CARA Think Tank meeting “Future fuels for heavy duty vehicles”
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«Future Fuel for Road Freight»

Techno-Economic & Environmental Performance Comparison of GHG-Neutral Fuels & Drivetrains for Heavy-Duty Trucks

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Structure

I. Introduction to the study and context

II. Setting the scene

III. Fuels & infrastructures (well-to-tank)

IV. Vehicle & drivetrains (tank-to-wheel)

V. Synthesis (well-to-wheel)

VI. Recommendations for deployment

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I. Introduction

The study partners

«Truck CO_2» study – A three partners' joint effort

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Hinicio

FONDATION TUCK
The Future of Energy

Fuels & drives
Techno-economics
Environment

Regulatory
Strategy

Sponsor
Sounding Board

LBST and HINICIO joined forces for this study

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- Strategic consultants specialized in sustainable energy and mobility
- Long experience with policy makers, public entities and industry
- Multidisciplinary team approach: engineers, economists, energy and transport policy experts.
- Long working relationship between our two cabinets with more than 30 joint assignments

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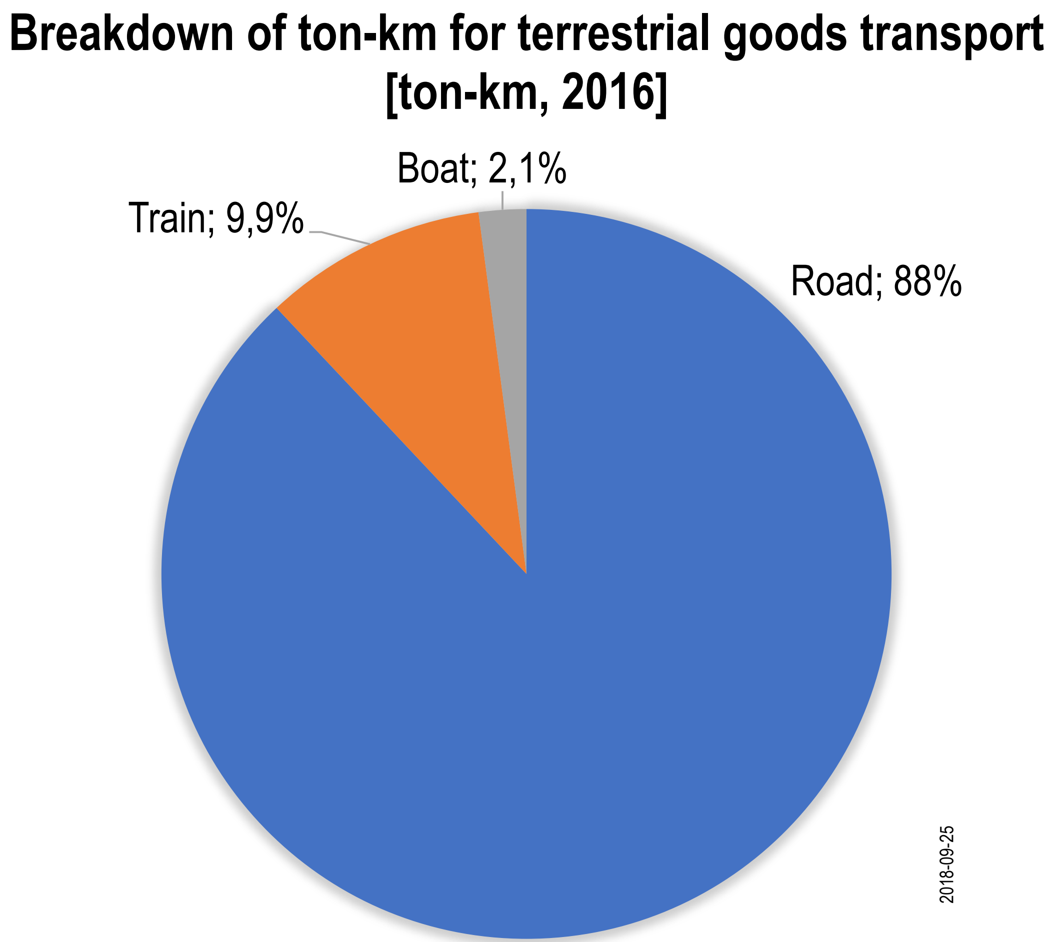
II. Setting the scene

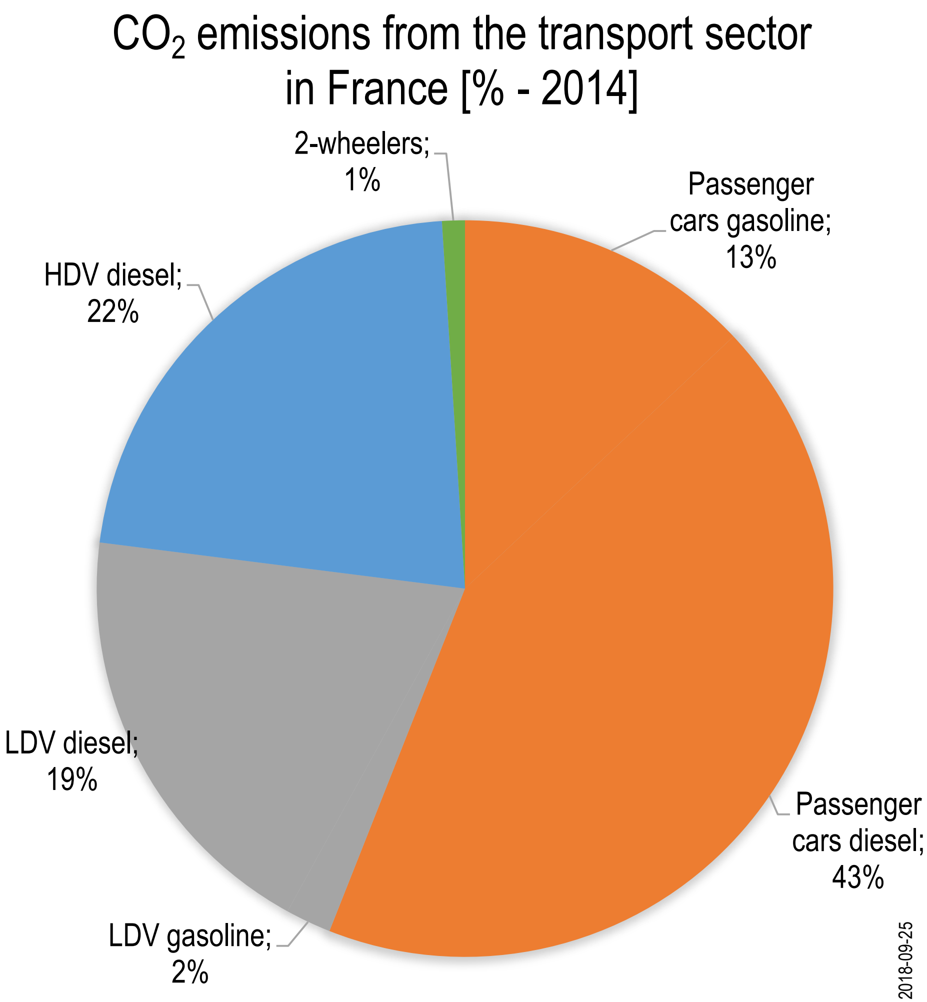
Understanding today‘s picture

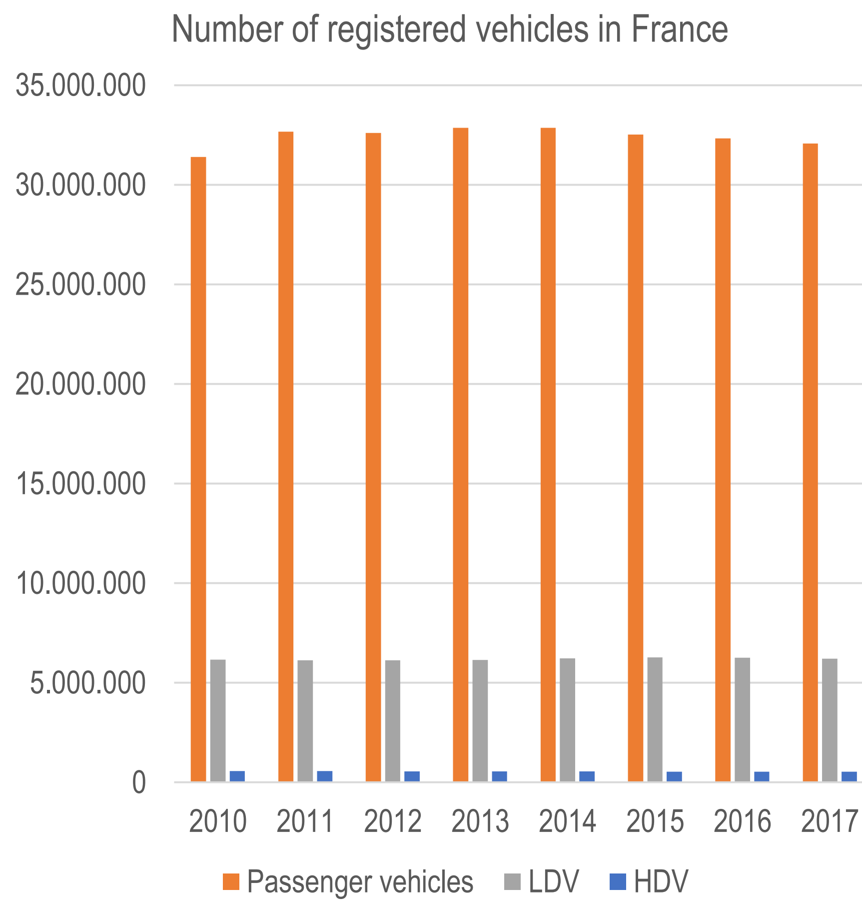
Today, the transport of goods in France is in majority done by road



Source: Chiffres clés du transport, Edition 2018, Commissariat général au développement durable, Mars 2018

Heavy duty vehicles are the elephant in the room





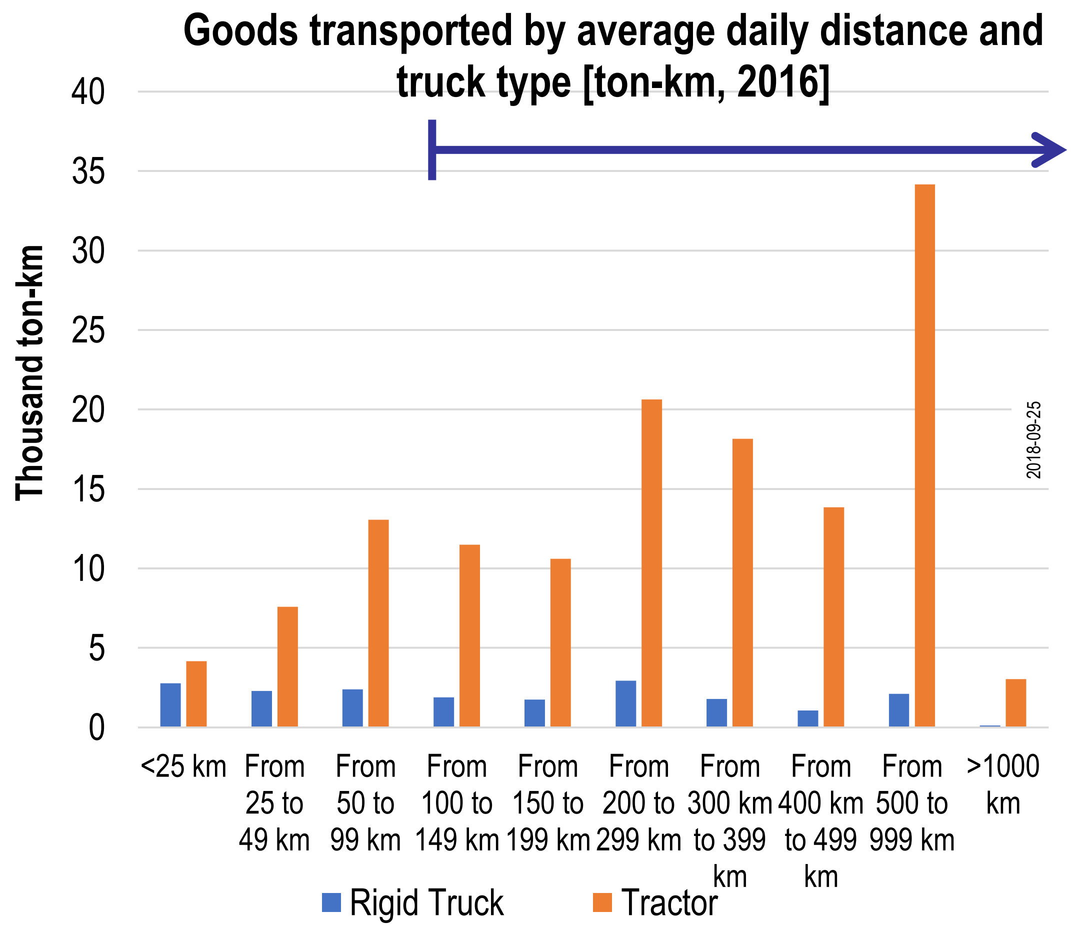
Source 1: CITEPA, Inventaire des émissions de polluants atmosphériques et de gaz à effet de serre en France, April 2016

Source 2: Répertoire statistique des véhicules routiers (RSVERO), Ministère de la transition écologique et solidaire, visited on 25/09/2018

The long-haul tractors are the biggest GHG contributors

Long-haul (>100km) tractors because

- Tractors transport most goods
- The majority of the goods in France are transported on long-haul distances (> 100km)



Source: Enquête transports routiers de marchandises (TRM) 2017, Ministère de la transition écologique et solidaire, visited on 25/09/2018

Trucks have in average not become more fuel efficient; the range of fuel consumption has increased

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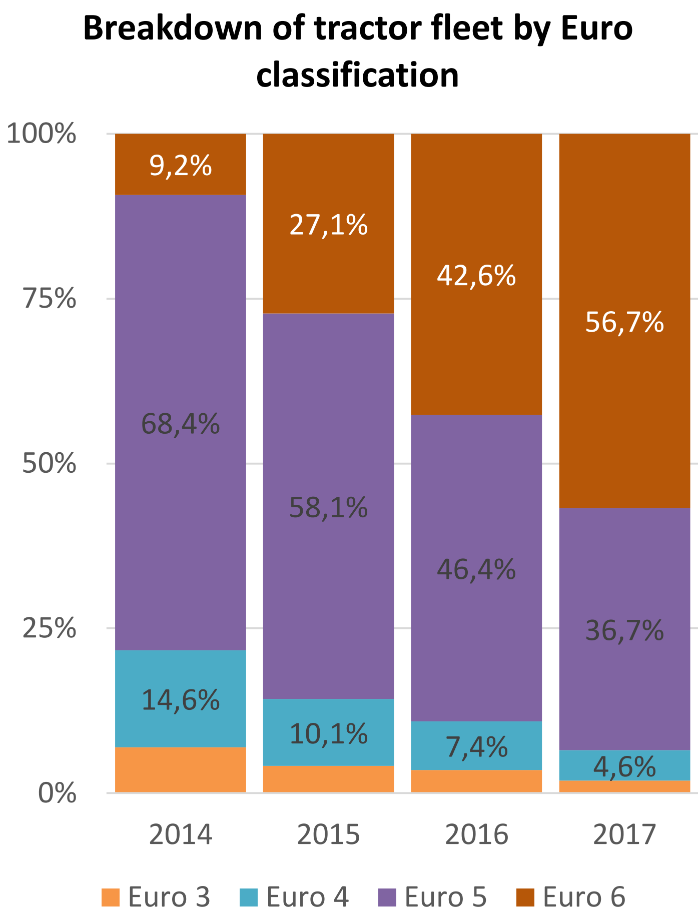

