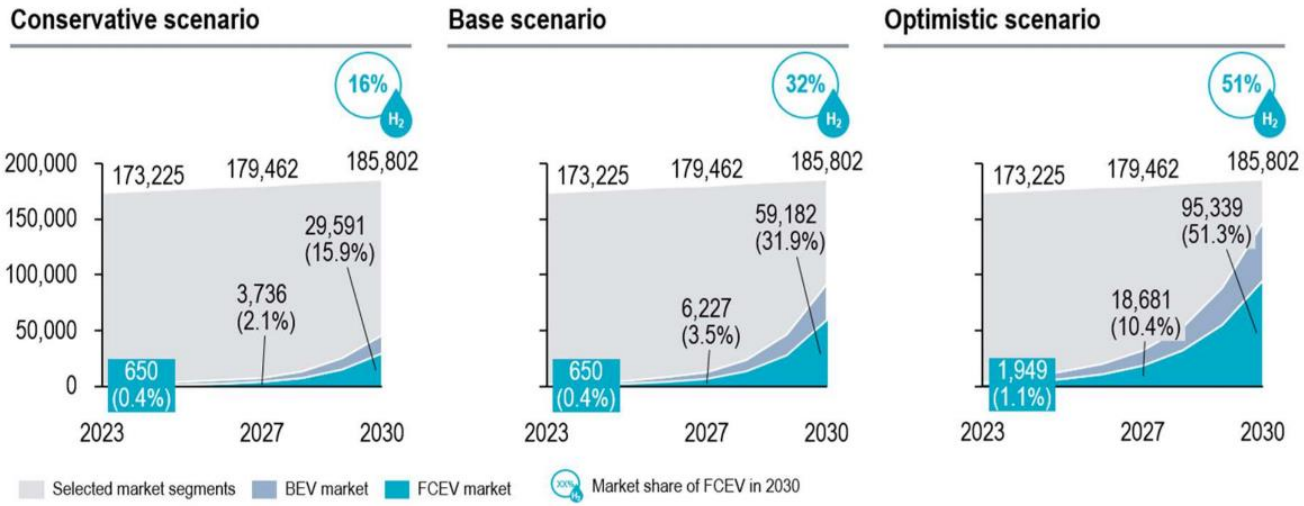
The H2 Revolution: Buckle Up for the Latest Developments in Hydrogen

GAMMA TECHNOLOGIES

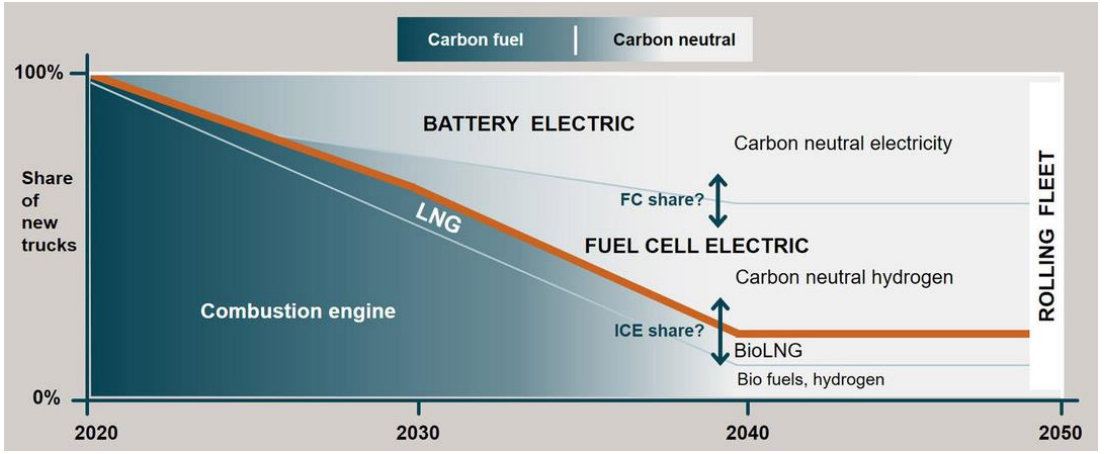

PRESS

The Transformation is Happening

- Reshaping the industry by …
  - Decarbonization and increased efficiency
  - Trends in electrification *(BEV, HEV, PHEV, FCEV)*
  - Digitization, shared mobility, vehicle connectivity and autonomous driving

