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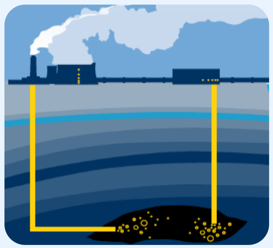
# Greenhouse Gas Emissions Reduction Potential in the Scottish Transport Sector

January 2017

# Greenhouse Gas Emissions Reduction Potential in the Scottish Transport Sector

For Transport Scotland

**Technical Annex**

January 2017

**Element Energy Ltd**

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# Contents

# This technical annex is intended to provide supporting information and detail to complement the findings of the main report

## Discussion

- Element Energy conducted a study for Transport Scotland on the emissions reduction potential for Scottish transport to 2032. This is one of two report outputs from this study.
- The main report (see above right) contains an overview of the project and its findings. In this technical report we present supplementary information on the following topics:
  - An overview of our fleet modelling approach
  - Detailed outputs from our review of technology trends, used to update the cost and performance assumptions in our modelling, and to give an overview of the market status of each sector within transport
  - Supplementary figures to the main report, including full emissions trajectories and market shares for the scenarios presented in the main report


elementenergy

GREENHOUSE GAS EMISSIONS REDUCTION POTENTIAL IN THE SCOTTISH TRANSPORT SECTOR FROM RECENT ADVANCES IN TRANSPORT FUELS AND FUEL TECHNOLOGIES

Final report

for

Transport Scotland

January 2017

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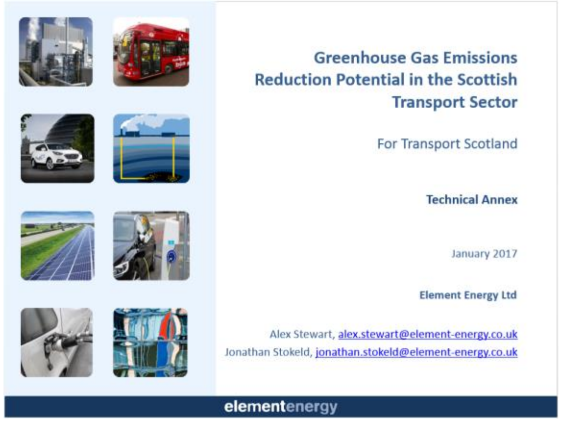
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# Acronyms used in this report

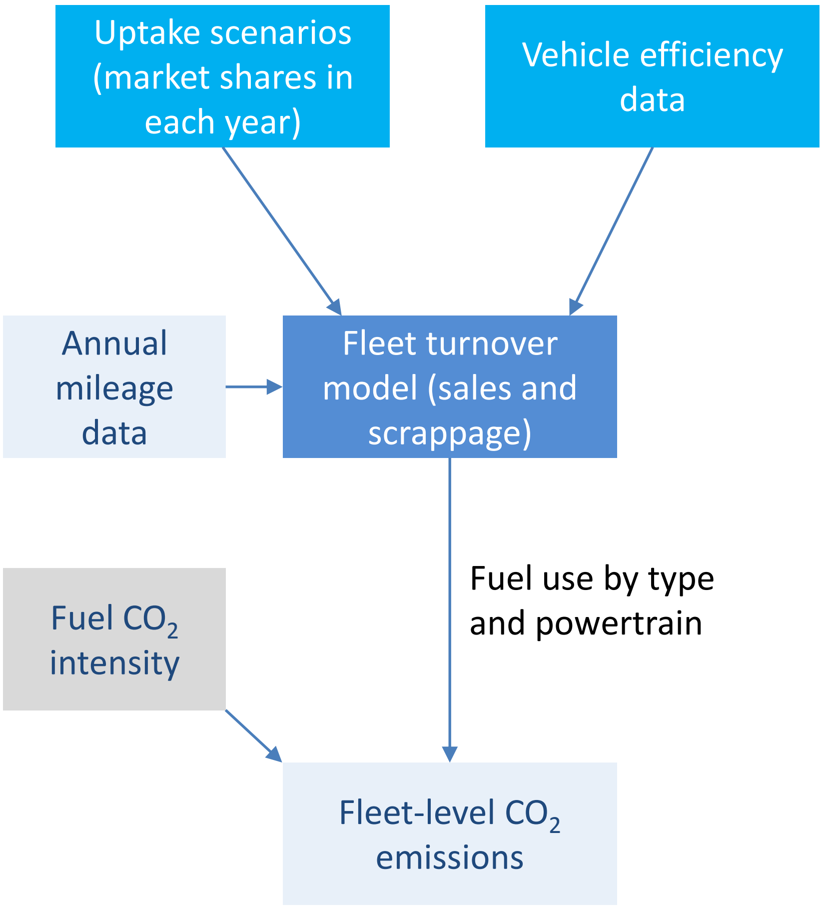
| | |
|---|---|
| ATM | Air Traffic Management/Air Traffic Movement |
| APU | Auxiliary Power Unit |
| BEV | Battery Electric Vehicle |
| BoP | Balance of Plant |
| BSOG | Bus Service Operators Grant |
| CNG | Compressed Natural Gas |
| DECC | Department of Energy & Climate Change |
| DfT | Department for Transport |
| DoD | (battery) Depth of Discharge |
| EC | European Commission |
| EEDI | Energy Efficiency Design Index |
| ETI | Energy Technologies Institute |
| ETS | Emission Trading Scheme |
| EU | European Union |
| EV | Electric Vehicle |
| FC | Fuel Cell |
| FCEV | Fuel Cell Electric Vehicle |
| FCH JU | Fuel Cell Hydrogen Joint Undertaking |
| FC RE-EV | Fuel Cell range-extended vehicles |
| FHV | Flywheel Hybrid Vehicle |
| GHG | Greenhouse Gases |
| GVW | Gross Vehicle Weight |
| $H_2$ | Hydrogen |
| HDV | Heavy Duty Vehicle |
| HEV | Hybrid Electric Vehicle |
| HGV | Heavy Goods Vehicle |
| HHV | Hydraulic Hybrid Vehicle |
| HP | Horsepower |
| HRS | Hydrogen Refuelling Station |
| ICAO | International Civil Aviation Organisation |
| ICCT | International Council for Clean Transportation |
| ICE | Internal Combustion Engine |
| IMO | International Marine Organisation |
| km | Kilometre |
| LCEB | Low Carbon Emission Bus |
| L-CNG | Liquefied and Compressed Natural Gas |
| LNG | Liquefied Natural Gas |
| LPG | Liquefied Petroleum Gas |
| MARPOL | International Convention for the Prevention of Pollution from Ships |
| MJ | Mega Joule |
| NEDC | New European Driving Cycle |
| NOx | Nitrogen oxide |
| NTS | UK National Travel Survey |
| OEM | Original Equipment Manufacturer |
| OLEV | Office for Low Emission Vehicles |
| PHEV | Plug-in Hybrid Electric Vehicle |
| pkm | Passenger km |
| PM | Particulate Matter |
| R&D&D | Research & Development & Demonstration |
| RE-EV | Ranger Extender Electric Vehicle |
| RPK | Revenue Passenger Kilometres |
| SOx | Sulfur oxide |
| TMfS | Transport Model for Scotland |
| TTW | Tank-to-Wheel |
| WP | Work Package |
| WTT | Well-to-Tank |
| WTW | Well-to-Wheel |

# Contents

# A detailed fleet model of surface vehicles in Scotland was used to calculate transport sector $CO_2$ emissions under different scenarios

**Surface transport fleet model – primary inputs**

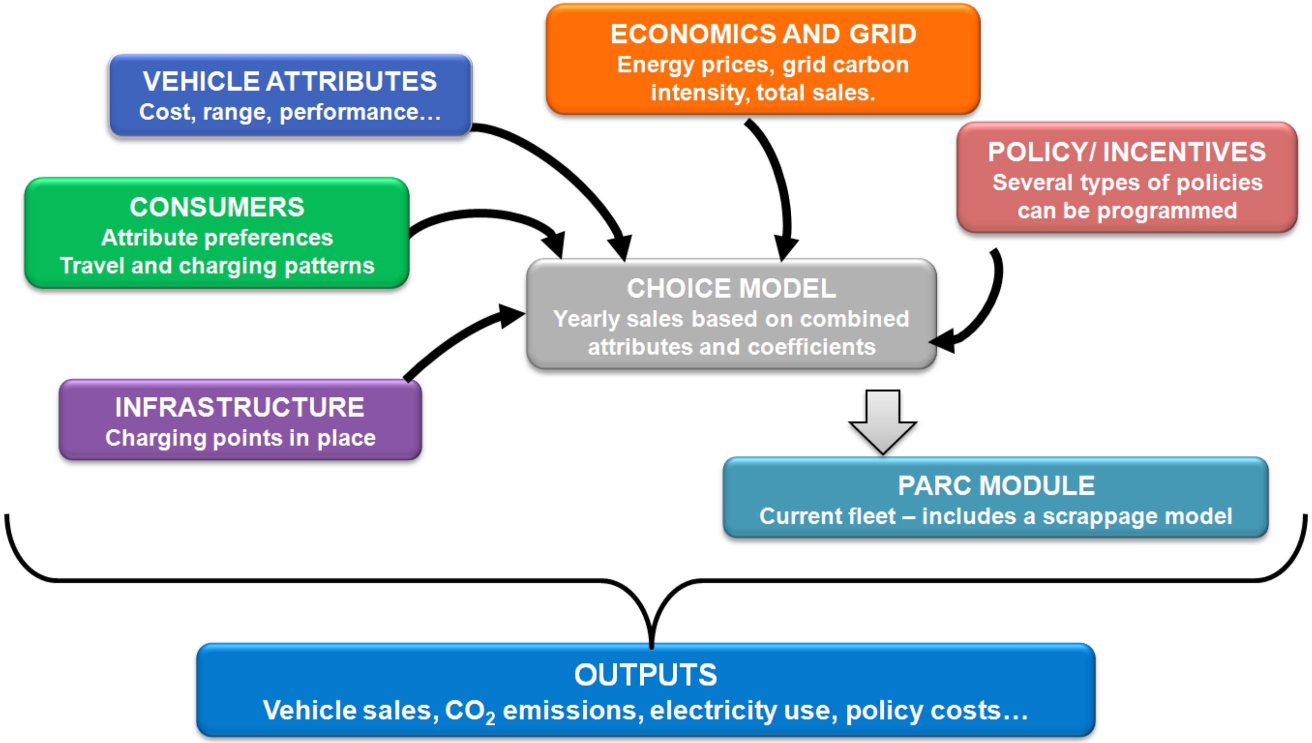
1. Stock growth trends by vehicle type (2010-2035)
2. Existing stock breakdown by vehicle type, age, segment and powertrain
3. Vehicle scrappage (survival) rate by vehicle type, segment and powertrain
4. Projected sales & market share by vehicle type, segment and powertrain (2010-2035)
5. Traffic (proportion of vehicle kilometres) by road type for each vehicle class (2010 -2035)
6. Annual Mileage by vehicle type (2010 – 2035)
7. Traffic (vehicle Km) by vehicle and road type (2010 – 2035) (*for calibration only*)
8. Fuel consumption (unit/km) and purchase price (£) for new vehicles by type and powertrain (2015 – 2030)
9. Average new vehicle fuel consumption (ICE powertrains historical 1970 -2014)
10. Fuel price trends (2015 – 2035)
11. TTW & WTW GHG emissions per fuel (2010 – 2015)
12. ICCT TTW GHG correction factors



# For cars and vans, our existing ECCo consumer uptake model was used to generate uptake scenarios

## Overview of ECCo model

Our Electric Car Consumer (ECCo) Model was used to generate market shares of light vehicle powertrains based on future developments in technology, infrastructure and policy support.




**Powertrains included**

ICE: petrol, diesel, stop-start, pure hybrid

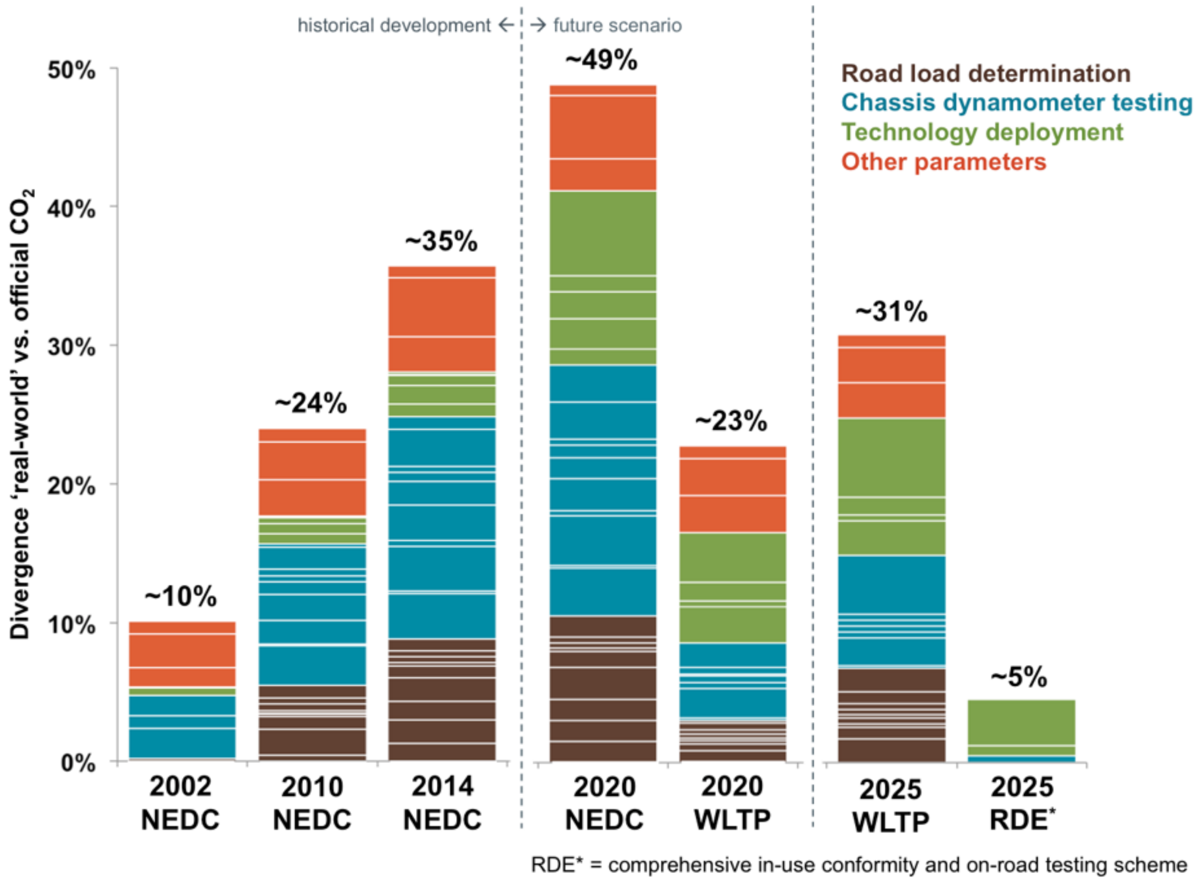
Plug-in: PHEV, RE-EV, BEV

Hydrogen: $H_2$ ICE, FCEV

**Inclusion of vehicle data and policy ensures relevance for three main stakeholders (customers, OEMs and governments)**

# We used real world emissions correction factors from a 2015 study for the UK Committee on Climate Change

- Element Energy/ICCT report in 2015 assessed the causes and likely future changes for the ‘real world gap’ between test cycle and real world emissions
- Future changes will be driven by the use of the new World Lightweight Test Procedure (WLTP), which is expected to reduce the gap for new vehicles
- Beyond 2025, in the baseline we assume that there is a continuing real world gap of 31% relative to the WLTP, with the gap decreasing due to on-road testing in the policies scenario (full details in the main report)



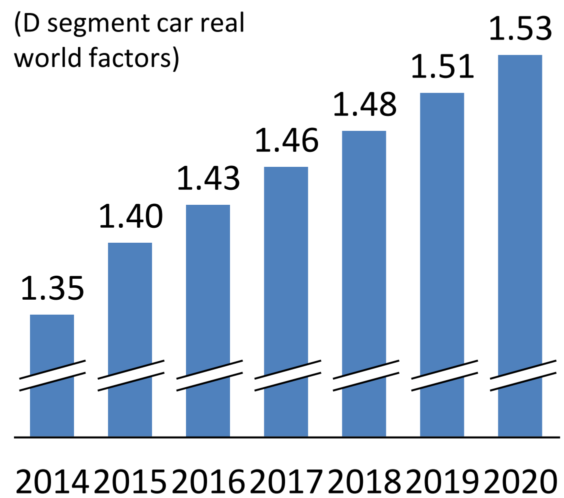

Source: Element Energy and ICCT report for the UK Committee on Climate Change – Quantifying the impact of real-world driving on total $CO_2$ emissions from UK cars and vans

# Emissions from our fleet model were calibrated to match overall emissions from the Scottish Transport sector

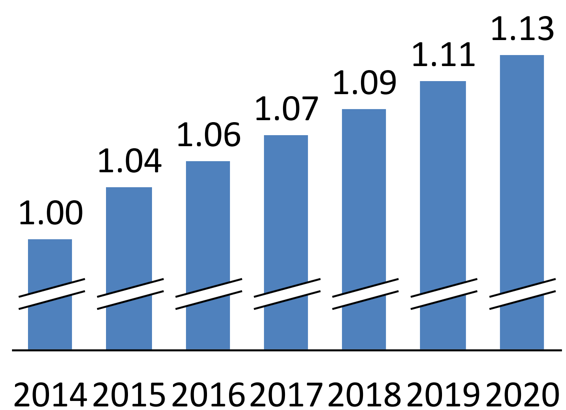
## Discussion

- The real world emissions gap is a known phenomenon – the fuel consumption of cars and vans as measured in NEDC testing is consistently lower than the fuel consumption achieved during real world driving. This gap is confirmed by widespread evidence from studies of user-submitted fuel consumption surveys (e.g. from Spritmonitor.de and company fuel cars, and recently from Peugeot-Citroen's own real world testing of its cars[1])
- However, the gap implied by NEDC emissions in a fleet model and Scottish fuel sales is significantly smaller, reflecting challenges in allocating fuel sales between different vehicle types and accurately measures the driving distances travelled by cars of different ages
- In our modelling, we took this discrepancy into account by scaling the real world emissions factors to unity in 2014, but retaining the year-to-year trends in the real world factor for each vehicle segment and powertrain. This ensures that the fleet model results match Scottish data on emissions from surface transport

## Example – Actual and scaled real world factors




Overestimation of car fuel sales and emissions



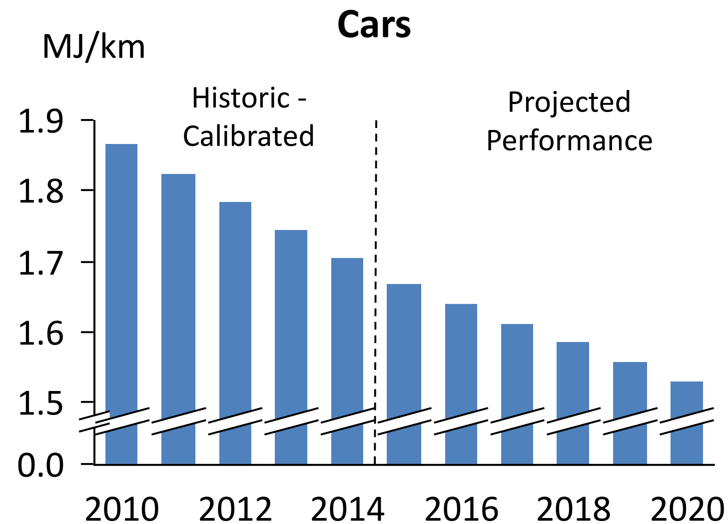

Real world factors which are consistent with historical fuel sales, but carry information on future changes in the real world emissions gap

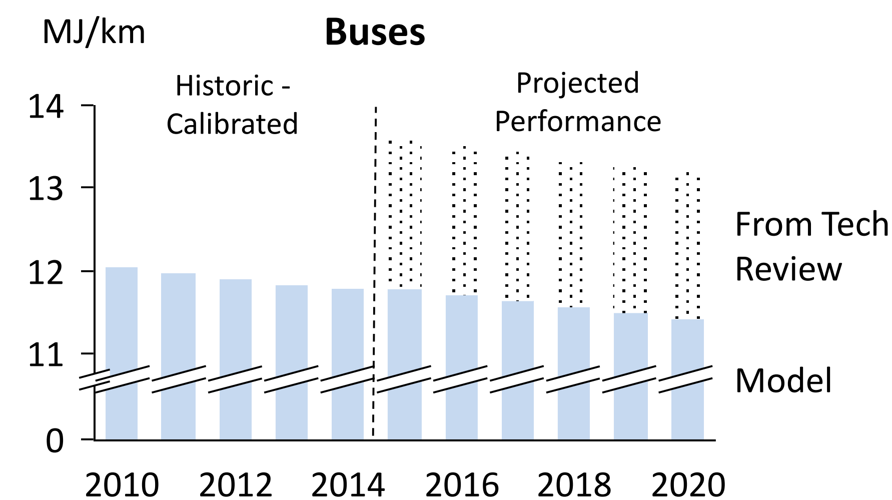
1 - http://www.autoexpress.co.uk/peugeot/94635/psa-peugeot-citroen-reveals-real-world-fuel-economy-for-30-cars

# Our fleet model was calibrated to match real world fuel sales data by sector, which required a scaling of bus MJ/km values

## Discussion

- Model outputs of fuel sales per year (and number of vehicles) from 2010 to 2013 were calibrated against historic data by adjusting historic MJ/km figures.
- The resulting MJ/km values were consistent with expected values and future trends for all cases except buses, where calibrated historic MJ/km were lower than known present values and expected future trends.
- As a result, future bus MJ/km values were scaled in order to ensure consistency with historic trends.



# Contents

# This technology review is dedicated to understanding the key transport technology trends relevant for Scotland between today and 2032

## Scope and process

- This work package reviews the cost and technical performance trends of key low carbon technologies. The exercise aims to understand improvements in the 'baseline' technologies (diesel and petrol Internal Combustion Engine vehicles) due to the introduction of new efficient components
- The work was informed by an extensive literature review and it benefits from our internal technology datasets developed over the past years
- The main findings of the work package are summarised, with a narrative on the expected improvements over time, such as the latest industry trends, commercial readiness and volume assumptions underpinning the most innovative solutions

### Technology Attributes

*Drivers / assumptions*

- Portfolio of efficiency measures and market readiness
- Technology R&D&D trends and market readiness
- International policies / market trends; etc.

*Existing EE bottom up performance and cost trend modelling*

*Latest literature data*

*Consultations*

*Attributes by vehicle type*

- Fuel economy
- Driving Range
- Vehicle cost

# Car and van powertrain analysis – methodological notes

| Vehicle | Powertrain technologies | Discussion |
|---|---|---|
| **Cars** | • ICEs (Petrol, Diesel, LPG)<br>• Hybrid ICEs (Petrol, Diesel)<br>• PHEVs / REEVs (Petrol, Diesel)<br>• BEV<br>• FCEVs | • Technical performance and cost trends for passenger cars and commercial vans (<3.5 tonnes) were reconstructed by using an in-house model able to return manufacturing cost and fuel efficiency trends to 2035<br>• The model breaks down each vehicle and powertrain solution into its main components (e.g. glider, engine, battery, tank, tyres, etc.) and reconstructs performance bottom-up.<br>• All input parameters have been reviewed and updated as part of this work and as such the emerging trends reflect the latest industry and literature data on cars and vans<br>• The same methodological assumptions and consistent inputs have been used for reconstructing the car and van trends in order to ensure comparability of results |
| **Vans** | • ICEs (Petrol, Diesel, LPG<br>• Full Hybrid ICEs (Petrol, Diesel)<br>• PHEVs (Petrol, Diesel)<br>• BEV<br>• FC REEVs | |

# Fuel efficiency and cost trends for new cars and vans are reconstructed via a detailed in-house bottom-up model populated with the latest data

- Our performance model was originally developed for the LowCVP and DfT to reproduce vehicle performance trends based on highly-disaggregated data
- All data was reconfirmed or updated to reflect the latest industry figures as a part of this study

**Input set 1 : definition of base vehicle archetypes**

| Segments: | Characteristics (for each segment) |
|---|---|
| A MINI | Cost vehicle retail price, exc. VAT |
| B SUPERMINI | Max ICE engine power (kW) |
| C LOWER MEDIUM | Kerb weight |
| D UPPER MEDIUM | Power to weight ratio |
| E EXECUTIVE | Fuel consumption (for ICE analysis) |
| H DUAL PURPOSE | |
| I MULTI PURPOSE | |

**Input set 2 : definition of base vehicle improvements**

Defined in terms of:
1) fuel economy improvements
2) added cost to base vehicle
3) introduction year in new vehicles

Measures:
- Aerodynamics improvement
- Low rolling resistance tyres
- Mild weight reduction
- Medium weight reduction
- Strong weight reduction
- Lightweight components other than BIW
- Thermo-electric waste heat recovery
- Auxiliary systems efficiency improvement

**Input set 4: power plant characteristics**

Defined for:
1) ICE
2) Batteries
3) FC systems

Parameters:
- Fuel Conversion Efficiency (%)
- DoD (%)
- Energy density
- Engine system weight penalty
- Relative engine sizes (%ICE)
- Relative motor sizes (%ICE)

**Input set 3 : definition of ICE-related improvements**

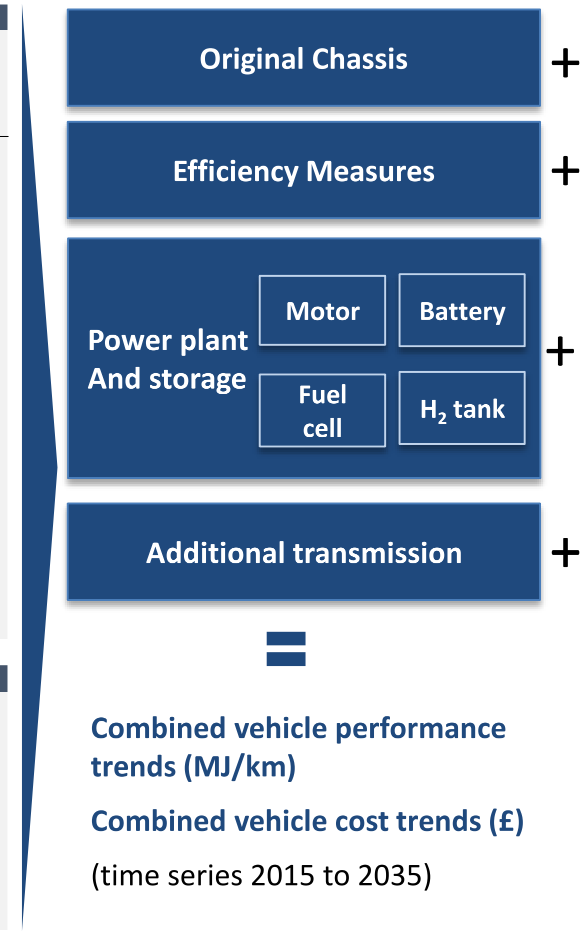
Defined in terms of:
1) fuel economy improvements
2) added cost to base vehicle
3) introduction year in new vehicles

Measures:
- Petrol - low friction design and materials
- Petrol - gas-wall heat transfer reduction
- Petrol - direct injection (homogeneous)
- Petrol - direct injection (stratified charge)
- Petrol - thermodynamic cycle improvements
- Petrol - cam-phasing
- Petrol - variable valve actuation and lift
- Diesel - variable valve actuation and lift
- Diesel - combustion improvements
- Mild downsizing (15% cylinder content reduction)
- Medium downsizing (30% cylinder content reduction)
- Strong downsizing (>=45% cylinder content reduction)
- Reduced driveline friction
- Optimising gearbox ratios / downspeeding
- Automated manual transmission (AMT)
- Dual clutch transmission (DCT)
- Regenerative braking (smart alternator)
- Start/stop
- Secondary heat recovery cycle

**Input set 5: energy storage / range**

Parameters:
- Range (ICE vehicles - benchmark)
- H2 range (to deduce H2 tank size)
- Distance in electric mode (to deduce battery size)

Note: parameters characterised in terms of electric range, range and added cost



# Trucks, buses and other applications – methodological notes

| Vehicle | Powertrain technologies | Discussion |
| --- | --- | --- |
| **HGVs and buses** | • ICEs (Diesel)<br>• Hybrid ICEs (FHV, HHV, HEV)<br>• ICEs LNG / CNG<br>• BEV<br>• FCEVs | • Technical performance and cost trends for trucks and buses were reconstructed using a combination of trusted engineering publications and our industry knowledge in these sectors<br>• Baseline assumptions were derived from well-accepted engineering studies commissioned by the European Commission in 2011/2012 and further validated by industry<br>• Additional scenarios have been included to reflect the latest technical data on novel powertrains, also based on recent UK pilot fleet operations |
| **Marine and aviation** | • Jet engines<br>• Propellers<br>• Marine engines<br>• Etc. | • For aviation and marine we have consulted specialised technical literature to understand the improvements in the fuel efficiency of incumbent solutions and likely market entrance for novel powertrains<br>• Although this is a less granular analysis, the approach is consistent with the GHG modelling approach for these technologies |

# Contents

# Surface transport

- **Cars and vans**
  - Cars
  - Vans
- Trucks and buses

# There are 3 types of development driving the efficiency improvement and cost trends of cars



**Core dimensions – summary** (non exhaustive)

1. **Improvement in the base components common to all vehicles**
   - Optimisation of conventional components: introduction of lightweight materials, optimisation of the energy requirement from auxiliary systems (ventilation, etc.), optimisation of gearbox, aerodynamic improvements, low rolling resistance tyres, etc.
   - Introduction of novel energy efficiency measures: stop-start systems, regenerative braking, etc.