Source: Comité National Routier, Enquête longue distance 2017, April 2018

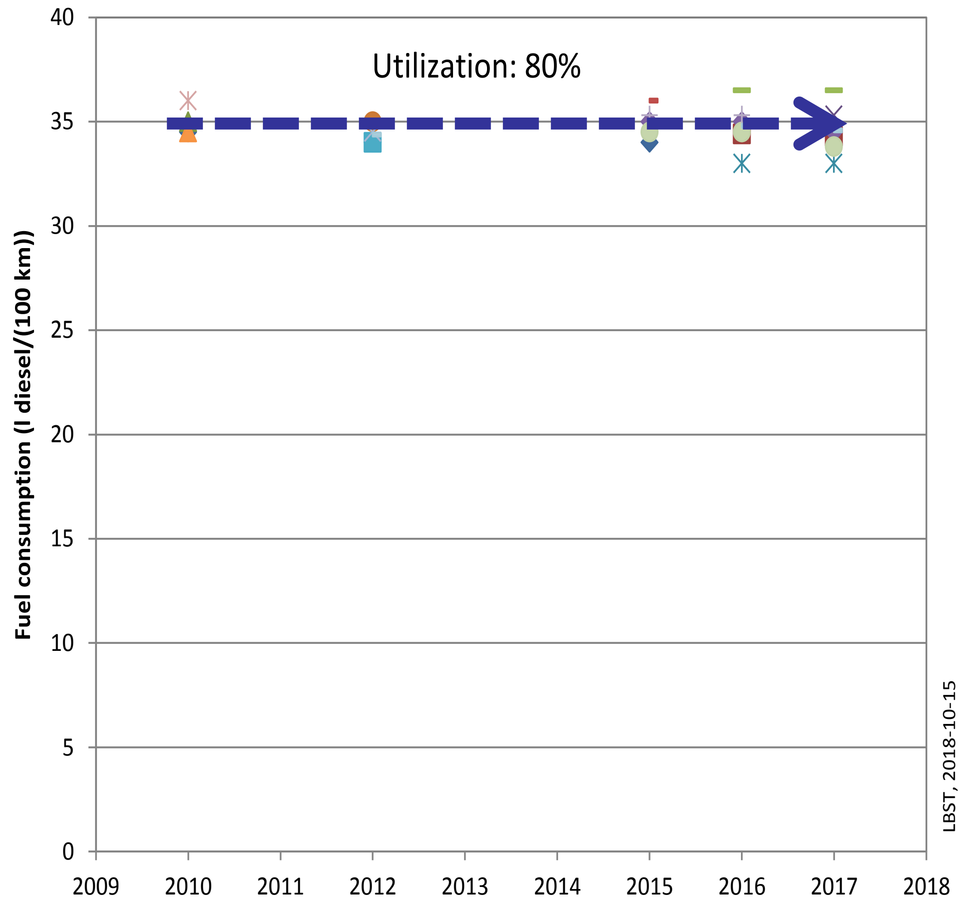

Image: LBST; Data: Lastauto Omnibus

An increase in GHG emissions is possible if no action is undertaken

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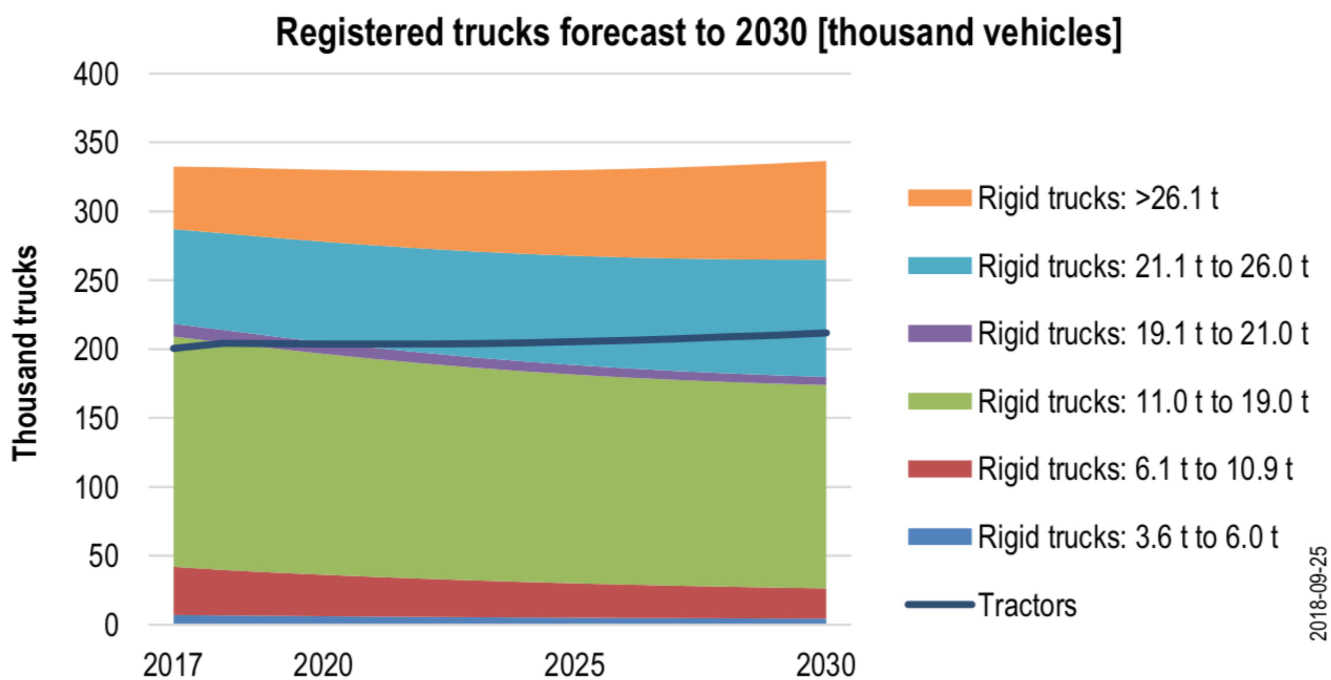
What impact on GHG emissions from until 2030 if nothing is done?



Source: Hinicio forecast; Source for CAGR: Trends in the truck & trailer market, market study, Roland Berger, August 2018 ; Source for 2017 vehicle registration: Enquête transports routiers de marchandises (TRM) 2017, Ministère de la transition écologique et solidaire, visited on 25/09/2018

Long-haul/inter-urban tractors is the focus of this study

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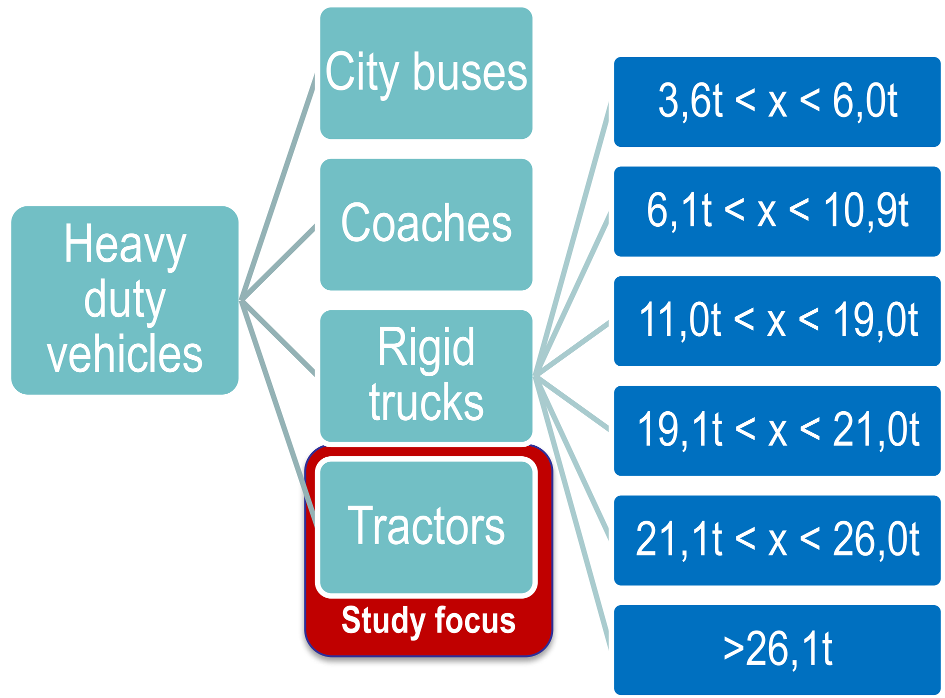
Long-haul tractors because

- Small fleet compared to other vehicles
- The majority of the goods in France are transported on long-haul distances
- The most GHG contributor in transport

Study objective

- Determine the most robust fuel/powertrain options to achieve deep-dive GHG reduction



Only regulation implemented in the mid to long-term will drive clean drivetrains

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Current EU and French environmental regulation in favour of zero or low carbon tractors:

- **Short-term:**
  - **No regulatory framework** at the EU level nor at the French national level is **favouring the adoption** of zero-emission long-haul tractors.
- **Mid to long-term:**
  - The **fuel efficiency standard** for HDVs,
  - the **RED 2**
  - **Eurovignette**

OEMs will need to sell LC or ZE trucks starting in 2025

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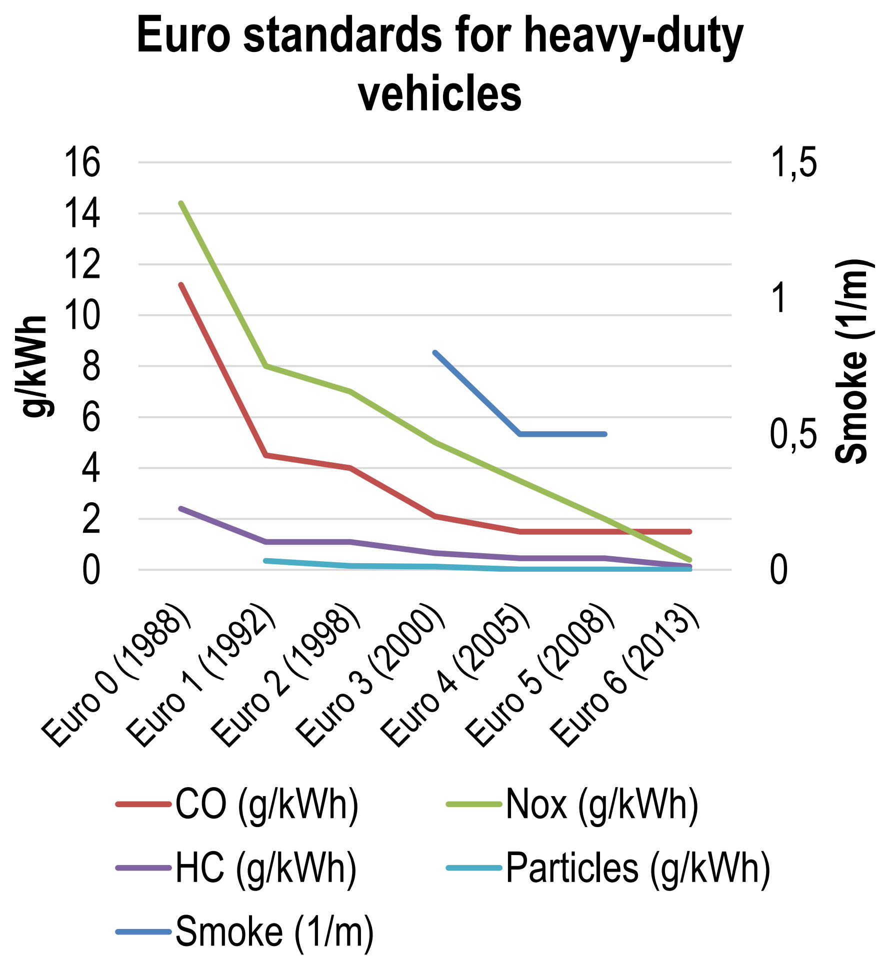
Current regulation

- Euro emissions standards
  - ➢ Big benefit on local pollution
  - ➢ No impact on GHG emissions

Upcoming regulation

- CO_2 emission monitoring of trucks
- New emissions standards for HDVs:
  - ➢ **-30% CO_2 by 2030** (compared to 2019)
  - ➢ **5% sales market share for low-carbon or zero emission trucks by 2025***
  - ➢ 20% by 2030*



* Still in discussion between the parliament and the commission at the time of writing

Source: TransportPolicy.net, European heavy-duty vehicles emissions, visited on 26/09/2018

The recast of the Renewable Energy Directive (RED 2) will be the biggest driver of change from 2023-25 onward

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European targets

Renewable Energy Directive 2

- **14% of renewable fuel** in transport energy consumption by 2030
- Specific GHG emissions criterias for each type of fuels
  - - 70% GHG for renewable fuels of non-biological origin*
  - - 65% GHG for biofuels**

GHG reduction

- 20% by 2020
- >40% by 2030
- 80-95% by 2050

Increase in renewable energy consumption

- 20% by 2020
- >32% by 2030*
- 14% of renewable energy in transport energy consumption by 2030

* Methodology still to be determined by the European Commission by delegated act as of writing of this study

** For production installations starting their operations after 2021. Otherwise, 60% compared to 94 gCO2/MJ with installations starting their operations after 2015. Otherwise, 55%.

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What about highway taxation of heavy duty vehicle circulation?

- Should take into account GHG emissions
- **Effective measure to push clean vehicles n the road**
  - **E.g., today it is more economical to operate a H2 (clean) fleet than pay road taxes in Switzerland**
- The **Eurovignette directive aims at** *
  - Taking into account CO2 emission for the toll pricing
  - Reducing by 75% the toll cost for zero-emission vehicles

* The Eurovignette directive is still under heavy debate in the Parliament on other topics than CO2 emissions so date of implementation is still uncertain at the moment of writing.

Fuels & powertrains investigated in this study

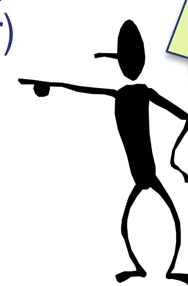
	Fuel	Pathway	Drivetrain
Reference	Diesel from crude oil	EU mix / fossil fuel comparator	ICE
	CNG / LNG from natural gas	EU natural gas mix, pipeline transport, onsite compression/liquefaction	
	Hydrogen from natural gas	EU natural gas mix, pipeline transport, onsite steam-methane reforming	FCEV
	Electricity	French grid mix, onsite buffer electricity storage	BEV + catenary
Low C	Diesel via power-to-liquid (France domestic)	Nuclear power, Fischer-Tropsch synthesis, refining	ICE
Renewable	Diesel via power-to-liquid (France domestic)	RE mix (wind, solar), Fischer-Tropsch synthesis, refining	ICE
	Diesel via power-to-liquid (import from MENA)	RE mix (wind, solar), Fischer-Tropsch synthesis, refining	
	Methane via power-to-CH_4 (France domestic)	RE mix (wind, solar), methanation, compression/liquefaction	
	Methane via power-to-CH_4 (import from MENA)	RE mix (wind, solar), methanation, compression/liquefaction	
	Hydrogen via power-to-H_2	RE mix (wind, solar), onsite electrolysis	FCEV
	Electricity	RE mix (wind, solar), onsite buffer electricity storage	BEV + catenary

Our study approach – What we did, and what not

- **Fundamental analysis** for a strategic assessment of robust long-term truck propulsion options (2030) against the backdrop of the Paris Agreement (2050). For this, short-term performance and opportunities (2020) are depicted and discussed on an equal basis.
- ASIF priority for mobility measure:
  - Avoid (sufficiency)
  - Shift (modal split)
  - Improve (efficiency)
  - Fuel (renewable energy)

Focus: efficiency + renewables

- Costs are calculated on a **full cost basis**, i.e. excluding taxes, duties, subsidies and inflation
- Electricity-based **(synthetic) fuels**
  - No biomass because of limited potential and competing uses)
  - 100 % renewable power mix from <u>new</u> capacities (wind, solar)
  - <u>New</u> nuclear capacity
  - Low-temperature electrolysis (PEM, alkaline)
  - CO_2 from air as carbon source (conservative assumption)
  - Technology learning-curves are applied (world market)



New capacities to cater new electricity demands from transport, thus avoiding competition in stationary sector and no 'carbon leakage'.

