

Creating a Sustainable Future for the IC Engine through Electrification

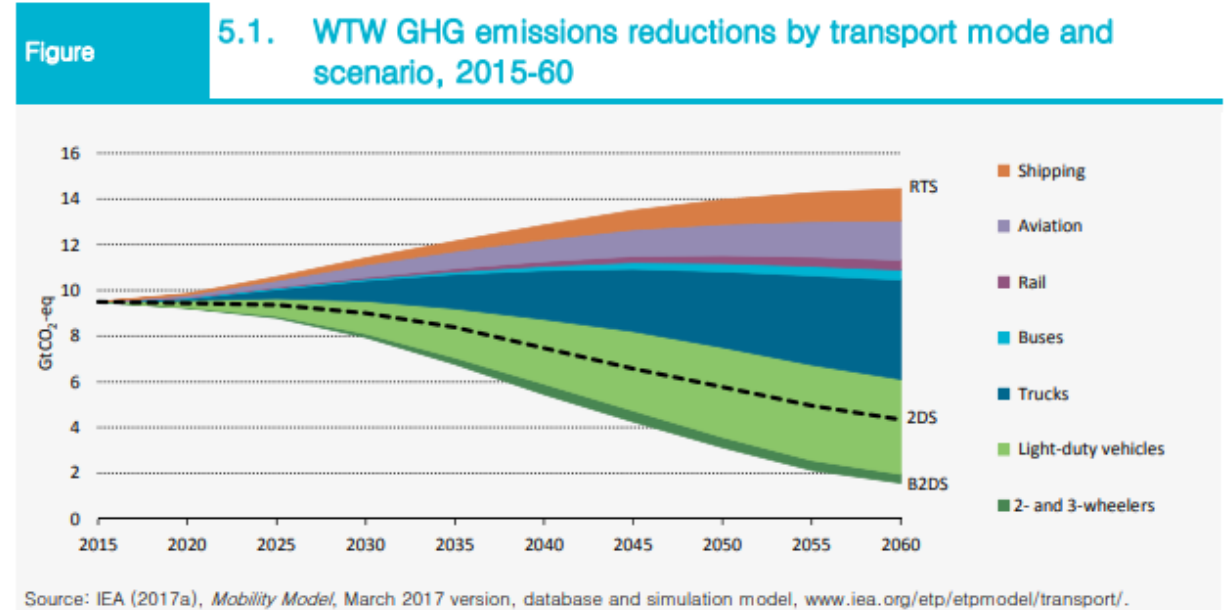
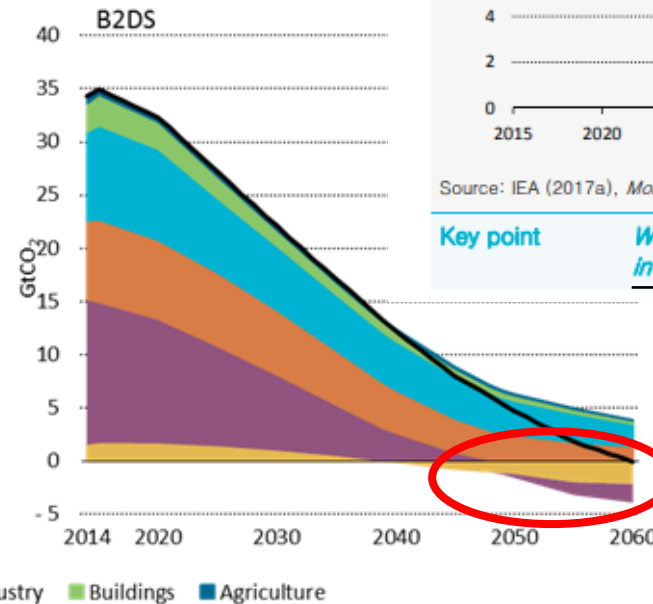
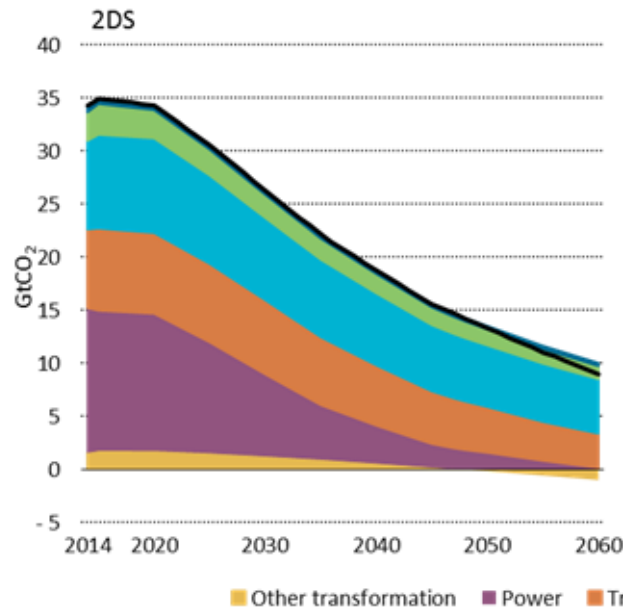
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The Challenge:

Massive Reductions in CO₂ are Required

The CO₂ reduction required for the 2 Degree Scenario is astounding (54%); the level required for Beyond 2 Degrees Scenario is even larger (83%)

Path to CO₂ reductions is being driven by regulations



Key point *WTW GHG emissions from transport are 83% lower in 2060 than in 2015 in the B2DS, while in the 2DS they decline by 54% over the same period.*

Source : ETP 2017 pg 219

Negative Carbon Emissions???

How Do We Currently Evaluate Passenger Cars?

- GHG emissions are measured at the vehicle's tailpipe
- When the 'box' is drawn around the vehicle the conclusion is obvious
 - With no tailpipe, electric vehicles are defined as 'zero' emissions