2. **Improvements in the incumbent engine solutions** (internal combustion engines)
   - Low friction materials, pistons downsizing, optimisation of valves and injectors, heat recovery optimisation, etc.

3. **Improvements in the key components specific to alternative powertrain solutions**
   - Battery cost and technical performance (e.g. weight, efficiency, energy density)
   - Fuel cell system & hydrogen tank cost and technical performance (e.g. weight, efficiency, power density)
   - Electric motor (and other components specific to electric drivelines) cost and performance

**NOTE 1**: All inputs are characterised by weight, efficiency and cost implications for the final (recombined) vehicle and have a time dimension (e.g. market availability, cost, performance in 2015, 2020, 2025, … 2040)

**NOTE 2**: Each powertrain (HEV, PHEV, REEV, BEV & FCEV) is characterised by different battery requirements. This allows the different use of a battery pack in the powertrain architecture and range (km) requirements in electric mode and size of the battery (rated battery total kWh capacity, i.e. from <15kWh to > 60kWh sizes) to be taken into consideration.

# The EC $gCO_2$ /km targets and penalty system have driven, and will continue to drive, the improvement of ICE fuel efficiency

## Discussion

- The efficiency improvement technologies are part of a long list of measures which can realistically be fitted on new vehicles before 2030
- Their deployment for ICE cars reflects the expectation that the EU-wide 2021 regulatory target (95 $gCO_2$/km[1] , a 40% reduction compared with 2007 fleet average data) will be achieved by improving conventional vehicles, rather than solely relying on significant introduction of alternative powertrains (i.e. hybrids, PHEVs, REEVs and BEVs) thanks to their cost-effectiveness (TNO, 2011)
- Overall, the approach taken is in agreement with the latest industry briefings which are reporting more fuel efficient and lighter cars being deployed by car OEMs, and a general tendency to move towards more compact engines (SMMT 2015)
- Efficiency improvement trends between 2010 and 2013 were calibrated against actual market data to reduce differences to a minimum (bottom up model returns drive cycle (NEDC) fuel consumption figures, thus directly comparable with market data)
- The fleet model will include correction factors to account for real world emissions (the current gap between NEDC fuel use and observed/real-world fuel use is over 40%). These factors were developed by EE and the ICCT for the Committee on Climate Change in 2015; these can be switched on and off to allow comments on implications.

TNO, 2011; from R-AEA for CCC; 1- Equivalent to around 4.1 l/100 km of petrol or 3.6 l/100 km of diesel

ICCT: International Council for Clean Transportation NEDC: New European Driving Cycle

# FOCUS SLIDE 1: improvements in the base vehicle and ICE engines are modelled via the progressive introduction of novel energy efficient solutions



**% of new vehicles adopting the improvement**

NOTE: different powertrains are improved over time by different combinations of measures and penetration rates

| Measure (non exhaustive, mainly for C/D) | 2010 | 2015 | 2020 | 2025 | 2030 | 2040 |
|---|---|---|---|---|---|---|
| Petrol - low friction design and materials | 10% | 15% | 50% | 70% | 90% | 100% |
| Petrol - gas-wall heat transfer reduction | 10% | 15% | 40% | 60% | 80% | 100% |
| Petrol - direct injection (homogeneous) | 10% | 15% | 55% | 50% | 45% | 40% |
| Petrol - direct injection (stratified charge) | 0% | 0% | 5% | 8% | 10% | 15% |
| Petrol - thermodynamic cycle improvements | 0% | 0% | 0% | 3% | 5% | 10% |
| Petrol - cam-phasing | 10% | 15% | 40% | 33% | 25% | 10% |
| Petrol - variable valve actuation and lift | 5% | 13% | 20% | 28% | 35% | 45% |
| Diesel - variable valve actuation and lift | 0% | 13% | 25% | 38% | 50% | 70% |
| Diesel - combustion improvements | 10% | 55% | 60% | 75% | 90% | 100% |
| Mild downsizing (15% cylinder content reduction) | 25% | 43% | 60% | 43% | 25% | 5% |
| Medium downsizing (30% cylinder content reduction) | 15% | 23% | 30% | 40% | 50% | 55% |
| Strong downsizing (>=45% cylinder content reduction) | 5% | 8% | 10% | 18% | 25% | 40% |
| Reduced driveline friction | 5% | 23% | 40% | 60% | 80% | 100% |
| Optimising gearbox ratios / downspeeding | 10% | 35% | 60% | 75% | 90% | 100% |
| Automated manual transmission (AMT) | 5% | 18% | 30% | 40% | 50% | 40% |
| Dual clutch transmission (DCT) | 1% | 11% | 20% | 30% | 40% | 60% |
| Regenerative braking (smart alternator) | 1% | 13% | 25% | 43% | 60% | 100% |
| Start/stop (Petrol) | 15% | 20% | 30% | 40% | 50% | 75% |
| Start/stop (Diesel) | 35% | 40% | 50% | 63% | 75% | 100% |
| Aerodynamics improvement | 5% | 18% | 30% | 50% | 70% | 90% |
| Low rolling resistance tyres | 20% | 60% | 100% | 100% | 100% | 100% |
| Mild weight reduction | 5% | 35% | 65% | 63% | 60% | 30% |
| Medium weight reduction | 3% | 7% | 10% | 18% | 25% | 50% |
| Strong weight reduction | 2% | 3% | 3% | 5% | 7% | 20% |
| Lightweight components other than BIW | 0% | 1% | 2% | 6% | 10% | 40% |
| Thermo-electric waste heat recovery | 0% | 0% | 0% | 3% | 5% | 20% |
| Secondary heat recovery cycle | 0% | 1% | 1% | 3% | 5% | 20% |
| Auxiliary systems efficiency improvement | 30% | 45% | 60% | 80% | 100% | 100% |
| Thermal management | 25% | 38% | 50% | 63% | 75% | 100% |

The introduction timeline by measure is derived from a combination of observed market data and technical literature:

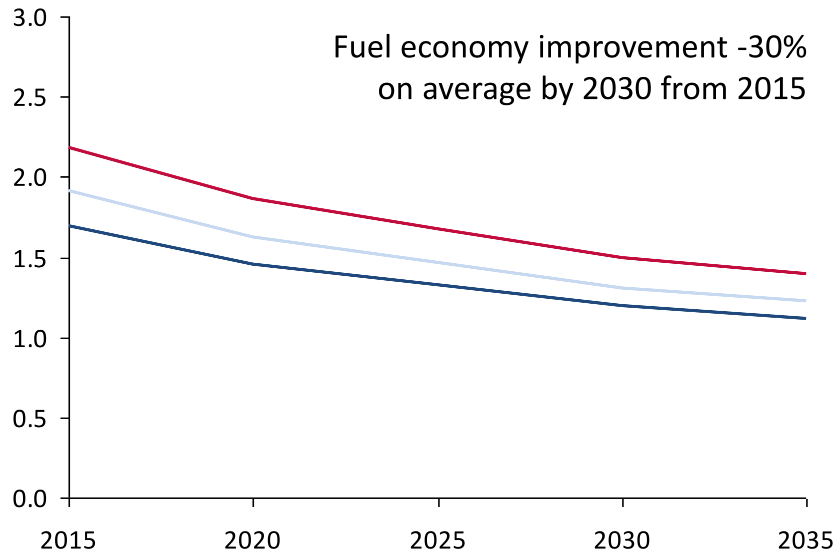
- 2010 and 2015 deployment: based on observed deployment (e.g. data on stop-start deployment in vehicles) and further calibrated to reproduce the average market data by segment (on cost and performance)
- Future deployment: based on the most cost-efficient way to improve conventional vehicles in line with EC targets by 2021 (from R-AEA analysis for the CCC – see annex)

# Projected performance of conventional ICE vehicles

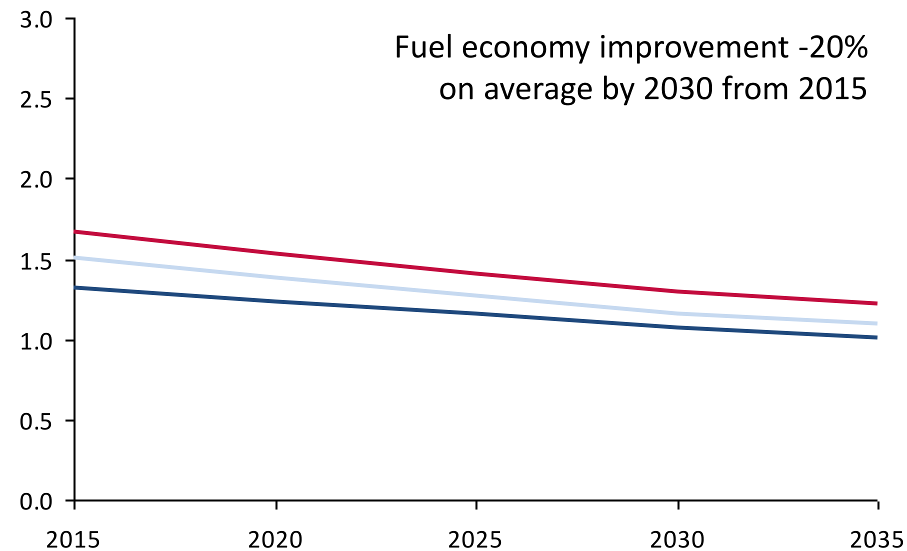


B SUPERMINI
C LOWER MEDIUM
D UPPER MEDIUM

**Petrol ICEs – MJ/km (NEDC)**




**Diesel ICEs – MJ/km (NEDC)**



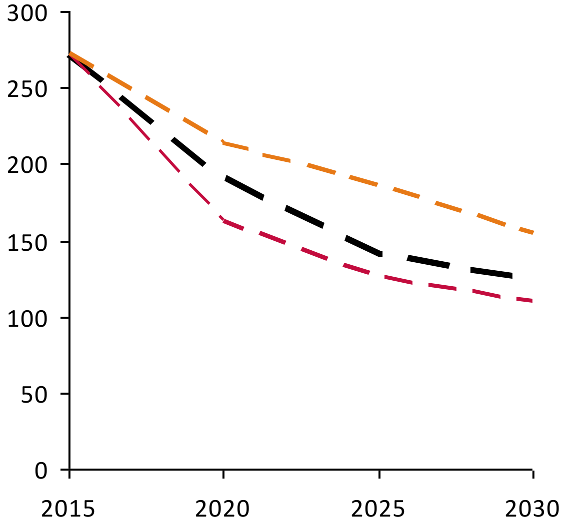

**Discussion**

- Best available technical literature and industry insights suggest that the introduction of improvements in the base vehicle and ICE engine components will gradually reduce the fuel consumption of new vehicles by ~ 30% from 2015 levels by 2030 (actual figures depend on vehicle segment and fuel type). Key improvements are described in the previous slides.
- Petrol vehicles are expected to experience the greatest fuel consumption reduction by 2030 as some of the petrol efficiency measures (i.e. direct injection, stratified charge, thermodynamic cycle improvements) have the highest fuel reduction potential
- However, diesel vehicles (especially for medium and large cars) are expected to remain more efficient than petrol equivalents

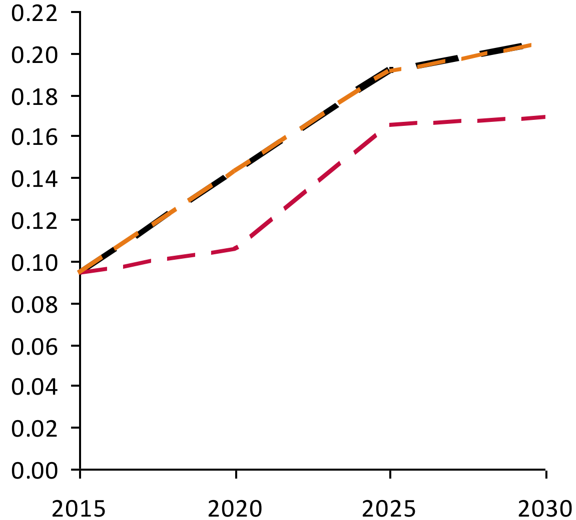
# FOCUS SLIDE 2: battery performance and costs trends - main assumptions

Baseline
Low ( = best case)
High (= worse case)

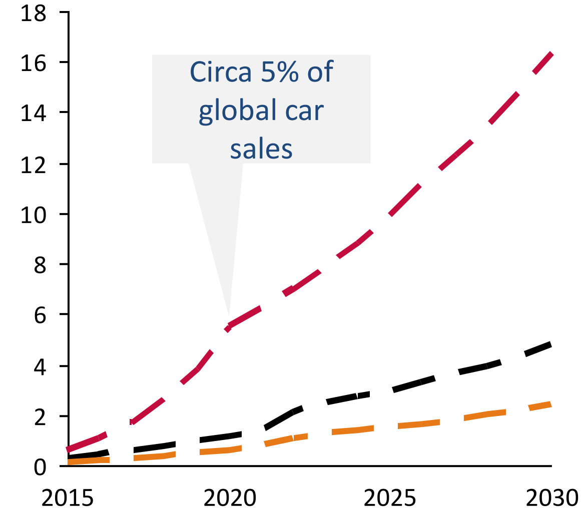
Battery cost (35-60 kWh)
(2014 £/kWh)




Battery energy density (35-60 kWh)
(kWh/kg)




Million PH/BEV sales
(global figures)

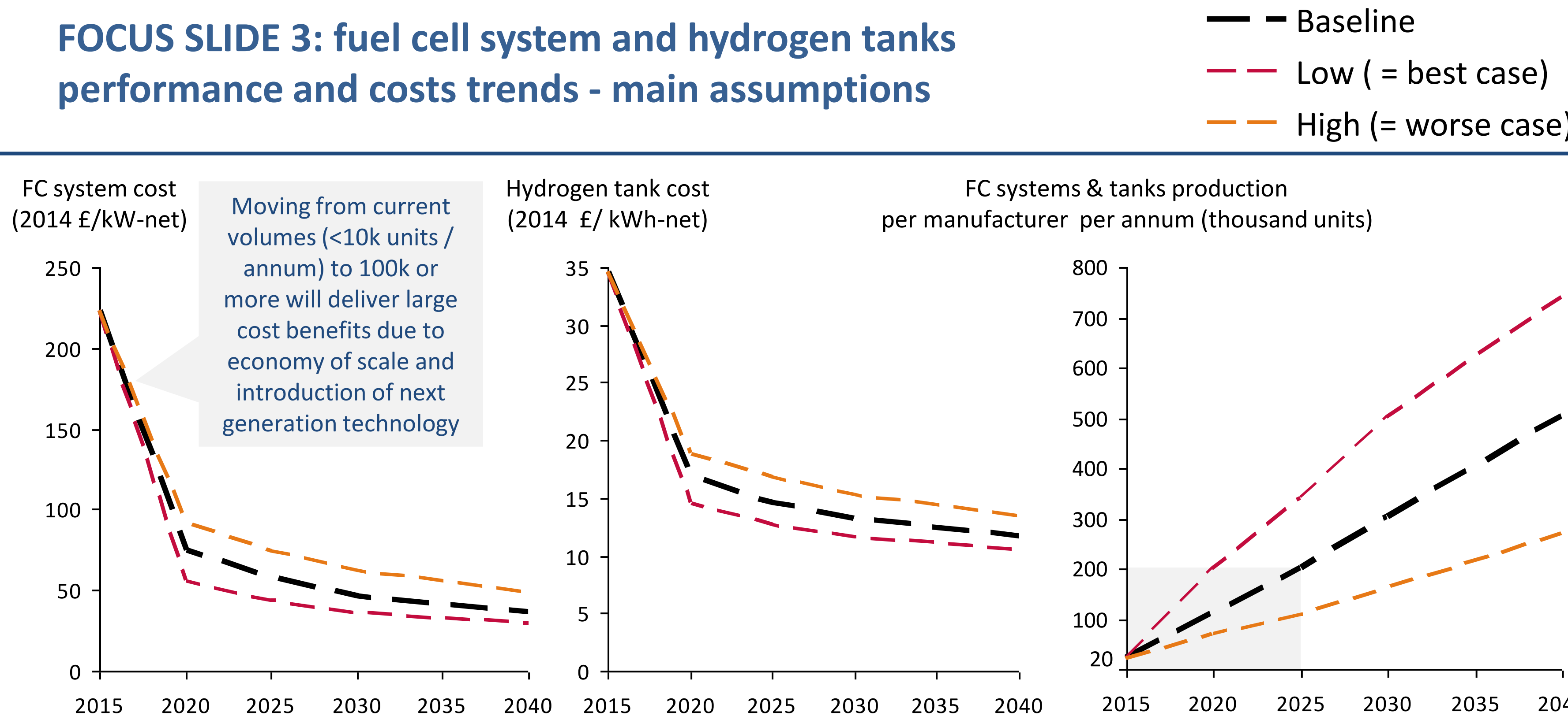



## Discussion

- Between 2010 and 2015 improvements in pack energy density for current technology (intercalated Li-ion) have been incremental, with an increase ca. 15% between 2010 and 2015. Other improvements include higher-density cathode chemistries, reduced weight and increase in depth of discharge (DoD) capabilities.
- In the following 10-15 years, given the length of the process to implement new breakthroughs in final applications and the stringent demands (life, power, size, safety) of the automotive industry, it is expected that lithium-ion chemistry will still be prevalent, with progressive improvements (in the energy density, DoD, thermal management, etc.) . It is thereby expected that no 'step change' technology will be fully introduced in the automotive market before 2030[1]
- In the **baseline scenario** we assume that policy support in developed countries brings the uptake of plug-in & BEV vehicles to follow the same trajectory as that of hybrid electric vehicles (~ 1% PH/BEV global uptake by **2020**). In the **worse case scenario** this is reduced to far less than 1% while in the **best case scenario** this reaches 5% of global sales by **2020** (note: the latter requires more aggressive zero-emission policy interventions in key national markets)

NOTE 1 - current R&D efforts are considering high energy 'chemical reaction' solutions with the potential to drastically increase the energy density with a theoretical 2,600Wh/kg for Li-Sulphur (compared to 550Wh/kg for current solutions). It is however unclear whether these solutions will make it in the market before 2030 due to the reasons discussed above

# FOCUS SLIDE 3: fuel cell system and hydrogen tanks performance and costs trends - main assumptions




## Discussion

- Large OEM-internal R&D programmes have delivered substantial improvements over the past 10 years in terms of: specific energy per unit weight and per unit volume (e.g. current systems are 2 to 4 times more compact and lighter compared to ~ Y2000 models), FC stack lifetime and performance (e.g. overall power plant efficiency well beyond 50%). Future improvements are expected to be available from better membranes, better cell designs, higher working temperature and streamlined FC system packaging but are unlikely to deliver the same gains over the coming 10-15 years. In all scenarios we assume that the next generation of FC stacks, systems and related BOP components enters the market when achieving the 200k units p.a. milestone. Further technology progress (such as extremely reduced catalyst loading, novel membrane materials, etc.) is assumed for higher volumes (consistent with the OEMs' statements and international R&D publications). Most of these technology solutions are aimed at simplifying and reducing the costs of the FC system, as well as improving life and reducing weight.
- In the **baseline scenario** we assume that the main manufacturers succeed in achieving sufficient scale economies via cooperative agreements (e.g. JVs) and international market demand capable to attract around 200k units per annum by **2025**. In the **worse case scenario** this is modelled to happen 10 years after (in **2035**) while in the **best case scenario** this happens in **2020**[1]

NOTE 1: this latter is the announced volume/year target by the major OEMs active in this sector; such results would however likely require more aggressive zero-emission policy interventions in key national markets such as Japan, US and Europe

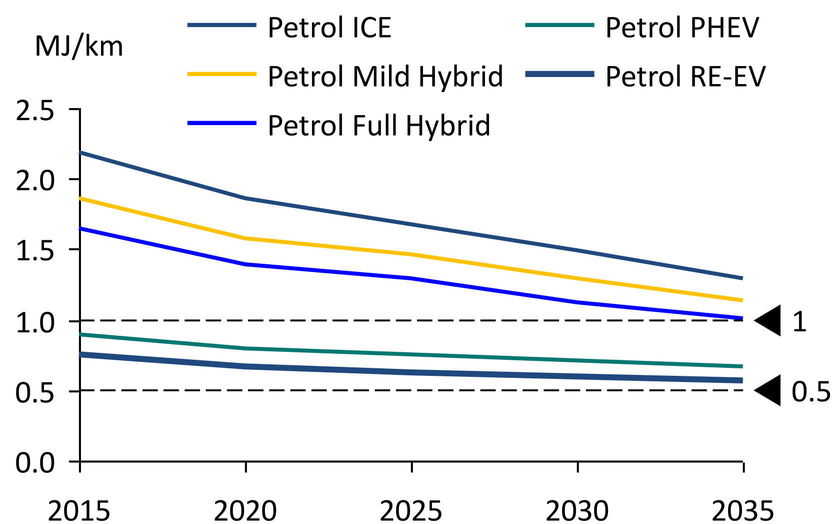
# Technical literature and our modelling suggest that PHEVs and RE-EVs will remain the most efficient ICE-equipped vehicles



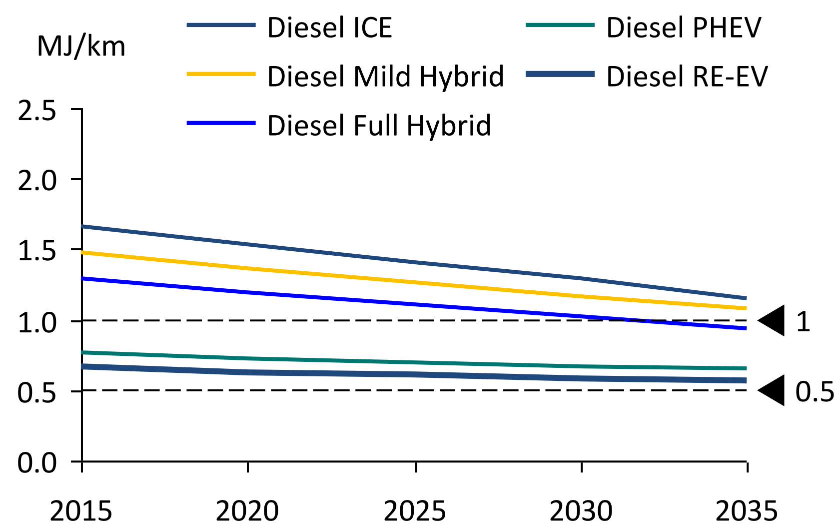
## Discussion

- Fuel efficiency improvement trends for hybrids, PHEV and RE-EVs to 2030 are likely to be less aggressive than for ICEs as key efficiency improvement technologies for ICEs are typically already integrated into hybrids from the outset (such as stop-start transmission improvements, etc. - all delivering major fuel consumption reductions). Similarly, a lower number of 'additional' efficiency measures apply to these powertrains
- The fuel efficiency measures applying to PHEVs and RE-EVs are the same. Differences in their fuel efficiency improvement trends are mainly due to the greater electric-only range for RE-EVs, which creates potentially greater room for improvement coming from battery advancements

### Petrol (D – upper medium) – MJ/km




### Diesel (D – upper medium) – MJ/km



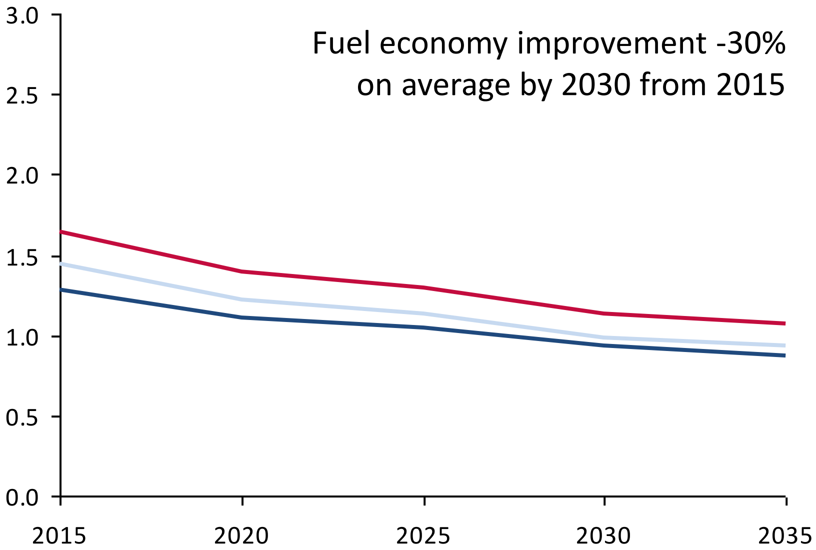

Element Energy analysis

# Projected performance of Hybrid ICE solutions

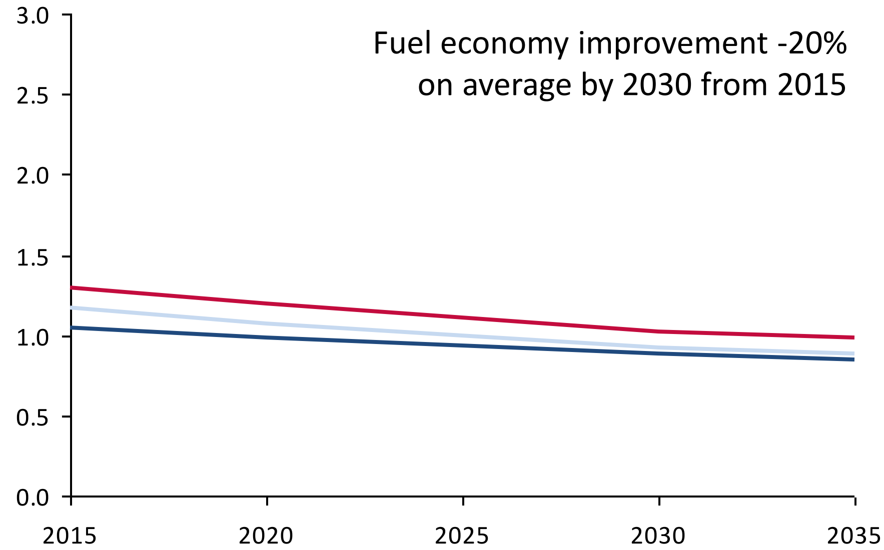


B SUPERMINI
C LOWER MEDIUM
D UPPER MEDIUM

**Petrol Full Hybrid – MJ/km (NEDC)**




**Diesel Full Hybrid – MJ/km (NEDC)**



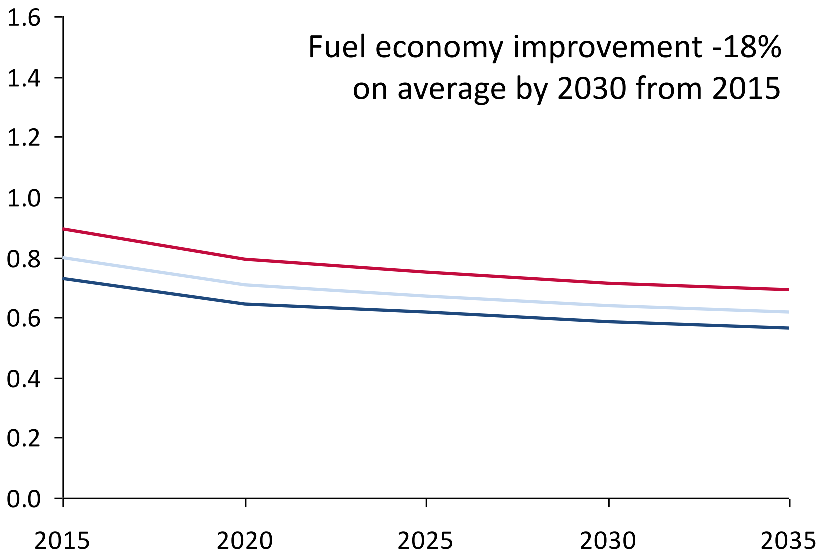

**Discussion**

- The figures reported in this slide are for full hybrids as our modelling (as well as actual real-world data) suggest minor differences between mild and full hybrid technologies (the main difference between the two solutions is the size of the electric motor). Our analysis suggests that the two technologies have close fuel efficiency performance given the similarity of their powertrain architecture (i.e. full hybrids show up to 10% improvement compared to mild hybrids on a MJ/km basis)
- Hybrid ICEs are expected to benefit from some of the efficiency improvement technologies for conventional ICEs (discussed above) as well as improvements in the electric components (battery and ancillary equipment)

