POLITECNICO MILANO 1863

DIPARTIMENTO DI ENERGIA

I.I.S.S. "A.GREPPI"

Sustainable mobility: technological, economical and ecological challenges

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Politecnico di Milano

January 24th, 2020

OUTLINE

- Few words on POLIMI and DENG
- The Energy Market
- Energy Technologies for Transportation: fundamentals and challenges
  - Internal Combustion Engine Vehicle (Biofuels)
  - Fuel-Cell Vehicle (H2-infrastructure)
  - Battery Electric Vehicle (fast recharge + range)
- Take-home messages

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MILANO 1863

QS WORLD UNIVERSITY RANKINGS®

THE LARGEST SCHOOL OF ENGINEERING, ARCHITECTURE AND DESIGN IN ITALY

2 Schools of Engineering, 1 Schools of Architecture, 1 School of Design.

ONE OF THE MOST OUTSTANDING TECHNICAL UNIVERSITIES

QS World University Ranking 2019, Engineering & Technology category:
16th in the World, 6th in Europe, 1st in Italy.

POLITECNICO DI MILANO

Faculty 2019

- **404** Full Professors
- **613** Associate Professors
- **407** Researchers
- **1,030** Adjunct Professors
- **894** Research Fellows

International Faculty

- **49** Professors
- **91** Visiting Professors
- **128** Research Fellows

Ph.D.s 2018/19

- **1,077** (**306** from abroad)

POLITECNICO DI MILANO

STUDENTS: 42,453

A.A. 2018/2019

31,811	6,541	4,101
Engineers	Architects	Designers

Employment rate: 94%
(one year after graduation)
97% for Engineering

June 2019

POLITECNICO
MILANO 1863

HIGH QUALITY RESEARCH: DEPARTMENTs

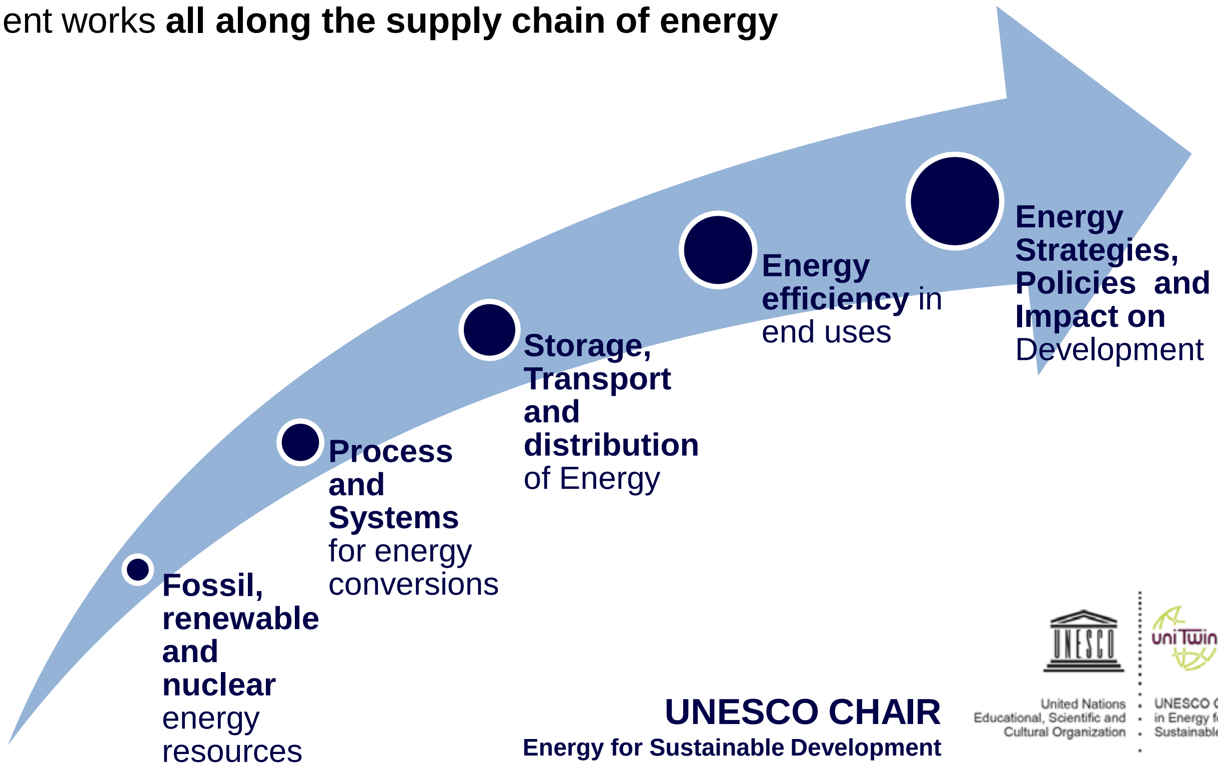
- Aerospace Science and Technology
- Architecture and Urban Studies
- Architecture, Built Environment and Construction Engineering
- Chemistry, Materials And Chemical Engineering “Giulio Natta”
- Civil and Environmental Engineering
- Design
- Electronics, Information and Bioengineering
- **Energy**
- Management, Economics and Industrial Engineering
- Mathematics
- Mechanics
- Physics

THE DEPARTMENT OF ENERGY

INTERDISCIPLINARY APPROACH

Research activity

The department works **all along the supply chain of energy**



UNESCO CHAIR

Energy for Sustainable Development

United Nations Educational, Scientific and Cultural Organization

UNESCO Chair in Energy for Sustainable Development

THE DEPARTMENT OF ENERGY
INTERDISCIPLINARY APPROACH

5 SPECIALIZED DIVISIONS

Joint researches to study, analyze, develop knowledge, technologies and strategies related to production, conversion, transport, distribution and final use of energy:

- Chemical Technologies and Processes and Nanotechnologies
- Electrical Engineering
- Nuclear Engineering
- Fluid Dynamic Machines, Propulsion and Energy Systems
- Thermal Engineering and Environmental Technologies

THE DEPARTMENT OF ENERGY
INTERDISCIPLINARY APPROACH

People

Infrastructure and experimental facilities

Competences and Knowledge

European Research Council
Established by the European Commission

United Nations Educational, Scientific and Cultural Organization

UNESCO Chair in Energy for Sustainable Development

POLITECNICO DI MILANO

MIUR Department of Excellence 2018-2022

ENERGY FOR MOTION

Energy technologies

for new-generation vehicles

1. Energy for new vehicles

2. New-ICE vehicles

3. Fuel Cell vehicles

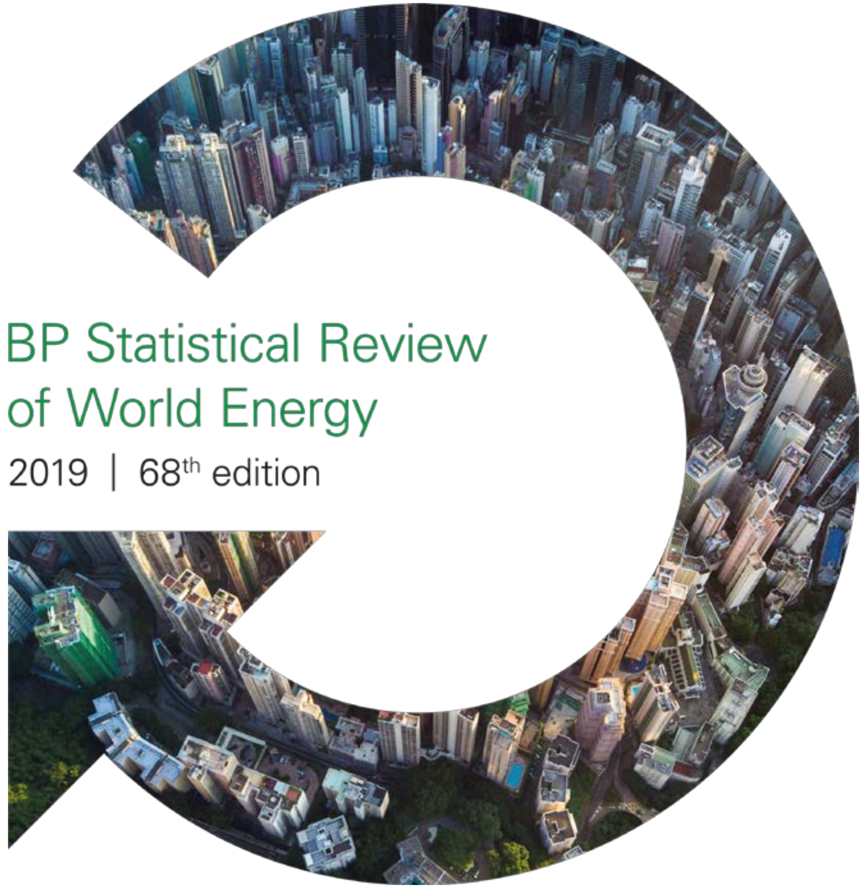
4. Battery electric vehicles

5. Cross-cutting themes

The Energy Market

BP Statistical Review of World Energy

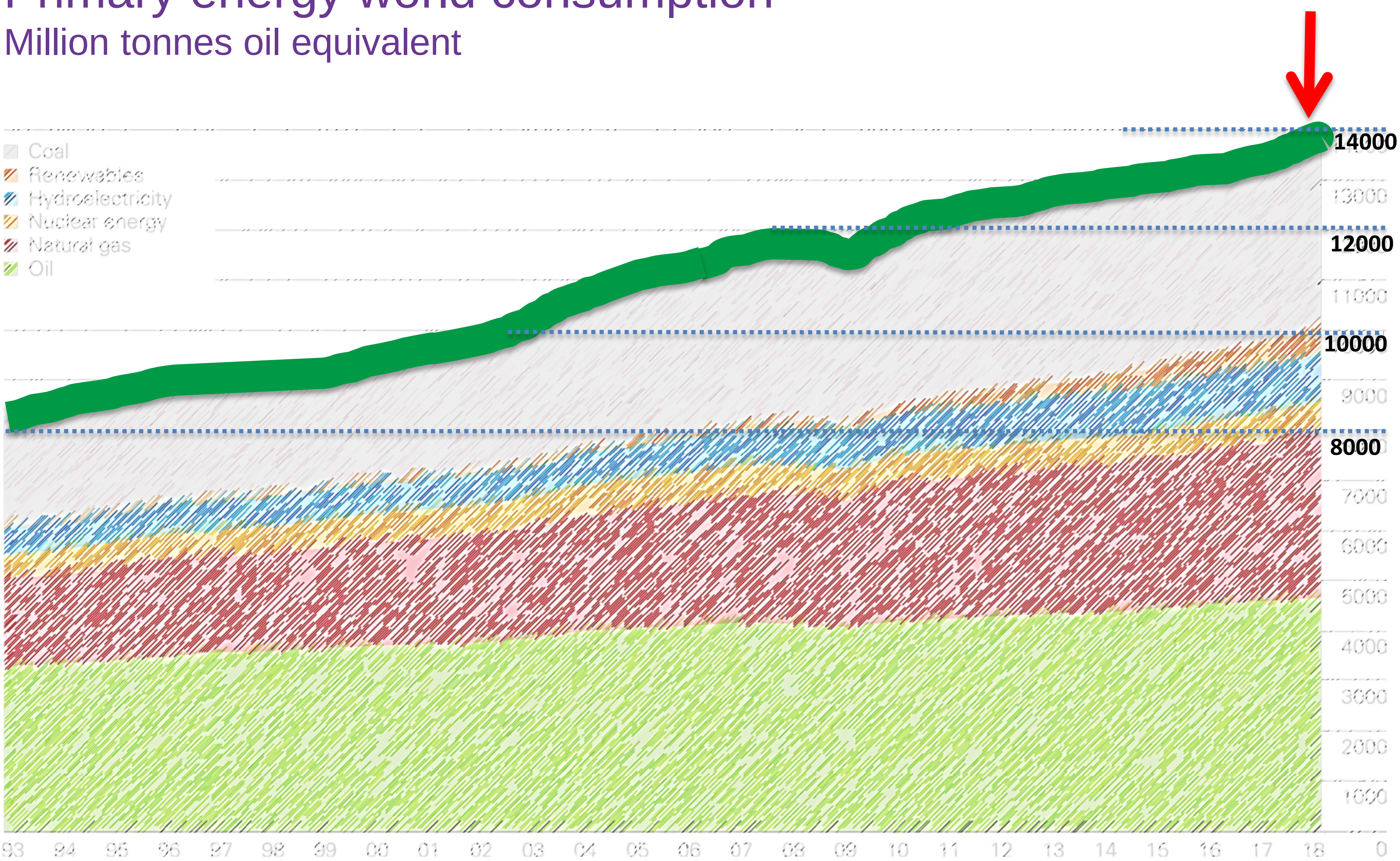
2019 | 68th edition



BP Statistical Review of World Energy 2019
© BP p.l.c. 2019

Primary energy world consumption
Million tonnes oil equivalent

In 2018: energy consumption grown by 3%
CO_2 emissions grown by 2%



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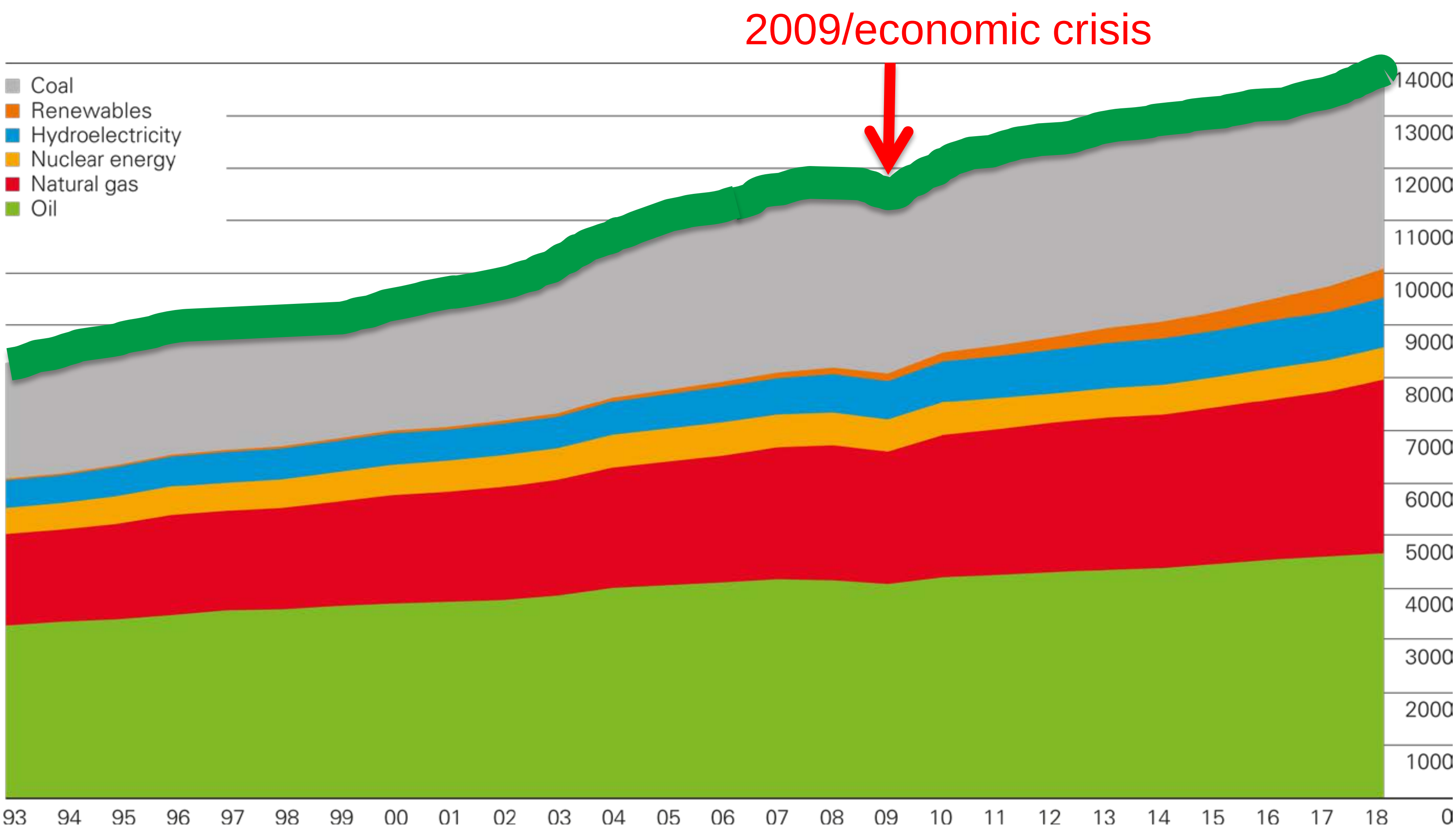
Primary energy world consumption

Million tonnes oil equivalent



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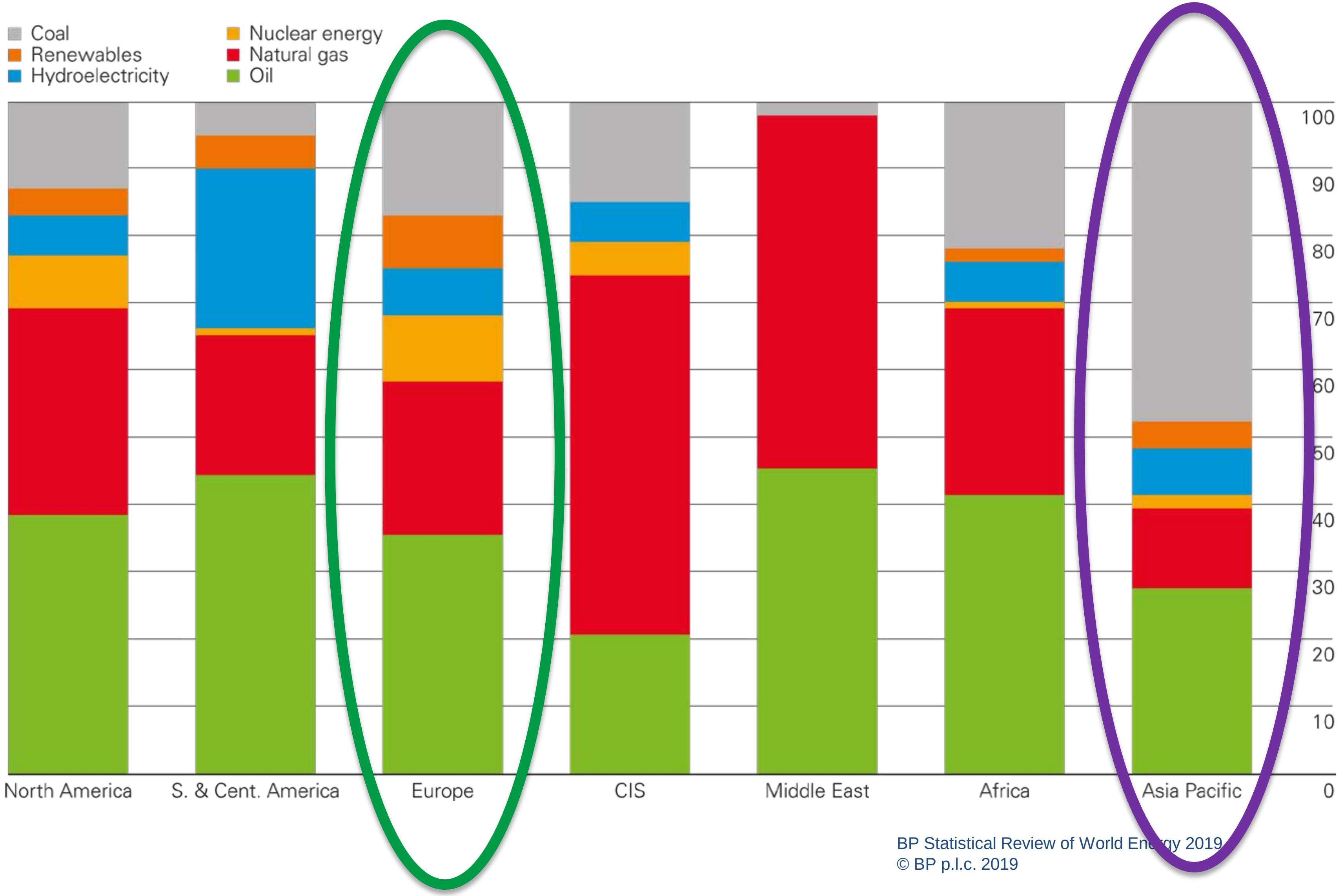
Primary energy regional consumption by fuel 2018
Percentage



