Universidade Federal de Santa Maria
1960

GPMOT
Grupo de Pesquisa em Motores Combustíveis e Emissões

The Future of Biofuels in Internal Combustion Engines

10TH INTERNATIONAL COMBUSTION INSTITUTE WINTER SCHOOL

Prof. Mario Martins, PhD – mario.martins@ufsm.br

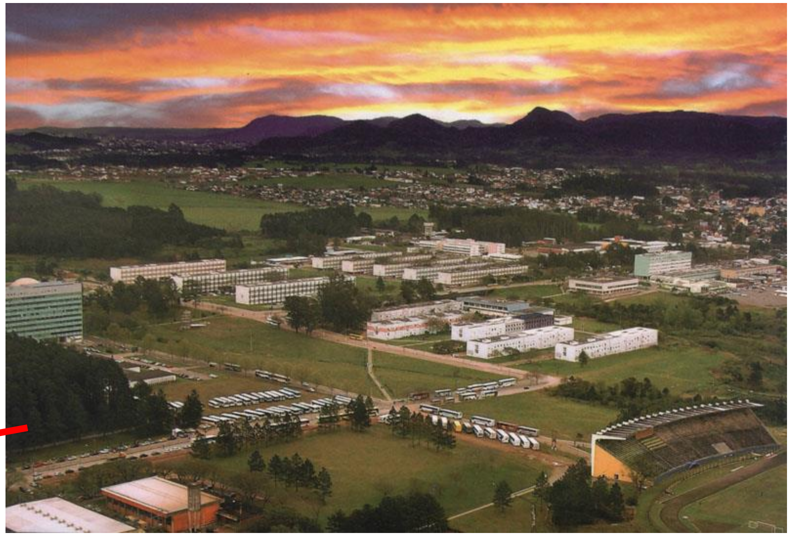
Engines, Fuels and Emissions Research Group
Federal University of Santa Maria - Brazil

10th School on COMBUSTION
CI-WS 2025

UFSM

Universidade Federal de Santa Maria

Rio Grande do Sul



- 28000+ students
- 2033 academic staff members
- 2609 tecnical staff members

GPMOT

Grupo de Pesquisa em Motores
Combustíveis e Emissões

Membros

- 5 Proferssors
- 1 Engineer
- 1 Technician
- Post-docs,
- PhDs, Masters and undergrad research assistants

GPMOT/UFSM Recent and ongoing research projects

- Ultra-high pressure injection for flex-fuel engines: technological challenges for ethanol use
ITA – USP – UNICAMP –IMT- UFSM – AVL – Marelli – Stellantis – GM
- Ozone utilization to increase efficiency of flex-fuel engines
UFSM – Marelli
- Development of a high-efficiency biogas engine for freight transport vehicles
USP – IPT – UNB – UFSM – AVL – CAOA(Hyundai) – Bosch
- Development of an automotive engine powered by bio-hydrogen for the Brazilian market
UFSM – Marelli – Horiba

- High-power density ethanol engine for small aircraft and/or UAVs
- Investigation of ultra-high pressure fuel injection for flex-fuel engines in a single-cylinder research engine
- Development of a high-efficiency engine powered by biogas and hydrogen for power generation
- Optimal control system based on artificial intelligence (AI) for an engine operating with green hydrogen.

- Investigation of ultra-high pressure fuel injection for flex-fuel engines
- Development and performance and emissions evaluation of a dual-fuel injection system for an agricultural tractor engine using diesel oil, biodiesel, and biomethane combinations

- Hydrogen propulsion solutions for internal combustion engines in agricultural machinery

Recent and ongoing research projects

GPMOT

Use of ozone to enhance combustion and improve efficiency in SI engines √

O_3

ROTA 2030

HPDI

Utra-high pressure direct injection for flex-fuel engines: technological challenges for using ethanol √

FUNDEP

Development of an ethanol-fueled aircraft engine

AeroEtOH

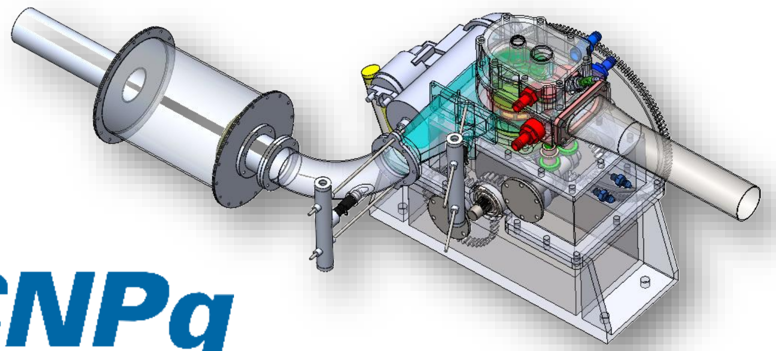
CNPq

Ethanol-fueled aeronautical engine development

GPMOT

PLANNING	DESIGN				IMPLEMENTATION		
DESIGN PLANNING	INFORMATIONAL DESIGN	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	PILOT PRODUCTION	LAUNCH	DESIGN VALIDATION

2 stroke
Boosted
Uniflow
Flathead design, ...



INPI INSTITUTO NACIONAL DA PROPRIEDADE INDUSTRIAL

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29409161951163213

Pedido nacional de Invenção, Modelo de Utilidade, Certificado de Adição de Invenção e entrada na fase nacional do PCT

Número do Processo: BR 10 2022 019272 3

Dados do Depositante (71)

Depositante 1 de 1

2023-01-1826/20239526 Published 24 Oct 2023

SAE INTERNATIONAL

The Flathead Valved Boosted Uniflow Two Stroke Engine

Roberto Begnis Hausen, Mario Martins, Juliano silveira, and Jean Lucca Fagundez PhD
Federal University of Santa Maria

Citation: Hausen, R.B., Martins, M., silveira, J., and Fagundez, J.L., "The Flathead Valved Boosted Uniflow Two Stroke Engine," SAE Technical Paper 2023-01-1826, 2023, doi:10.4271/2023-01-1826.

Received: 01 Jun 2023 Revised: 15 Sep 2023 Accepted: 19 Sep 2023

Abstract

Experimental aviation engines face numerous challenges, including the need for energy efficiency, alternative fuel aviation. At the maximum speed of 3000 rpm, the engine achieved a power of approximately 23 kW with boost around 3bar, while at cruise speeds between 2400 and 2700 rpm, the

CNPq

Ongoing research projects

GPMOT

Development of a high-efficiency biogas engine for cargo vehicles

BIOCH$_4$

ROTA 2030

FUNDEP Finep INOVAÇÃO E PESQUISA

Development of a high-efficiency engine powered by biogas and hydrogen for power generation

H$_2$Agro

Development of an automotive engine powered by biohydrogen for the Brazilian market

H$_2$Auto

Projects with state co-funding

- **Hydrogen propulsion solutions for internal combustion engines in agricultural machinery**
- **Finep EMPRESAS: Biomethane integrated silencer and aftertreatment module**

- Development of a Flex-Fuel VCR Engine

- Confidential

New projects GPMOT/UFSM

- Confidential

- FUELTECH: Development of hydrogen powered Racing engines

- Confidential

Past projects

Volkswagen

raízen

- Dry ethanol as commercial fuel in Brazil: opportunities and risks

Volkswagen

- Current scenario and outlook for biogas and natural gas businesses in the mobility sector in Brazil

Indutry Partners

GPMOT

Volkswagen

MWM
UMA EMPRESA TUPY

FuelTech

OKOFLEX
AUTOMOTIVO

CAOA

silenkar
Escapamentos

SFW
SISTEMAS TÉRMICOS

BLUME
DISTILLATION

GM

raízen

DUO
engenharia criativa

BOSCH

STELLANTIS

MARELLI

AVL

AGROVEC
CARRETAS AGRÍCOLAS E INDUSTRIAIS

STIHL®

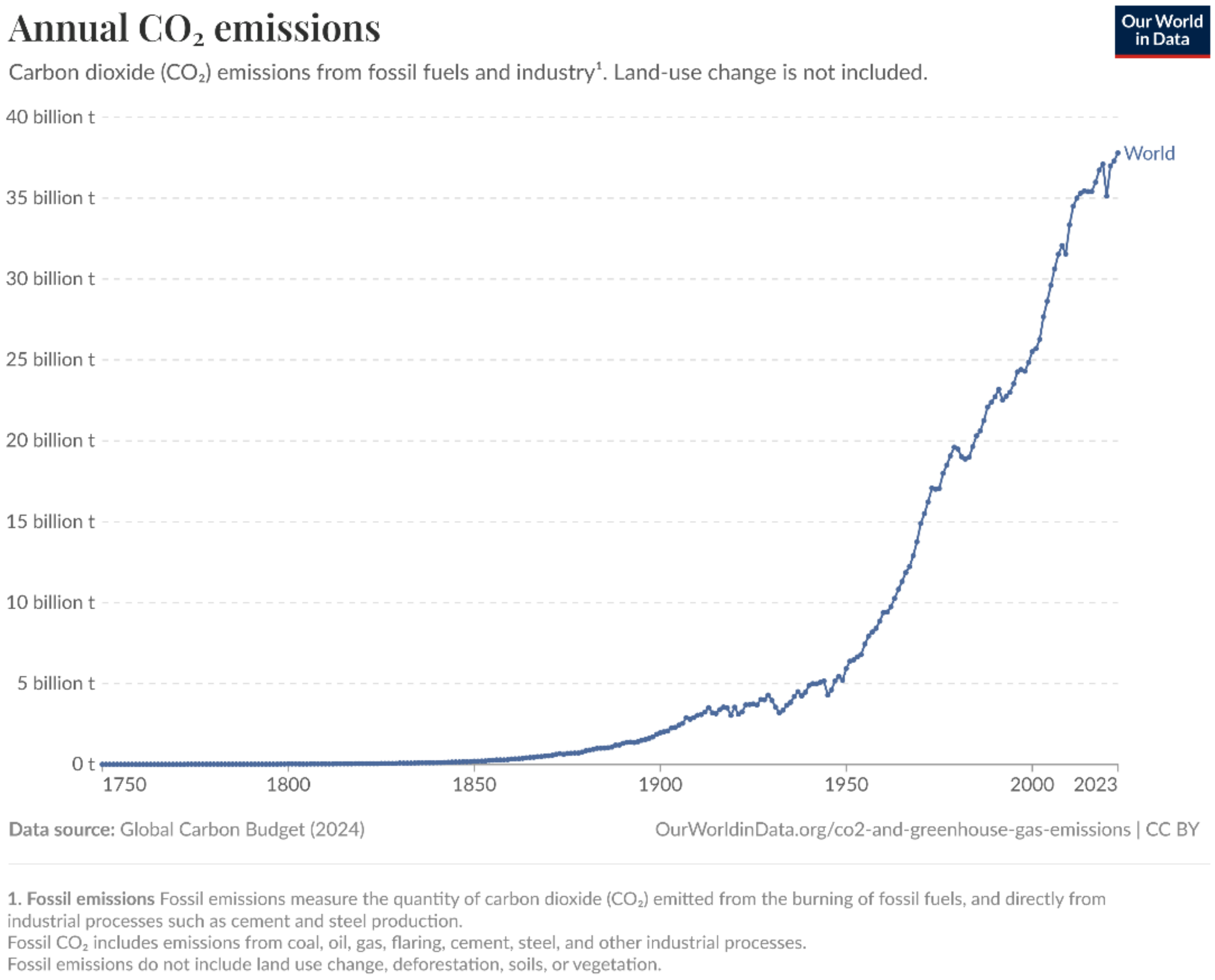
Academic and governamental partners

GPMOT

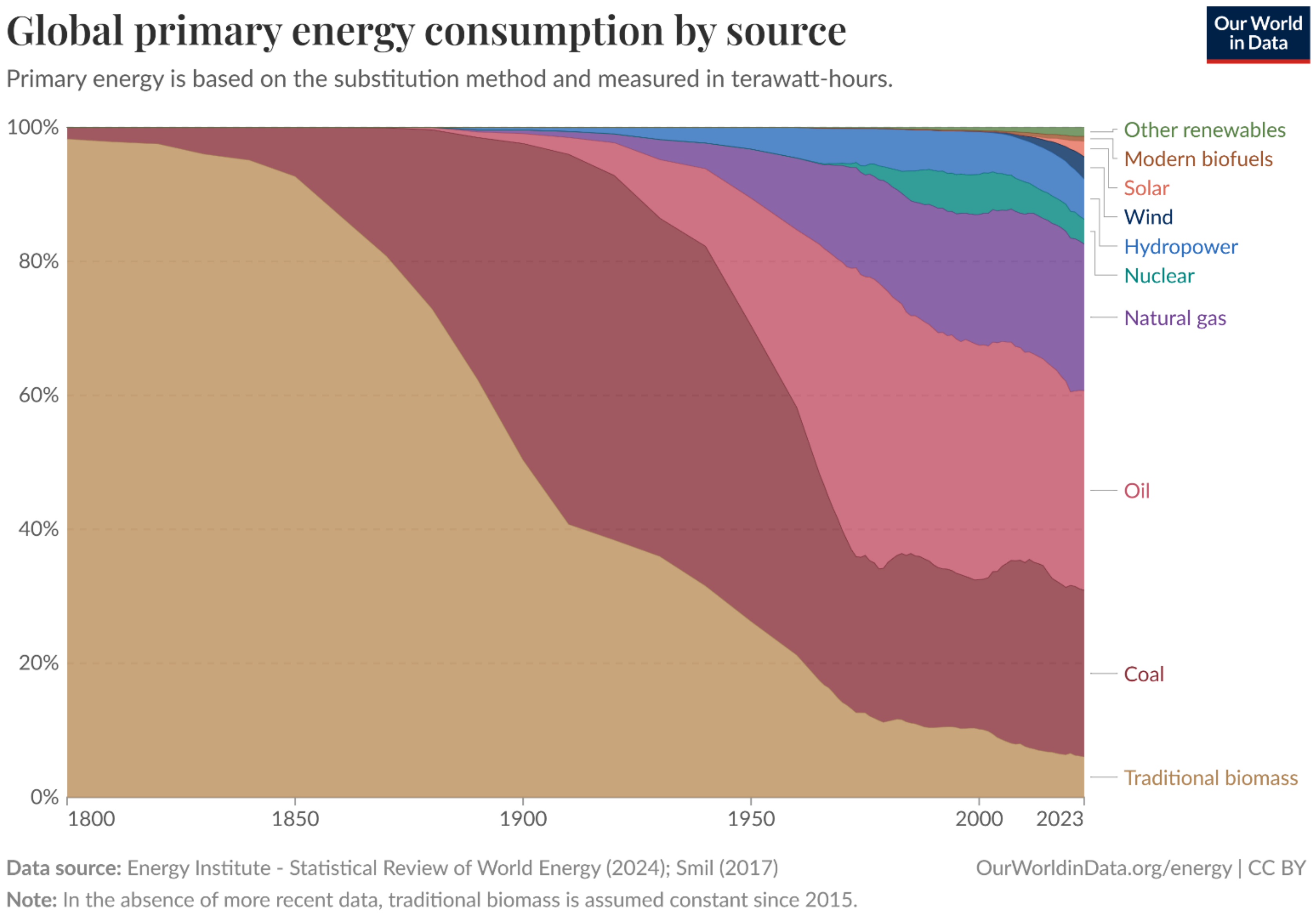
INTRODUCTION AND MOTIVATION

Motivation

- Why biofuels? Why now?
- Do combustion engines still have a future?
- Sustainability, energy security, and existing infrastructure