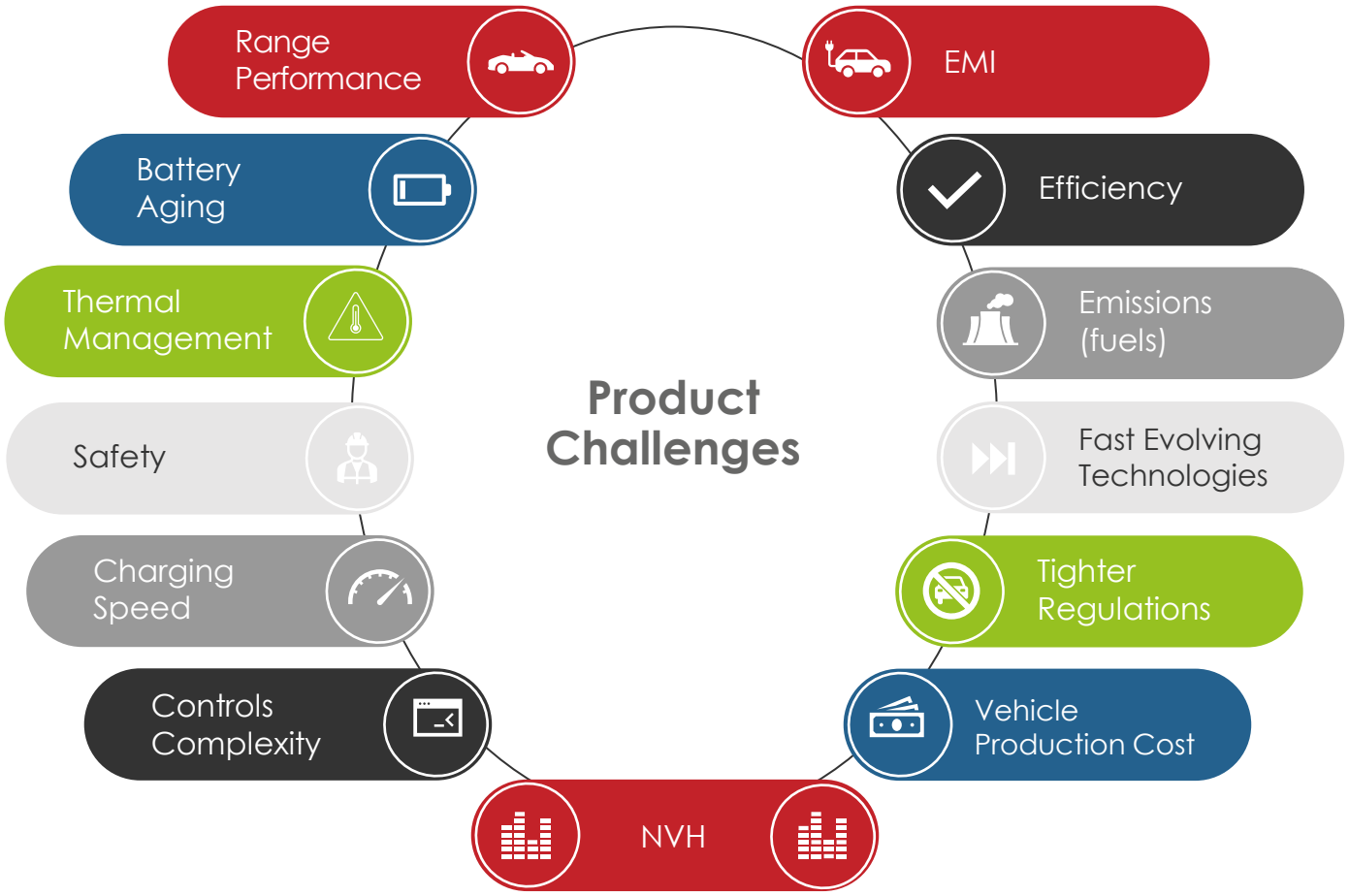


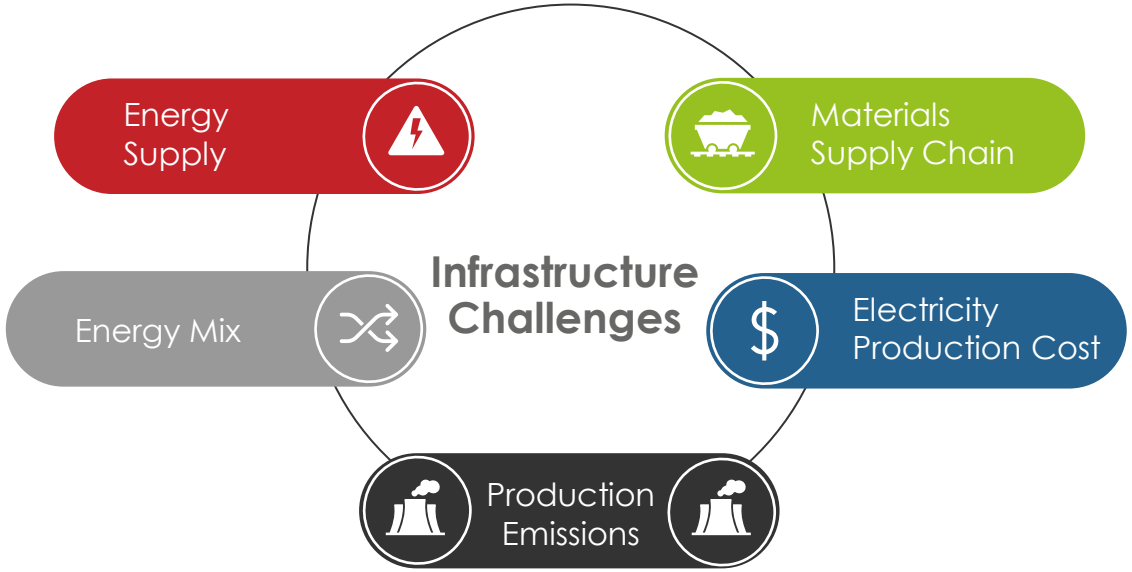
Source: Roland Berger



Source: Volvo Group

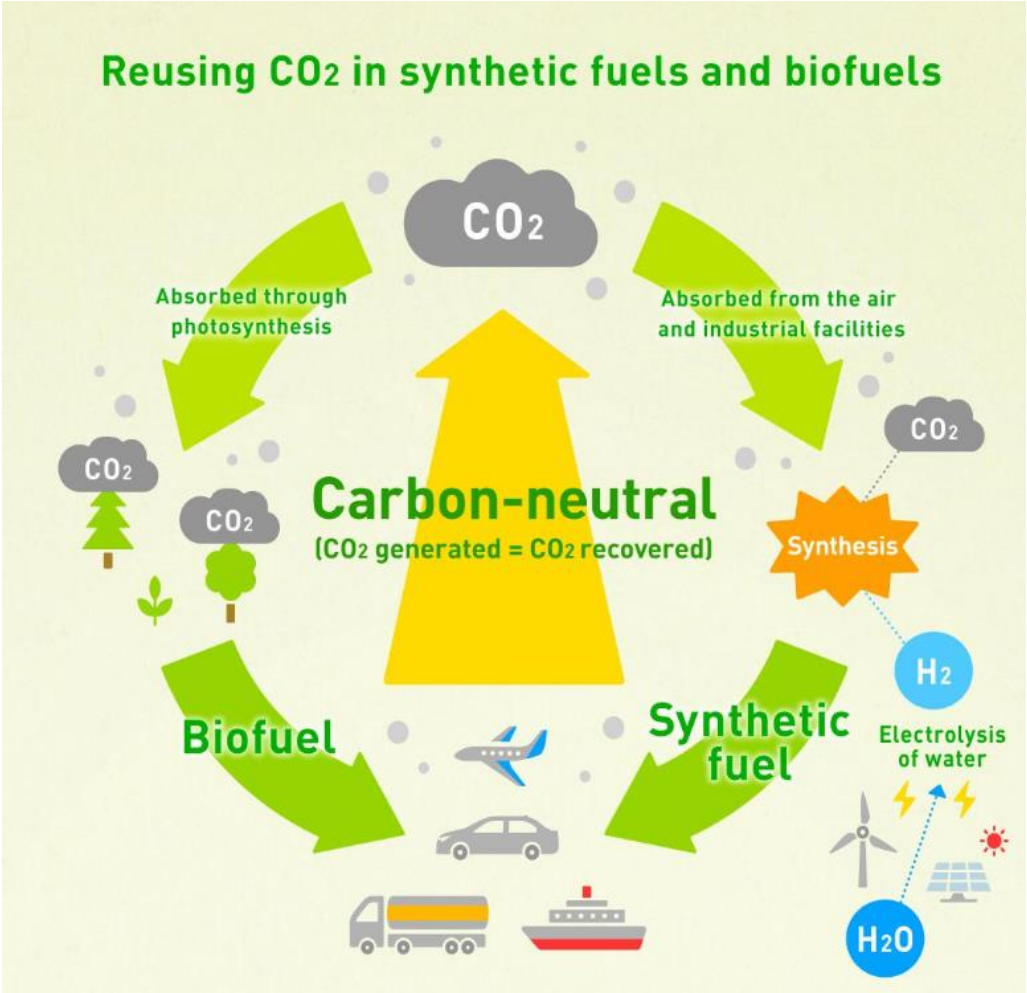
Challenges



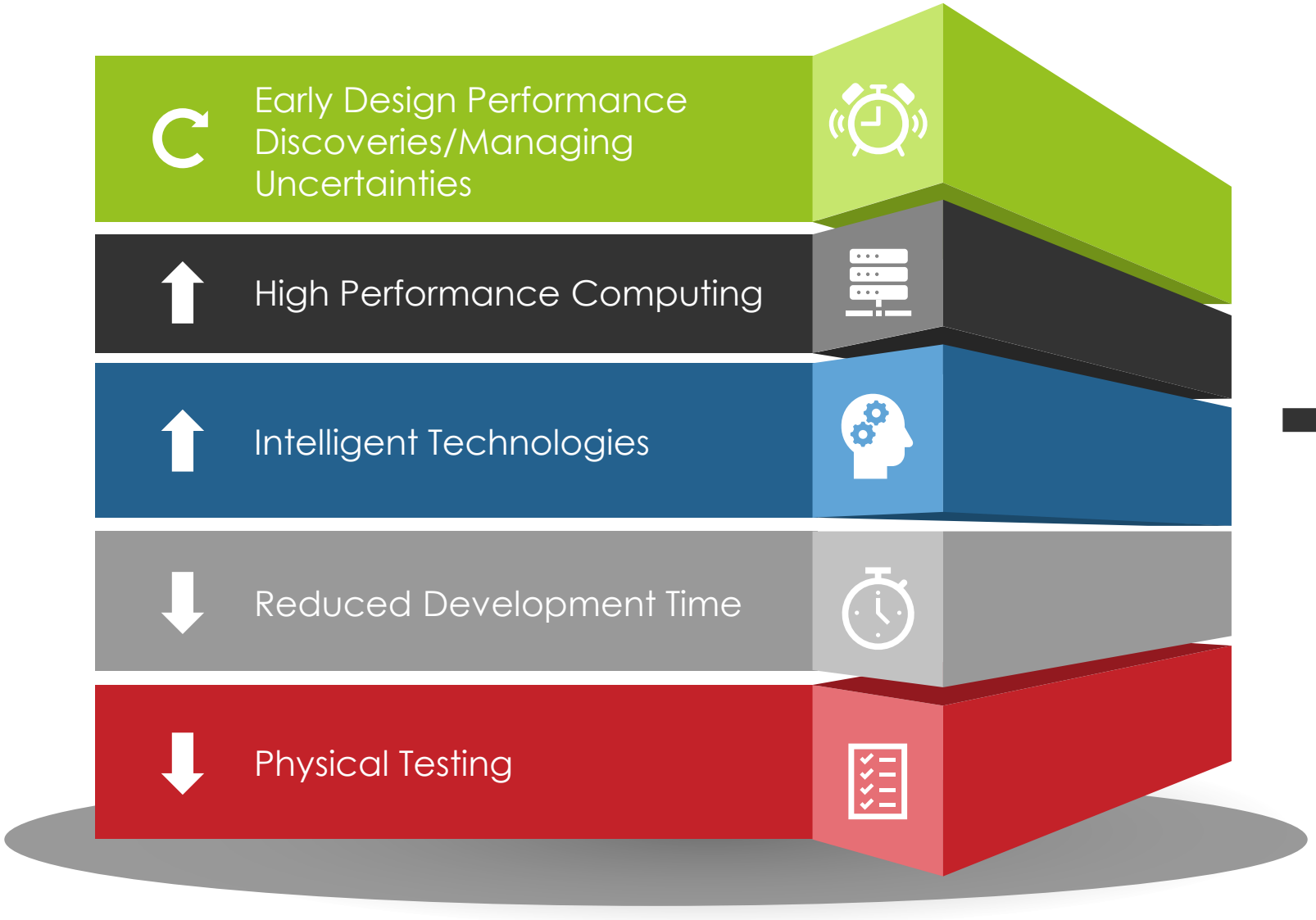


Where will ICE go?