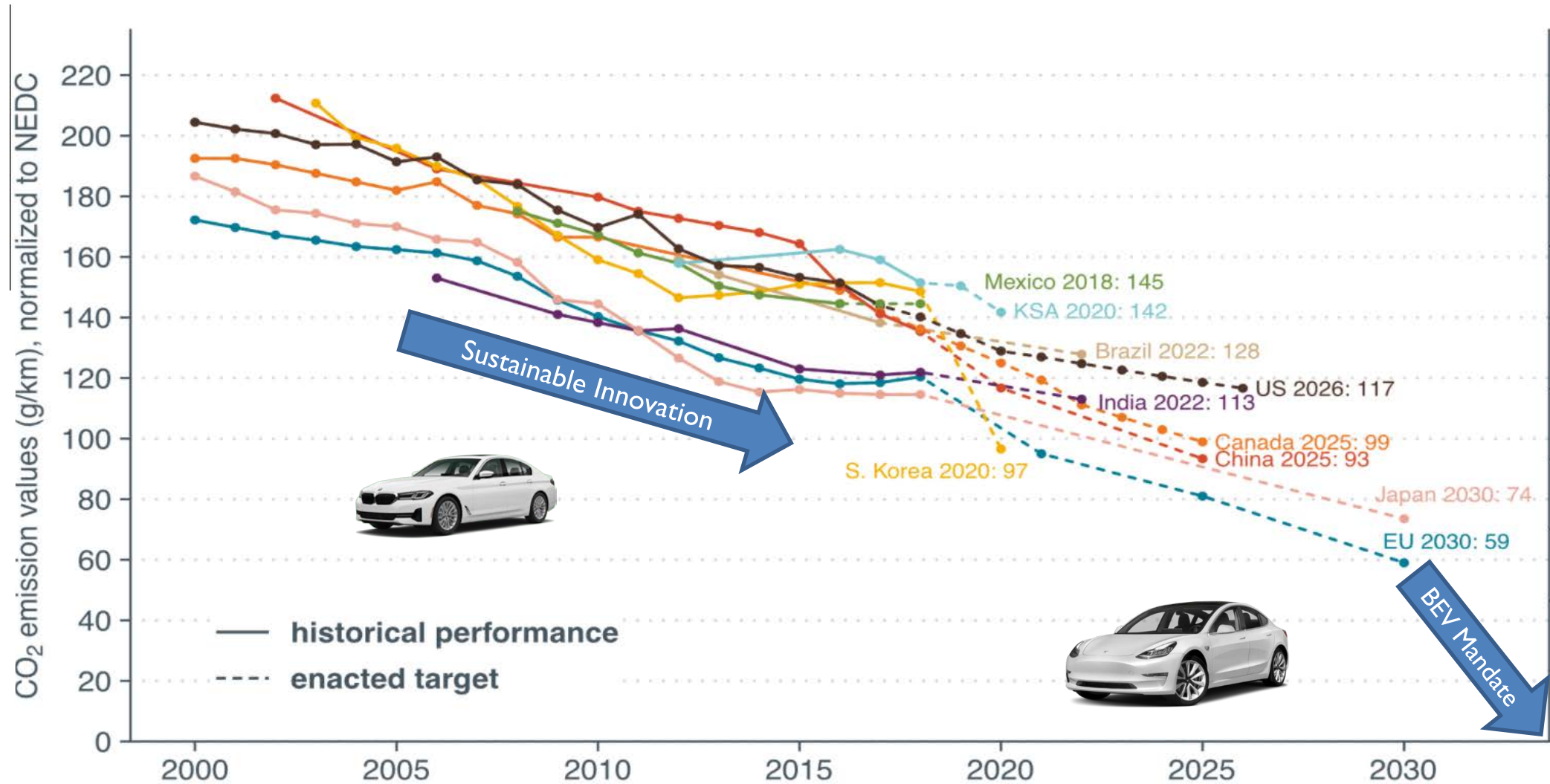
Measured CO₂ = 0 g/mile



Measured CO₂ = 200 g/mile



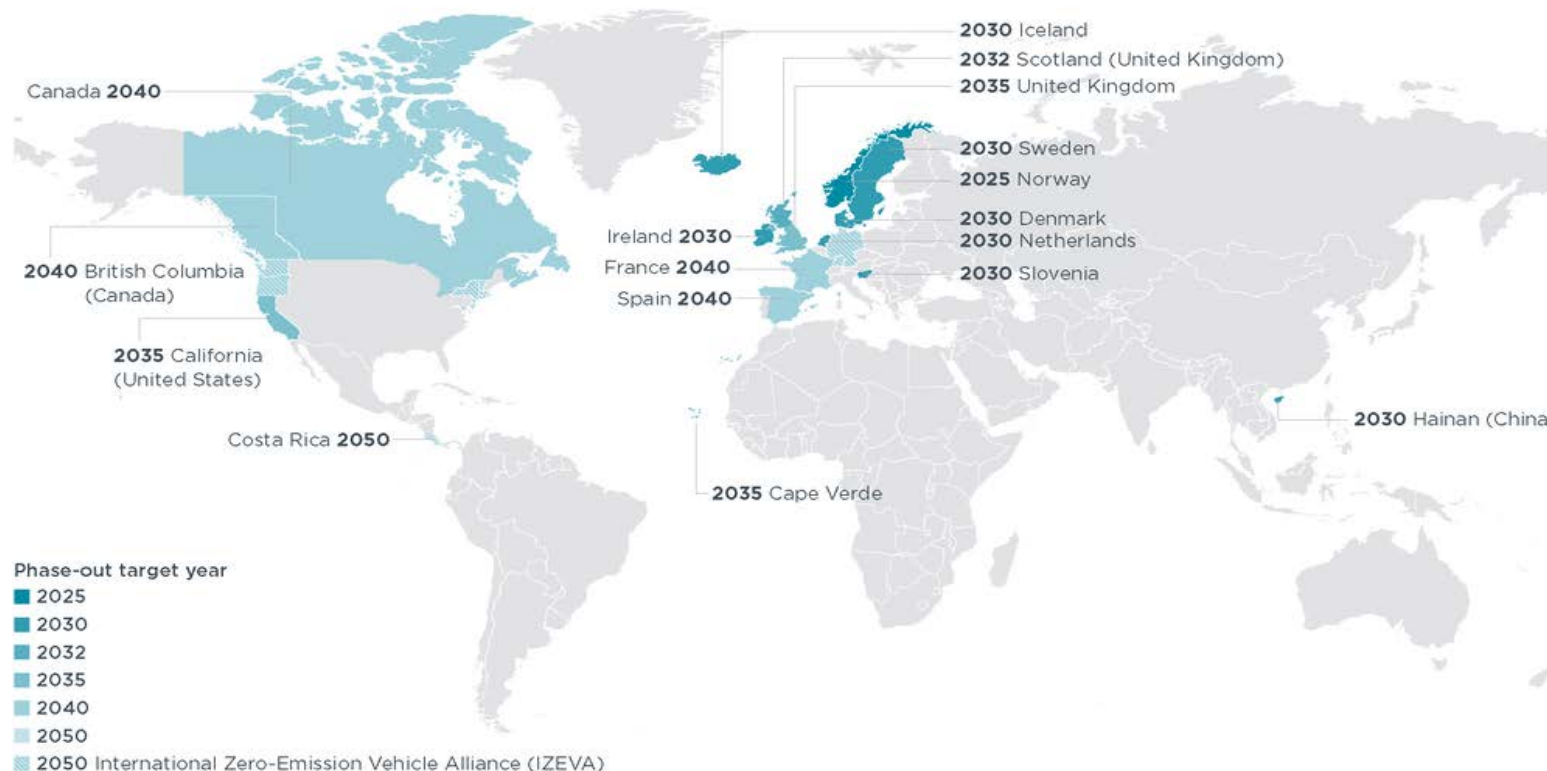
CO₂ Regulations (Tailpipe)



Evolutionary Improvements Do Not Proceed at a Pace Fast Enough for Some Regulators

- By defining electric vehicles as ‘zero emissions’ the path forward is obvious to rule makers
 - Mandate the electric vehicle by banning other technologies

Governments with set targets for phasing out all new sales of internal combustion engine passenger cars



BUSINESS
California's Ban on New Gas Cars Further Upends Auto Industry
Tougher emission rules threaten internal combustion engine; investors flock to Tesla, electric-vehicle startups

UK plans to bring forward ban on fuel vehicles to 2030

Denmark to EU: Ban sale of internal-combustion engine cars come 2040

How Do We Determine What is Really Carbon-Neutral or “Zero CO₂”?