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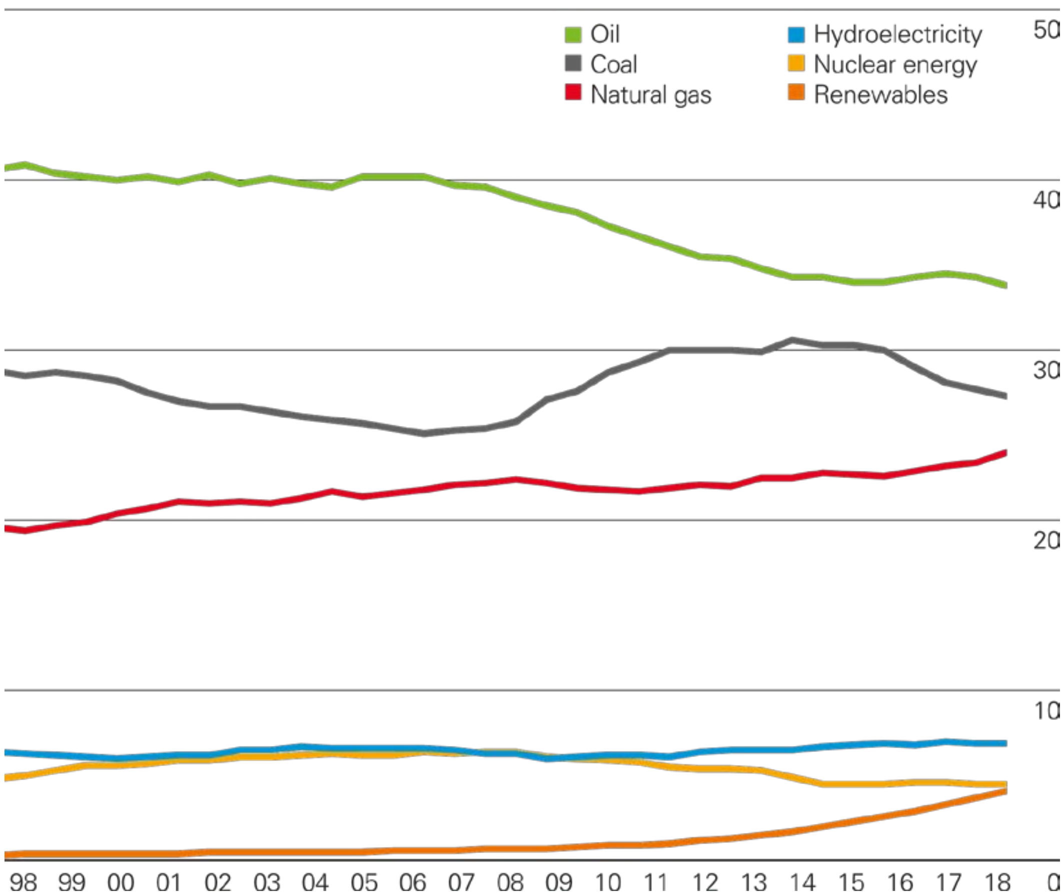
Shares of global primary energy consumption
Percentage



Oil = 34%
Coal = 27%
Natural gas = 24%

85% fossil fuels

Hydroelectric = 7%
Nuclear = 4%
Renewables = 4%
Sun
Wind
Biomass

15% non fossil fuels

BP Statistical Review of World Energy 2019
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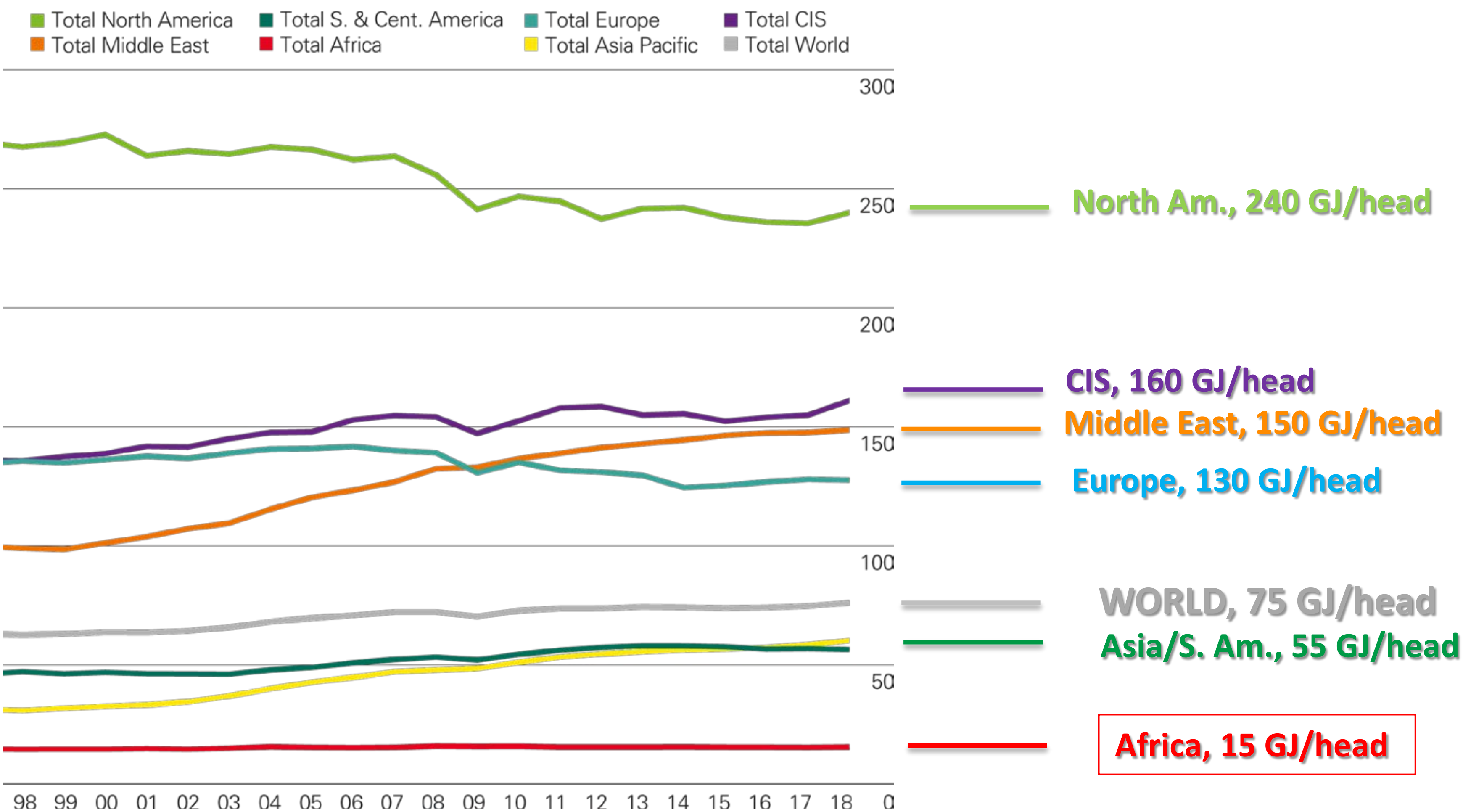
Energy per capita by region
Gigajoules per head



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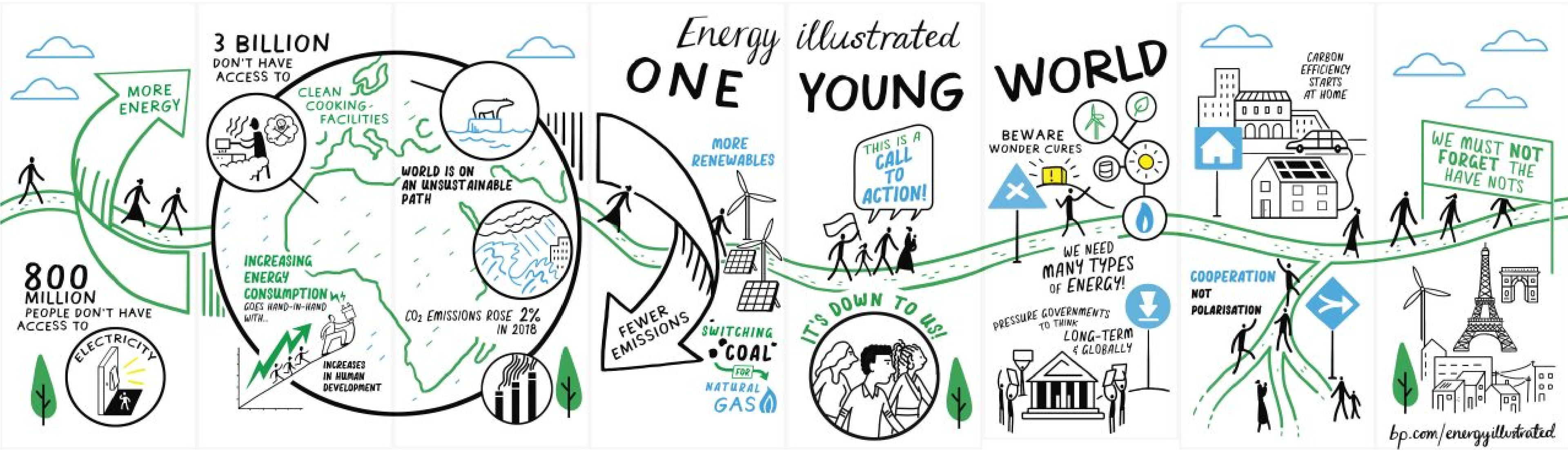
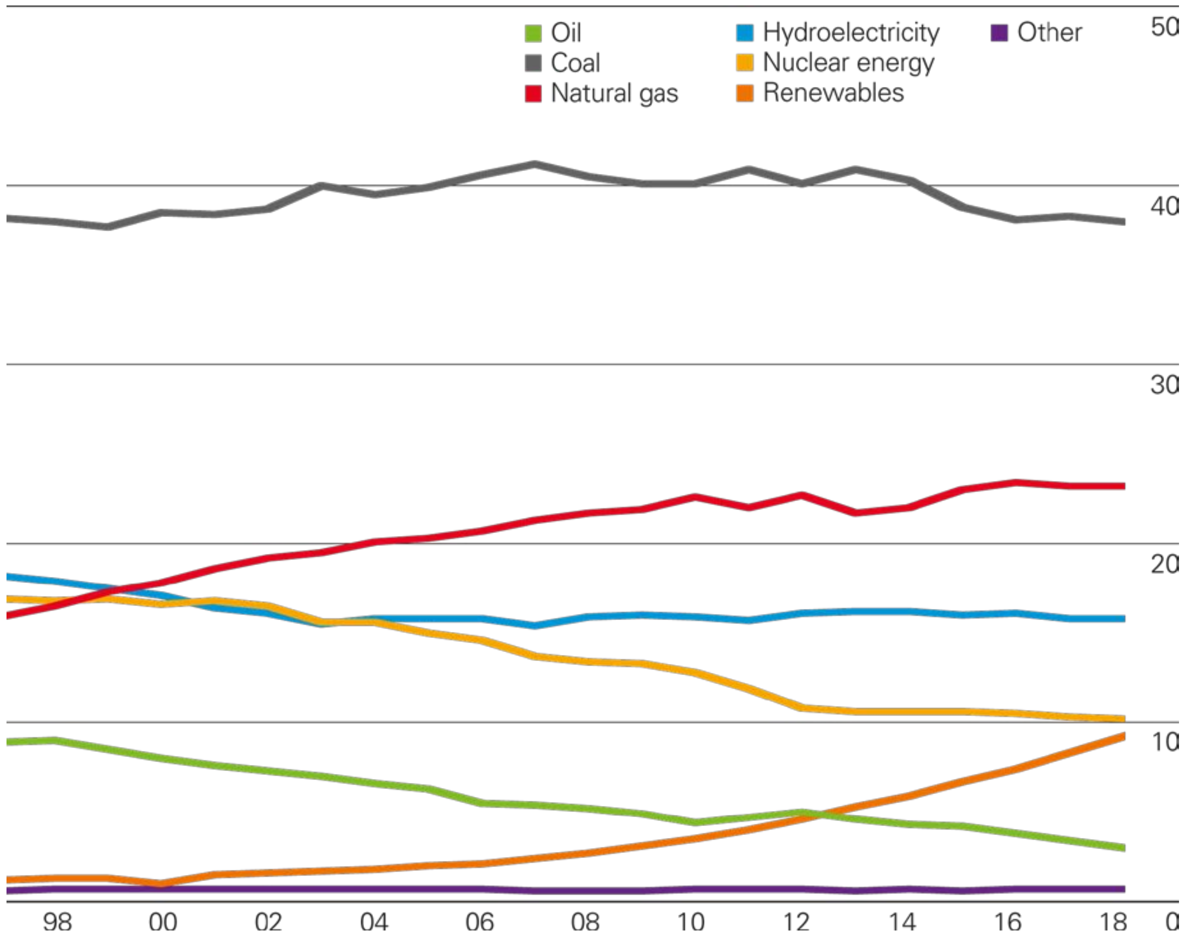


https://www.bp.com/en/global/corporate/energy-economics/spencer-dale-group-chief-economist/energy-illustrated.html

Share of global electricity generation by fuel
Percentage



coal, 38%

renewables, 9%

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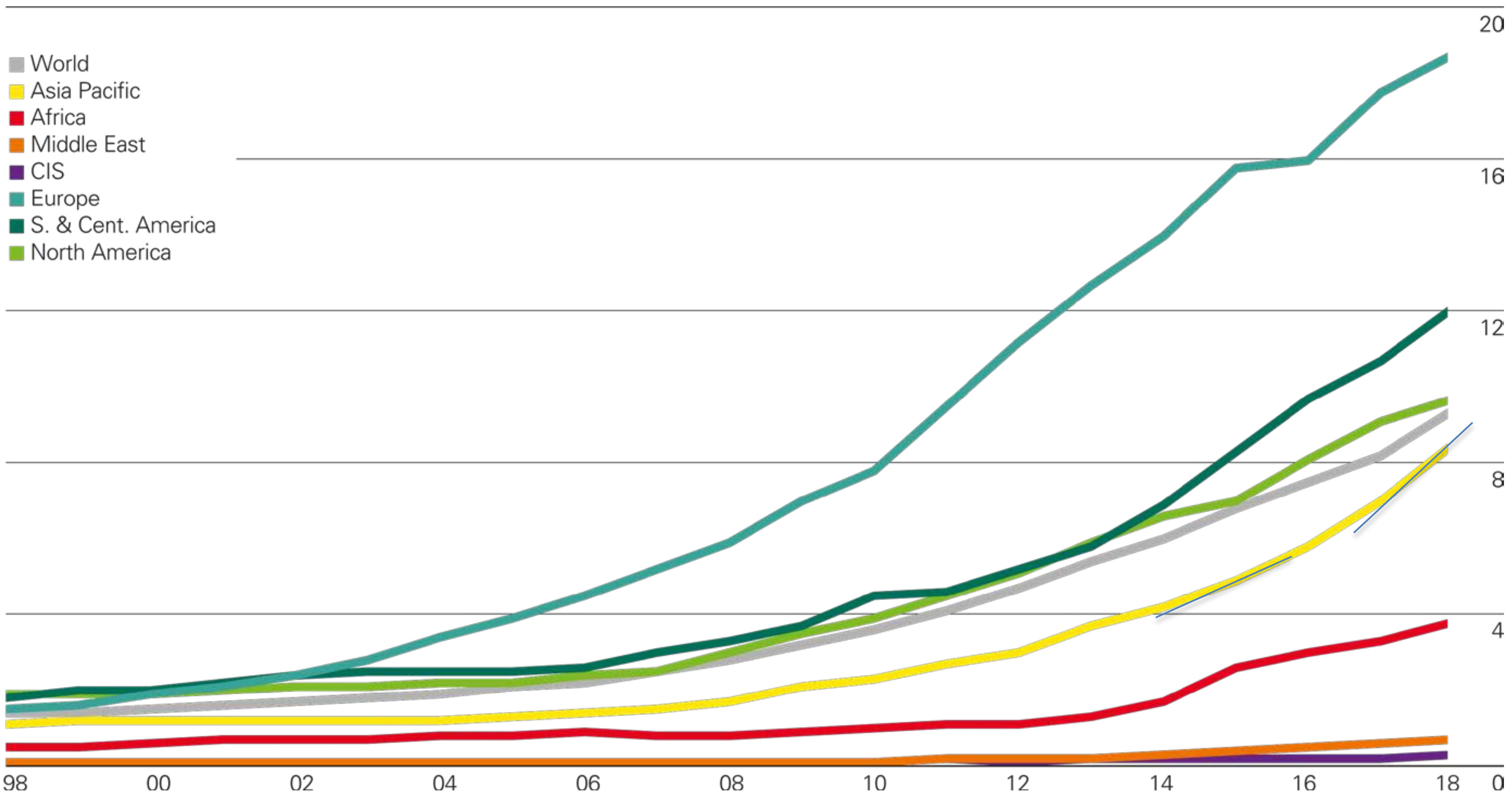
Renewables share of power generation by region
Percentage



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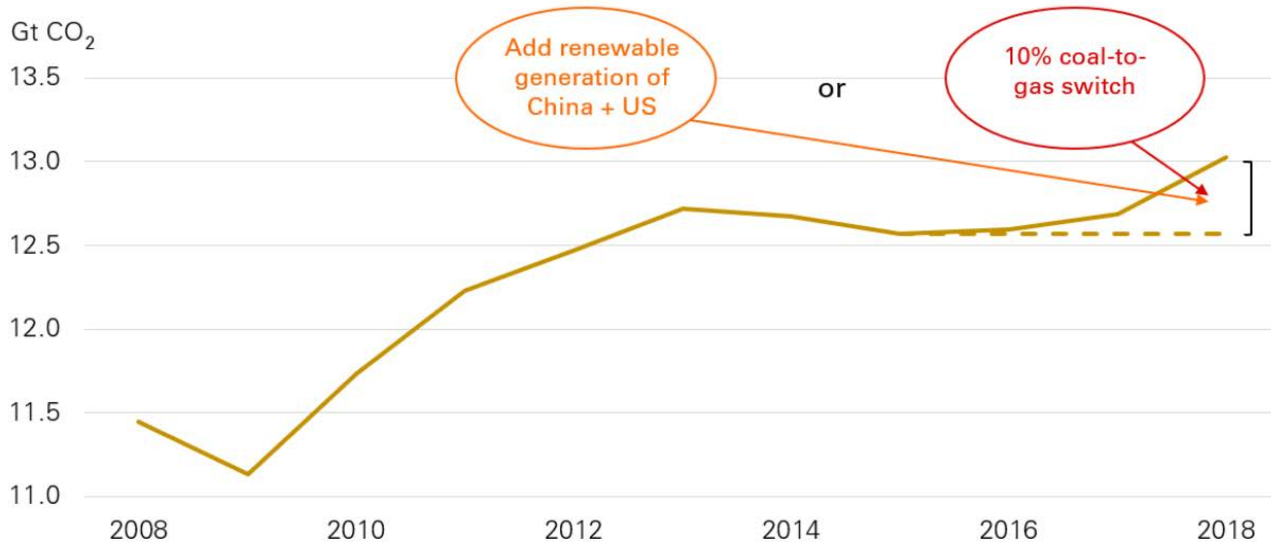
Carbon emissions from power sector



BP Statistical Review of World Energy

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The extra-amount of CO2 emitted since 2015, could have been avoided by:

- replacing 10% of the coal with natural gas
- increasing the installed renewable power by the same total renewable power of USA and China (in practice an increase by 100% of renewables)

RENEWABLES – Critical issues

By ENI:

Renewables – main issues

- Renewable energy sources, with the exception of Hydroelectric, which already uses mature and reliable technologies, but can give only a limited contribution, have constraints that limit their market penetration and the economic break-even:

  - energy density
  - cost
  - Availability/intermittency

Courtesy of Paolo Pollesel, ENI (2018)

RENEWABLES – Critical issues

Renewables – energy density and costs

Solar PV	5 – 20 MW/km^2
Wind	1 – 2.5 MW/km^2
Biomass	0.5 – 2 MW/km^2
Fossil	100 – 1000 MW/km^2

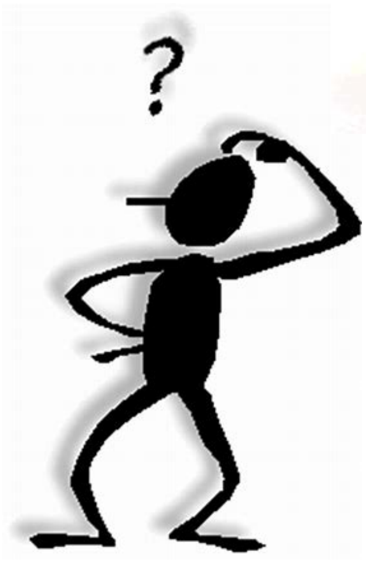
Environmental footprint

"effective" power: takes in account for example day-night cycles, onshore/offshore wind conditions, etc.