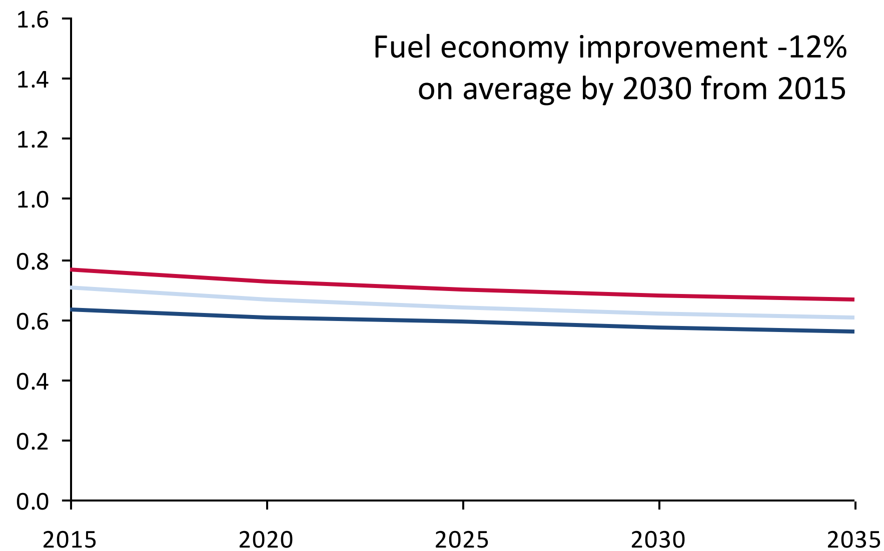
# Projected performance of PHEV solutions

B SUPERMINI
C LOWER MEDIUM
D UPPER MEDIUM

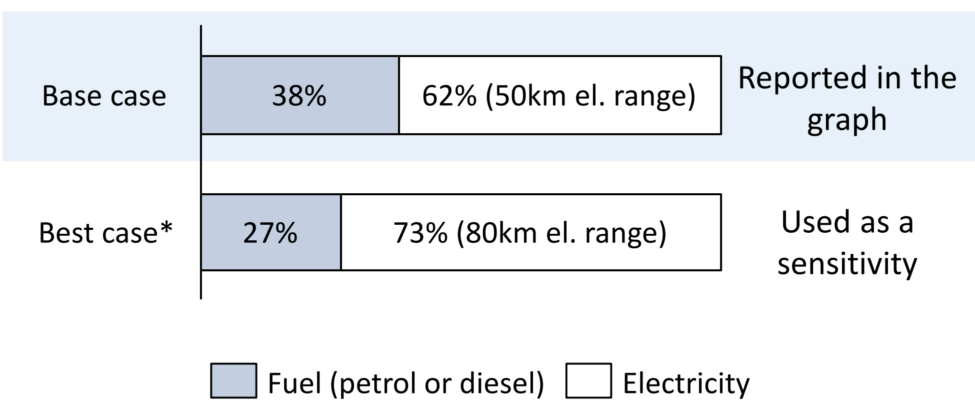
## Petrol PHEV – MJ / km (fuel + electricity, NEDC)




## Diesel PHEV – MJ / km (fuel + electricity, NEDC)




**Share of mileage driven in fuel or electric mode (%)**




- The % of mileage driven in electric mode was calculated based on the full-electric range expected for new vehicles (derived from latest market data - e.g. *Mitsubishi Outlander* - and trends) and the distribution of UK travel lengths
- 'Base' and 'best' cases reflect the impact of different levels of electrification ambition on the Tank to Wheel emissions

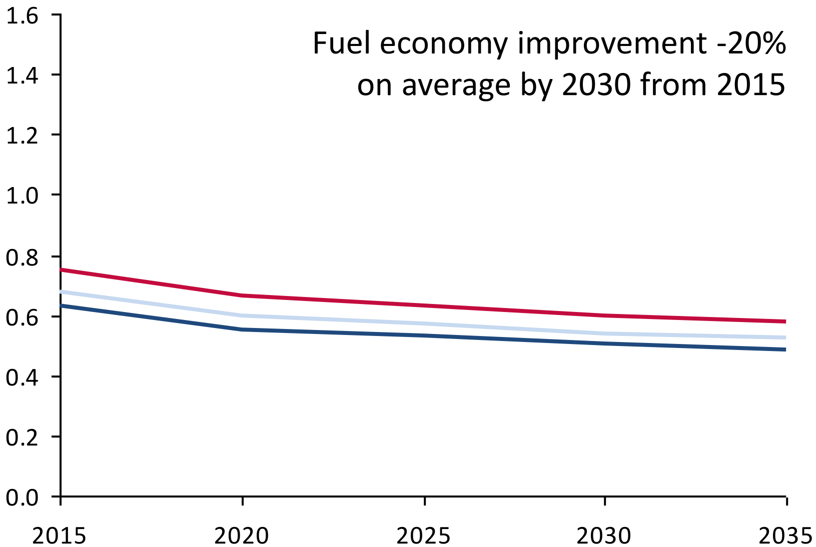
Element Energy analysis; * Note: for the Best case we assume 62% in electric mode in 2015, increasing linearly to 73% in 2020. This reflects the underlying assumptions on range for this scenario of 50 km in 2015 and 80km in 2020

# Projected performance of RE-EV solutions

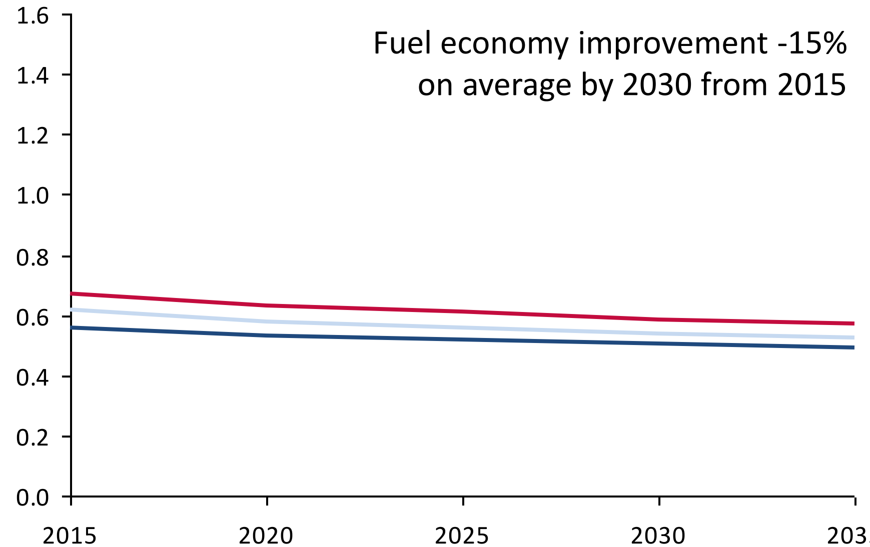


B SUPERMINI
C LOWER MEDIUM
D UPPER MEDIUM

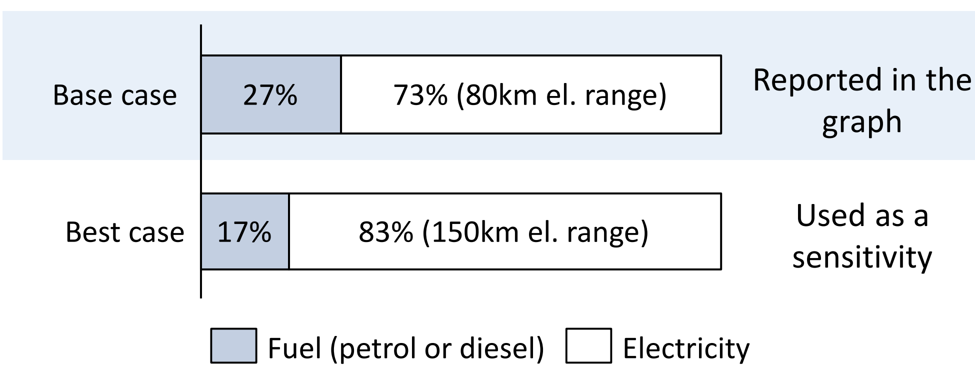
**Petrol RE-EV – MJ/km (fuel + electricity, NEDC)**




**Diesel RE-EV – MJ/km (fuel + electricity, NEDC)**




**Share of mileage driven in fuel or electric mode (%)**




- The % of mileage driven in electric mode was calculated based on the full-electric range expected for new vehicles (derived from latest market data - *BMW i3, Volt/Ampera*, etc. - and trends) and the distribution of UK travel lengths
- 'Base' and 'best' cases reflect the impact of different levels of electrification ambition on the Tank to Wheel emissions

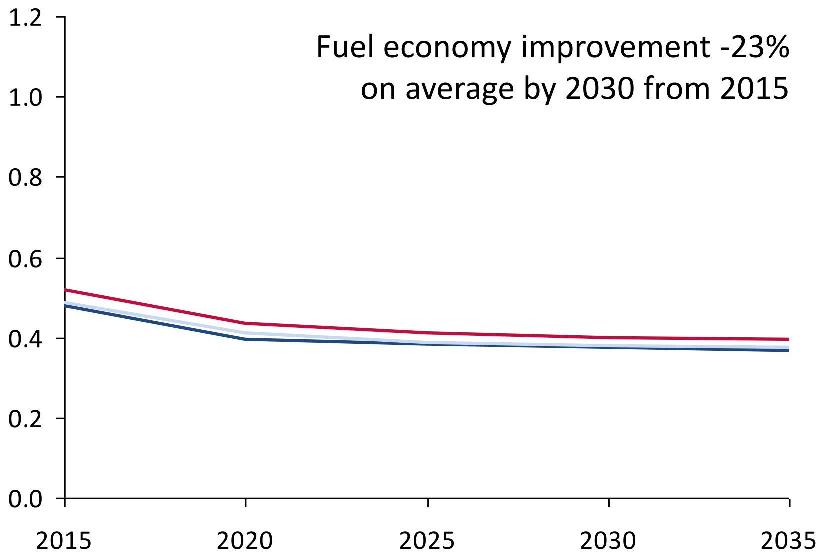
Element Energy analysis

# Projected performance of BEV and FCEV solutions

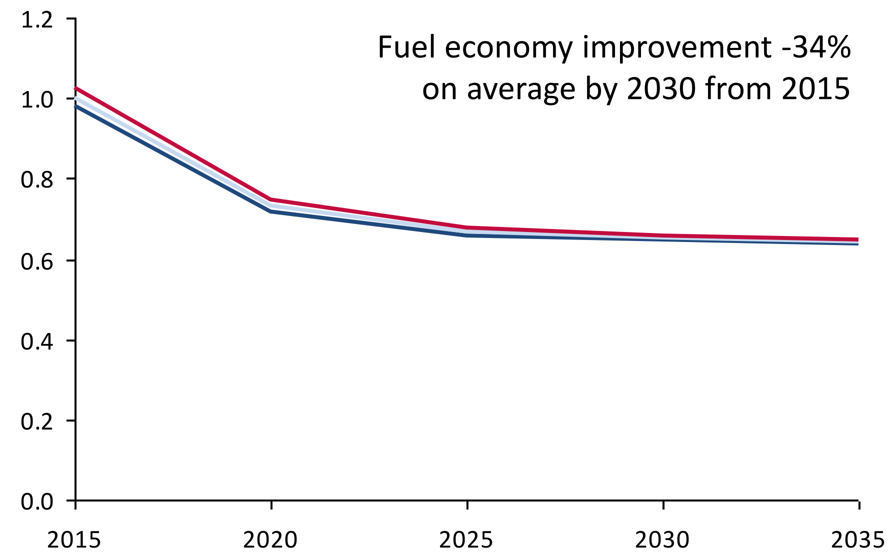
B SUPERMINI
C LOWER MEDIUM
D UPPER MEDIUM



**BEV – MJ/km (NEDC)**




**FCEV – MJ/km (NEDC)**




**Discussion**

- Battery electric vehicles are 70% to 80% more efficient than petrol or diesel ICE solutions. They are the most efficient surface transport technology thanks to the simplicity of the powertrain (battery & electric motor), the excellent lithium-ion battery electrical performance (80-90% charge / discharge efficiency) and the motor efficiency (>75%)
- Fuel cell vehicles are 40% to 60% more efficient than petrol or diesel solutions. The lower fuel economy performance of FCEVs compared to BEVs is mainly due to the lower efficiency of the main power plant (average fuel cell system efficiency is assumed close to 55% by 2020 in this study)
- Both BEVs and FCEVs benefit from some of the same efficiency improvement technologies as conventional ICE & hybrid vehicle solutions (discussed above) as well as improvements in the electric and fuel cell components (battery, fuel cell system and ancillary equipment)

Element Energy analysis

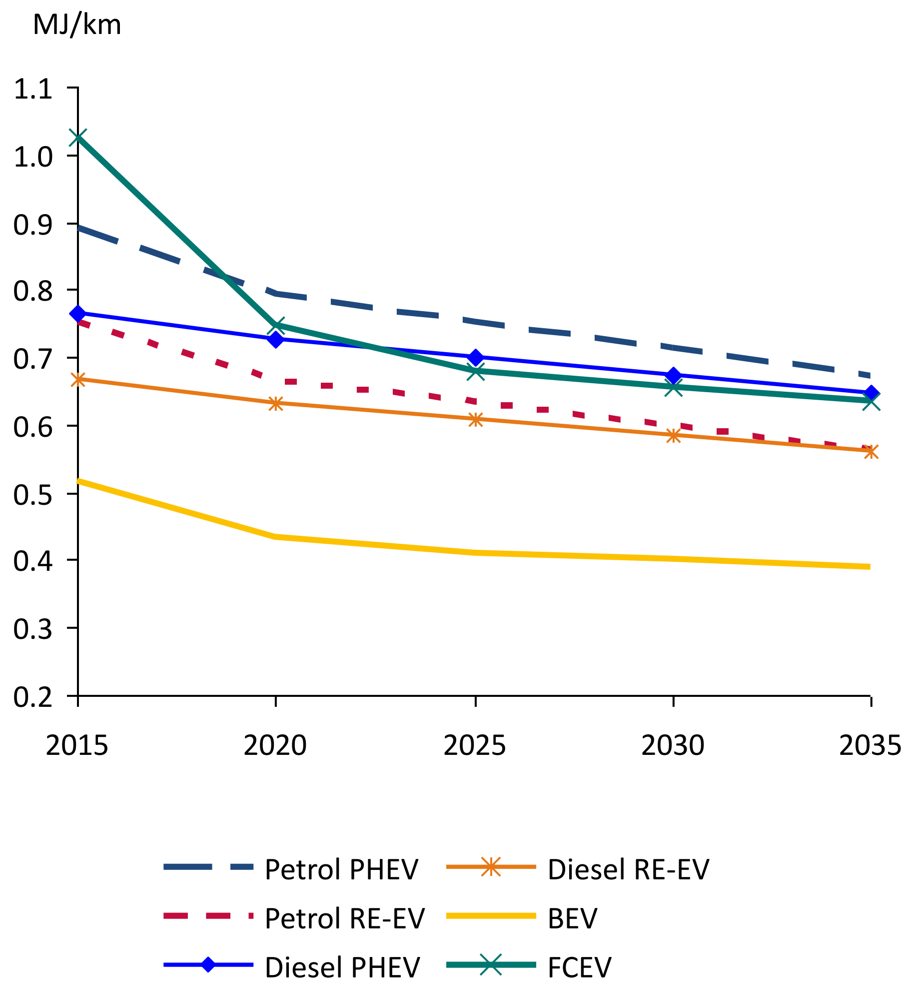
# Efficiency comparison between PHEV, REEV, BEV and FCEVs – final remarks



## Discussion

- When compared against PHEV and RE-EV solutions, BEVs are still the most efficient powertrain
- FCEVs are expected to perform between best-of class PHEV and RE-EV solutions by 2020/2025 onwards on a MJ/km basis (e.g. as the next generation of purpose-built FCEVs enter the market and thus fully benefit from streamlined architecture and optimised components)
- FCEVs and BEVs are the only zero-tailpipe-emission technologies available for surface transport applications, therefore their societal benefits go well beyond the improved fuel economy (i.e. no TTW GHG emissions and no toxic tailpipe emissions such as SOx, NOx, and PMs)
- It is worth noting that FCEVs are the only technology providing zero emission transport and long driving range: this is assumed to be *minimum* 500km throughout the time horizon considered in this study and for *all segments* (BEV maximum range is expected to depend on the segment, with values between 200 to 400km by 2030)

## D – upper medium car – MJ/km



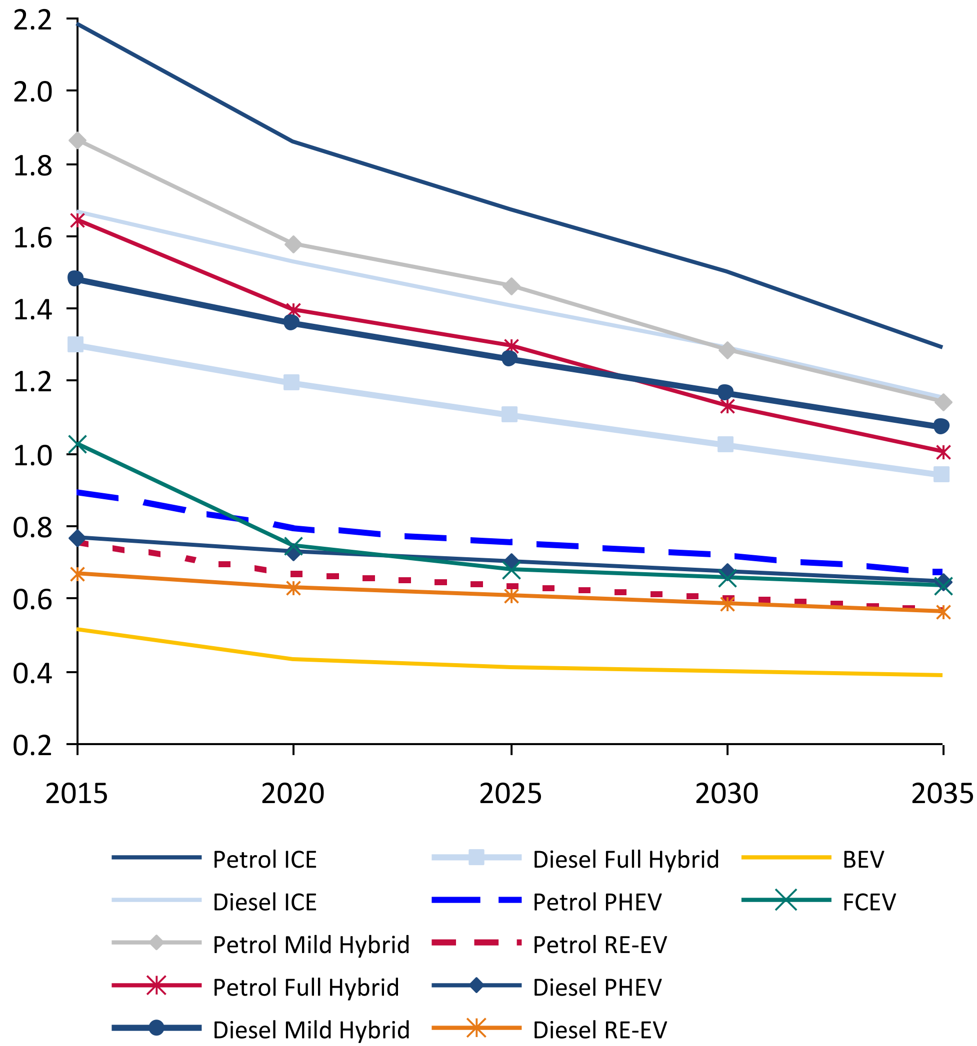
# All passenger vehicle solutions are expected to substantially improve their fuel efficiency performance over the next 15 years



## Discussion

- ICE vehicles are likely to experience the greatest fuel consumption reduction by 2030 (e.g. ~ 30% from 2015 levels on average), reflecting 1) the industry efforts to meet the EC GHG regulations by 2021 and 2) the greatest potential for fuel optimisation in their powertrain architecture.
- All of the advanced hybrid solutions (PHEV and RE-EVs) can deliver substantial fuel (and thus emission) savings per km driven compared to ICE and hybrid ICE vehicles.
- BEVs are by far the most efficient powertrain available. FCEV are expected to perform between best-of class PHEV and RE-EV solutions by 2020/2025 onwards on a MJ/km basis.
- FCEVs and BEVs are the only zero-tailpipe-emission technologies available. Their societal benefits thereby go well beyond the improved fuel economy (i.e. no TTW GHG emissions and no toxic tailpipe emissions such as SOx, NOx, and PMs).
- Efficiency improvement trends for BEVs and advanced hybrids are less aggressive than for ICE solutions by 2030, as key efficiency measures and optimisations are typically integrated from the outset.

## Segment D (upper medium car) – MJ/km (NEDC)



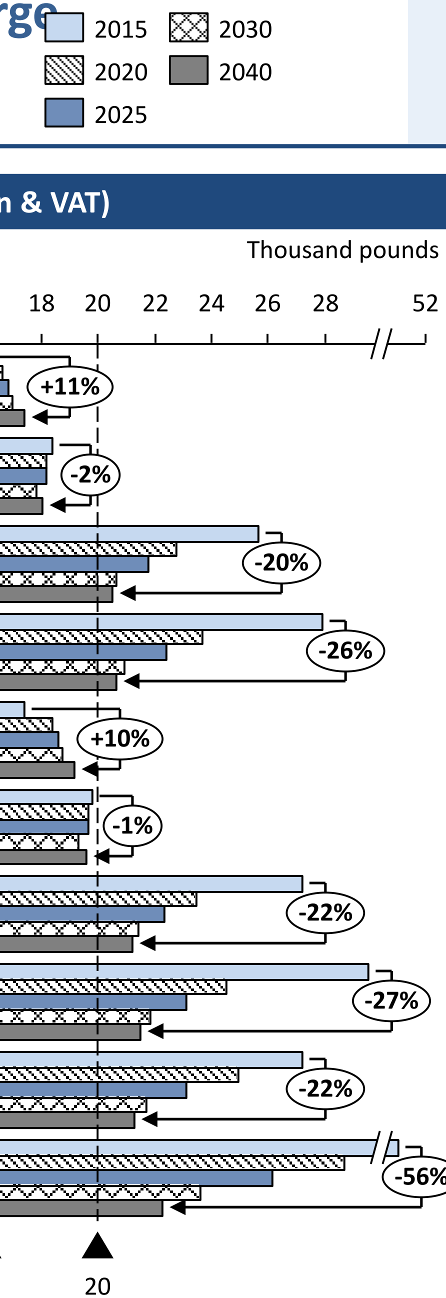
# Cost premiums over conventional ICEs are expected to converge but not fully disappear by 2030 for alternative powertrains



## Discussion

- Technical literature and our bottom-up modelling suggest that the cost premium between conventional ICE and alternatives (hybrid ICE, BEV and FCEV solutions) will substantially shrink throughout the 2015-2030 period
- Reductions will mainly be driven by larger manufacturing volumes for non conventional powertrains (especially BEV and FCEV) and reduction in battery & FC costs and ancillary equipment
- Some of the cost reductions for hybrid ICEs are hindered by the increase in the base ICE vehicle costs (due to the progressive inclusion of novel efficiency improvement technologies and optimised components)
- PHEV / RE-EV premium over baseline ICE is expected to reduce to ~15% by **2030**
- Cost premium over the ICE for BEVs and FCEVs is also expected to be 15-25% by 2030 while the cost difference between FCEV and BEV solutions is expected to be marginal (~£2,000 by 2030)

## D – upper medium car – cost (excluding margin & VAT)




**NOTE:** Costs only. This discussion does not take into consideration margin and pricing strategies as these may considerably change year on year and are OEM specific

# Surface transport

- **Cars and vans**
  - Cars
  - Vans
- Trucks and buses

# Key dimensions driving the reconstruction of the commercial van technical and cost trends



## Discussion

- The van cost and performance model works as the passenger car model discussed in the previous section
- The performance trends are thereby driven by the same key dimensions (see picture on right hand side)
- All inputs are however adapted to the van case to reflect specific market requirements in terms of powertrain architecture
- Unlike in the case of cars, a Fuel Cell RE-EV is modelled for vans (instead of full FCEV), to reflect market trends (e.g. SymbioFCell, Nissan-Intelligent Energy)

### There are 3 types of development driving the efficiency improvement and cost trends of cars

CARS

**Core dimensions – summary** (non exhaustive)

1. **Improvement in the base components common to all vehicles**
   - Optimisation of conventional components: introduction of lightweight materials, optimisation of the energy requirement from auxiliary systems (ventilation, etc.), optimisation of gearbox, aerodynamic improvements, low rolling resistance tyres, etc.
   - Introduction of novel energy efficiency measures: stop-start systems, regenerative braking, etc.
2. **Improvements in the incumbent engine solutions** (internal combustion engines)
   - Low friction materials, pistons downsizing, valves and injectors optimisation, heat recovery optimisation, etc.
3. **Improvements in the key components specific to alternative powertrain solutions**
   - Battery cost and technical performance (e.g. weight, efficiency, energy density)
   - Fuel cell system & hydrogen tank cost and technical performance (e.g. weight, efficiency, power density)
   - Electric motor (and other components specific to electric drivelines) cost and performance

**NOTE 1**: All inputs are characterised by weight, efficiency and cost implications for the final (recombined) vehicle and have a time dimension (e.g. market availability, cost, performance in 2015, 2020, 2025, … 2040)

**NOTE 2**: Each powertrain (HEV, PHEV, REEV, BEV & FCEV) is characterised by different battery requirements. This allows the different use of a battery pack in the powertrain architecture and range (km) requirements in electric mode and size of the battery (rated battery total kWh capacity, i.e. from <15kWh to > 60kWh sizes) to be taken into consideration.