▪ Horse

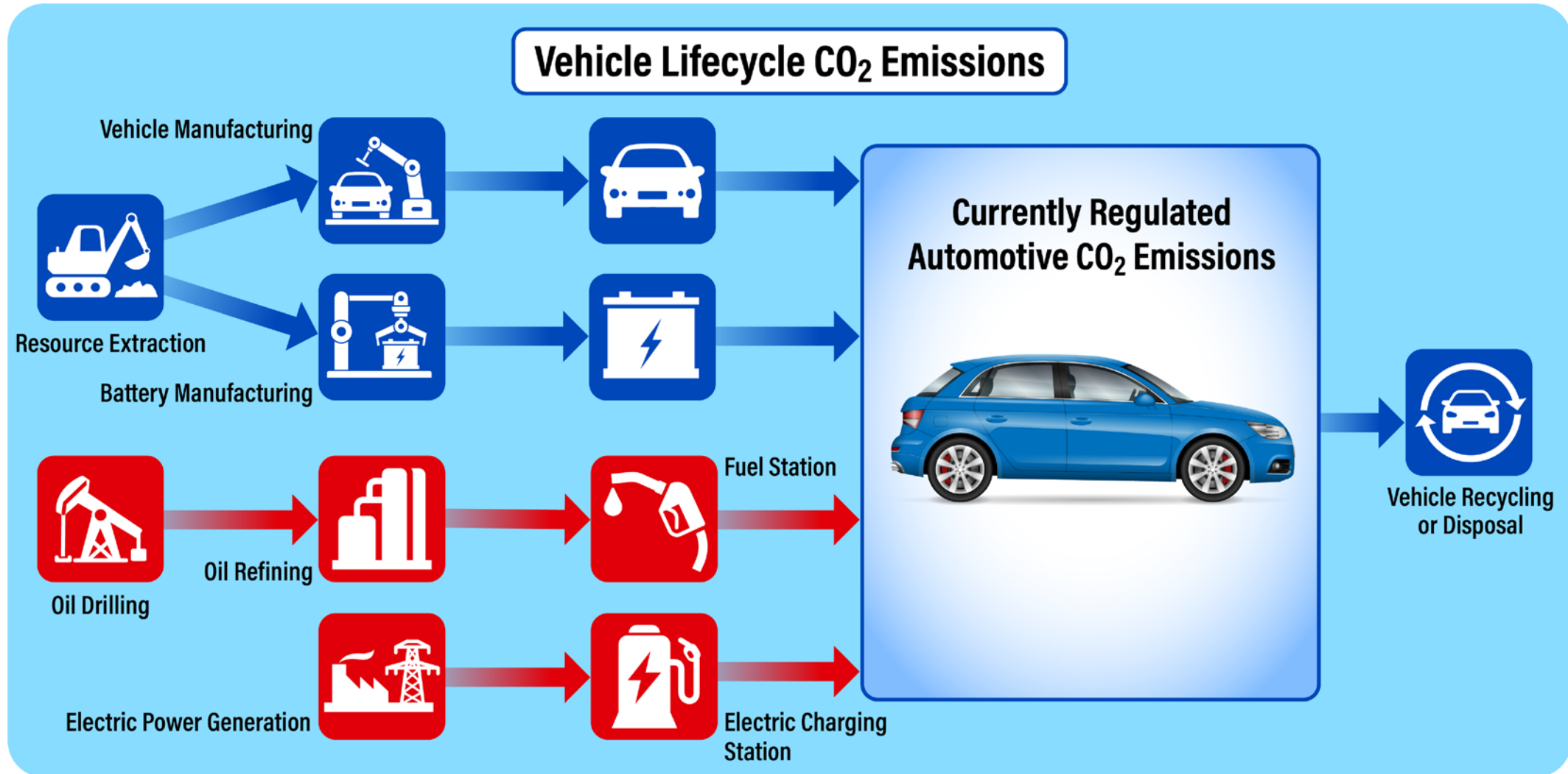
- 4 mph walk
- 55 L lung capacity (11 L usable)
- 36 breaths per minute
- 5,940 liters per mile
 - CO₂ concentration 4.5% higher in exhaust
 - CO₂ density 1.98 g/L
- **530 g/mile CO₂**
 - (16.8 mpg equivalent)



▪ Potential Improvement

- 2-3 speed transmission could cut CO₂ emission by 50%
- Is this a renewable resource? How can we understand what net CO₂ is generated?

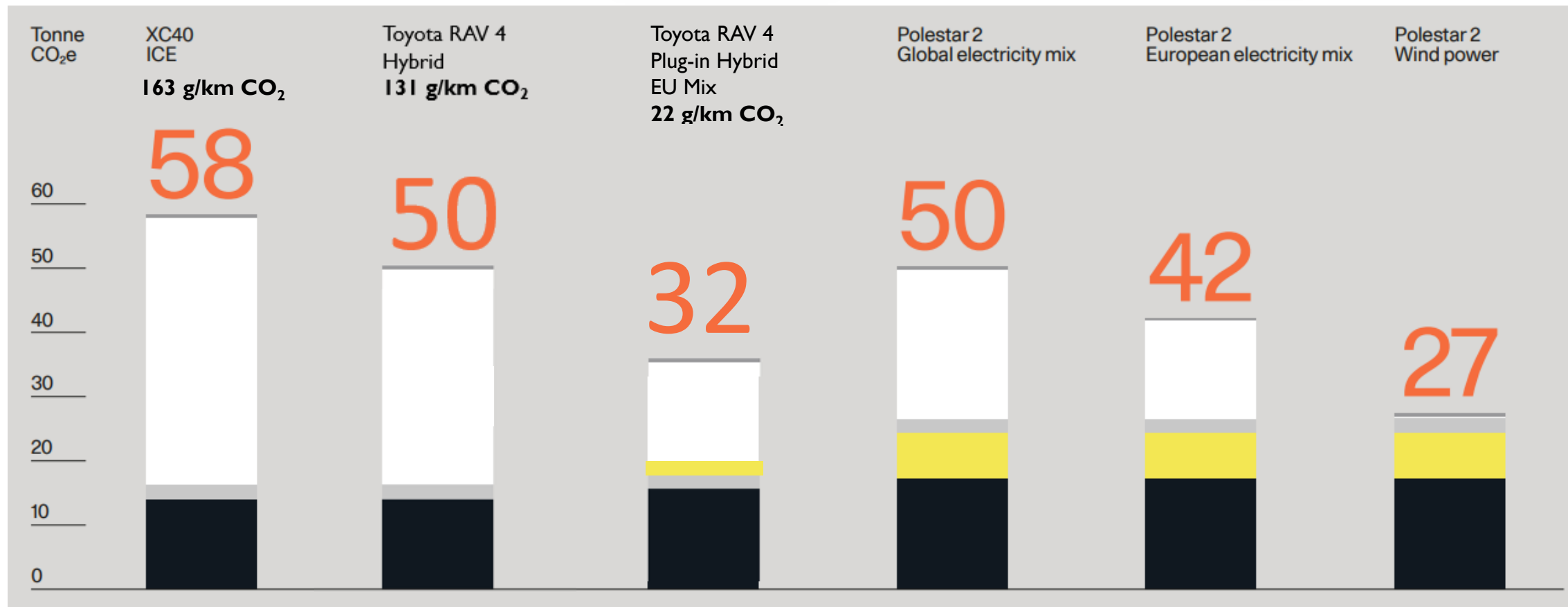
Using Life Cycle Analysis to Minimize Net CO₂ Emissions