- Industry trend towards Net-Zero Carbon (NZC) fuels continues:
  - H2 Engines are released
  - Certification of engines for 100% biodiesel by several makers
  - Research and infrastructure to make carbon-neutral fuels continues
- GT is keeping up with this trend
  - H2 & other fuels combustion capabilities
  - Biodiesel validated by users in global warming potential
  - Chemical systems team developing biomethane, green ammonia and reformer models

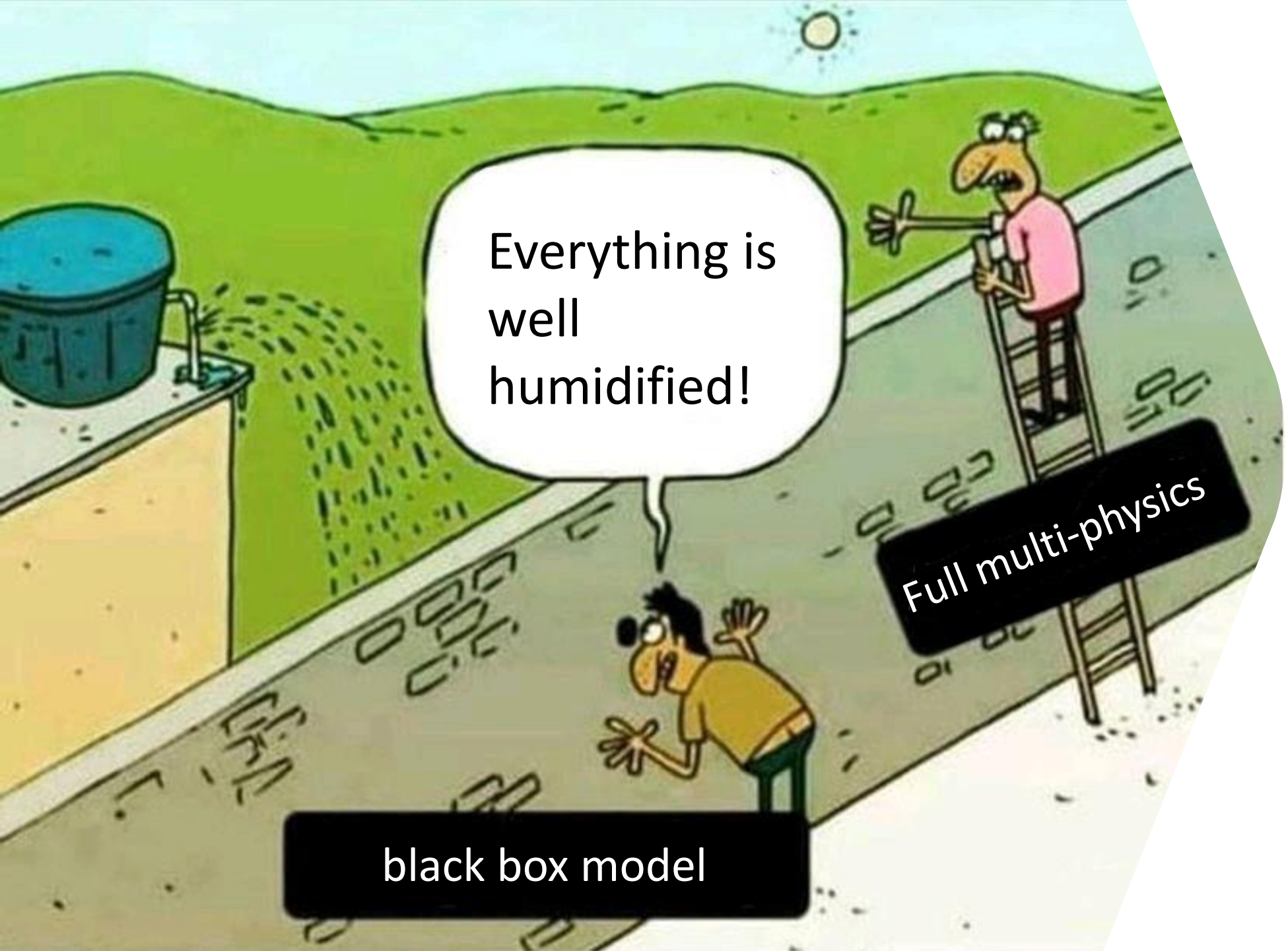


How to get the best out of each technology?



Increased Reliance on Simulation

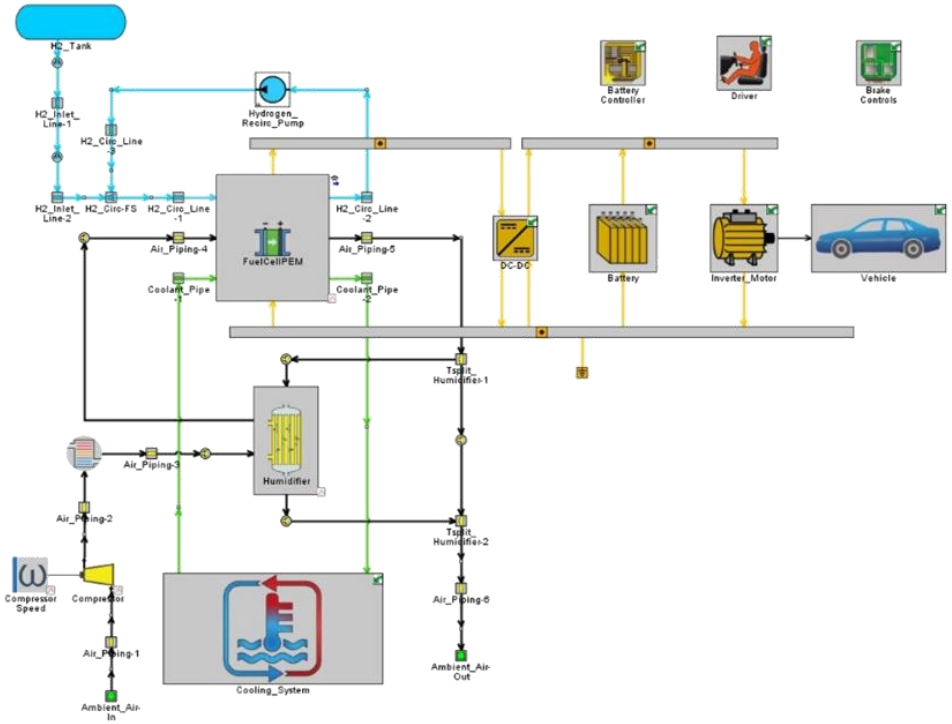
Virtualization of Complete Vehicle Design and Validation


Everything is well humidified!
Full multi-physics
black box model

GT Holistic Solution Overview

GT-SUITE is a versatile multi-physics platform for constructing models of general systems based on many underlying fundamental libraries:

- Flow library (any fluid, gas or liquid or mixture)
- Acoustics library (both non-linear and linear)
- Thermal library (all types of heat transfer)
- Mechanical library (kinematics, multi-body dynamics, frequency domain)
- Electric and Electromagnetic library (circuits, electromechanical devices)
- Chemistry library (chemical kinetics)
- Controls library (signal processing)
- Built-in 3D CFD and 3D FE (thermal and structural)



Challenges of Fuel Cell Developments

A Fuel Cell is a very complex System:

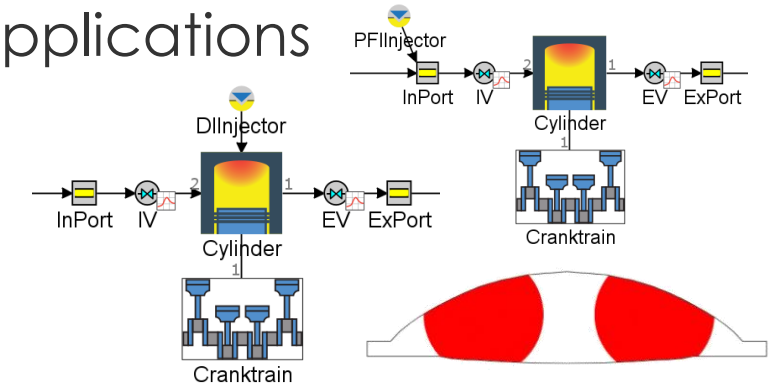
- Interaction of all the operating parameters such as
  - Power demand
  - System temperature
  - External conditions including humidity and temperature

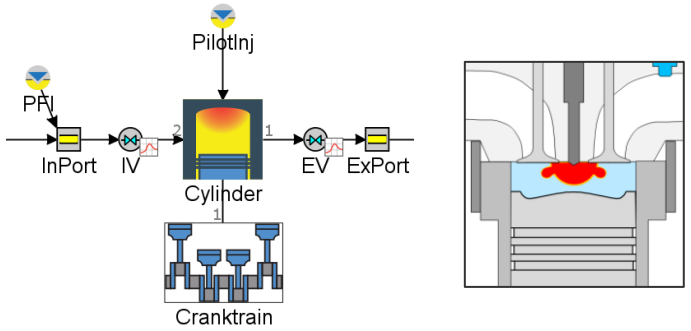
A Fuel Cell stack needs to be operated within an optimum operating range:

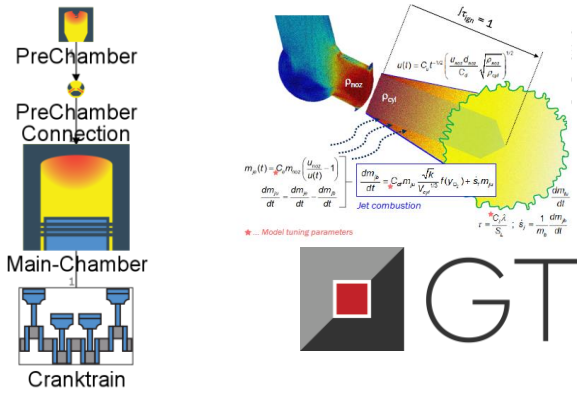
- Quality of the operating strategy is critical for a long lifetime of the fuel cell
- Avoid degradation and optimize durability.
- Maximize power output of the fuel cell
- Reduce the relative cost $/kW

Hydrogen ICE - Predictive Combustion in GT-SUITE

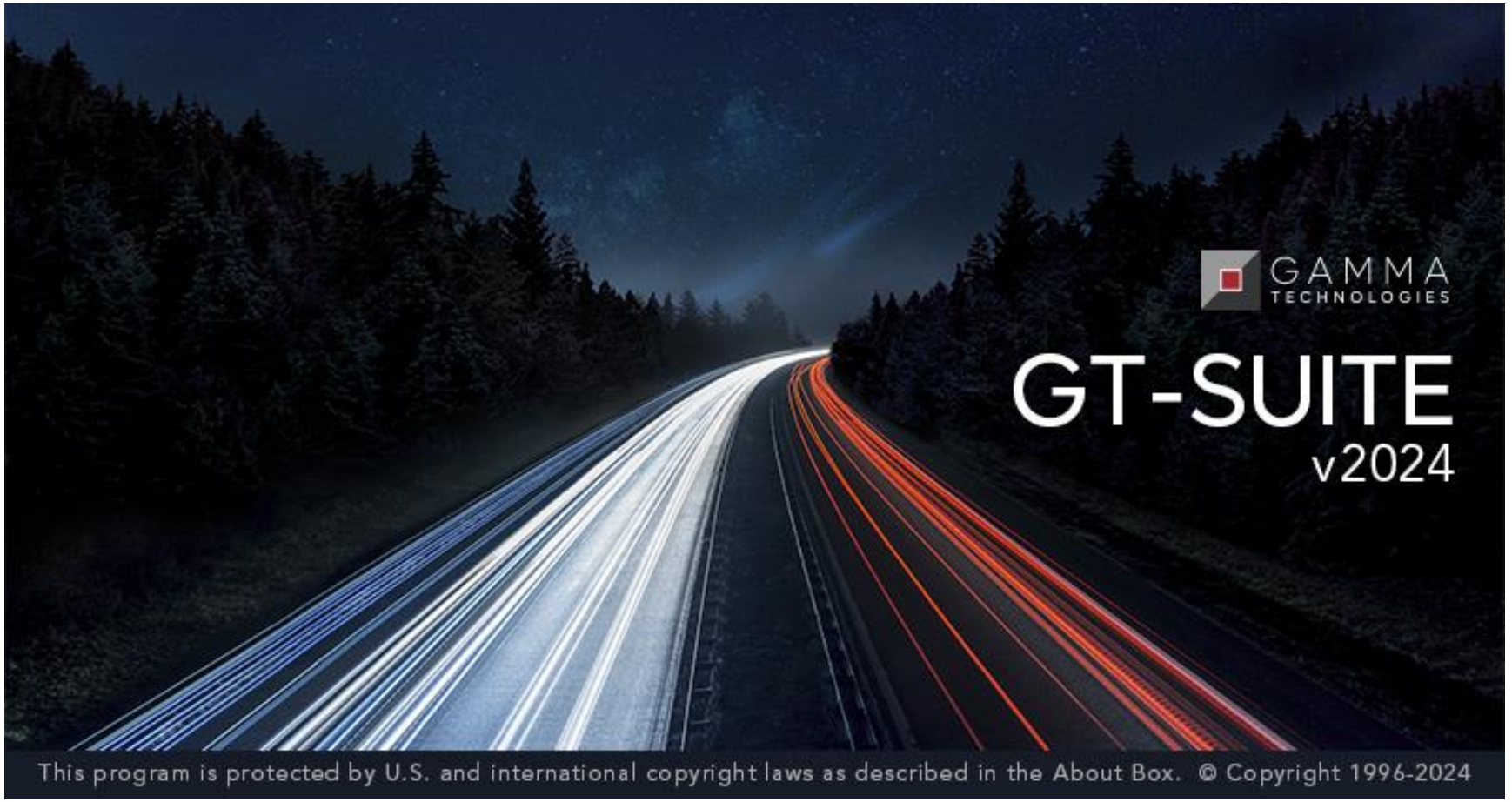
- GT-SUITE supports predictive H2 combustion in different applications
  - Spark-Ignited Engines
    - Can be used for port fuel injection and direct injection
    - Mixture formation, flame propagation and flame-wall interaction (EngCylCombSITurb)
    - Most commonly used for predictive H2 ICE
  - Dual Fuel Engines
    - Predictive pilot injection ignition + predictive flame transition and propagation (EngCylCombDualFuel)
    - High pressure direct injection of two different fuels (EngCylCombDIPulse)
    - E.g., Direct-injected H2 / NH3 ignited by a pilot fuel like Diesel
  - Pre-Chamber Engines
    - Mass and heat transfer between pre- and main-chamber
    - Predictive combustion in both pre-chamber (EngCylCombSITurb) and main-chamber (EngCylCombJetIgnition) possible







What is new?



Membrane electrode assembly (MEA) Freezing

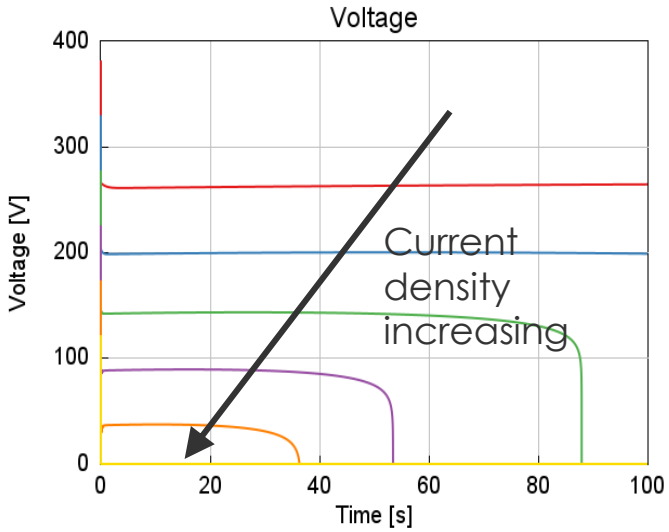
Water in MEA inevitable during operation

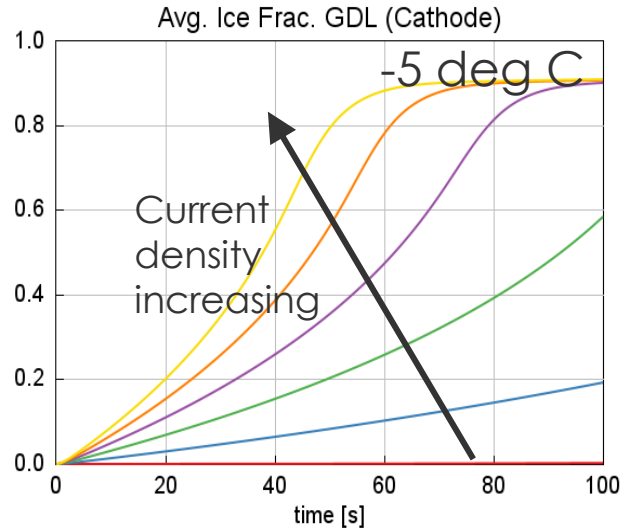
Requirements to start in sub-zero temperature lead to ice formation