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# The efficiency improvement trends for ICE vans are driven by the industry progress in the car segment and the EC $CO_2$ targets



## Discussion

- Vans and cars share a large number of the same efficiency improvement technologies and thereby cross-segment benefits / transfers are expected to accelerate their penetration in both markets (for example, many Class I (small) vans often use the same powertrain platform as passenger cars)
- The rate of penetration of such measures in the van market is expected to be slower than for cars but still in line for the industry to meet the EU-wide 2021 regulatory target (147 $gCO_2$/kilometre, 19% less than the 2012 average)
- As for cars, it is expected that the 2021 target will be mainly achieved by improving conventional ICE vehicles rather than accelerating the introduction of alternative powertrains (i.e. hybrids, PHEVs, BEVs) due to cost-effectiveness
- For heavy van classes (Class II and above, which do not generally share the same powertrain with car equivalents) fuel efficiency improvements are also influenced by commercial pressures, where a higher weight on fuel costs in the overall cost of ownership (due to higher mileages) incentivises manufacturers to promote more fuel efficient solutions
- Efficiency trends between 2010 and 2013 were calibrated to reflect weighted average fuel sales and this calibration has also been used to align future trends (2015-2030)
- As for the case of cars, a ‘real-world factor’ can be applied to modelled real world emissions/fuel use, based on our recent work with the ICCT

# FOCUS SLIDE 1: van-specific efficiency measures and expected deployment over time



**% of new vehicles adopting the improvement**

NOTE: different powertrains are improved over time by different combination of measures and penetration rates

| Measure (non exhaustive, mainly for medium/large vans) | 2010 | 2015 | 2020 | 2025 | 2030 | 2040 |
|---|---|---|---|---|---|---|
| Diesel - variable valve actuation | 0% | 0% | 0% | 8% | 15% | 55% |
| Diesel - combustion improvements | 5% | 28% | 50% | 63% | 75% | 85% |
| Mild downsizing (15% cylinder content reduction) | 25% | 38% | 50% | 30% | 10% | 0% |
| Medium downsizing (30% cylinder content reduction) | 10% | 15% | 20% | 33% | 45% | 65% |
| Reduced driveline friction (mild reduction) | 0% | 10% | 20% | 33% | 45% | 55% |
| Reduced driveline friction (strong reduction) | 0% | 8% | 25% | 23% | 20% | 30% |
| Optimising gearbox ratios / downspeeding | 5% | 20% | 55% | 68% | 80% | 90% |
| Improved M/T transmission | 5% | 20% | 55% | 68% | 80% | 90% |
| Downspeeding via slip controlled clutch and DMF deleted | 5% | 8% | 10% | 13% | 15% | 20% |
| Automated manual transmission (AMT) | 0% | 10% | 20% | 28% | 35% | 25% |
| Dual clutch transmission (DCT) | 0% | 10% | 30% | 28% | 25% | 45% |
| Regenerative braking (smart alternator) | 0% | 10% | 20% | 33% | 45% | 85% |
| Start/stop | 50% | 65% | 100% | 100% | 100% | 100% |
| Aerodynamics improvement - minor | 0% | 5% | 20% | 28% | 37% | 50% |
| Aerodynamics improvement - major | 0% | 5% | 20% | 23% | 25% | 50% |
| Low rolling resistance tyres | 25% | 40% | 90% | 88% | 85% | 85% |
| BIW mild weight reduction (10% weight reduction) | 5% | 10% | 20% | 33% | 45% | 15% |
| BIW medium weight reduction (25% weight reduction) | 0% | 8% | 10% | 10% | 10% | 35% |
| BIW strong weight reduction (40% weight reduction) | 0% | 5% | 15% | 8% | 0% | 13% |
| Lightweight components other than BIW | 0% | 10% | 25% | 13% | 0% | 30% |
| Thermo-electric generation | 0% | 0% | 0% | 0% | 0% | 15% |
| Secondary heat recovery cycle | 0% | 0% | 0% | 0% | 0% | 15% |
| Auxiliary systems improvement (thermal) | 5% | 10% | 35% | 43% | 50% | 60% |
| Auxiliary systems improvement (lubrication, vacuum) | 5% | 15% | 25% | 30% | 35% | 25% |
| Other thermal management | 10% | 20% | 40% | 50% | 60% | 85% |
| Electrical assisted steering (EPS, EPHS) | 0% | 5% | 10% | 15% | 20% | 25% |

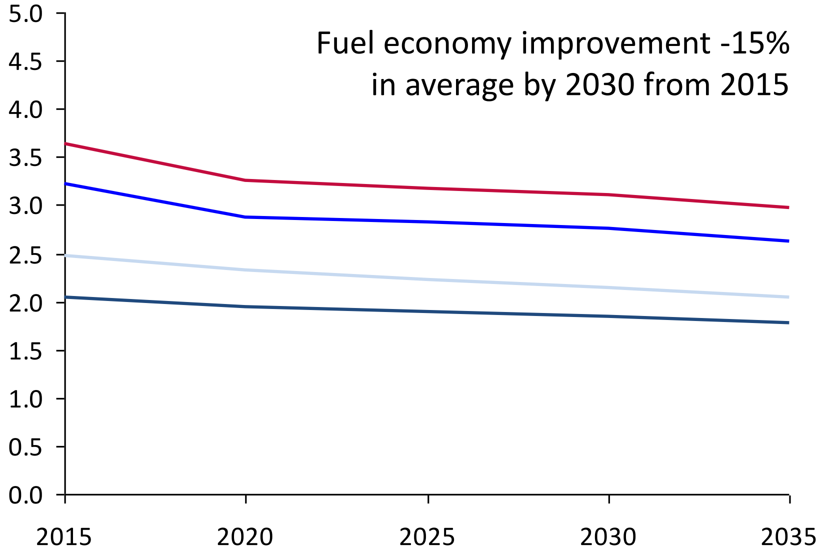
**Note**: As for the car case (discussed above), the introduction timeline by measure is derived from a combination of observed market data (current deployment data and fine-tune calibration to observed cost and performance values by main segment) and technical literature (future deployment: R-AEA analysis for the CCC )

# Projected performance of conventional ICE commercial vans

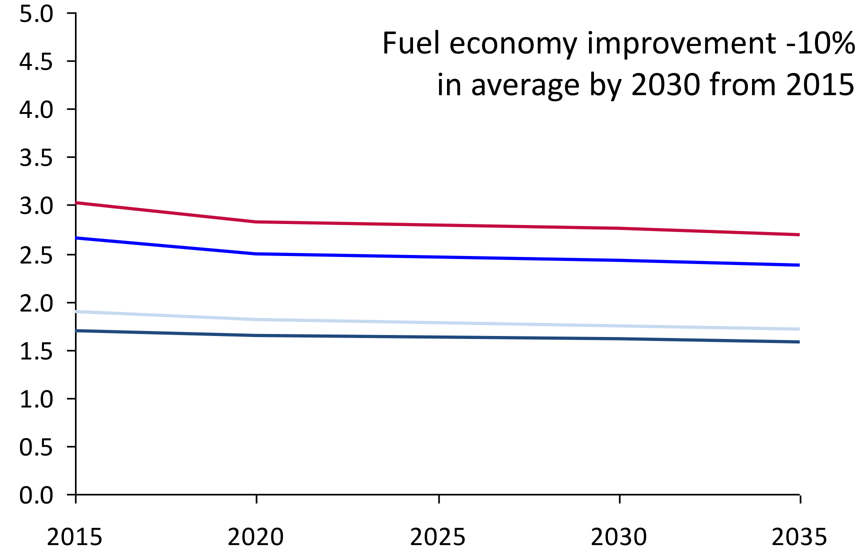
1 Small Car Derived
2 Large Car Derived
3 Standard Panel
4 Large Panel



## Petrol ICEs – MJ/km (NEDC)




## Diesel ICEs – MJ/km (NEDC)




### Discussion

- As for cars, vans are expected to become more fuel efficient over time as an increasing number of efficiency improvement technologies (most of which shared with cars) are introduced in new vehicles (see previous slide)
- Best available technical literature and industry insights however suggest a slower rate of penetration than for cars, resulting in an overall lower fuel efficiency improvement by 2030 – between 10% to 20% from 2015 levels (actual figures depend on vehicle segment and fuel type)
- This reflects a van market characterised by a higher sensitivity to price premium and an overall less ambitious EU-wide $CO_2$ regulatory target (in relative terms)

Element Energy analysis; 1 – vans are defined as vehicles used to carry goods weighing up to 3.5 tonnes

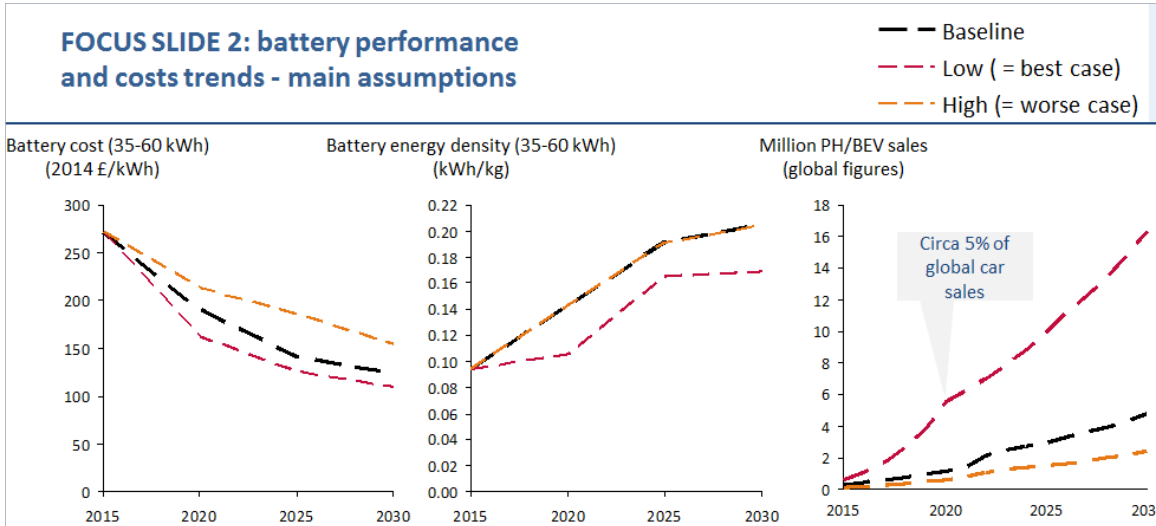
# FOCUS SLIDE 2: the battery performance and cost trend assumptions for vans are as for cars

## Discussion

- The van cost and performance model uses the same battery assumptions as per passenger cars in terms of technology roadmap (improvement of lithium-ion batteries)
- For small to medium size vans, the battery pack size (kWh) is very similar to the case of cars and therefore so is the £/kWh
- For larger vans fitted with large packs (e.g. >50kWh), the battery price is lower in £/kWh terms. This is because large packs spread the fixed costs over a greater size and also because they can use large cells (>50Ah)

### FOCUS SLIDE 2: battery performance and costs trends - main assumptions

CARS




**Discussion**

- In the past 5 years improvements in pack energy density for current technology (intercalated Li-ion) have been incremental, with an increase ca. 15% between 2010 and 2015. Other improvements include higher-density cathode chemistries, reduced weight and increase in depth of discharge (DoD) capabilities.
- In the following 10-15 years, given the length of the process to implement new breakthroughs in final applications and the stringent demands (life, power, size, safety) of the automotive industry, it is expected that lithium-ion chemistry will still be prevalent, with progressive improvements (in the energy density, DoD, thermal management, etc.) . It is thereby expected that no 'step change' technology will be fully introduced in the automotive market before 2030[1]
- In the **baseline scenario** we assume that policy support in developed countries brings the uptake of plug-in & BEV vehicles to follow the same trajectory as that of hybrid electric vehicles (~ 1% PH/BEV global uptake by **2020**). In the **worse case scenario** this is reduced to far less than 1% while in the **best case scenario** this reaches 5% of global sales by **2020** (note: the latter requires more aggressive zero-emission policy interventions in key national markets)

NOTE 1 - current R&D efforts are considering high energy 'chemical reaction' solutions with the potential to drastically increase the energy density with a theoretical 2,600Wh/kg for Li-Sulphur (compared to 550Wh/kg for current solutions). It is however unclear whether these solutions will make it in the market before 2030 due to the reasons discussed above

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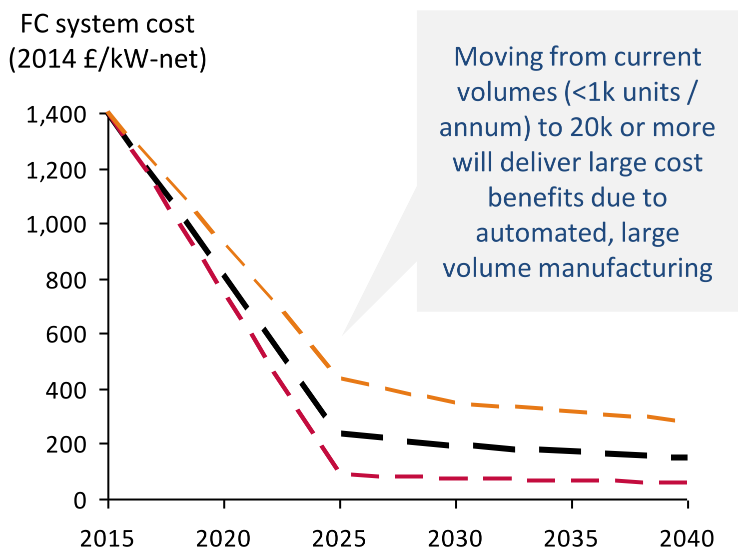
# FOCUS SLIDE 3: fuel cell system and hydrogen tanks performance and costs trends for vans - main assumptions



Baseline
Low ( = best case)
High (= worse case)

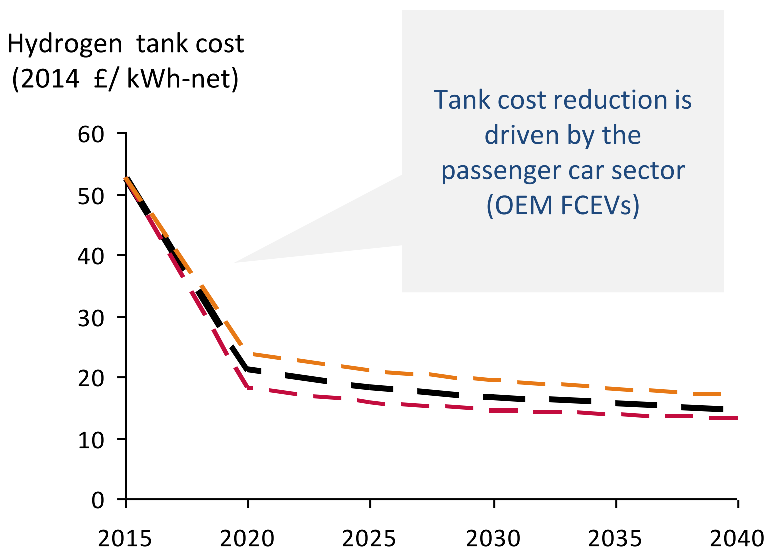
## FC system cost

- Fuel cell systems (and related BoP components) for FC RE-EV commercial van applications are currently based on dedicated, small-volume (<<1k per annum) solutions and thereby have a far higher production cost than for passenger car applications
- As the solution gains more commercial traction, costs are expected to reduce as manufacturers are able to adopt large volume automotive-inspired production models (as well as potentially use passenger car stacks)
- FC system costs per kW are nevertheless expected to remain higher than for passenger applications by 2030 as dedicated system integration and BoP components will still be required to meet the specific sector requirements




## Hydrogen tank cost

- 700bar tanks for FC RE-EV van applications are fundamentally based on the same technology as for passenger OEM FCEVs and thereby follow the same cost reduction trends as per passenger vehicle applications
- RE-EV van applications have lower on-board hydrogen storage requirements and thereby use smaller tanks (typically up to 2kg of hydrogen). This is the main reason why the tank costs per stored kWh are expected to be higher than for passenger FCEVs
- This study does not consider 350bar technology – although this is the refuelling pressure for existing solutions, all manufacturers expect to move to 700bar technology over the coming few years to align with the OEM FCEV standards

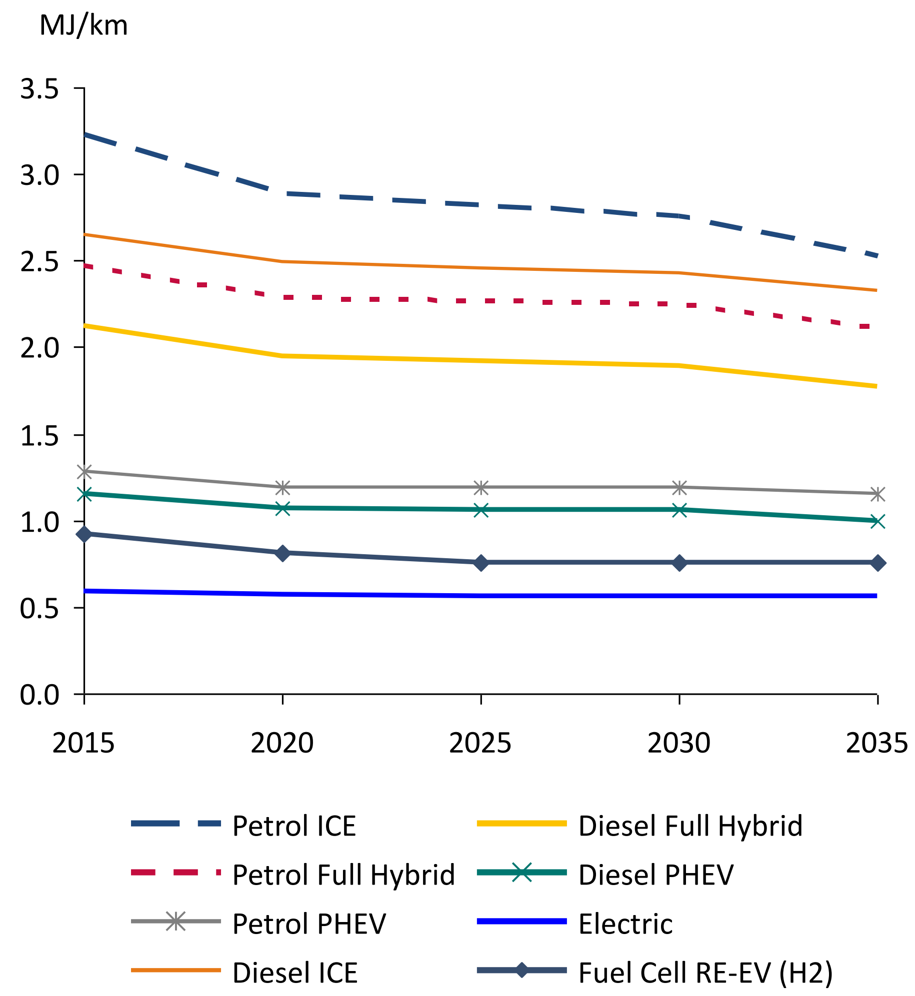


# Efficiency comparison between all modelled powertrain for vans

## Discussion

- BEV vans are the most efficient powertrain. FC RE-EV vans are expected to perform substantially better than the best-of-class Diesel PHEV
- Given the lower efficiency of a FC system compared to battery technology, FC RE-EV vans require more energy per km driven. The difference with BEV vans is however substantially reduced compared to the passenger car case (FCEVs), as the powertrain architecture relies on a much smaller FC power plant (typically 10% of the electric motor rated power)
- FC RE-EVs and BEVs are the only zero-tailpipe-emission technologies available for commercial van applications therefore their societal benefits go well beyond the improved fuel economy (i.e. no TTW GHG emissions and no toxic tailpipe emissions such as SOx, NOx, and PMs)
- It is worth noting that FC RE-EVs are the only technology providing zero emission transport and long driving range (FC RE-EVs typically double the range of battery-only solutions, e.g. to around 500km or more)

## Standard panel – MJ/km (NEDC)

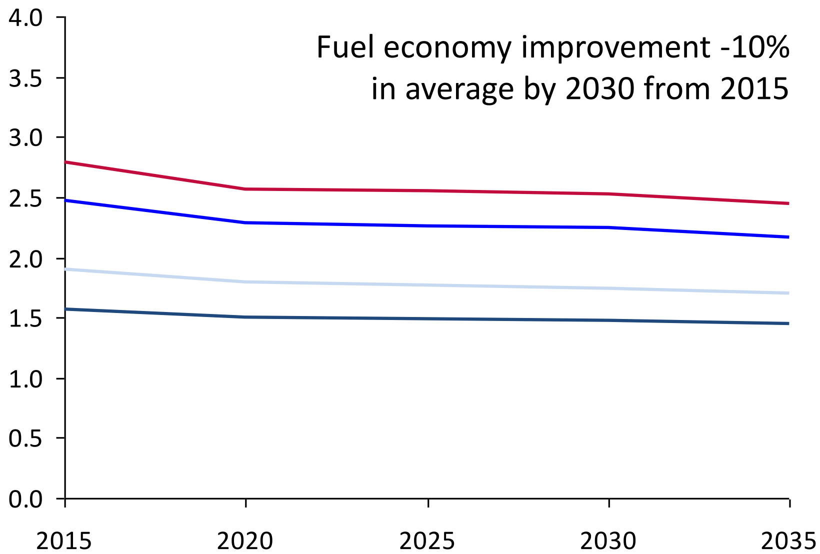


# Projected performance of Hybrid ICE commercial vans

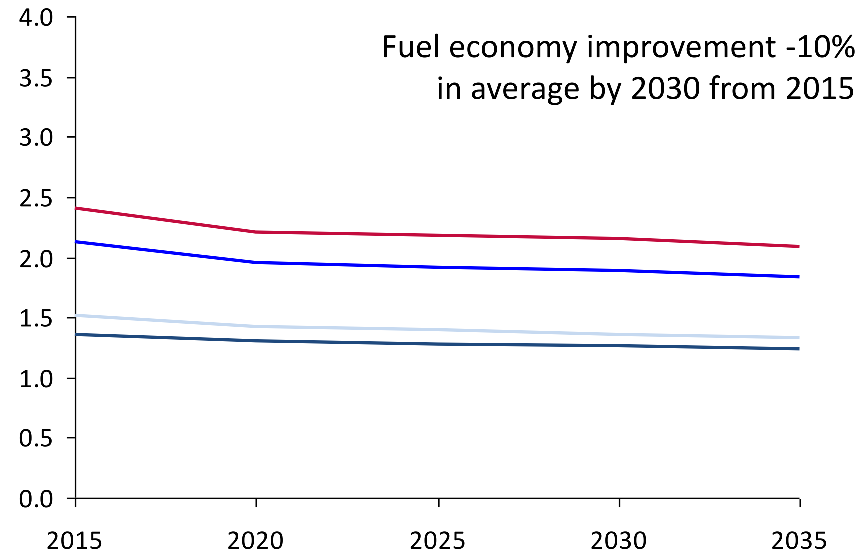
1 Small Car Derived
2 Large Car Derived
3 Standard Panel
4 Large Panel



## Petrol Hybrid – MJ/km (NEDC)




## Diesel Hybrid – MJ/km (NEDC)




## Discussion

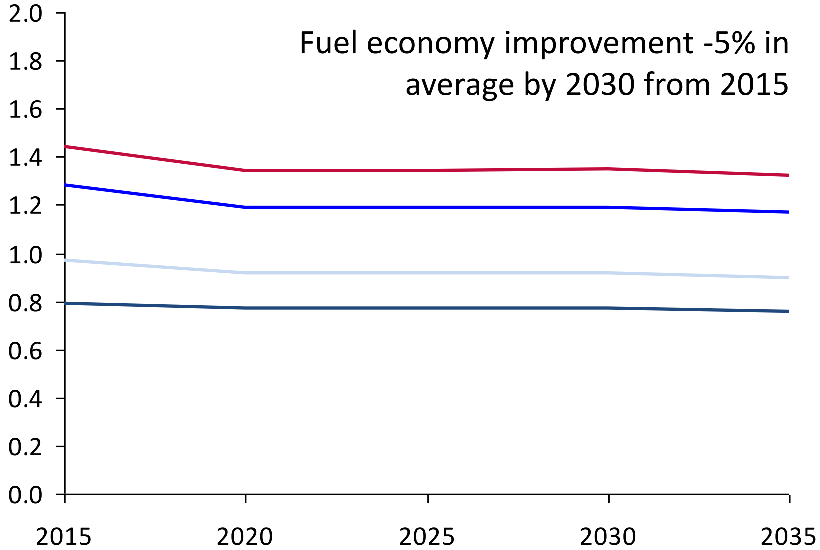
- As for the car segment, efficiency trends for Hybrid ICE vans reflect the progressive introduction of novel efficiency improvement technologies (see previous slides) as well as improvements in the electric components (battery and ancillary equipment)
- Fuel consumption reduction potential is lower than for ICEs by 2030 as hybrids (as well as PHEV and other electric powertrains) are typically equipped with the most efficient measures (stop-start, etc.) from the outset

# Projected performance of PHEV commercial vans

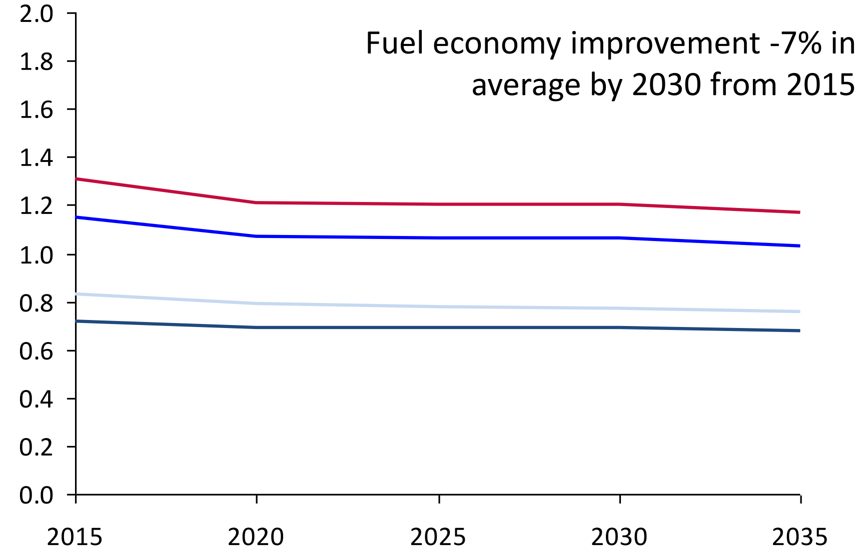


1 Small Car Derived
2 Large Car Derived
3 Standard Panel
4 Large Panel

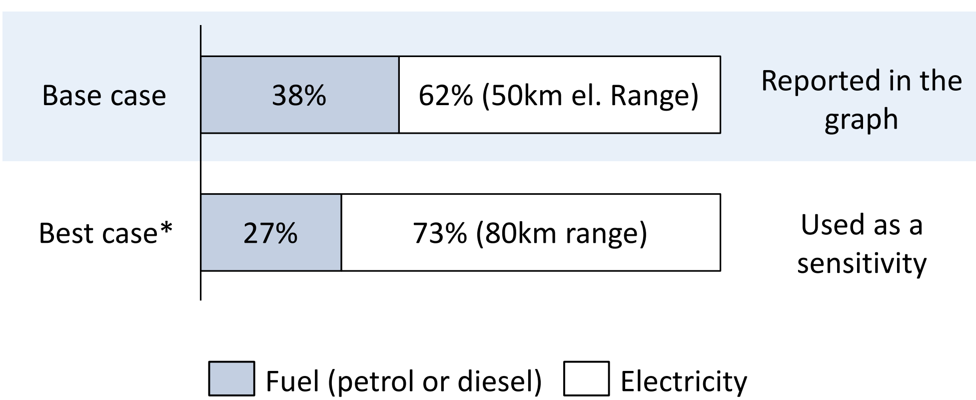
## Petrol PHEV (fuel + electricity, MJ/km NEDC)




## Diesel PHEV (fuel + electricity, MJ/km NEDC)




**Share of mileage driven in fuel or electric mode (%)**



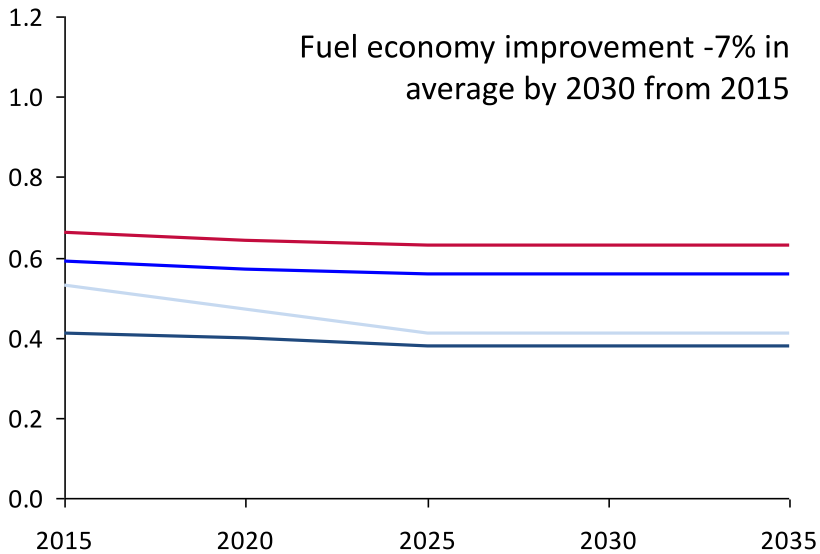

- The % of mileage driven in electric mode and range assumption are as for cars (see previous section), as it is widely expected that the van sector will adopt a similar powertrain architecture as in the car sector to benefit from volume
- 'Base' and 'best' cases reflect the impact of different levels of electrification ambition on the TTW emissions

Element Energy analysis; * Note: for the Best case we assume 62% in electric mode in 2015, increasing linearly to 73% in 2020. This reflects the underlying assumptions on range for this scenario of 50 km in 2015 and 80km in 2020

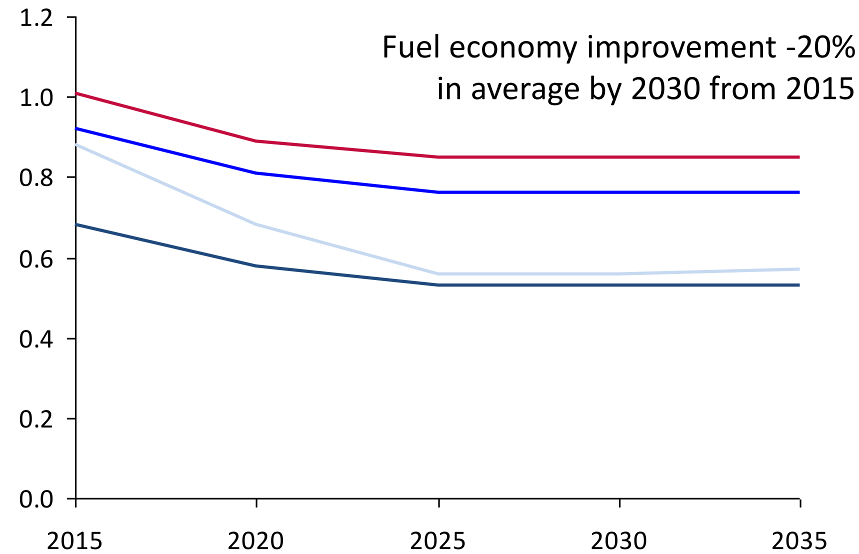
# Projected performance of BEV and FC RE-EV solutions