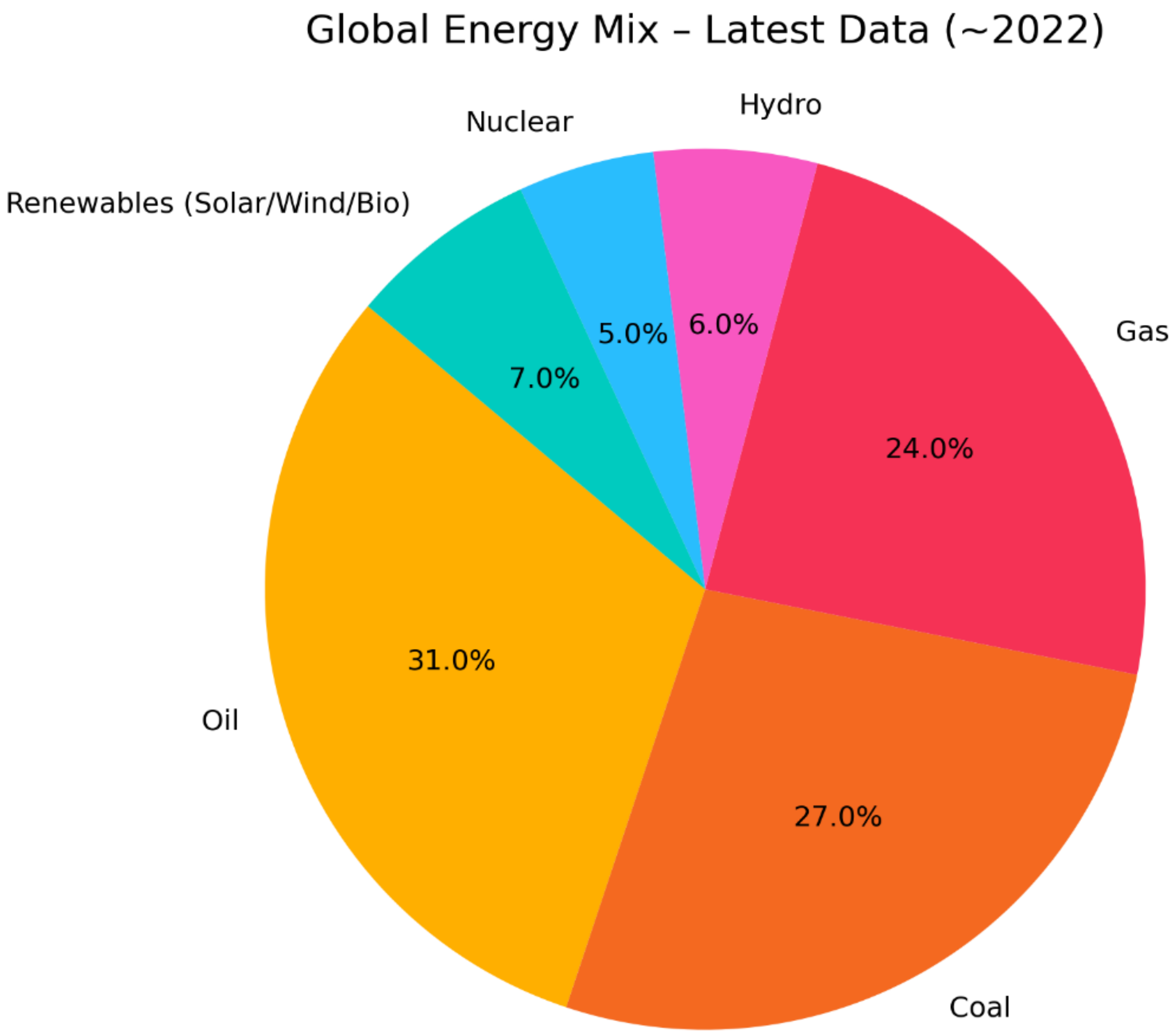


Global energy matrix



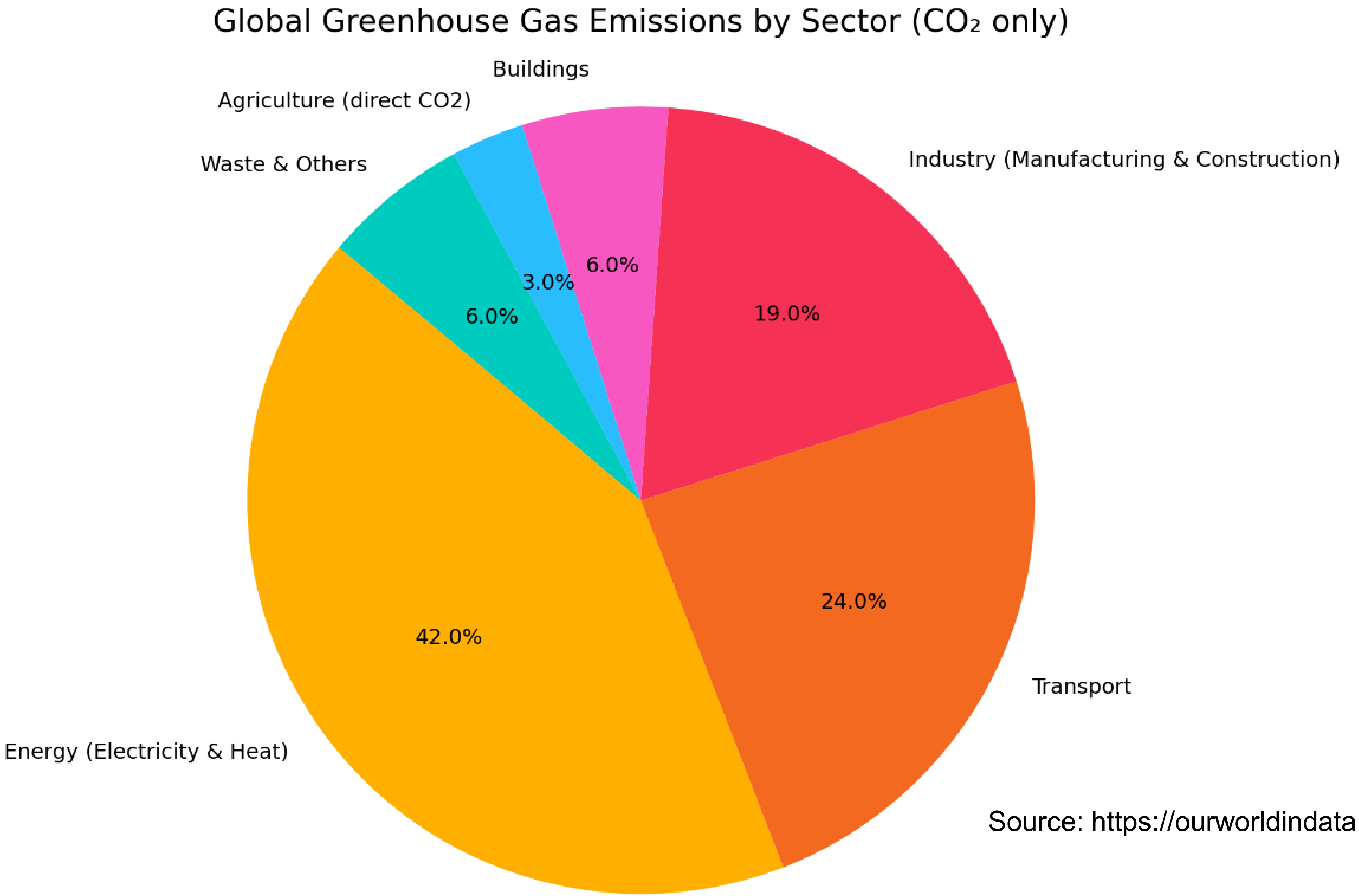
Global energy mix

- Oil and coal take the highest share



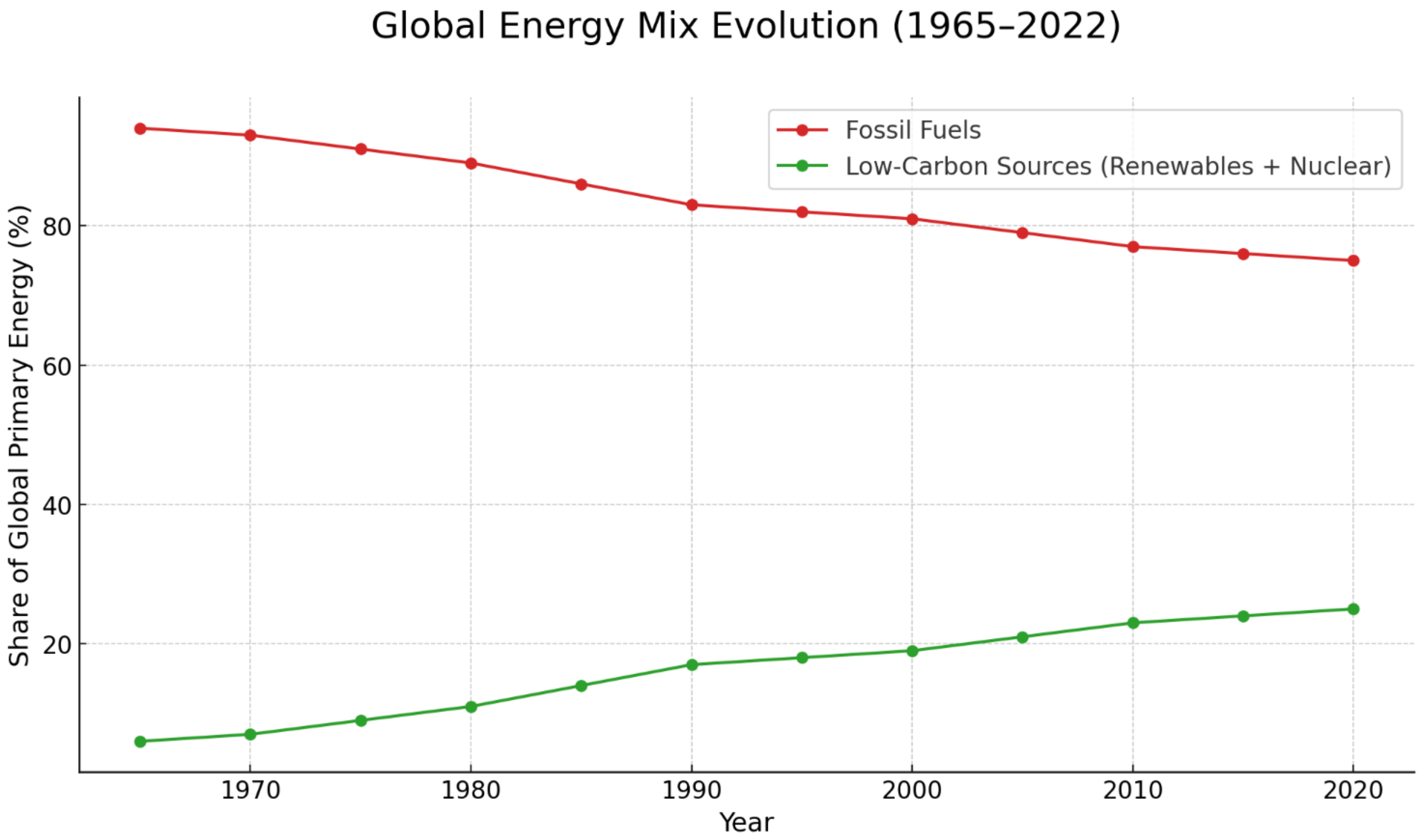
CO2 Emissions

- Transport has a large share



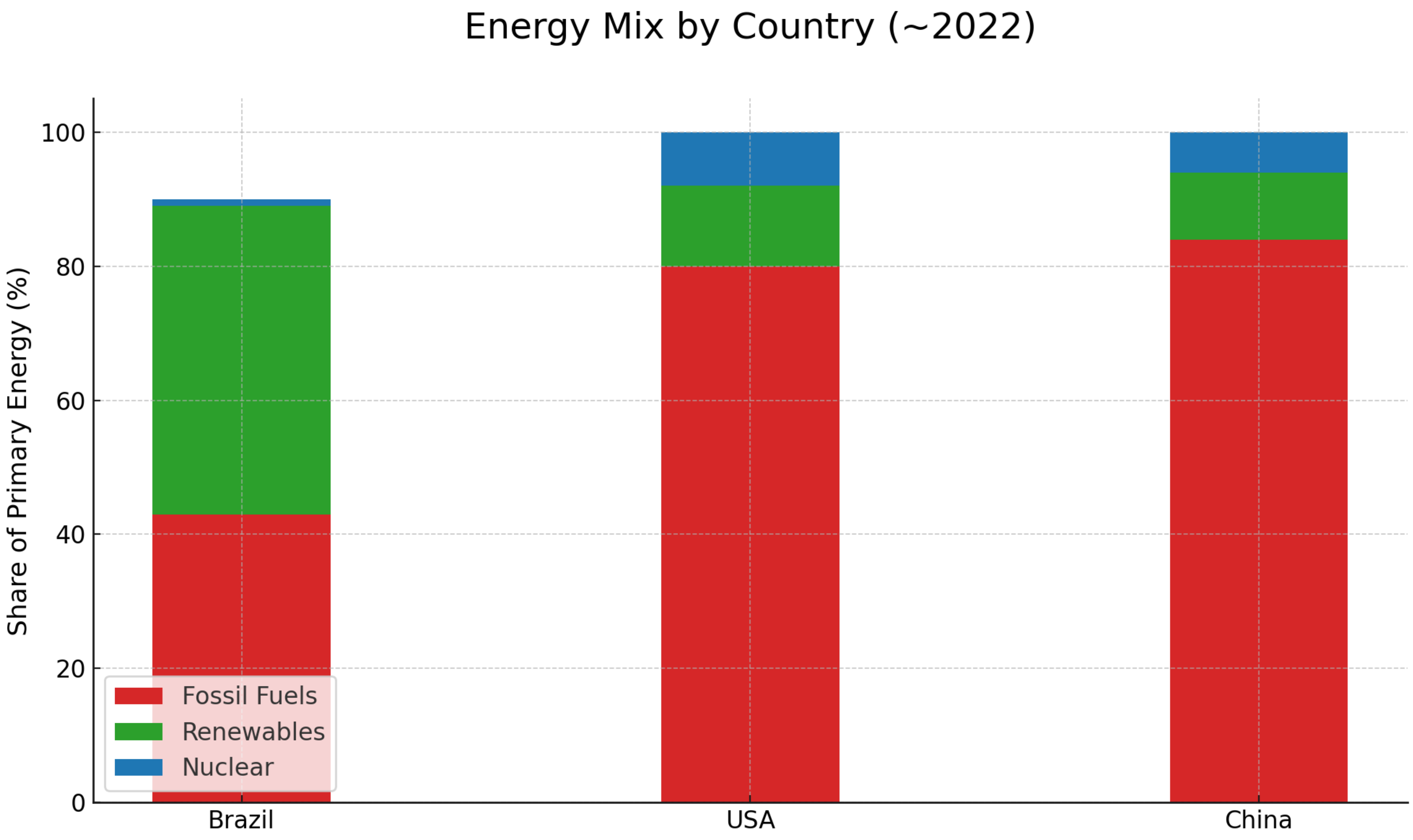
Source: https://ourworldindata.org/

The rise of low carbon energy



Source: Our World in Data (https://ourworldindata.org/energy-mix)

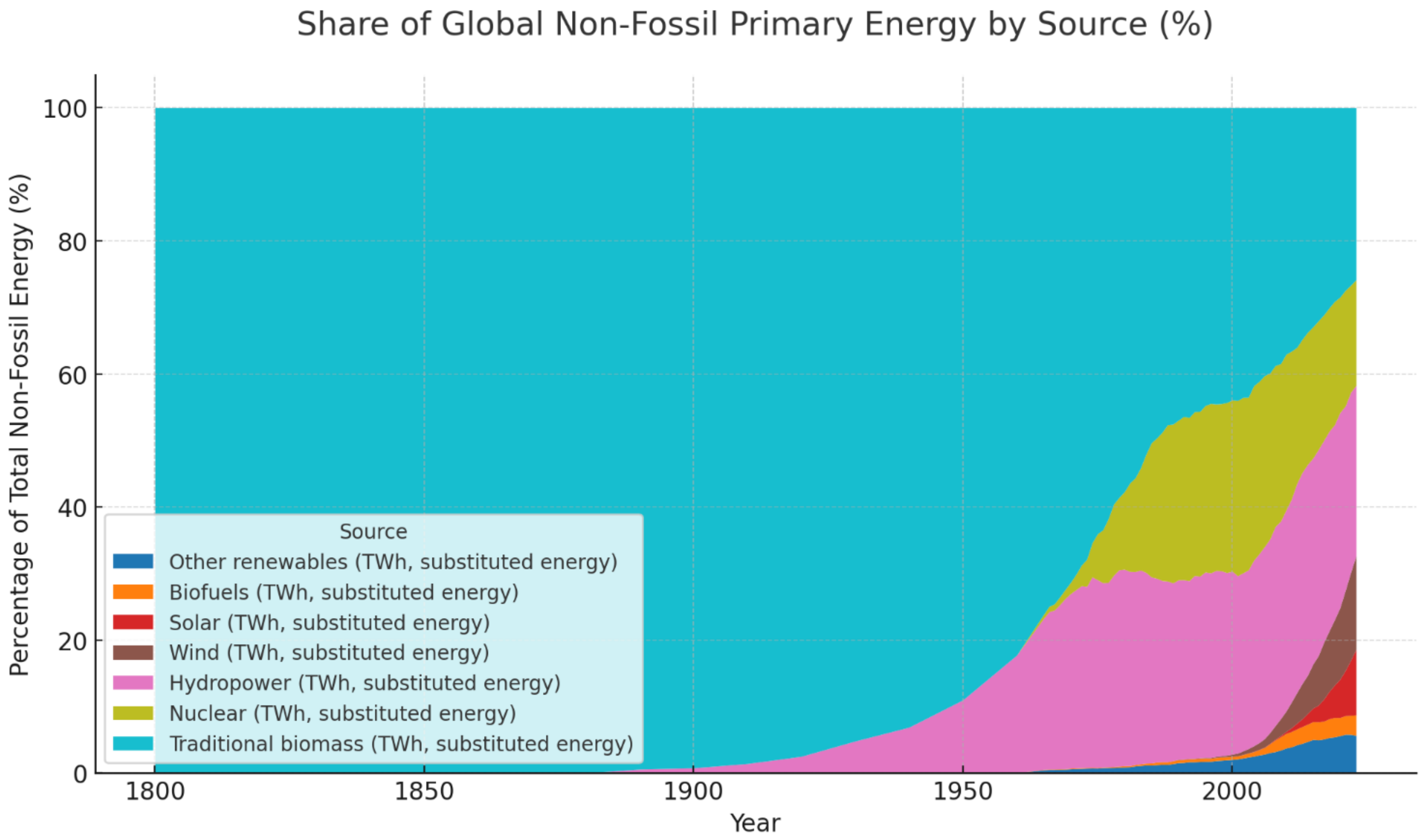
Brazil is a global leader in renewable energy



Source: Our World in Data (https://ourworldindata.org/energy-mix)

Non-Fossil Primary Energy by Source

- Biomass progressive reduction since 1900

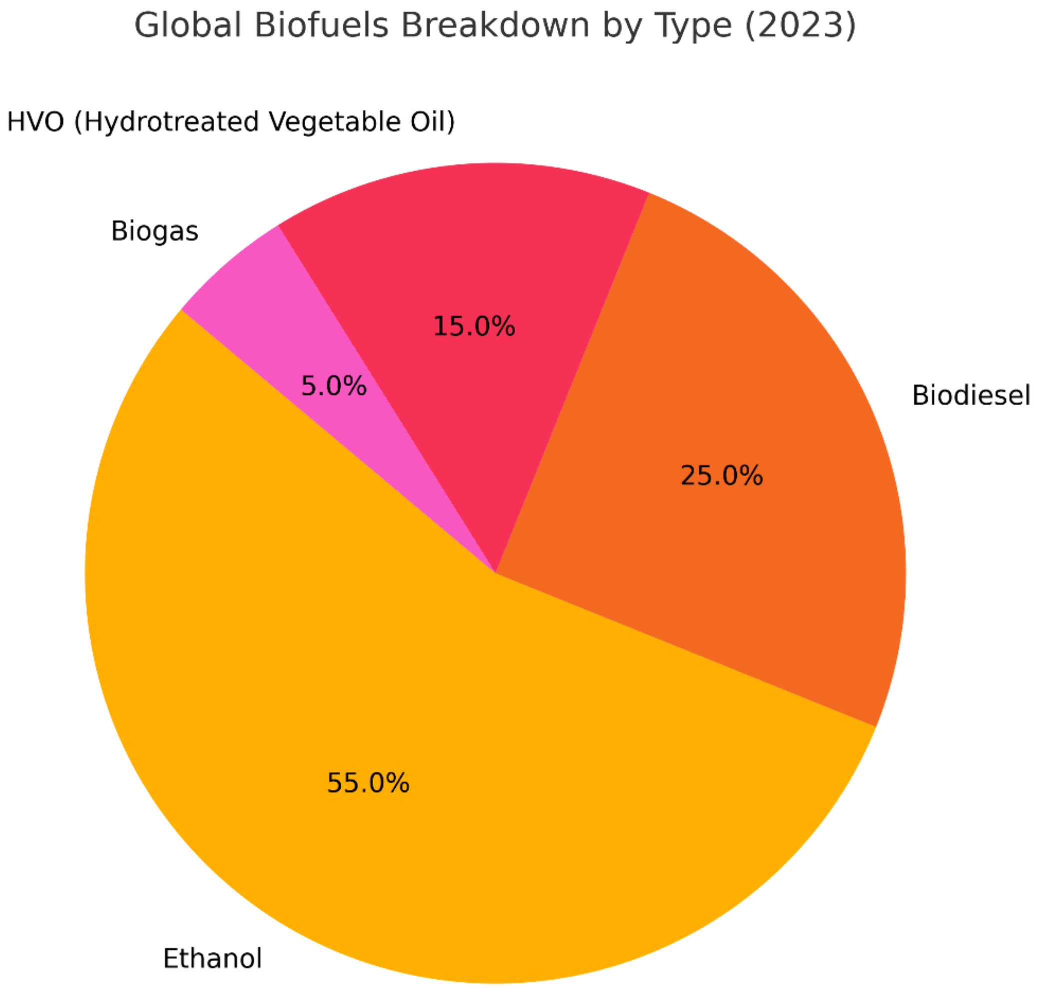


Data: Our World in Data – global-energy-substitution.csv (normalized)

The re-birth of biofuels

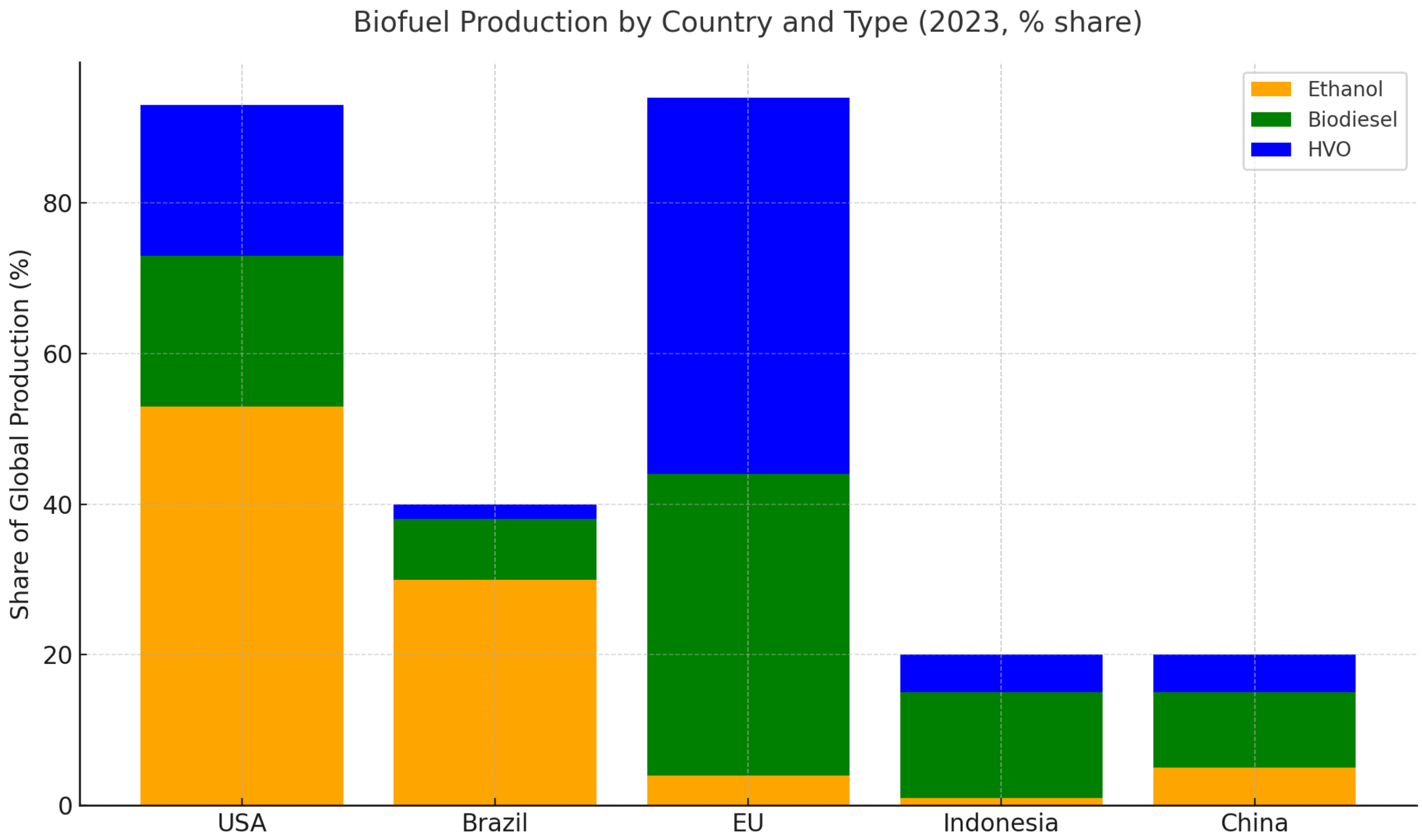
Global Biofuels Breakdown by type

- Ethanol is the global leader



Source: IEA (2023), Renewables 2023 – Biofuels Report (https://www.iea.org/reports/renewables-2023/biofuels)

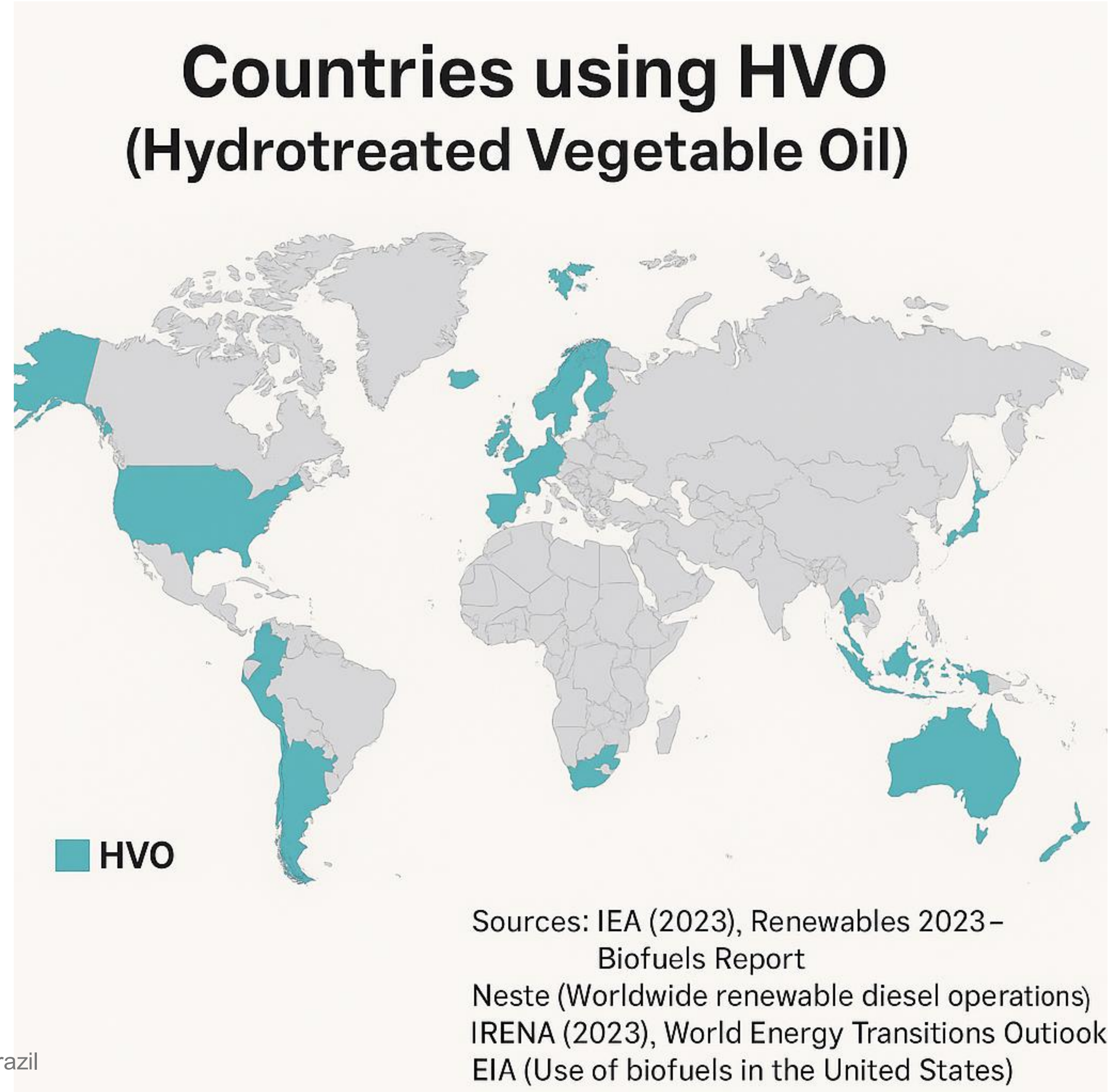
Biofuel Share by Country



Common Biofuels Share by Country

Country	Ethanol (%)	Biodiesel (%)	HVO (%)	Notes
United States	~53%	~20%	~20%	World's largest producer of ethanol and HVO
Brazil	~30%	~8%	<2%	Dominated by sugarcane ethanol
Indonesia	<1%	~14%	~5%	Strong in palm oil-based biodiesel
European Union	~4%	~40%	~50%	HVO grows with support from climate policies
China	~5%	~10%	~5%	Gradually increasing

HVO consumption



HVO in diesel

Country	% HVO in Diesel Consumed (Estimate)	Source/Justification
Sweden	>40%	100% HVO in public fleets; full tax incentive; available at all stations
Finland	~30–35%	Strong decarbonization policy; Neste's home market
Netherlands	~15–20%	Blending with fossil diesel encouraged by RED II
Germany	~10–15%	Use in private logistics fleets and tests in road transport
France	~10%	Expanding; focus on SAF (Sustainable Aviation Fuel) and transportation

HVO: the Swedish experience

- Climate Goals: Sweden has ambitious climate targets;
- Drop-in Fuel:HVO is a "drop-in" fuel, meaning it can be used directly in existing diesel engines;
- Reduced Emissions: HVO significantly reduces greenhouse gas emissions, NOx, and particulate matter compared to traditional diesel.
- Sustainability: HVO is produced from renewable sources like vegetable oils, making it a sustainable alternative to fossil fuels.
- Swedish Leadership: Sweden has been a leader in adopting sustainable fuels, with a significant portion of its bus fleet already running on HVO or electric power.
- Policy Support: Sweden has policies and frameworks in place to support the transition to alternative fuels.

HVO: the Swedish experience

SWEDEN | **STOCKHOLM**

Sweden's buses are now nearly 100% fossil-free

17 MAR 2025 • ENVIRONMENT

How did they achieve this remarkable feat?

Sweden's public transport sector is at the forefront of sustainability, surpassing both national and European climate targets. Today, around 10% of the country's bus and coach fleet is electric, while nearly all remaining vehicles run on biodiesel, such as HVO100.

