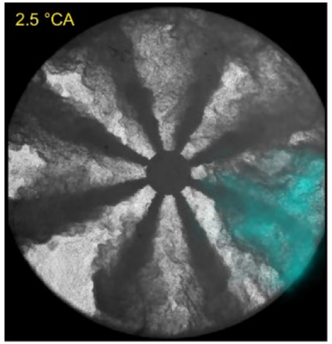
Requirements

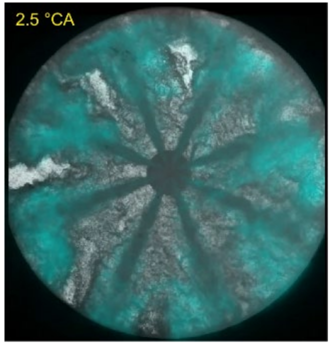
- Efficiency
- Power density
- Fuel storage & demand
- Operational conditions:
  - robustness,
  - rough environment

SFOE / FPT project "EMOCION"
SBB, armasuisse *(co-financing)*
FHNW, Empa, CFS

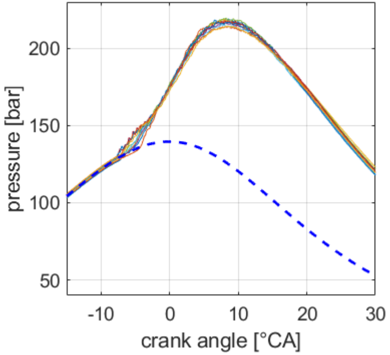
"standard" conditions





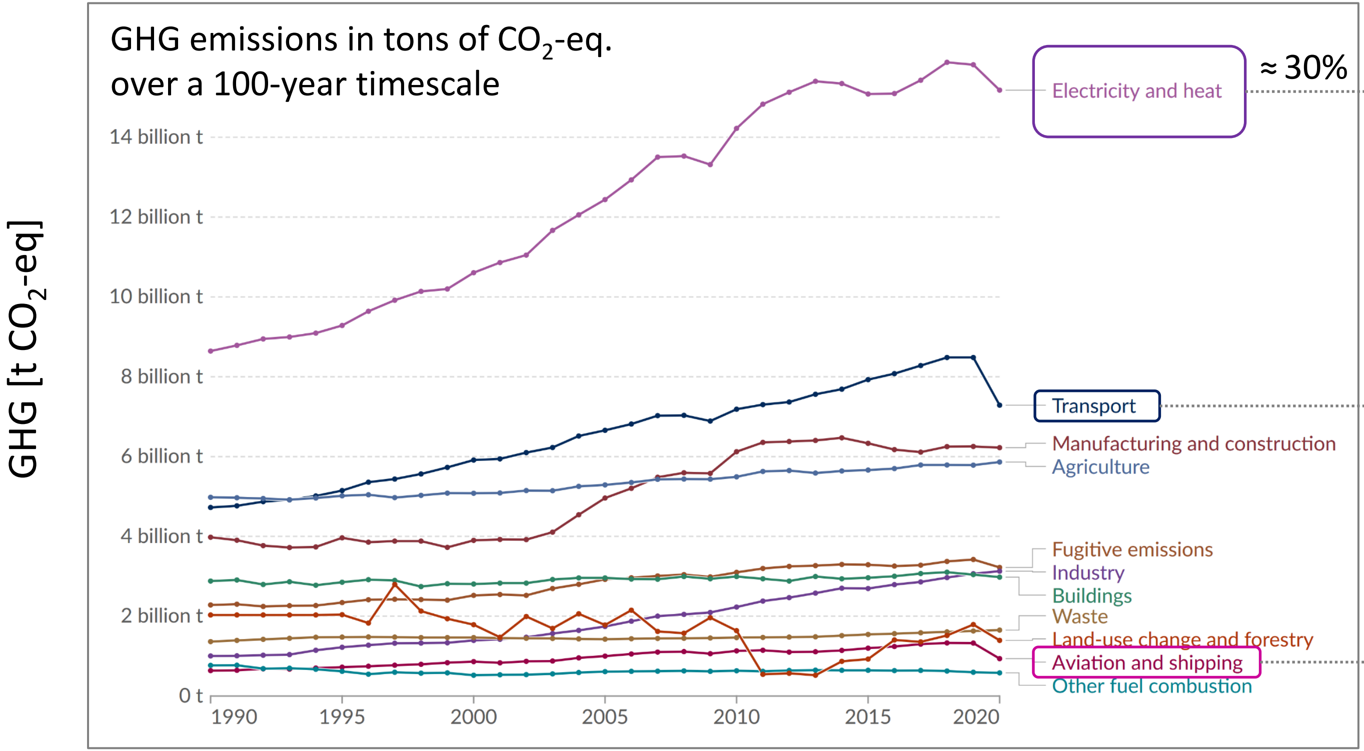


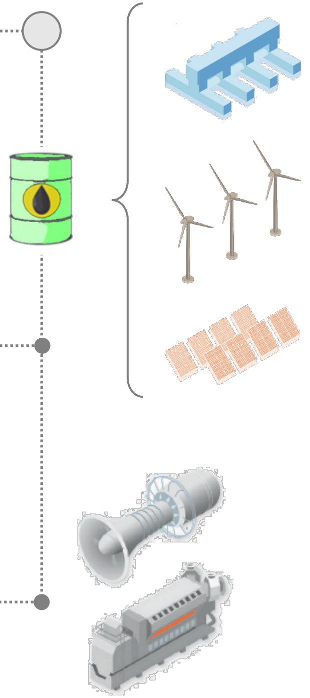