Embracing the Power of “and” ...

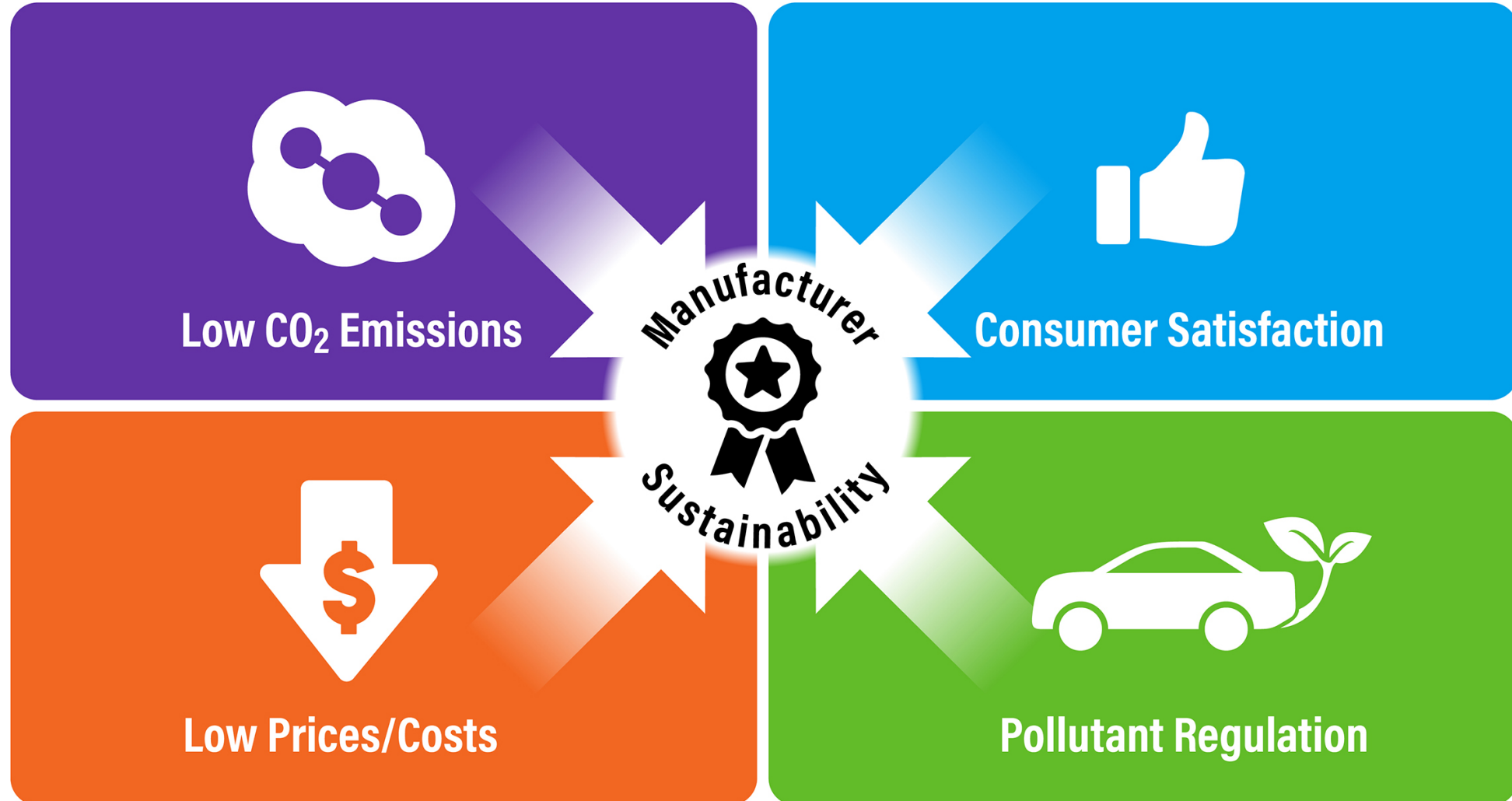


- Materials production
- Li-ion battery modules
- Manufacturing
- Use phase
- End-of-life