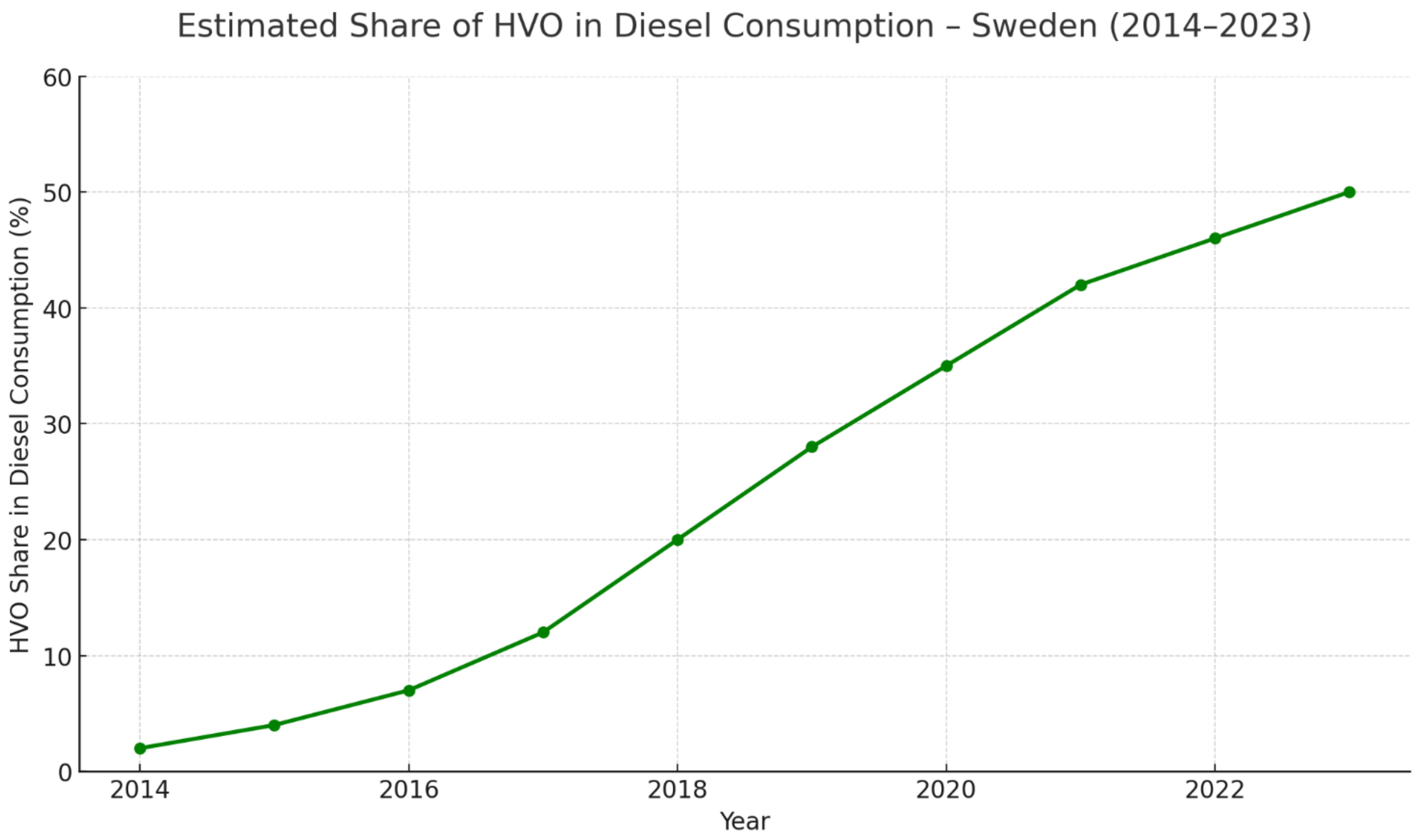
How they did it

Since 2008, Sweden's Public Transport Agreement Committee – made up of representatives from both public transport authorities and operators – has worked towards a shared vision of sustainable mobility. Through common goals, guidelines, recommendations and standards, they have aligned political ambitions with practical industry solutions.

"Our sector has successfully combined public procurement demands with our own standards and recommendations for the tendering process," said Anna Grönlund, Deputy Managing Director of the **Swedish Bus and Coach Federation** and President of the IRU Passenger Transport Council. "This has enabled us to run on fossil-free fuels such as HVO100 and start the electrification of buses. In total, the bus and coach fleet

Sweden's buses are now nearly 100% fossil-free | IRU | World Road Transport Organisation. Disponível em: <https://www.iru.org/news-resources/newsroom/swedens-buses-are-now-nearly-100-fossil-free>. Acesso em: 15 jul. 2025.

HVO: the Swedish experience



Sources: Swedish Energy Agency, Scania, Neste (2023 estimates)

Biofuels: the Swedish experience

< Latest market news

Sweden to up biofuel mandates again after slashing them

Market: Biofuels, Oil products | 28/08/24

Sweden's government announced that the country will raise its greenhouse gas (GHG) reduction obligations to 10pc for gasoline and diesel from 6pc, with changes due to come into effect on 1 July next year according to Swedish bioenergy association Svebio.

The country announced in May last year that it was planning to lower GHG reduction mandates for 2024-2026 to 6pc for both diesel and gasoline, from 30.5pc for diesel and 7.8pc for gasoline in 2023. The government at the time said this was because higher GHG reduction targets in Sweden, compared with the rest of the EU, were pushing diesel prices up at the pump.

The biofuels industry in Sweden welcomed the new 10pc mandate, as it will support domestic demand for its fuels. The drop in Sweden's mandates to 6pc had a significant effect on domestic biofuels usage and wider biofuel prices in Europe, particularly hydrotreated vegetable oil (HVO). Because fatty acid methyl ester

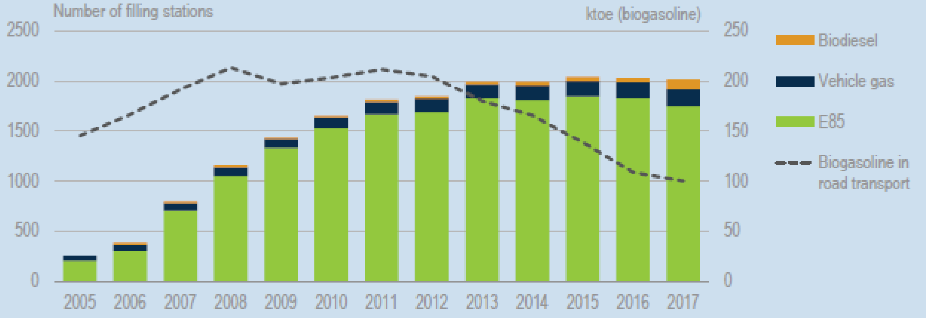
Box 3.1 The Swedish Pump Act

In December 2005, the parliament adopted the Pump Act (2005:1248), which obliged all large filling stations to supply at least one renewable fuel. The objective was to improve the availability of renewable fuels and thereby remove a major obstacle to reducing CO_2 emissions in the transport sector.

By not promoting any specific fuel, the Pump Act was intended to be technology neutral. In practice, the act has resulted mostly in installations of pumps that provide ethanol (E85), which has been the cheapest option for the station owner. By the end of 2017, there were 1 749 filling stations for E85, which represented 87% of the total biofuel filling stations (Figure 3.9). The rapid growth in HVO consumption is not represented by an increase in biodiesel filling stations since the HVO is mostly blended into regular diesel fuel.

The Pump Act succeeded in increasing the availability of biofuels at Swedish filling stations. However, this does not guarantee that consumers use renewable fuels. Ethanol cars can drive on either E85 or regular gasoline, and consumption of biogasoline has declined in recent years despite the high availability of E85 fuelling stations (Figure 3.11). Fulfilling the obligation in the Pump Act has also led to extra costs for the station owner.

Figure 3.11 Filling stations for renewable transport fuels, 2005-17



The Pump Act successfully increased the number of biofuel filling stations in Sweden, but not a guaranteed growth in biofuel consumption.

Sources:
Sweden to up biofuel mandates again after slashing them | Latest Market News. Disponível em: <https://www.argusmedia.com/en/news-and-insights/latest-market-news/2602511-sweden-to-up-biofuel-mandates-again-after-slashing-them>. Acesso em: 15 jul. 2025.
Energy Policies of IEA Countries: Sweden 2019 Review – Analysis - IEA. Disponível em: <https://www.iea.org/reports/energy-policies-of-iea-countries-sweden-2019-review>. Acesso em: 15 jul. 2025.

E-fuels and the synthetic gasoline

- Porsche’s Haru Oni Plant

About

HIF Haru Oni is the first operating e-Fuels facility in the world.

The plant uses renewable energy from the wind and a process called electrolysis to produce green hydrogen. The project captures CO_2 from a biogenic source and use a process of synthesis to combine the CO_2 and hydrogen to produce e-Fuels, including synthetic green gasoline (e-Gasoline) and synthetic green Liquefied Gas (e-LG). The facility is preparing for the installation and future operation of the first Direct Air Capture unit in the world for e-Fuels production.

HIF Haru Oni has received over 2,000 visitors from all over the world since its inauguration.

What about biogas?

- Huge untapped potential in Latin America


ERS • PODCAST

THE BRAZILIAN REPORT

All Power Insider Coronavirus 2022 Race Business Tech Podcast Society Environment Latin America Opinion Tourism Guide to Brazil

ENVIRONMENT

Brazil's untapped biomethane potential

A byproduct of organic waste, this clean energy source could replace diesel and play an important role in the energy transition

Biomethane-powered truck in front of the presidential palace, as the government launches a biomethane program in March 2022. Photo: José Cruz/ABr

Landfill biogas

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Sanitary landfill flare in the city of Manaus

CH_4 direct emission is approximately 28 times worse than its burning to CO_2

Source: https://d.emtempo.com.br/dia-a-dia/58063/aterro-de-manaus-gera-40-mil-toneladas-de-credito-de-carbono
https://ourworldindata.org/greenhouse-gas-emissions

The problem: incorrect urban waste disposal – the Brazilian case

- **2022: 2518 dumps, 2257 landfills, 795 municipalities that did not informed their numbers;**
- **By law, all dumps in Brazil should have been closed by 2014, a deadline given by the National Solid Waste Policy in 2010;**
- **New deadline for the end of dumps: 2024;**
- **Huge atmospheric methane generation that could be generating energy.**

Source:
https://www12.senado.leg.br/radio/1/noticia/politica-nacional-de-residuos-solidos-completa-8-anos-sem-cumprir-meta-de-fechar-lixoes
http://www.lixoes.cnm.org.br/

Impacts of incorrect waste disposal

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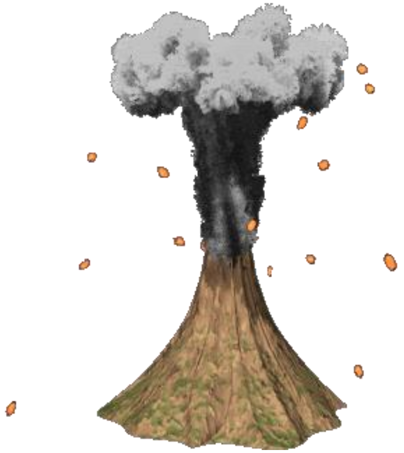
- Brazil: dumps deliver around 216,000 tons per year of methane or 6 million tons of CO_2eq;
- Equivalent to the annual environmental impact of Etna Vulcan or 3.2 million gasoline vehicles;
- Enough to generate electricity for a city of 600,000 people.
- What about other countries?



216,000 Tons/year CH_4

3.2 million vehicles

125 g CO2eq/km
15000 km per year

Electricity for 600,000 people

Sources:
-Estimativas Anuais de Emissões de Gases de Efeito Estufa no Brasil, 3° edição. Ministério da Ciência, Tecnologia, Inovações e Comunicações. Brasília, 2016.
-Price Waterhouse Coopers Ltd., Índice de Sustentabilidade da Limpeza Urbana, 2019.
-Indicadores de Desenvolvimento Sustentável, Instituto Brasileiro de Geografia e Estatística – IBGE.

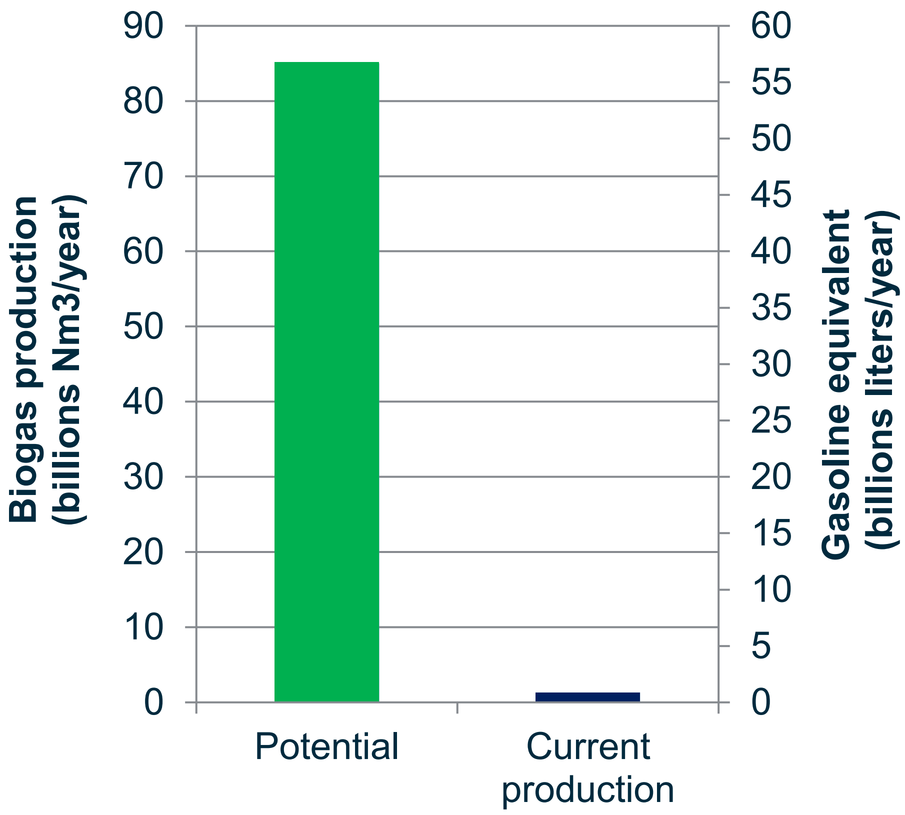
The solution

Grupo de Pesquisa em Motores, Combustíveis e Emissões

Source: https://www.curitiba.pr.gov.br/conteudo/aterro-sanitario-de-curitiba/454

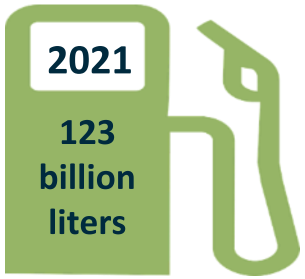
Sanitary landfill in the city of Curitiba-Brazil

Current scenario in Brazil and possibilities

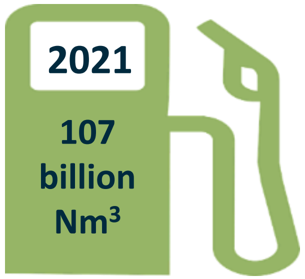


*Gasoline LHV: 32.24 MJ/L)

- Total Brazilian consumption in 2021

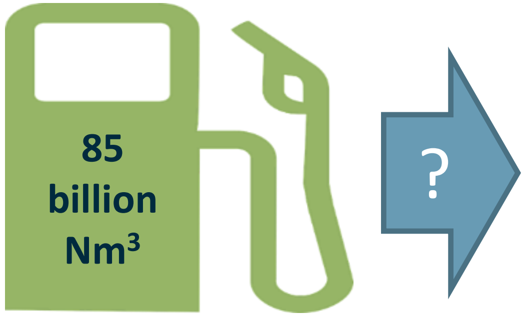


Gasoline+diesel+ethanol



Biomethane

- Potential:

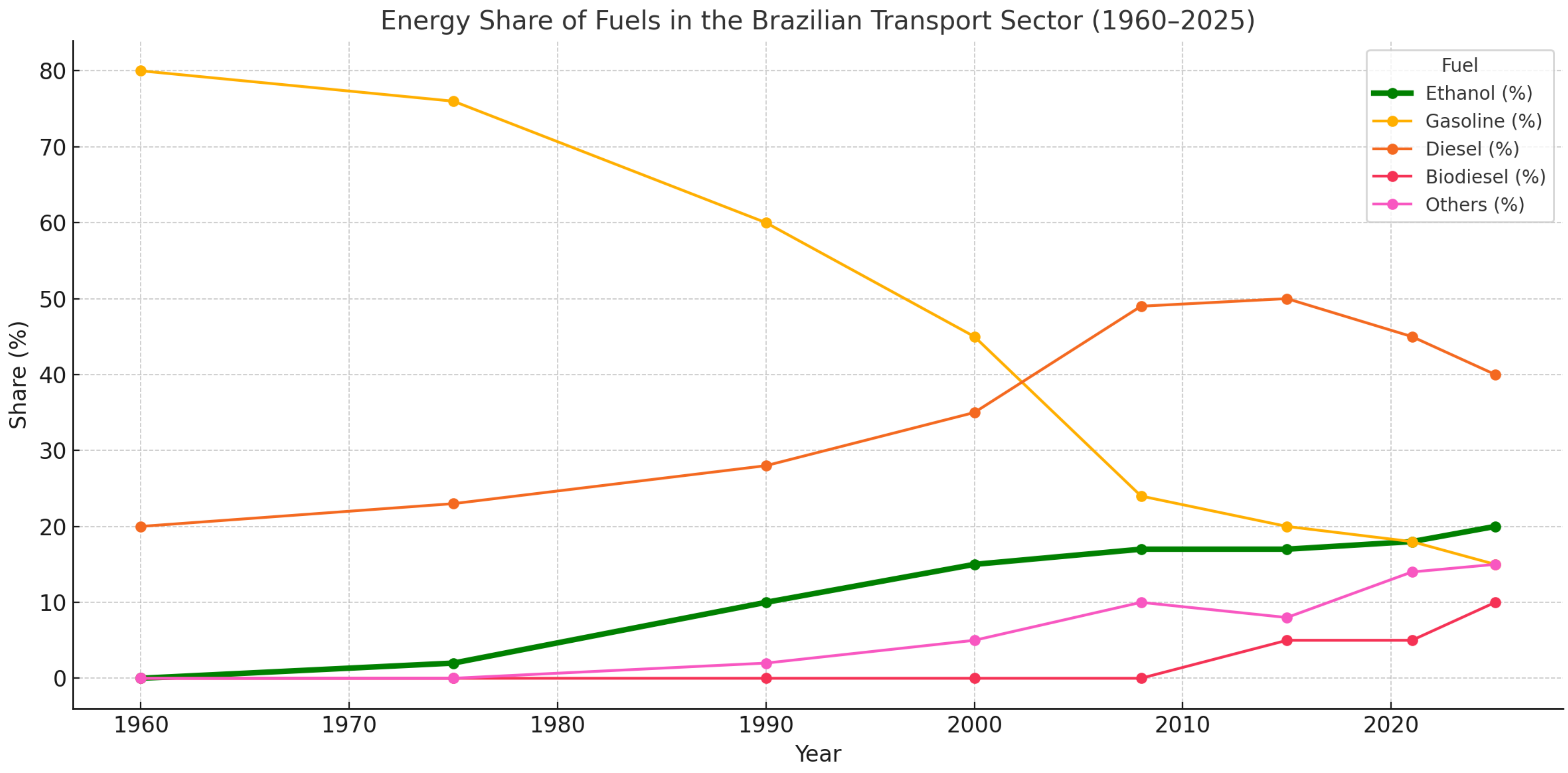


Biomethane

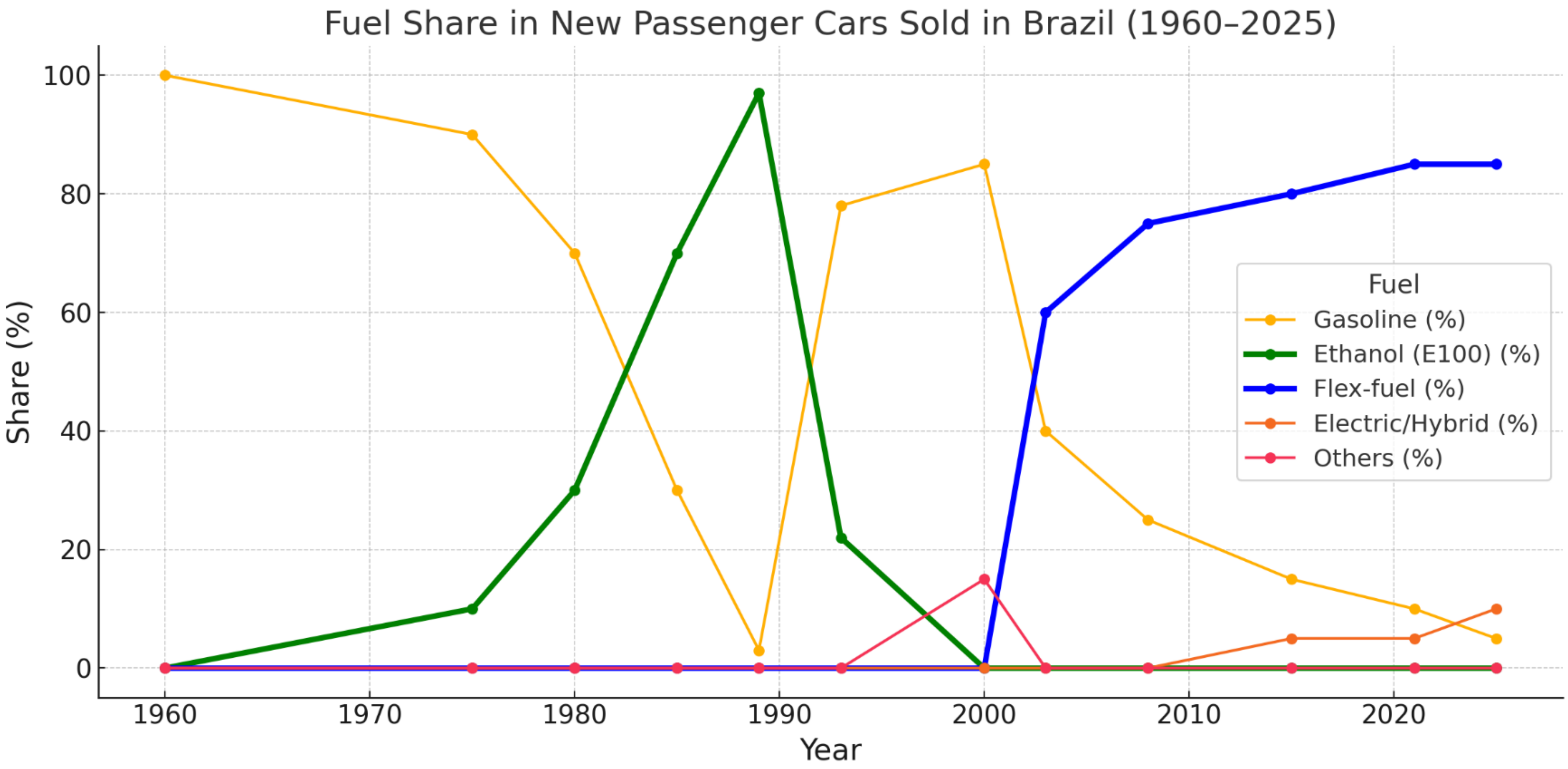
Green Hydrogen

Source:
CIBIOGÁS, "Panorama do biogas no Brasil 2021," 2021.
ANP, " Vendas de etanol e gasolina A no Brasil – 2010-2019" .
Infomoney: https://www.infomoney.com.br/minhas-financas/brasil-bate-recorde-de-venda-de-combustivel-em-2021-puxado-por-diesel-e-gasolina/

The Brazilian scene



The Brazilian scene

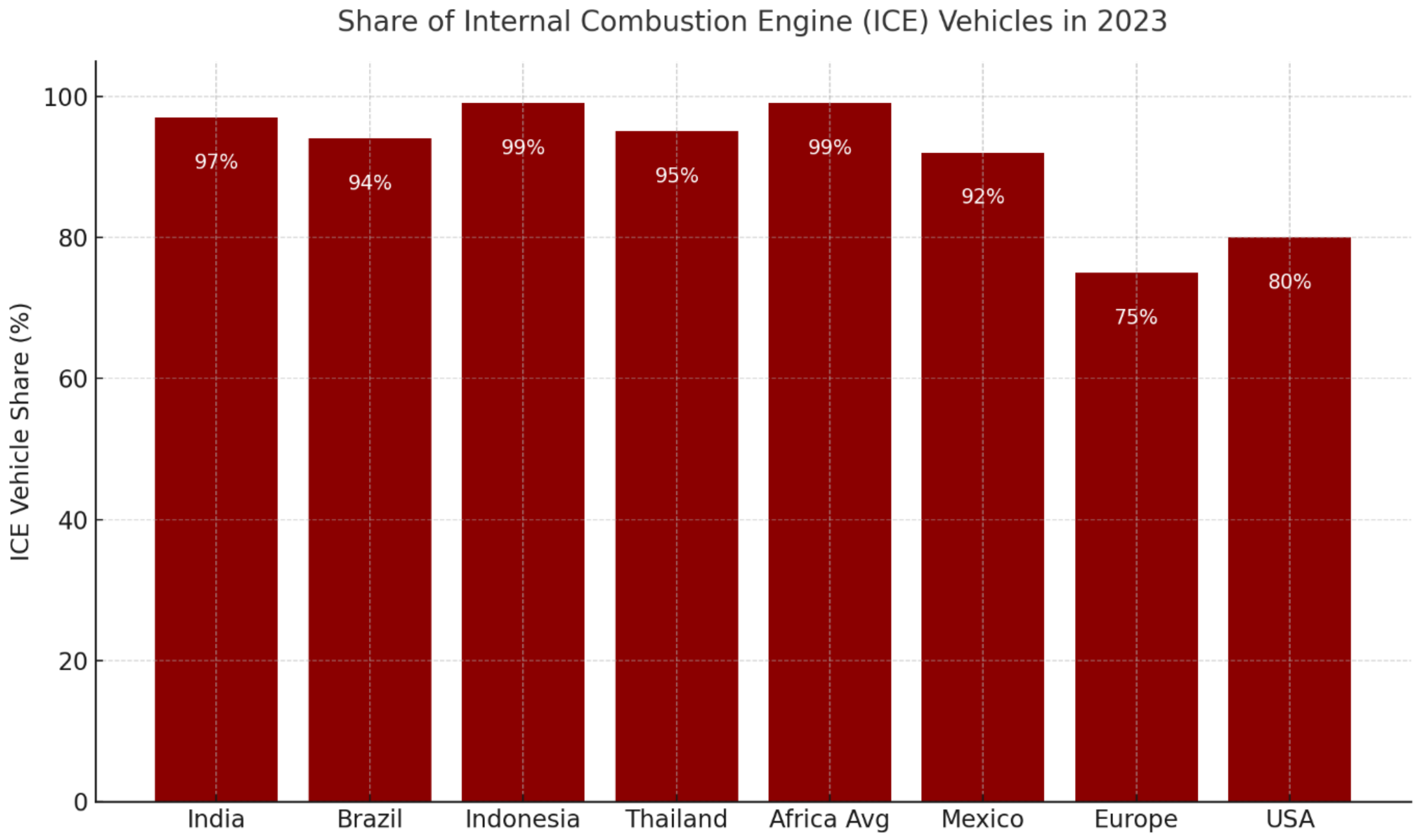


Ethanol: the Brazilian Journey

- 1975: Proálcool program is created to avoid the oil crisis with sugar-cane ethanol
- 1979: First vehicle running on E100 is launched by FIAT
- 1989: 97% of the national passenger car fleet runs on ethanol (E100)
- 1993: mandatory blend of 22% ethanol in gasoline (E22)
- 2003: VW Brasil launches the first flex-fuel vehicle – 515 millions of CO_2 emissions avoided!
- 2007: E25
- 2015: E27
- 2025: E30
- 2030 and beyond?