1 Small Car Derived
2 Large Car Derived
3 Standard Panel
4 Large Panel

**BEV – MJ/km (NEDC)**




**FC RE-EV – MJ/km (NEDC)**




## Discussion

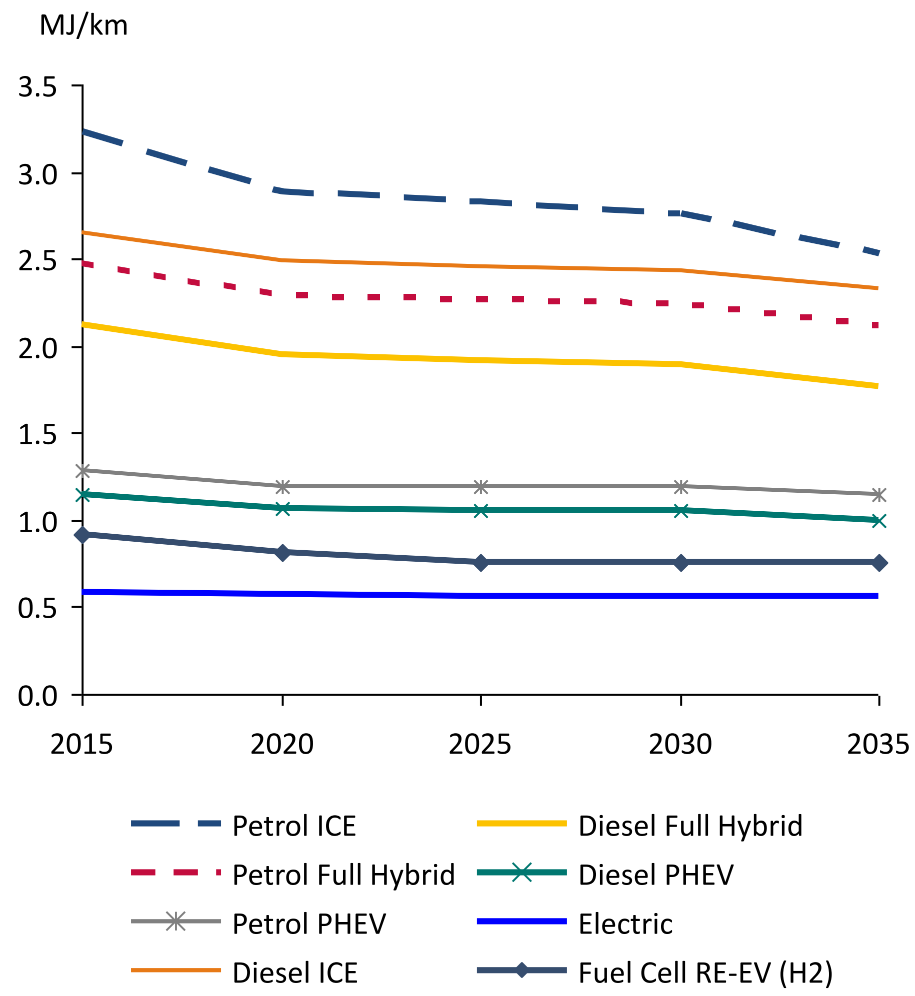
- BEV van solutions are 70% to 80% more efficient than Diesel ICE van solutions and – as for the passenger cars case – the most efficient  transport technology
- Fuel cell range-extended vehicles are designed to double the electric range of the BEV can counterparts  (e.g. around 50% extra driving range) and – given the lower efficiency of the main power plant (fuel cell system) – are circa 30% to 40% less efficient than battery vans
- Both BEV and FC RE-EV vans benefit from some of the same efficiency improvement technologies as conventional ICE & hybrid vehicle solutions (discussed above) as well as improvements in the electric and fuel cell components (battery, fuel cell system and ancillary equipment)

# Vans will progressively become more fuel efficient, with the sharpest improvement expected by 2021 to meet the EC target for new fleets

## Discussion

- ICE vans are expected to experience the greatest fuel consumption reduction by 2030, but to a lesser extent than for passenger vehicles (average ~15% from present day). This is a consequence of a few factors: not all vans share the same powertrain architecture as cars, the EU target to 2021 is in proportion slightly less aggressive than for cars, and finally the sector is more sensitive to cost premiums.
- Advanced hybrids (PHEV), FC RE-EV and BEV vans are the most efficient powertrains. BEVs are the most efficient, while FC RE-EV vans are expected to perform substantially better than best-of-class diesel PHEV.
- Given the lower efficiency of a FC system compared to battery technology, FC RE-EV vans require more energy per km driven. The difference with BEV vans is however substantially reduced compared to the passenger car case (FCEVs), as the powertrain architecture relies on a much smaller FC power plant (typically 10% of the electric motor rated power in current designs).

## Standard panel van – MJ/km (NEDC)



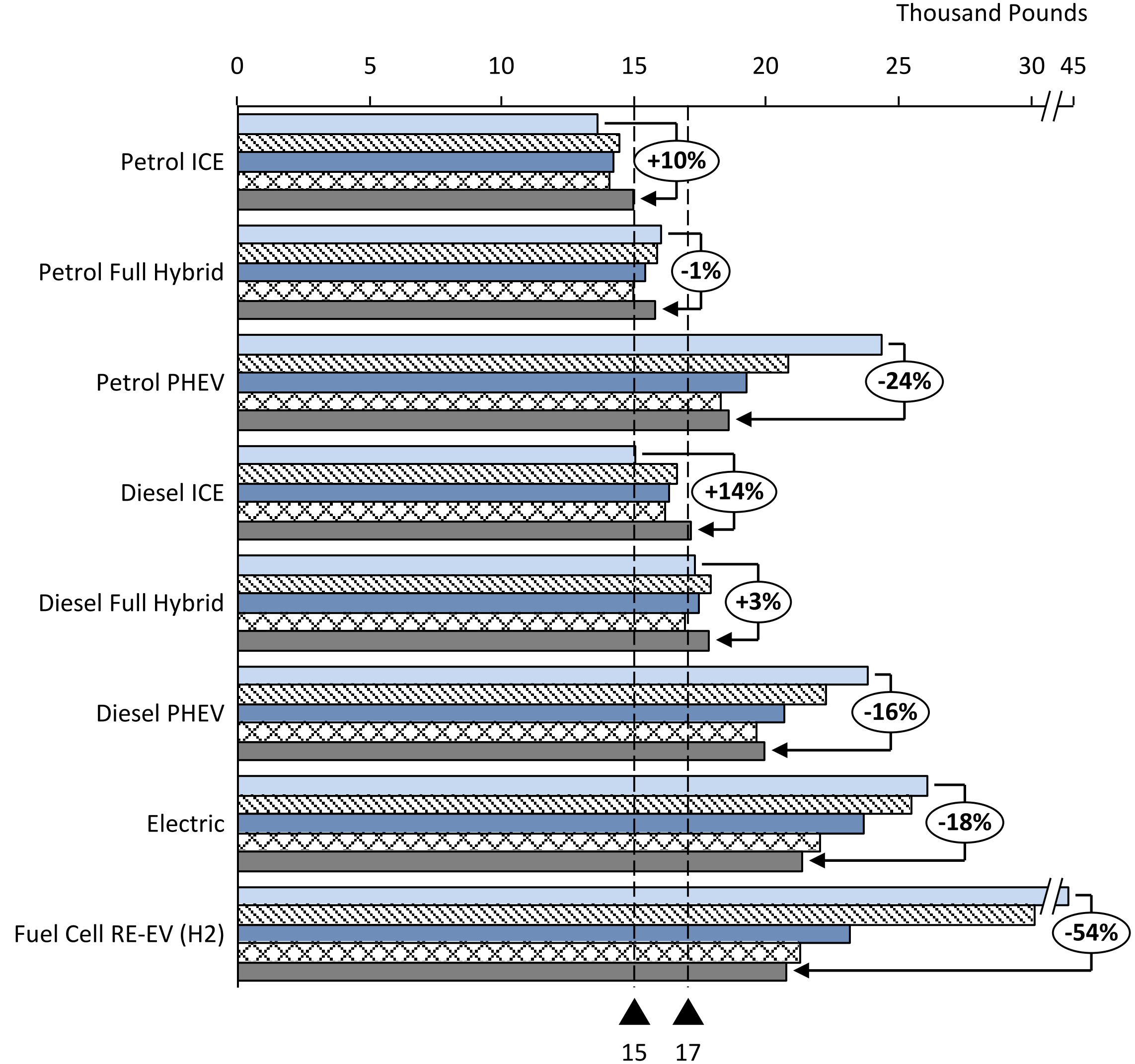
# As per passenger cars, premiums for alternative powertrains over conventional ICEs are expected to converge but not fully disappear



## Discussion

- As for passenger cars, the cost premium for hybrid ICE, BEV and FCEV solutions over conventional ICE vehicles will substantially shrink throughout 2015-2030 period
- Reductions will mainly be driven by: larger manufacturing volumes for non conventional powertrains (especially BEV and FCEV) and reduction in battery & FC costs and ancillary equipment
- Some of the cost reductions for hybrid ICEs are hindered by the increase in the base ICE vehicle costs (due to the progressive inclusion of novel efficiency improvement technologies and optimised components)
- PHEV / RE-EV premium over baseline ICE is expected to reduce to 20-30% than ICEs by **2030.**
- Cost premium for BEV and FC RE-EV is also expected to be 30-35% compared to ICEs by 2030 while the cost difference between FC RE-EV and BEV solutions is expected to be marginal (<£1,000 by 2030 in the central scenario)

## Standard panel van – cost (excluding margin & VAT)




**NOTE:** Costs only. This discussion does not take into consideration margin and pricing strategies as these may considerably change year on year and are OEM specific

# Surface transport

- Cars and vans
- **Trucks and buses**

# Surface transport

- Cars and vans
- **Trucks and buses**
    - **Trucks**
    - Buses

# We use the outputs of third party modelling, which constructs efficiency trends based on efficiency measures available to 2035



## Discussion

- Vehicle efficiency trends can be constructed by considering the efficiency improvement measures available in the 2010-2035 timeframe.
- For each measure, the efficiency improvement potential is estimated through technical analysis and stakeholder consultation. A breakdown of the main measures available for trucks is given in this section.
- The rate of deployment into the new vehicle fleet is projected by analysing the level of technical maturity and cost of a measure each year.
- For each truck type (articulated truck, large rigid truck, small rigid truck), a package of technologies is selected, according to the applicability of a technology to a certain truck type, and accounting for some measures being incompatible with one another.
- By combining the efficiency improvement potential with the projected deployment for each measure in each package, an overall efficiency improvement trend through time can be constructed for each truck type.
- Similarly,  cost trends can be constructed by considering cost projections for each efficiency measure, and by applying a reduction in the cost of a measure through time as a technology matures.
- The above analysis has been performed in detail in R-AEA for CCC 2012, and efficiency trends have also been constructed in this way in other reports such as ICCT 2015 (1). The outputs of these reports inform our own base and best case efficiency trends.

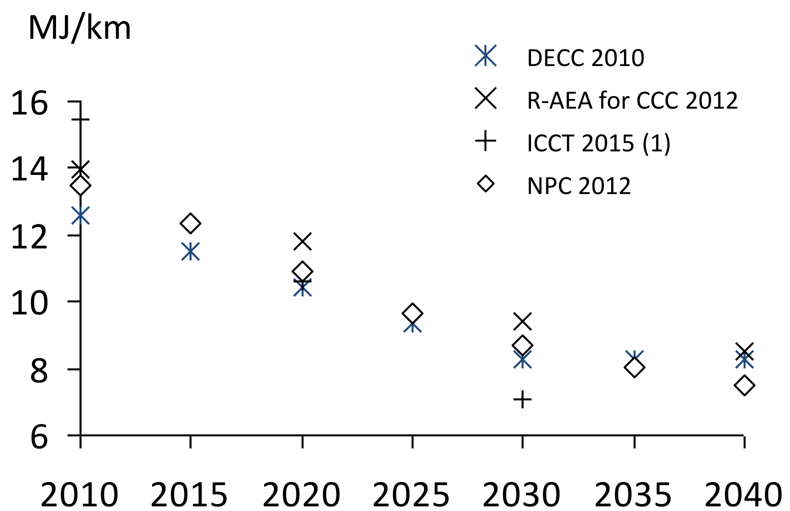
R-AEA for CCC 2012, ICCT 2015(1)

# Base case and best case efficiency trends were selected based on the trends from the literature

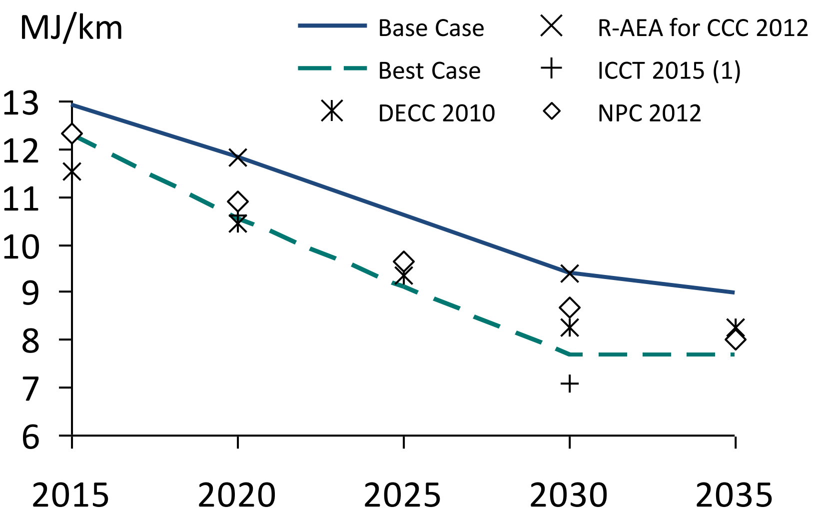


- The outputs from various reports truck efficiency are shown below.
- The data from R-AEA for CCC 2012 are based on a comprehensive bottom-up analysis of expected truck efficiencies to 2050.
- The data from ICCT 2015 (1) are based on an analysis of the measures that could be implemented for trucks in the USA, so start from a worse efficiency than those in R-AEA. The ICCT study projects the total potential improvement, and hence is significantly more aggressive than R-AEA, which accounts for only partial deployment of measures due to economic factors.
- DECC 2010 contains truck efficiency scenarios to 2050. Scenario “Level 2” has been used, which assumes a large proportion of efficiency measures are adopted, excluding hybridisation. It is not calculated as rigorously as the above, but is in agreement with them, and remains useful as it has trends for both articulated and rigid trucks, which ICCT 2015 does not.
- To represent the spread of the data, base and best case trends were chosen. All base cases are an interpolation of R-AEA data. Diesel ICE best cases are an average of ICCT and DECC trends, with some adjustments to prevent averaging effects from causing some unrealistic worsening of efficiency with time. Only DECC 2010 was used for rigid trucks as ICCT 2015 addresses only articulated trucks.

**Articulated Trucks – Trends from Literature**




**Articulated Trucks – Base Case and Best Case**




R-AEA for CCC 2012, ICCT 2015(1), DECC 2010, NPC 2012

# There are no current EU or UK regulations on HDV emissions – without these only a customer 'pull' will lead to the introduction of new technologies



## Discussion

- There are no European or UK regulations controlling the fuel efficiency of trucks; only local pollutants are regulated through e.g. the Euro VI regulations. As a result, penetration of new technologies will generally be manufacturer competition based on the anticipated needs of fleet operators (i.e. trade-offs between increased upfront cost and ongoing fuel savings for efficient trucks)
- The European Commission is currently developing an HDV strategy, which will at first include mandatory '$CO_2$ labelling' for trucks. A fleet $CO_2$ target (similar to existing regulations for cars and vans), could be introduced in the future, mirroring developments in the US which has ambitious fuel efficiency goals
- Some measures to reduce NOx and particulate matter (PM) have a negative impact on fuel efficiency. As a result, the overall efficiency of trucks in the EU has been flat for more than a decade, as efficiency improvements are negated by local pollutant reducing measures[1].
- Factors affecting the adoption of efficiency technologies by operators:
  - Operators are unwilling to spare capital expenditure for measures with long payback times.
  - Operators rarely have complete information on the real world fuel savings of new technologies
- Hence, measures with higher investment costs/longer payback times are considered too risky to adopt.
- For long haul articulated trucks, the biggest losses occur in the engine, through aerodynamics, and through rolling resistance, whereas for short haul trucks, engine and braking losses dominate.
- There is significant potential for aerodynamic improvements as currently the tractor-trailer interface is not designed for aerodynamic efficiency. Fairings between the tractor and trailer as well as between the trailer wheels are key technologies which are relatively simple to implement.
- There is also potential for significant reductions of rolling resistance through single wide tires and low rolling resistance tires.

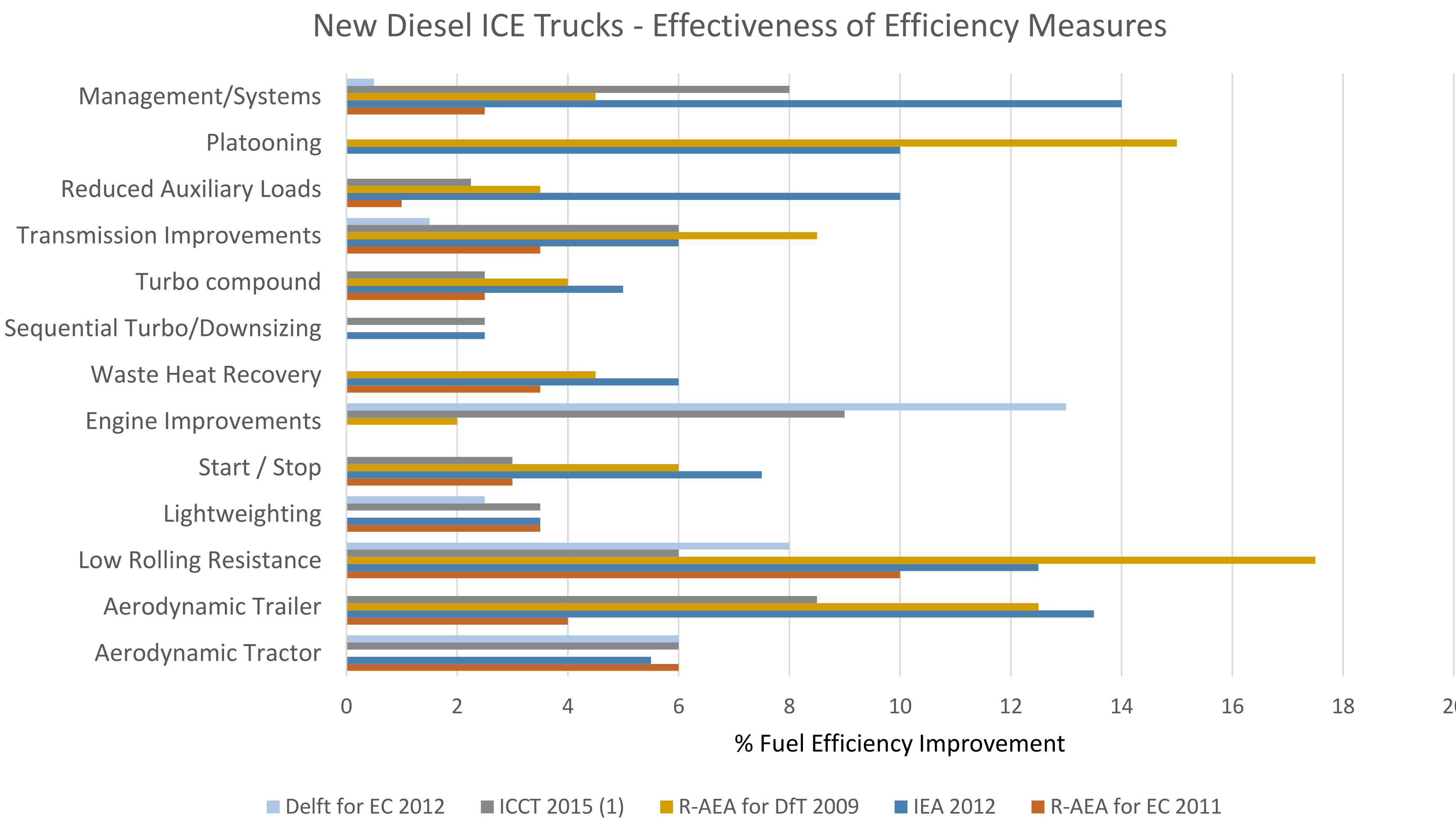
ICCT for IEA 2015, ICCT 2015(3), Transport Environment 2015

1 - It's worth noting EURO VI trucks and buses are not following this trend, with fuel efficiency improvements reported by fleet operators (compared to EURO V HDVs)

# A variety of technological, vehicle, and operational measures can be implemented to improve truck efficiency



NOTE: Some measures are not relevant to all powertrains and vehicle sizes. The effectiveness of a measure also depends on the powertrain and vehicle size.




Sources reported in appendix.

# The selected publications model the introduction of truck efficiency measures over time following an approach consistent with market data and manufacturers projections



**% of new vehicles adopting the improvement – example reported from the baseline scenario in R-AEA for CCC (2012)**

| Measure (for large rigid trucks) | 2020 | 2030 | 2040 |
|---|---|---|---|
| General improvements (+ impact AQ emission control) | 100% | 100% | 100% |
| Mechanical Turbocompound | 0% | 10% | 20% |
| Electrical Turbocompound | 0% | 1% | 25% |
| Heat Recovery (Bottoming Cycles) | 0% | 1% | 10% |
| Controllable Air Compressor | 0% | 20% | 50% |
| Automated Transmission | 20% | 50% | 100% |
| Stop / Start System | 100% | 100% | 100% |
| Pneumatic Booster – Air Hybrid | 0% | 0% | 0% |
| Aerodynamic Fairings | 95% | 100% | 100% |
| Spray Reduction Mud Flaps | 5% | 20% | 80% |
| Aerodynamic Trailers / Bodies | 7% | 40% | 45% |
| Aerodynamics (Irregular Body Type) | 1% | 20% | 35% |
| Active Aero | 7% | 40% | 45% |
| Low Rolling Resistance Tyres | 95% | 90% | 60% |
| Single Wide Tyres | 5% | 10% | 40% |
| Automatic Tyre Pressure Adjustment (ATPA) | 50% | 100% | 100% |
| Light weighting | 4% | 30% | 60% |
| Predictive Cruise Control | 50% | 70% | 20% |
| Smart Alternator, Battery Sensor & AGM Battery | 30% | 90% | 100% |
| Alternative Fuel Bodies (for RCV /Refrigeration /Tipper) | 5% | 10% | 22% |
| Advanced Predictive Cruise Control | 5% | 30% | 80% |

NOTE: The same set of measures also applies to all truck segments (including articulated) with different penetration rate assumptions

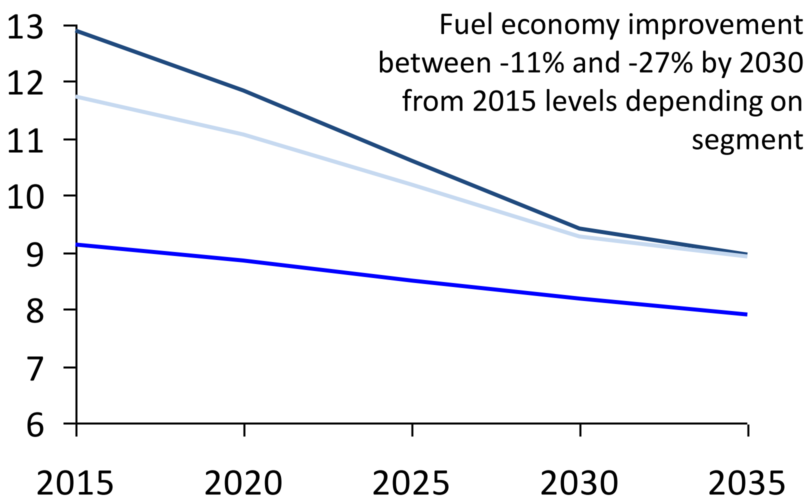
Large rigid trucks = trucks > 15t GVW excluding articulated

Data source: R-AEA for CCC (2012)

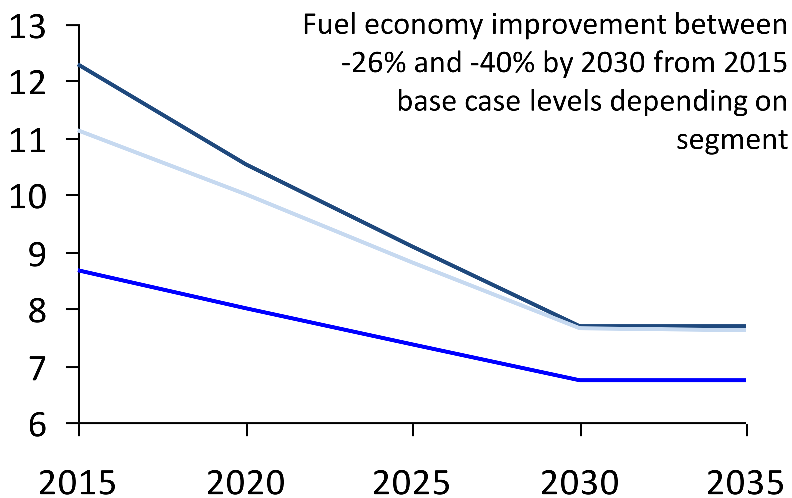
# Projected performance of diesel ICE vehicles



## Diesel ICE Trucks Base Case – MJ/km



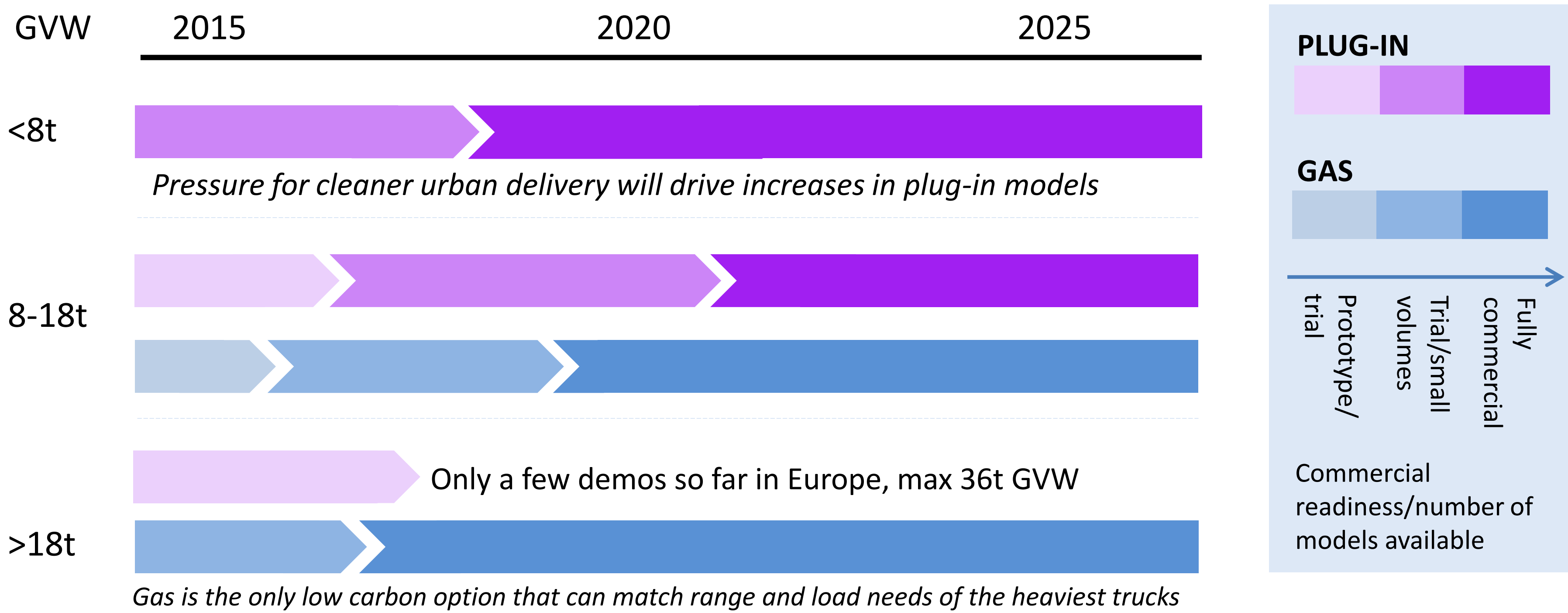

## Diesel ICE Trucks Best Case – MJ/km




## Discussion

- Best available technical literature suggests that the introduction of improvements in the base vehicle and ICE engine components will gradually reduce the fuel consumption of new vehicles by ~25% from 2015 levels by 2030 (actual figures depend on vehicle segment and fuel type).
- Articulated trucks experience the greatest reduction in fuel consumption (27% in the base case). Articulated and large rigid trucks comprise the majority of $CO_2$ emissions, and so the overall improvement can be expected to be close to 27%.
- The base case articulated truck trend represents a move from 32.3 l/100km in 2015 to 23.6 l/100km in 2035, and the best case represents a move from 30.7 l/100km to 19.2 l/100km by 2030.
- Small rigid trucks remain the most fuel efficient, and articulated trucks remain the least fuel efficient.
- Some curves level off after 2030, as the majority of available improvements are expected to be implemented by then.