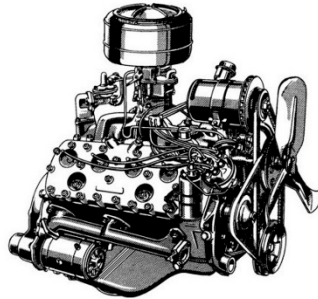
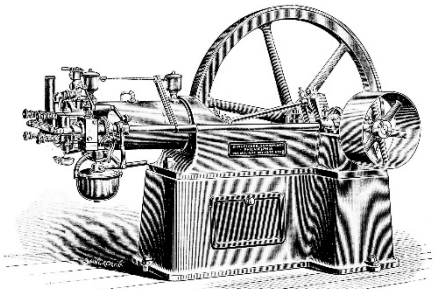
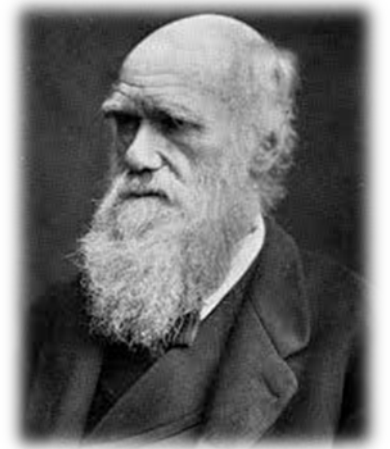
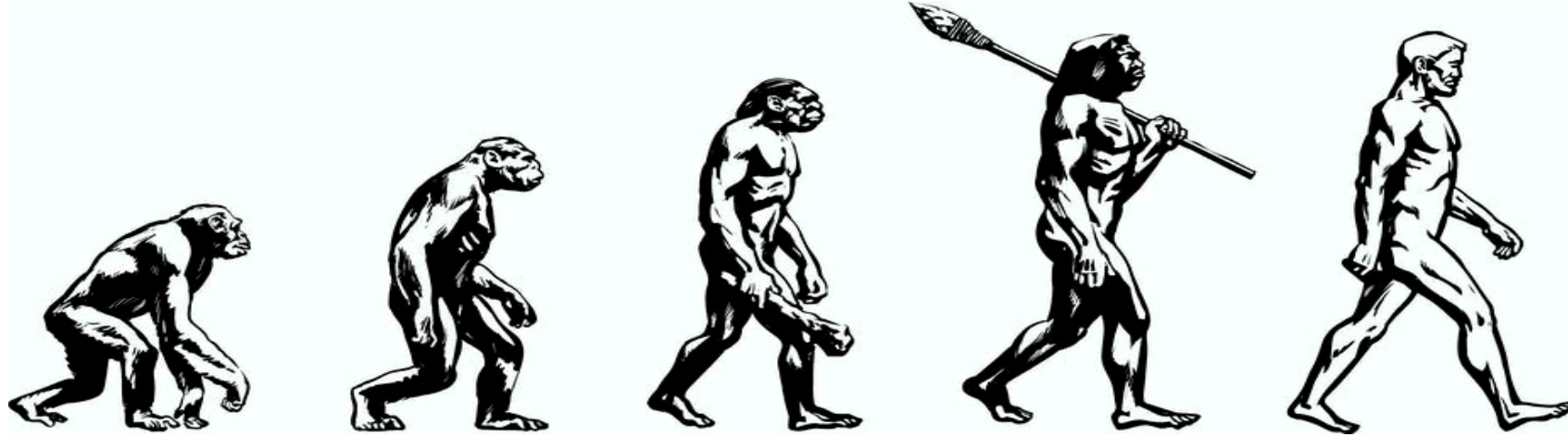


Embracing “AND”

Sustainability is not just about Low CO₂ technology



The Engine Must Evolve



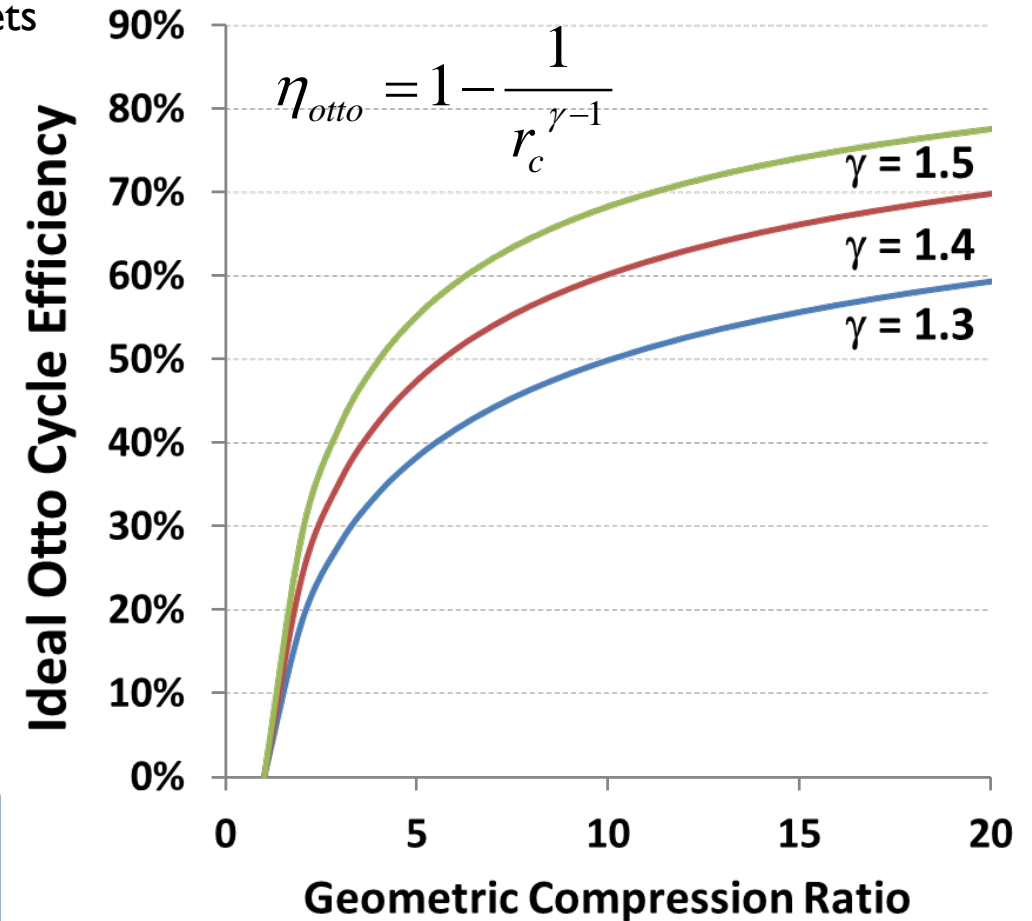
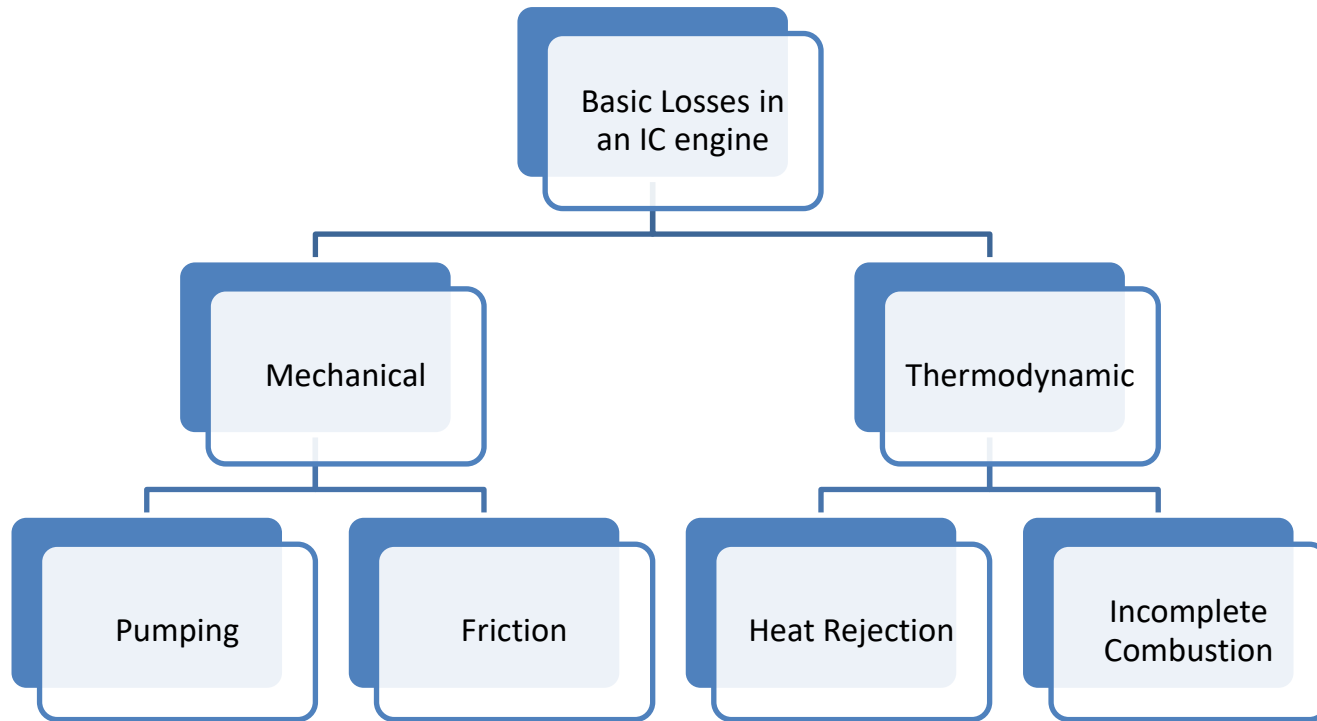
Dedicated Hybrid Engine