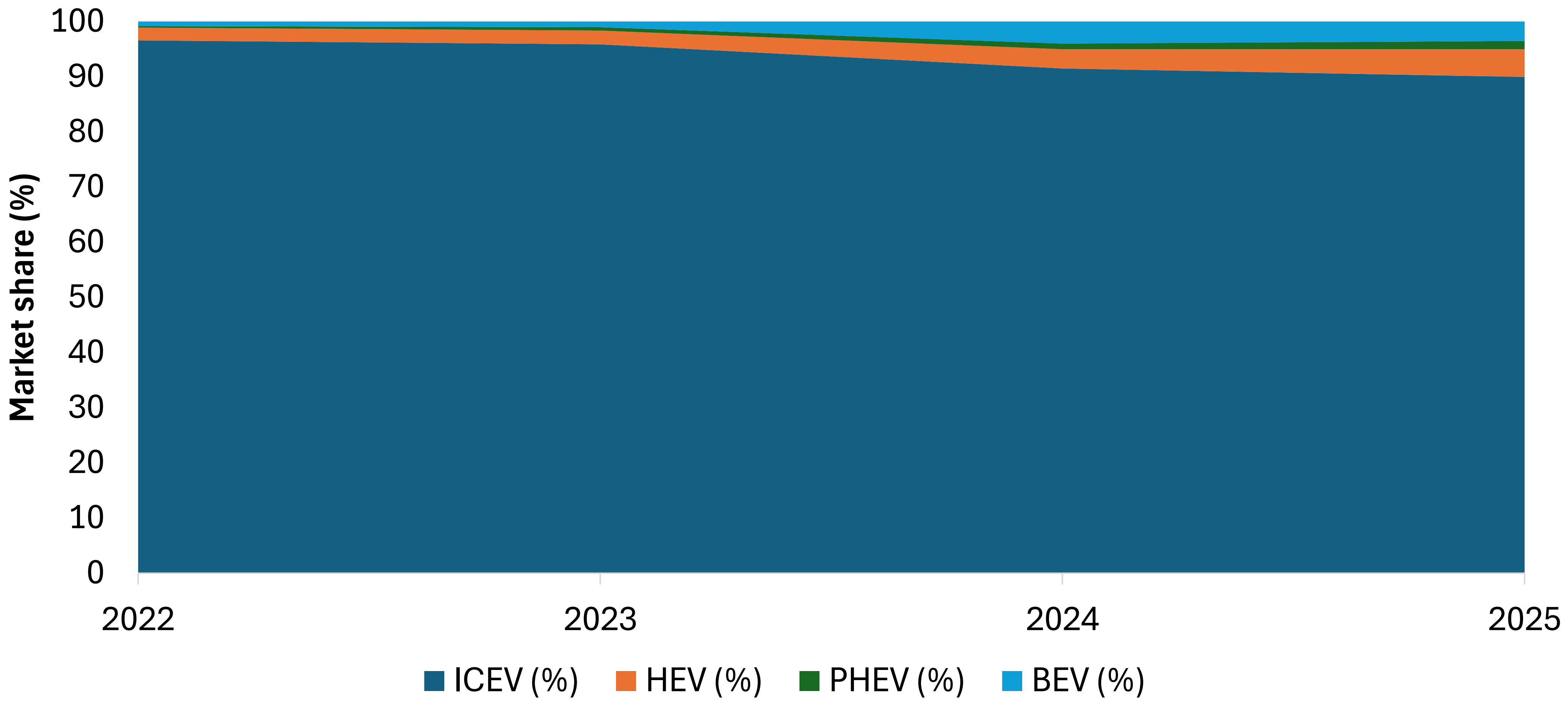
Sources: https://unica.com.br/noticias/uso-do-etanol-evita-515-milhoes-de-toneladas-de-co2-na-atmosfera/
https://energy.economictimes.indiatimes.com/news/oil-and-gas/brazils-ethanol-journey-from-a-fuel-of-the-future-to-the-future-of-fuel/90941877

The lasting presence of ICE vehicles



Source: IEA Global EV Outlook 2023; regional government and industry reports (estimates)

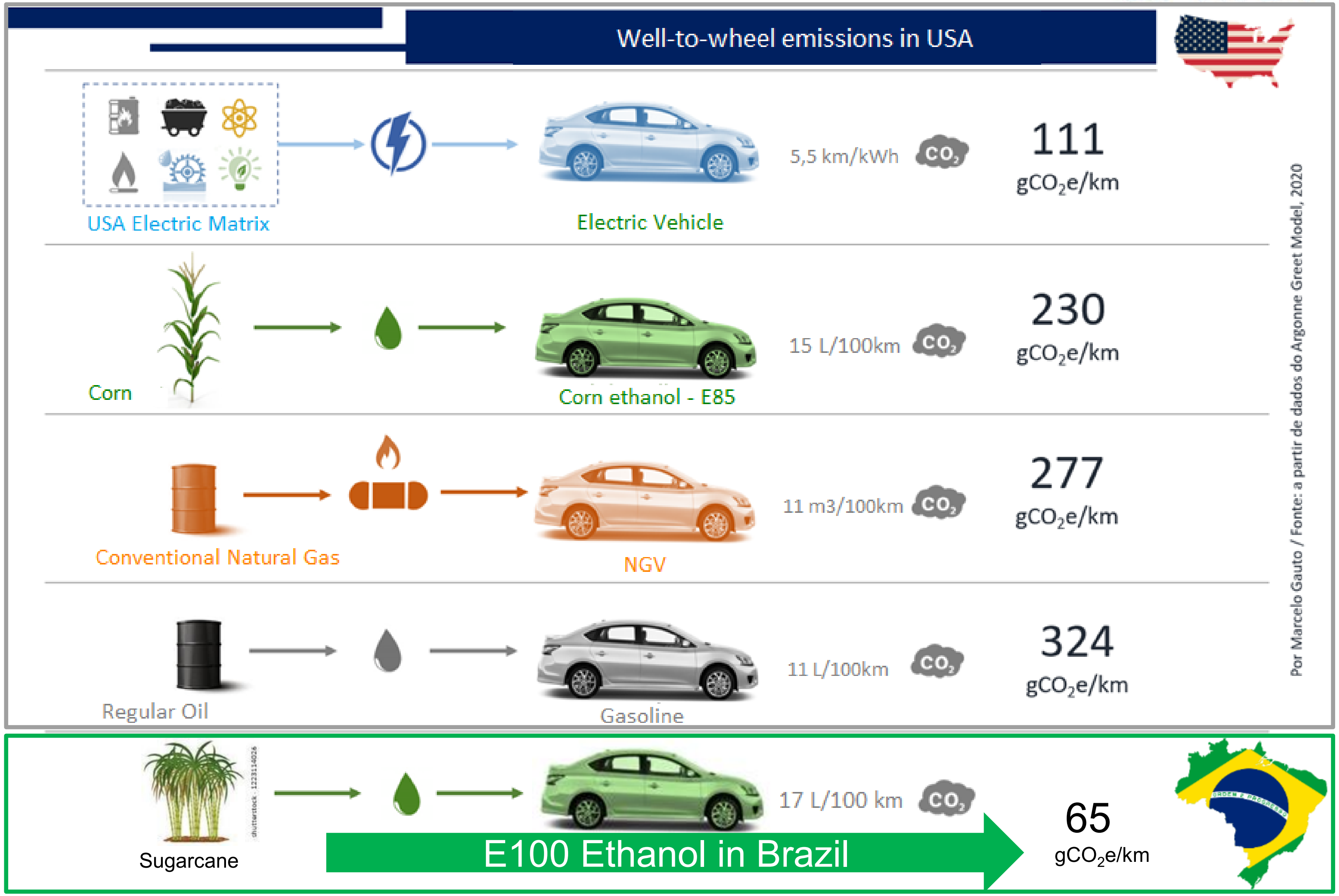
Vehicle sales in Brazil by propulsion source



Source: ANFAVEA – Anuário da Indústria Automobilística 2024; RENAVAM (Senatran), dados de emplacamentos de veículos leves 2022–2025.

BEVs are not always advantageous

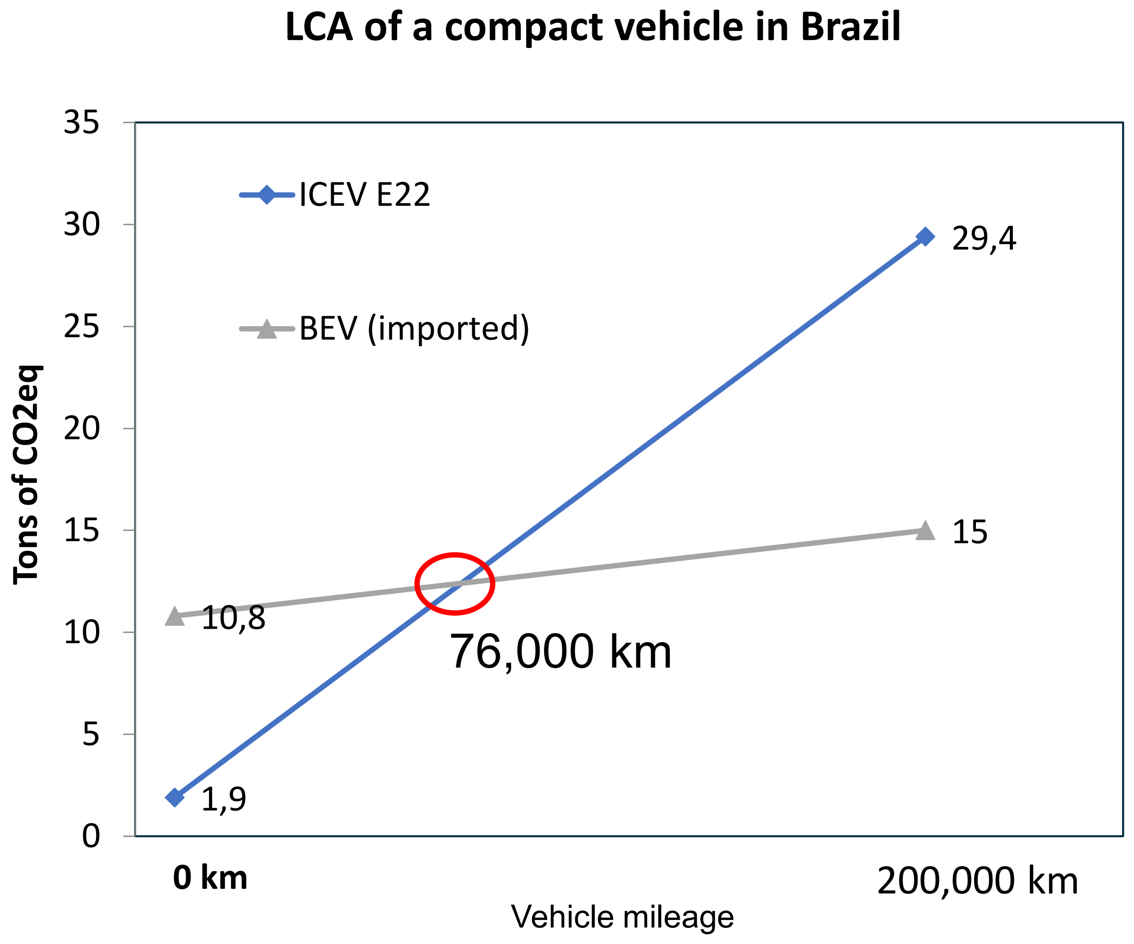
- It always depends on the energy source
- Brazil: 65 gCO_2e/km vs. 230 gCO_2e/km in USA (corn ethanol)



Adapted from: Marcelo Gauto:, https://www.linkedin.com/posts/quimicogauto_transiaexaetoenergaeztica-activity-6801143016477216768-Jf_m
Data based on Argonne Greet Model, 2020

BEVs vs. Ethanol ICE: the Brazilian case

- The Brazilian case: ICEVs emit less CO_2 than BEVs for a large part of their life cycle
- With gasoline (E22): trade-off around 76,000 km

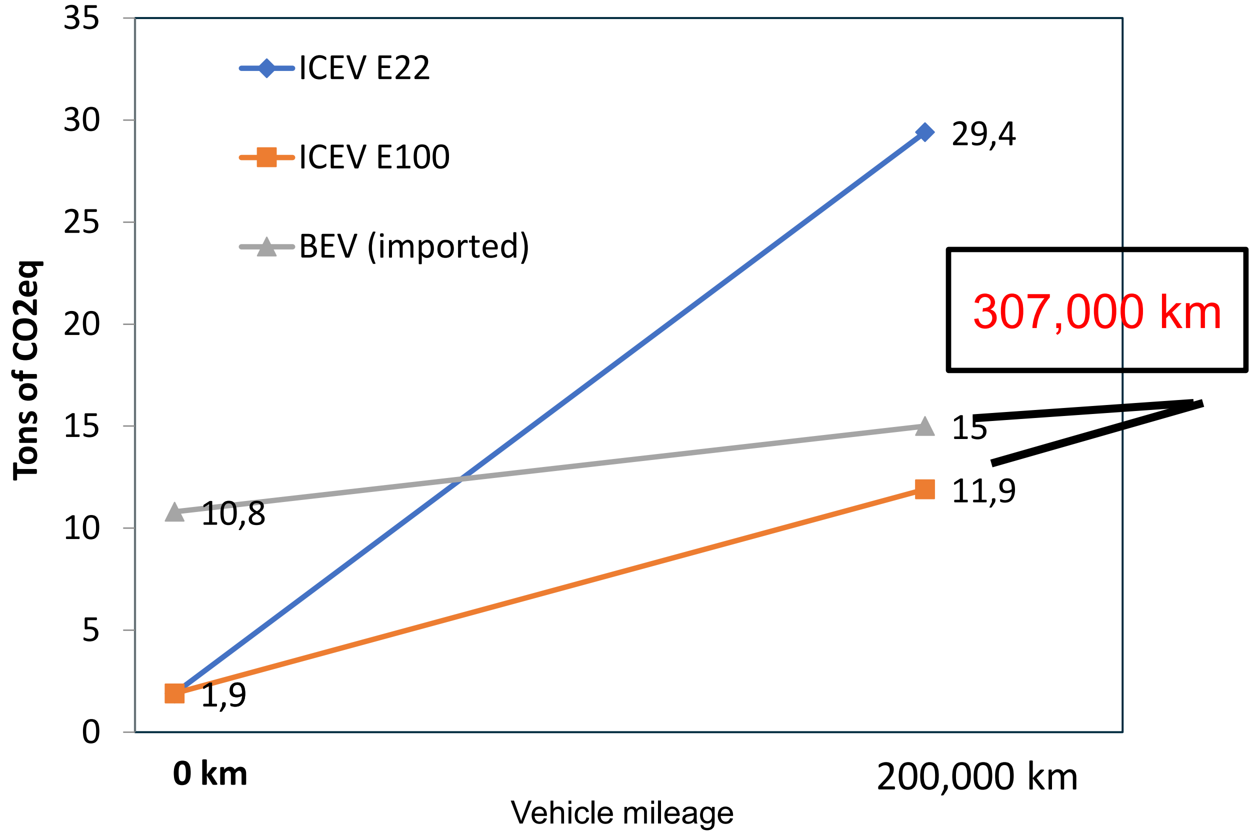


Adapted from: Tomanik, E., Policarpo, E., Rovai, F. “Life Cycle Assessment of Vehicular Electrification”. Manuscript submitted for publication. 2021.

BEVs vs. Ethanol ICE: the Brazilian case

- Compared to an imported BEV, ICEVs with ETHANOL emit less CO_2 up to to 307,000 km of their life

LCA of a compact vehicle in Brazil

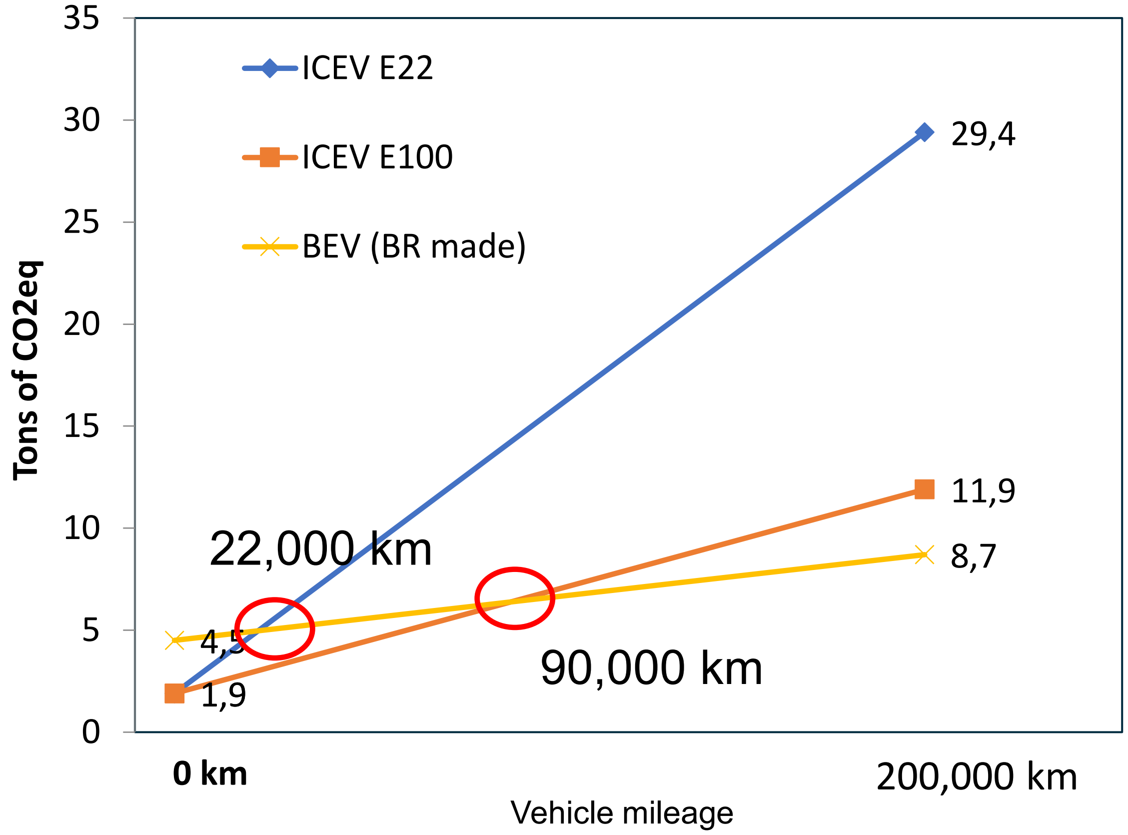


Adapted from: Tomanik, E., Policarpo, E., Rovai, F. “Life Cycle Assessment of Vehicular Electrification”. Manuscript submitted for publication. 2021.

BEVs vs. Ethanol ICE: the Brazilian case

- BEV produced locally: breakeven point around 90,000 km due to a very renewable energy matrix.
- With gasoline (E22), this value would be around 22,000 km.
- With **E30**, this should go **even further**.

LCA of a compact vehicle in Brazil



Adapted from: Tomanik, E., Policarpo, E., Rovai, F. “Life Cycle Assessment of Vehicular Electrification”. Manuscript submitted for publication. 2021.

Biofuels and Technical Challenges

- Energy Density: Many biofuels and e-fuels have lower energy density than gasoline or diesel, reducing vehicle range or performance.
- Engine Compatibility: Some fuels require engine modifications or dedicated systems (e.g., hydrogen, biogas).
- Cold Start and Stability: Issues with ignition, stability, or performance in varying weather conditions.
- Retrofitting? Adaptation to the existing fleet?
- The case of vegetable oil

Economic Challenges

- **High Production Cost:** Fuels like e-fuels, SAF, and green hydrogen are still significantly more expensive than fossil fuels.
- **Lack of Economies of Scale:** Many technologies are not yet widely adopted, leading to higher per-unit costs.
- **Market Volatility:** Fossil fuel price fluctuations affect the competitiveness of renewable alternatives.

Infrastructure Challenges

- **Distribution Networks**: Most fueling stations and logistics are designed for fossil fuels, most of them liquid.
- **Storage and Safety**: Hydrogen and biogas require pressurized or cryogenic storage, demanding new infrastructure.
- **Retrofit Needs**: Existing engines, vehicles, and industrial processes may need adaptation.
- How do **Biogas** and biomethane or **Hydrogene** are affected?

Social and Policy Challenges

- **Public Awareness and Acceptance**: Limited knowledge and trust in new fuel technologies.
- **Policy and Regulation Gaps**: Lack of long-term, stable incentives or mandates to support transition.
- **Global Inequities**: Developing countries may lack the resources to adopt alternative fuel systems.

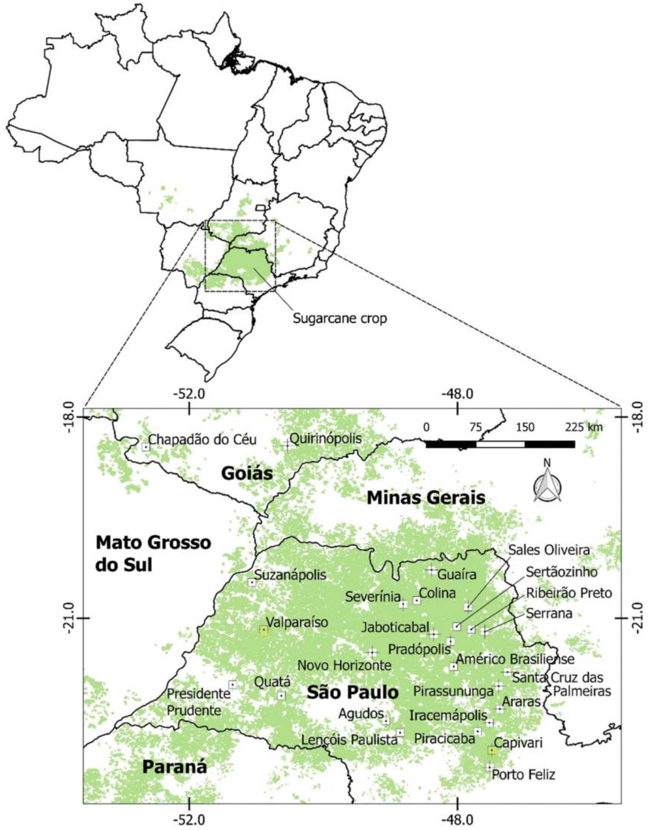
Policies and Global Trends

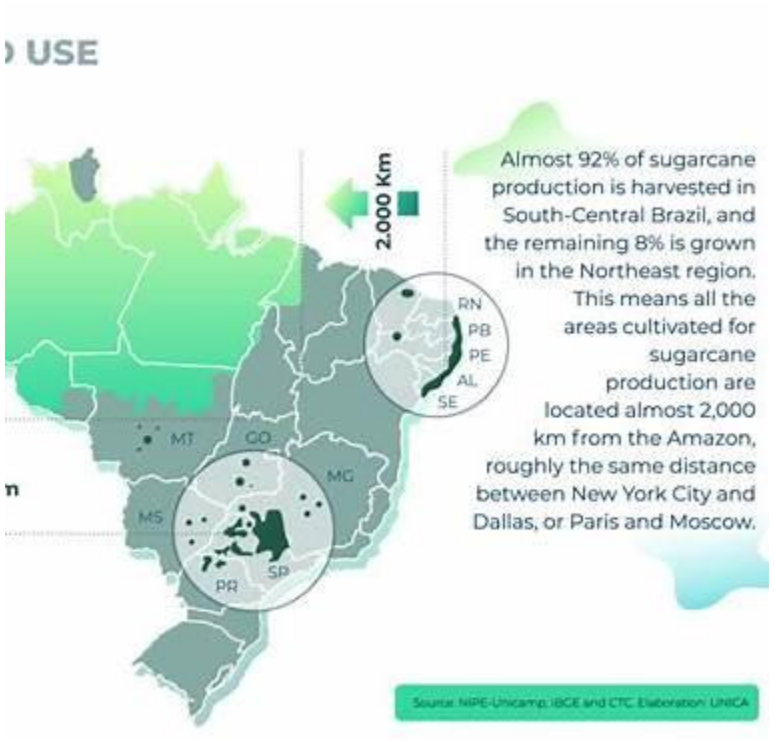
- Public policies in Brazil, Europe, and the U.S.
- Blending mandates, carbon credits, fiscal incentives
- Strategic role of biofuels in the energy transition
- Net zero by 2050?