- Energy density very low compared to fossil fuels (high land footprinting): solar has the highest density among renewables
- For biofuels, also water demand and competition with food crops have to be carefully taken in account
- Only hydro and wind power have reached the grid parity
- Solar power costs range between the upper limit of conventional power generation and 4 times more (0,12 – 0,45 $/kW)

Courtesy of Paolo Pollesel, ENI (2018)

VITAMIN C DENSITY



RENEWABLES – Critical issues

From the IEA World Energy Outlook 2015…

- In the future, renewable sources will probably be the most important energy sources; but we need to do something from now, to answer to the increasing energy demand, the CO2 issue, sustainable growth,…

- Where it replaces more carbon-intensive fuels or backs up the integration of renewables, **natural gas is a good fit for a gradually decarbonising energy system**: a consumption increase of almost 50% makes it the fastest-growing of the fossil fuels. (from IEA)

FROM FOSSIL FUELS TO RENEWABLES – A transition is needed

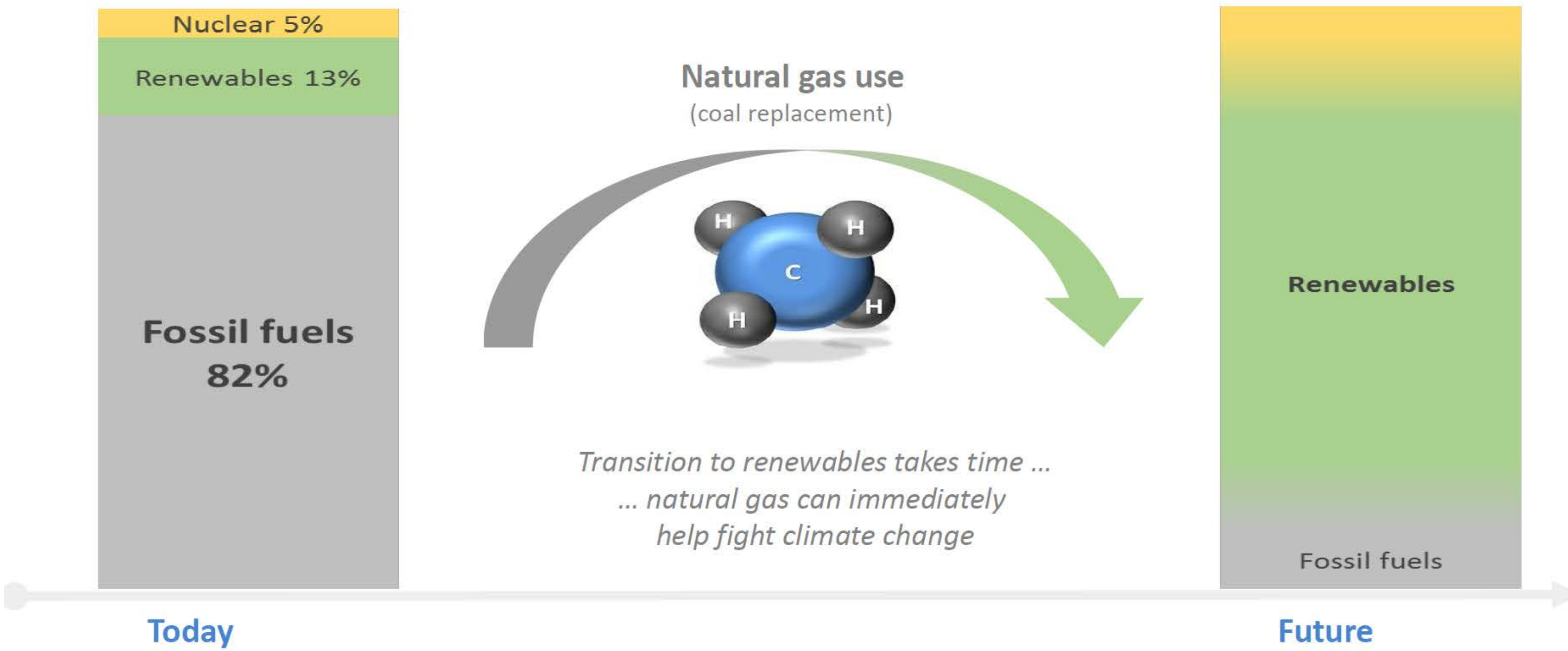
How natural gas can contribute to the decarbonization of the energy system?

$$C_xH_y + O_2 \longrightarrow CO_2 + H_2O$$

	C/H ratio	Energy content (kJ/g)	CO_2 released (mol/MJ)
Coal (C_xH_x)	1/1	39,3	2,0
Oil (C_xH_{2x})	1/2	43,6	1,6
Natural gas(CH_4)	1/4	51,6	1,2
Hydrogen (H_2)	0	120	0

Courtesy of Paolo Pollesel, ENI (2018)

ENI's Energy Transition Program: focus on Natural Gas
A reliable «bridge» to a low-carbon-economy

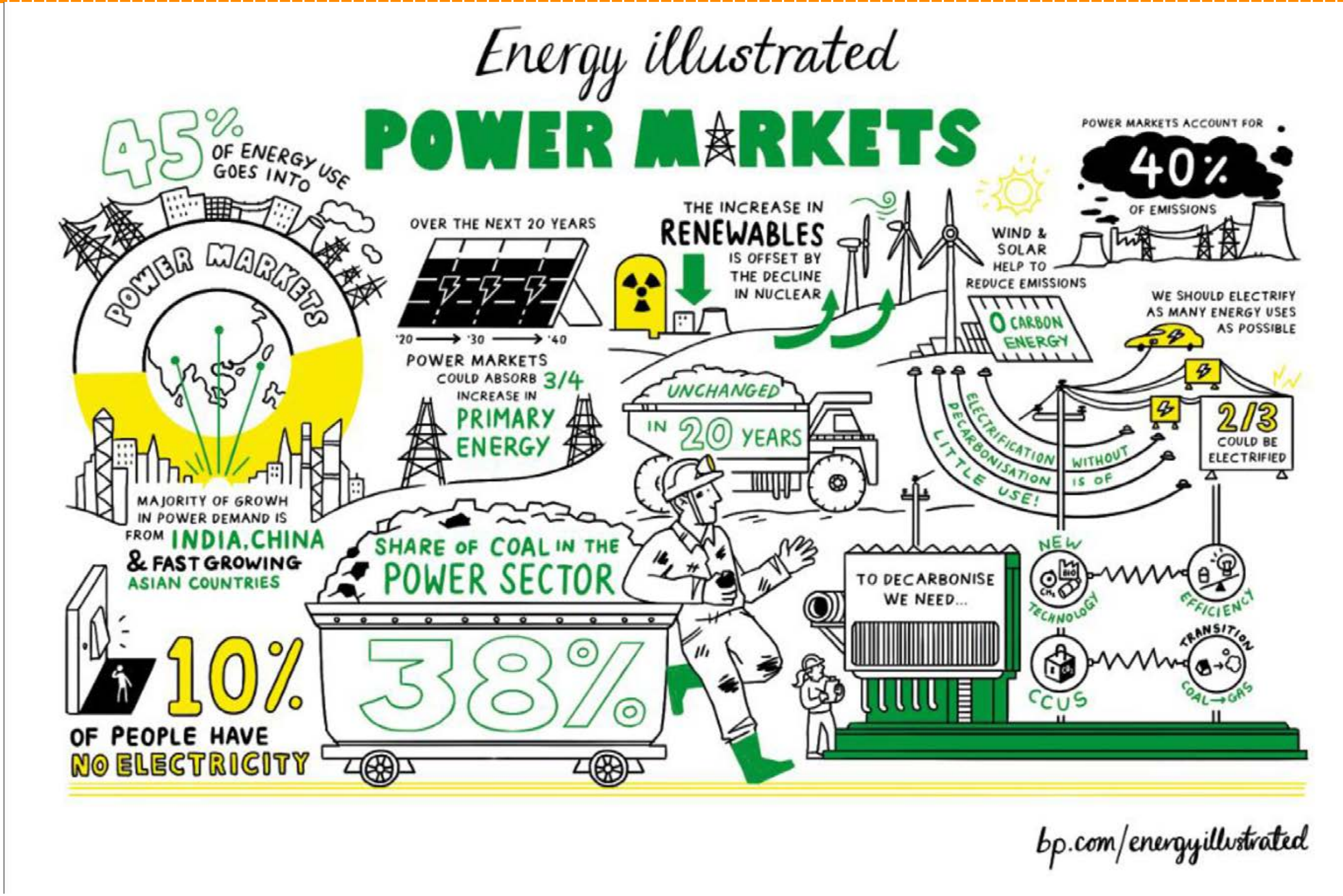


Natural gas pros:

- abundant & widely used
- well known & available technology
- less carbon intensive (CO_2 emissions) than coal or oil
- CCS & CCU could be applied to further reduce carbon emissions

Courtesy of Paolo Pollesel, ENI (2018)

TAKE-HOME MESSAGES - 1



TAKE-HOME MESSAGES - 1

- The energy demand of the world is increasing. CO_2 emissions also have grown.

- The power demand in developing countries greatly adds to the difficulty of decarbonizing the power sector.

- The penetration of renewables is also increasing, but it would need to have grown more than twice as quickly as it actually did over the past three years.

- In perspective: rapid growth of renewable energy is essential, but it is unlikely to be sufficient. This highlights the importance of adopting a range of technologies and fuels, rather than just relying on renewables.

- To win the race to Paris, the world is likely to require many fuels and technologies for many years to come.
  This include: coal-to-gas switch, carbon capture, use and storage (CCUS), increasing energy efficiency, especially in developed world, where the vast majority of people enjoy high levels of electricity consumption.

FOCUS ON TRANSPORT SECTOR

In 2017, 27 % of total EU-28 greenhouse gas emissions came from the transport sector (22 % if international aviation and maritime emissions are excluded).

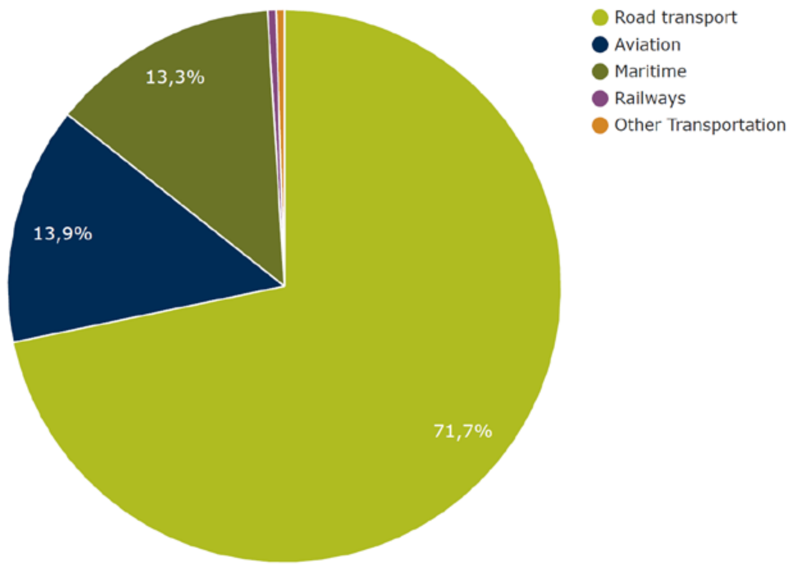
CO_2 emissions from transport increased by 2.2 % compared with 2016

Data sources:

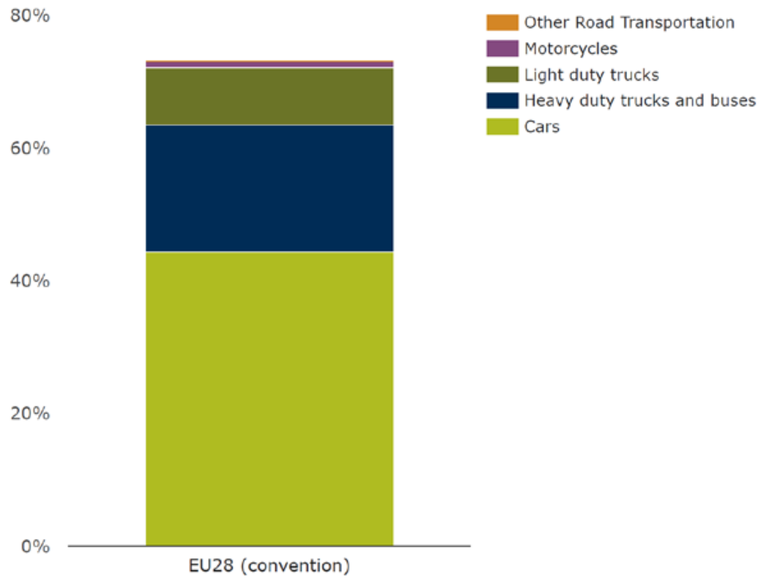
- National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism provided by **European Environment Agency (EEA)**

Greenhouse gas emissions from transport in Europe

Share of transport greenhouse gas emissions

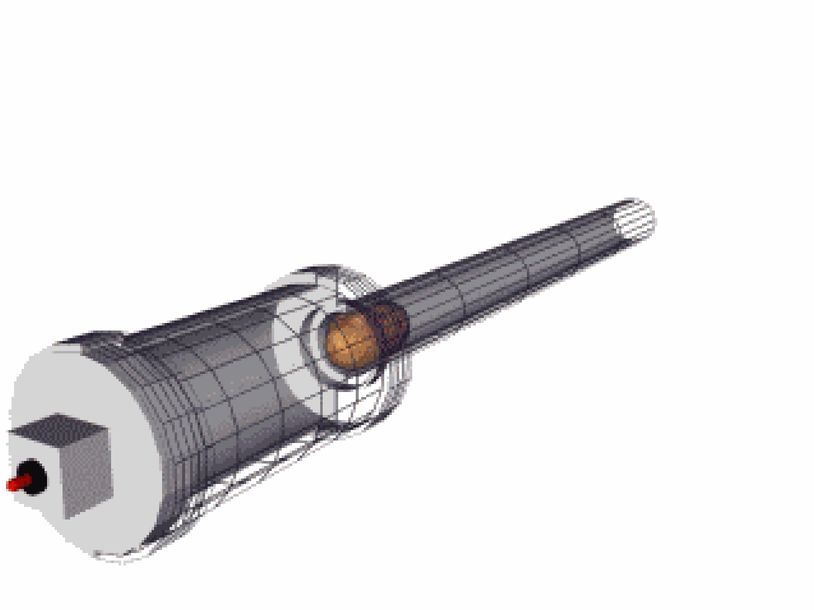


Road transport



- Internal Combustion Engine Vehicles
- Fuel-Cell Vehicles
- Fully Electric Vehicles (BEVs)

- Internal Combustion Engine Vehicles
- Fuel-Cell Vehicles
- Fully Electric Vehicles



The thermal engine exploits the rapid combustion of the fuel that creates a pressure wave that moves the piston.

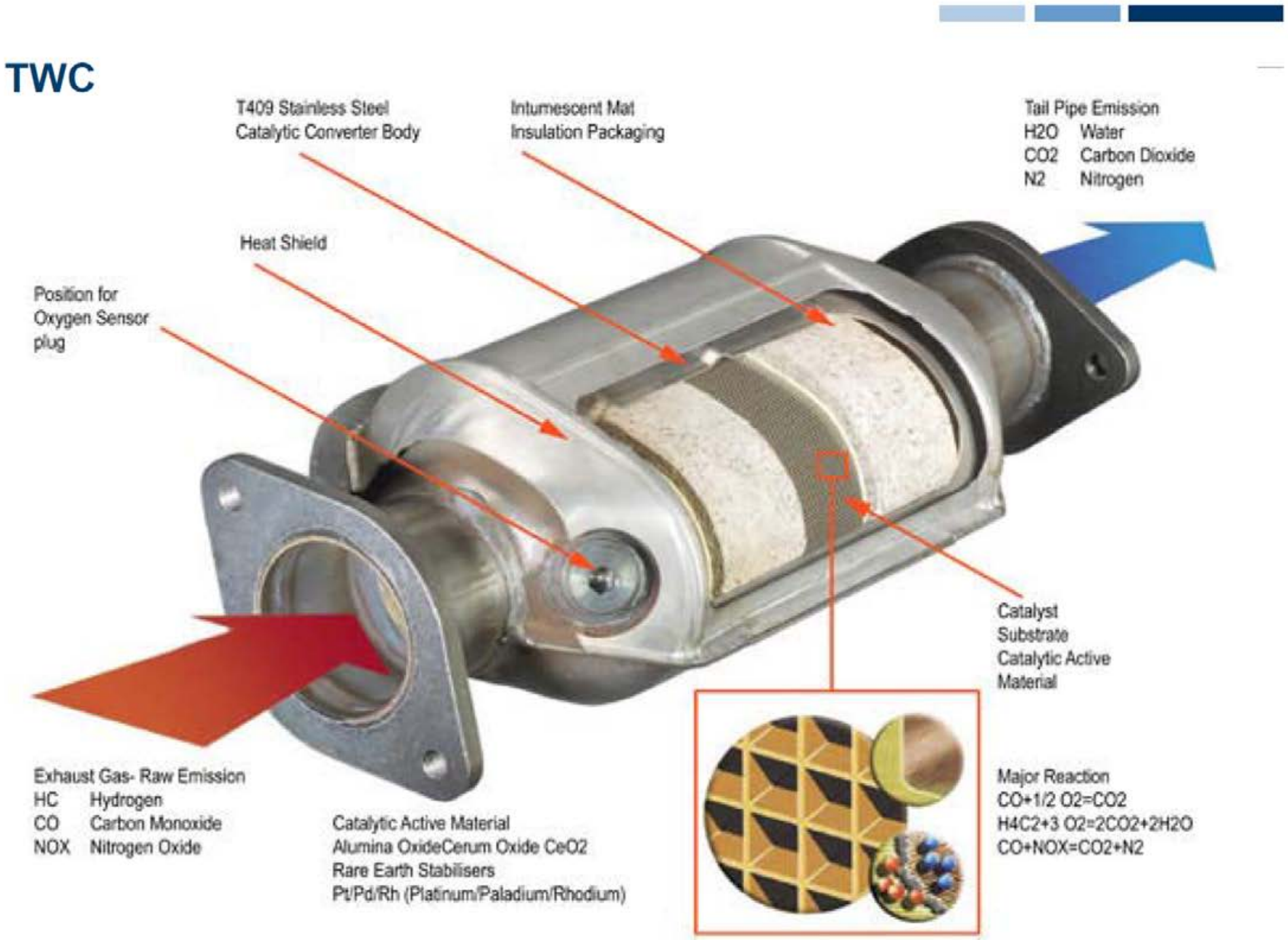
CO_2 Emissions + Polluting Emissions

- Exhaust for ideal combustion: $$C_nH_{2n+2} + (3n+1)/2\ O_2 \rightarrow n\ CO_2 + (n+1)\ H_2O$$
  - Nitrogen (N_2)
  - Carbon dioxide (CO_2)
  - Water(H_2O)