- **Vehicles** are assessed assuming a thriving world-market for each technology investigated (improved combustion engines, fuel cells, catenary, pantograph)

III. Fuels & Infrastructures

well-to-tank

Development of cost of wind and PV electricity (world)

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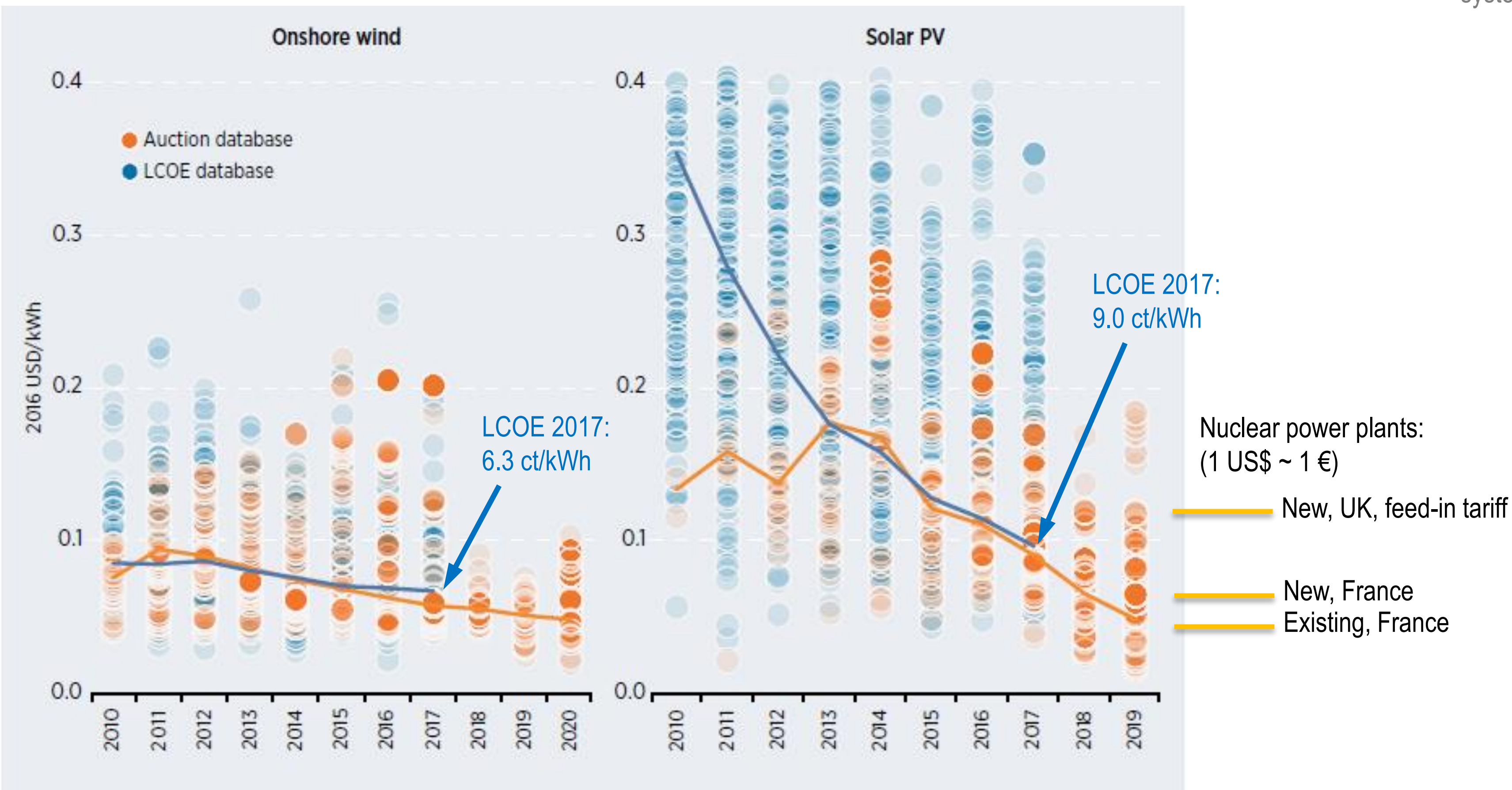


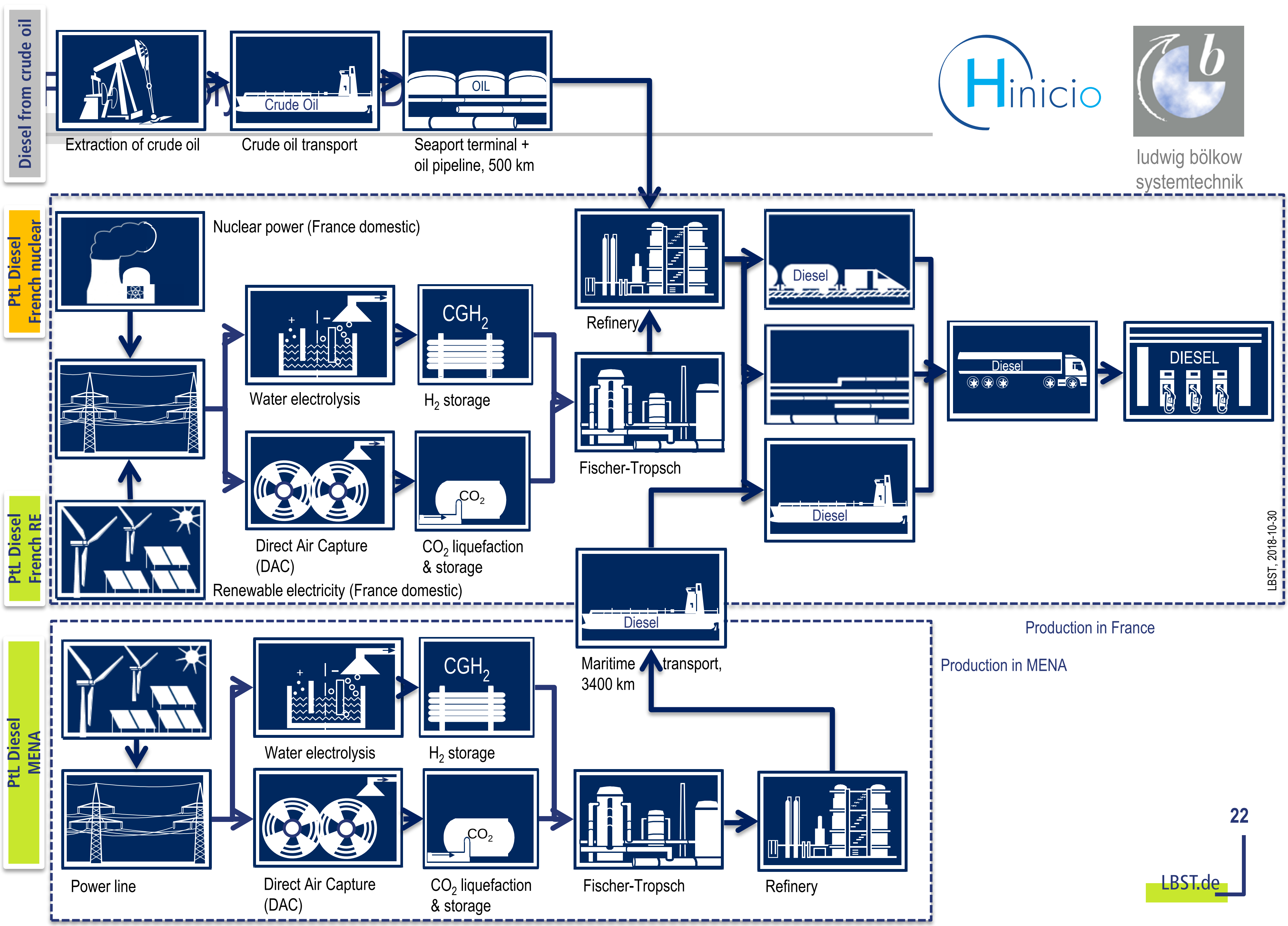
Source: IRENA Renewable Cost Database and Auctions Database.

Note: Each circle represents an individual project or auction result, while the solid line is the capacity-weighted average from each database.

Electricity generation: PV/wind hybrid 2020

- Production profiles of wind and PV are very complementary
- Conservative full annual equivalent load hours assumed in this study

		2020			2030		
		PV	Wind (onshore)	Hybrid plant	PV	Wind (onshore)	Hybrid plant
CAPEX	€/kW_p	**750**	**1570**	-	**486**	**1437**	-
O&M	€/(kW_p*yr)	10	56	-	10	56	-
Equiv. full load period	h_{eq}/yr	1340	3360	4465	1340	3360	4465
PV/wind share	%	-	-	50:50	-	-	50:50
PV/wind overlap	%	-	-	5	-	-	5
Total	**ct/kWh**			4.8			4.2



Diesel from crude oil
Crude Oil
OIL
Extraction of crude oil
Crude oil transport
Seaport terminal +
oil pipeline, 500 km
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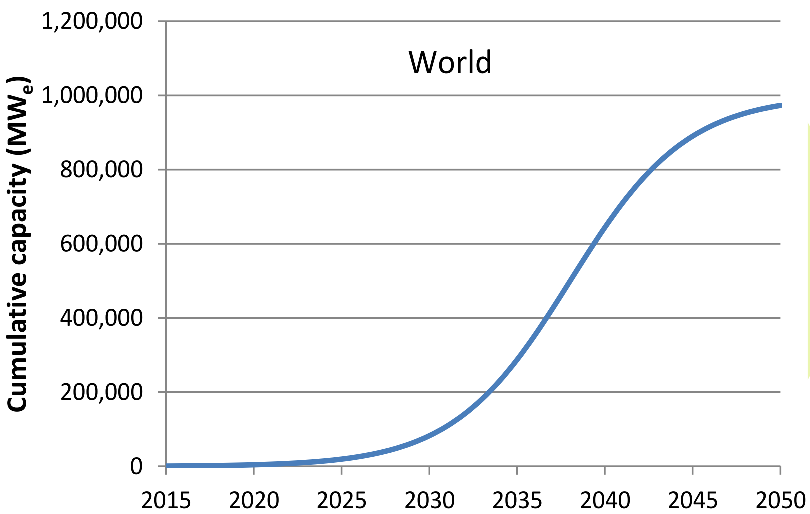
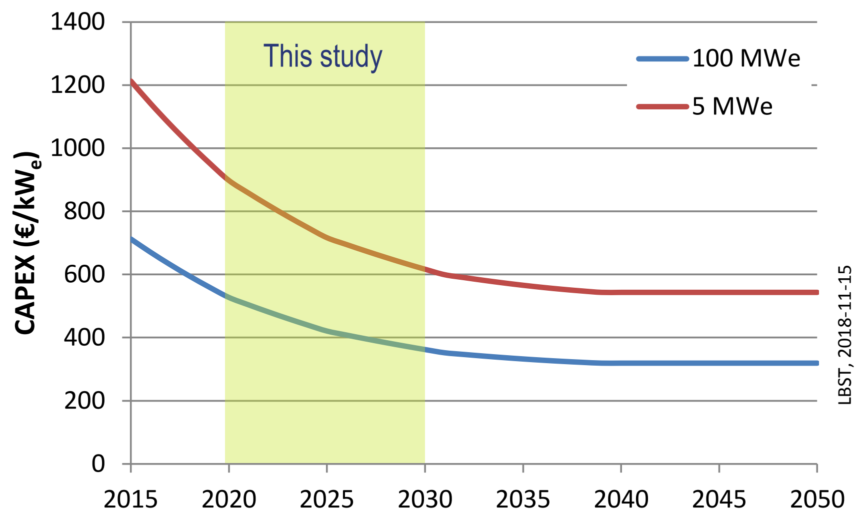
PtL Diesel
French nuclear
Nuclear power (France domestic)
CGH2
Water electrolysis
H2 storage
Refinery
Diesel
Fischer-Tropsch
DIESEL
CO_2
Direct Air Capture
(DAC)
CO_2 liquefaction
& storage
PtL Diesel
French RE
Renewable electricity (France domestic)
LBST, 2018-10-30
Maritime transport,
3400 km
Production in France
Production in MENA
PtL Diesel
MENA
Power line

LBST.de

Water electrolysis

- PEM electrolyser technology is assumed in this study
- Efficiency: **59 $\%_{LHV}$** in 2020 => **71 $\%_{LHV}$** by 2030
- CAPEX:
  - Learning curve based on global electrolyser market
  - **5 MW_e** class in 2015 based on the average of 5 quotations from manufacturers and 1 study [DLR et al. 2015], **100 MW_e** class based on [DLR et al. 2015]





Fischer-Tropsch plant

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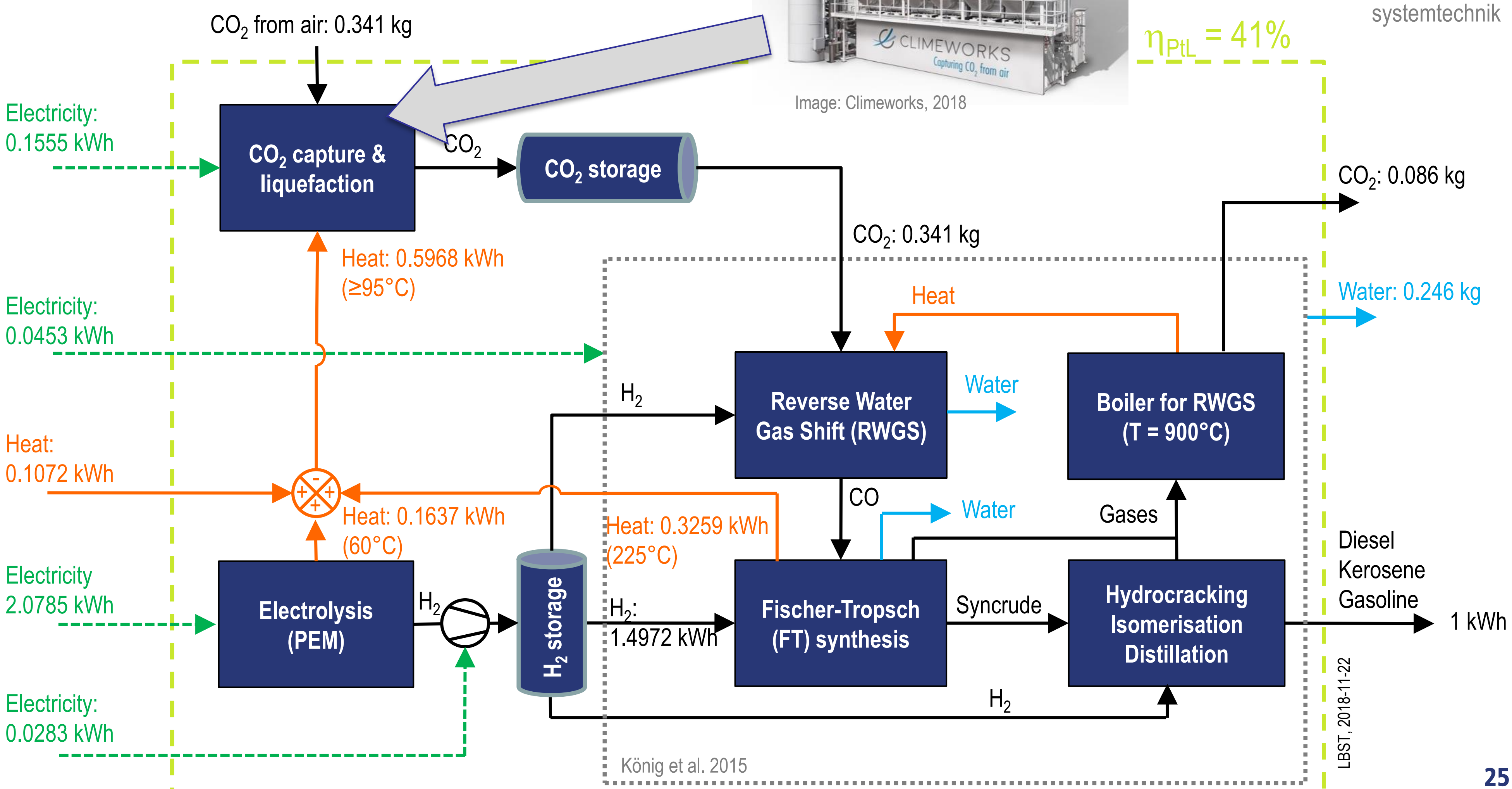
- Connected with a 500 MW_e electrolysis plant
- Capacity
  - 2020: 197 MW_{PtL}
  - 2030: 237 MW_{PtL}
- Based on data in
  - [Becker et al. 2012]
  - [König et al. 2015]
- Cost data adjusted using the chemical engineering plant cost index (CEPCI)