Ice can reduce performance and damage cell

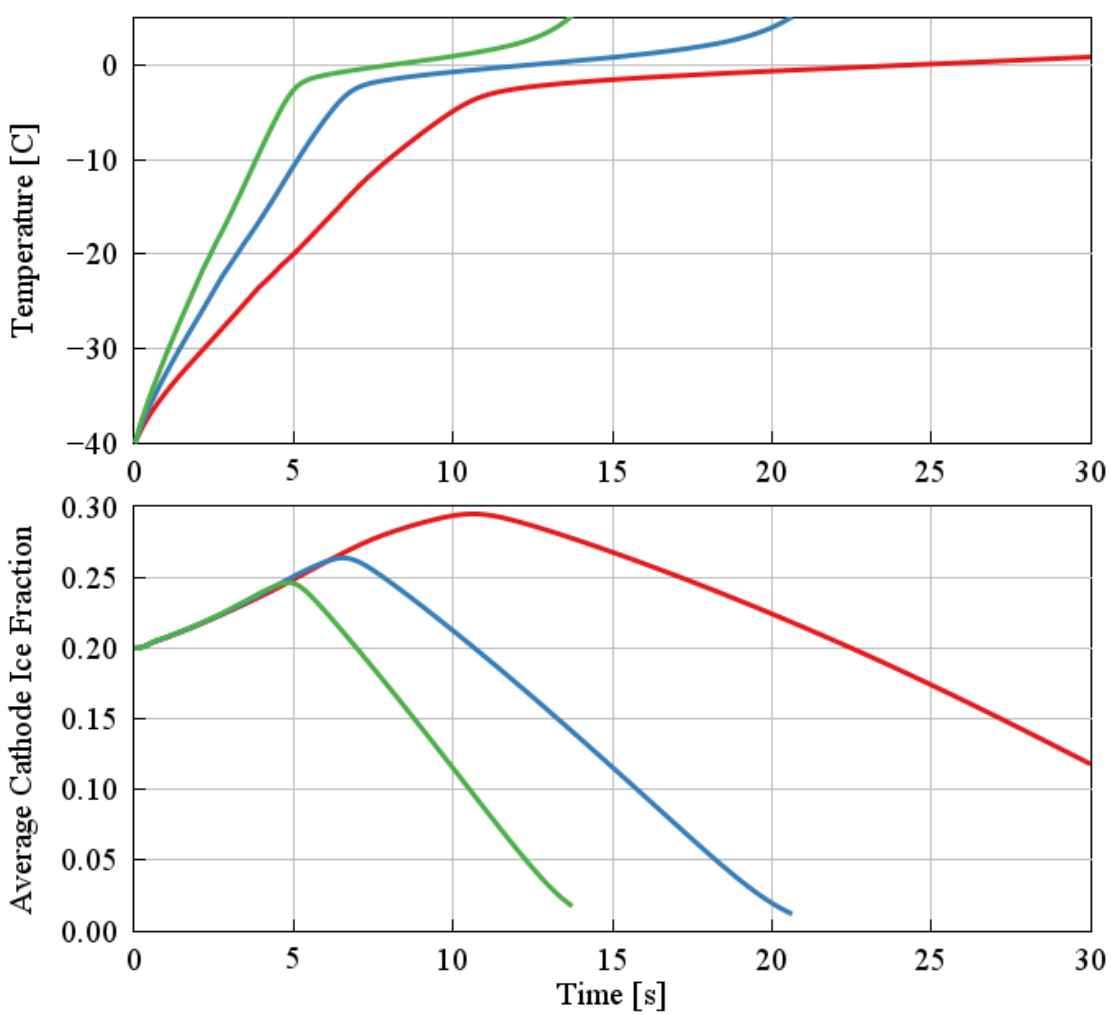
Phase change in GDL and membrane (CL in future):

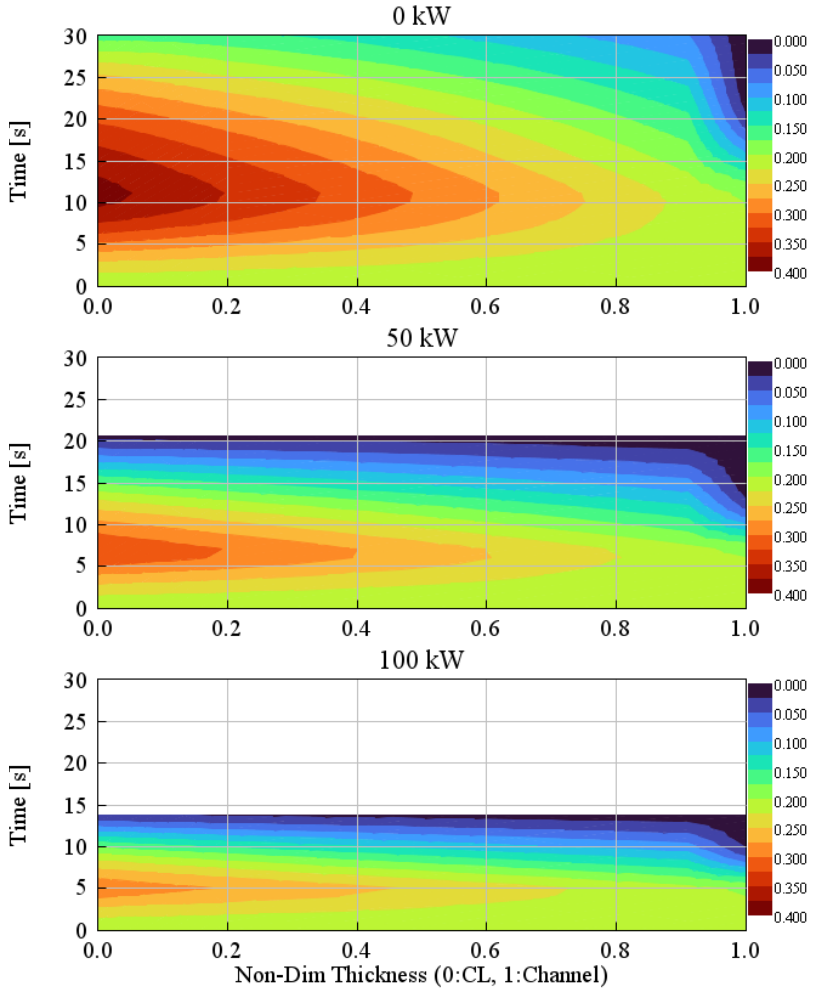
- Liquid to Ice (freezing)
- Ice to Liquid (melting)
- Vapor to Ice (deposition)
- Ice to Vapor (sublimation)





Fuel Cell Cold Start Modeling (external heater)

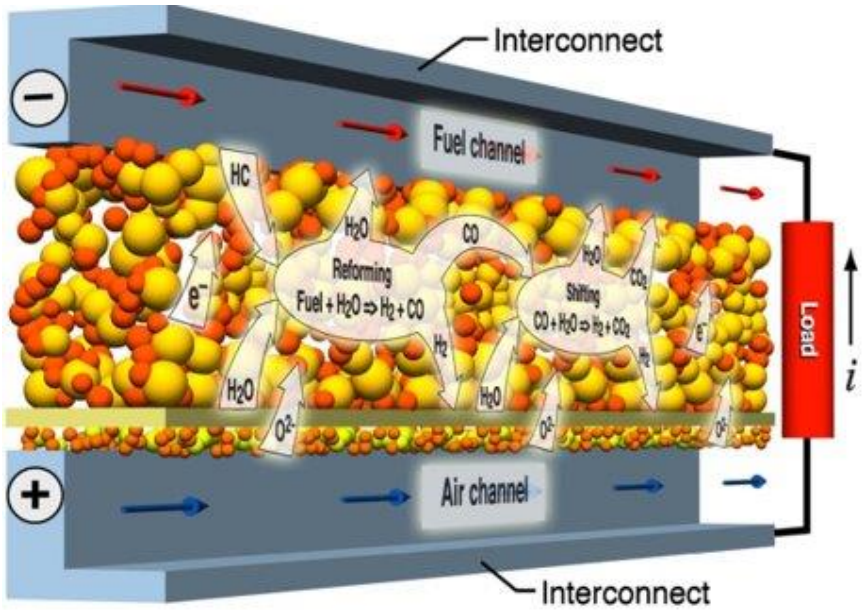




Note: All simulations with external heating maintained < 5 MJ of total energy consumption.

SOFC: Predictive E-Chem and Mass Transport

- Dynamic solution based on operating conditions of the cell:
  - Ohmic resistance through electrolyte
  - Exchange current density for Hydrogen Oxidation Reaction and Oxygen Reduction Reaction
  - Diffusion of species through support layers