- Real combustion:
  - Carbon monoxide (CO)
  - VOC (fuel not consumed)
  - UHC
  - Oxides of nitrogen(NO_x)
  - Particulate matter

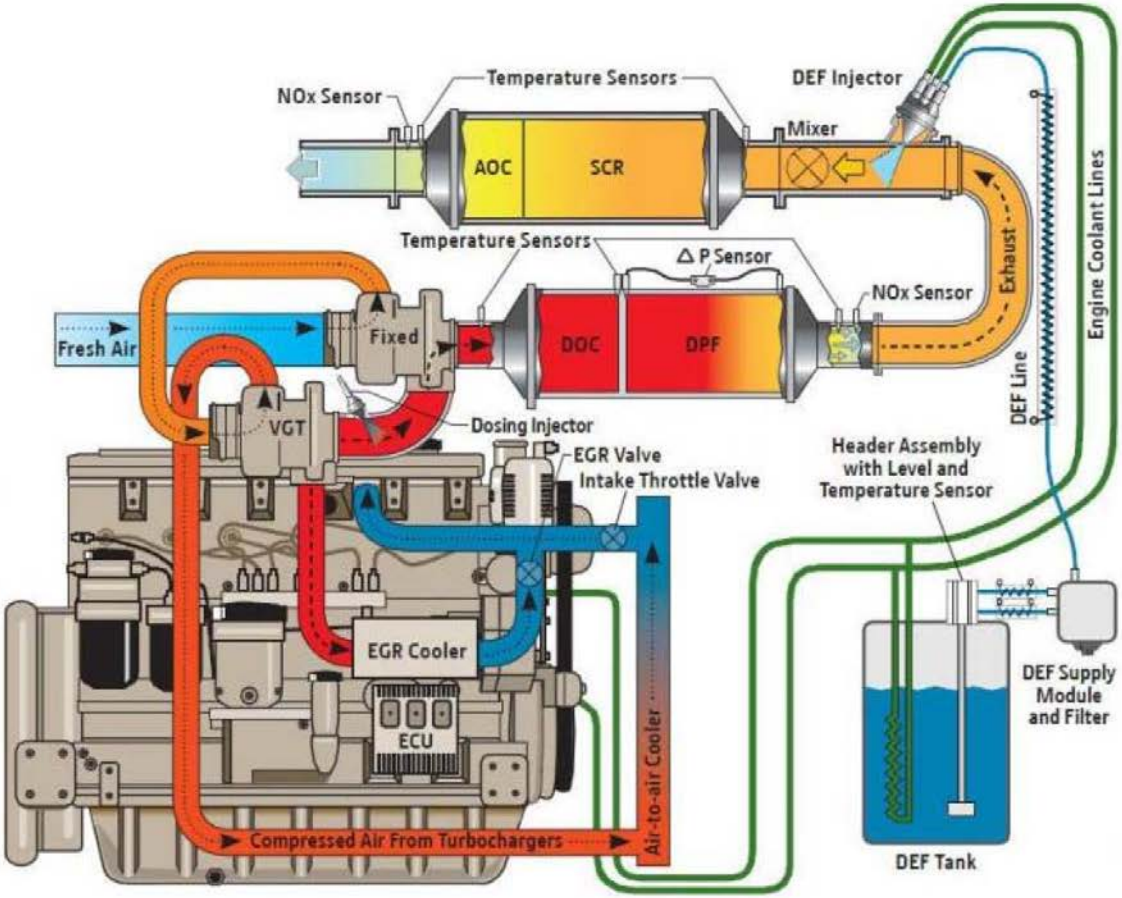
Polluting emissions:
the anwer comes from aftertreatment technologies

Gasoline engines: Three-way-catalyst



Polluting emissions:
the anwer comes from aftertreatment technologies

Diesel engine: aftertreatment train



Emission regulations over years

Passenger cars Diesel Engines

Stage	Date	CO	HC	$HC+NO_x$	NO_x	PM	PN
		g/km					#/km
Compression Ignition (Diesel)							
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	0.14 (0.18)	-
Euro 2, IDI	1996.01	1.0	-	0.7	-	0.08	-
Euro 2, DI	1996.01[a]	1.0	-	0.9	-	0.10	-
Euro 3	2000.01	0.64	-	0.56	0.50	0.05	-
Euro 4	2005.01	0.50	-	0.30	0.25	0.025	-
Euro 5a	2009.09[b]	0.50	-	0.23	0.18	0.005[f]	-
Euro 5b	2011.09[c]	0.50	-	0.23	0.18	0.005[f]	6.0×10^{11}
Euro 6	2014.09	0.50	-	0.17	0.08	0.005[f]	6.0×10^{11}

* At the Euro 1.4 stages, passenger vehicles > 2,500 kg were type approved as Category N_1 vehicles

† Values in brackets are conformity of production (COP) limits

a. until 1999.09.30 (after that date DI engines must meet the IDI limits)

b. 2011.01 for all models

c. 2013.01 for all models

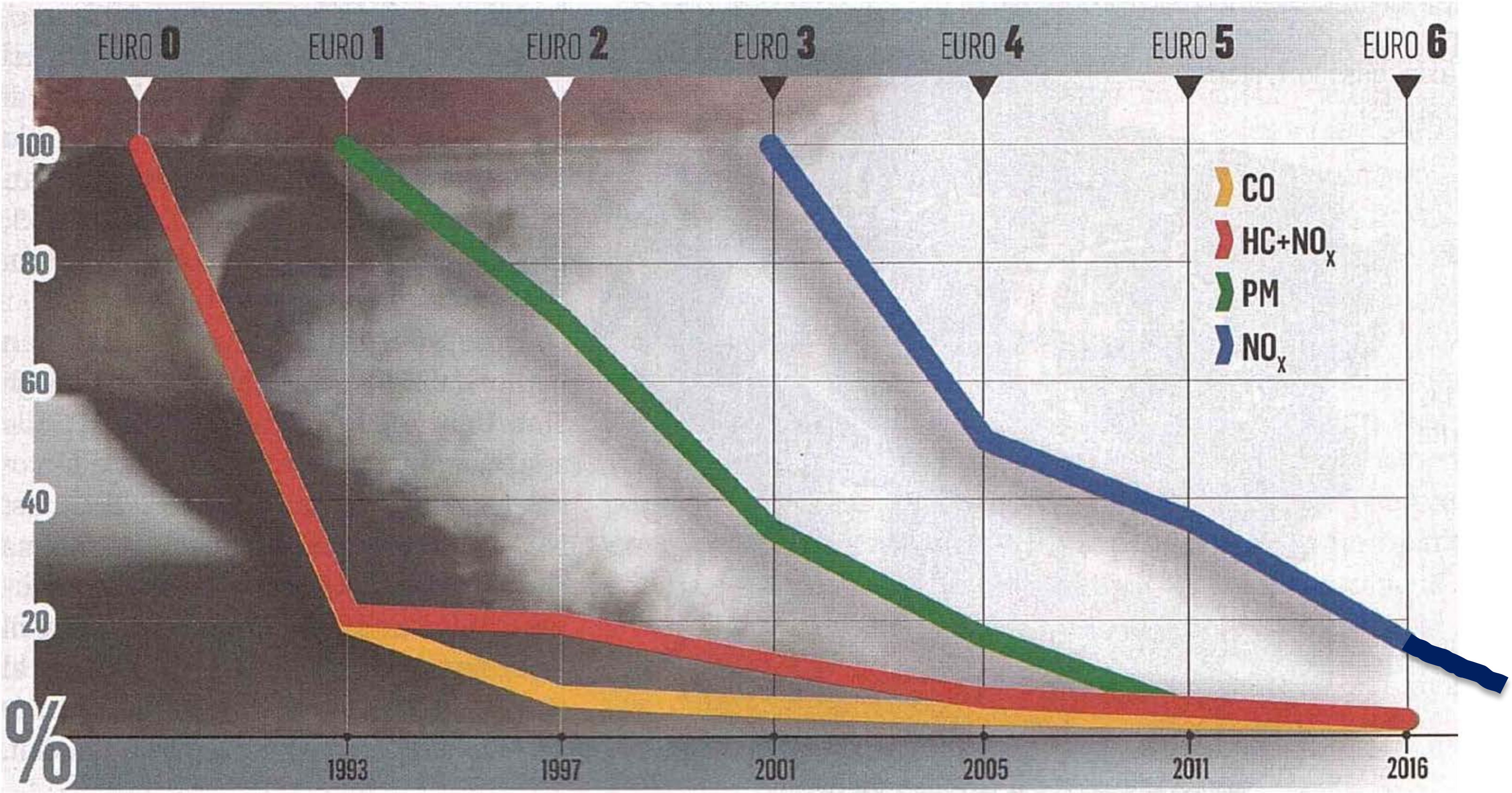
d. and NMHC = 0.068 g/km

e. applicable only to vehicles using DI engines

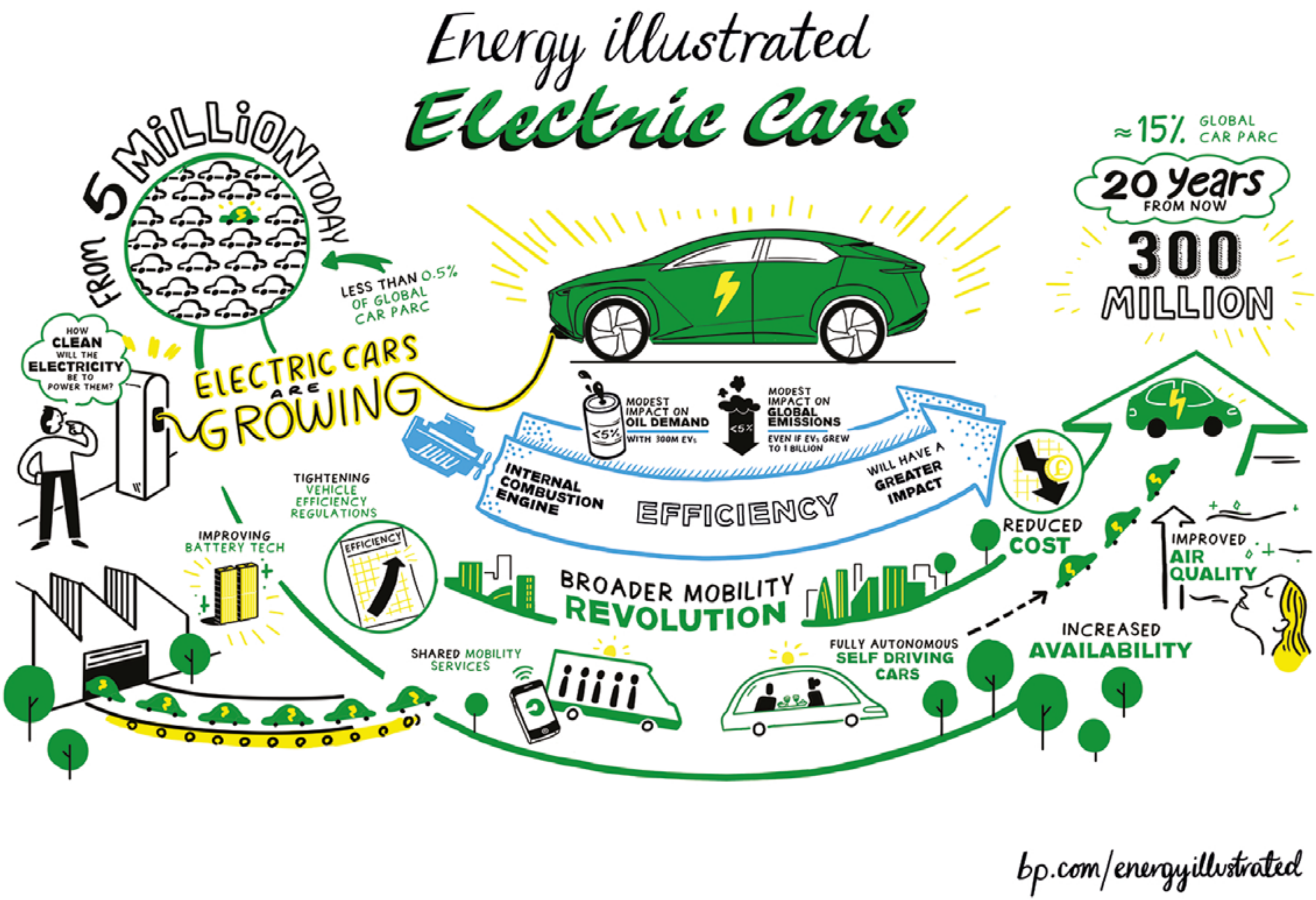
f. 0.0045 g/km using the PMP measurement procedure

g. 6.0×10^{12} 1/km within first three years from Euro 6 effective dates

Emissions percentage reduction



THE (R-)EVOLUTION OF THE TRANSPORT SECTOR



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ENERGY FOR MOTION
Department of Excellence 2018-2022

ENERGY FOR MOTION
ANNUAL SEMINAR 2019

Milano, November 22nd, 2019

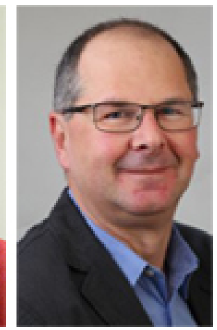
THE (R-)EVOLUTION OF THE TRANSPORT SECTOR @ DENG
WE MEET THE EXPERTS


H. Gasteiger


F. Venturini


S. Passerini


P. Pollesel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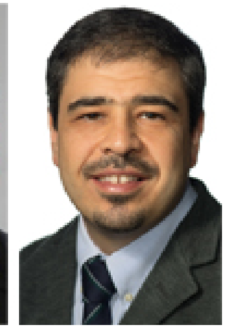

A. Yezerets


Discussion

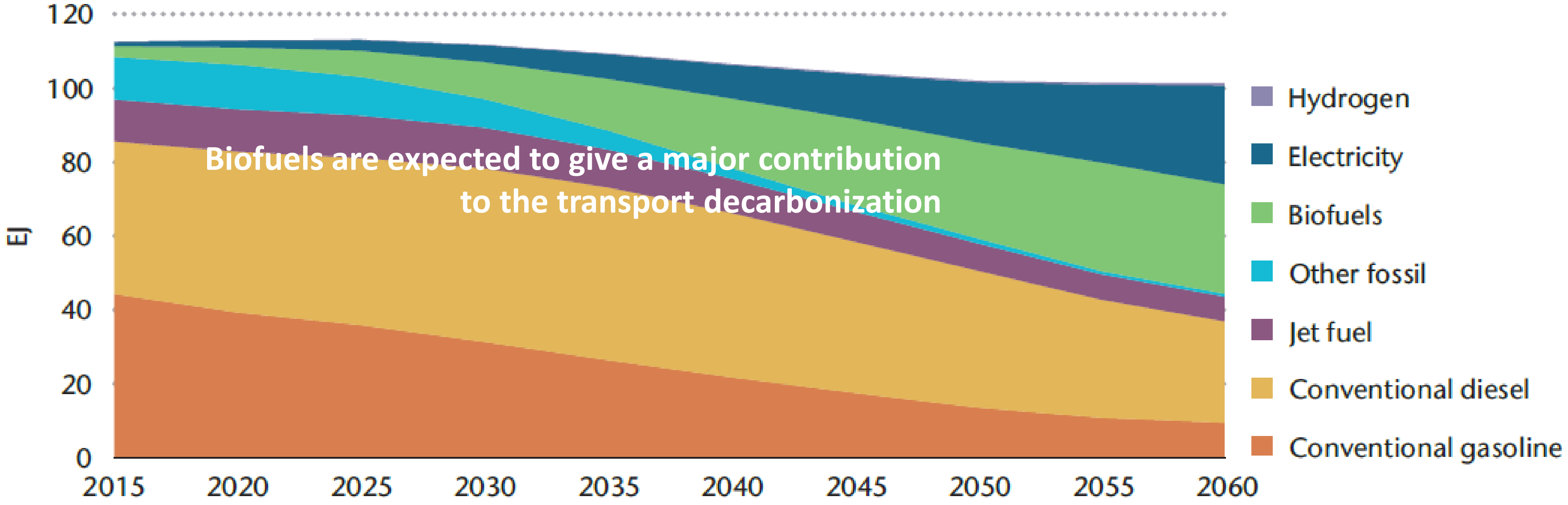
THE FUTURE OF THERMAL ENGINES?

Paolo Pollesel

"From waste and biomass to advanced biofuels"

DECARBONISATION STRATEGY FOR THE TRANSPORT SECTOR: BIOFUELS & ELECTRIFICATION

The fuel evolution requested to meet max 2 °C global warming target



- Reduction of fossil fuel consumption (gasoline, diesel and jet fuels)
- Major expansion in the role of biofuels, reaching nearly **30 EJ in 2060** (**nearly 10 times 2016 levels**), and providing **29% of total transport final energy demand**.
- Sharp growth electricity to nearly 27 EJ (26% of total transport final energy demand) in 2060.