Its final form depends on the environment

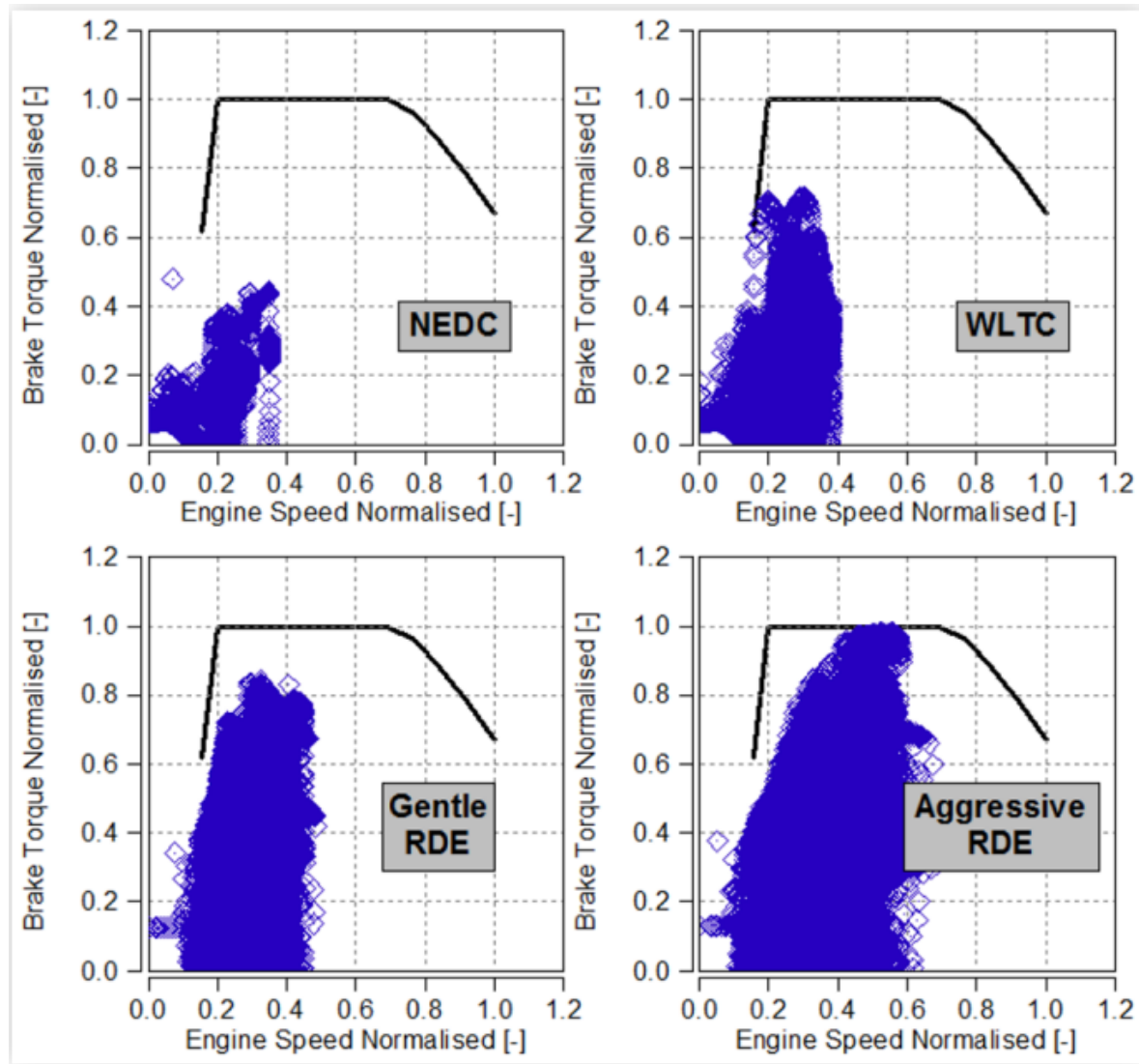
Can We Get to the Future with IC-Only?

- Probably not
 - Reaching the point of diminishing returns on ICE efficiency improvements
 - Combustion options constrained to meet criteria pollutant targets
 - Other options, e.g. light-weighting, have not been as successful as anticipated