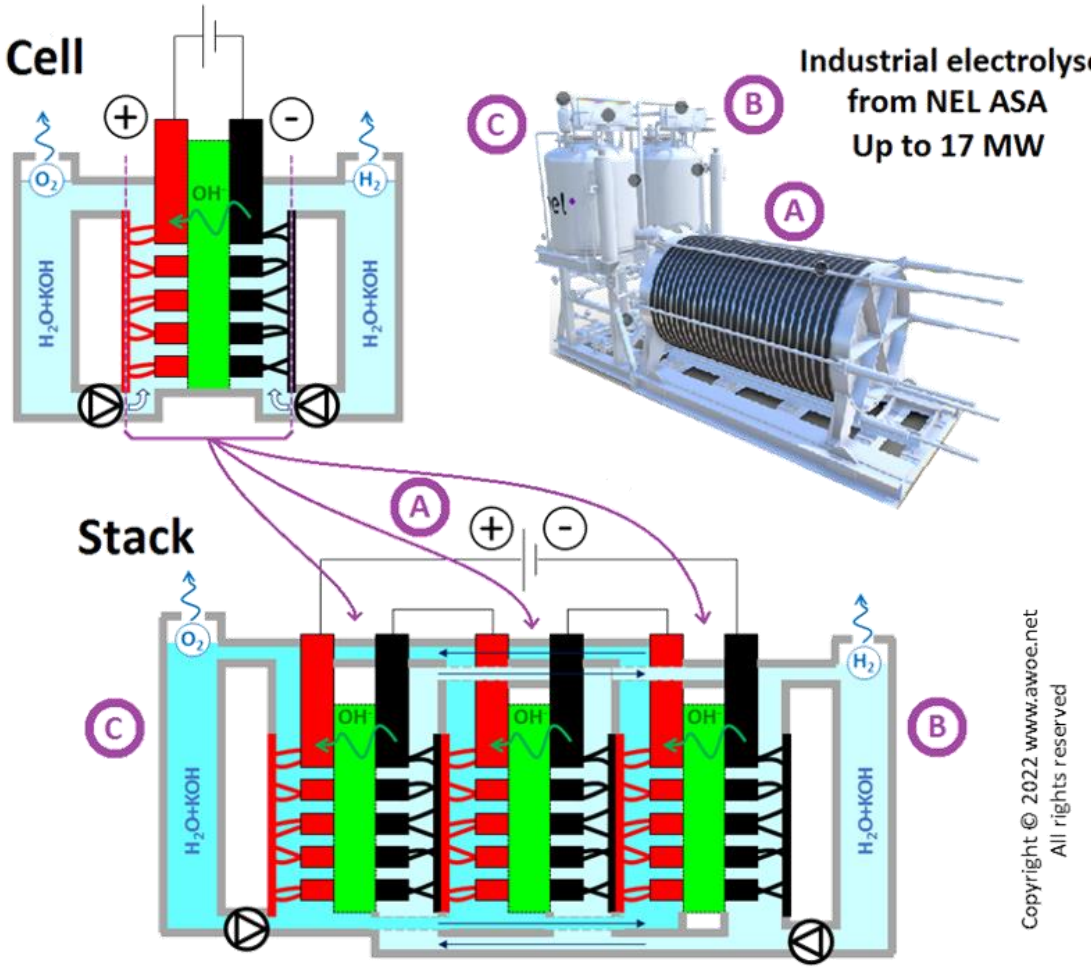


Source: Colorado School of Mines

Electrolyzer Enhancements

- Alkaline – new reference object for empirical e-chem (SpecsAEC)

- PEM - predictive exchange current density as function of temperature



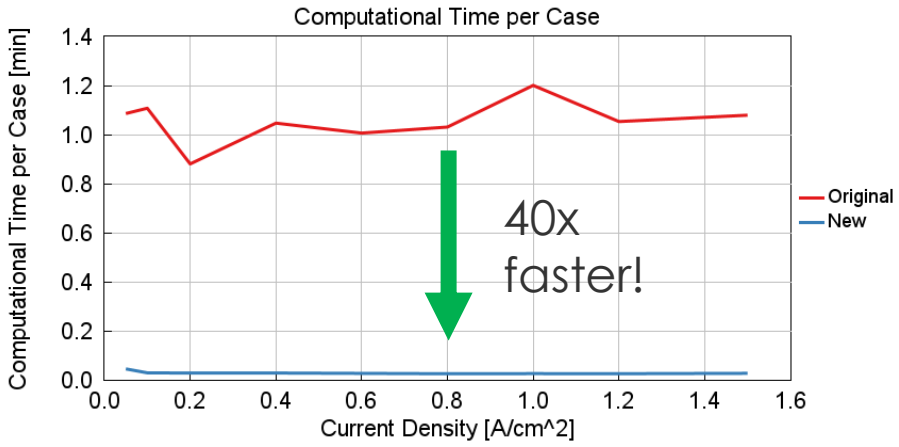
Implicit Solver Enhancements

```
*WARN:The implicit flow solution did not
converge (check FlowCircuit plots):
```

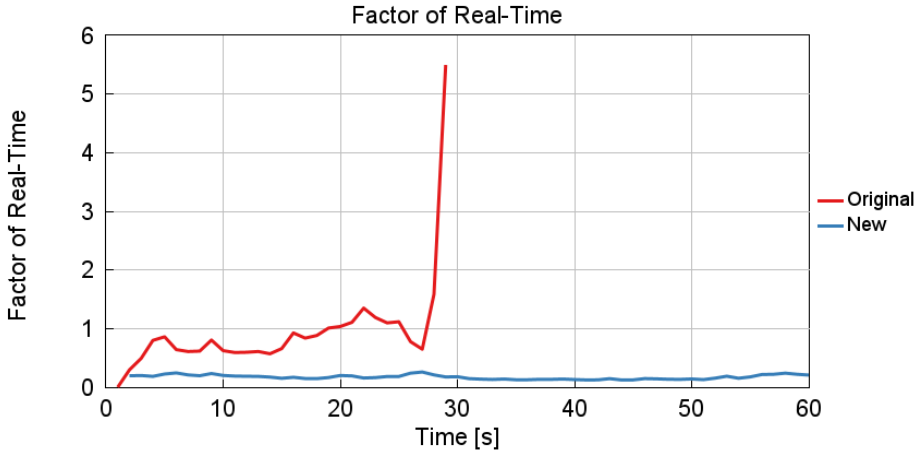
```
*FAIL:Species Mass Fractions
do not add to 1
```

- FASTER and more STABLE solution
  - Balanced Operator Splitting
  - Newton transport solution
  - Improved condensation
- Support GDL Liquid Saturation

Customer Test Bench

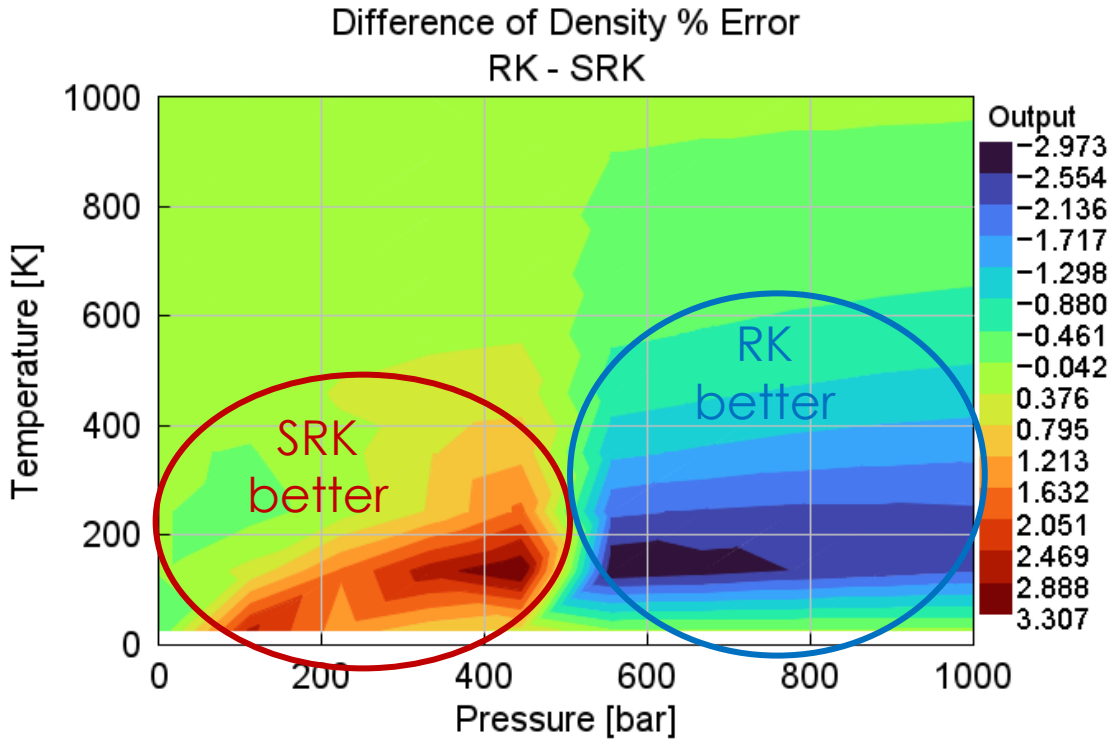


System Model



New equations of state – SRK & PR

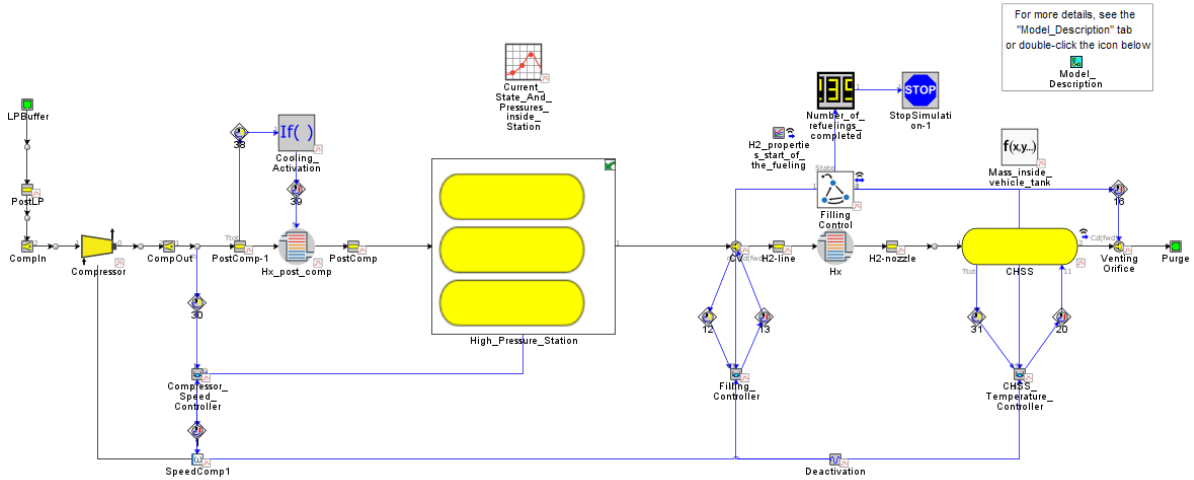
- 2 new equations of state available
  - Soave-Redlich-Kwong (SRK)
  - Peng-Robinson (PR)
- Consider the effect of the shape of fluid molecules in the calculation of the thermodynamic fluid properties
- Integrated in the Flow Solver as well as the LookupFluidProps template
- Acentric Factor added as attribute in FluidGas and FluidNASA-LiqGas templates