Source: IEA -Technology Roadmap - Delivering Sustainable Bioenergy Report 2017

The biofuels policy (Europe)

European Commission

2020 TARGETS (RED/ILUC Directive)	2030 TARGETS (RED II Directive)
20% Global renewable energy target	**32%** Global renewable energy target
10% Transport renewable energy target	**14%** Transport renewable energy target
0.5% sub-target on non-crop based “advanced” biofuels	**3.5%** sub-target on non-crop based “advanced” biofuels
7% Cap on food-based biofuels	Gradual decrease to **0% of HIGH-ILUC** food-based biofuels Certification required for **LOW-ILUC** food-based biofuels
60% GHG emission reduction from 2015	**65%** GHG emission reduction from 2021 (fossil fuels ref. emissions: 94 g $CO_{2\ eq.}$/MJ)

In Europe the challenge is to produce advanced diesel biofuels starting from LOW ILUC raw material

Biofuels Overview

1st

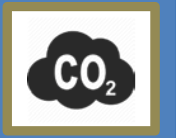
First Generation Biofuels

2nd

Second Generation Biofuels

Advanced

Advanced Biofuels



E-Fuel

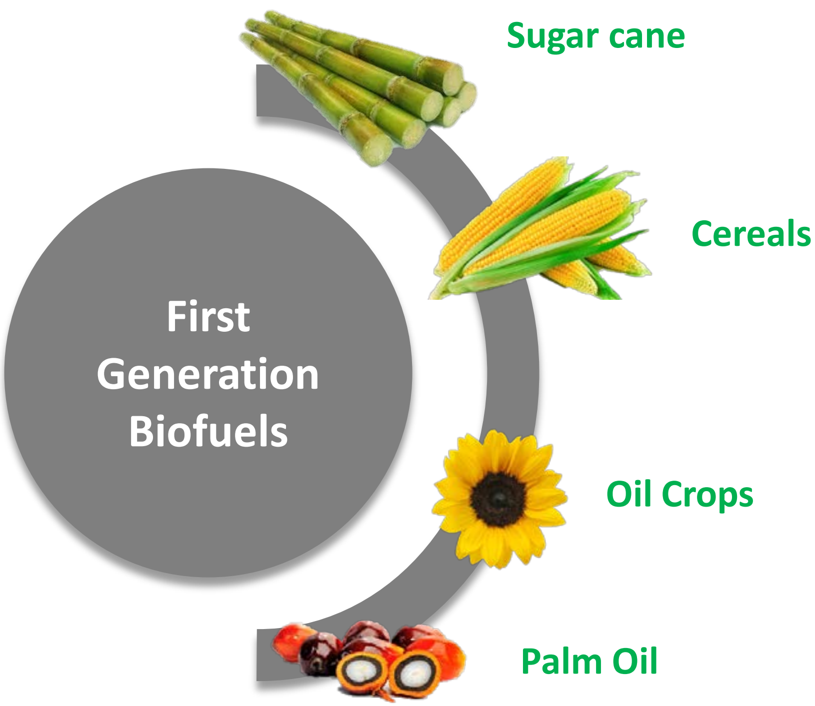
E-Fuels

Description

- First generation or conventional biofuels are biofuels made from food crops grown on arable land
- Second generation biofuels are biofuels made from biomasses not in competition with food
- Advanced biofuels are biofuels produced starting from waste materials (es. Municipal wastes, lingo-cellulosic materials, etc.)
- E-Fuels can be produced starting carbon dioxide, water, and electricity with a process powered by renewable energy sources

eni

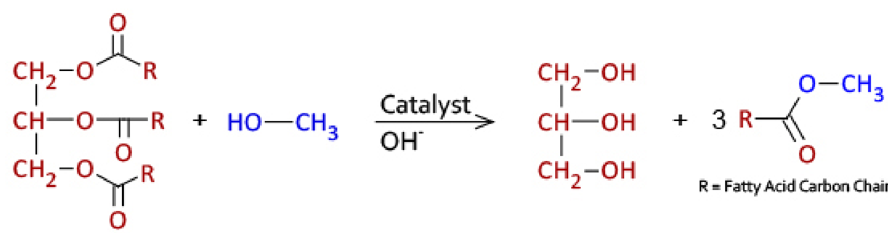
1st Generation Biofuels



From Sugar to Gasoline (Ethanol)

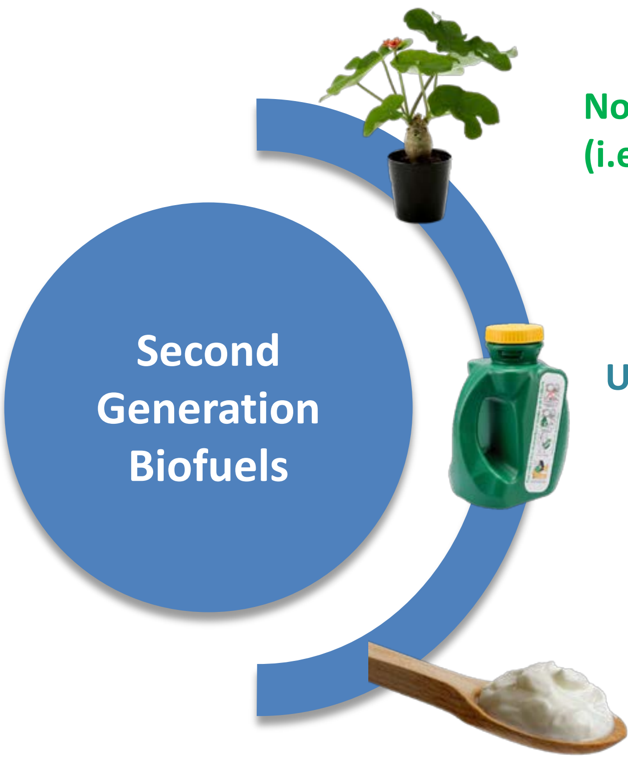
$$C_6H_{12}O_6 \longrightarrow \underset{\text{ethanol}}{2C_2H_5OH} + 2CO_2$$

From Vegetable Oil to Diesel (FAME-HVO)

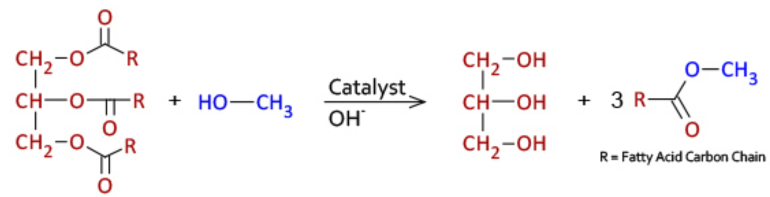


FAME: Fatty Acid Methy Esther

2^{nd} Generation Biofuels

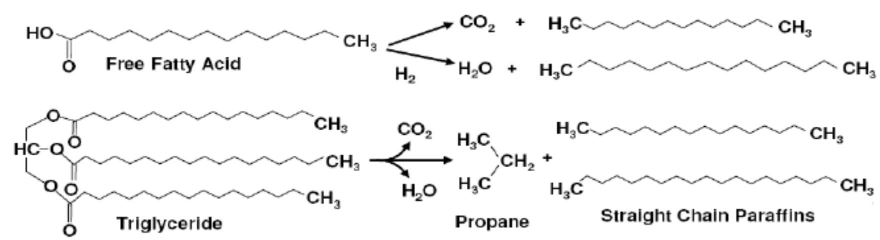


Not edible oil crops
(i.e. jatropha oil)



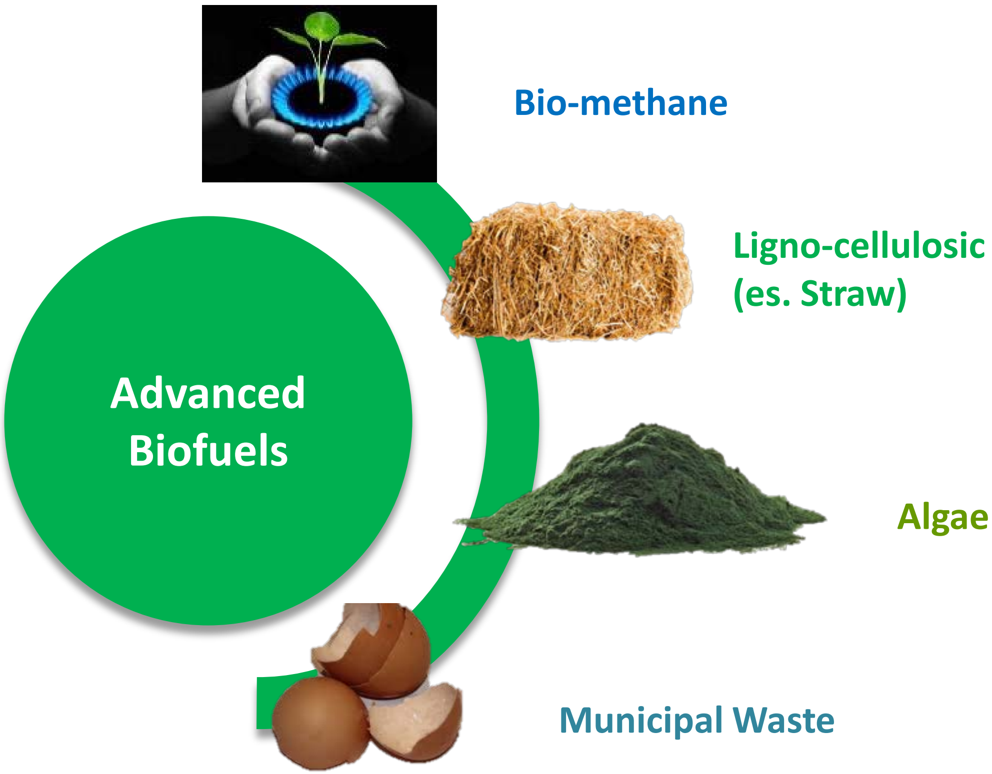
Used Cooking Oils

From Alternative Oil to Diesel (FAME-HVO)



Animal Fats

Advanced Biofules



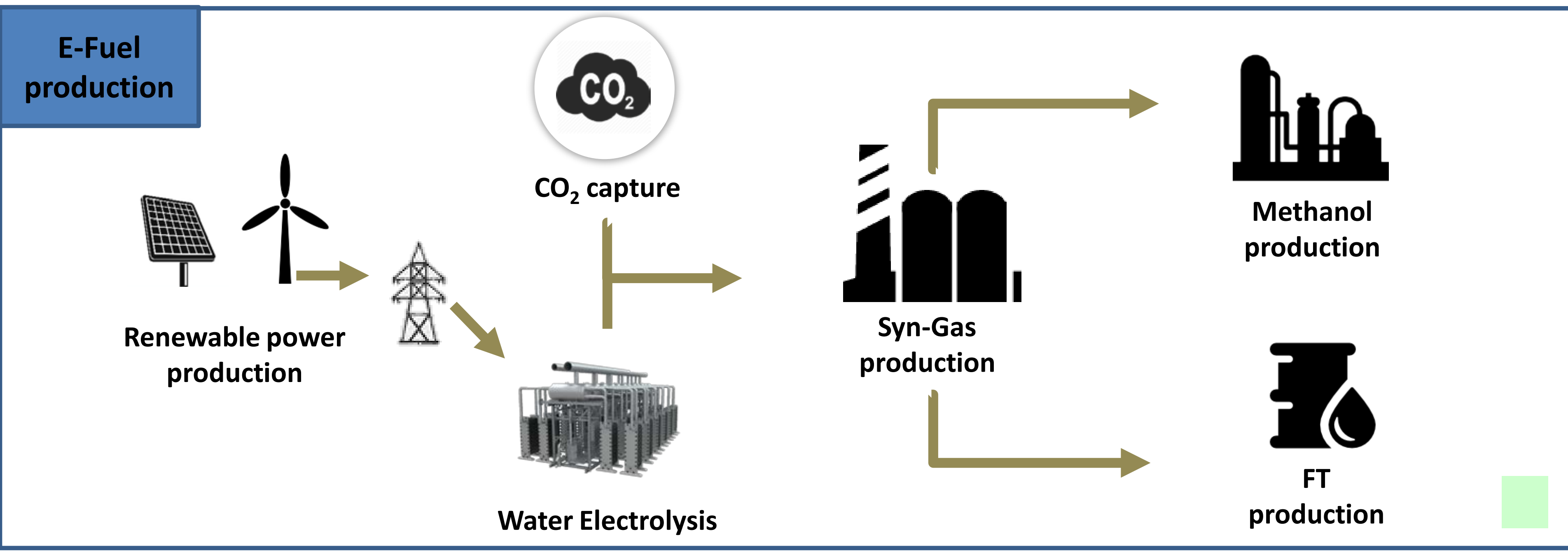
...and even more

- Crude Glycerine
- Bagasse
- Palm Oil mill effluent
- Tall Oil
- Sewage sludge

E-Fuels

Towards a zero-emission scenario: Fuels from emissions

Emissions-to-liquids



Eni Green Refinery projects: Ecofining Technology

Conversion of a fossil refinery into a bio-refinery ➔ environmental and technological but also economic and social significance. It allows us to give new life to the plant and guarantees employment through innovation.


Venice Green Refinery

- The facility is **on stream since April 2014** with a green diesel production capacity of **360 kt/year.**
- The final configuration target will be **560 kt/year**.


Gela Green Refinery

- The conversion of eni Gela refinery into an Ecofining based green refinery has been **completed in 2019.** The plant has a production capacity up to **670 kt/year.**

15% renewable component

Available in over 3,500 fuel stations all over Italy from January 2016

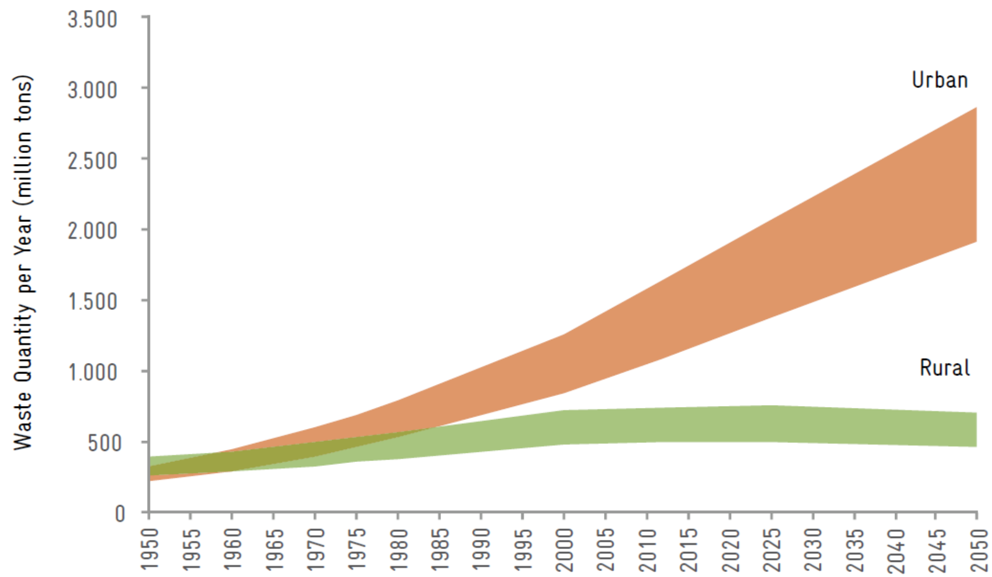
GREEN - DIESEL QUALITY

Properties	Fossil Diesel	FAME	Green Diesel (HVO)
Oxygen, %	**0**	**11**	**0**
Specific weight	0.840	0.880	0.780
Sulphur, ppm	< 10	< 1	< 1
Heating value, MJ/kg	**43**	**38**	**44**
Cloud Point, °C	**From 0 to -5**	**From -5 to +15**	**Up to -20**
Polyaromatics, %wt	**< 8**	**0**	**0**
Cetane number	**51 – 55**	**50 – 55**	**70 – 90**
Oxidation Stability	Standard	Pour	Excellent

HVO: Hydrogenated Vegetable Oil

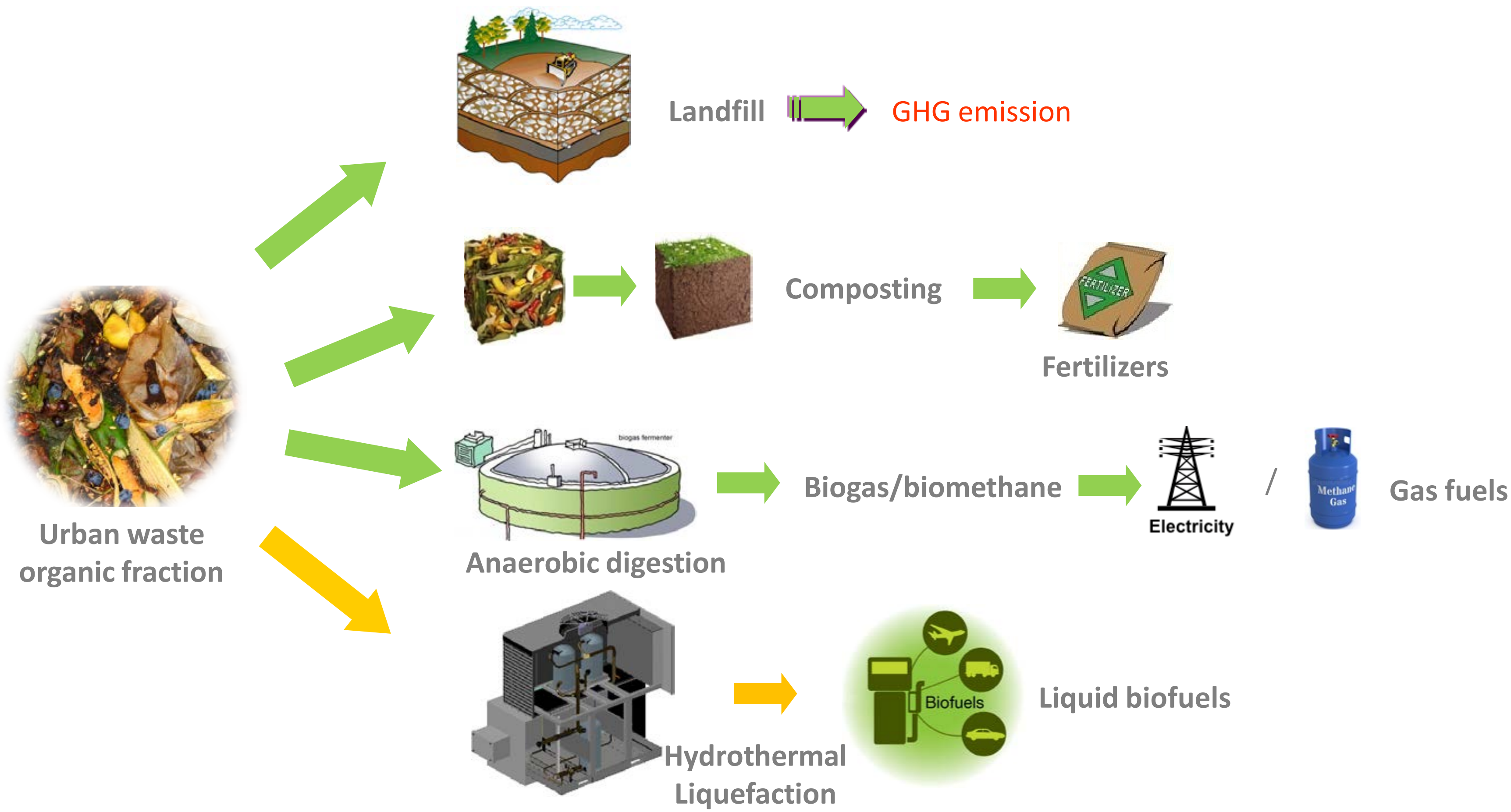
Wet biomass: Municipal Solid Waste

- The World generates **2 billion tonnes of municipal solid waste** annually.
- Taking in account the population increase, plus the income level and rate of urbanization it is expected to increase up to **3.4 billion tonnes by 2050**



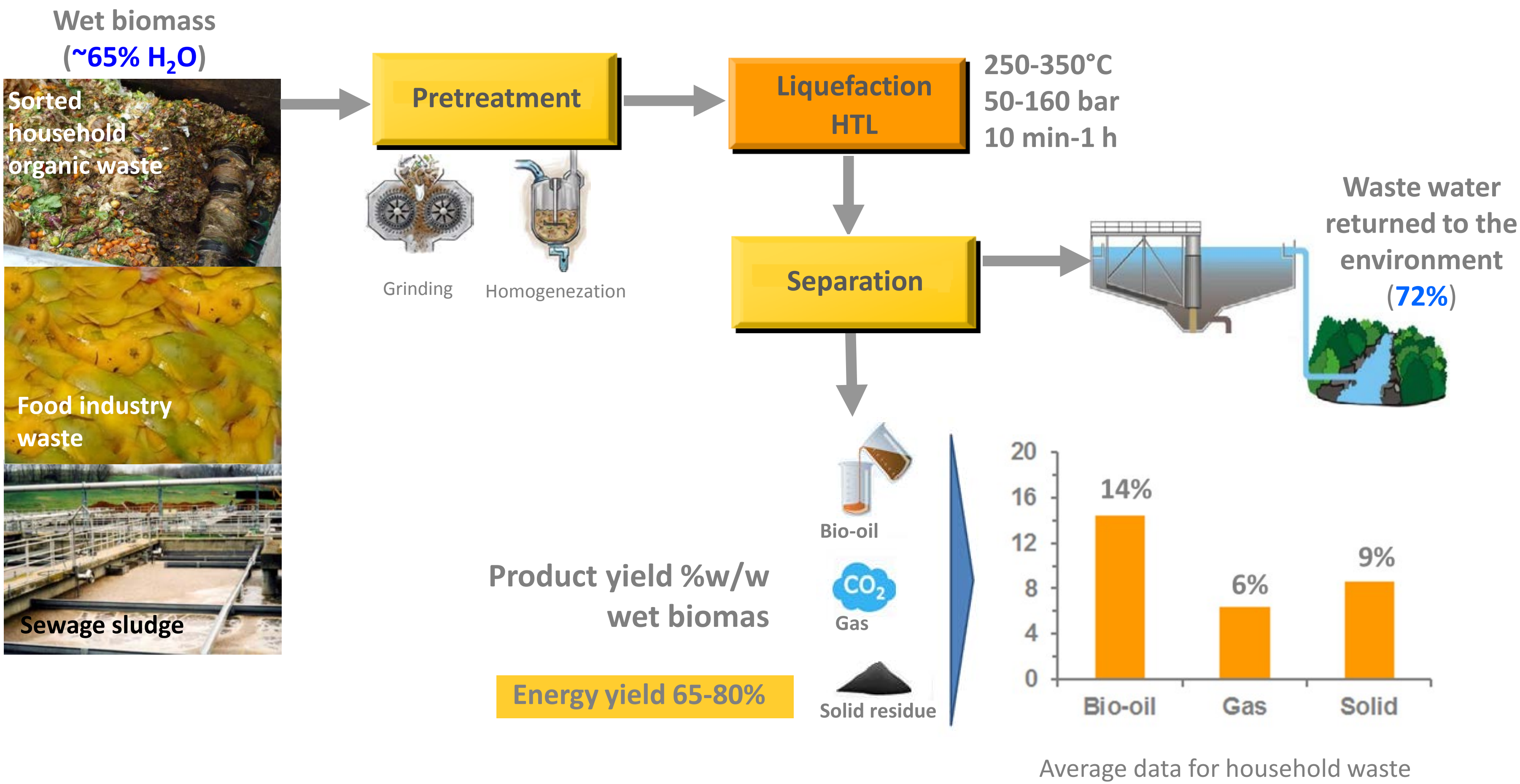
Source: https://www.worldbank.org/en/news/immersive-story/2018/09/20/what-a-waste-an-updated-look-into-the-future-of-solid-waste-management