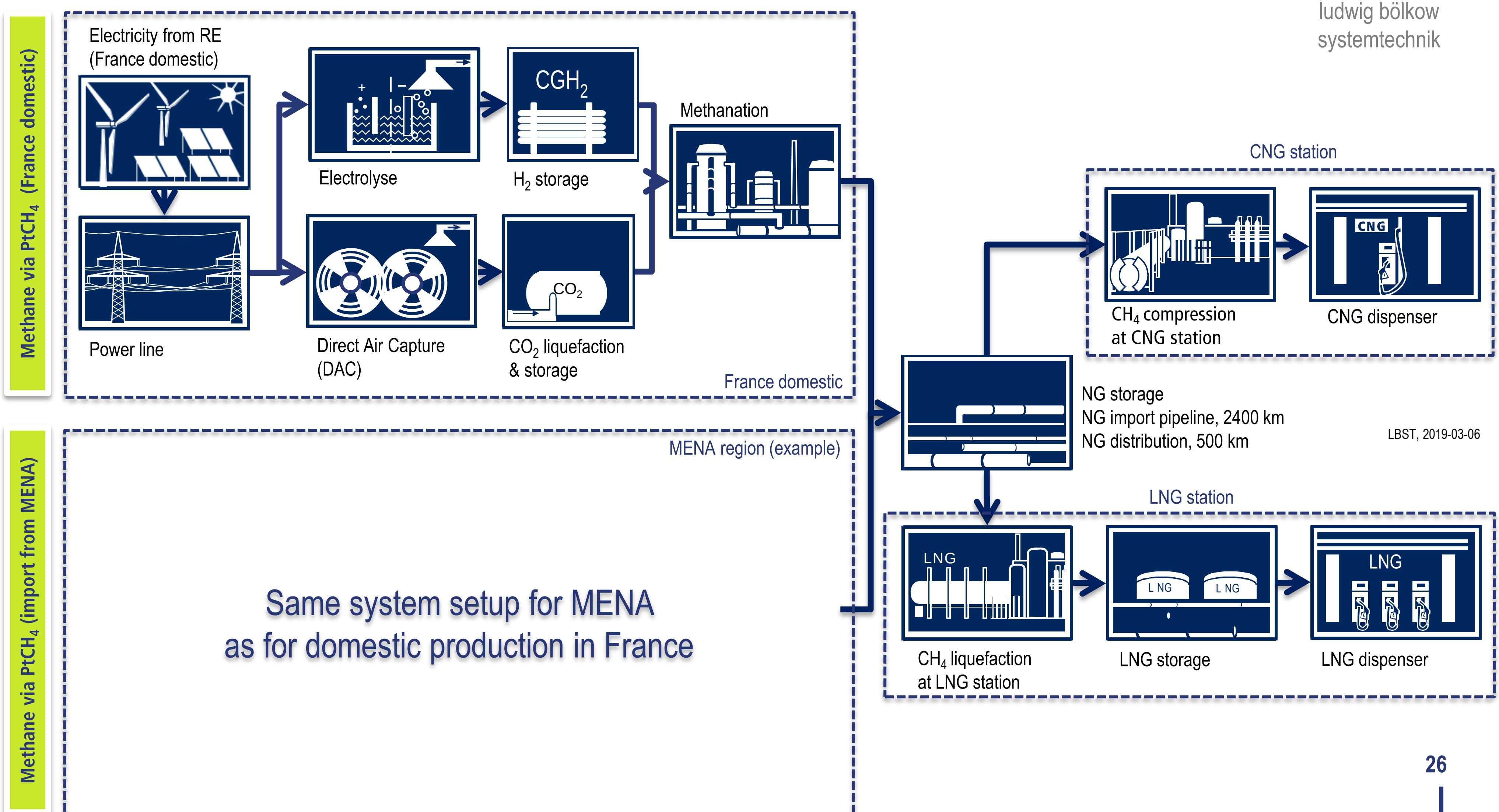
CAPEX (million €)	2020	2030
Burner	34.07	41.00
FT reactor	21.23	25.55
RWGS	4.06	4.58
PSA	5.08	5.79
Distillation	1.78	2.03
Wax hydrocracker	16.35	18.61
Distillate hydrotreater	9.14	10.41
Naphtha hydrotreater	2.50	2.85
Catalytic reformer/platformer	13.46	15.33
C5/C6 isomerization	2.24	2.55
Total installed cost	109.92	128.69
Total direct costs	**123.11**	**144.13**
Engineering & design	16.00	18.74
Construction	17.23	20.18
Legal and contractor fees	11.08	12.97
Project contingency	18.47	21.62
Total indirect costs	**62.78**	**73.51**
CAPEX total	**185.89**	**217.64**

Power-to-liquid (PtL) plant 2030

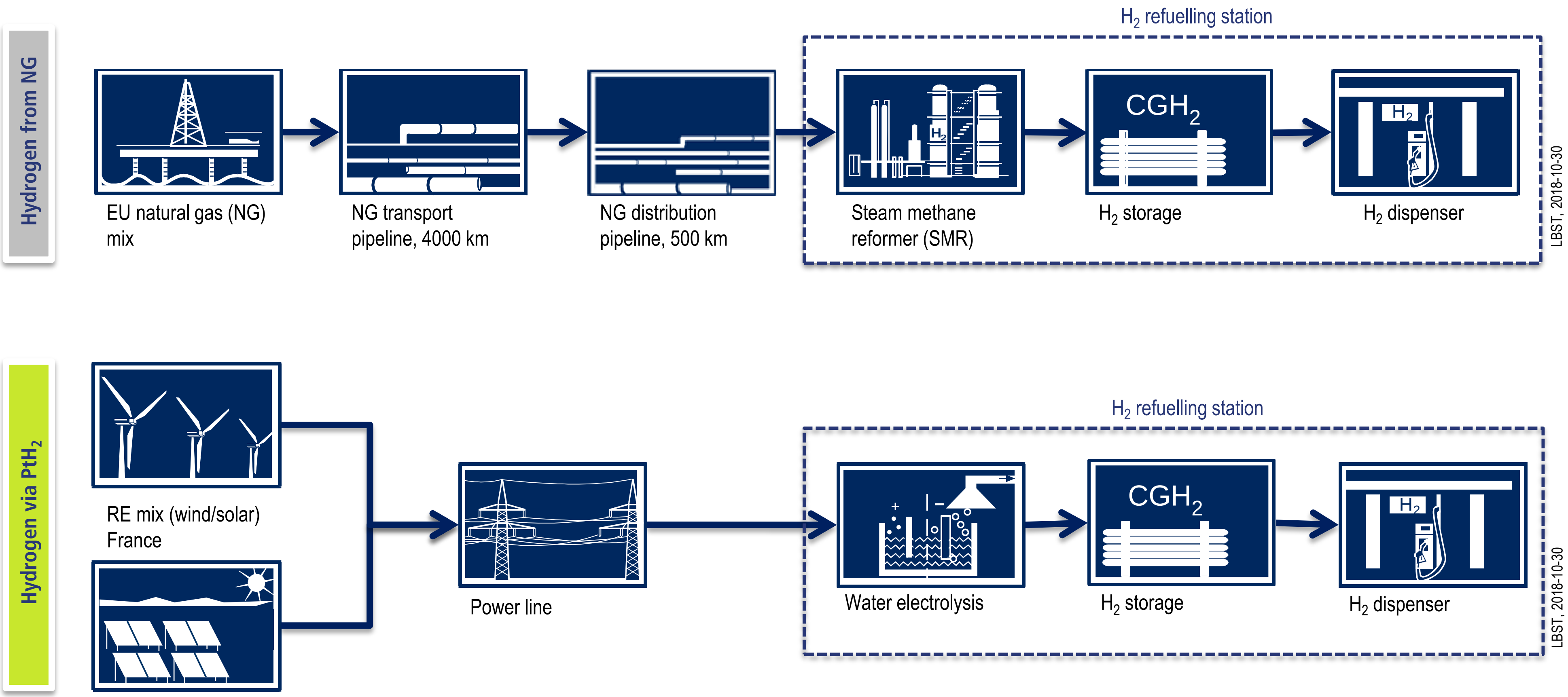
Image: Climeworks, 2018



Fuel supply chain | Methane via $PtCH_4$

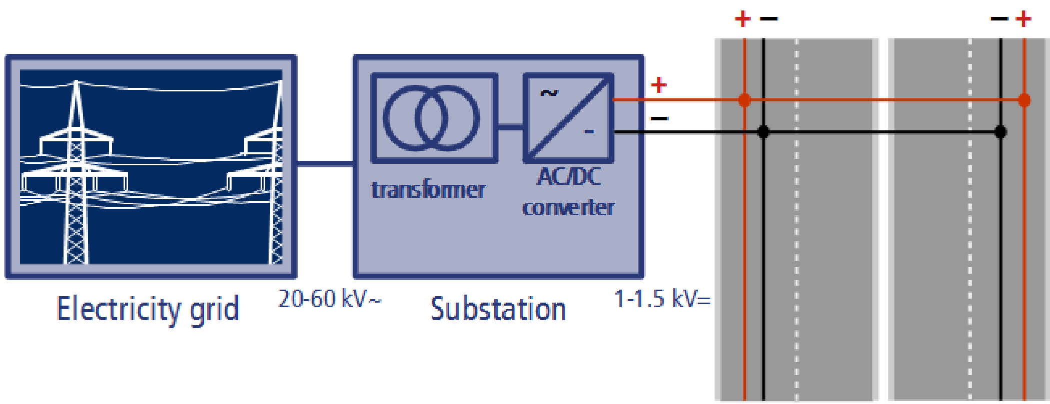


Fuel supply chain | Hydrogen (CGH_2)



Catenary infrastructure

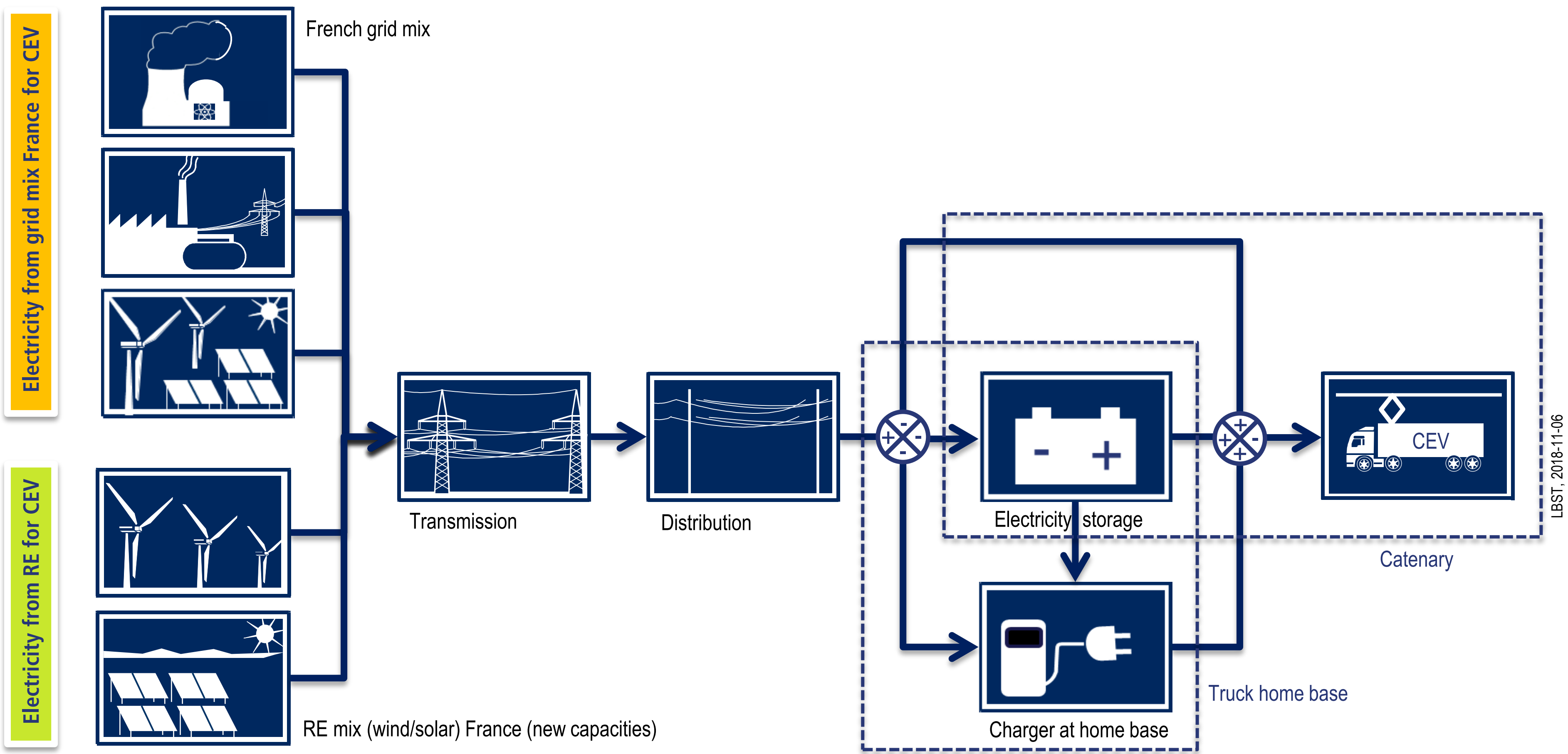
- Two overhead wires (+, – poles) per road direction
- Electricity feed-in station every 2-3 km along the road (see right container)
- Stationary electricity storage at each feed-in point for grid integration (2030)



Graphic: LBST, derived from: BMVI, Machbarkeitsstudie zur Ermittlung der Potentiale des Hybrid-Oberleitungs-Lkw, Feb'2017

Photo: PS/LBST, Groß-Dölln, 2013

Fuel supply chain | Electricity for catenary (CEV)