Countries in South America with net Zero Goals	
Argentina	2050
Colômbia	2050
Brazil	**2060**
Equador	2050
Peru	2050
Uruguay	2030
Chile	2050
French Guyana	2050

Environmental and Resource Constraints

- **Land Use and Competition with Food**: Some biofuels (especially first-generation) compete with food crops for land and water.
- **Feedstock Availability**: Sustainable, large-scale biomass or waste availability can be a bottleneck.

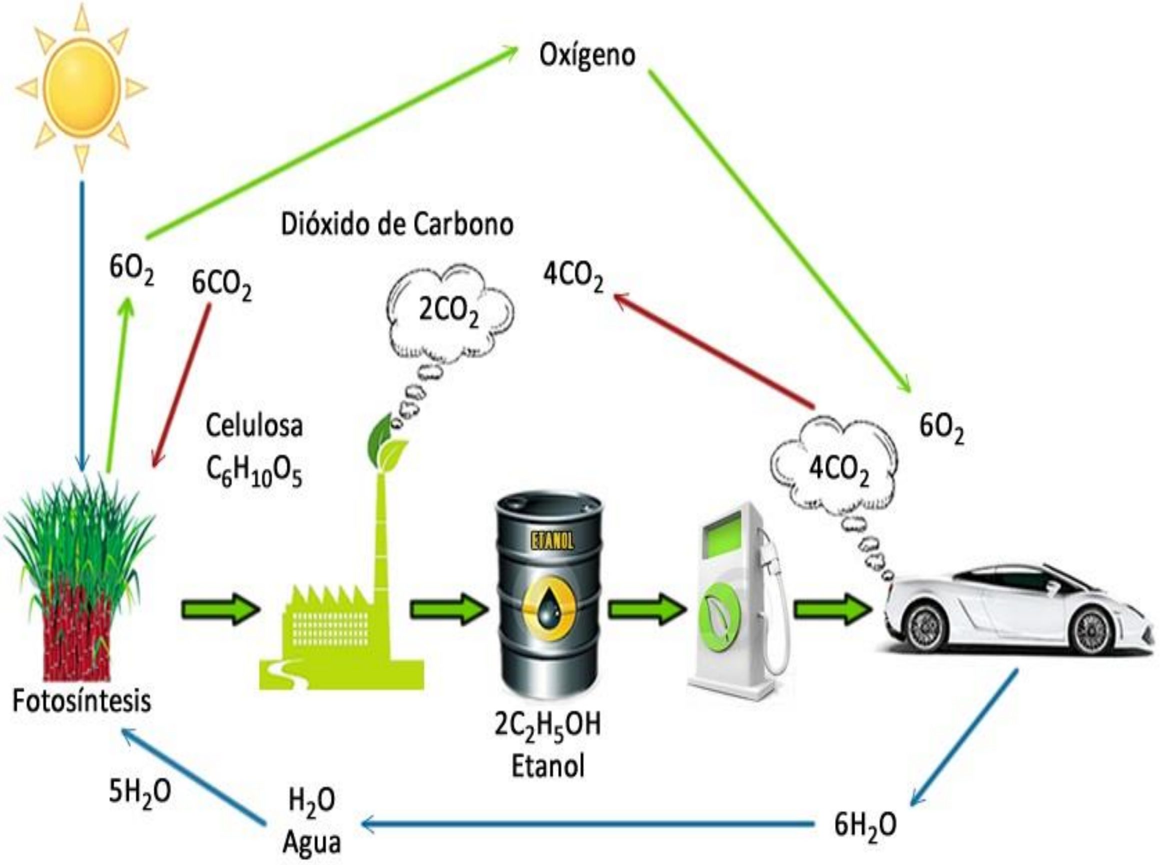




- **Sugarcane for ethanol does not compete with Amazon land.**
- **92% of production is concentrated in the southeastern region**
- **O**nly **8% in the Northeast**, both **far from the Amazon**.
- The use of **existing pastureland and agricultural areas** ensures that expansion does **not impact fragile ecosystems**.

Key Characteristics of Biofuels

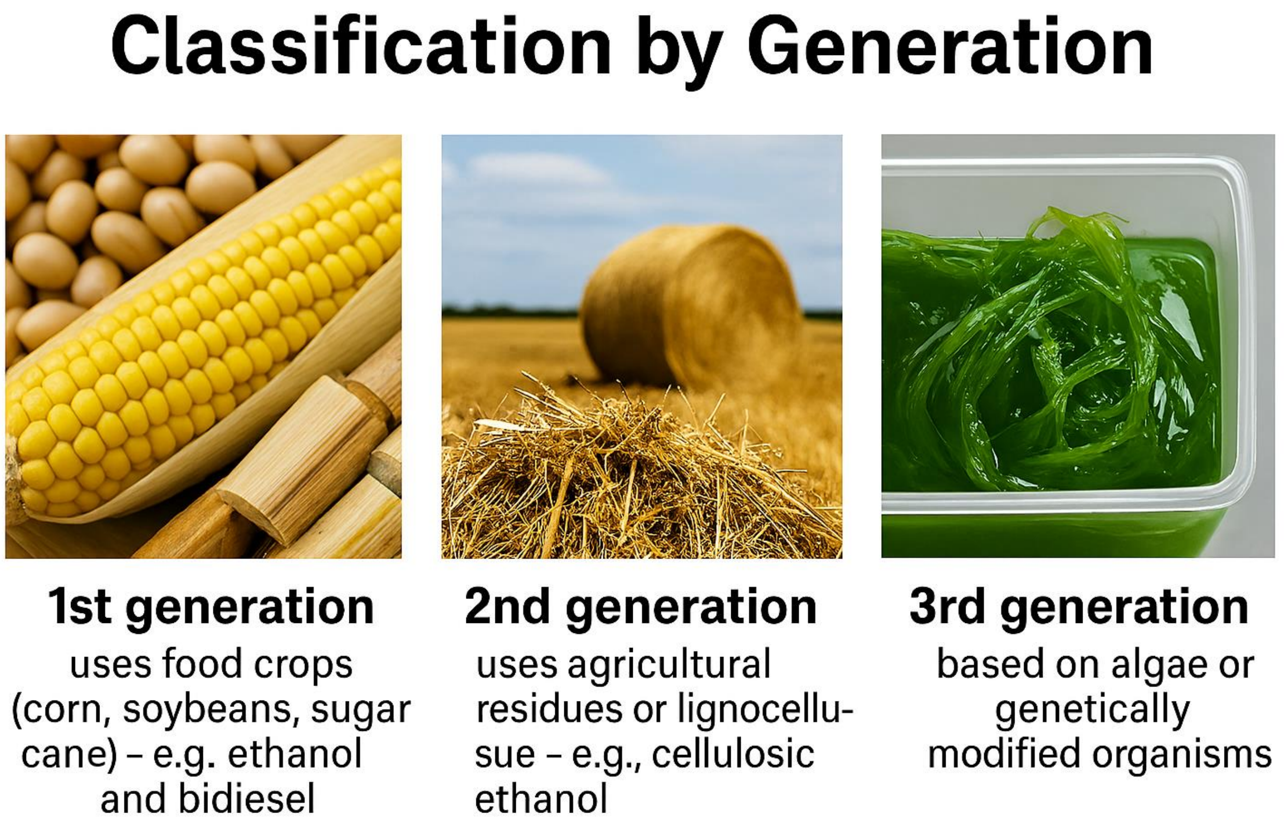
- CO_2 Emission Reduction: In many cases, up to 90% lower than fossil fuels (especially HVO and biogas)
- Renewable Origin: Derived from plants, agricultural residues, or organic waste
- Circular Potential: Many utilize waste as an energy input
- Compatibility: Some are *drop-in* fuels, meaning they can directly replace fossil fuels without engine modification



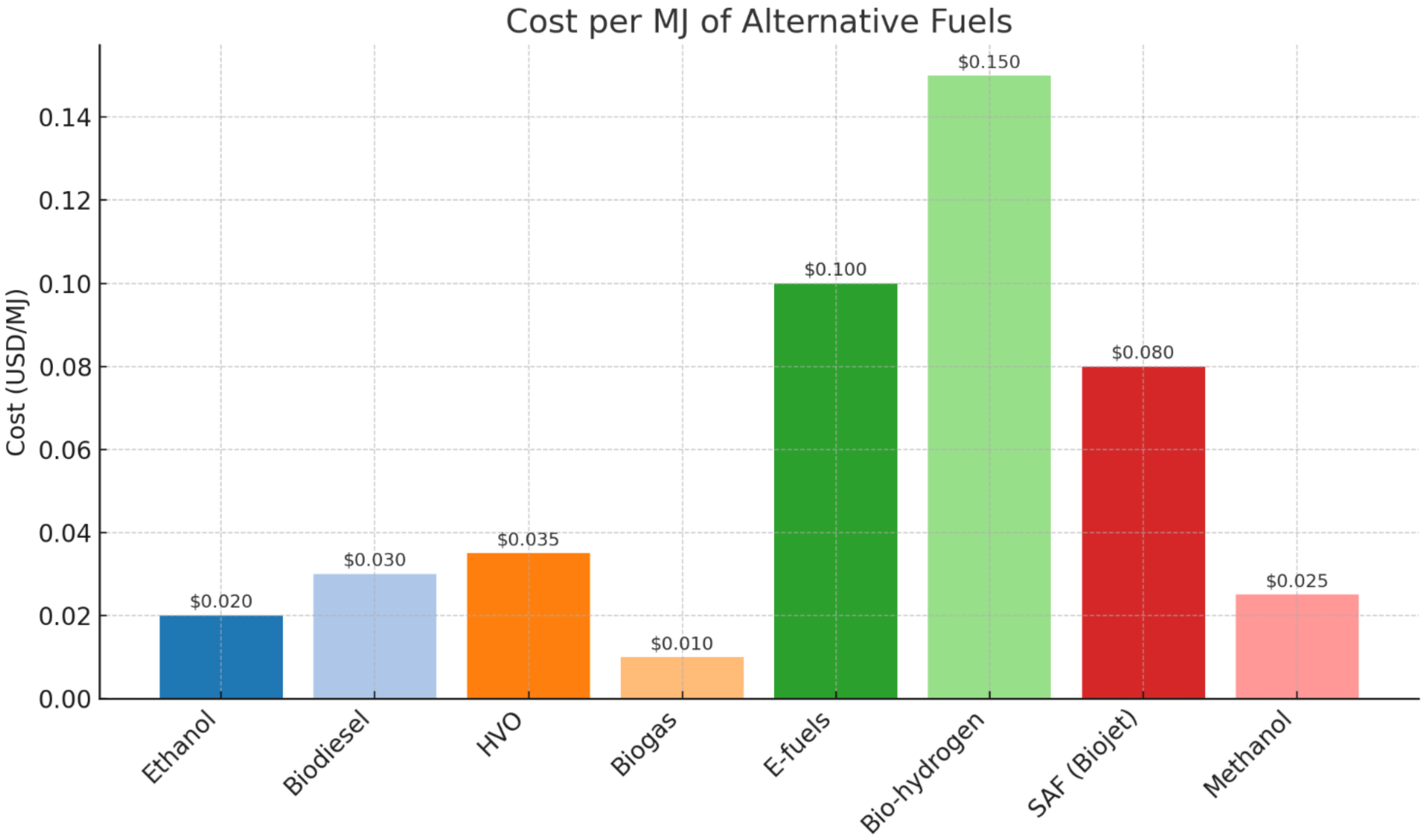
Biofuels

Classification by Generation:

- **1st generation:** uses food crops (corn, soy, sugarcane) – e.g., ethanol and biodiesel
- **2nd generation:** uses agricultural residues or lignocellulose – e.g., cellulosic ethanol
- **3rd generation:** based on algae or genetically modified organisms



The cost of energy



Spark ignition engine's fuel properties

Property	Unit	Fuel					
		Gasoline	**Ethanol**	**Methane**	**Hydrogen**	**ABE**	**Butanol**
Lower Heating Value (LHV)	$MJ.kg^{-1}$	44,79	26,9	46,72	119,70	27–30	33.1
Density	$kg.m^{-3}$	720-775	785	0,67	0,08	810	810
Diffusion Coefficient in Air	$cm^2.s^{-1}$	0,05	0,02	0,189	0,61	0.025	0.026
Octane Number (RON)	-	92-98	107	120	≥ 120	98	96
Stoichiometric Air/Fuel Ratio	-	14,6	9,0	17,23	34,3	10.5	11.2
Laminar Flame Speed	$m.s^{-1}$	0,37-0,43	0,39	0,38	2,65-3,25	0.35	0.37
Flammability Limits in Air	vol %	1,2-6,0	3,3-19	5,3-15,0	4,0-75,0	2–12	1.4–11.2
Minimum Ignition Energy	MJ	0,25	0,23	0,28	0,02	0.20	0.30
Quenching Distance	mm	2,0	1,65	2,03	0,64	1.7	1.9
Autoignition Temperature	K	500-750	698	813	858	685	670
Adiabatic Flame Temperature	K	2470	2193	2224	2379	2150	2160

J. Gao, X. Wang, P. Song, G. Tian, and C. Ma, "Review of the backfire occurrences and control strategies for port hydrogen injection internal combustion engines," *Fuel*, vol. 307, Jan. 2022, doi: 10.1016/j.fuel.2021.121553.
G. Nicoletti, N. Arcuri, G. Nicoletti, and R. Bruno, "A technical and environmental comparison between hydrogen and some fossil fuels," *Energy Convers. Manag.*, vol. 89, Jan. 2015, doi: 10.1016/j.enconman.2014.09.057.
F. Yan, L. Xu, and Y. Wang, "Application of hydrogen enriched natural gas in spark ignition IC engines: from fundamental fuel properties to engine performances and emissions," *Renew. Sustain. Energy Rev.*, vol. 82, Feb. 2018, doi: 10.1016/j.rser.2017.05.227.
C. Bae and J. Kim, "Alternative fuels for internal combustion engines," *Proc. Combust. Inst.*, vol. 36, no. 3, 2017, doi: 10.1016/j.proci.2016.09.009.
X. Li, X. Zhen, S. Xu, Y. Wang, D. Liu, and Z. Tian, "Numerical comparative study on knocking combustion of high compression ratio spark ignition engine fueled with methanol, ethanol and methane based on detailed chemical kinetics," *Fuel*, vol. 306, Dec. 2021, doi: 10.1016/j.fuel.2021.121615[1] U.S. Department of Energy, "Alternative Fuels Data Center – MTBE," [Online]. Available: https://afdc.energy.gov/. [Accessed: Jul. 18, 2025].
[2] National Institute of Standards and Technology (NIST), "MTBE and n-Butanol Data," NIST Chemistry WebBook, [Online]. Available: https://webbook.nist.gov/. [Accessed: Jul. 18, 2025].

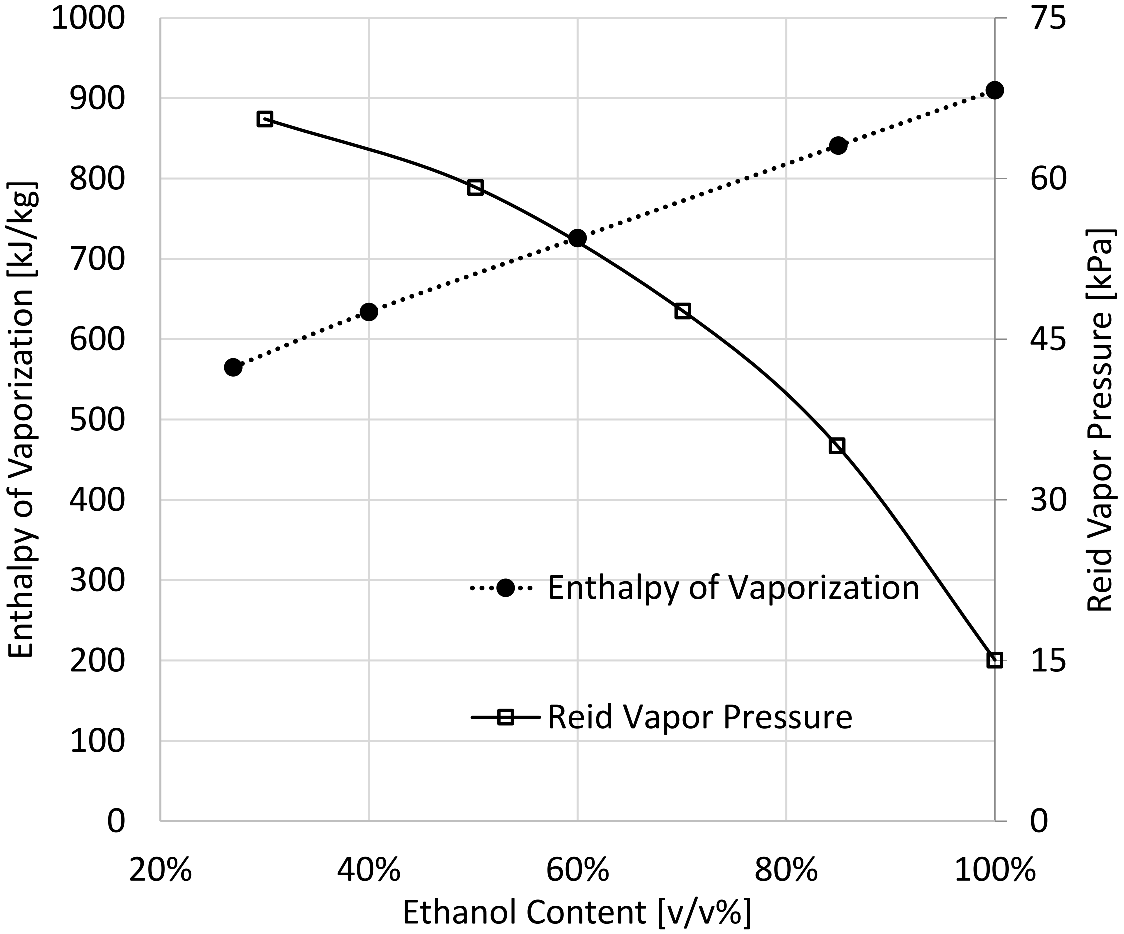
Compression ignition engine's fuel properties

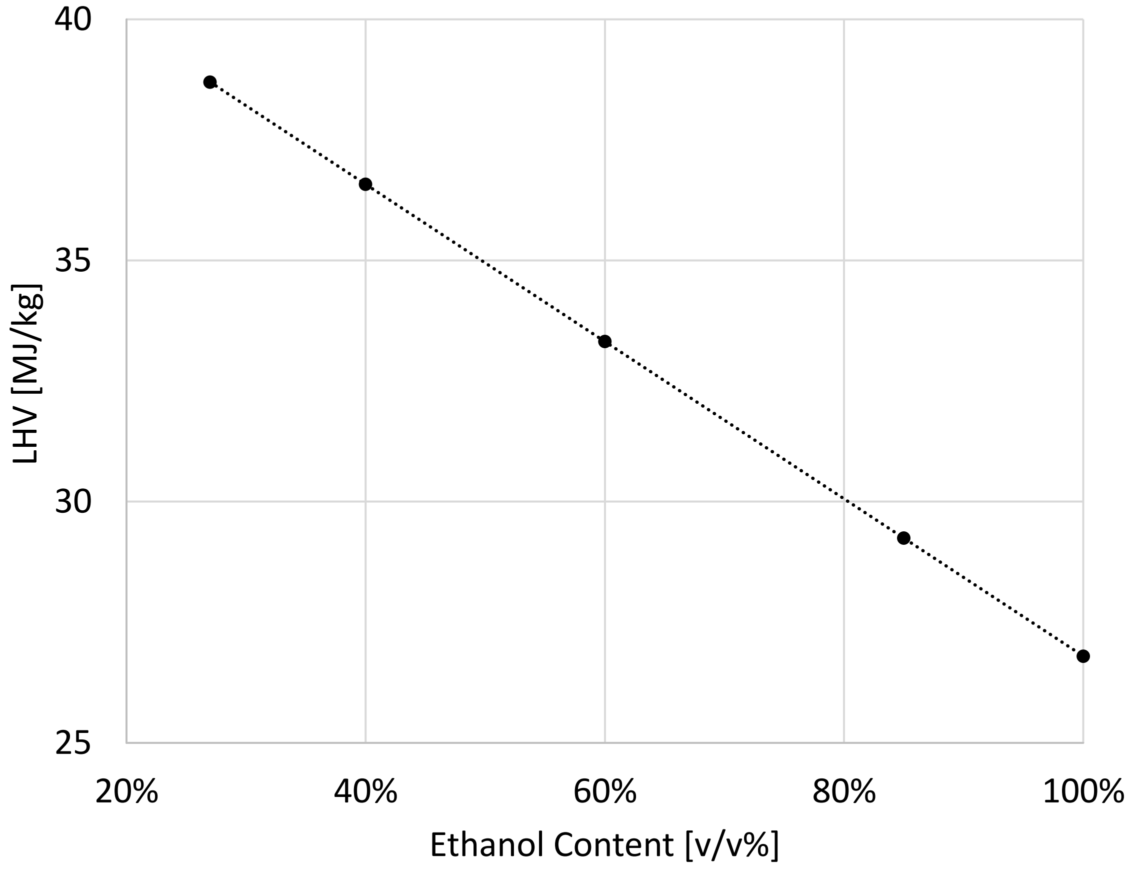
Property	Fossil Diesel	FAME Biodiesel	HVO	Vegetable Oil	DME (Dimethyl Ether)	DEE (Diethyl Ether)
Cetane Number	45–55	50–65	75–90	35–45	>55	>125
Density (kg/m³ @ 15°C)	820–845	860–900	770–790	900–950	660	710
Viscosity (mm²/s @ 40°C)	2.0–4.5	4.0–6.0	2.0–4.0	30–40	0.2	0.3
Oxygen Content (%)	0	~10	0	~11	34.8	21.6
Aromatic Content (%)	~20–35	0	0	0	0	0
Lubricity	Good	Excellent	Good	Very Good	Very Low	Low
Cold Flow Properties	Moderate	Poor (feedstock-dependent)	Excellent	Poor	Excellent	Excellent
Sulfur Content (ppm)	<10 (ULSD)	0	0	0	0	0
Renewable Origin	No	Yes	Yes	Yes	Yes (biomass/gasification)	Yes (bioethanol dehydration)
Microbial Susceptibility	Moderate	High	Low	High	Low	Low
Hygroscopicity	Low	High	Low	High	Low	Low
Boiling Point (°C)	180–360	>300	>250	>300	-25	34.5
Latent Heat of Vaporization (kJ/kg)	~250	~220	~200	~250	~460	~380

Knothe, Gerhard, Jon Van Gerpen, and Jürgen Krahl. *The Biodiesel Handbook*. Champaign, IL: AOCS Press, 2005.
Demirbaş, Ayhan. "Progress and Recent Trends in Biodiesel Fuels." *Energy Conversion and Management* 50, no. 1 (2009): 14–34.
Turns, Stephen R. *An Introduction to Combustion: Concepts and Applications*. 3rd ed. New York: McGraw-Hill, 2012.
Heywood, John B. *Internal Combustion Engine Fundamentals*. New York: McGraw-Hill, 1988.
Papagiannakis, R. G., and D. T. Hountalas. "Combustion and Emission Characteristics of a Dual Fuel Engine Operating on Natural Gas and Diesel Fuel." *Energy Conversion and Management* 45, no. 18–19 (2004): 2971–87.
National Institute of Standards and Technology (NIST). "NIST Chemistry WebBook." Accessed July 2025. https://webbook.nist.gov/chemistry/