# Gas is currently the main option for trucks and trailers over 18t, with electric powertrains mostly available in the <18t segment




- **Gas trucks** in the **8-18t** category are available in markets outside the UK and could become available given the right signals from policy and infrastructure development
- Trial versions of **hydrogen trucks** are now starting to be developed by some manufacturers, either as range-extended electric vehicles or as converted diesel hybrids
- For refrigerated vehicles, emissions from refrigeration units could be addressed by emerging **"liquid air" technology** (not discussed here as it is a longer term technology)

Source: Element Energy
Indicative timings. Extent of commercialisation and availability will depend on demand, fuel prices and policy measures

# The gas truck market has recently shifted from a dominance of dual fuel converted models to a broader dedicated OEM model offer

**EXISTING and *EXPECTED* EURO VI MODELS**

| | | OEMs | Converters[3] | Typical HP & range |
|---|---|---|---|---|
| **BI-FUEL** | <7t GVW | • Mercedes Sprinter | | • 150 HP (110 kW)<br>• 400km on NG<br>• > 1100km total |
| **DUAL FUEL** | 26-44 GVW | • *Volvo FM (2015)* | • Prins Autogas (MB Actros)<br>• DIESELGAS (DAF XF, Iveco)<br>• *Vayon[1] (2015), G-Volution (2015) and Clean Air Power* | • 450 HP (335 kW)<br>• Range > 1000 km |
| **DEDICATED** | 6-26 GVW | • Iveco Daily & Stralis<br>• Mercedes Econic<br>• Scania P<br>• Volvo FE CNG<br>• *MAN TGM (2016)* | | • 136 - 350 HP<br>• 400km (urban) to 700km extra urban |
| **DEDICATED** | 26-44 GVW | • Iveco Stralis<br>• Mercedes Econic<br>• Scania P & G | | • 300 - 450 HP<br>• 400-1100 km (CNG -LNG) |
| **DEDICATED** | 18-26 GVW | • Mercedes Econic<br>• Scania P<br>• Volvo FE CNG<br>• *MAN TGM, Renault[2]* | | • 320-340 HP<br>• 400-600 km |

Source: Element Energy     1 - formerly Hardstaff     2 - Renault D Wide CNG2, not currently in the UK
3 – Conversions are made on a EURO 6 engine but the converted vehicle is not re-tested for EURO 6.

# Fleets that have adopted gas vehicles reported a short payback period for high mileage applications

## Government support

- **Preferential gas fuel duty differential** to be maintained to 2024
- **Low Carbon Trucks trial** that includes installation of 17 new gas stations
- Further **£4m** from OLEV to support development of **HGV gas network** (expected to open in 2016)

## Dual fuel HGVs

- Conversions of MB Actros, DAF and Iveco trucks available (26-44t GVW)

**Compared to diesel equivalents (EURO VI):**

- Vehicle premiums of £15,000 to £36,000
- Maximum substitution rate c. 60%
- Indicative fuel cost savings **c.7p/mile** for a large rigid truck, i.e. up to **£7k/year** based on 100,000 miles[1]
- No certification yet on EURO VI performance of converted vehicles



## Dedicated gas HGVs

- Range of OEM vehicles available in 6-44 GVW categories, and also for Refuse Collection Vehicles (see next slide)

**Compared to diesel equivalents (EURO VI):**

- Vehicle premiums of £12,000 to £30,000
- Indicative fuel cost savings **c.12p/mile** for a large rigid truck, i.e. **£12k/year** based on 100,000 miles[1]
- Up to 17% reduction in PM, 40% for $NO_x$ **compared to EURO VI thresholds**
- No increase in hydrocarbon emissions based on available data
- 50% noise reduction

Source: Element Energy. Running costs are indicative: dependent on duty cycle, loading level etc.

1 – Based on Low Carbon Truck trial data and CCC modelling, using a gas price of 90p/kg. **Savings depend on substitution rate.**

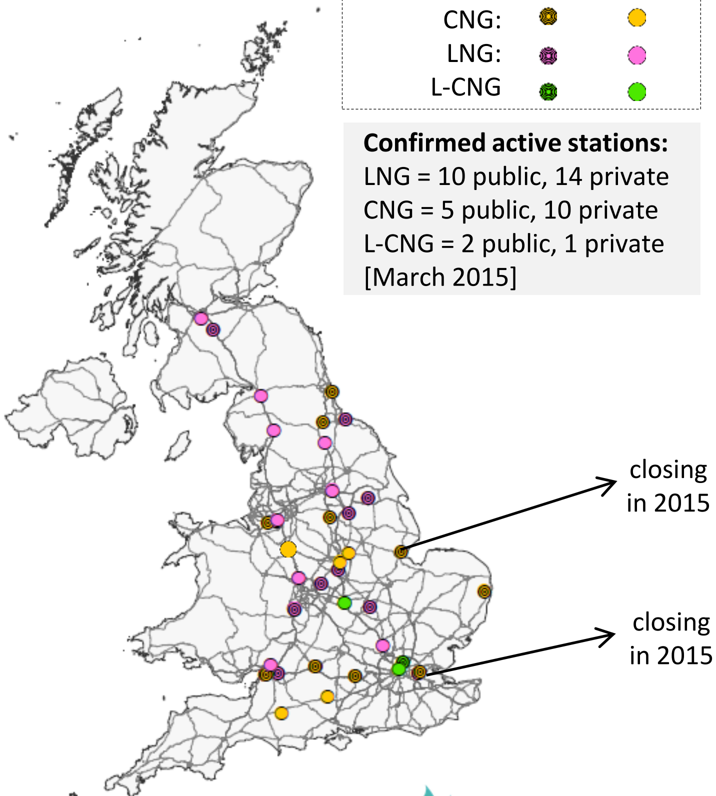
# Gas refuelling infrastructure technology is mature but public coverage in the UK is low; fleets tend to rely on in-depot refuelling

## Natural gas refuelling stations in the UK

**Natural gas refuelling points**

| | Private | Public |
|---|---|---|
| CNG: | ● | ● |
| LNG: | ● | ● |
| L-CNG | ● | ● |

**Confirmed active stations:**
LNG = 10 public, 14 private
CNG = 5 public, 10 private
L-CNG = 2 public, 1 private
[March 2015]




## Gas refuelling


- Similar to conventional fuelling process
- Price ranges: £0.75-£1.08/kg

- Gas is available:
  - In gaseous form (**CNG - compressed natural gas,** 200/250 bar) or
  - in super-cooled liquid form (**LNG – liquefied natural gas,** -170°C, <10bar)
- Currently few publically accessible stations
- Dedicated depot filling points possible
- A number of fleet operators have **semi-private refuelling facilities** allowing pre-agreed operators to share facilities
- Existing gas network creates wide opportunities for new filling stations (subject to constraints due to the local network pressure level)

Sources: Gasrec, ENN, Calor, Gas Bus Alliance, BOC, Low Carbon Truck Trial, Element Energy
Gas prices as observed in Low Carbon Truck trial, reported in 2014

# Over 300 CNG/LNG/Dual Fuel Trucks were funded by the Government Low Carbon Truck Trial but further testing has been commissioned

**Low Carbon Truck Trial**

- Most of the funded vehicles were dual fuel using either CNG or LNG with diesel, other technologies included dedicated gas trucks and biodiesel dual fuel trucks
- Results from the trial have shown that the level of methane slip (unburnt methane escaping through the exhaust pipe) could be high in some cases and overall tailpipe $CO_2$ emission reductions were low (compared to diesel trucks). However the trucks were dual fuel conversions and not representative of EURO VI OEM trucks.

**New DfT testing program**

- While EURO VI OEM trucks are expected to perform better (than converted trucks), there is a lack of real world data regarding both $CO_2$ and pollutant emissions ($NO_X$ and PM)
- DfT has commissioned the LowCVP to run some real world gas truck tests to bring evidence on how they compare to their EURO VI diesel equivalents
- Results are expected by mid-2016 and will release (if positive for gas trucks) the £4m funding OLEV has earmarked for gas infrastructure

Iveco Stralis Euro VI CNG/LNG

Scania Euro VI CNG/LNG

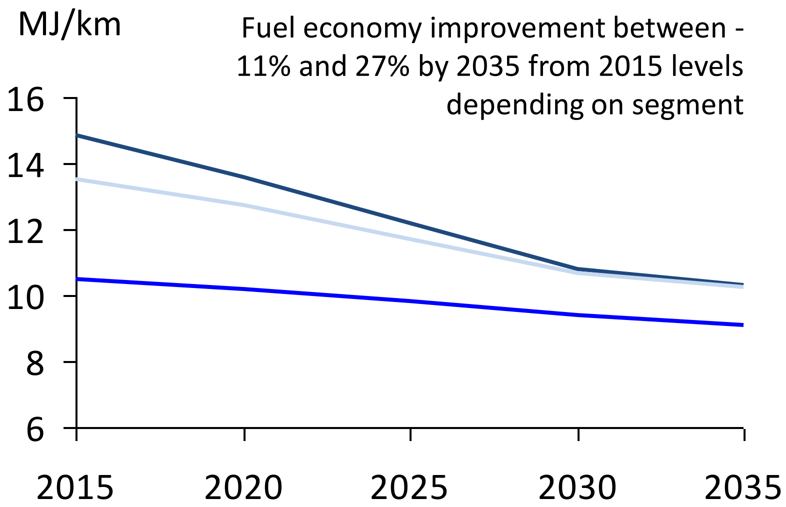

Mercedes Benz Econic CNG

Volvo FM Methandiesel LNG Dual Fuel

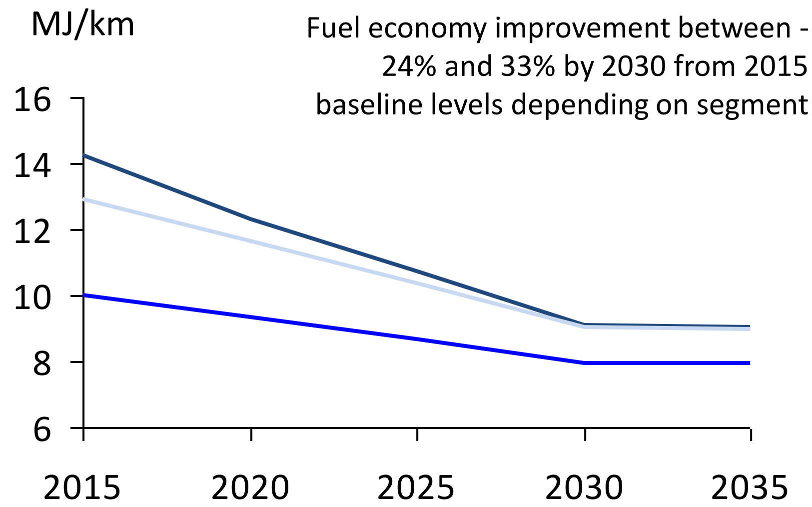
# Projected performance of CNG/LNG trucks

Articulated Truck
Large Rigid Truck
Small Rigid Truck

## Base Case (Dedicated gas ICE)




## Best case (Dedicated gas ICE)




- Base case fuel efficiency improvements of ~25%, the same as for diesel ICEs, due to mostly the same efficiency measures being available for each.
- As the same reductions are possible for diesel ICE and CNG in the base case, it is assumed that this is also true for the best case. Hence, the CNG best case was found by taking the diesel ICE base case-best case offset and applying it to the CNG base case.
- Gas engines are less fuel efficient than diesel engines as they are spark-ignited rather than compression-ignited. However natural gas emits less $CO_2$ per MJ so is a lower emitter overall.
- Dual fuel engines offer improved efficiency over the efficiencies shown here, as the presence of diesel in the fuel mixture facilitates compression ignition. They also solve problems of range while gas refuelling infrastructure is not widespread. Their exact efficiency depends on the ratio of gas to diesel (substitution ratio).
- It is important to minimise WTT methane emissions, which can otherwise negate $CO_2$ savings on a WTW basis.

Element Energy analysis, ICCT 2015(2)

# The majority of OEMs in Europe are developing hybrid technology, and some have hybrid trucks in the market already

## Discussion

- Hybrid technology was initially developed for motorsport (e.g. Williams flywheel in Formula 1) and it is currently being developed especially for short-haul freight delivery and refuse handling applications
- Manufacturers are developing three main diesel hybrid solutions: Electric hybrids (HEVs), Flywheel hybrids (FHVs) and Hydraulic hybrids (HHVs) (further discussed in the next slide)
- Only a small number of diesel hybrid  trucks are available in the UK, generally in the trial phase

DAF LF Hybrid

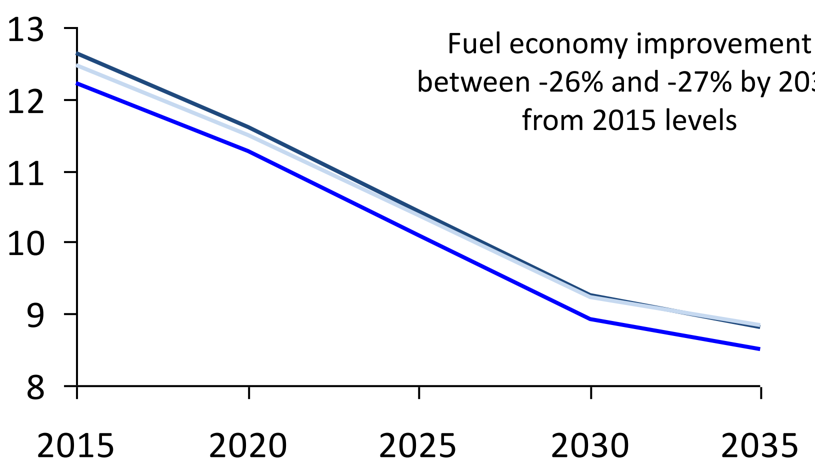

Iveco Eurocargo Hybrid


Volvo FE Hybrid (Refuse Handling)

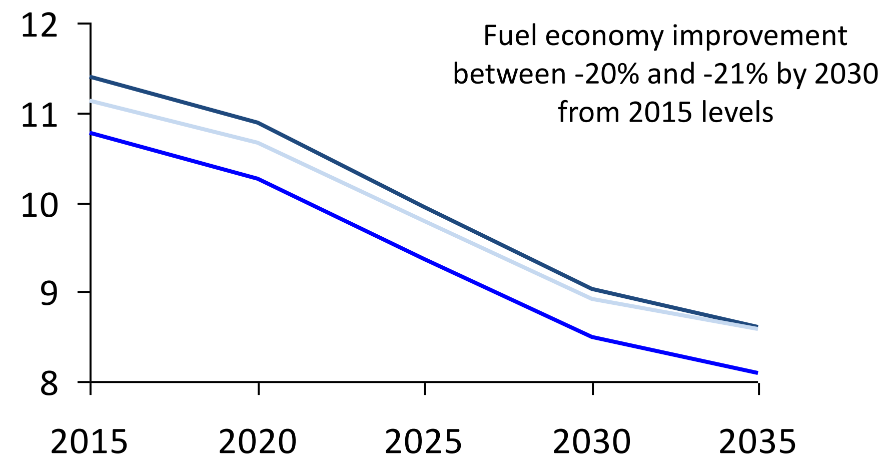
# Projected performance of hybrid trucks

Hydraulic Hybrid
Flywheel Hybrid
Electric Hybrid

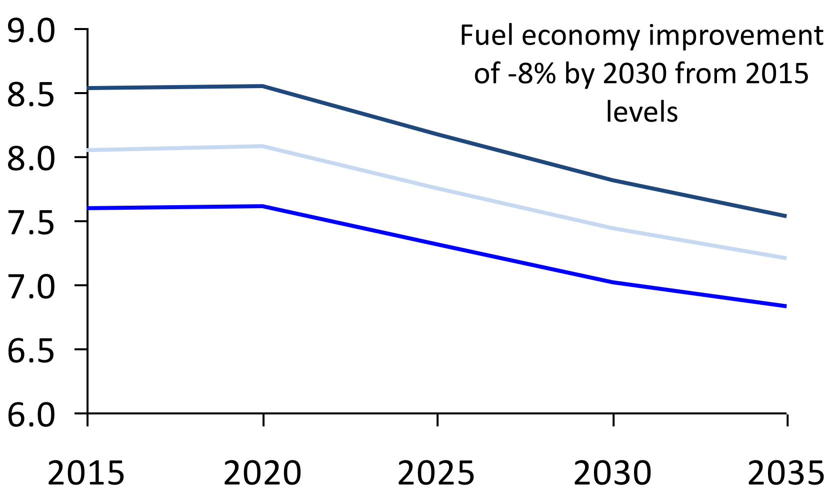
## Articulated Hybrid Truck – MJ/km




## Large Rigid Hybrid Truck – MJ/km




## Small Rigid Hybrid Truck – MJ/km




- The graphs show the base case, taken from R-AEA for CCC 2012. Best case trends were constructed in the same way as for gas trucks, but are not shown.
- The figures reported in this slide are for full hybrids. There are three types:
  - Electric hybrids (HEVs) are the current standard, storing energy electrically in a battery.
  - Flywheel hybrids (FHVs) store energy in the high-speed rotation of a flywheel in a vacuum. They are new to the market at this point.
  - Hydraulic hybrids (HHVs) store energy as compressed fluid, and will be entering the market over the next few years.

# Hybrid powertrain solutions deliver the largest benefits for small truck applications, e.g. characterised by urban duty cycles with frequent stop-start events

## Discussion

- HEVs, FHVs, and HHVs show very similar efficiency trends to 2030, with HEVs remaining slightly more efficient than FHVs and HHVs as they offer greater regenerative breaking, offset only partially by battery round-trip losses.
- Hybrid ICEs are expected to benefit from some of the efficiency improvement technologies for conventional ICEs as well as improvements in the electric/flywheel/hydraulic components (energy storage and ancillary equipment).
- Best cases were hence selected in the same manner as for CNG trucks, using the diesel ICE base case-best case offset, as most efficiency improvements that apply to diesel ICE trucks also apply to hybrid trucks. (Some will not apply, such as stop/start, but it is assumed that the difference will be accounted for by other improvements such as battery technology).
- FHVs and HHVs offer greater power density but lower energy density than HEVs. FHVs and HHVs are hence particularly useful for trucks (and buses) that are heavy and operate stop/start duty cycles, where power is more important than storage capacity.
- The efficiency improvements of hybrid trucks depend on a favourable total cost of ownership, similarly to those of diesel ICEs, as there are no UK policy drivers in place.

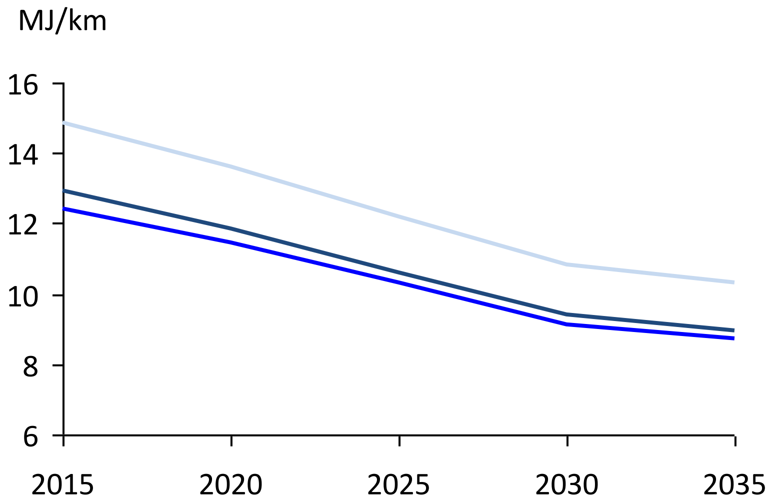
# Technical literature suggests that hybrids will remain the most efficient ICE-equipped vehicles

Diesel ICE
CNG ICE
Hybrid Average

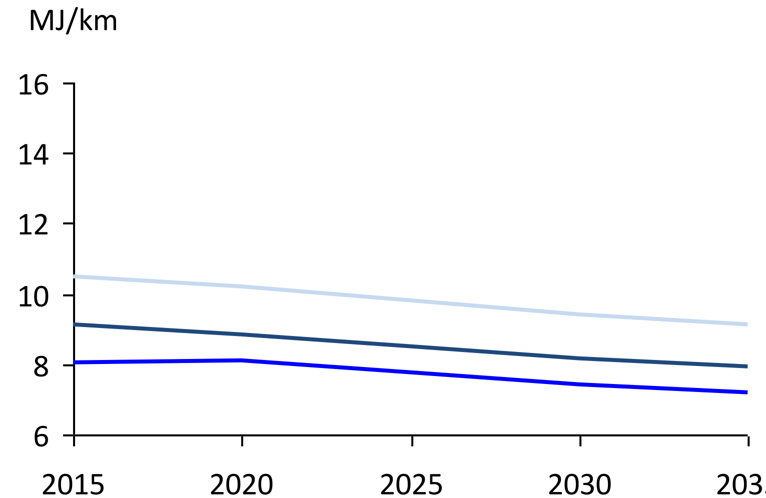
## Discussion

- Hybrids are predicted to remain the most efficient ICE-powered truck powertrain, but with the gap to ICEs closing. This is because many ICE-specific improvement technologies are already present in hybrids, such as stop-start technology, meaning there is less room for improvement in hybrids.
- The gap is larger for smaller trucks as hybrids are more useful on urban duty cycles where there are large braking losses. On the contrary, long haul articulated trucks rarely need to brake and so the benefit from hybrids is small.
- CNG is has the highest MJ/km, but has a lower $gCO_2e$/km as natural gas has a lower carbon intensity.
- A significant proportion of efficiency measures are expected to be implemented by 2030, so the rate of improvement is slower after then.

### Diesel Articulated Truck – Efficiency Comparison

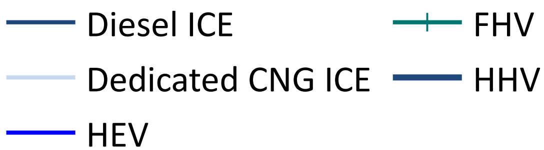



### Diesel Small Rigid Truck – Efficiency Comparison




R-AEA for CCC 2012, ICCT 2015(2), ICCT 2015(1), DECC 2010

# Diesel ICE will remain the least expensive option in the 2015-2035 timeframe

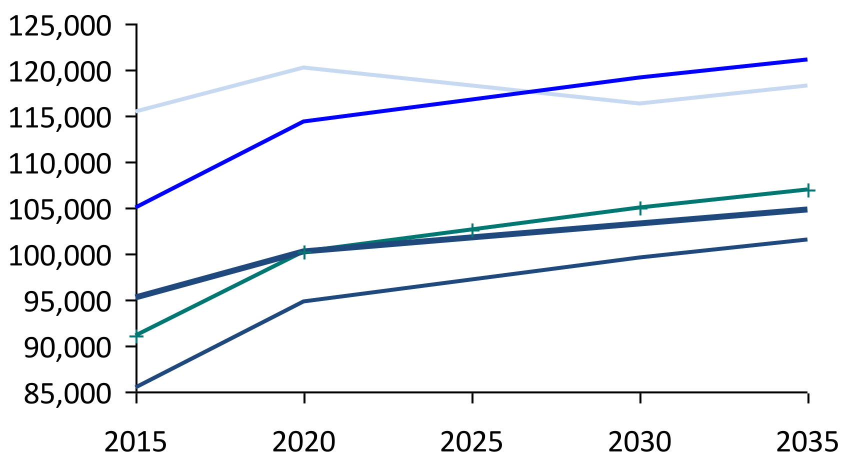




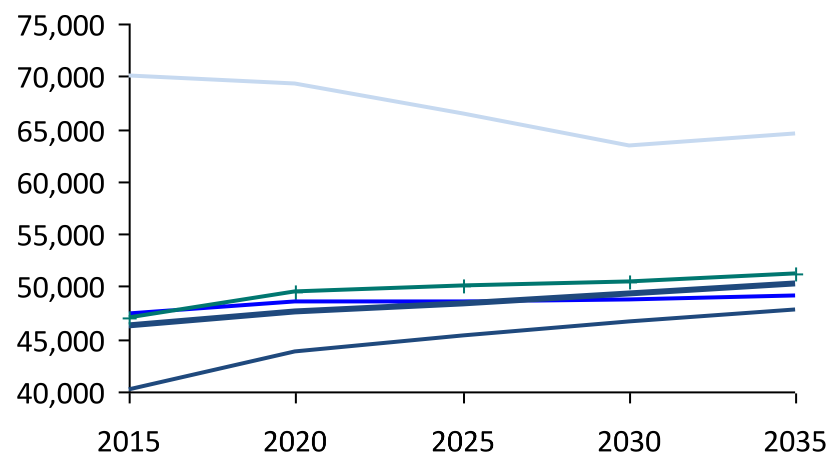

## Discussion

- Technical literature suggests that the cost premium between diesel ICE and hybrid vehicles will shrink throughout 2015-2035 period. Diesel ICE will remain the least expensive, and CNG the most expensive for rigid trucks.
- Trends from R-AEA for CCC 2012 were used as a start point, and some HEV, FHV, and CNG trends were updated based on TIAX for ICCT 2011 and Element Energy's own internal analysis. This suggests that there is a large cost premium for articulated HEVs of ~£20k. This premium is likely to some down with time as hybrid technology improves, but this is not captured in the trends presented. There is also a large cost premium for CNG trucks, which is expected to have decreased by 50% by 2035.
- As new efficiency technologies are introduced, they will cause vehicles to get more expensive. Some small reductions will arise as technologies mature and as alternative powertrain trucks are manufactured in larger volumes.
- Costs are expected to increase the most in 2015-2020 due to the introduction of expensive measures such as aerodynamic fairings, automated transmission, and automatic tyre pressure adjustment.

### Diesel Articulated Truck – Cost (excluding margin & VAT)




### Diesel Small Rigid Truck – Cost (excluding margin & VAT)




R-AEA for CCC 2012, TIAX for ICCT 2011

# EV and FCEV solutions for trucks are less developed than for passenger car and van applications



- The integration of electric and hydrogen fuel cell powertrains in heavy-duty applications present challenges of durability, operational range, energy density, and availability of recharging/refuelling infrastructure and (as a consequence of very limited industry interest) costs.
- A few developers have nevertheless demonstrated a few solutions dedicated to applications with short ranges and predictable, back to base operations (such as transporting containers in manufacturing plants/ports and urban deliveries, e.g. UPS operate c. 30 (soon 50) pure electric 7t GVW trucks in London)
- Electric trucks have been trialled in Europe in GVWs of 3.5-12t, with a few trials of tractors (7.5-18t) and RCVs (for example, a small number of electric refuse vehicles are in operation in French cities)
- FCEV and EV trucks are very early stage technologies; and work on their development is ongoing. They are not costed in this study, but there is a need for them in the 2032 timeframe, as highlighted in the results of the main study presented in the main report.

Vision Tyrano
fuel cell truck

Used for hauling cargo around shipping ports in California

BMW
Electric Truck

Used for carrying vehicle parts between BMW facilities in Munich

Motiv
Electric Garbage Truck

Used for refuse handling in Chicago

Renault Trucks / Symbio
FCell fuel cell range extended electric truck

Demonstrated for urban deliveries

Element Energy analysis

# Electric HGVs are mostly at demonstration stage, with greater prospects for urban delivery trucks where the required driving range is lower

## Grants and incentives available

- Electric vehicles are exempt from the Vehicle Excise Duty and from MOT (goods vehicles only)
- **£32 million fund** for installation of charging infrastructure across the country (focus on light vehicles)

### Typical payback period of 1- 6 years

- 50%-200% vehicle cost premium over diesel versions (conversions most costly)
- Indicative fuel cost savings **30p/mile** for a small truck, **i.e. £7,500/year** based on 25,000 miles[1]
- Lower maintenance costs than diesel versions

### Constraints for HGV applications

- Size and weight of batteries leads to compromise on payload and vehicle range;
- Appropriate for predictable, back to base operations within range of vehicle

## Trucks have been trialled in Europe in GVWs of 3.5-12t, with a few trials of tractors (7.5-18t) and RCVs

Renault Maxity (3.5t)

EMOSS & HyTruck, conversions up to 18t

Trials by Heineken, De Rooy

Terberg/BMW (36t)


Trucks:
- Payloads 0.8-8t
- Ranges <100 miles

Tractors:
- Payloads 4.5-10t (BMW tractor payload unknown)
- Ranges up to 120 miles

Source: Element Energy. Running costs are indicative: dependent on driving conditions, loading level etc.