Catenary infrastructure

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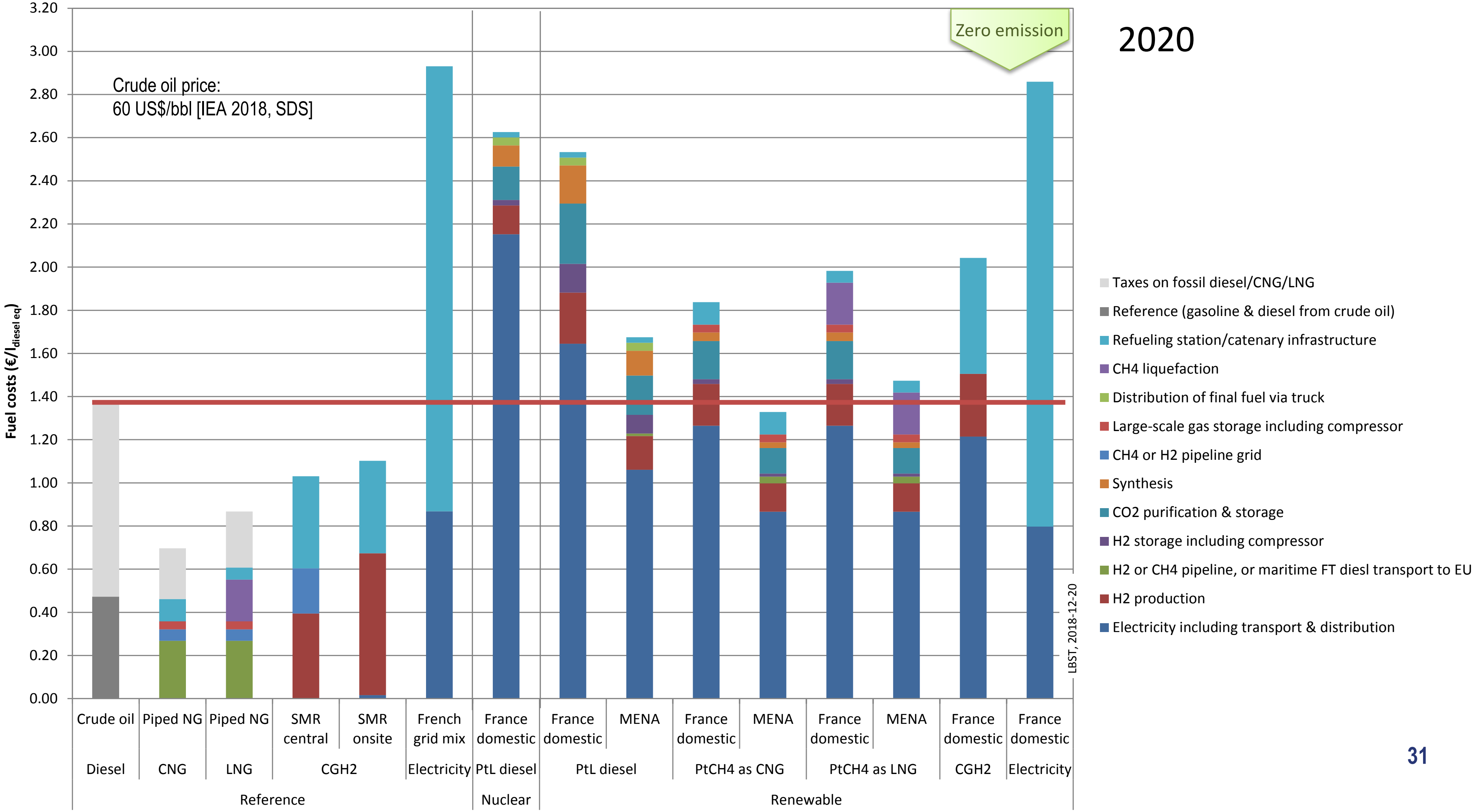
- Catenary infrastructure including stationary electricity storage in 2030

	Unit	2020 (211 km)	2030 (3900 km)
CAPEX total without electricity storage	€/(km motorway)	1,669,250	4,089.250
	billion €	0.35	15.9
Required power electricity storage	GW	-	26
CAPEX electricity storage	€/kWh	726	336
	€/kW_e	1451	672
	billion €	-	17.5
CPEX catenary infrastructure total	**billion €**	**0.35**	**33.4**

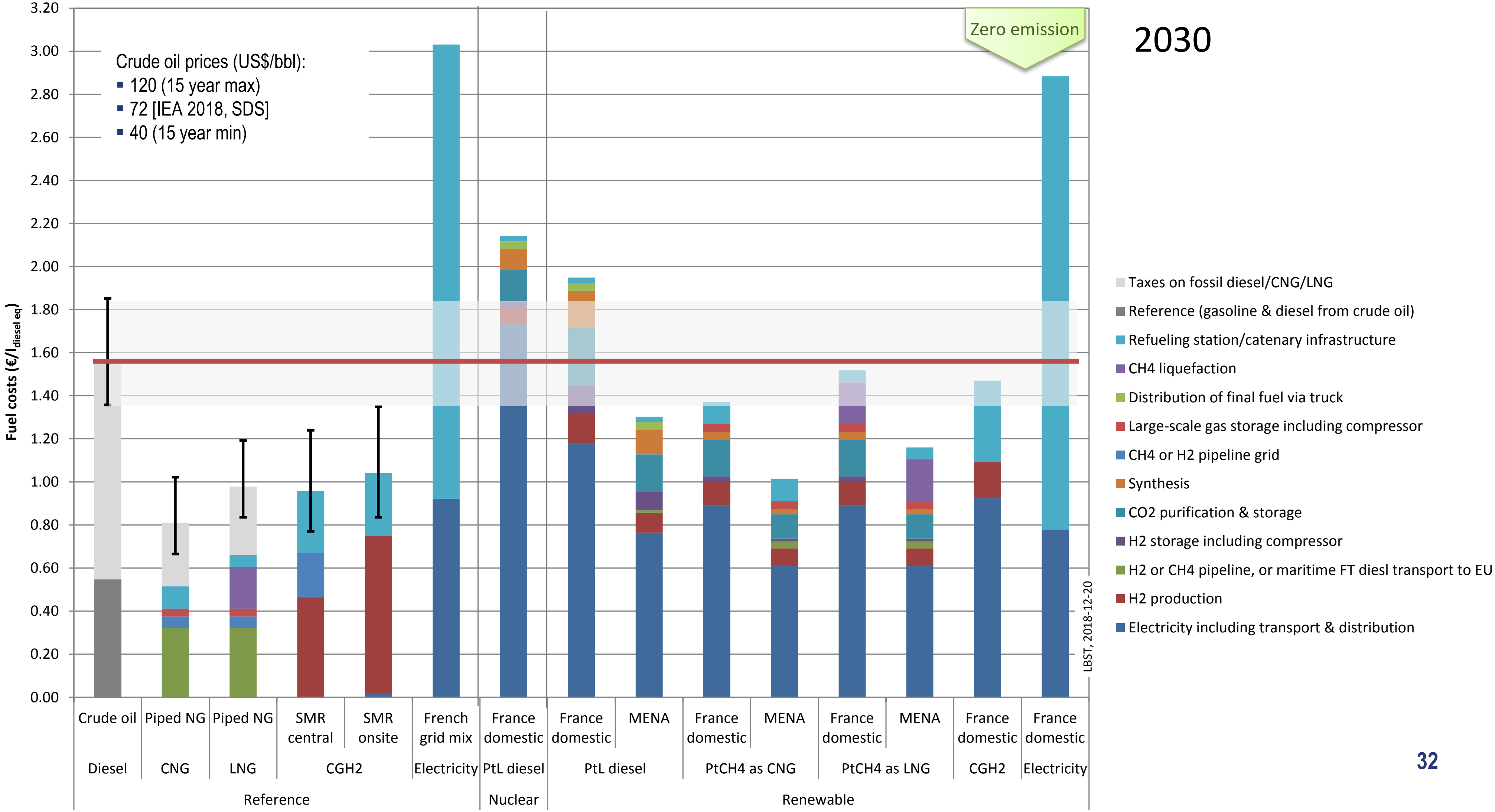
LBST, 2018-12-07

- Catenary electric vehicle (CEV) recharger at home base
  - CAPEX: ~31,000 €/CEV
  - O&M: 3400 €/yr [ABB 2017]
- Total cumulated CEV infrastructure investment: €38 billion by 2030

Fuel specific full costs 2020



Fuel specific full costs 2030



IV. Vehicle & Drivetrains

tank-to-wheel

Truck | Basic assumptions

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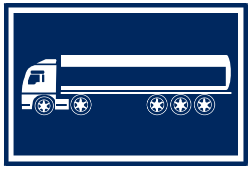
- Tractor-semitrailer
- Maximum allowable gross weight: 40 t
- Payload: 27 t
- Lifetime: 9 yr
- Mileage: 114,100 km/a



Truck | Catenary-battery-electric vehicle (CEV)

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- Two overhead wires (+, –) per road direction
- Electricity feed-in station every 2-3 km along the road
- Performance:
  - 350 kW_e electric motor
  - 200 kWh_e battery
  - 140-160 km autonomy without catenary
- Invest [Moultak et al. 2017]:
  - 2020: 178,000 €/truck
  - 2030: 136,000 €/truck
- Home base charger (overnight):
  - 50 kW
  - 31,000 €/truck

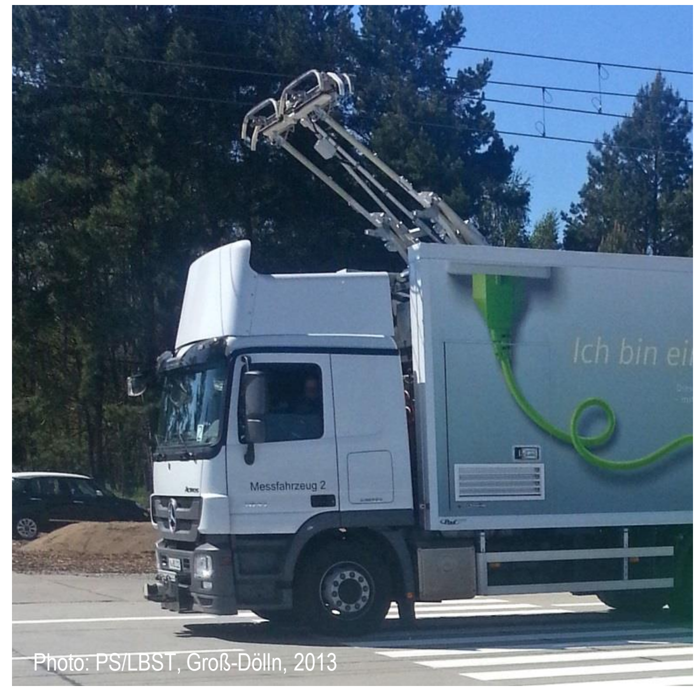


Photo: PS/LBST, Groß-Dölln, 2013

Truck | Fell cell electric vehicle (FCEV)

- Comparison of existing FCEV with assumptions in this study

	Unit	ESORO (Hyundai)	Nikola Two	Nikola Tre	Toyota (alpha)	This study 2020**
Region	-	CH	USA	EU	USA	EU
Maximum gross weight	t	34	36		36	40
Capacity H_2 tank	kg_{H2}	31 (net)	60-80		40	77
Pressure H_2 tank	MPa	35	70		70	70
Range	km	375-400	750-1200	500-1200	241-386*	1050
Fuel consumption	kg H_2/100km	7.5-8.0	6.67-8.00		10.36-16.5*	7.33
	MJ_{LHV}/km	9.9	8.0-9.6		12.4-19.9*	8.8
	kWh_{LHV}/km	2.75	2.22-2.67		3.45-5.52*	2.45
Production start	-	(2019)	2022/2023	2022/2023		2020

* Depending on the transport capacity utilisation (16-27 t)
** Based on [Moultak et al. 2017]

LBST, 2018-12-18

Truck | Fuel consumption

2020	Fuel consumption		
	MJ/km	kWh/km	l_{DE}/100 km
Diesel	12.0	3.33	33.4
CNG Otto cycle	14.0	3.89	39.0
LNG Otto cycle	14.0	3.89	39.0
LNG HPDI	13.0	3.61	36.2
FCEV	8.8	2.45	24.6
CEV	5.3	1.47	14.8

2030	Fuel consumption		
	MJ/km	kWh/km	l_{DE}/100 km
Diesel	9.0	2.50	25.1
CNG Otto cycle	11.0	3.06	30.7
LNG Otto cycle	11.0	3.06	30.7
LNG HPDI	10.0	2.78	27.9
FCEV	7.6	2.11	21.2
CEV	4.5	1.25	12.5

-26%
-56%
-14%
-16%

Efficiency package according to [Moultak et al. 2017], e.g. aerodynamic improvements, low rolling-resistant tires

Reference: LBST based on [Moultak et al. 2017]

Truck | CAPEX assumptions

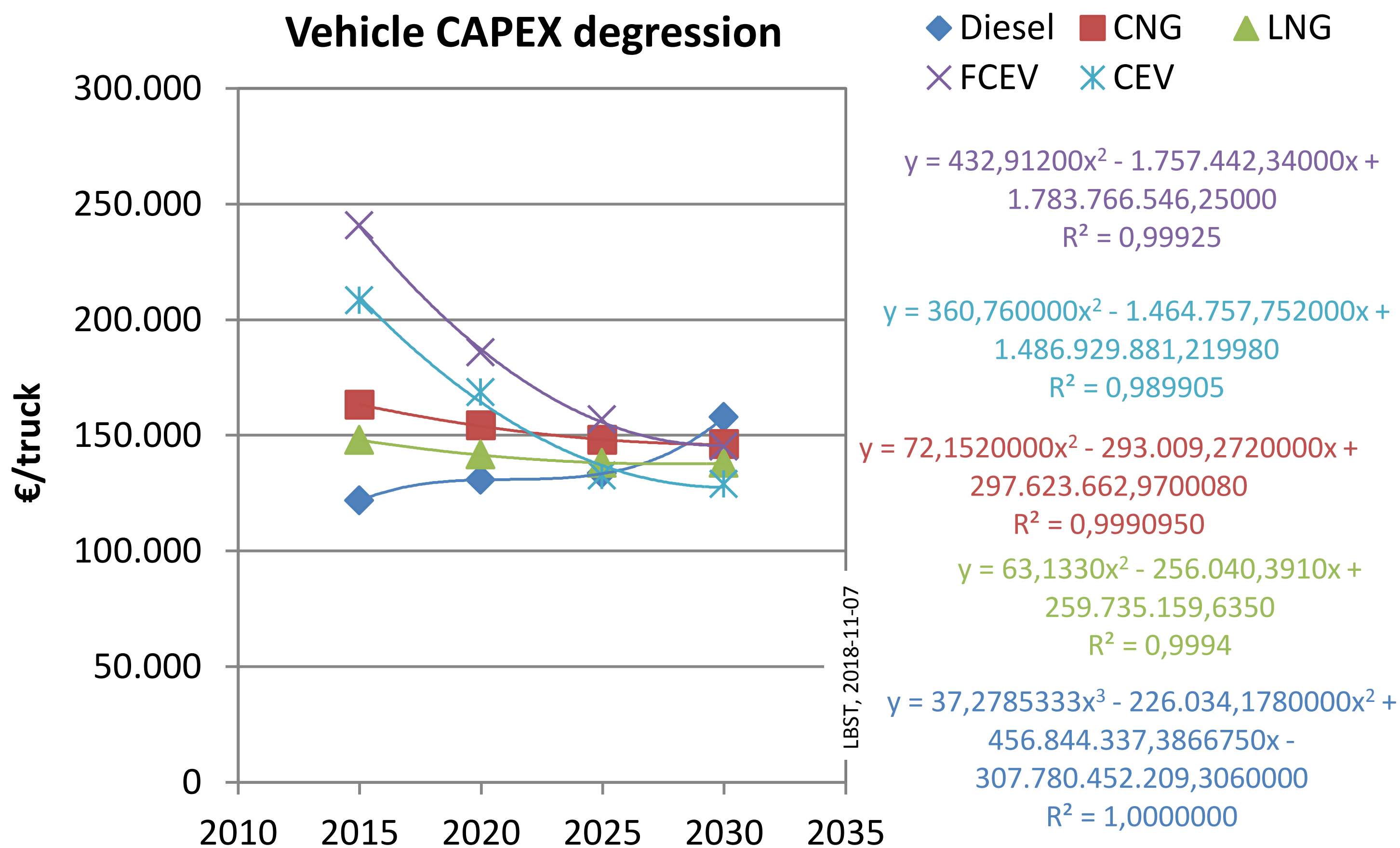


Image / interpolation: LBST; Data: [Moultak et al. 2017, p18]