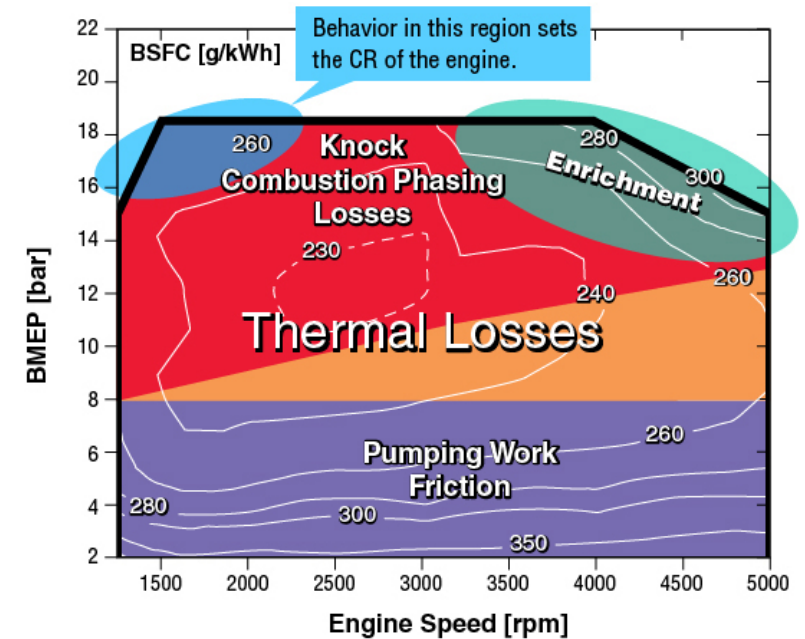
Practical Efficiency in the IC Engine



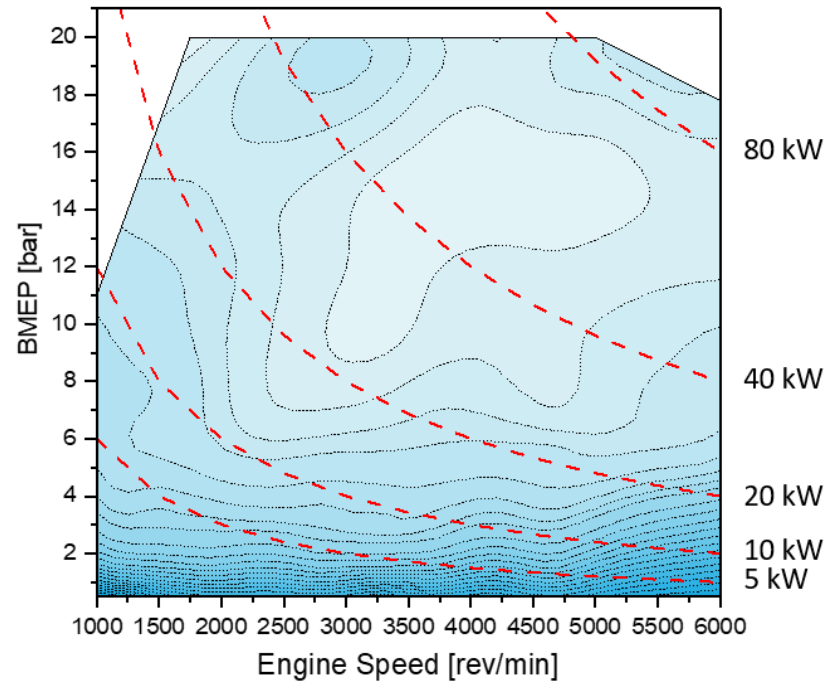
Engine Utilization



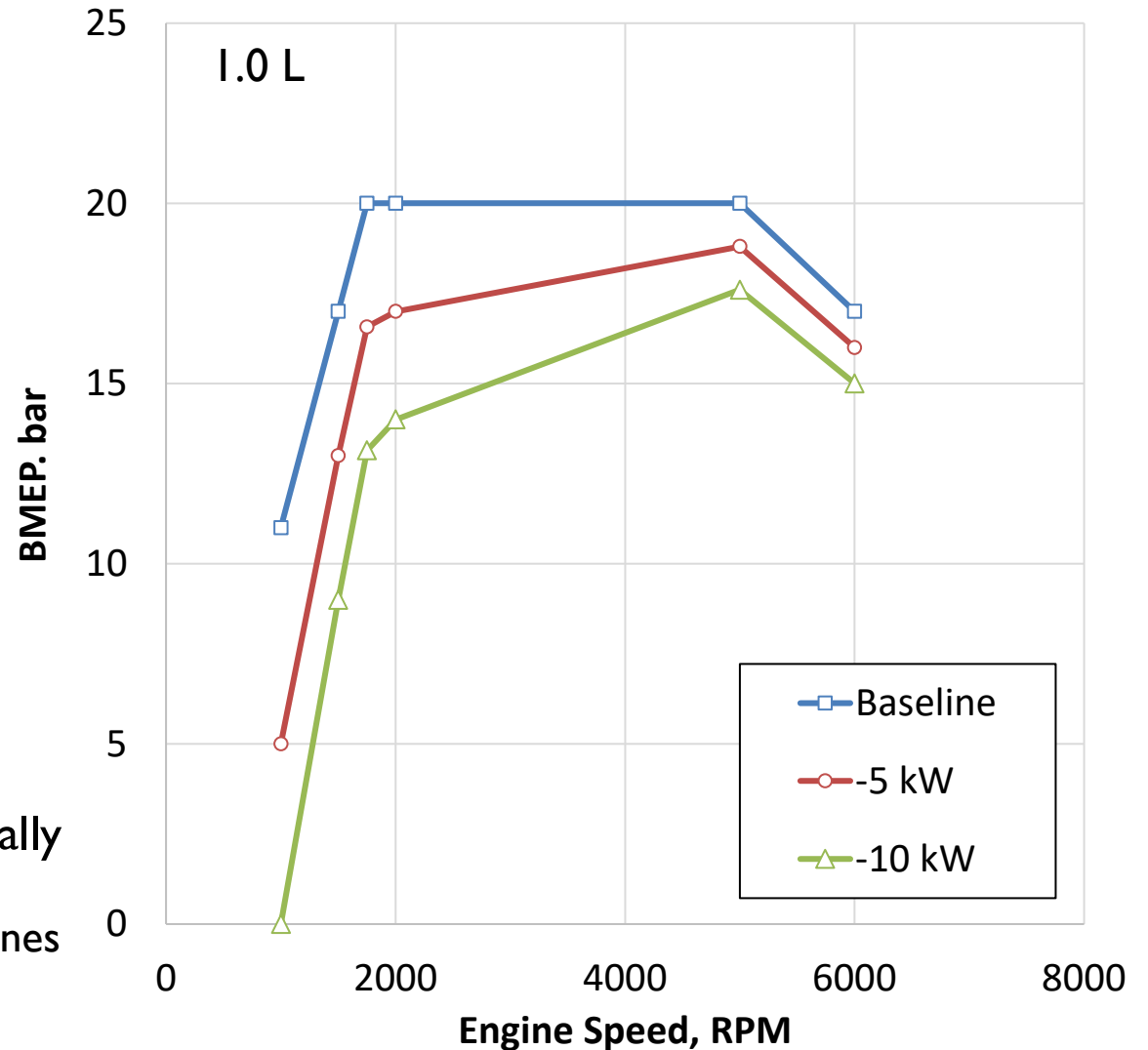
- High-load operation results in compromises that limit engine efficiency
 - Not employed very often
 - Is there another way?