1 – ex. VAT, based on diesel cost of £1.21/litre. Energy consumption data from CCC and TNT (Smith Newton)

# Hydrogen vans are available in both hybrid and fully electric powertrains, and HGV hydrogen hybrids may soon be available



## Range-extended electric power trains

### Battery + hydrogen fuel cell

- Extends the range of battery-only vans and trucks
- Zero emissions
- Vehicle must be charged and filled with hydrogen to achieve full range

### Symbio Fcell convert the Renault Kangoo ZE van, and now also the Renault Maxity (4.5t)

- La Poste have 21 "HyKangoo" vans and are trialling the converted Maxity
- HyTruck (Netherlands) also plan to convert trucks to hydrogen

## Hydrogen and diesel hybrid vehicles

### Diesel tank + hydrogen tank

- Range equal to that of a diesel vehicle
- Hydrogen tank can be used alone, enabling zero emissions driving
- Diesel tank can be used if hydrogen is not available (or for longer journeys)

### ULEMCo now convert vans and plan to convert HGVs


- >20 vans on the road

- 2 refuse trucks to be converted in Fife

# Surface transport

- Cars and vans
- **Trucks and buses**
  - Trucks
  - **Buses**

# As with the truck analysis, we used the outputs of third party modelling which has been revised and updated based on proprietary real-world data



## Discussion

- For buses we used the same approach adopted for trucks (see box on the right hand side)
- Literature data is used to construct efficiency and cost trends to 2035
- Data has been sense-checked and updated where possible with proprietary data which has been collected by Element Energy as a part of an on-going discussion with UK and EU bus operators and manufacturers

### Discussion

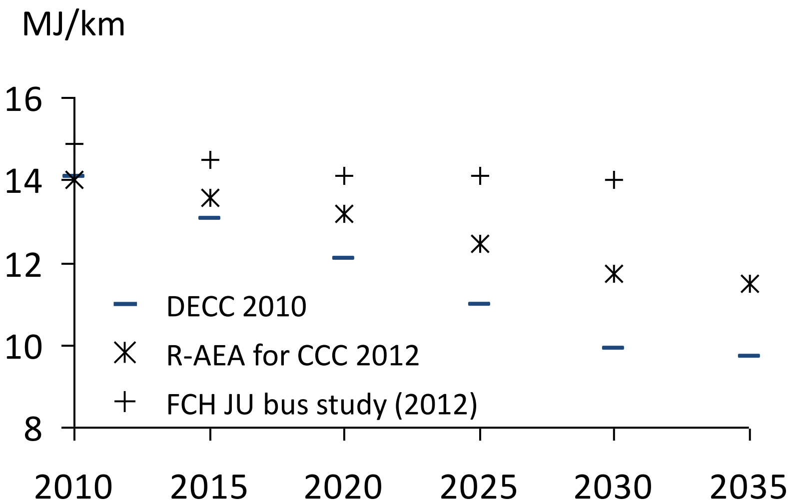
- Vehicle efficiency trends can be constructed by considering the efficiency improvement measures available in the 2010-2035 timeframe.
- For each measure, the efficiency improvement potential is estimated through technical analysis and stakeholder consultation. A breakdown of the main measures available for trucks is given in the next slide.
- The rate of deployment into the new vehicle fleet is projected by analysing the level of technical maturity and cost of a measure each year.
- For each truck type (articulated truck, large rigid truck, small rigid truck), a package of technologies is selected, according to the applicability of a technology to a certain type, and accounting for some measures being incompatible with one another.
- By combining the efficiency improvement potential with the projected deployment for each measure in each package, an overall efficiency improvement trend through time can be constructed for each truck type.
- Similarly, cost trends can be constructed by considering cost projections for each efficiency measure, and by applying a reduction in the cost of a measure through time as a technology matures.
- The above analysis has been performed in detail in R-AEA for CCC 2012, and efficiency trends have also been constructed in this way in other reports such as ICCT 2015 (1). The outputs of these reports will be used to inform our own base and best case efficiency trends.

# Efficiency trends for buses were selected from literature and were adjusted using the latest observed data

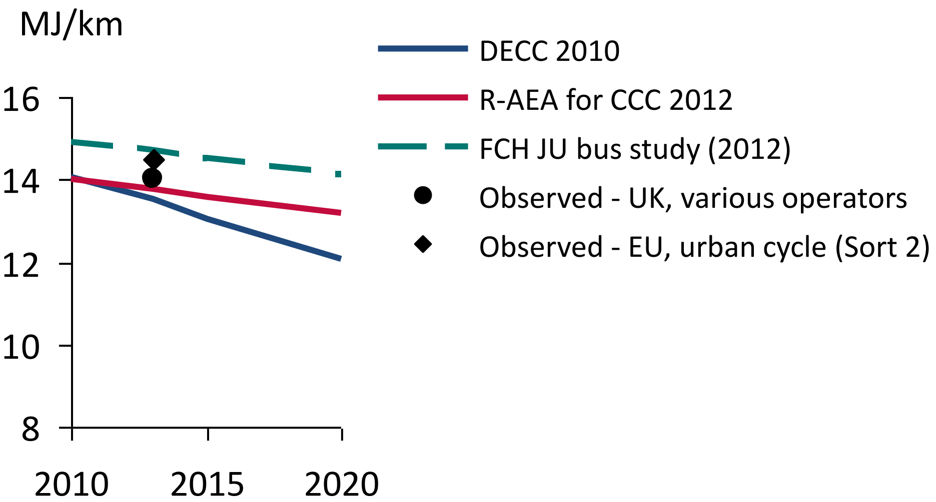


- The data from R-AEA for CCC 2012, is based on a bottom-up analysis of expected truck efficiencies to 2050 and is used as the source for the 'base case' trends
- The FCH JU 2012 report is based on an extensive consultation with all of the major bus OEMs in Europe and therefore reflects a more conservative view on the development of different powertrains in the industry. This report is used to produce the 'worst case' trends
- DECC 2010 contains several bus efficiency scenarios to 2050. Scenario "Level 2" has been used (consistent with the trucks analysis), which assumes that a large proportion of efficiency measures are adopted, excluding hybridisation. It is not calculated as rigorously as the above, but is in agreement with them and the overall industry expectations for an upper case
- Data points from 2015 to 2035 are an interpolation of the data provided by these reports. Data has been corrected and updated where possible to reflect the latest information from UK bus operators and UK trials (the nature of this data is confidential and cannot be discussed in disaggregated form)
- Data represents new vehicles tested on conventional driving cycles (such as SORT)

**Standard city buses – Trends from literature**




**Standard city buses – Literature vs. observed (2013/14)**

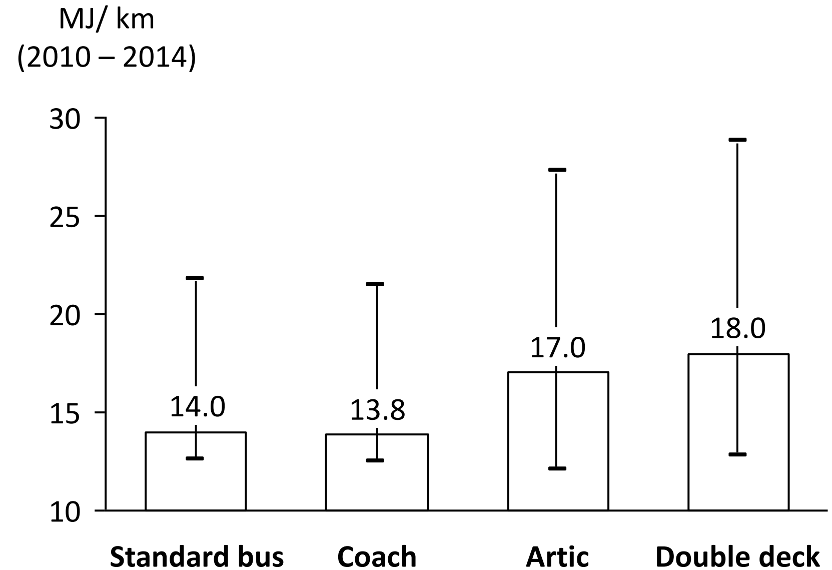



R-AEA for CCC 2012, FCH JU Bus study 2012, DECC 2010

# In this study we distinguish between four main bus archetypes reflecting the main market segmentations

| Type | Typical specifications | Example |
|---|---|---|
| **Standard city bus** | Length: 10 to 13m<br>Weight: ~ 18t<br>Passengers: 30 to ~ 40 seated |  |
| **Coach** | Length: 12 to 13m<br>Weight: ~ 18t<br>Passengers: ~ 50 seated |  |
| **Articulated** | Length: ≥18m<br>Weight: up to 30t<br>Passengers: up to 70 seated or more |  |
| **Double deck** | Length: 10 to 14m<br>Weight: up to 30t<br>Passengers: ~ 80 seated or more |  |

**Typical variations between buses – data from operators**




- Comparing the relative fuel efficiency of different bus types is methodologically difficult as buses' actual fuel economies depend on driving cycle, usage patterns, driving style etc.
- The graph above reports some observed figures coming from over 6 bus operators based in UK and Europe.
- Broadly speaking, the observed variation mirrors the technical specification of the buses (buses with similar weight and passenger capacities tend to have similar fuel efficiencies).

Element Energy – anonymised data from multiple bus operators.

# The efficiency improvement trends for buses are driven by costs to operators, air quality regulations, and public sector initiatives



## Discussion

- The efficiency improvement technologies are part of a long list of measures which can realistically be fitted on new vehicles before 2030. The largest improvements are expected from light weighting, down-sizing the engine, as well as provide better training to drivers (e.g. more regular/smoother driving).
- Buses are often operated or regulated by public bodies, so there is greater scope for the adoption of new solutions, because efficiency improvements are not driven by economics as strongly as for trucks, which are commercially operated.
- EU air quality regulations require reduced pollutant emissions. Some vehicle efficiency improvements are driven by the need to reduce local pollutant emissions, however some engine measures to reduce emissions of pollutants can worsen efficiency. This is mostly the case for retrofit, as EURO VI buses show better fuel efficiency than EURO V versions.
- Government initiatives (such as the Green Bus Fund in the past) also lessen the cost to operators of adopting fuel efficient technologies, and hence accelerate the rate of adoption.
- Buses share many efficiency improvement technologies with trucks so synergies between the two sectors are expected over the coming years.
- Similar bus configurations (such as standard city buses and coaches) benefit from many of the same improvements, particularly in the engine and transmission. The urban duty cycles of urban buses (standard, articulated and double deck) mean that they can particularly benefit from stop/start technology and light weighting. Likewise coaches can benefit from aerodynamic improvements on their long distance duty cycles, however these are not as significant as for trucks, where there is much more scope for improvement on the tractor-trailer configuration.

TTR for Low CVP 2014, R-AEA for EC 2011, Delft for EC 2012; Element Energy

# The efficiency improvement trends for ICE buses (and other powertrains) reported in the consulted studies are reconstructed by stacking available efficiency measures

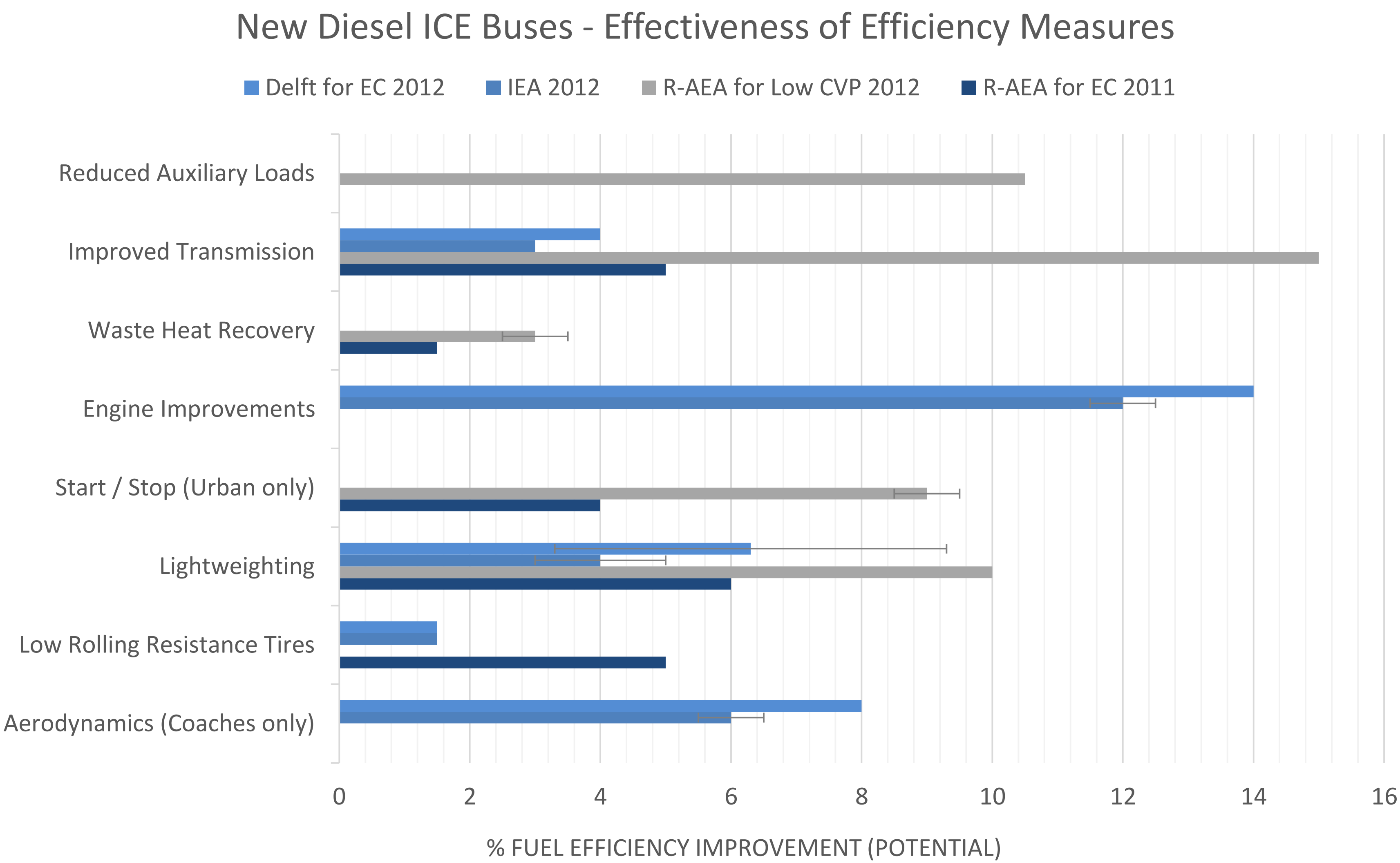
## % of new vehicles adopting the improvement – example reported from the baseline scenario in R-AEA for CCC (2012)

| Measure (non exhaustive, for buses) | 2020 | 2030 | 2040 |
|---|---|---|---|
| General improvements (+ impact AQ emission control) | 100% | 100% | 100% |
| Mechanical Turbocompound | 0% | 10% | 30% |
| Electrical Turbocompound | 0% | 1% | 15% |
| Heat Recovery (Bottoming Cycles) | 0% | 0% | 5% |
| Controllable Air Compressor | 0% | 0% | 0% |
| Automated Transmission | 30% | 80% | 100% |
| Stop / Start System | 90% | 100% | 100% |
| Pneumatic Booster – Air Hybrid | 0% | 0% | 0% |
| Aerodynamic Fairings | 0% | 0% | 0% |
| Spray Reduction Mud Flaps | 50% | 100% | 100% |
| Aerodynamic Trailers / Bodies | 0% | 0% | 0% |
| Aerodynamics (Irregular Body Type) | 0% | 0% | 0% |
| Active Aero | 0% | 20% | 50% |
| Low Rolling Resistance Tyres | 25% | 50% | 80% |
| Single Wide Tyres | 0% | 10% | 20% |
| Automatic Tyre Pressure Adjustment (ATPA) | 50% | 100% | 100% |
| Light weighting | 4% | 30% | 60% |
| Predictive Cruise Control | 0% | 0% | 20% |
| Smart Alternator, Battery Sensor & AGM Battery | 15% | 35% | 70% |
| Alternative Fuel Bodies (for RCV /Refrigeration /Tipper) | 0% | 0% | 0% |
| Advanced Predictive Cruise Control | 0% | 0% | 0% |

NOTE: a different combination of measures and penetration rates is applied for each powertrain

# Different energy efficiency measures have a different technical (energy efficiency) potential. The baseline, best and worse case scenarios reflect different levels of ambition for the market penetration and effectiveness of these technologies





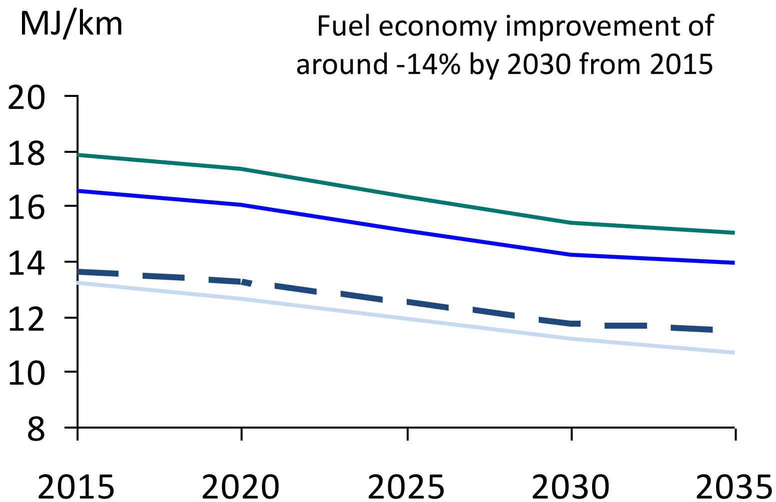

Delft 2012; IEA 2012; R-AEA 2012; R-AEA 2011

# Emerging trends: ICE powertrain efficiency improvement – Buses

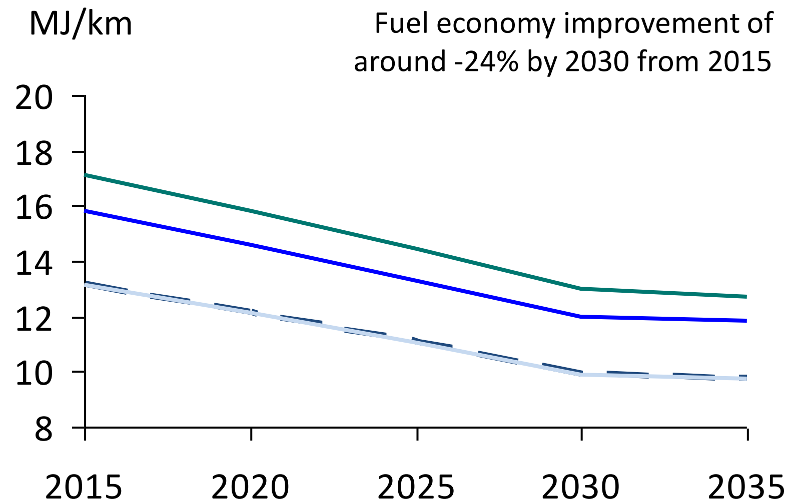


Standard bus
Artic
Coach
Double deck

## Central – all bus types




## Best case – all bus types




## Discussion

- Buses (of all types) are predicted to improve in fuel efficiency as engine, transmission, and vehicle improvements come into the market, with the majority of improvements being available before 2030
- Baseline projections suggest a 14% reduction in the fuel consumption for new vehicles in average by 2030, with greater savings possible if driven by regulation/high effective fuel prices
- Best case scenarios come from DECC 2010, which contains “ambitious” vehicle efficiency trends, making use of all vehicle, engine and transmission improvements as detailed on the previous slides. Overall, the consulted studies suggest that the introduction of improvements in the base vehicle and ICE engine components can reduce the fuel consumption of new vehicles by ~25% from 2015 levels by 2030

Element Energy analysis

# Low emission bus technologies: a portfolio of solutions exists as an alternative to conventional diesel buses

**Increasing potential for reduction in pollutant & GHG emissions // Increasing complexity // Decreasing maturity**

**NOTE**: may all have very similar environmental performance depending on e.g. driving cycle, payload, bus route, etc.

**Efficient Diesel (EURO VI)**

EU regulation implies all buses purchased from 2015 need to be Euro VI.

**Status quo from 2015**

**Retrofit**

Pre-EURO VI bus retrofitted with emission control devices to reach EURO VI level.

**CNG buses**

Spark-ignition engine.

Bus equipped with CNG fuel tanks.

**Hybrid powertrain**

Electric and ICE engine components .

Main mover is electric for series and plug in hybrids.

(hydraulic and flywheel systems also included)

**Electric powertrain**

Powertrain is completely electric (e.g. electric motor(s) + battery / supercaps).

**Fuel cell electric powertrain**

Bus powertrain is completely electric (same as per electric buses) but main power plant is a fuel cell system using hydrogen as fuel.

Bus equipped with hydrogen fuel tanks

**Zero tailpipe emission options**

**Requires specific refuelling infrastructure**

CNG = compressed natural gas;
ICE = internal combustion engine

# Gas buses have a modest penetration in the UK (c. 100) but are benefitting from mature markets outside the UK



## Grants and funding available

- **£30 million fund** for low emission buses in 2015-2020 (Round 1 results pending)
- Natural gas is eligible under the **Bus Service Operators Grant** (BSOG) in the same way as other fuels (operators can claim 18.88p per kg, e.g. ~ 6.5p/km). Biomethane can directly qualify for the LCEB incentive (~6p/km)

### Typical costs compared to diesel buses

- Vehicle premiums of ~£25k to £35k
- Indicative fuel cost savings **23p/mile** for a 12m bus, **i.e. £11,500/year**[1] based on 50,000 miles

### Typical specifications

- 70-120 passenger payload for non-articulated
- Emissions easily meet EURO 6
- 50% noise reductions

MAN Lion's City Bus

- Arriva buses across the North-East and North-West of England, including in Runcorn

Scania/ADL E300

- 34 in Reading bus fleet, 40+ in Sunderland. New biogas in Bristol

- Double deck model from Scania is expected to come to market in 2016, along with more single decker options
- A CNG hybrid bus from Tata is also available, currently operating in Spain

Source: Element Energy. Running costs are indicative: dependent on driving conditions, loading level etc.

1 – ex. VAT, based on diesel cost of £1.21/litre. Consumption figures and annual mileage based on CCC modelling

# CNG solutions are mainly available as single deck buses although Scania is preparing the introduction of a double deck model

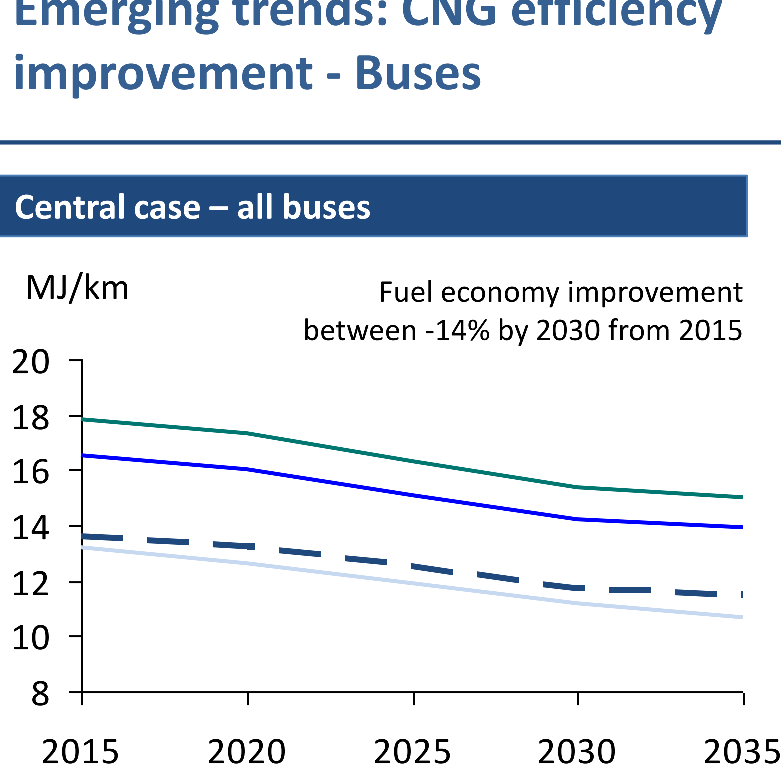


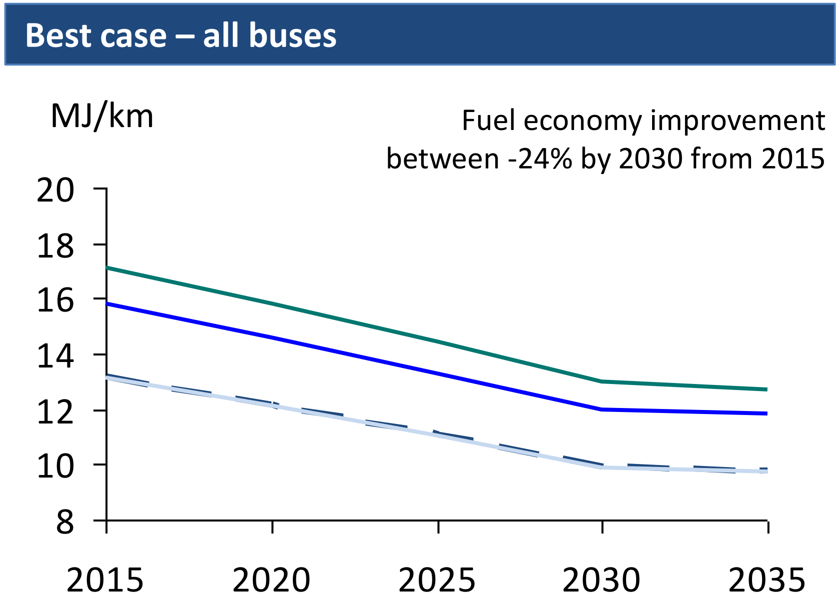
**Blue** = model not yet available

| | Models | Power | Size & passengers | Range |
|---|---|---|---|---|
| **Single deck**  | • **Man** - *Lion's City*<br>• **Iveco** - *Urbanway*<br>• **Scania** - *ADL E300*<br>• **EvoBus-** *Citaro - NGT*<br>• **Tata** - *Starbus CNG/hybrid* | • 270 to 300 HP<br>• 200 to 222 kW<br>• 1050 to 1350 Nm | • 12 to 14.7m<br>• 70 to 120 passengers | • 250 to 500 km |
| **Double deck**  | • **Scania** – *model based on the ADL ENVIRO 400 body*<br>*(available early 2016)* | • 280 HP<br>• 206 kW<br>• 1350 Nm | • 10.2 to 11.4m<br>• 75 seats | • 350 km |
| **Articulated**  | • **Man** - Lion's City<br>• **Iveco** - Urbanway<br>• **EvoBus** - Citaro NGT | • 300 to 380 HP<br>• 222 to 280 kW<br>• 1200 to 1300 Nm | • 18 m<br>• 115 to 165 passengers | • 250 to 500 km |

Source: Element Energy; slide reports the main suppliers for the UK. Other OEMs / models available across Europe

# Emerging trends: CNG efficiency improvement - Buses




## Discussion

- Gas buses are expected to benefit from many of the same efficiency improvements as conventional diesel ICEs. CNG engines are less fuel efficient (on a MJ basis per km driven) than diesel ICE engines, but emit slightly less $CO_2$ overall, provided methane emissions are minimised, as natural gas emits less $CO_2$ per MJ burned
- Reduction of emissions via CNG buses will depend on payback times for operators, and infrastructure. The solution is often considered as a way of improving air quality in urban areas (although difference with EURO VI diesel engines is marginal in most driving cycles) . All CNG buses in the UK are run on biomethane (which delivers substantial WTW emissions savings compared to diesel) through the purchase of Green Gas Certificates, as this give operators access to the LCEB incentive (~6p/km)

# There currently are well over 2,000 diesel hybrid buses in the UK, making it the most common low emission bus technology in the country



## Grants and funding available

- **£30 million fund** for low emission buses in 2015-2020 (Round 1 results pending)
- Can qualify for the LCEB incentive (~6p/km) on top of the BSOG

### Typical costs compared to diesel

- Vehicle **cost premiums typically around 30% to 50%** compared to diesel equivalents
- Indicative fuel savings around 10% to 30% compared to diesel equivalents[1]
- Variable payback, e.g. can be 8 or more years if unsubsidised according to LowCVP/TTR

### Typical specifications

- Payload and range similar/equal to conventional diesel alternatives
- Two main powertrain choices: **parallel** (ICE engine is the main mover) or **series** (electric motor is the main mover, ICE engine used for powering a generator & recharging the battery)

ADL – ENVIRO 200H


Wrightbus - New Route Master

Volvo – *7900H articulated*

1 - Lower bound from LowCVP and TfL studies. Upper bound potential stated by manufacturers for single deck buses
ICE: Internal Combustion Engine

# Around 65% of the hybrid electric (HEV) diesel buses in UK are series hybrids. Overall, there is a broad choice of platform and manufacturers

| | Models (main OEMs) | Typical size & passengers | Range and other considerations |
|---|---|---|---|
| **Single deck**  | • **Wrightbus** - *StreetLite*<br>• **ADL** – *ENVIRO 200H and ENVIRO 350H*<br>• **Volvo** – *7900H*<br>• **Optare** – *Versa HEV (midibus), Solo HEV (midibus)* | • 8 to 15m<br>• Min 30 seated to 120 (seated + standing) passengers | • Range ~ as per the diesel equivalents<br>• Very short electric-only range (typically up to 1 km for parallel hybrids and up to 10km for series hybrids)<br>• Fuel economy: actual figures depend on driving cycle, route, payload, etc.<br>• Manufacturers state up to 30% savings for double deck buses and up to 40% for single deck buses |
| **Double deck**  | • **Wrightbus** - *New Road Master; Gemini 2*<br>• **ADL** – *ENVIRO 400H*<br>• **Volvo** – *B5LH (Wrightbus Gemini 2 body)* | • 10 to 12m<br>• Typically 60 to 90 passengers | |
| **Articulated**  | • **Volvo** – *7900H articulated*<br>• **EvoBus** – *Citaro G* | • Typically ~ 18 m<br>• Typically 150 – 160 passengers | |

**NOTE**: companies like **Vantage Power** and **MagTec** retrofit existing buses (single or double deck) with hybrid powertrains

Source: Element Energy, LowCVP, manufacturers' website. Note: other hybrid bus developers in EU are Van Hool, MAN, Solaris and others.