Truck | Cost assumptions

- All costs are given without inflation based on volume assumptions

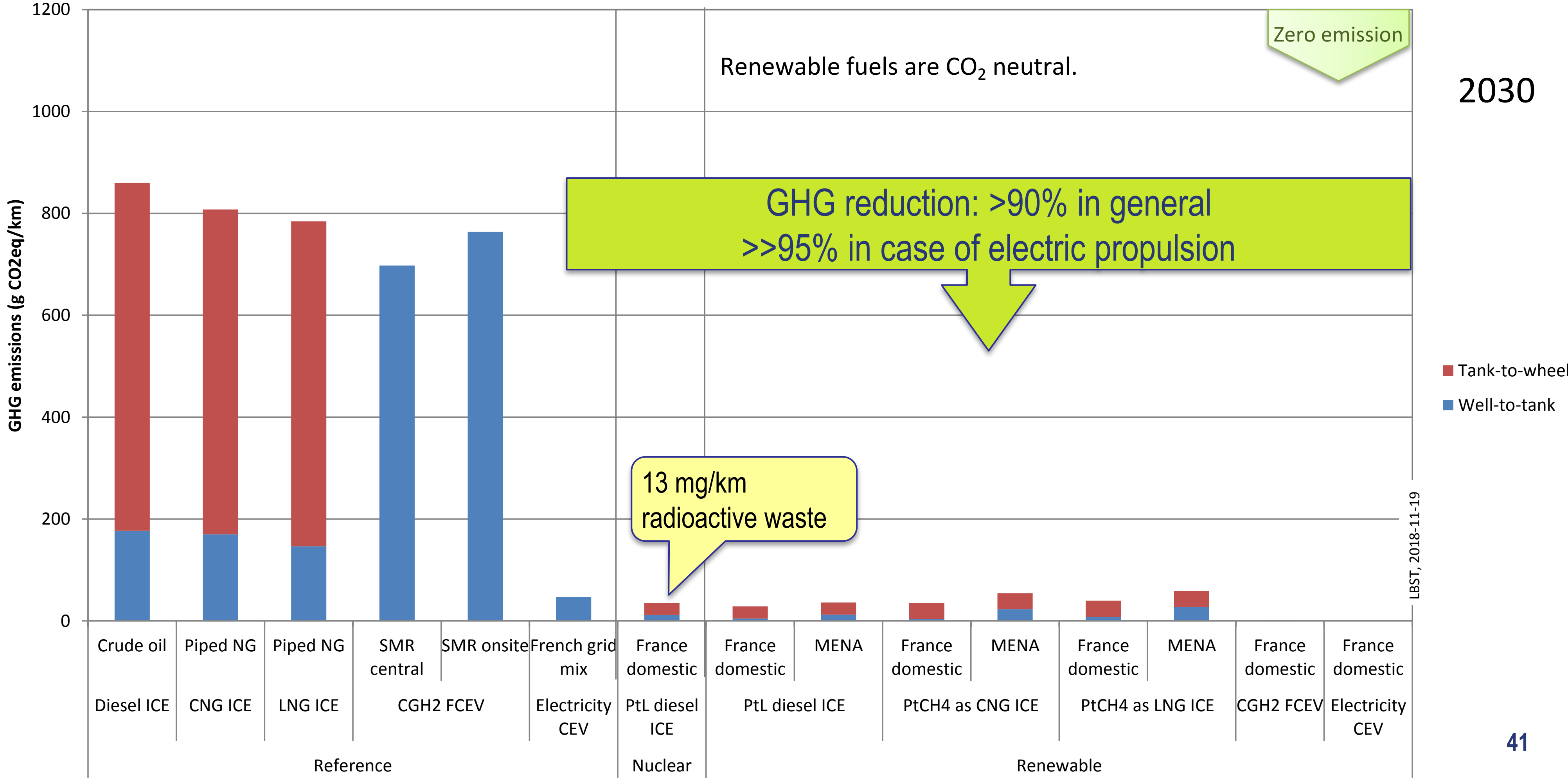
	CAPEX (€)	O&M (€/km)	Overhead, insurance €/km)	Driver Salary & expenses (€/km)	Road toll & axle taxes (€/km)
2020					
Diesel	116,000	0.105	0.195	0.365+0.086	0.089
CNG Otto cycle	154,000				
LNG Otto cycle	142,000				
LNG HPDI	167,000				
FCEV	186,000				
CEV incl. 200 kWh battery @ 200 €/kWh	178,000				
2030					
Diesel	129,000	0.105	0.195	0.365+0.086	0.089
CNG Otto cycle	146,000				
LNG Otto cycle	138,000				
LNG HPDI	162,000				
FCEV	145,000				
CEV incl. 200 kWh battery @ 110 €/kWh	136,000				

CAPEX data: [Moultak et al. 2017, p18]; O&M cost data: [CNR 2018]

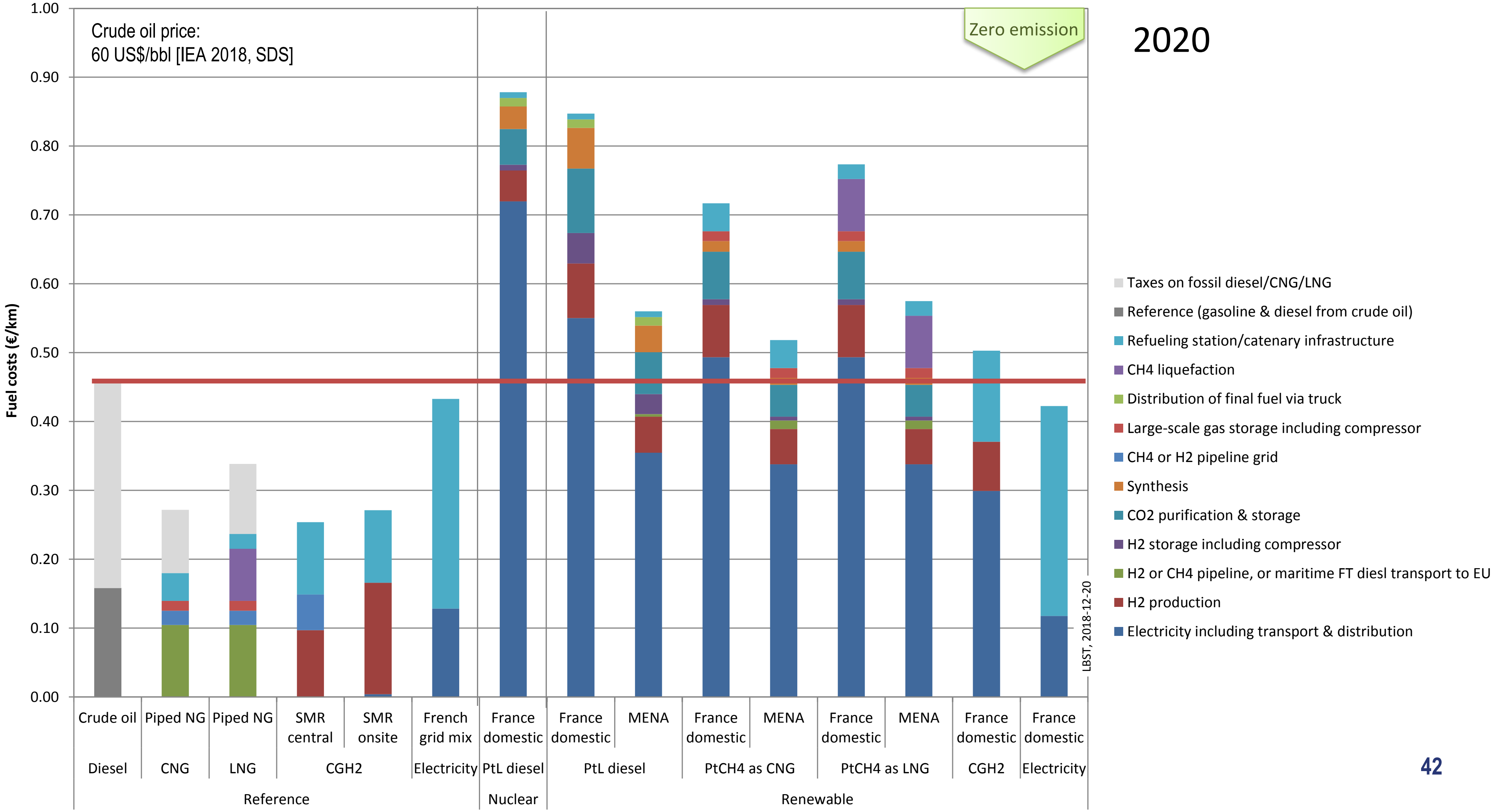
IV. Synthesis

well-to-wheel

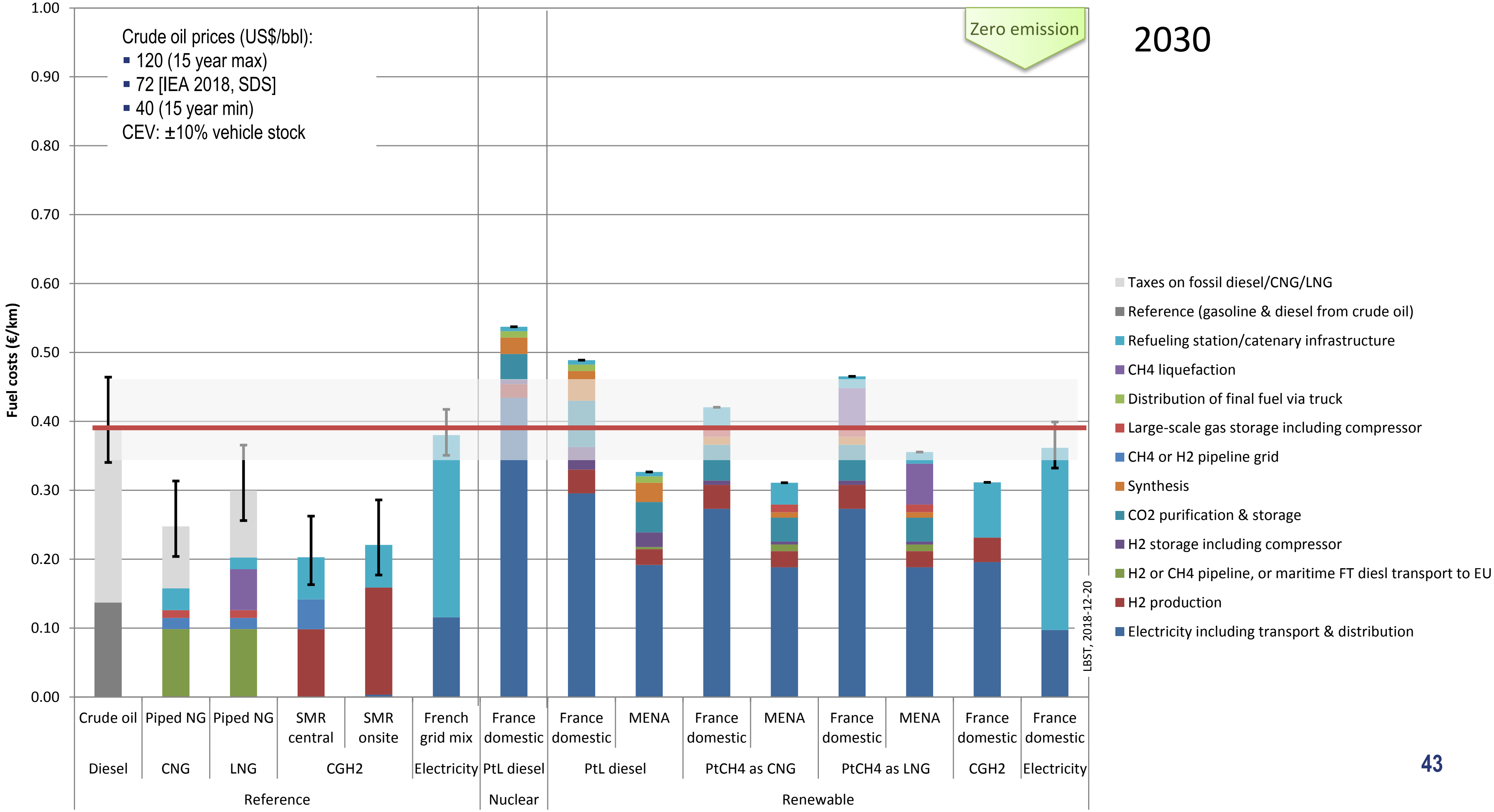
Well-to-wheel greenhouse gas emissions 2030