Experimental results

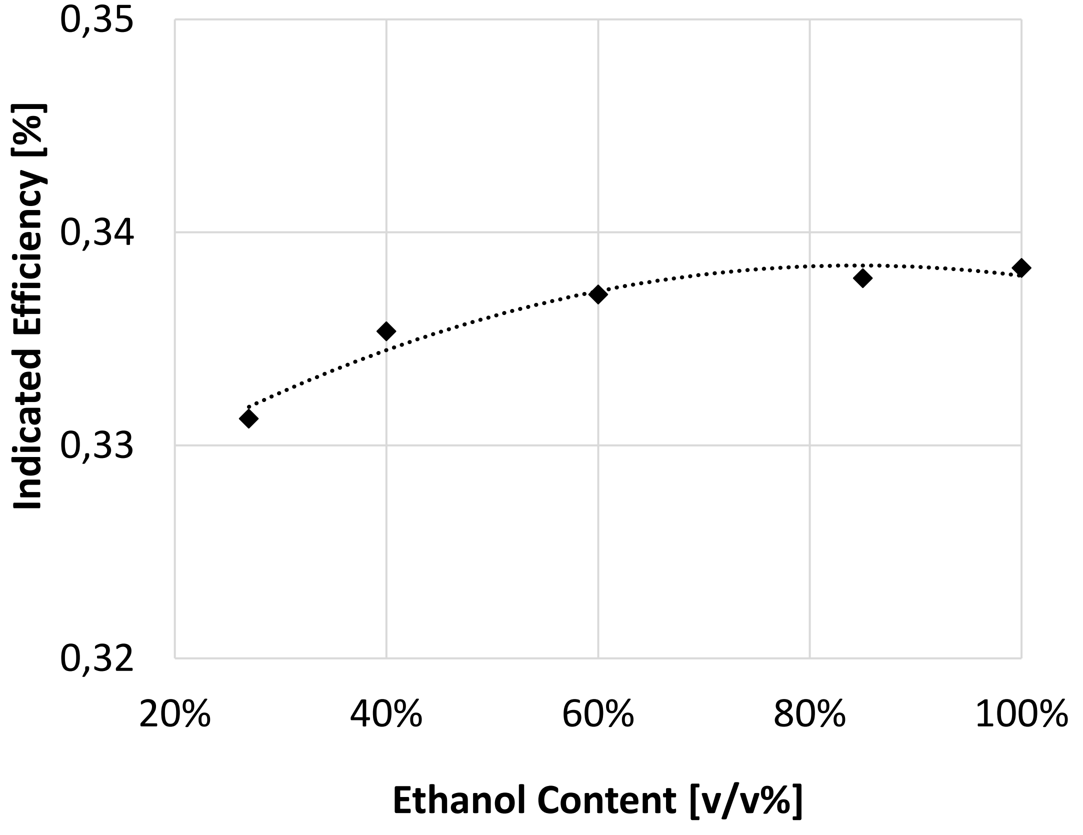
Ethanol-gasoline blends



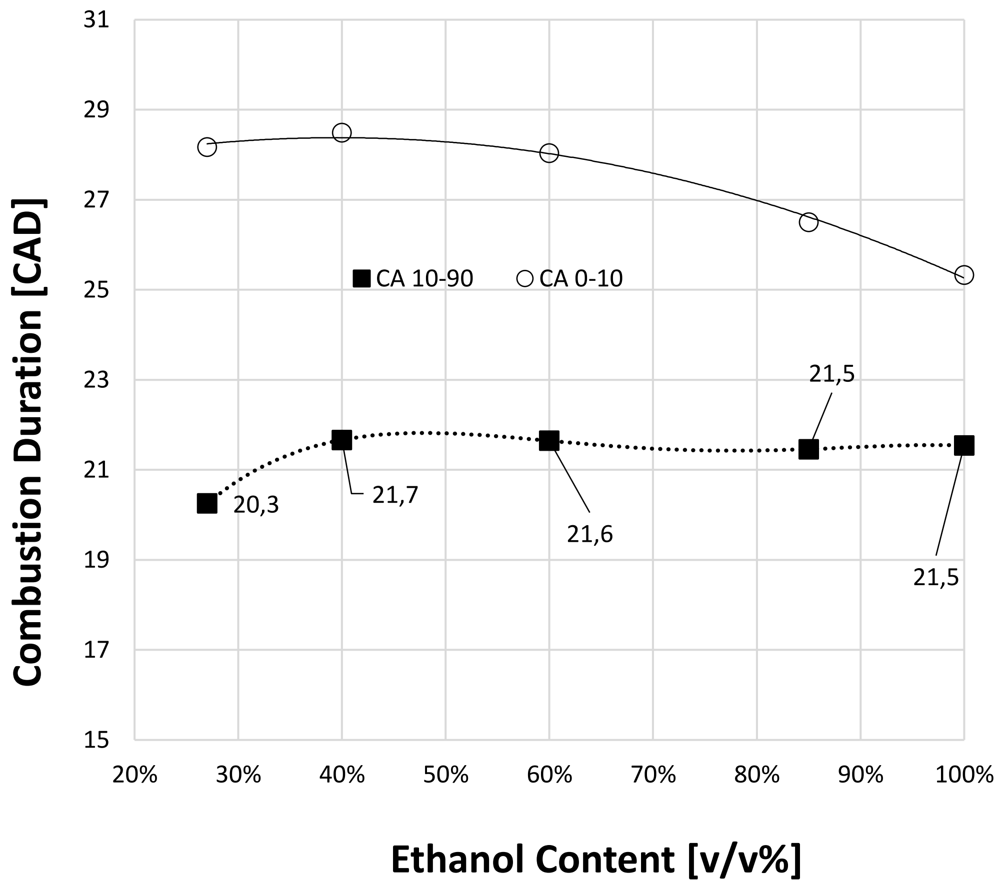


Ethanol-gasoline blends on a single cylinder research engine

Indicated efficiency

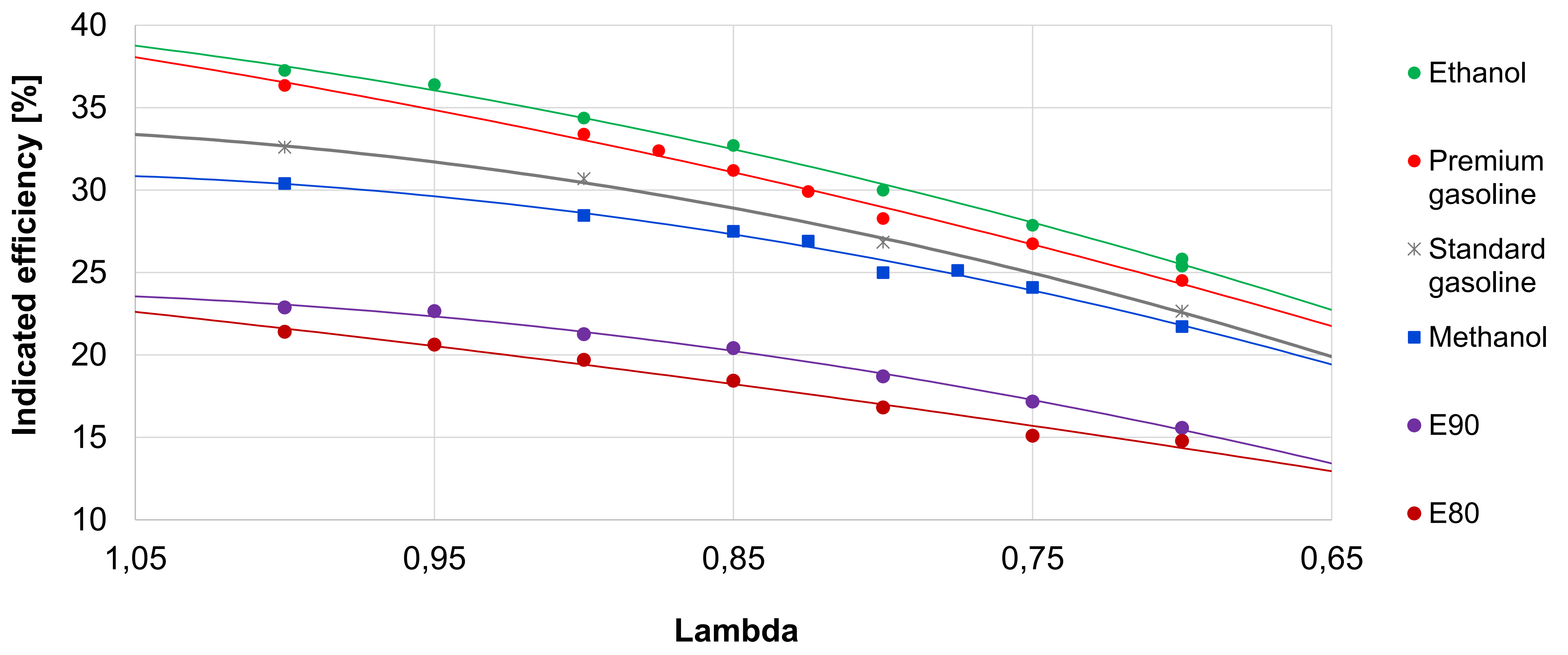


Combustion duration



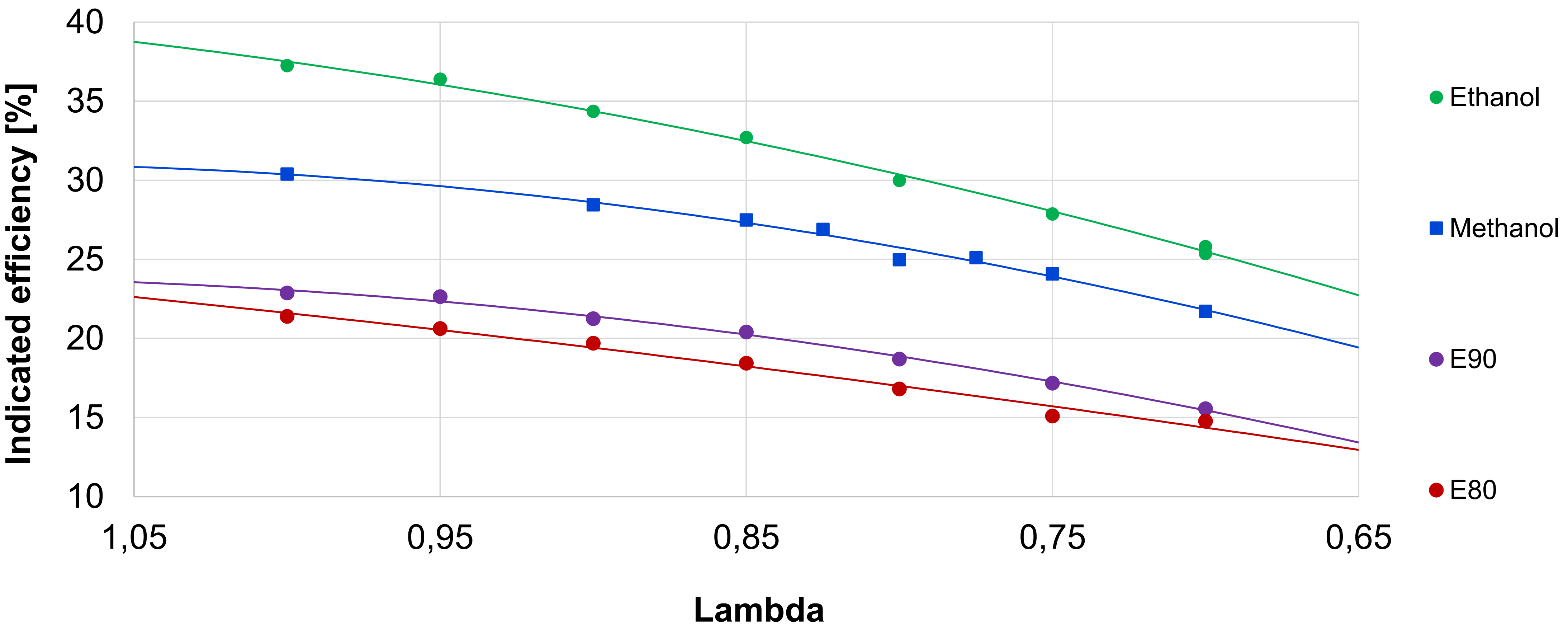
Fuel comparison: indicated efficiency vs lambda

Single cylinder research engine at 1400 RPM – WOT, MBT ignition, CR=11.6:1



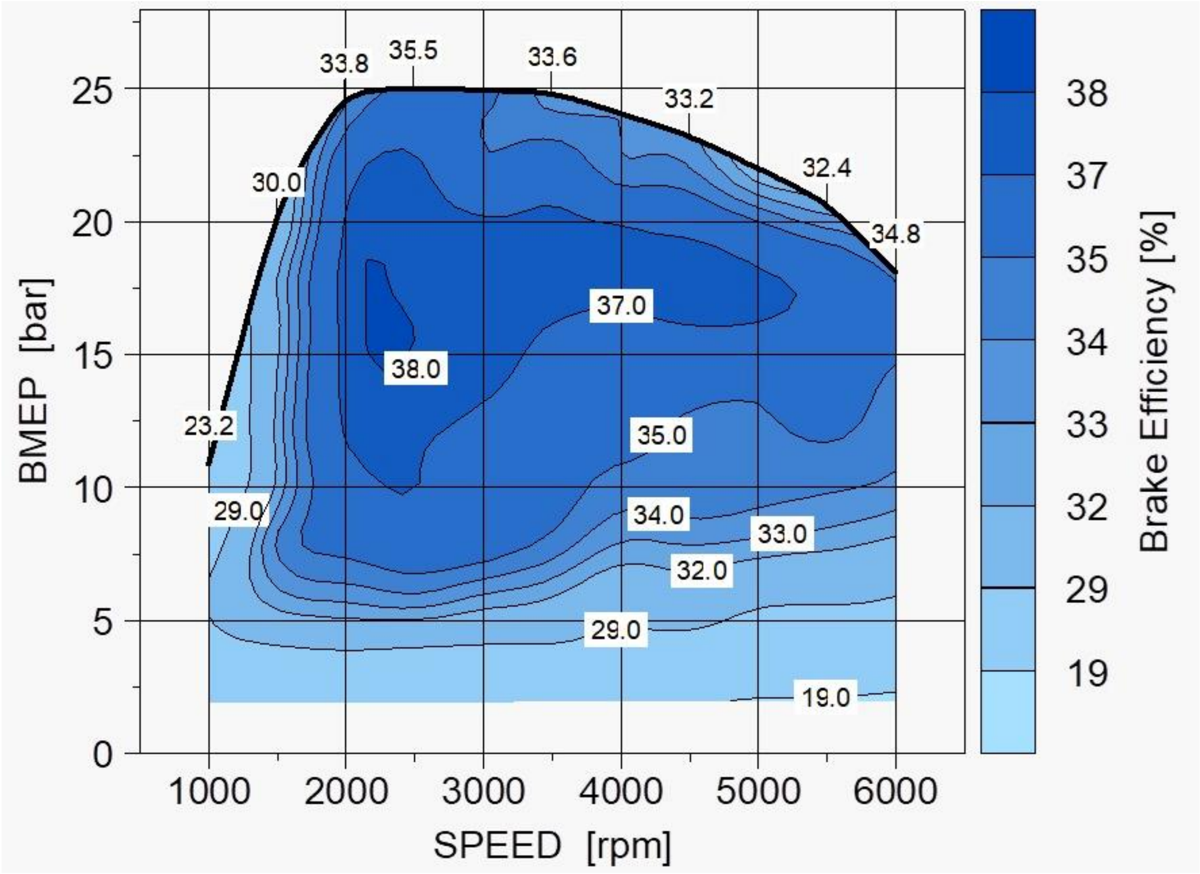
Fuel comparison: indicated efficiency vs lambda

Single cylinder research engine at 1400 RPM – WOT, MBT ignition, CR=11.6:1

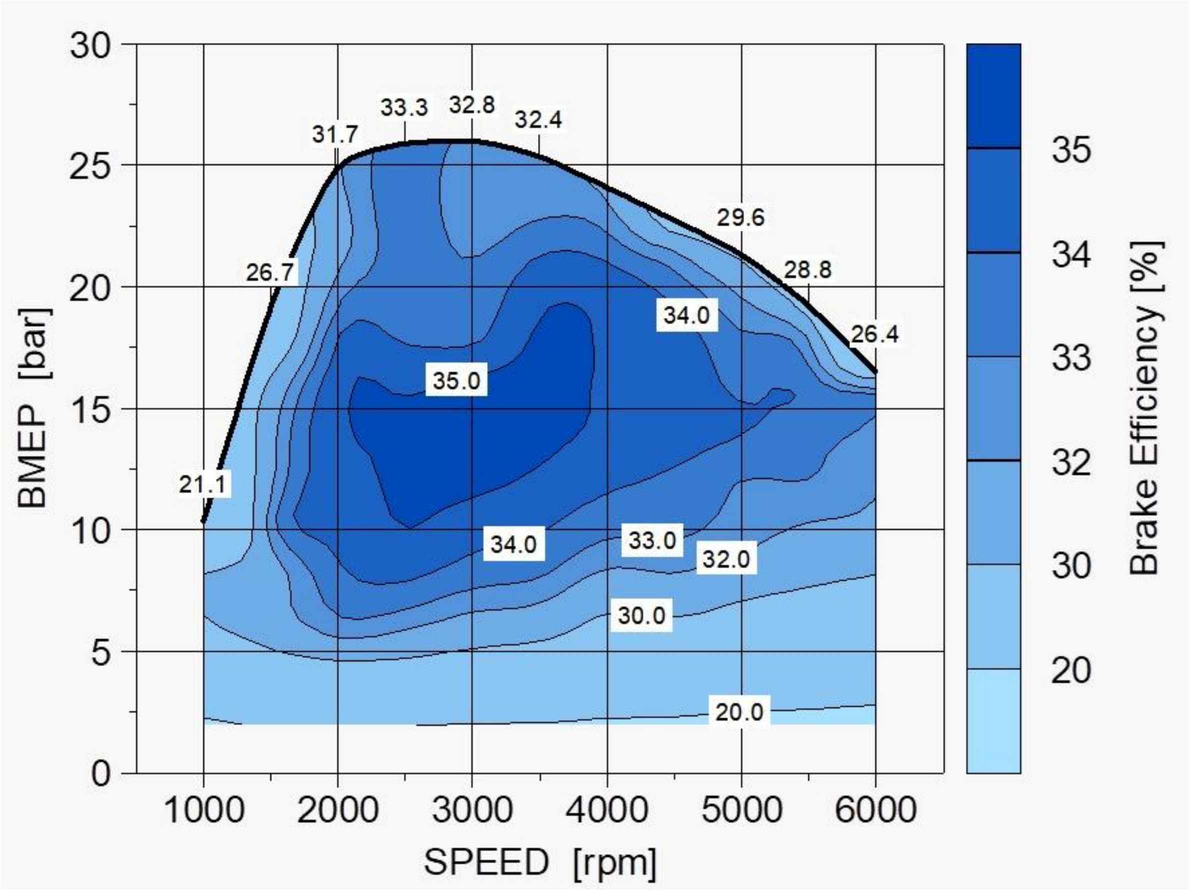


Efficiency of a modern flex-fuel engine

Hydrous Ethanol: 37% Brake efficiency

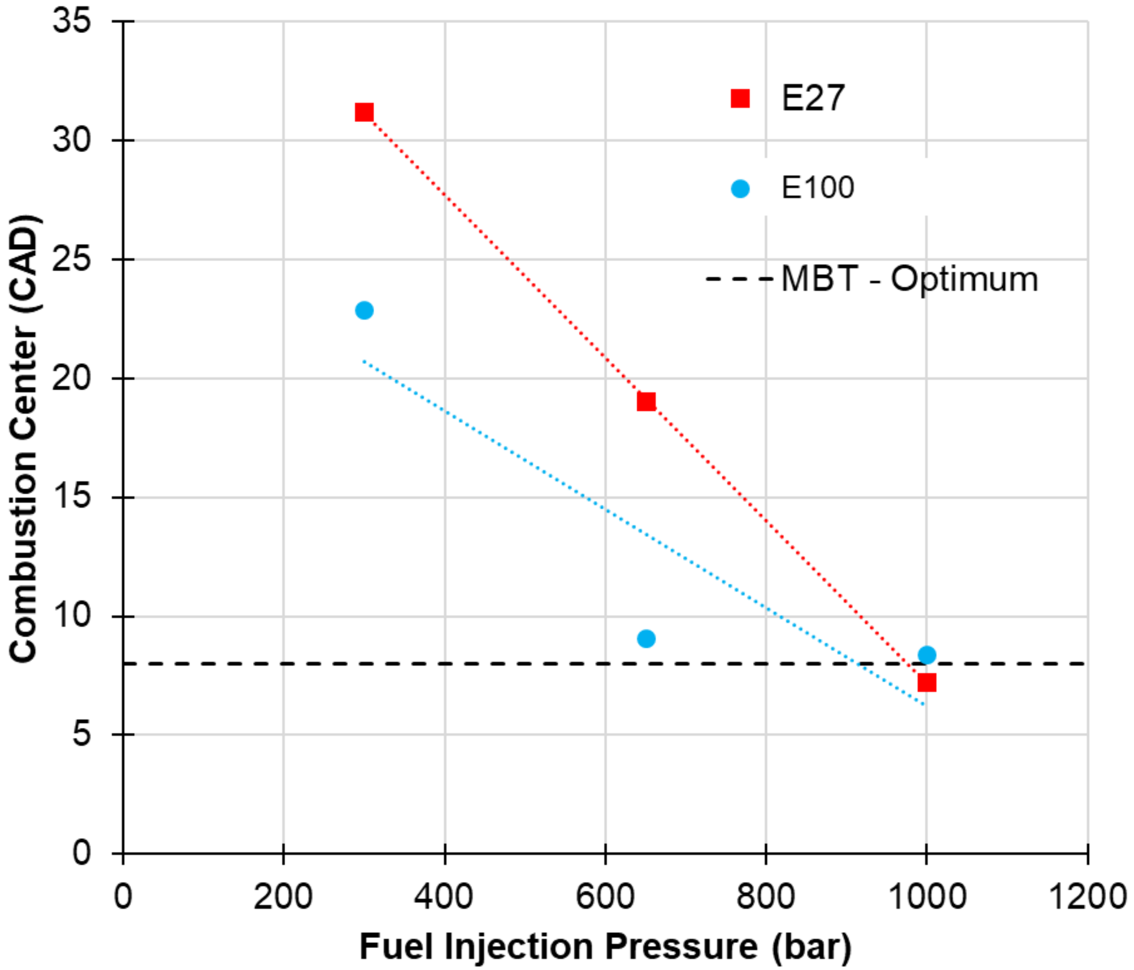


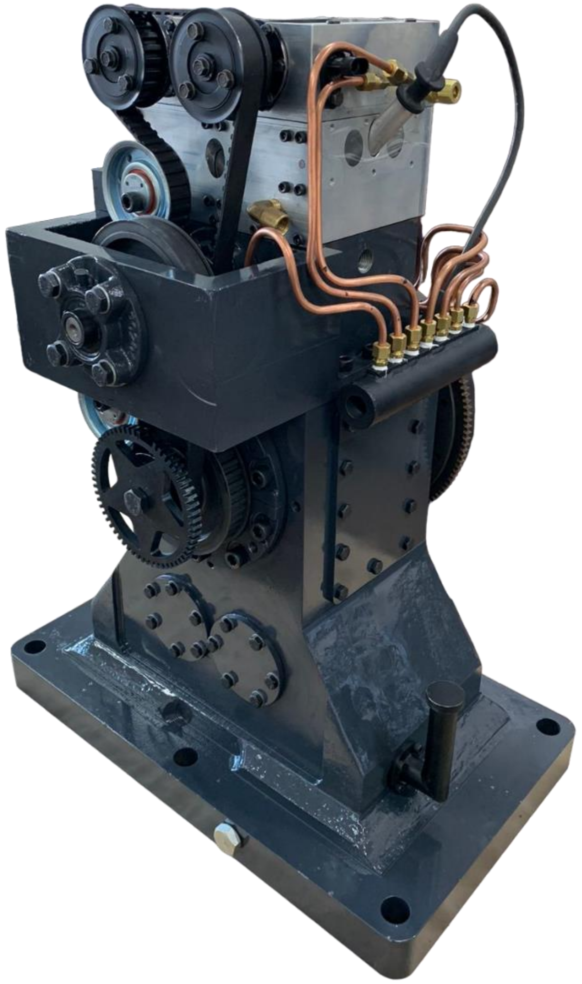
E27 Gasoline: Brake efficiency of 35%



Ultra-High Pressure Direct Injection on SCRE

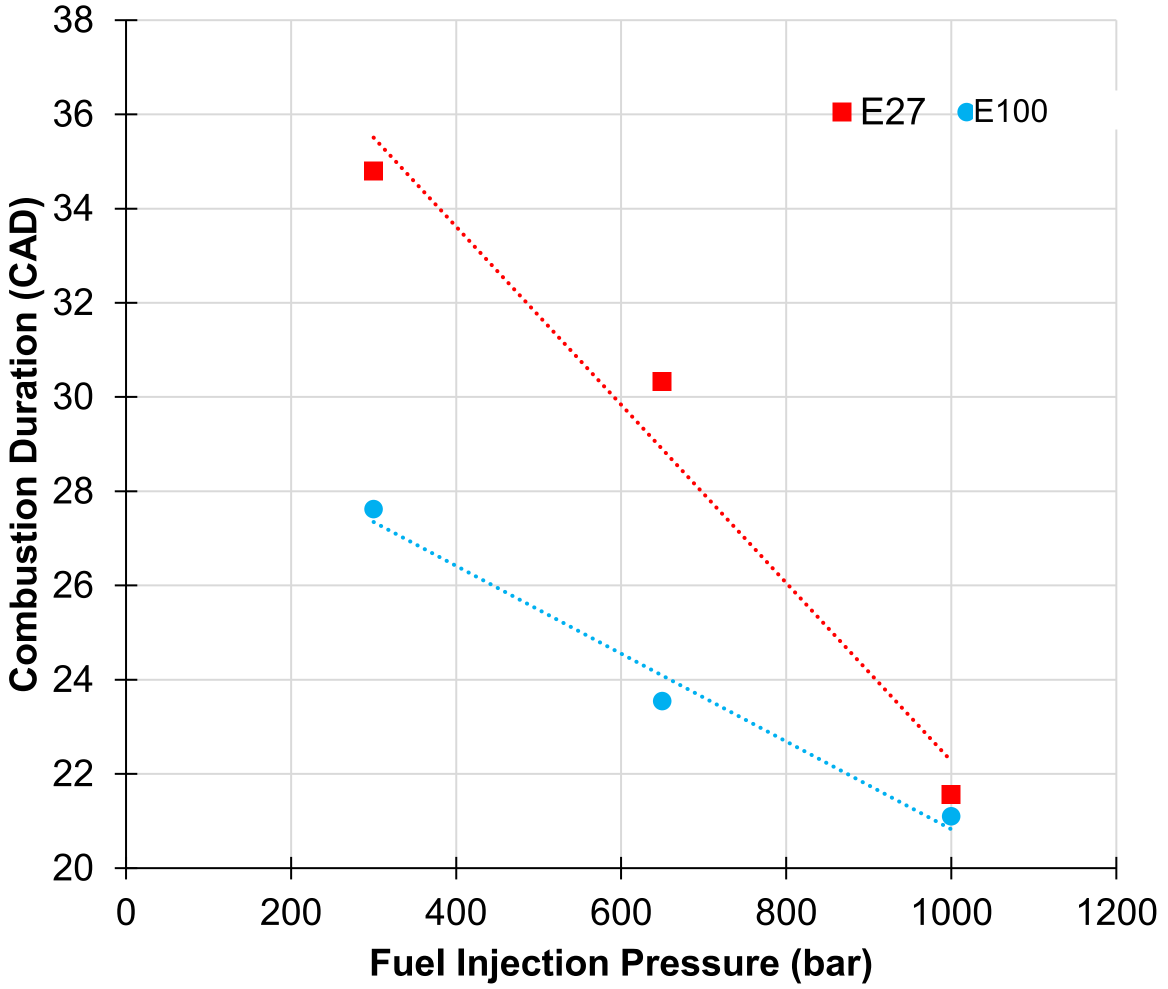
- Knock Limited Spark Advance – Mitigating Effect of ultra high-pressure direct injection