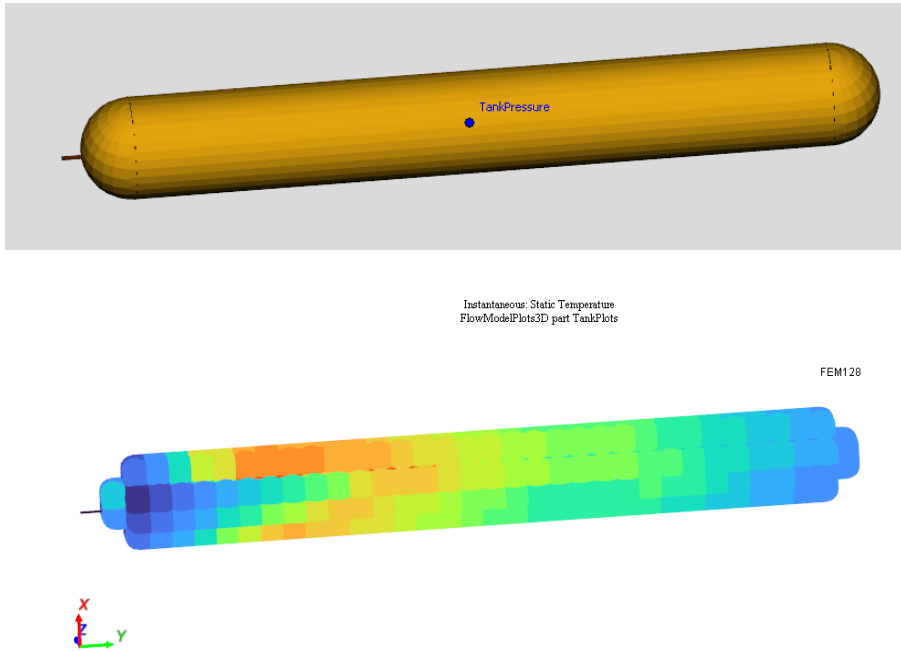
Compared to RefProp

New Example Models

- Hydrogen Filling Station

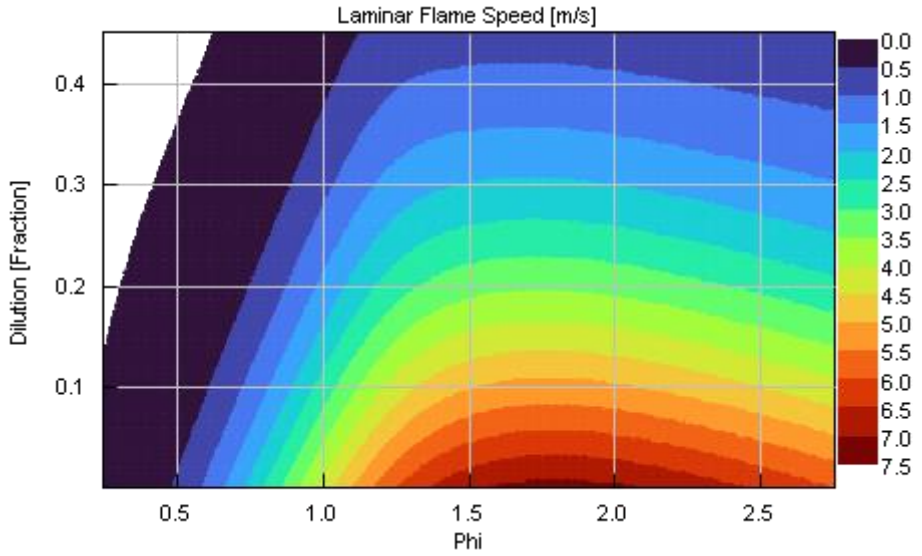


- GEM3D Hydrogen Tank Filling



Hydrogen ICE - Predictive Combustion in GT-SUITE

- New laminar flame speed model for hydrogen since v2022
  - Supported by SITurb, DualFuel, and JetIgnition combustion models
  - Offers improved accuracy at lean conditions

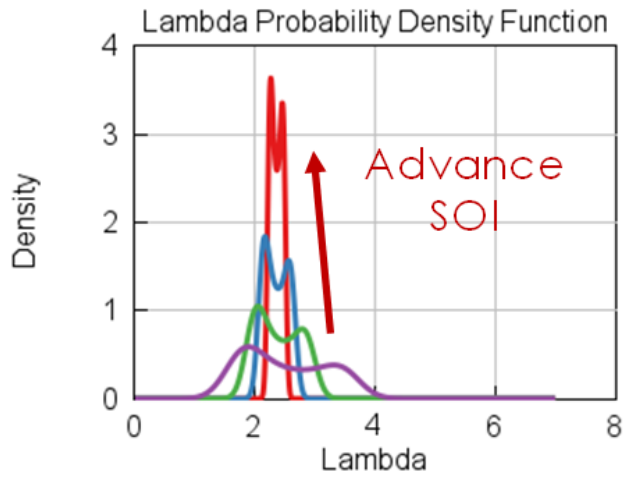


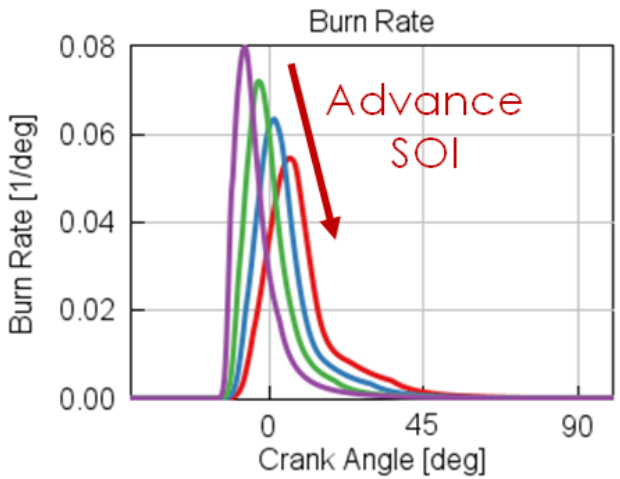
- New knock model for hydrogen since v2022
  - Based on a kinetic-fit approach

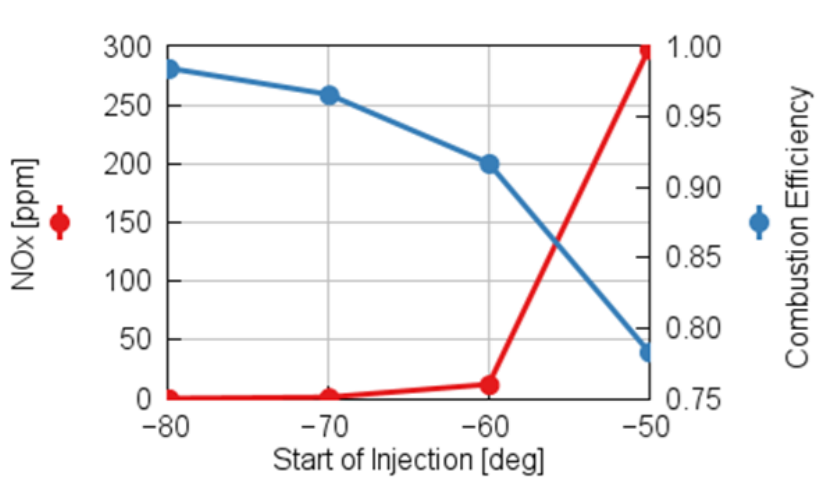
- Nitrogen oxide emissions
  - NO and NO_2 calculation based on built-in Zeldovich mechanism
  - Alternatively based on detailed chemistry

Hydrogen ICE – Injection and mixture formation

- Port Fuel Injection
  - 1D flow solver helps to predict fuel distribution amongst multiple cylinders
  - 3D effects can be investigated by coupled CFD solution
- Direct Injection
  - Impact of injection momentum on turbulence prediction
  - Consideration of effects on fuel stratification