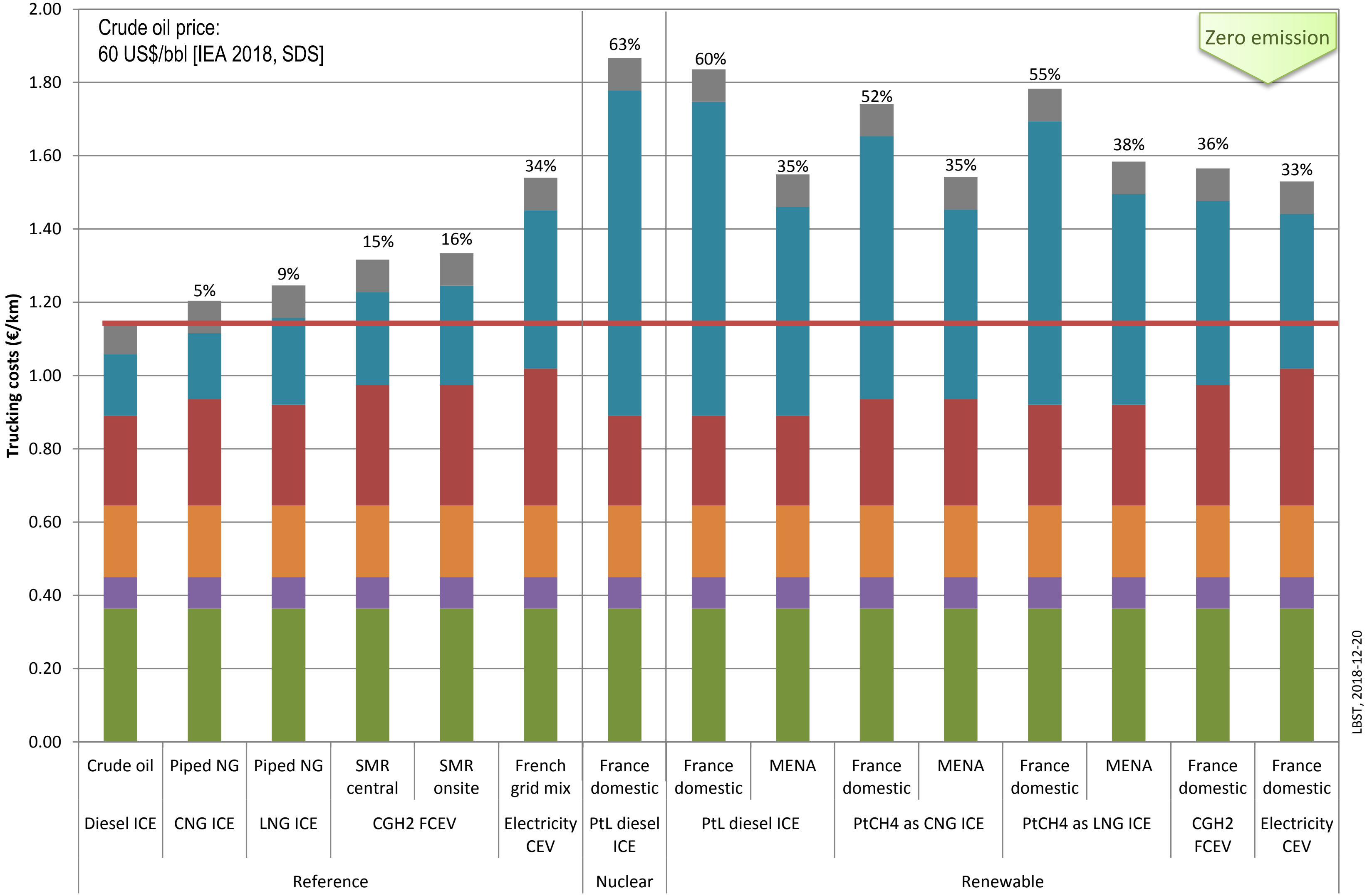
Well-to-wheel fuel costs 2020



Well-to-wheel fuel costs 2030



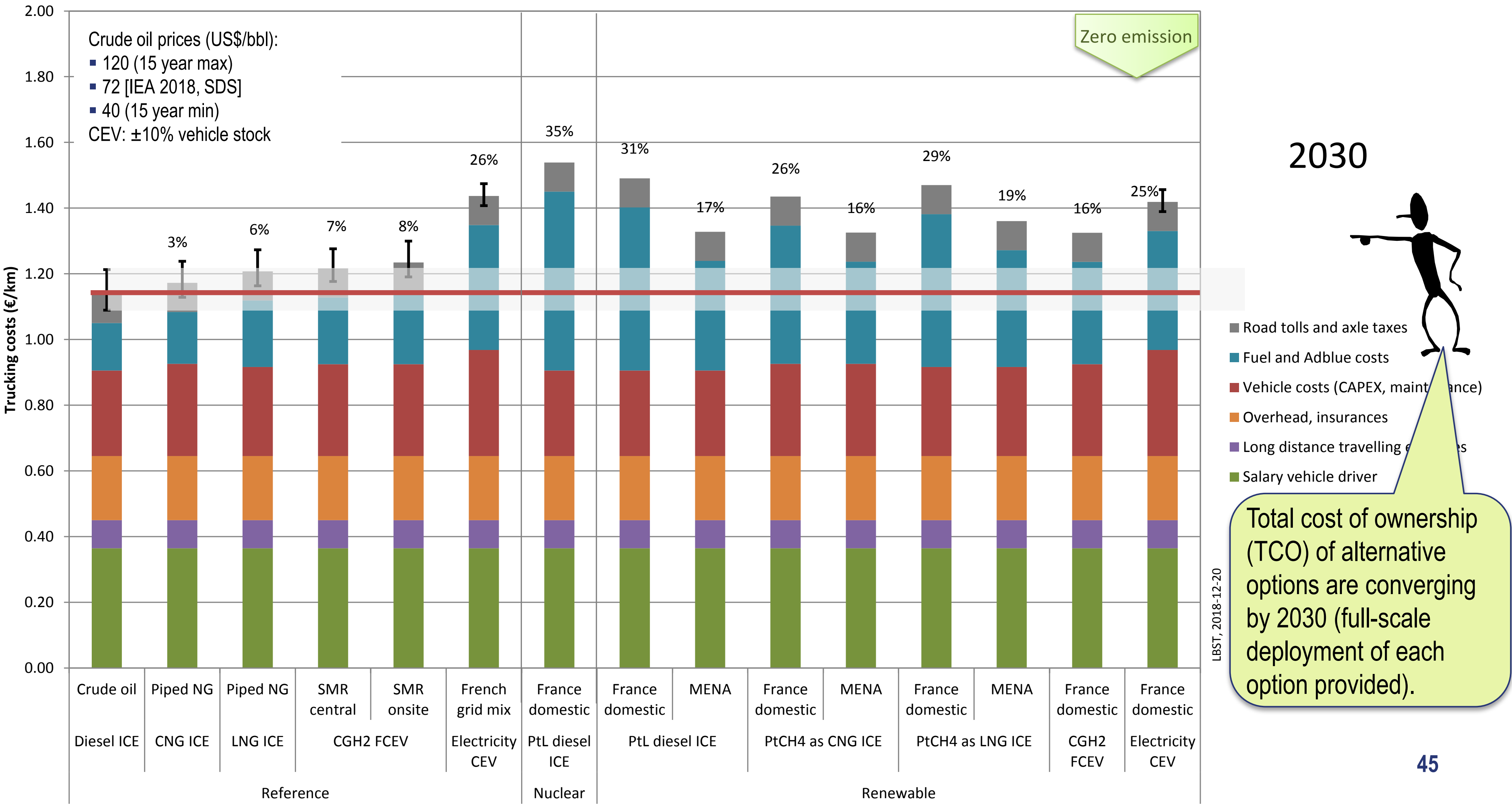
Well-to-wheel full costs 2020



Fuel costs comprise primary energy (incl. fuel conversion efficiency) and depreciation of the conversion plant.

Salary, overhead, insurance and road toll are the same for all pathways.

Well-to-wheel full costs 2030



‘Ceteris paribus‘ deployment of alternative fuels/powertrains

Development of vehicle stock

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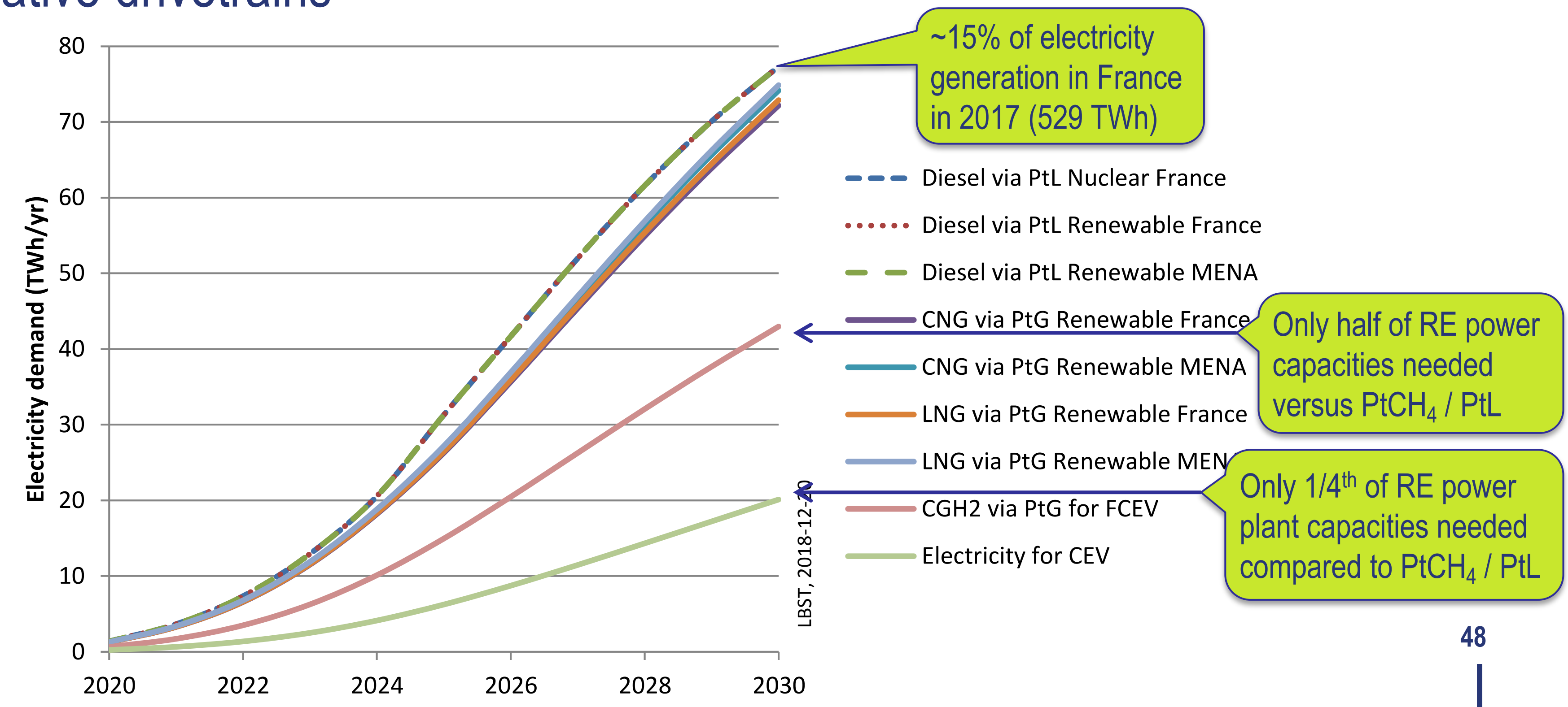
- Vehicle stock development is based on tractor-truck scenario in France
- Same deployment rate for all alternative powertrains (ceteris paribus)
- Continuous stock roll-over, i.e. no early force-out of legacy vehicles

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Development of vehicle stock (long-haul total)	144,650	144,493	144,554	144,805	145,222	145,784	146,474	147,276	148,176	149,163	150,229
Legacy vehicles operated with Diesel from crude oil	143,462	141,189	137,579	131,916	123,686	112,868	99,921	85,490	70,141	54,262	38,091
# of vehicles going out because of age (9 years avrg.)	16,505	16,505	16,505	16,505	16,505	16,505	16,505	16,505	16,505	16,505	16,505
# of vehicles going in (replacement + growth)	16,505	16,348	16,566	16,756	16,921	17,067	17,194	17,306	17,405	17,492	17,570
Share of alternative vehicles in new vehicles (ceteris paribus: CNG or LNG or FCEV or CEV)	7%	13%	22%	35%	51%	67%	79%	88%	93%	96%	98%
# of alternative fuel-powered new vehicles	1,189	2116	3,672	5,914	8,646	11,381	13,637	15,232	16,250	16,866	17,236
Stock of alternative fuel-powered vehicles	1,189	3,304	6,976	12,890	21,536	32,916	46,553	61,785	78,035	94,902	112,137

LBST, 2018-12-20

Renewable/nuclear electricity demand (per year)

- Ceteris paribus, based on the vehicle stock in France (~210,000 in 2030, thereof long-haul: ~150,000)
- Share of PtL diesel based on same market development as for the fuels for alternative drivetrains



Absolute GHG emissions 'ceteris paribus'

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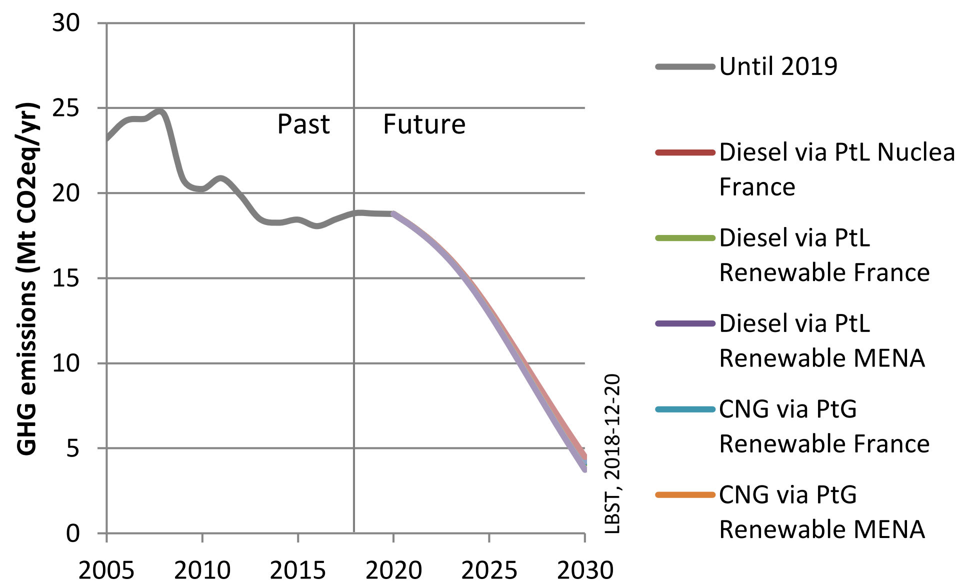
- Past GHG emission reductions mainly due to
  - fewer tractor trucks,
  - decreasing annual mileage, and
  - slight reductions in fuel consumption.
- GHG emission savings until 2030:
  - further reductions in ICE fuel consumption
  - introduction of renewable fuels
- Results from explorative and non-disruptive 'ceteris paribus' analyses:
  - All fuel/powertrain combinations analysed in this study could have the potential for GHG emission reductions of between 76-80 $\%_{2020}$ until 2030.
  - While 98 % of new vehicles in 2030 come with alternative fuel/propulsion, about 75 % of the vehicle fleet and fuel consumed are alternative fuels and powertrains only.
  - Remaining GHG emissions in 2030 are due to legacy vehicles in the fleet using fossil diesel.



- GHG emissions reduced by ~80 %
- 98 % of new trucks equipped with alternative fuels/powertrains
- 25 % is legacy stock (Diesel)

Cumulated investments 'ceteris paribus' | Methodology

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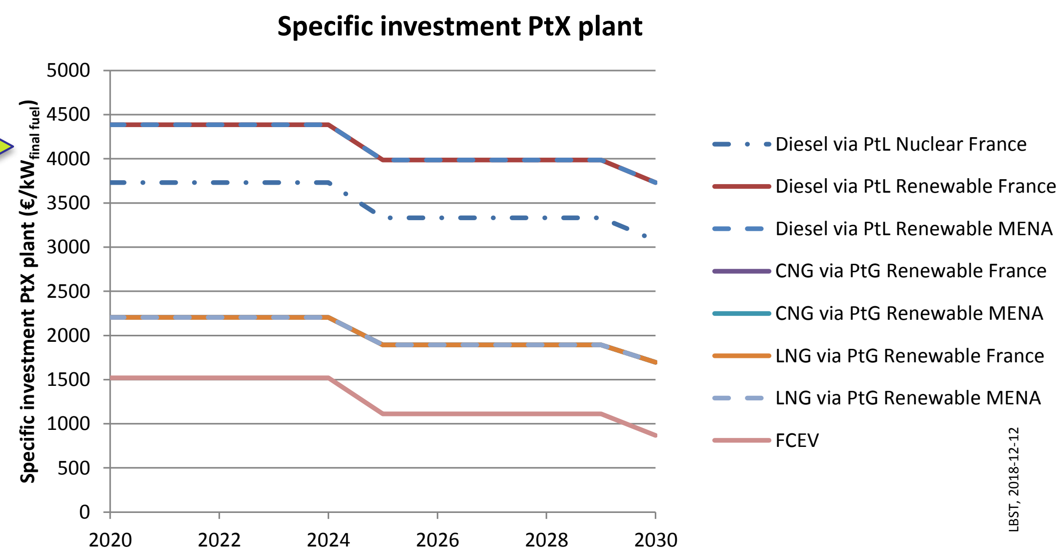
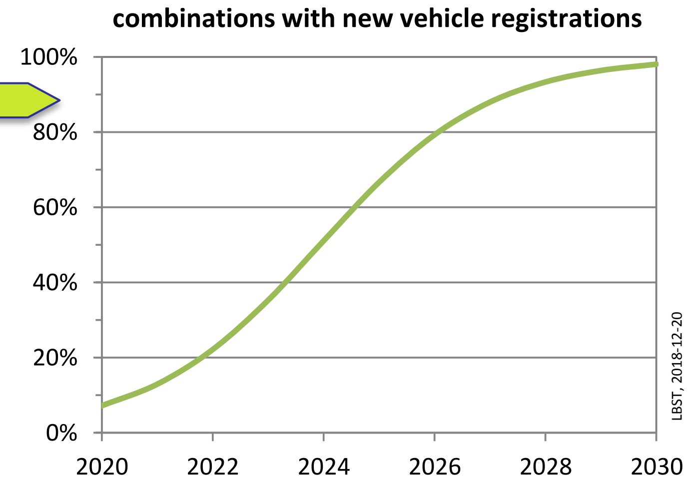
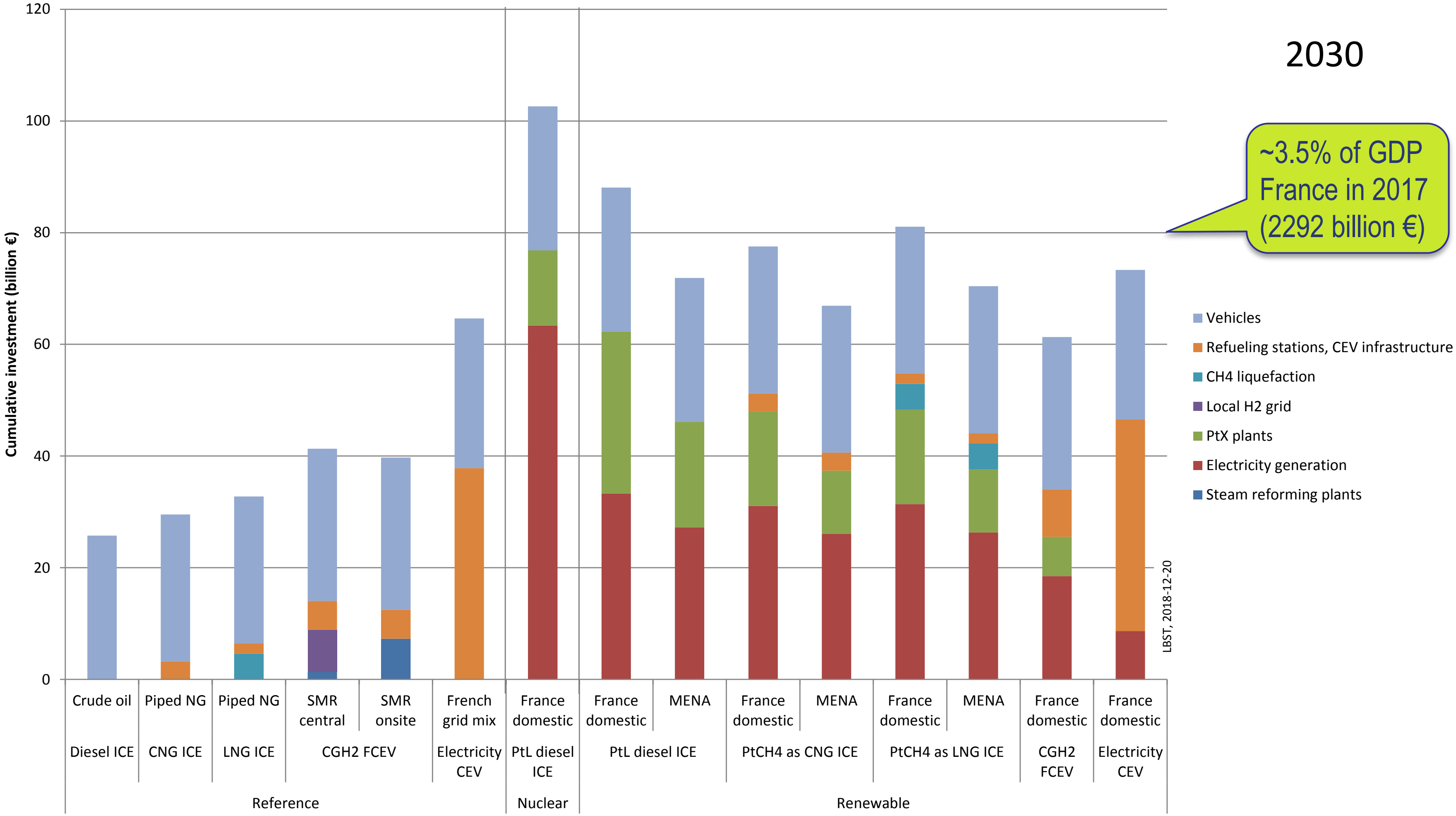
- The cumulated investments comprise the following elements:
  - Renewable power plants
  - PtX production plants
  - Alternative fuel infrastructure for transport & distribution
  - Vehicles (incl. re-investments for vehicle end-of-life replacements)
- Learning curves assumed for key components, i.e. the 1st PtX production plant is more expensive than the nth one.
- Evolutionary change in fleet composition, i.e. no active phase-out of conventional vehicles before its end of usable lifetime.
- The calculation is done independent from who is investing (investor) or where investments are placed (geography).