Wet organic waste disposal options



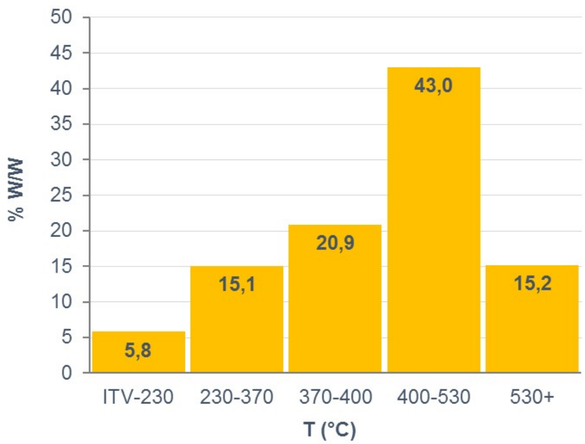
Organic waste hydrothermal liquefaction (HTL) process

eni technology



Hydrothermal liquefaction: bio-oil quality

Bio-oil is quite similar to heavy fuel oil



Bio-oil boiling points distribution (distillation test)

	Liquefaction bio-oil	Heavy fuel oil
H_2O content %	0,16	0,1
Density (kg/l)	0,94	0,9
Viscosity (50°C, cp)	180	185
Composition %:		
C	74-76	83-86
H	8	11
O	12-16	1
N	3-4	>1
S	>0,1	>4
Heating Value (MJ/kg)	32-35	40
TAN (mgKOH/g)	30-60	>1

W2F – waste valorization

HOUSEHOLD ORGANIC WASTE

DISPOSAL

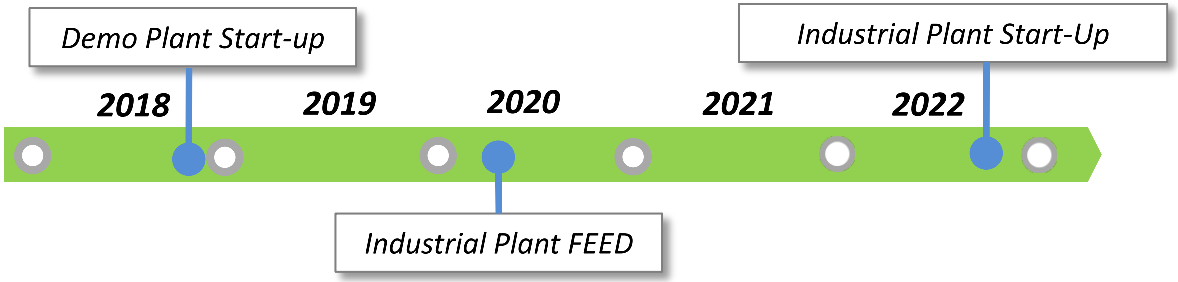
	COMPOSTING 	***BIOGAS*** 	***WASTE TO FUEL*** 
Mass Yield	*25%*	*15% (4% Bio-CH_4)*	***14%***
CO_2 generated / 1 ton waste	*0,11 t*	*0,14 t*	***0,03 t***
Energetic Yield	*-*	*50%*	***80%***
Byproducts	*- Compost with saturated market - Water and percolate to be treated*	*- Water and percolate to be treated - Bio stabilized waste to disposal*	***- Water recovery - Biomethane production***
Process Treatmet timing	*months*	*Weeks*	***Hours***
Soil Utilization m^2/1 ton FORSU	*0,7-1,5*	*0,2-0,4*	***<0,3***

W2F Gela Demo Plant

OBJECTIVES

- Bio-oil characterization and valorization as Advanced Biofuel
- Continuous test of entire process form reaction to separation
- Checks on equipment design and reliability for industrial technology development
- Ream the quality of feedstock and process products (organic waste, bio-oil, byproducts)
- Check on operational requirements
- Lessons learnt consolidation for technology industrial development

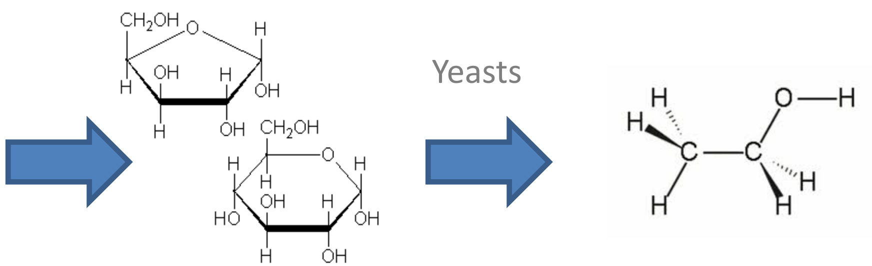
Plant size: 0,7 ton/day of organic waste



Oils from lignocellulosic biomass

A vegetable oil-like feedstock can be obtained starting from waste lignocellulosic biomass (agricultural and forestry residues, eg. wheat straw, corn stover, poplar, cassava residues, palm empty fruit bunches) .
A technology to produce another biofuel, bioethanol as gasoline component is already available.

Agricultural wastes – energy crops



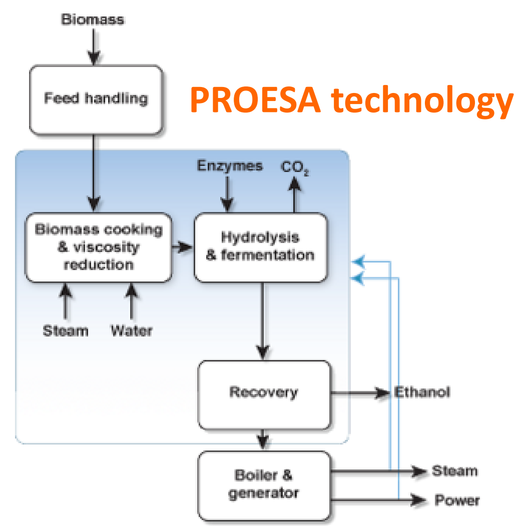
C5 and C6 sugar

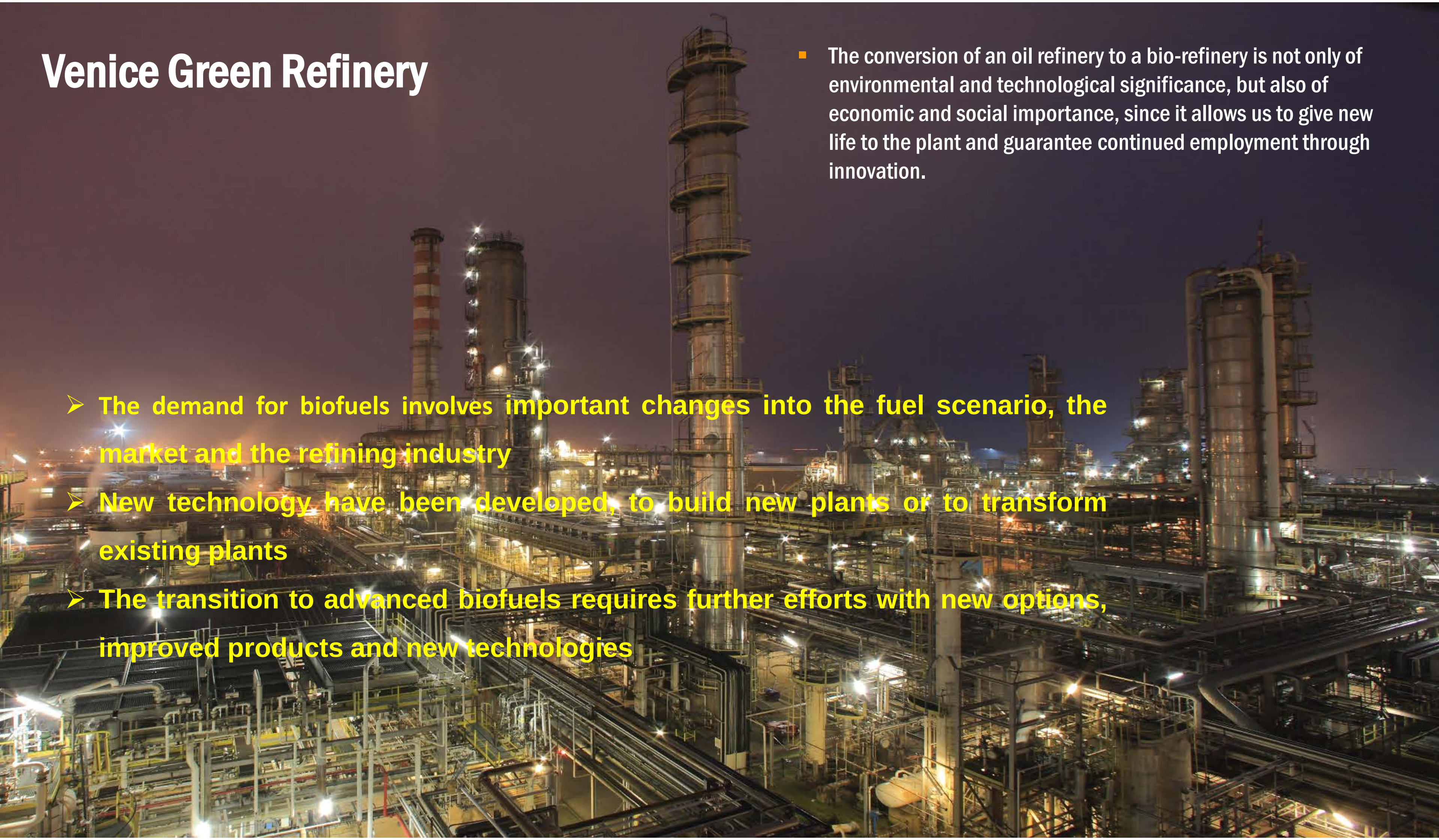
Cellulosic ethanol

Cellulosic ethanol commercial plant

The plant, was started in 2013 by BETARENEWABLES GRUPPO MOSSI & GHISOLFI

In 2018, after the financial failure of M&G group the plant has been the acquired by eni versalis





Venice Green Refinery

- The conversion of an oil refinery to a bio-refinery is not only of environmental and technological significance, but also of economic and social importance, since it allows us to give new life to the plant and guarantee continued employment through innovation.

- **The demand for biofuels involves important changes into the fuel scenario, the market and the refining industry**
- **New technology have been developed, to build new plants or to transform existing plants**
- **The transition to advanced biofuels requires further efforts with new options, improved products and new technologies**

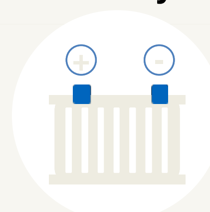
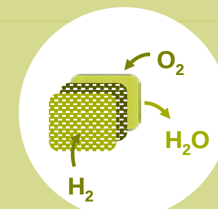
Hubert Gasteiger

"Technological, Economical and Ecological Constraints for Electromobility"

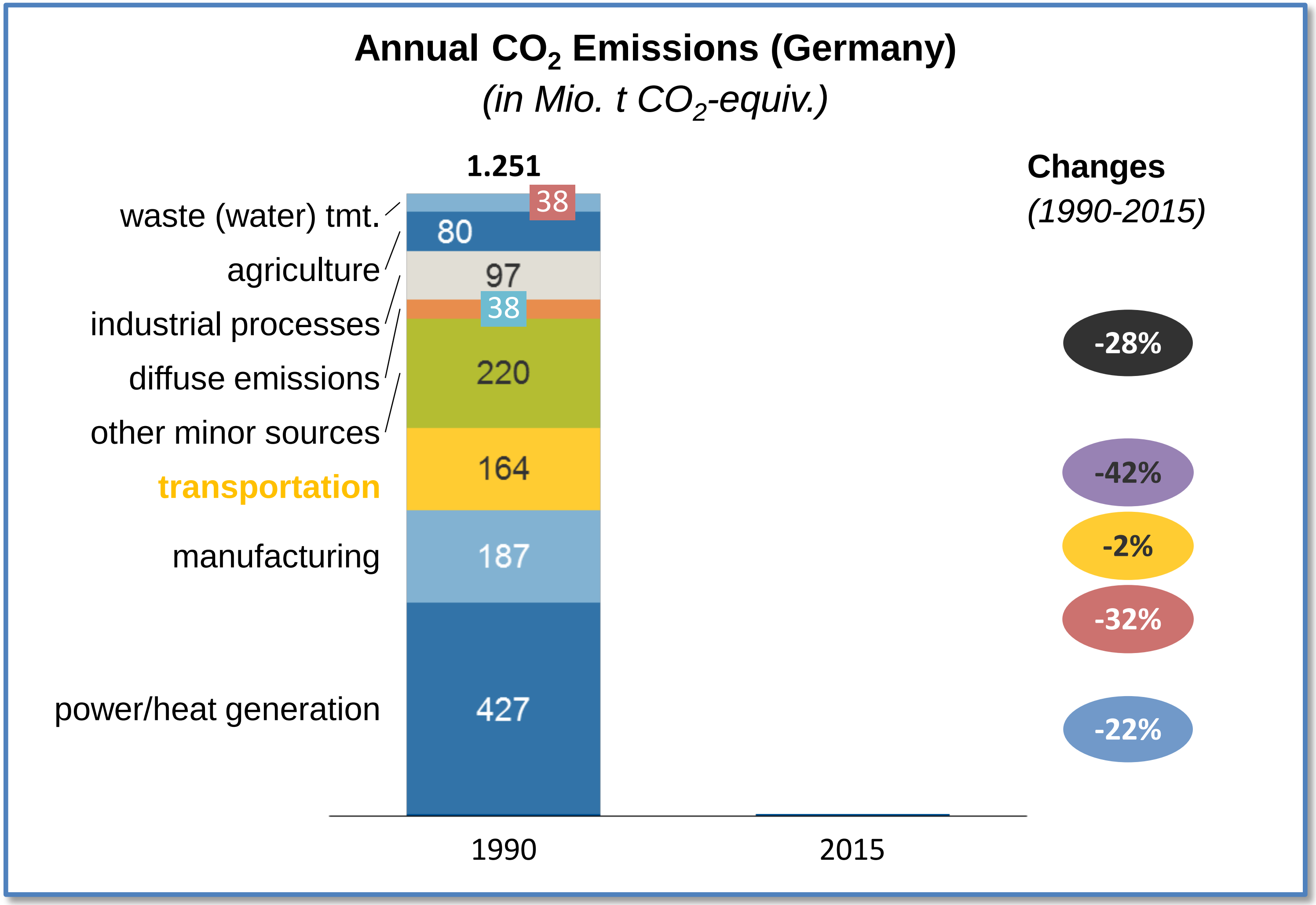
Technological, Economical, & Ecological Constraints for Sustainable Electromobility

Energy for Motion Seminar
Politecnico di Milano

Hubert Gasteiger
Chair of Technical Electrochemistry
Technical University of Munich, Germany

	gasoline/diesel	battery	fuel cell
			
cost per 100 km *(€/ 100 km)*	6 – 9 €	? €	? €
emissions per km *(g CO_2/ km)*	~120	? (2018) ? *(2050)*	? (2018) ? *(2050)*
driving range *(in km)*	1000 km	? km	? km
time for charging *(in min)*	< 3 min	? min	? min
critical resources	fossil fuels	?	?

CO_2 Emissions Sources in Germany



CO_2 emission contribution from transport sector: 13% (1990) → 18% (2015) !

→ 2020 EU target <95 g_{CO2}/km (currently ca. 120 g_{CO2}/km)

Source: Umweltbundesamt u.a.