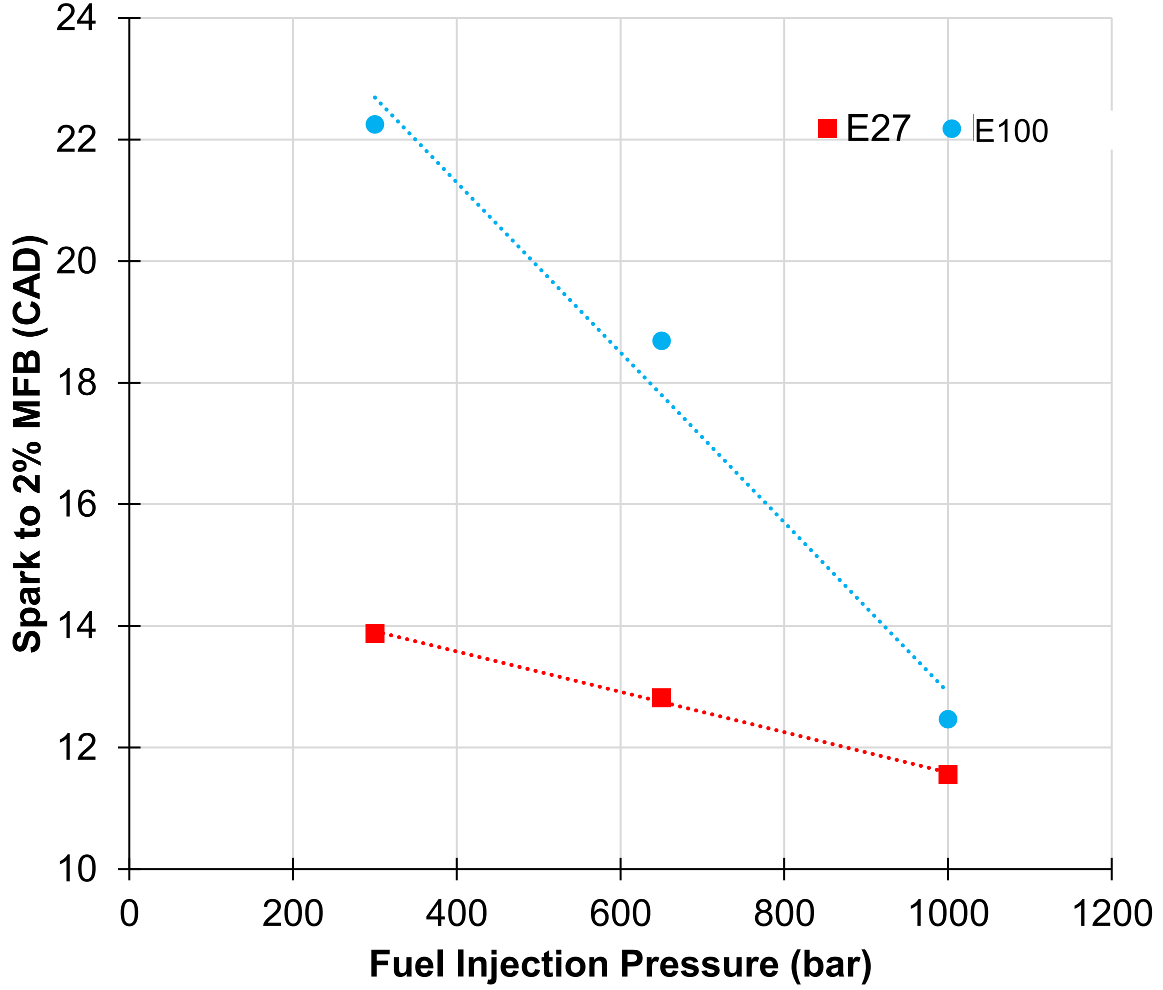


Ultra-High Pressure Direct Injection on SCRE

Combustion Duration

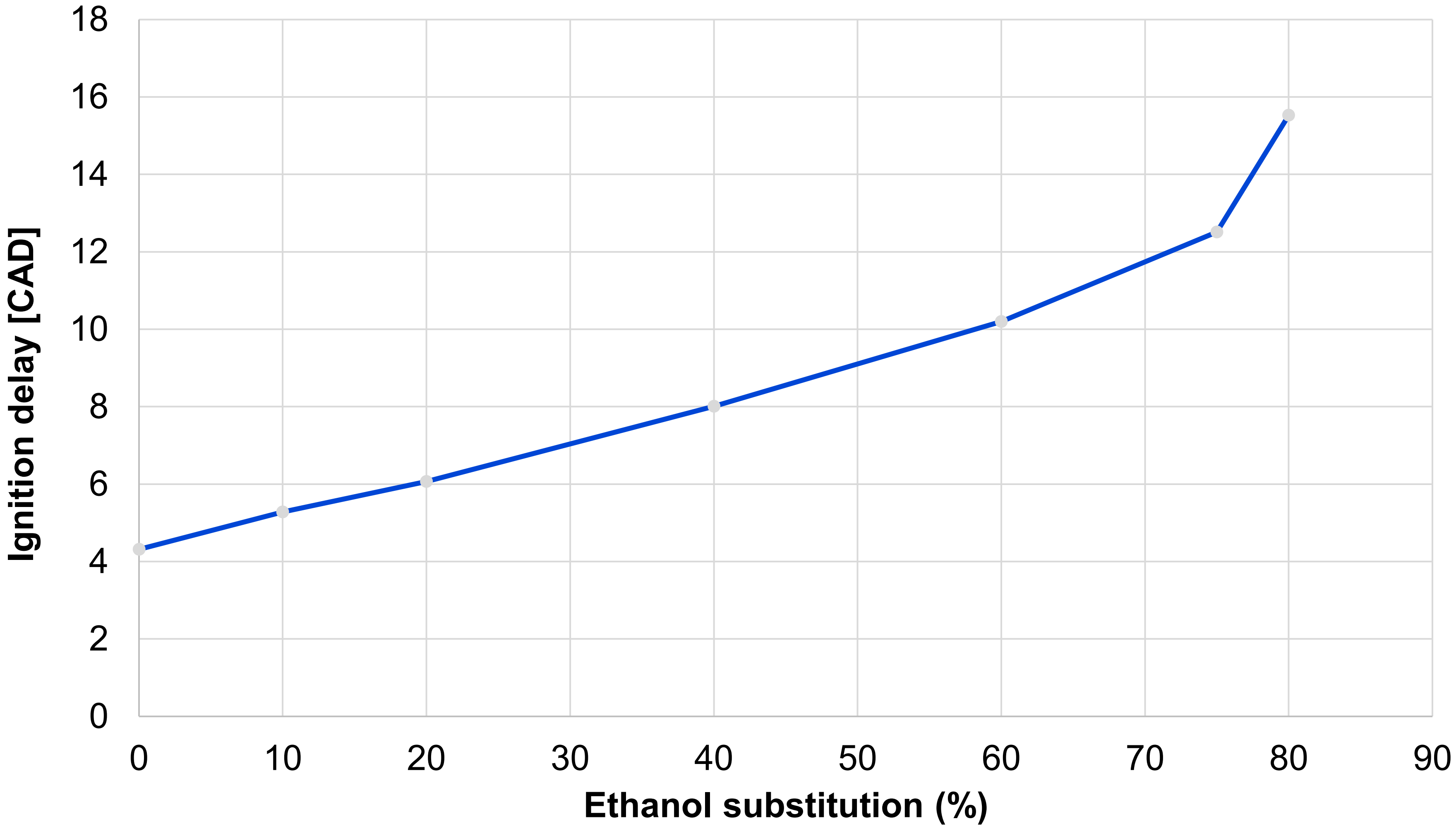


Ignition Delay



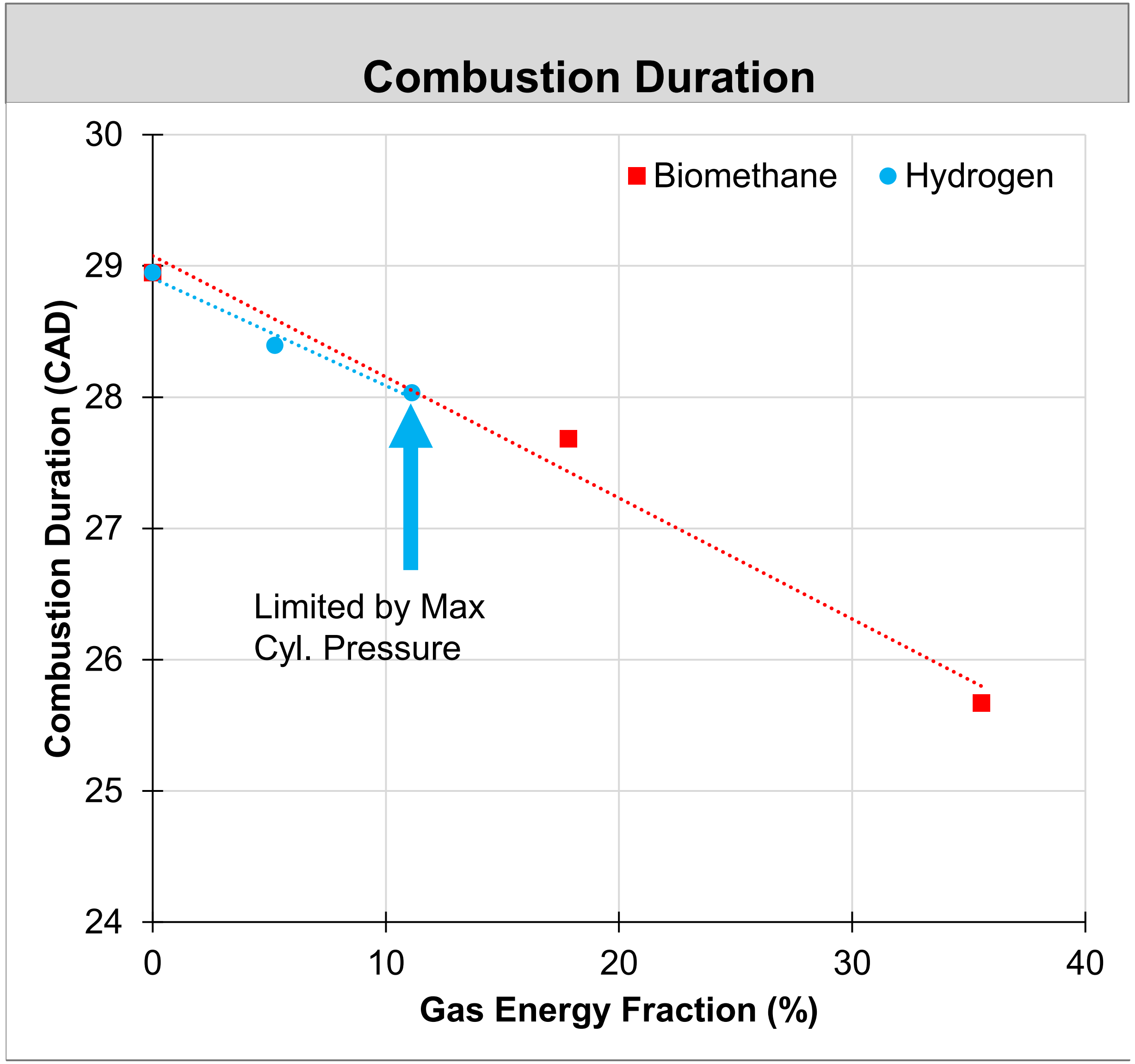
Ethanol and biodiesel a single cylinder research engine

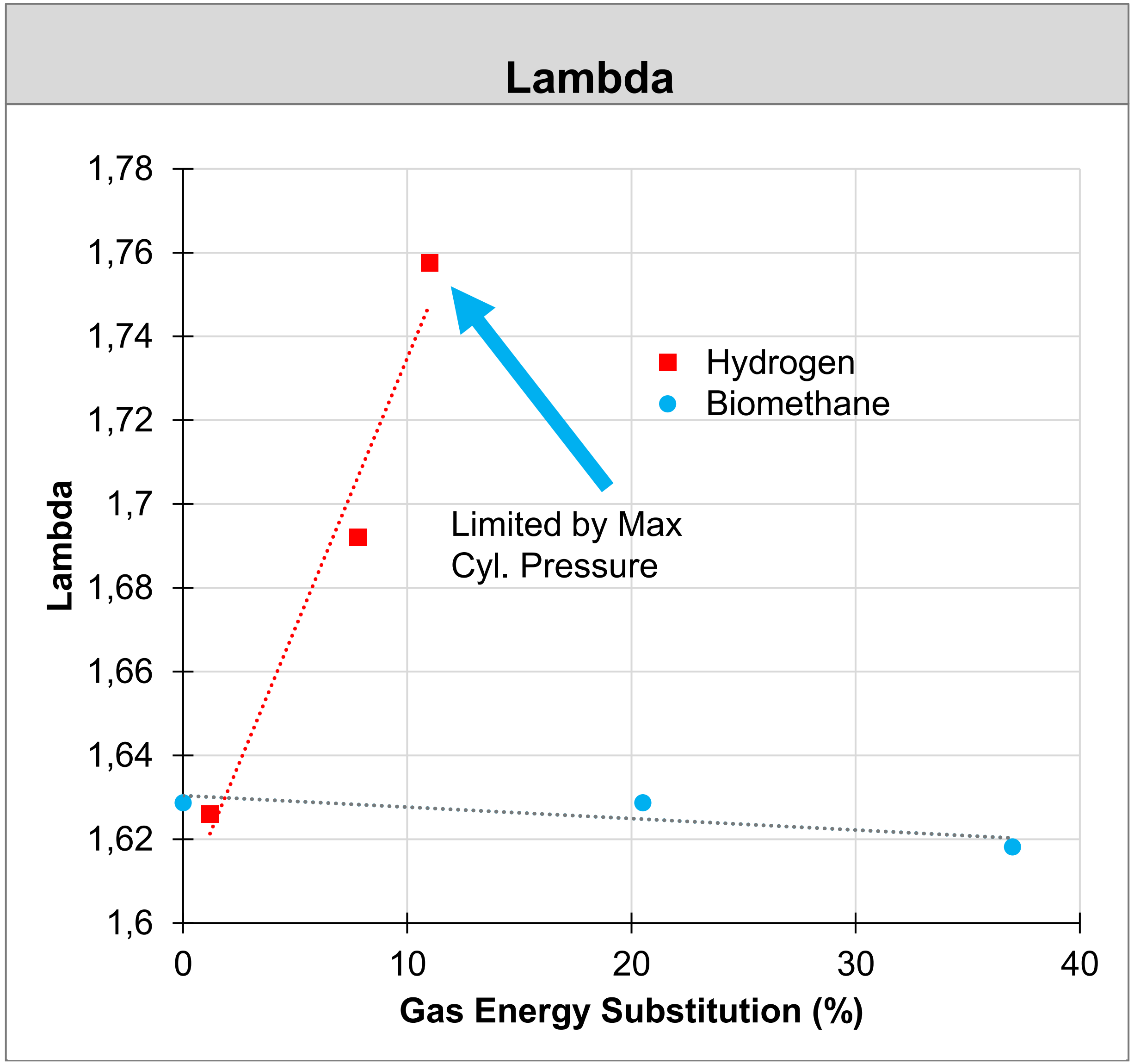
- Longer ignition delay



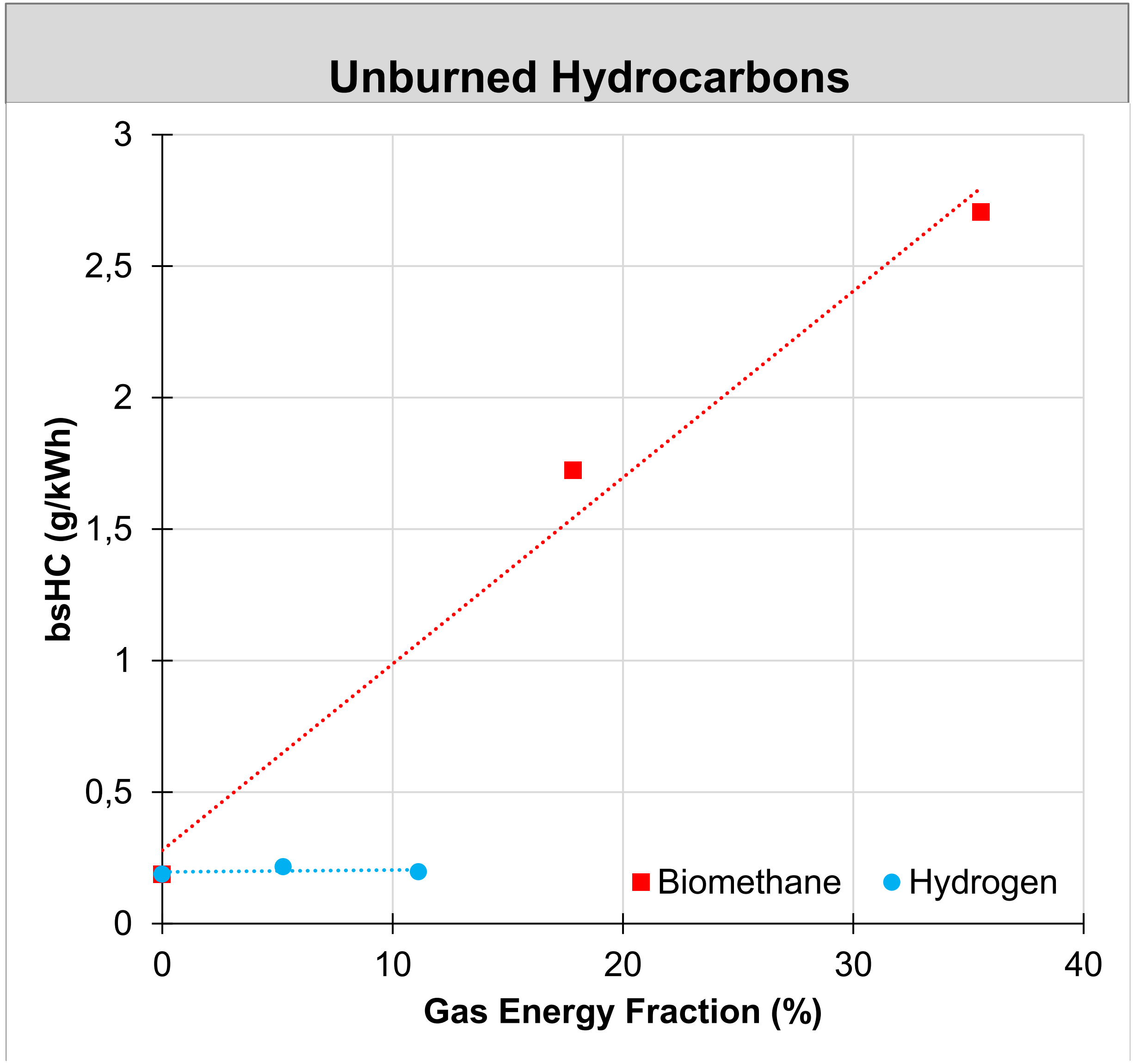
H2 and biometane substitution in an Agricultural Compression Ignition Diesel Engine