Cumulated investments ‘ceteris paribus’ until 2030

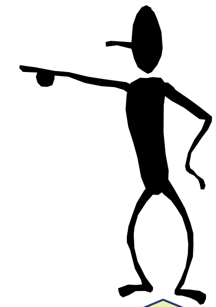
- Ceteris paribus, based on the vehicle stock in France (~210,000 in 2030, thereof long-haul: ~150,000)



Conclusions from well-to-wheel analyses

Conclusions from well-to-wheel analyses

- Cost of truck powertrains is converging, series production provided.
- Cost of new fossil, nuclear and renewable power is converging.
- Cost of imported synthetic fuels ($PtCH_4$, PtL) are ~20% lower than domestic.
- Cumulative investments seem manageable for all options.
- Fuel cell and catenary trucks offer zero GHG and zero pollutant emissions.
- Fuel cell truck propulsion:
  - Low cumulative investment among renewable options
  - Shares technology basis and infrastructure with other H_2 uses.
- Catenary system:
  - Exclusive to (relatively few) long-distance trucks (and possibly buses)
  - Competing with rail freight (and possibly public rail transport)
  - Ideal for frequent point-to-point relations



Criteria other than costs are of decisive strategic importance, e.g. zero pollutant emission, energy demand, universal infrastructure.

⇒ Promising fuel/powertrain combinations further investigated in this study:

- ✓ Hydrogen FCEV as universal solution for HDVs
- ✓ Battery-CEV as option for dedicated fleets

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VI. The way forward

High-level market introduction strategy for FCEV and CEV heavy duty tractors

Key questions

- Identify **short-term barriers** hindering market introduction of FCEVs and CEV
- Define a **market entry strategy** for FCEV and CEV trucks
  - Infrastructure developers
  - Fleets
- Provide **policy recommendations** for supporting the introduction of FCEV and CEV trucks at the France and EU level
  - In the short term (push and pull measures)
  - In the long run (pull measures only)

Reaching a critical size of fleet is a key challenge to ensure profitability

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Barriers	Description	FCEV	CEV	
Infrastruc-ture business case	➢ No visibility on demand ➢ High resulting fuel cost if low utilisation factor	**10-15**	**50-60**	**... min. vehicles per site / 10km of lines**
	➢ High investment	**3-4 M€**	**17 M€**	**... Investment per site / 10km of lines**

Costs are a major barrier today for fleet operators

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Barriers	Description	FCEV	CEV	
Vehicle technology	➢ Lack of maturity (technology risk)	4	3	... pilot projects Worldwide
	➢ High TCO	+36%	+33%	... compared to diesel in 2020
	➢ High Purchase price	+60%	+53%	... compared to diesel in 2020

Nikola and Hyundai are the only companies that have announced commercial plans for trucks in Europe

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Barriers	Description
OEM and value chain lack of readiness	➢ No commercial availability ➢ No visibility on demand for OEMs ➢ High investment needed ➢ Maintenance of vehicles: High costs and lack of reliability for low volumes

FCEV | **CEV**

Positioned truck OEMs

FCEV: TOYOTA, HYUNDAI, VDL, DAF (A PACCAR COMPANY), NIKOLA™, KENWORTH

CEV: SCANIA, VOLVO TRUCKS

Commercial plans

FCEV: NIKOLA™, HYUNDAI

Who will be the first movers?

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What type of fleet operators should infrastructure developers target first?

Key success factors	Description
Types of fleets	➢ **For FCEVs: captive fleets to…** ➢ Lower the infrastructure entry barrier (less stations to be deployed) ➢ Long-term visibility for the infrastructure operator ➢ **For CEVs: ONLY point-to-point logistics**
Size of fleets	➢ **Very large fleets for:** ➢ A lower fuel cost ➢ A lower vehicle cost (OEM visibility on demand) ➢ A lower total industrialization costs (society-level) ➢ A higher availability and lower maintenance costs
Visibility	➢ The fleets exposed to societal pressures
Types of goods transported	➢ Transport of high added-value products (>35,000 €/t) will be least sensitive to costs increase

Hydrogen infrastructure developers need to pursue immediate economies of scale to reduce costs

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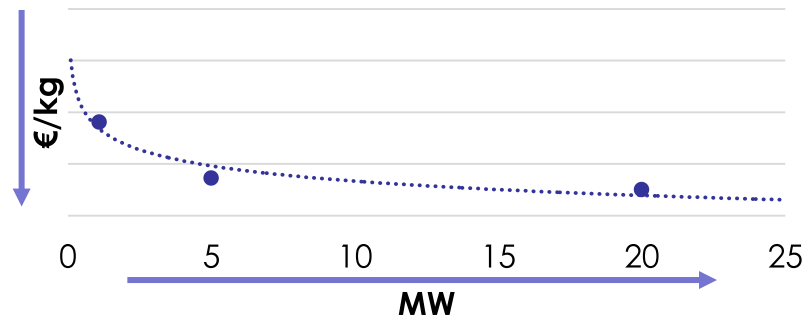
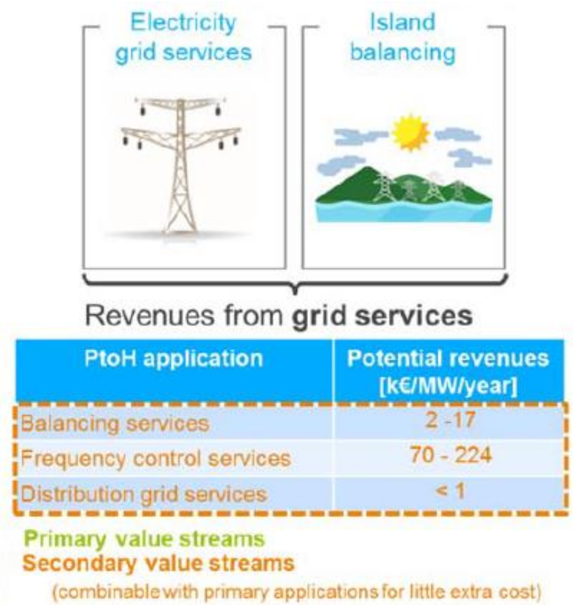
Key success factors	Description
Securing long-term supply contracts	▪ **Long-term supply contract(s)**
Ensuring fuel costs competitiveness	▪ **Focus on large fleets** ▪ Procure the electricity from the grid at the start
Reaching acceptable profitability levels	▪ **Stack up revenue streams**

Production costs of hydrogen in function of size of plant





PtoH application	Potential revenues [k€/MW/year]
Balancing services	2 - 17
Frequency control services	70 - 224
Distribution grid services	< 1

Source: Hinicio figure and Hinicio copyright

Only large fleets should be targeted by infrastructure developers in the introduction phase

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>2030:
Small fleet operators and individuals using the widely available public infrastructure

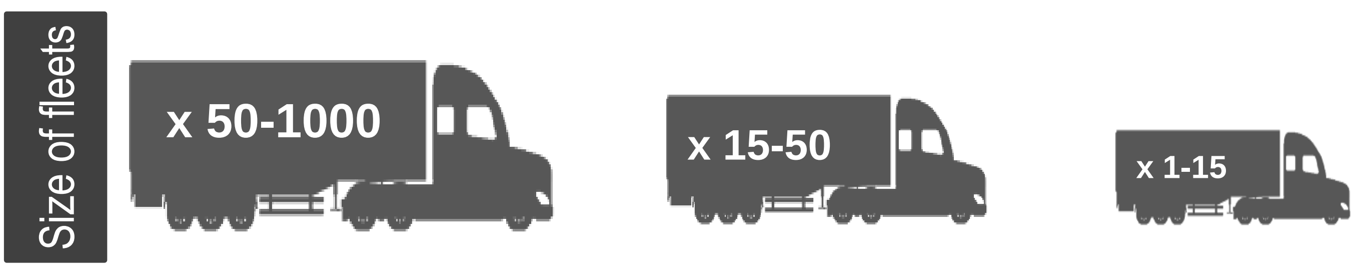
Going mainstream // Small fleet operators using the widely available infrastructure and buying commercially available tractors

2025-2030:
Large and medium fleet operators using the first public or their private infrastructure

Semi captive fleets // Large and medium semi-captive fleets relying on private infrastructure and leveraging the first public infrastructure on specific routes

2020-2025:
Very large fleet operators with private infrastructure

Addressing very large captive fleets with private infrastructure, allowing for economies of scales



Source: Hinicio copyright

The CEV infrastructure business case is very complex

Key success factors	Description
Ensuring fuel costs competitiveness	▪ **Secure a critical mass of 5 to 6 vehicles per km of catenary line**
Securing long-term supply contracts	▪ **Association of many (>5-10) actors**. ▪ **Long-term supply contract(s) with all the fleet operators**
Reaching acceptable profitability levels	▪ **Stacking up revenue streams:** grid services, other types of HDVs (buses, rigid trucks)

Market push tools are needed in the short term

<table>
<tr><th></th><th>Short term policy recommendations</th><th>Long-term policy recommendations</th></tr>
<tr><td>1</td><td>Market push instruments
➢ Subsidies
➢ Exemptions from taxes, fees, road tolls, etc.</td><td></td></tr>
<tr><td>2</td><td>Infrastructure de-risking instruments
➢ Take-or-pay contracts
➢ Public co-financing</td><td></td></tr>
<tr><td>3</td><td colspan="2">Market pull instruments
➢ Carbon pricing
➢ Emissions restrictions (low-emission zones, emissions requirements or targets, road and axle taxes linked to emissions)
➢ Specific mandates for renewable energy content
➢ Zero-emission vehicle quotas</td></tr>
<tr><td>4</td><td colspan="2">Allowing for complementary revenues
➢ Gas grid injections (for FCEV only)
➢ Enabling participation of all consumers to all balancing services & markets</td></tr>
</table>

Take-away messages

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- **Long-haul tractors are the biggest greenhouse gas emission contributors**
- Their fuel efficiency in average has hardly change over the past 10 years
- There may be more tractors on the road by 2030
- FCEV and CEV are the most robust fuel/powertrain solutions
- **Market introduction strategies will naturally focus on large fleets in the start**
- Regulatory "pull" measures (CO_2 taxes, will start favour zero-emission tractors starting 2023-25 so "push" **(subsidies, exemptions) measures will be necessary at the start**

Thank you!

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FONDATION TUCK
The Future of Energy

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ANNEX

Acronyms & abbreviations

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bbl	Barrel
BEV	Battery-Electric Vehicle
CAPEX	Capital Expenditures
CEV	Catenary-Electric Vehicle
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
DAC	Direct Air Capture
E, e	Electricity(-based)
FCEV	Fuel Cell-Electric Vehicle
FT	Fischer-Tropsch
GHG	Greenhouse Gases
h	hour
H_2	Hydrogen
ICE	Internal Combustion Engine
kWh	Kilowatt hour
LCOE	Levelised Cost Of Electricity
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
MJ	Mega joule
MW	Megawatt
NPP	Nuclear Power Plant
O&M	Operation & Maintenance
OPEX	Operating Expenditures
PEM	Polymer Electrolyte Membrane
PtH_2	Power-to-Hydrogen
PtL	Power-to-Liquids
RE	Renewable Electricity
RWGS	Reverse Water Gas Shift
th	thermal
WHR	Waste-Heat Recovery
yr	year

Technology Readiness Levels (TRL) | Definition

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#	TRL definition according to EU Horizon2020 [EC 2017]
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment
6	Technology demonstrated in relevant environment
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment

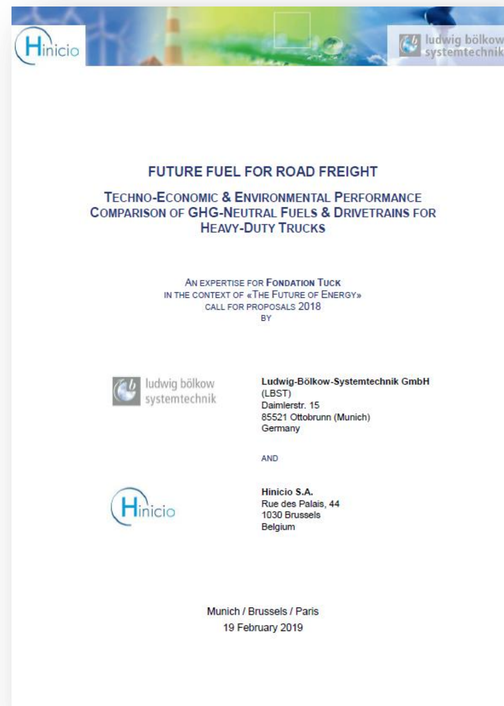
[EC 2017] European Commission (EC): Horizon 2020 – Work Programme 2018-2020: General Annexes: G. Technology readiness levels (TRL); 2017; https://ec.europa.eu/research/participants/data/ref/h2020/other/wp/2018-2020/annexes/h2020-wp1820-annex-g-trl_en.pdf

Reference

Patrick Schmidt, Werner Weindorf, Tetyana Raksha, Reinhold Wurster (LBST), Henri Bittel, Jean-Christophe Lanoix (Hinicio)

Future Fuel for Road Freight – Techno-Economic & Environmental Performance Comparison of GHG-Neutral Fuels & Drivetrains for Heavy-Duty Trucks

An expertise for Fondation Tuck
Munich / Brussels / Paris, February 2019


FUTURE FUEL FOR ROAD FREIGHT

TECHNO-ECONOMIC & ENVIRONMENTAL PERFORMANCE COMPARISON OF GHG-NEUTRAL FUELS & DRIVETRAINS FOR HEAVY-DUTY TRUCKS

AN EXPERTISE FOR FONDATION TUCK
IN THE CONTEXT OF «THE FUTURE OF ENERGY»
CALL FOR PROPOSALS 2018
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19 February 2019

=> Study available for download from Fondation Tuck website soon