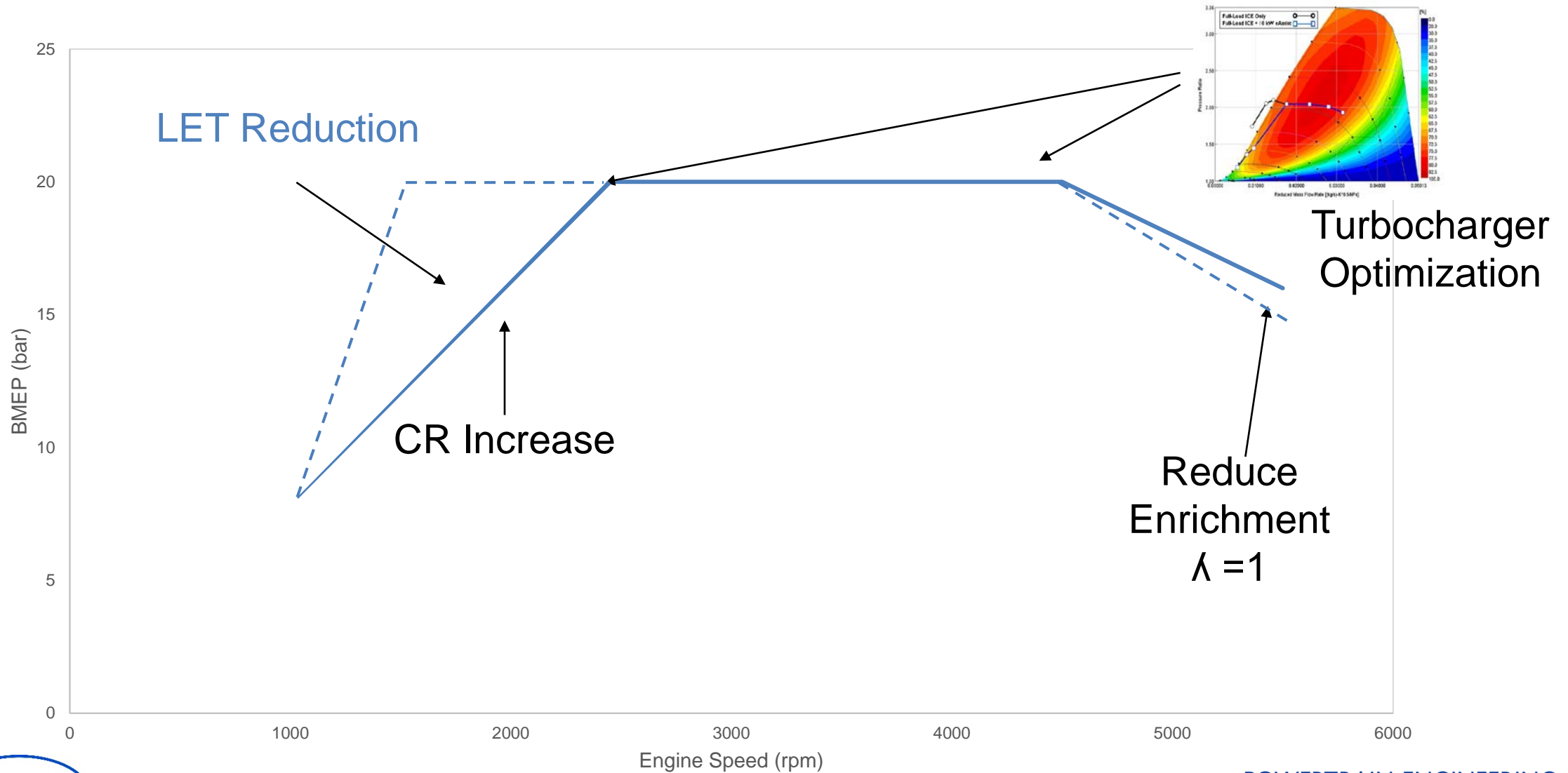
Modify the Torque Curve for a Dedicated Hybrid ICE



- 48 V P2 MHEV can support around 25 kW power addition
- Just 5 kW of crankshaft power-assist can dramatically reduce the low end-torque requirement
 - The effect is greater for smaller displacement engines

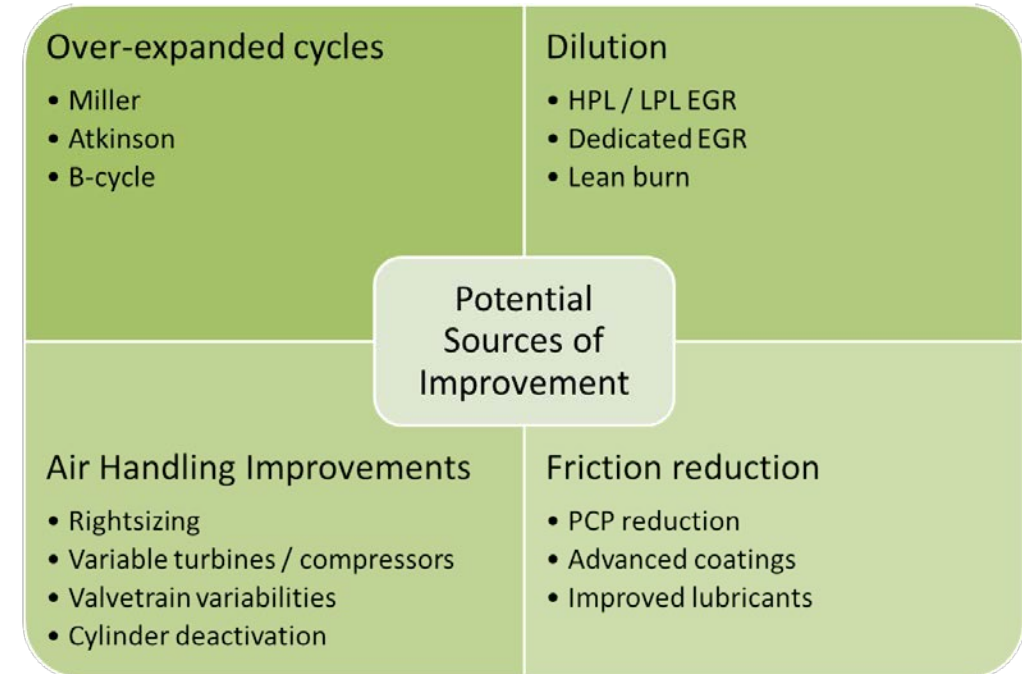


Efficiency Potential with the Dedicated Hybrid ICE



Enabling Other Technologies

- Over-expanded and Dilute applications often suffer from boosting challenges
 - Improved turbo match or electric-assisted boosting with a Dedicated Hybrid optimized torque curve
- Reduction in transient severity using electric machines may make alternative combustion modes possible
 - SACI, etc.
- Many other opportunities for synergies with electric machines and energy storage
 - Electrified components for reduced friction
 - WHR devices coupled to EST devices
- CAV applications will benefit from the flexibility offered by xHEVs



	Over-Expanded Cycles	EGR	Lean Burn
Knock	++	+++	+
Heat Transfer / γ impact	0	++	+++
Pumping	++	+	+++
Emissions	0	++	---

Electrification is the **KEY** to **UNLOCK ICE** Potential

- Regulatory environment is moving quickly to favor xEVs
 - ICE-only has significant regulatory challenges
 - Mass adoption of BEVs presents some challenges
 - Cost, customer acceptance, materials sourcing
- Combining an ICE with electric machines is the logical, most cost-effective path for high efficiency vehicles
 - Benefits of energy dense, relatively cheap petroleum combined with efficiency improvements from electrification
 - Significant room for innovation
- A low power density, high efficiency ICE designed to be mated with an electric machine and on-board energy storage may offer a sustainable combination of low life-cycle CO₂ and good performance at the lowest cost



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