"improved" conditions



Relevance

Greenhouse gas emission (GHG) by sector worldwide





Our World in Data

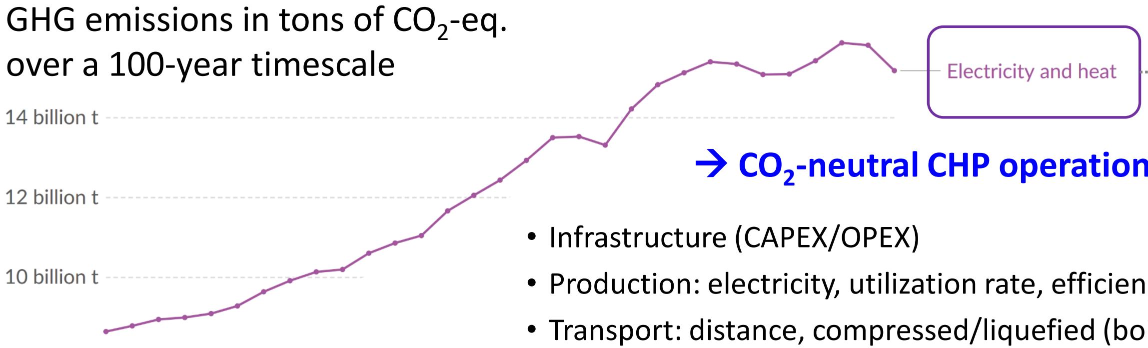
Climate Watch (2023) by Our World in Data https://ourworldindata.org/co2-and-greenhouse-gas-emissions

Image source: Wärtsilä Corporation

Relevance

Greenhouse gas emission (GHG) by sector worldwide

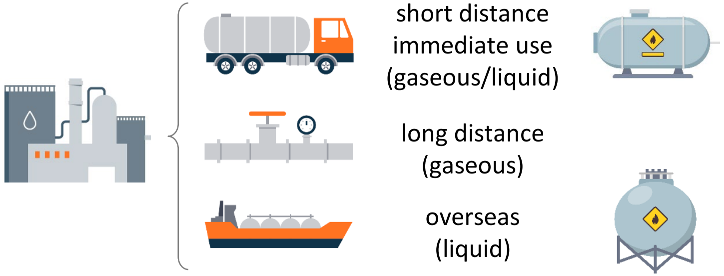
GHG [t CO_2-eq]