- BEV Technology Roadmap / Constraints
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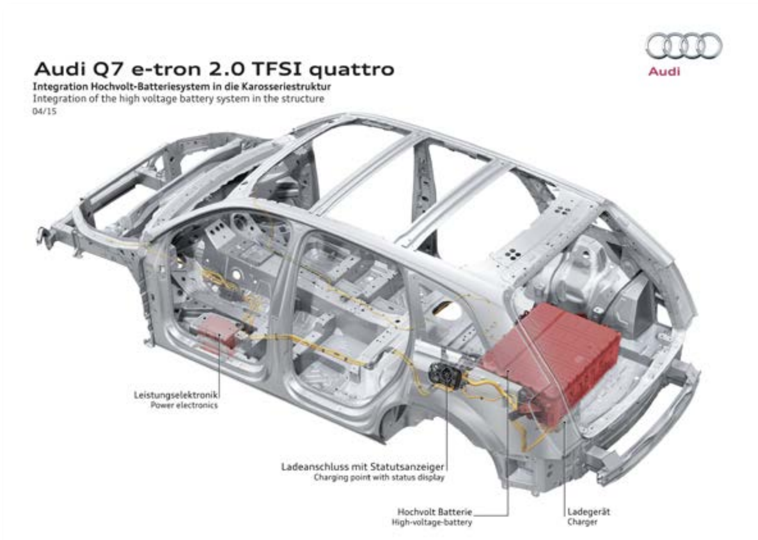
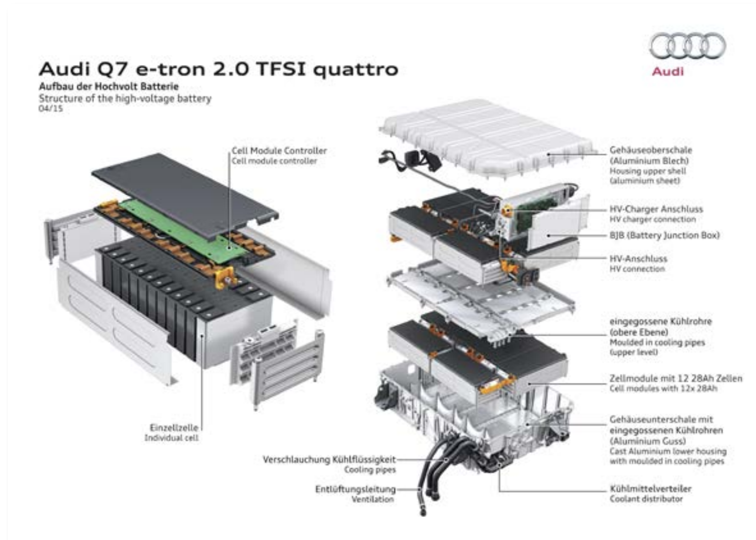
- Comparison ICE ↔ BEV ↔ FCEV

Lithium-Ion Battery (LIB) Technology



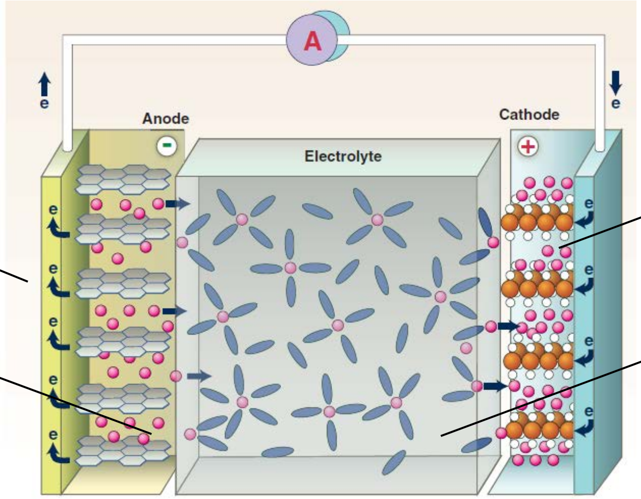


electron conduction
metallic current collectors (Al, Cu)

anode *(graphite, silicon)*

$$Li^+ + e^- + 6\,C \rightleftharpoons LiC_6$$

$$E_0 = 0.1\,V\ vs.\ Li/Li^+$$



cathode *($LiCoO_2$, $LiNi_xMn_yCo_zO_2$)*

$$Li^+ + e^- + 2\,Li_{0.5}CoO_2 \rightleftharpoons 2\,LiCoO_2$$

$$E_0 = 4.2\,V\ vs.\ Li/Li^+$$

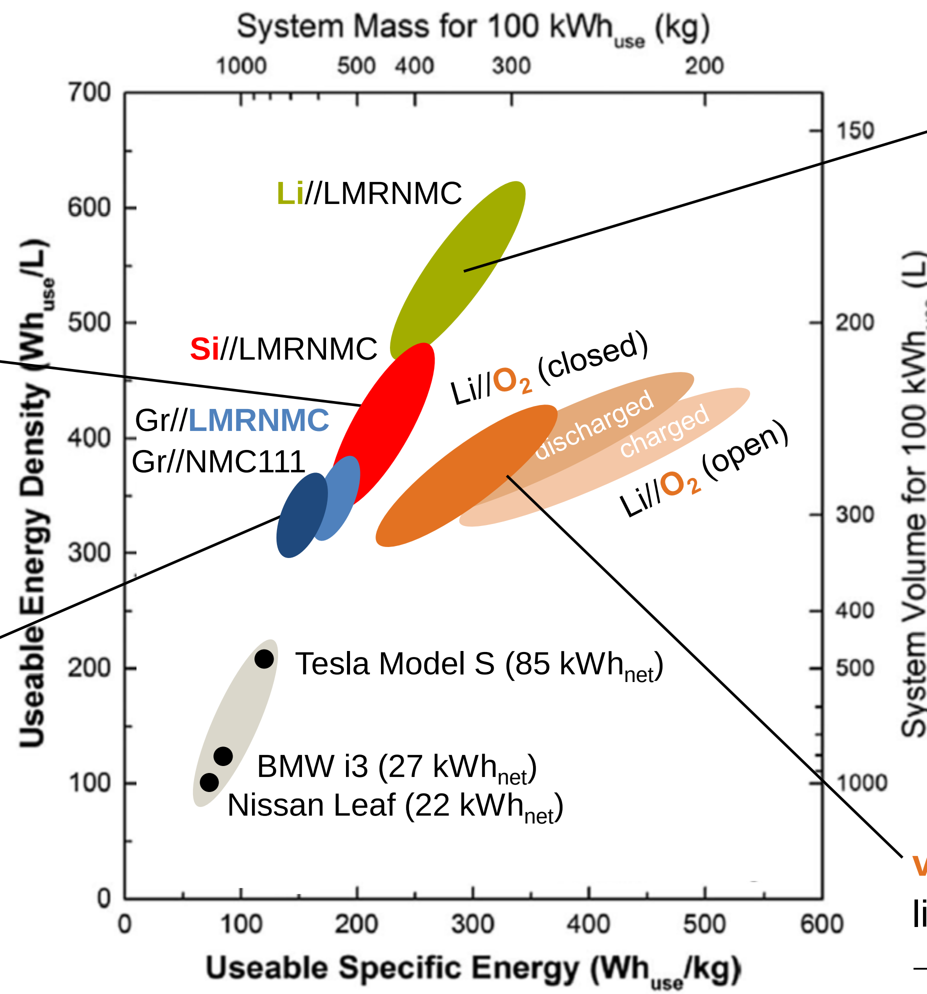
ion transport
aprotic electrolyte with $LiPF_6$ salt

from: www.audi-mediacenter.com (accessed: 02/08/2018) | Dunn, Kamath, Tarascon; *Science 334* (2011) 928

Energy Density of LIB Technologies

mid-term (2025):
silicon-anodes
high voltage/energy
cathodes
~250 Wh/kg$_{battery-system}$

today:
graphite//$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$
~150 Wh/kg$_{battery-system}$



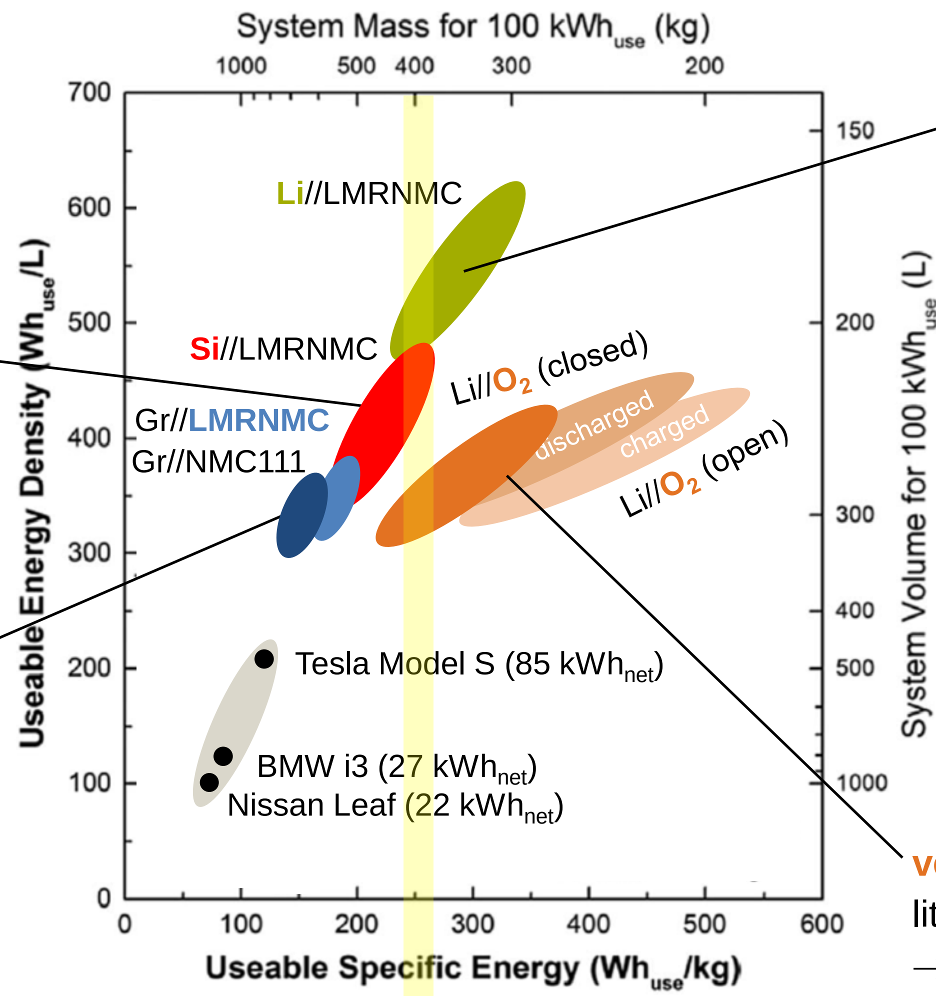
long-term (???)
lithium metal anodes,
high voltage/energy
cathodes
~350 Wh/kg$_{battery-system}$

very long-term (???)
lithium-air batteries
→ no stable electrolyte yet

*) Wandt, Jakes, Granwehr, Gasteiger, Eichel, *Angew. Chem. Int. Ed. 55* (2016) 6892

from: Gallagher, Goebel, Greszler, Mathias, Oelerich, Eroglu, Srinivasan; *Energy Environ. Sci. 7* (2014) 1555

Energy Density of LIB Technologies



long-term (???)
lithium metal anodes,
high voltage/energy cathodes
~350 Wh/kg$_{battery-system}$

mid-term (2025):
silicon-anodes
high voltage/energy cathodes
~250 Wh/kg$_{battery-system}$

today:
graphite//$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$
~150 Wh/kg$_{battery-system}$

very long-term (???)
lithium-air batteries
→ no stable electrolyte yet

≈250 Wh$_{use}$/kg expected for mid-term

from: Gallagher, Goebel, Greszler, Mathias, Oelerich, Eroglu, Srinivasan; *Energy Environ. Sci. 7* (2014) 1555

Range of LIB-Powered Vehicles (BEVs)

assumptions:

- 250 Wh/$kg_{battery\text{-}system}$
- 80% energy utilization,
  95% discharge efficiency
- 20 kWh per 100 km
  (BMW i3 nominally 13 kWh per 100 km)

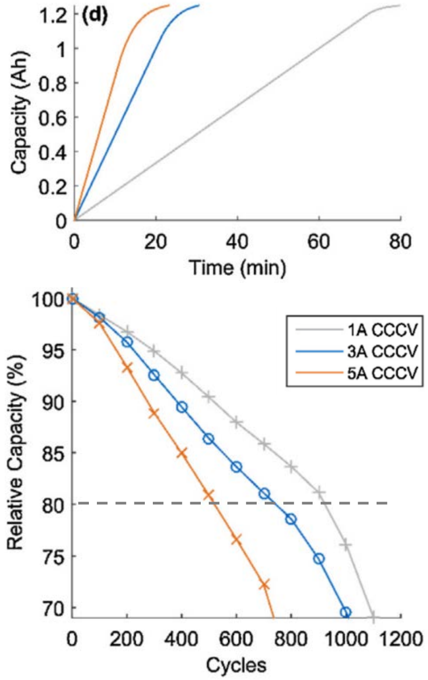
driving range	**100 km**	**200 km**	**300 km**
required net energy **[kWh_{net}]**	20	40	60
name-plate energy **[$kWh_{name\text{-}plate}$]**	~26	~53	~79
Battery-system weight **[kg]**	~105	~210	~315

from**:** Gröger, Gasteiger, Suchsland; *J. Electrochem. Soc. 162* (2015) A2605 | Franke, Krems; *Transport Policy* 30 (2013) 56

BEV Fast-Charging Challenges

fast-charging issues

- **rapid charging** (<20 min) reduces **battery life** due to lithium plating
  → compromises safety
  → lower capacity and round-trip efficieny



electrical power supply requirements
- example for Munich in 202X -

200,000 BEVs

↓ **~5% charge at same time**

10,000 BEVs charging

↓ charging with **120 kW** Tesla super-charger

10,000 x 120 kW

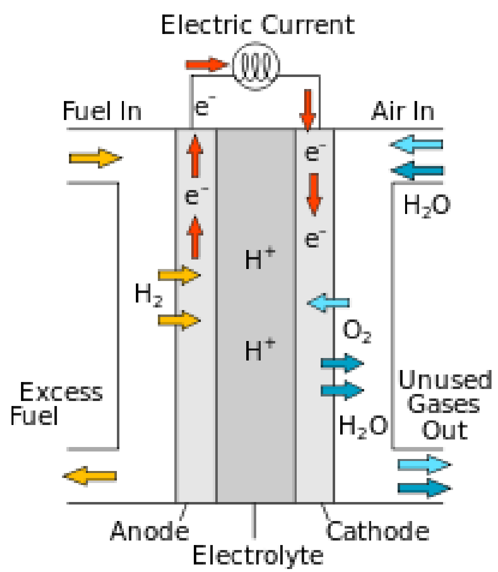
↓

1.2 GW

(~ installed power supply of Munich)

from: Keil, Jossen; *J. Energy Storage* (2016) 125

- ❑ BEV Technology Roadmap / Constraints
- ❑ FCEVs Status & Projections
- ❑ Material Constraints for Large-Scale PEM-E
- ❑ Comparison ICE ↔ BEV ↔ FCEV



FCEV vs. BEV Cost Projections

- **FCEV assumptions:**
  - 100 kW_{net} and 5kg H_2 for 500 km range
  - current cost projected for 500,000 FCEVs/year

  from: D. Papageorgopoulos, “Fuel Cell Program“, as well as from N.T. Stetson, “Hydrogen Storage Program Area“, presented at the 2015 DoE Annual Merit Review

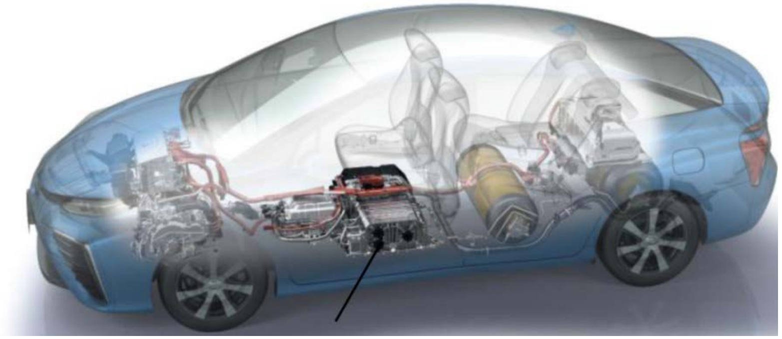
	projected current cost [k$]	projected long-term cost [k$]
fuel cell system	≈5.5	≈4.0
H_2-tank system	≈2.8	≈1.7
prop. battery (2kWh/35kW)	≈1	≈0.8
H_2 fuel cell + tank system	≈9.3	≈6.5

⇒ **cost of 500 km FCEV projected to be comparable to 200 km BEV**

Fuel Cell Electric Vehicle Constraints

- **500 km & refill in <4 min.**

Toyota *Mirai*



from: Konno et al., *SAE Int. J. Alt. Power 4(1)* (2015)

- **H_2 generation & distribution infrastructure**
  → more complex than for BEVs…

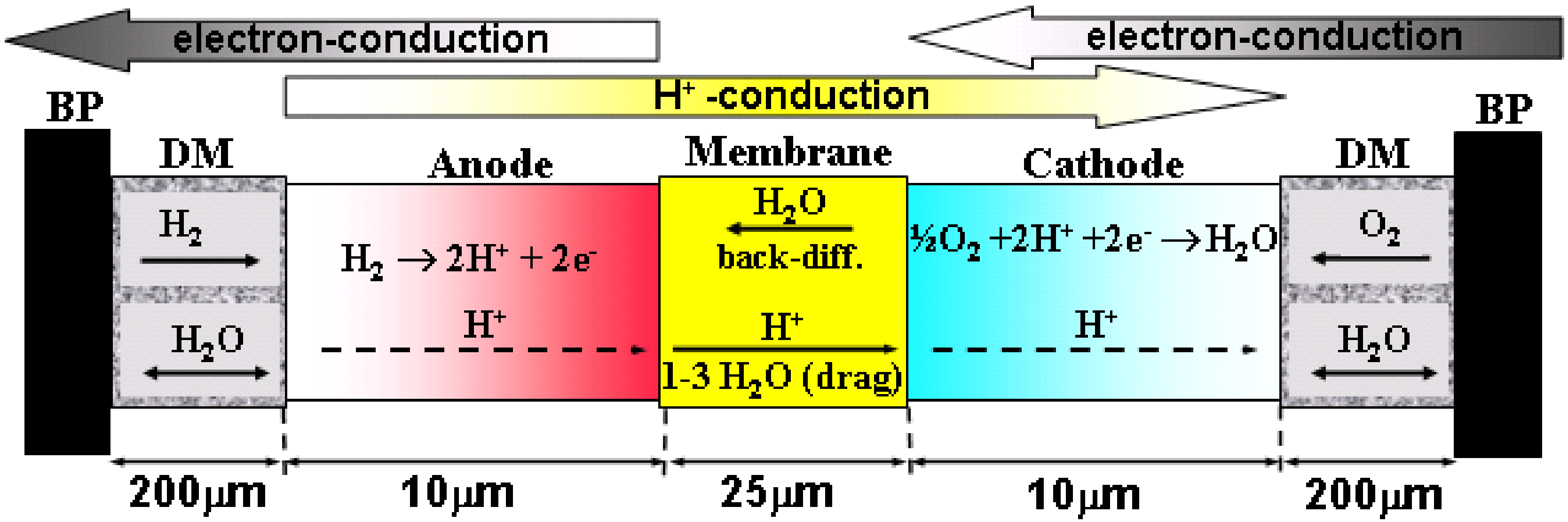
- **catalyst cost & supply (100kW car):**

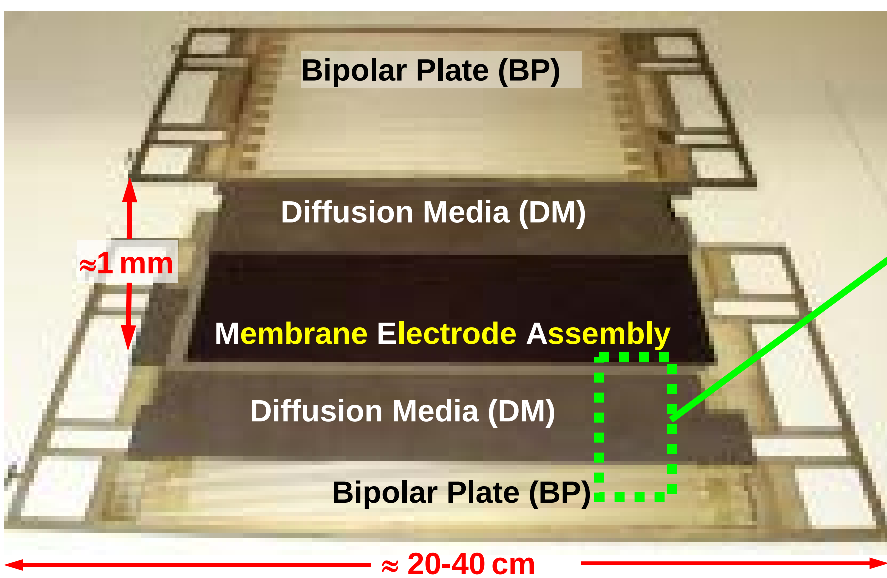
  current: ≈0.3 g_{Pt}/kW ≡ 30g_{Pt}/car in Toyota *Mirai*
  → ≈5-10x vs. automotive emission catalysts

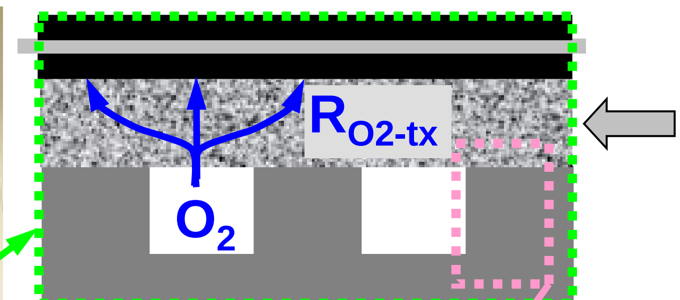
  long-term: <0.1g_{Pt}/kW ≡ <10g_{Pt}/car
  → large-scale viability