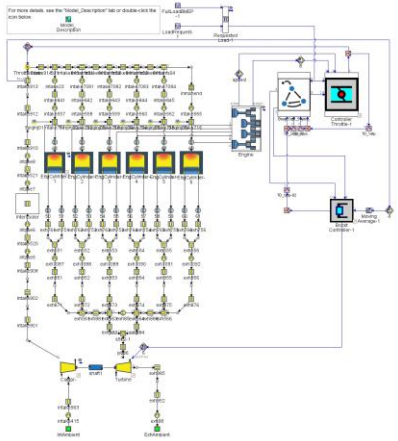




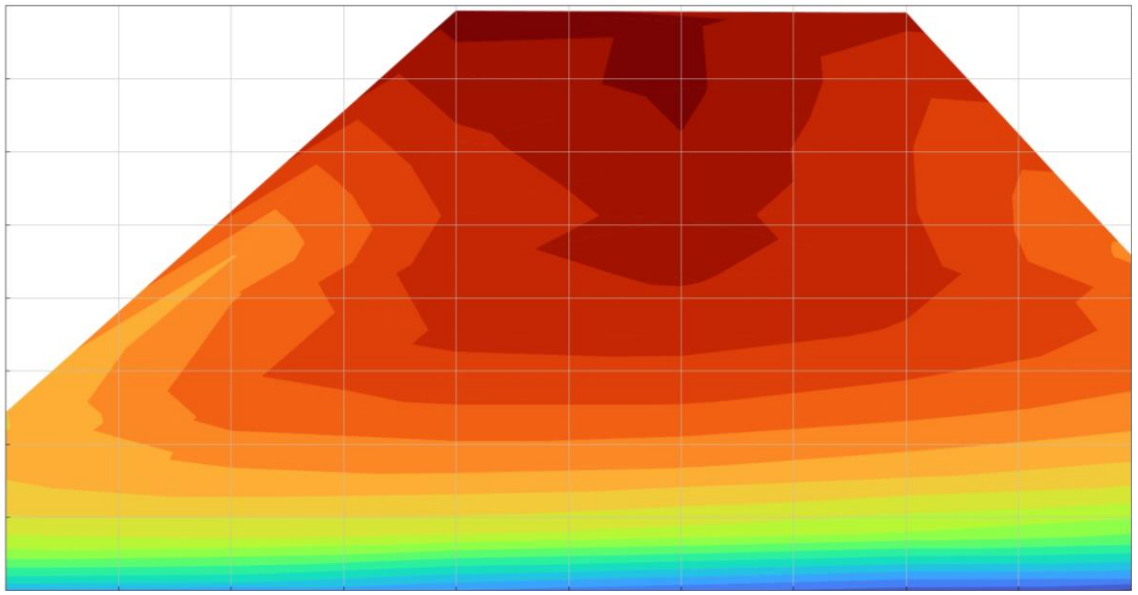


Hydrogen Engine Example

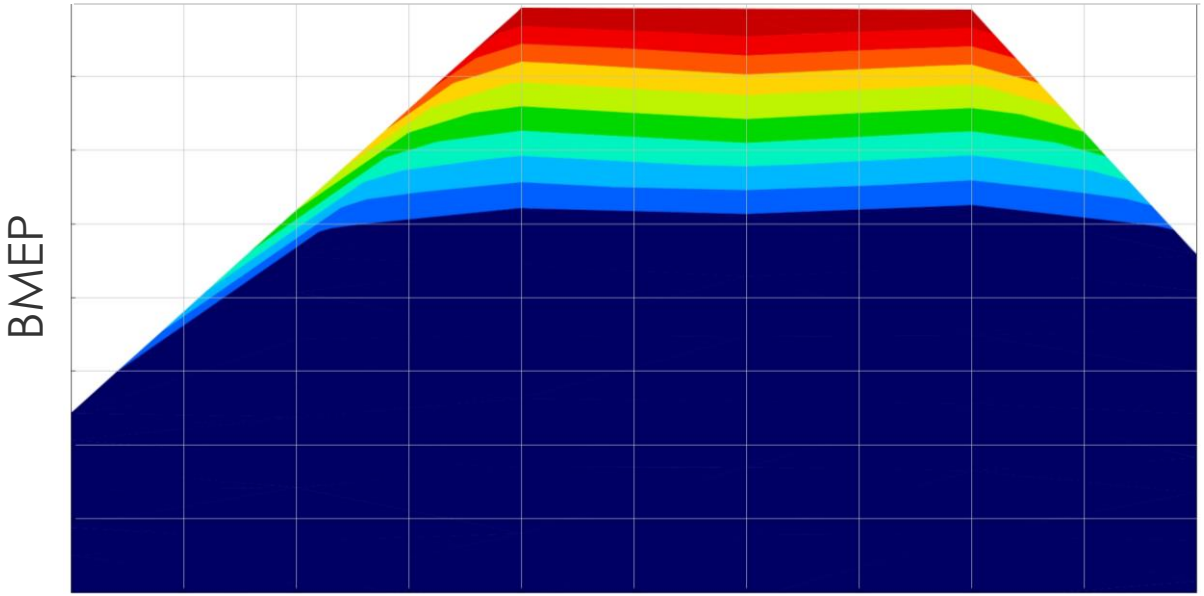
- 6Cyl, 11.5L, max 18 bar BMEP (1700 Nm, 280 kW)
- Predictive combustion model SI-Turb & port injection
- Single stage turbocharger with VGT
- Lambda varies from 2 to 2.5, lower mixture @ high load to keep reasonable boost pressure & temperature on compressor side.



Brake Efficiency



Lambda



Hydrogen ICE - Engine Performance Validation

- Several presentations between 2021 and 2023 Global GT Conference which are demonstrating hydrogen combustion modeling in GT-SUITE

2021	Heavy-duty holistic Engine and exhaust after-treatment development for future post EURO VI regulation **IAV GmbH** Christopher Hayduk	Predictive Methodology for Hydyrogen Combustion Engine Performance within GT-SUITE **Daimler Truck** Amer Avdic	Hydrogen Combustion Engine for Commercial Vehicle Applications – New Requirements for Combustion Simulation **KEYOU** David Leymann	Synergetic application of 0/1/3D-CFD simulation approaches for the development of hydrogen-fueled spark ignition engines **Politecnico di Torino** Federico Millo
2022	H2 ICE: Air system Concepts for the Heavy-Duty Application **Robert Bosch GmbH** Gabriele Sgroi	Calibration Optimization of a Dual Fuel (Diesel + Hydrogen) Engine Using GT-SUITE **PUNCH Torino** Alessandro Grosso		
2023	Combustion Modeling for a Hydrogen Port Fuel Injection Engine using GT-SUITE **Punch Torino** Alessandro Gallone	A Comprehensive Approach to Predict the Combustion Process, the Cycle-by-Cycle Variability & Knock Tendency in a Hydrogen-Fuelled Internal Combustion Engine **Politecnico di Torino** Federico Millo		

What are the next steps of the journey on the road ahead?

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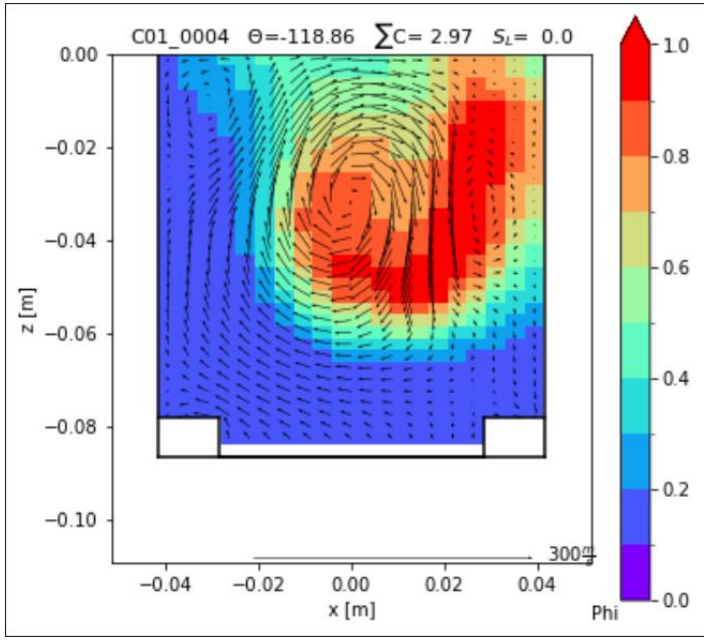
Fuel Cells, Electrolyzers & Hydrogen Infrastructure

- V2025 Likely Features
  - Freezing in catalyst layer
  - Startup/Shutdown
  - Improve implicit choked flow (and other system level bottlenecks)
  - Stability during starvation
  - Predictive ejector

ICE

- V2025 Likely Features
  - Model in-cylinder fuel stratification
  - Improvements of non-spherical flame model
  - Evaporation models for alternative fuels (methanol, ammonia)
  - Ignition delay models for DF / HPDI fuels (hydrogen, methanol, ammonia)
  - Laminar flame speed and knock models for CH4 + H2 blends



Questions?

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