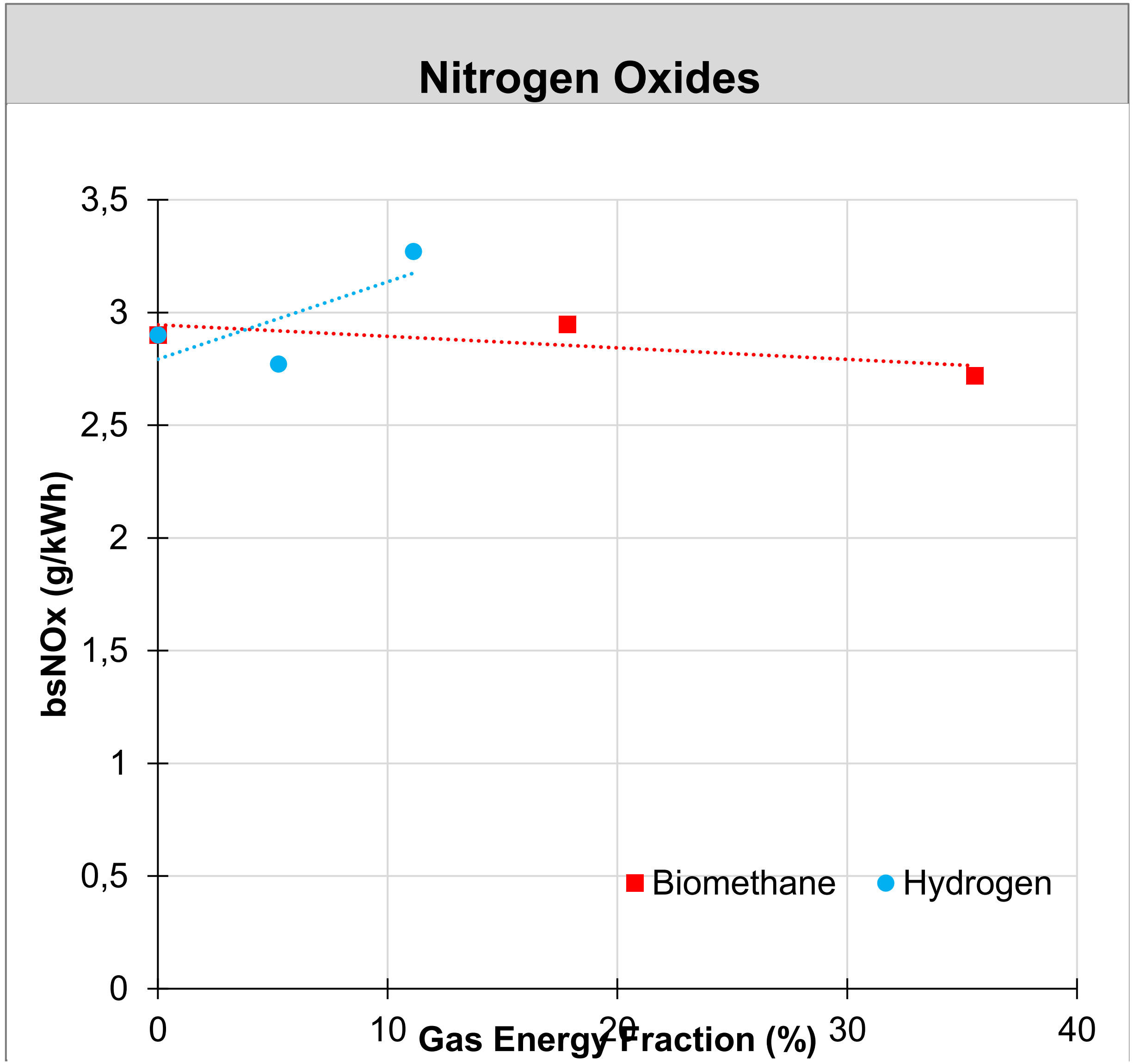
GPMOT



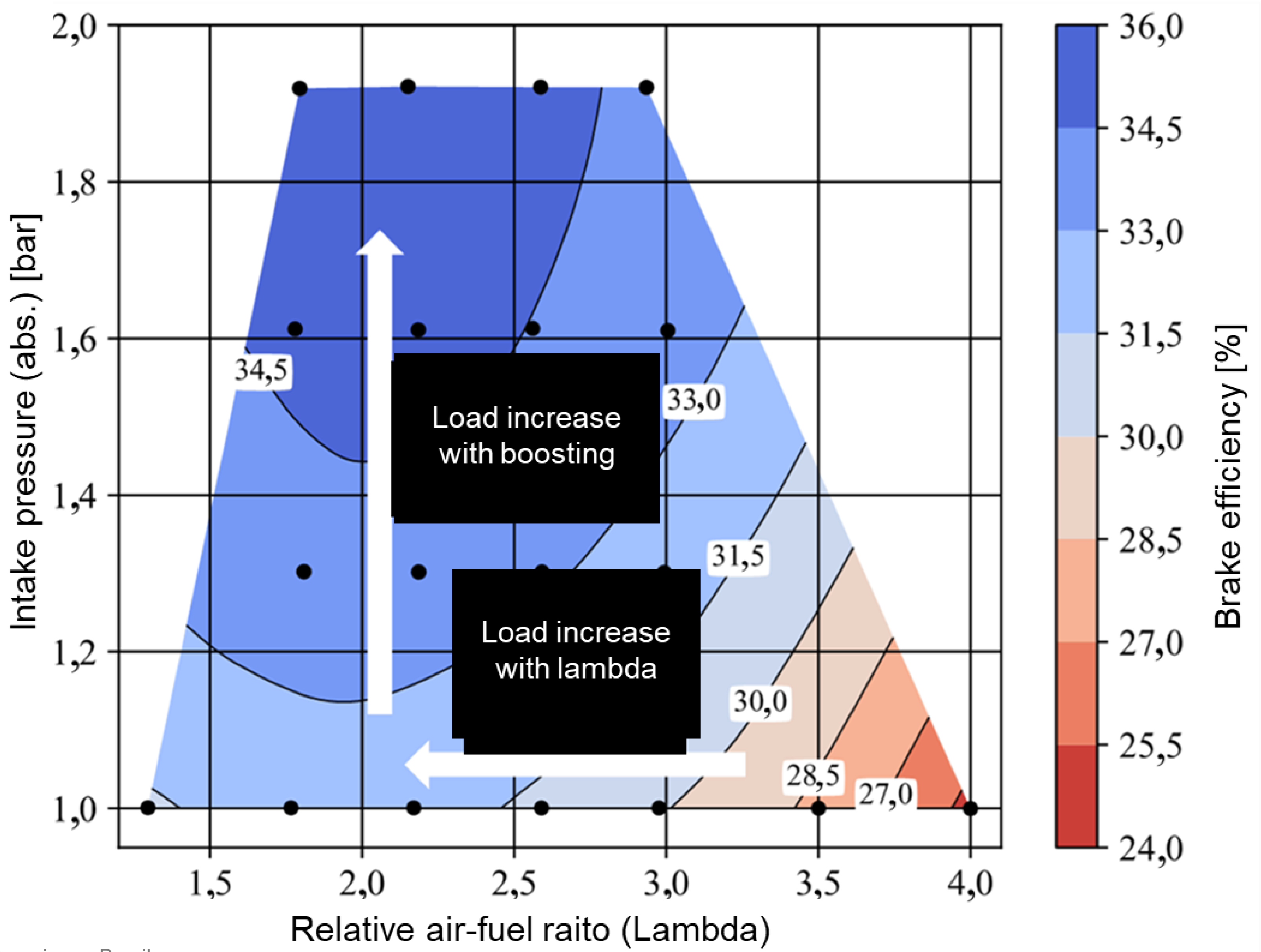


H2 and biometane substitution in an Agricultural Compression Ignition Diesel Engine

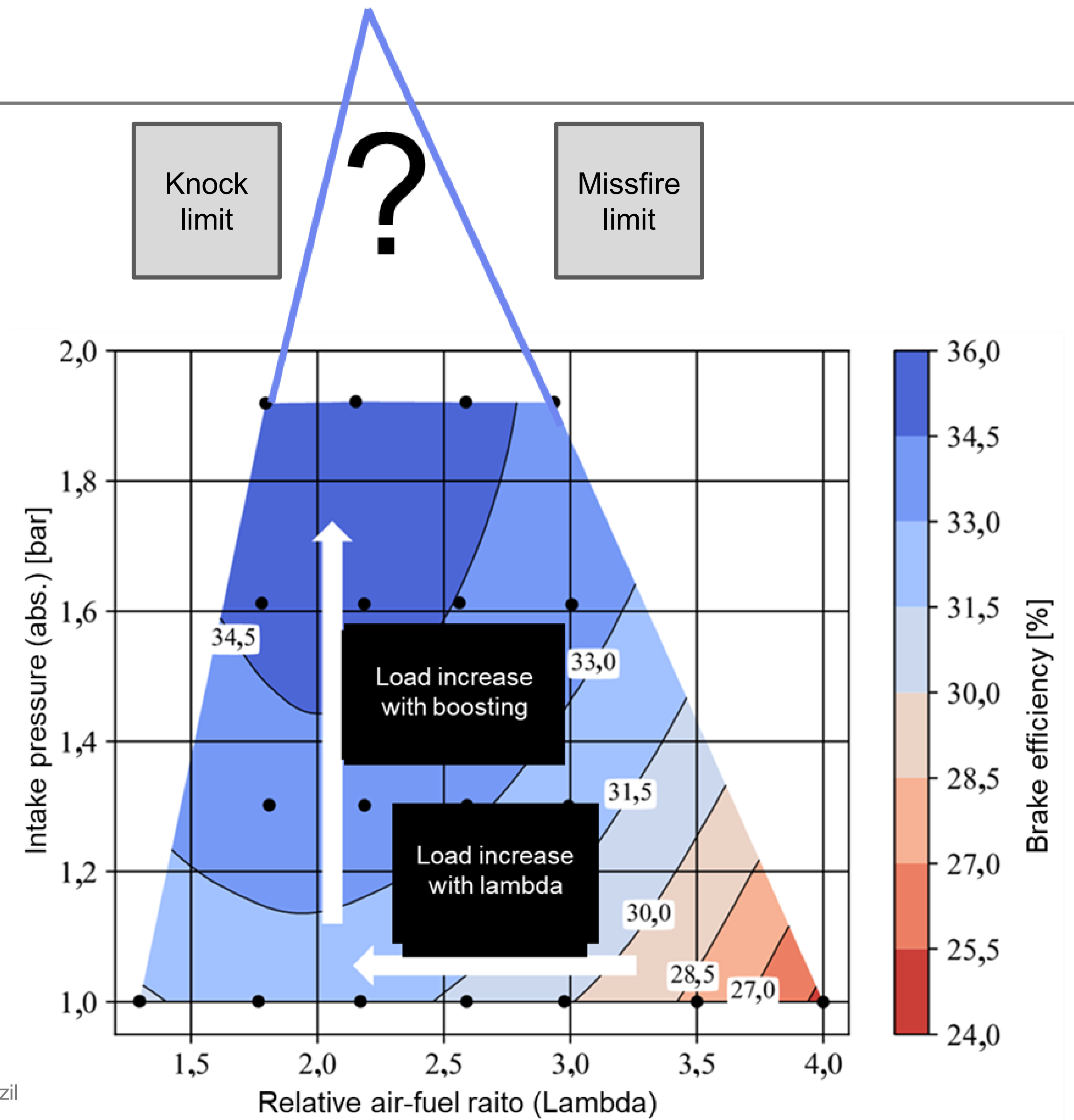




Only Hydrogen?



Hydrogen



Knock limit
?
Missfire limit
Load increase with boosting
Load increase with lambda
34,5
33,0
31,5
30,0
28,5
27,0
2,0
1,8
1,6
1,4
1,2
1,0
1,5
2,0
2,5
3,0
3,5
4,0
Intake pressure (abs.) [bar]
Relative air-fuel raito (Lambda)
36,0
34,5
33,0
31,5
30,0
28,5
27,0
25,5
24,0
Brake efficiency [%]

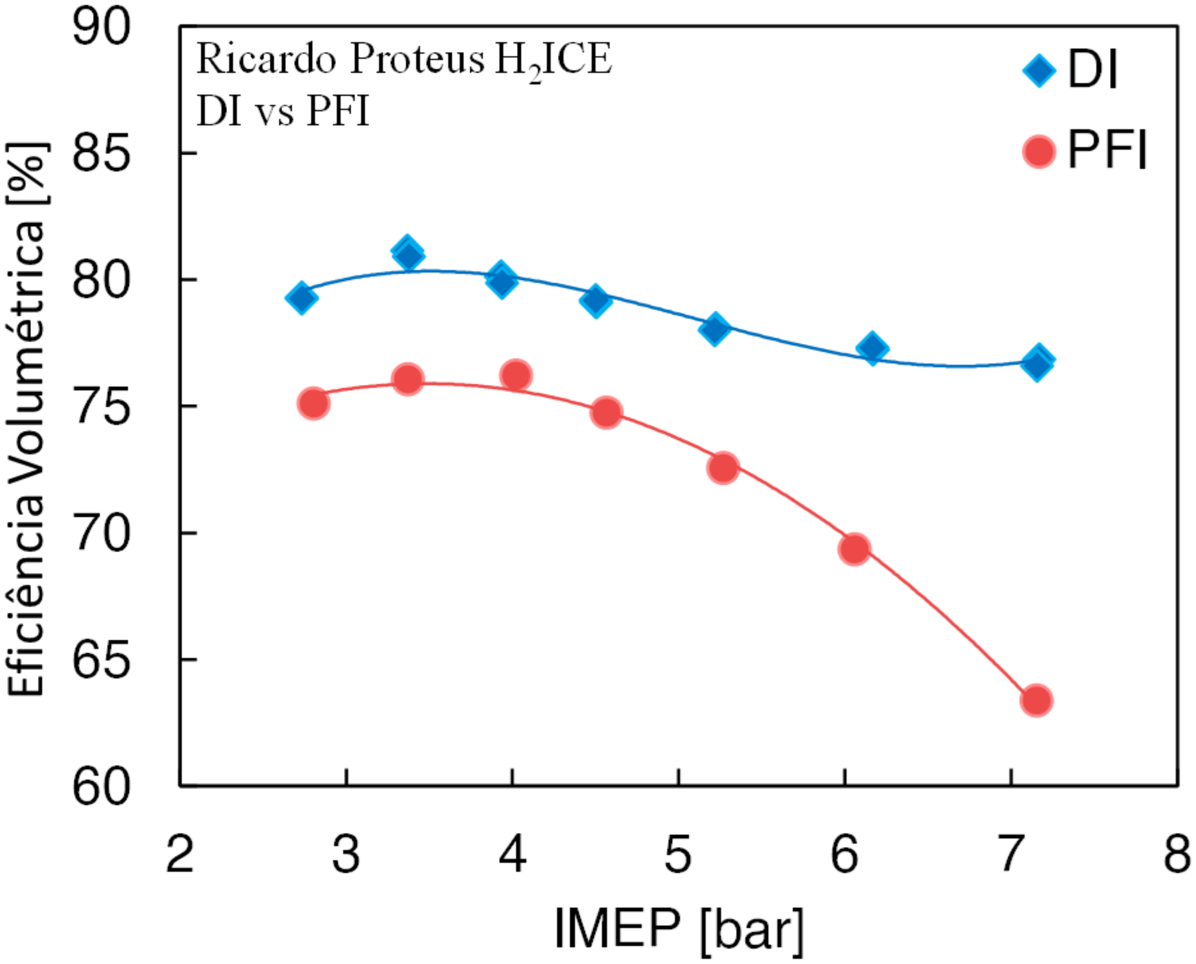
Hydrogen DI vs PFI

Challenges with PFI systems:

- Hydrogen displaces a big volume of air for near stoichiometric mixture (34:1)
- Very prone to backfiring
- Possibility of **H2 slip**

Solution:

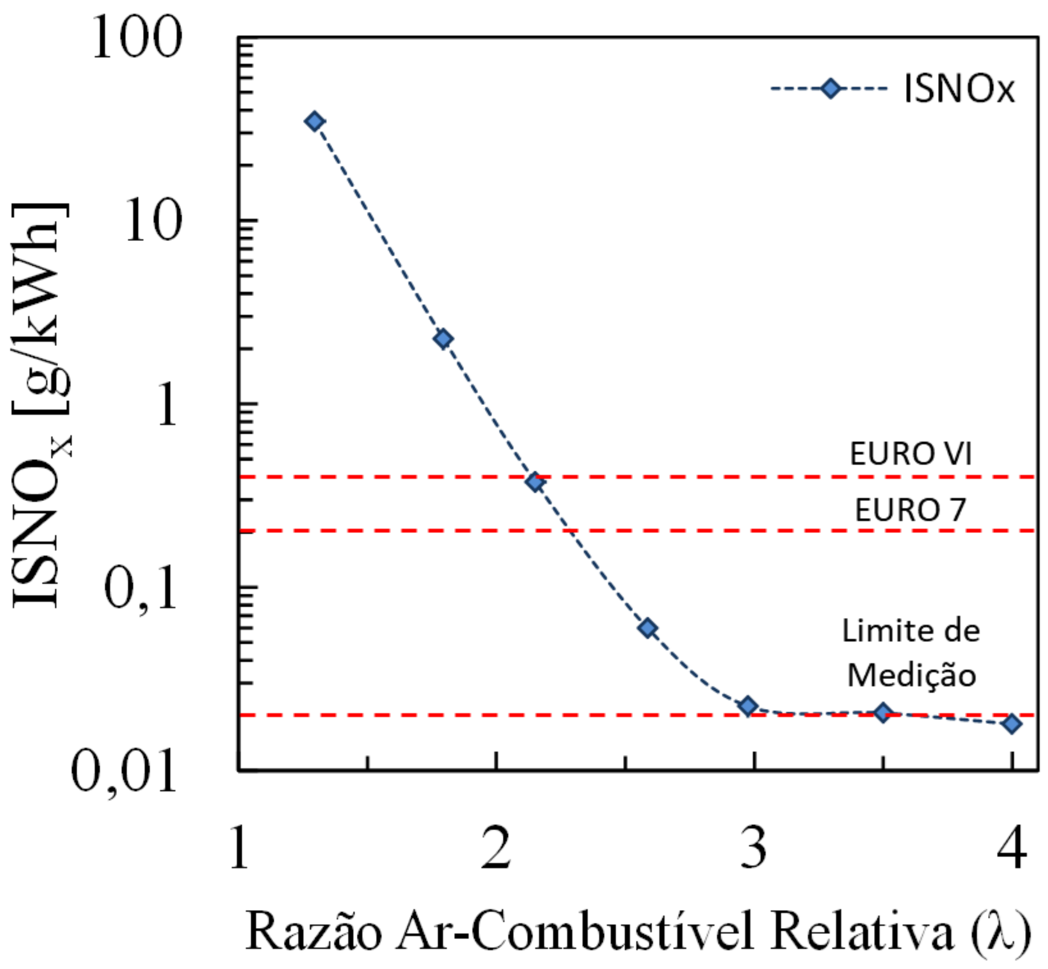
- Direct injection systems
- Cons: costly and of difficult integration into existing engines (retrofit)



N = 1500 rpm

Is Hydrogen the new diesel?

- Unthrottled operation with load controled by fuel mass only
- Load limited by emissions of NOx
- Potentially zero emissions, with enough dillution
- Challenges with boosting systems
- May need more powerfull ignition with very dilluted mixtures



ZERO

Pollutant Emissions

HIGH

Efficiency

H_2

Future

Innovations and Future Research

- What does the future hold?
- More etanol? More Methanol?
- Advanced fuels: e-fuels, bio-hydrogen, ammonia
- Engines dedicated and optimized to biofuels
  - Ethanol/Methanol heavy-duty engine for passenger cars and cargo vehicles
  - Extensive use of biomethane
  - H2 in cargo vehicles, ICE or fuel cell
- Aviation? SAF, ethanol?
- Emission standards focusing more on lifecycle emissions analysis and economic feasibility

Ammonia (NH_3) as a Fuel

- High hydrogen content, carbon-free combustion
- Used in ICEs or fuel cells with modifications
- Challenges: ignition delay, NOx emissions, NH_3 slip, toxicity
- Potential for marine, stationary and heavy-duty transport

- **To remove IC engines from marine transport is very difficul**t!!

High-Efficiency Ethanol Combustion Concepts

- What makes an engine eficient?

Concept	Fuel	Max BTE (%)	Key Technologies / Notes
Conventional SI Engine	E100	34–36%	High CR, optimized ignition, PFI or basic DI
Atkinson/Miller Cycle	E100	37–40%	FVVT, longer expansion, hybrid-focused
Turbocharged DI + EGR	E100	38–41%	Knock resistance, intake charge cooling
HCCI / PCCI	E100 / E85	42–44%	Homogeneous charge, low-temperature combustion

High-Efficiency Ethanol Combustion Concepts

Concept	Fuel	Max BTE (%)	Key Technologies / Notes
Passive Pre-Chamber SI	E100	44–46%	Faster combustion, knock mitigation, lean burn
Active Pre-Chamber	E100	46–48%	Ultra-lean combustion, dual injection or spark
Pre-Chamber + Miller	E100	48–50%	Advanced valve timing, high expansion ratio
Variable Compression Ratio (VCR)	E100	44–47%	CR adapted to load and speed, optimized thermal efficiency under all conditions

Advanced Concept	E100/M100	≥ 45% (Full Load) ≥ 40% (Part Load)	Spray-Guided DI @ >500 bar or pre-chamber, Rc ≥ 14:1, EIVC/LIVC, Boosted

Current vs. Advanced SI Engines concepts with ethanol

Parameter	Current SI Engine (Optimized for E100)	Technological advanced Engine
Brake Thermal Efficiency (Full Load)	34–36%	≥ 45%
Brake Thermal Efficiency (Part Load)	30–33%	≥ 40%
Peak Cylinder Pressure (PMAX)	130–160 bar	≥ 220 bar
Compression Ratio	12:1 to 13:1	≥ 14:1
Injection System	Port or DI (100–200 bar)	Spray-Guided DI, @>500 bar or pre-chamber-ignition
Variable Valve Timing	VVT / DVVT	Fully Variable (FVVT with EIVC/LIVC)
IMEP at Max Load	22–28 bar	> 35 bar
Boosting	Single turbo, wastegate	E-Gate, E-Booster
Emission Compliance	L6 / L7, EURO 7-8	L6 / L7, EURO 7-8

CONCLUSION

Conclusion

- Summary: ICEs remain relevant with biofuels
- Outlook for the next 10 years
- Call for collaboration among academia, industry, and government
- Sustainability, **energy security**, and existing infrastructure

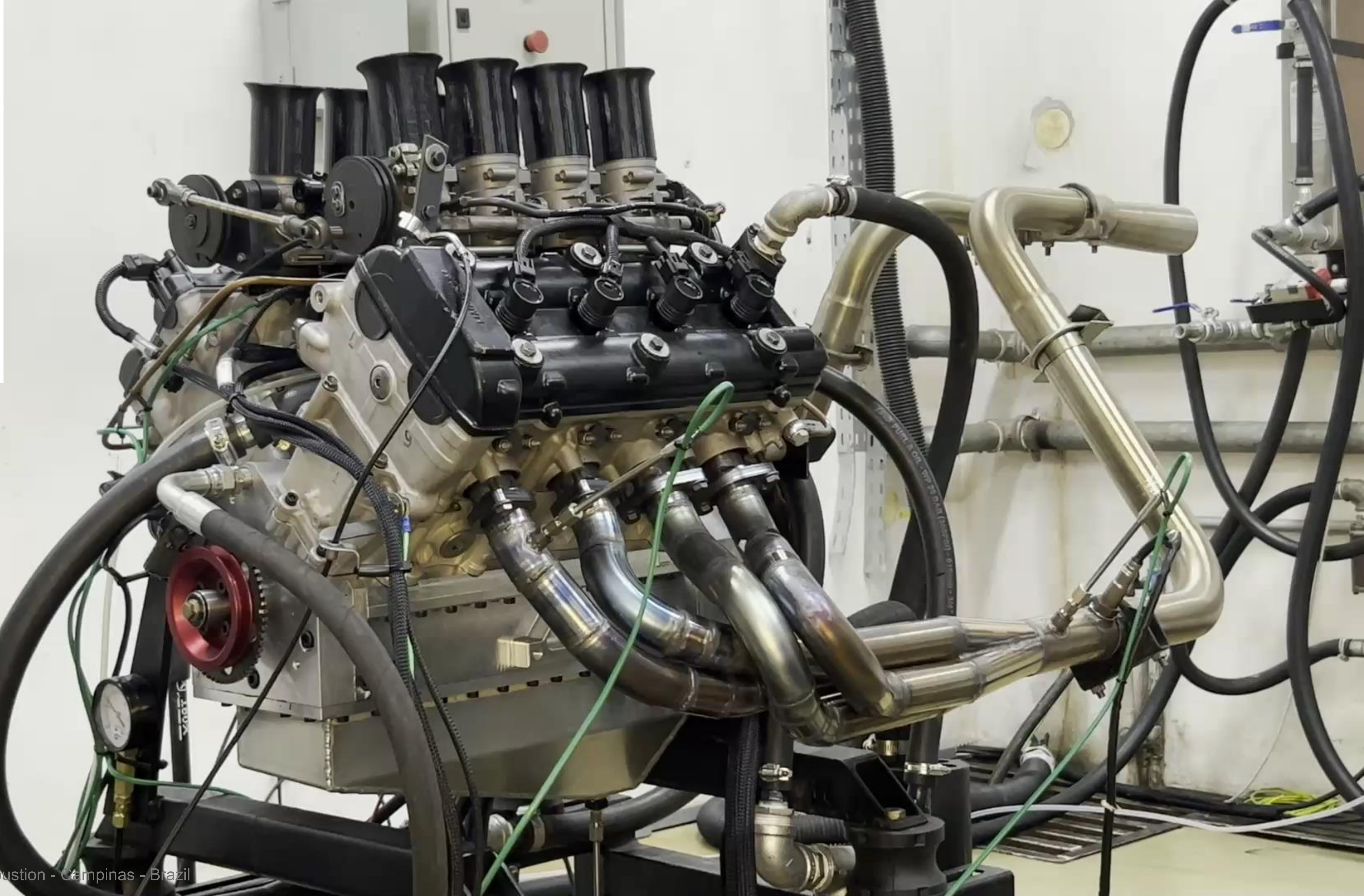
The energy that wins is always the cheapest!

Demonstration Project HAYABUSA V8

Volume deslocado: 2,6 L

Potência máxima: 259,8 kW – 353,2 cv a 9500 rpm

Torque máximo: 282,6 Nm a 8000 rpm



Thank you!

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GPMOT

Grupo de Pesquisa em Motores Combustíveis e Emissões

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