- **approaches to get to <0.1 g_{Pt}/kW ?**

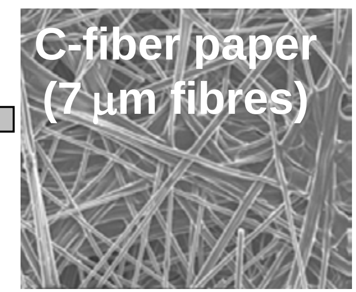
H_2/Air Fuel Cell Components



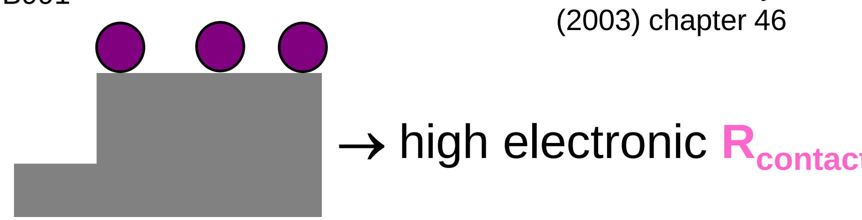




Baker, Caulk, Neyerlin, Murphy; *J. Electrochem. Soc. 156* (2009) B991

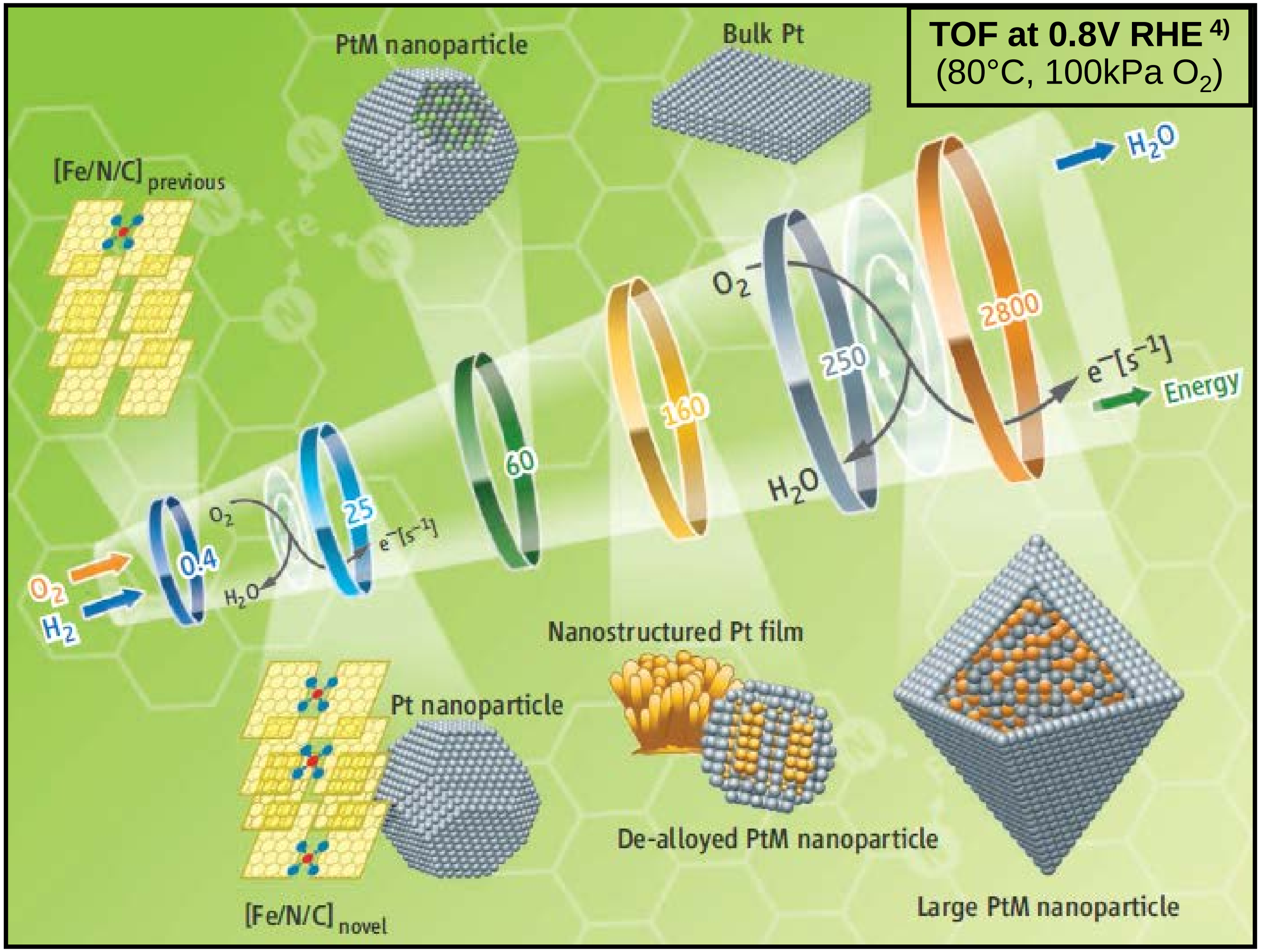


Mathias, Roth, Fleming, Lehnert; in: *Handbook of Fuel Cells*; Wiley, *vol. 3* (2003) chapter 46



PEMFC O_2 Catalyst Options – 2009

- **options envisaged in 2009:** ultra-high activity Pt-based **or** Pt-free



from: Gasteiger & Marković; *Science 324* (2009) 48

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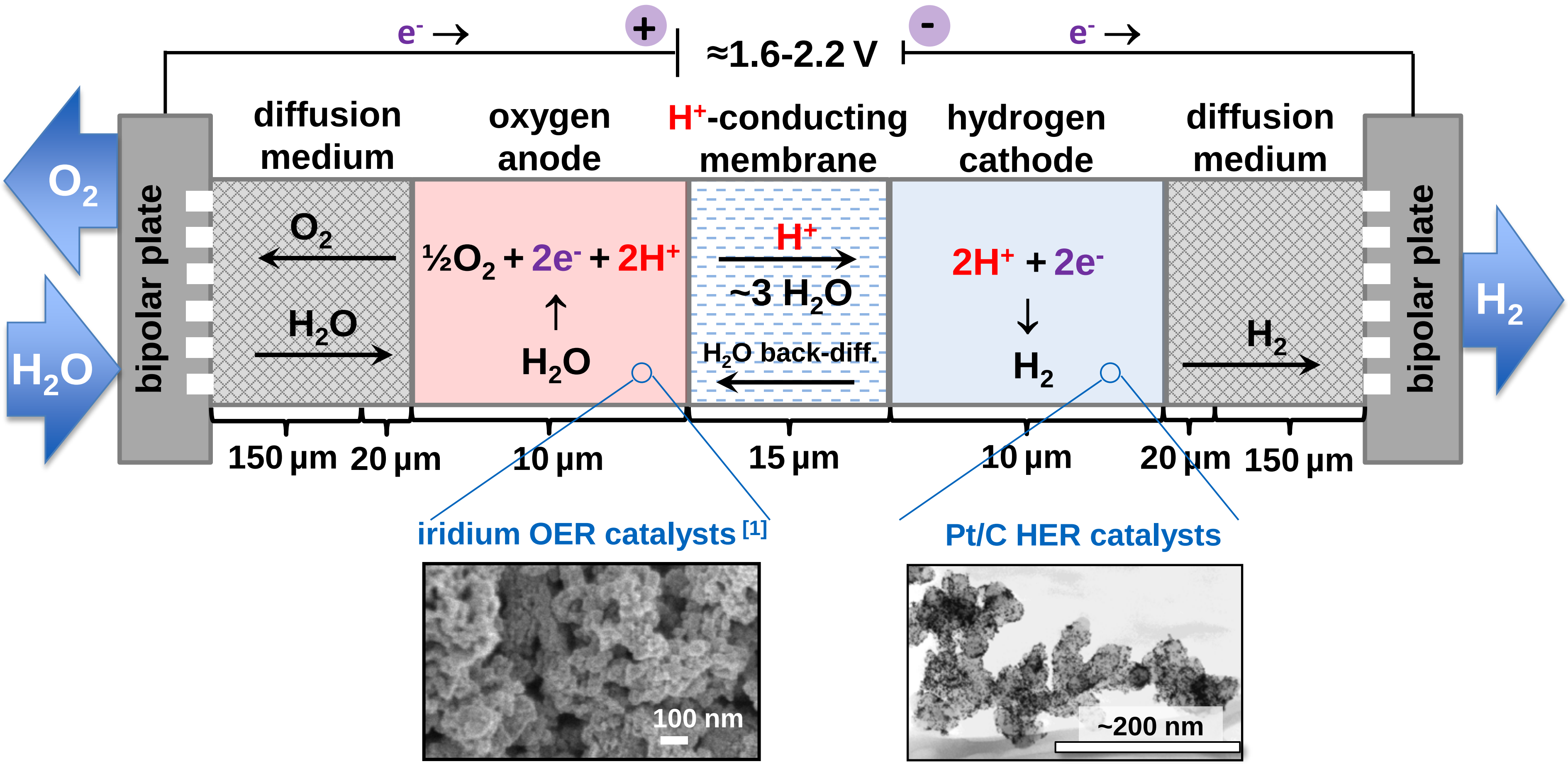
Principle of a PEM Electrolyzer

- analogous to PEMFC, except for catalyst & DM in O_2 evolution compartment
  → advantage over KOH-based electrolyzers: differential H_2 pressure up to 100's of bars



→ only ≈4 tons/year [2]

→ same as in PEMFC

[1] Carmo, Fritz, Mergel, Stolten, *Int. J. Hydrog. Energy 38* (2013) 4901
[2] Babic, Suermann, Büchi, Gubler, Schmidt, *J. Electrochem. Soc. 164* (2017) F387

Global Iridium Requirement for PEM-E

global decarbonization of transportation:

- global fossil fuel energy : 10^{20} Joule (2016) [1] ≡ **700 Mio.t_{H2} / year** (HHV)
- H_2O electrolysis at 1.79 V (≡83%$_{HHV}$): ≡ **3800 GW**
- coupling with fluctuating renewable energy sources (e.g., ≈1/3 annual utilization of wind energy)
  → required electrolyzer power capability: **≈12000 GW**

iridium supply / need:

- global iridium production: ≈**4 t_{Ir}/year** [2] → allow 50% for use in electrolysis
- today's Ir-specific power density: ≈**0.4 g_{Ir}/kW**
  → annual electrolyzer installation limit: **≈5 GW/year**

- for 12000 GW until 2100 → ~**150 GW/year**
  → requires lowering of the Ir-specific power density to ~**0.01 g_{Ir}/kW** to even consider global fuel decarbonization by PEM electrolysis

[1] Key World Energy Statistics by the International Energy Agency (2017)
[2] Babic, Suermann, Büchi, Gubler, Schmidt, *J. Electrochem. Soc. 164* (2017) F387

Water Electrolysis – Energy Demand

- **decarbonization of transportation (example Germany)**

<u>tranportation:</u> 0.025 $\cdot 10^{20}$ J transportation fuels (DE, 2013[1)]) ≡ **17 Mio.t_{H2} / year** (HHV)

→ if via H_2O electrolysis at 1.79 V (≡83%$_{HHV}$): ≡ **96 $GW_{electr.}$**

→ compares to **≈90 $GW_{peak\text{-}electr.}$** from renewables (DE in 2015[2)])

→ would require a ≈3-5x expansion of installed renewable power

[1)] <u>from:</u>: http://www.umweltbundesamt.de/sites/default/files/medien/384/bilder/dateien/2_abb_entwicklung-eev_2015-10-05.pdf

[2)] <u>from:</u> Bundesnetzagentur: https://www.energy-charts.de/power_inst_de.htm

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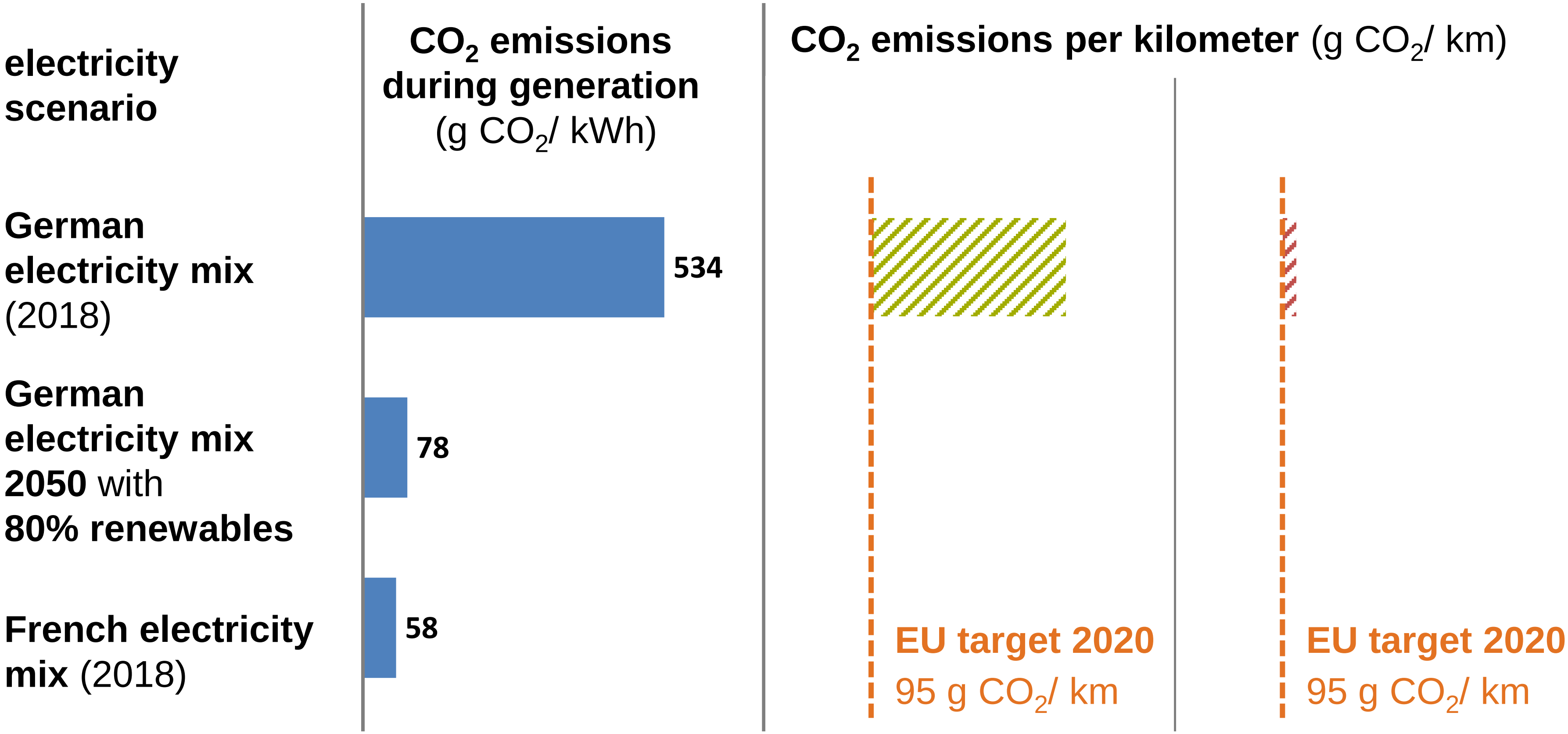
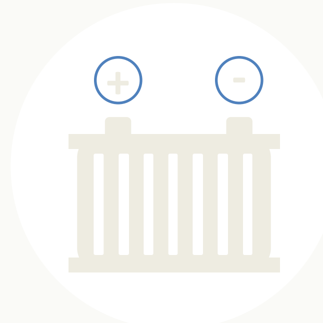
CO_2 Generation per Driven km

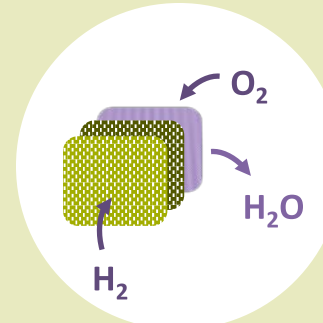


- production of **1 kg H_2** requires ≈**50 kWh** (≡ ca. 1.8 V)
- **1 kg H_2** in an FCEV correspond to a range of ≈**100 km** → **≡0.5 kWh/km**
- in comparison: **BEV** requires **≈0.2 kWh/km**

source: German environmental agency

TAKE-HOME MESSAGE 2:
Economical & Ecological Comparison

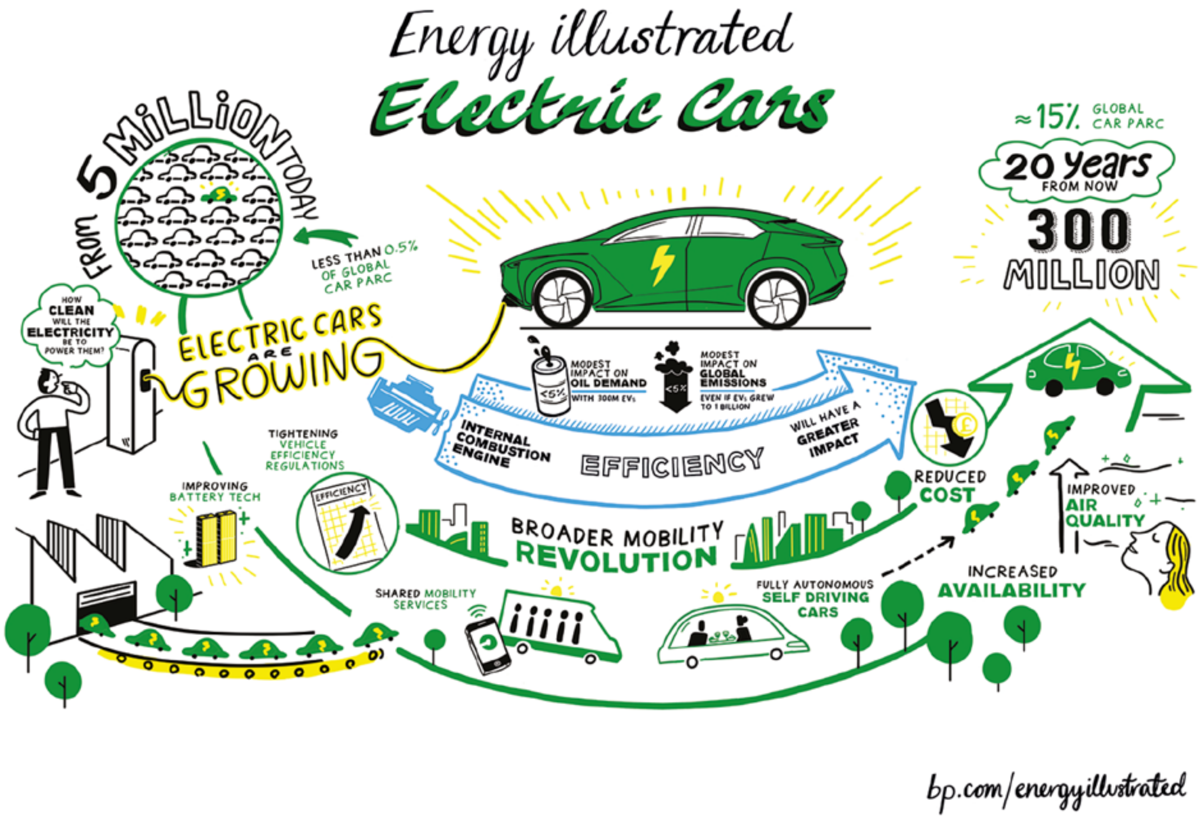




	gasoline/diesel	battery	fuel cell
driving range *(in km)*	1000 km	200-300 km	500-600 km
time for charging *(in min)*	< 3 min	<20 min	< 4 min
critical resources	fossil fuels	cobalt	platinum, iridium

note: values for mid-size cars; costs for Germany

THE (R-)EVOLUTION OF THE TRANSPORT SECTOR



economic & ecological comparison of ICE vs. battery or fuel cell vehicles

→ requires consideration of both vehicle technology & energy generation

→ resource availability (Co, Pt, Ir) critical factor for large-scale implemtability

DISCUSSION?

Acknowledgements

ENERGY FOR MOTION

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