≈ 30%

→ **CO_2-neutral CHP operation !!!**

- Infrastructure (CAPEX/OPEX)
- Production: electricity, utilization rate, efficiency
- Transport: distance, compressed/liquefied (boil-off)
- Storage: systems, volume, short/long duration



short distance
immediate use
(gaseous/liquid)

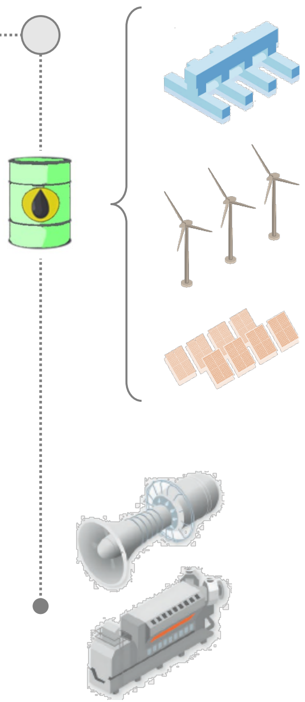
long distance
(gaseous)

overseas
(liquid)

→ **which fuel?**

H_2 CH_4 NH_3 CH_3OH

need: immediate vs. flexible use



Our World in Data

Climate Watch (2023) by Our World in Data https://ourworldindata.org/co2-and-greenhouse-gas-emissions

Image source: Wärtsilä Corporation

Conclusions

Research

- Establishment of **"optical engine" test facilities**
- Carrying out **optical** & **thermodynamic analysis**
- Investigation of **carbon-reduced combustion**

  → CH_4 , H_2 , NH_3 , CH_3OH / blends: H_2/CH_4 , H_2/NH_3
- Exhaust **emission** measurement: N_2O, NO_X , …
- Evaluation of **renewable PtX synthetic fuels**

  → **diversification according to use**

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Collaboration

→ attention in the **research community** (CH & Intl.)

→ Accelleron, combustion and flow solutions, DUAP, FPT, GANSER, KISTLER, WIN GD, BOSCH, DEUTZ, HATZ DIESEL, L'orange, PORSCHE

Publications

S. Wüthrich, P. Albrecht, P. Cartier, K. Herrmann, "*The GHG reduction potential of high-IMEP pure ammonia combustion*", Prof. Dr.-Ing. Bert Buchholz (Editor), The Future of Large Engines, 8th Large Engine Symposium, Rostock 2024.

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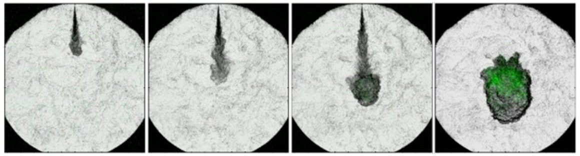
K. Herrmann, S. Wüthrich, P. Cartier, P. Süess, R. de Moura, G. Weisser, "*Initial investigations into ammonia combustion at conditions relevant for marine engines*", #396, 30th CIMAC World Congress on Combustion Engine Technology, June 12-16, 2023, Busan, South Korea.

S. Wüthrich, P. Albrecht, P. Cartier, K. Herrmann, "*Comparison of pilot fuel ignited premixed ammonia versus methane dual-fuel combustion*", Prof. Dr.-Ing. Bert Buchholz (Editor), The Future of Large Engines, 7th Large Engine Symposium, Rostock 2022.

S. Wüthrich, P. Cartier, P. Süess, B. Schneider, P. Obrecht, and K. Herrmann, "*Optical investigation and thermodynamic analysis of premixed ammonia dual-fuel combustion initiated by dodecane pilot fuel*", Fuel Communications 12 (2022) 100074.

Thank you very much for your kind attention!



→ *comments, suggestions, questions?*