# OEMs are introducing new diesel hybrid bus concepts aimed at increasing fuel savings and electric range

| Solution | New concept/technology introduced | Example OEMs |
|---|---|---|
| **Flywheel-hybrid diesel bus (FHV)** | • The bus uses a flywheel (in a vacuum) to boost kinetic energy recovery and decelerate<br>• The stored energy is mechanically used to accelerate the bus thus saving fuel and reducing emissions | • **Wrightbus** prototype based on Euro VI StreetLite bus with Flybrid® KERS technology |
| **Hydraulic hybrids (HHVs)** | • Hydraulic hybrids (HHVs) store energy as compressed fluid, and will be entering the market over the next few years. | • UK: demonstrated by **Artemis** in collaboration with Lothian Buses and Alexander Dennis |
| **GPS assisted diesel-hybrid bus** | • 'Virtual electric' hybrid bus concept: an on-board GPS system switches off the engine in emission sensitive area and delivers a higher electric-only range where needed | • **ADL** is testing the concept on an ENVIRO 400H in London |
| **Plug-in hybrid and range-extended solutions (PHEV)** | • Same configuration as for parallel or series hybrids but with a larger battery and off board charging facility (requires a charging infrastructure - bridge solution between hybrid diesel and battery electric buses)<br>• Volvo is also testing a hybrid solution (7900 Electric Hybrid) which runs on electricity for up to 70% of a normal route. It requires a opportunity charging infrastructure along the bus route (up to 6 minutes per charging). In UK it will be tested by Lothian<br>• In 2016, TfL will demonstrate range-extended hybrid electric diesel buses (ADL E400H) with inducting recharging at either end of demonstration route | • **Volvo -** 7900 Plug-in Hybrid (parallel) and 7900 Electric Hybrid (EH) (series) |

***Volvo's 7900EH model being used in Hamburg***

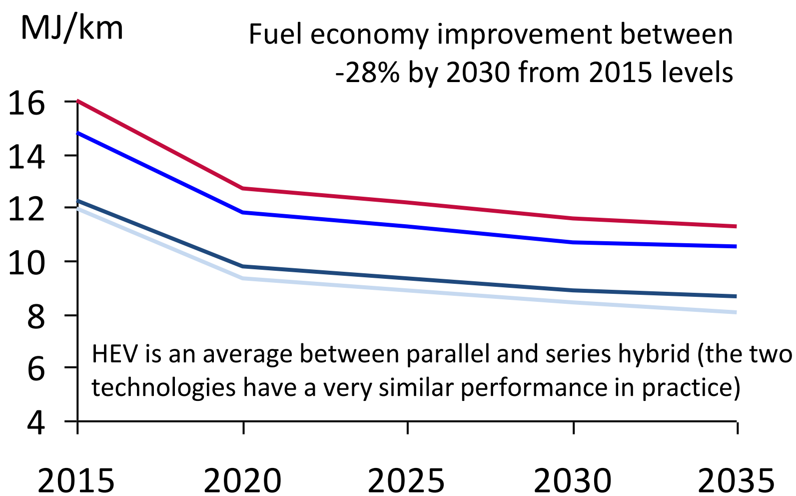
*Not modelled due to lack or literature and trial data*

Source: Element Energy, manufacturers' website. Note: not exhaustive

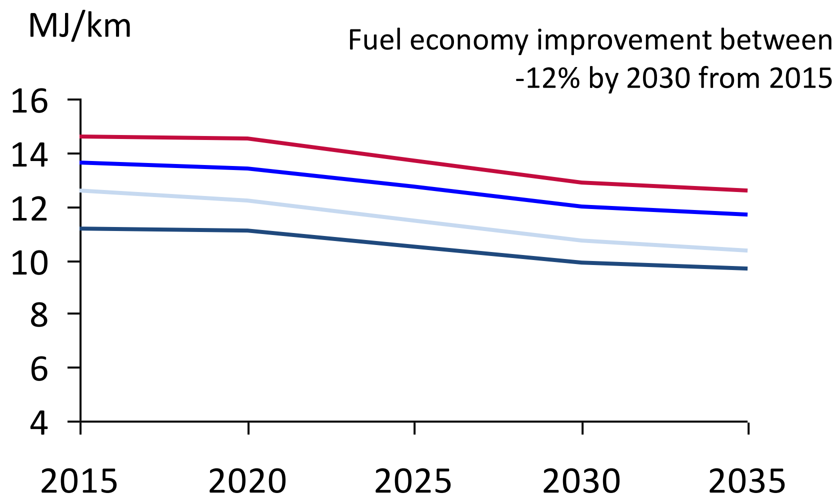
# Emerging trends: Hybrid ICEs efficiency improvement – Buses

Standard bus | Artic | Coach | Double deck

## Diesel Electric Hybrid (HEV) - baseline

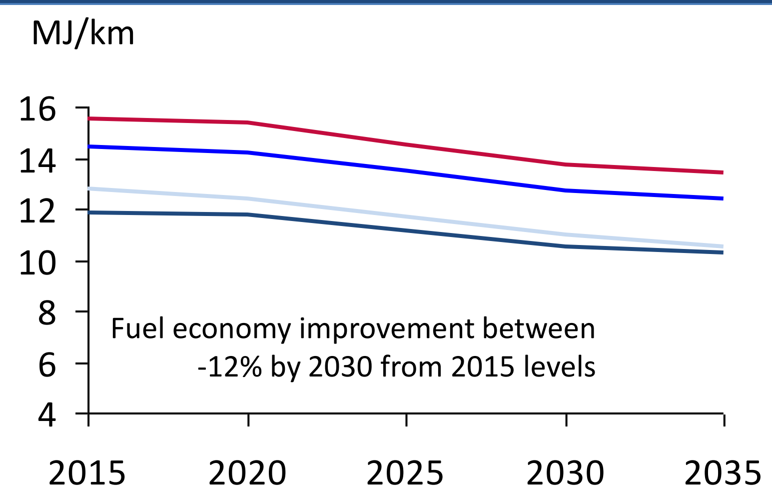



## Diesel Flywheel Hybrid (FHV) - baseline




- Diesel electric hybrids were the first hybrid powertrain to be introduced. The sharp improvement between 2015 and 2020 reflects the on-going industry efforts to optimise this technology (early solutions proved to have a fuel economy only marginally better than incumbent as well as reliability problems).
- The other hybrid solutions are thereby expected to benefit from the past industry experience with HEV and offer a more optimised architecture from the outset.
- All hybrids are expected to benefit from some of the efficiency improvement technologies for conventional ICEs (weight reduction, etc.) as well as improvements in the electric/ flywheel/hydraulic components (energy storage and ancillary equipment).

## Diesel Hydraulic Hybrid (HHV) - baseline



# Several electric buses are being trialled in the UK and product offer is expanding from 12m to double decker and articulated buses

## Grants and funding available

- **£30 million fund** for low emission buses in 2015-2020 (Round 1 results pending)
- Qualify for the LCEB incentive (~6p/km) on top of the Bus Service Operators' Grant
- European funding available for trial, e.g. current trial in London of 12m BYD full electric buses

### Typical costs compared to diesel

- Typically **twice as expensive** to buy, depending on bus platform and battery specifications (e.g. premium of ~ £100k to 200k or more)
- Indicative fuel cost savings **45p/mile** for a 12m bus, **i.e. £13,500/year**[1] based on 30,000 miles

### Typical specifications

- Restricted range compared to other options **(e.g. topically no more than 150 miles)**
- Innovative solutions are being trialled to improve range (e.g. **wireless charging** in London & Milton Keynes)

WrightBus StreetLite (midibus)

- Arriva: 8 in Milton Keynes

Optare Versa & MetroCity (12m)

- Nottingham, London

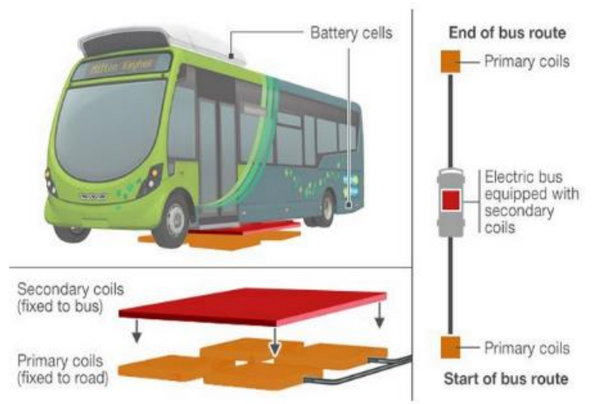
**Double deck models**:

- Magtec converted a double deck bus to electric in York (City Sightseeing bus, operated by Transdev)
- Other double deck models expected by 2016 for trial (e.g. from BYD)

Source: Element Energy. Running costs are indicative: dependent on driving conditions, loading level etc.
1 – ex. VAT, based on diesel cost of £1.21/litre. Bus performance based on TfL trial data

# Electric buses require dedicated high voltage charging infrastructure (e.g. 3 phase/400V) at the depot or along the bus route

| Charging at the Depot ('overnight') | | Charging along the road ('opportunity') | |
|---|---|---|---|
| Manual process | Automated process (e.g. guided via Wi-Fi and/or other sensors) | | |
| *Large bus battery required to deliver full range; long charging times (2 to 7 hours, depending on daily top-ups)* | | *Electric range is shorter than overnight-charged buses with brief (2-15 minutes) charging in dedicated areas* | |
| **Conductive (plug-in)** | **Inductive** | **Conductive** | **Inductive** |
| • Cable solutions typically use <60kW systems although up to 200kW possible<br>• Most common solution adopted in current trials. Circa ~ £30k per charger (LowCVP) | • Wireless can be preferred for operational reasons<br>• 60-300 kW depending on use and battery type | • Overhead solutions can use 100-450 kW fully automated systems<br>• System to be tested by Lothian in UK (for Volvo 7900EH units) | • Up to 300 kW (Milton Keynes project uses 120kW). TFL to also test systems for hybrid buses (Enviro 400H)<br>• Static only in the UK (dynamic used in S. Korea) |

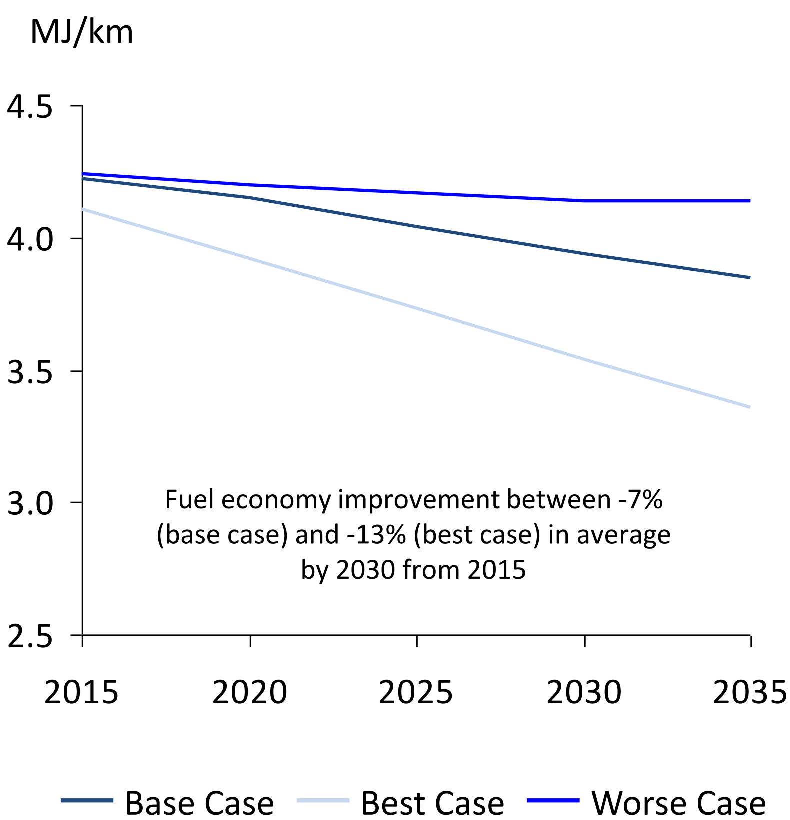





Source: Element Energy for Centro, 2015

# Emerging trends: BEV fuel efficiency improvement

## Electric Buses – standard bus




**NOTE**: due to lack of sufficient literature data and experimental evidence, Overnight and Opportunistic buses are modelled to have same TTW efficiency. Industry discussions suggest that the weight penalty for extra battery can add up to 0.5 MJ/km per extra tonne of added weight

## Discussion

The efficiency of electric buses is driven by:

- *Improvement in the base vehicle*: electric buses will benefit from the same basic measures as for all other buses (weight reduction, reduced energy requirements for ancillary equipment and air conditioning / heating, etc.).
- Benefits are expected from the optimisation of the battery system (integration, system management, ancillary equipment) although – as per the passenger car case – improvements on this over the next 10 to 15 years are expected to be only incremental (please also refer to the car part of this report)
- The TTW efficiency for all electric bus solutions are expected to be close although weight penalty may account in practice of different fuel efficiency performance:
    - *Overnight Charging:* the battery is charged only overnight. Hence, more batteries must be used, reducing passenger capacity and increasing weight
    - *Opportunistic Charging:* the battery is topped up using inductive charging at bus stops. Hence their size (and thus weight) is greatly reduced compare to overnight solutions

# Battery electric buses today account for ~ 4% of the low emission bus technology adopted across UK (all based on single deck to date)


***BYD/ADL's electric bus***

***Wrightbus's electric bus***


***Optare's electric bus***

## BYD

- Supplying Nottingham City Council with 13 electric buses plus charging equipment
- 12m buses with ~150 miles range on a c. 5 hour charge (at the depot)

## ADL & BYD

- Supplying 51 single decker, 90 passenger battery electric buses to Go-Ahead London. This will be the largest fully electric fleet in Europe.
- Buses will be built on BYD's chassis and use BYD electric drivetrain and battery technology. They will be bodied by ADL.

## Wrightbus

- Supplied Arriva with 8 electric single decker buses (9.6m, Streetlite midibus ) for Milton Keynes. Induction charging so that buses can run 17 hours / day by charging at each end of the route (est. min 80 miles range between charges)

## Optare

- Have deployed over 80 fully electric buses across the UK and in other countries
- 12 single decker battery electric buses (60 passengers) operating in York's Park & Ride scheme
- 90 mile range with one hour fast recharging. Top ups at the P&R facilities allow 120 mile range per day

Source: Element Energy, manufacturers' website. Note: other battery electric bus developers are active in EU. MAGTEC provide completed EV drive systems to retrofit buses up to 18t GVW including traction, battery and charging systems

# Availability of Fuel Cell buses is limited but rising interest from EU cities could bring costs down through large scale procurements

**Grants and funding available**

- Funding for hydrogen buses is available for European projects via the FCH-JU; London and Aberdeen are currently involved in projects for the commercialisation of hydrogen buses
- **£30 million fund** for low emission buses in 2015-2020 (funds for $H_2$ buses not expected to cover cost premium)
- Can qualify for the LCEB incentive (~6p/km) on top of the BSOG

**Likely future costs**

- Fuel costs will be equivalent to or lower than diesel
- Future deployment through large scale procurement which could bring cost down to c. **£500k** (from >£700k) in the near term, even when excluding synergies with the fuel cell car sector

WrightBus/ Ballard (12m)

- 8 buses in London

Van Hool (13m)

- 10 buses in Aberdeen

**Lessons from current trials**

- Fuel economy at least 30% improvement over conventional buses
- Maintenance is currently more time-consuming than for diesel buses (lack of experienced technicians)
- Immature supply chain → reliability issues with some bus components, which is typical for a technology on its final demonstration phase
- **Existing UK and EU trials are reporting substantial improvements on these topics**

# Fuel cell electric buses require hydrogen gas refuelling via a dedicated refuelling infrastructure at the depot




**Bus HRS in Switzerland with on-site electrolytic H2 production. Total H2 storage capacity: 450 kg; total footprint: 295 m$^2$ (CHIC)**

**Bus HRS in Milano with on-site electrolytic H2 production. Total H2 storage capacity: 250kg; footprint: 330 m$^2$ (CHIC)**

## Hydrogen refuelling


**Aberdeen's bus HRS**

- Hydrogen fuel is provided as **pressurised gas 350bar**
- **Onsite fuel production by electrolysis is an option** (usually a 3 phase connection is required (11kV or 33kV))
- HRS footprint depends on number of buses and H2 production methods . HRS footprint can be lower than 400 m$^2$ for a 10 bus feet
- HRS cost for a 10+ bus fleet: around ~ £1m (more if on-site production is included)

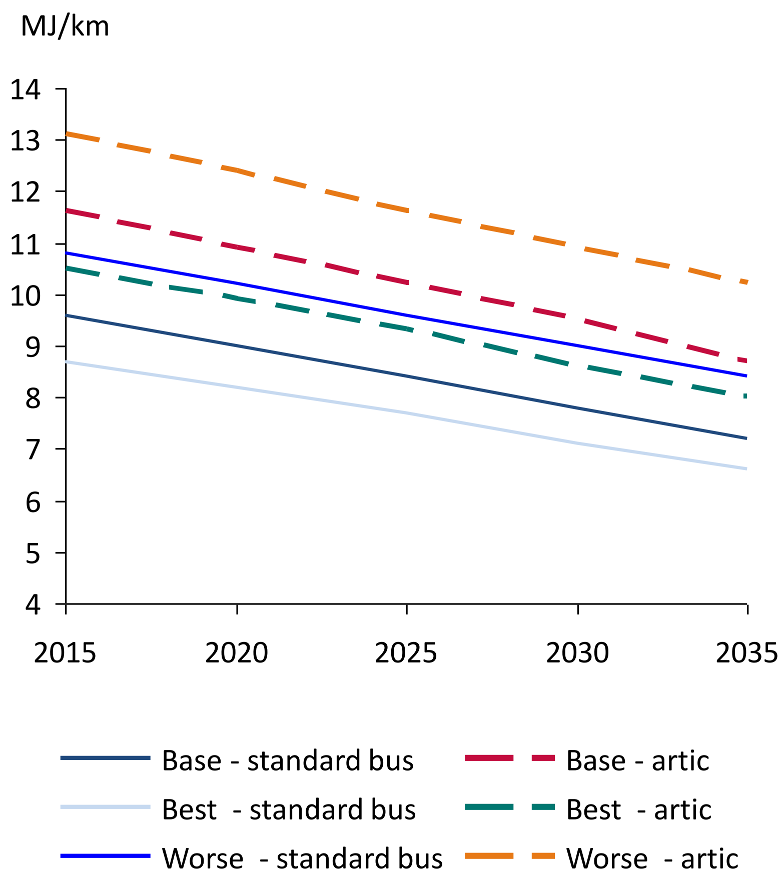
- **Refuelling at depot**, similar to conventional fuels (**refuelling time: <10 minutes per bus**)
- Very few existing HRS across UK (for cars and buses)


**The London bus HRS is a very compact station with a footprint of <35m$^2$ and 850kg of on-site hydrogen storing capacity. This is achieved via the use of liquid instead of gaseous hydrogen tankers (delivered)**

Sources: CHIC, HyTransit, Element Energy

# Emerging trends: FCEV efficiency improvement

## Fuel Cell Buses – standard and articulated bus




## Discussion

The efficiency of fuel cell buses is driven by:

- *Improvement in the base vehicle*: fuel cell buses will benefit from the same basic measures as for all other buses (weight reduction, reduced energy requirements for ancillary equipment and air conditioning / heating, etc.).
- *Optimisation of the fuel cell system BoP and electric hybridisation architecture*, which currently is in a somewhat less developed stage than for FC cars. Benefits are expected from optimised bus operations, as this may *reduce the number of* $H_2$ tanks needed on the roof and the FC kW size (thus reducing weight)
- Improvement in the efficiency of the fuel cell system - this is in turn lead by:
    - *Growth in the passenger car market for fuel cells* - this will help expand the overall supply chain (and develop better stacks) for specialty heavy-duty applications too
    - *Streamlined FC system packaging and optimised integrated powertrain architectures for bus applications* – the existing FCH JU and international trials are producing invaluable learnings for the manufacturers around how to best streamline their designs

Element Energy analysis, Civitas 2013, FCH JU 2012

# Fuel cell bus technology can serve most bus applications although no manufacturer has developed double deck bus solutions to date

| Solution | New concept/technology introduced |
|---|---|
| **Single deck**<br><br>(standard city buses and coaches) | • **Wrightbus** – supplied TfL with 8 fuel cell electric buses (the buses were bodied by Wrightbus and integrated by a third party)<br>• **Van Hool** – is supplying Aberdeen with 10 fuel cell electric buses as well as other transport operators across Europe (a further ~ 40 units in total). Van Hool also deployed 22 FC bus units in the USA<br>• **EvoBus** (Daimler) – supplied several transport operators across Europe with ~ 20 fuel cell electric buses |
| **Single deck articulated** | • **APTS** – supplied transport operators across Europe with 4 articulated fuel cell electric buses (the buses were integrated by Vossloh Kiepe)<br>• **Solaris** – supplied the transport operator in Hamburg with 2 articulated fuel cell electric buses |




**NOTE**: range between 150 to 250 miles depending on number of $H_2$ tanks on the rooftop. Less than 10 minutes for full refuelling. Up to around 80 to 100 passengers capacity for non-articulated and around 150 for articulated FC buses

Source: Element Energy, manufacturers' website. Note: not exhaustive. Van Hool can also do articulated FC buses

# Overview of the main low emission bus technologies
## (excluding diesel ICE retrofit) – current characteristic

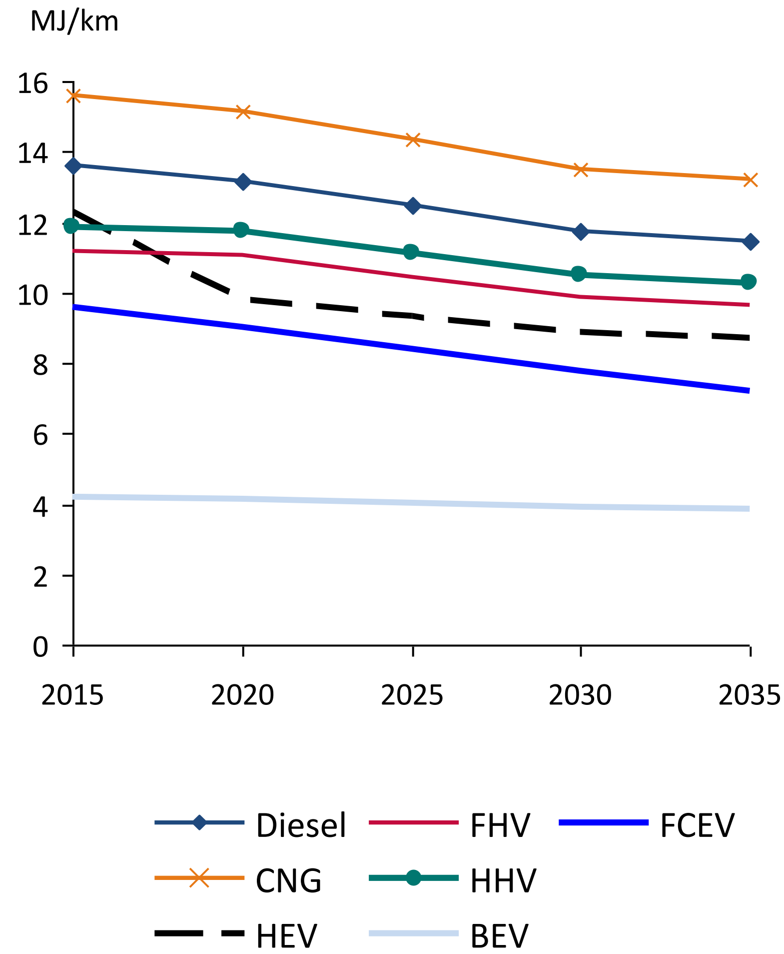


| | Gas | Hybrid | Battery Electric Vehicles (BEV) | Fuel Cell Electric Vehicles (FCEV) |
|---|---|---|---|---|
| *Drivetrain* | **Spark-ignition engine** | **Diesel engine and electric motor** | **Battery and electric motor** | **Hydrogen fuel cell and electric motor** |
| *Logistics of operation* | Currently ~40 gas filling stations in the UK<br><br>Possibility of direct connection to gas network at depot | Refuelling process identical to conventional diesel<br><br>Electric-only range depends on the degree of hybridisation | Battery can be recharged at depot (overnight 2 to 5+ hours) or along the route (opportunity, up to 10 minutes). Recharging infrastructure need to be purchased | Refuelling process similar to petrol/diesel<br><br>Limited stations available in Scotland |
| *Operational flexibility and productivity* | **Range**: 300+ miles<br><br>**Passenger capacity**: as per base vehicle<br><br>**Refuelling time**: as per diesel vehicles | **Range**: 300+ miles<br><br>**Passenger capacity**: as per base vehicle<br><br>**Refuelling time**: as per diesel vehicles | **Range**: 50-150 miles<br><br>**Passenger capacity**: can be reduced (depending on need)<br><br>**Refuelling time**: may require multiple charges and longer charging times | **Range**: 150-250+ miles<br><br>**Passenger capacity**: very close to base vehicle<br><br>**Refuelling time**: close to diesel vehicles |

Source: Element Energy

# Fuel efficiency – comparison between the different powertrain options for buses and coaches

## Standard Buses – Efficiency Comparison – Base case



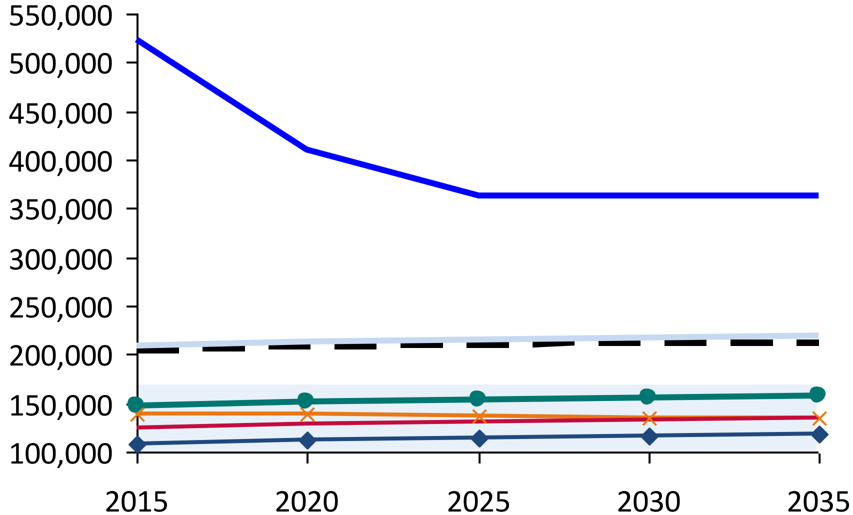

## Discussion

- As for all other transport modes (cars, vans and trucks), pure electric buses are the most efficient bus solution on a MJ per km driven basis
- Among the hybrids, electric hybrid buses are expected to offer the best fuel economy (largely due to a progressively larger electrification of the powertrain and optimisation of the hybrid electric architecture)
- Fuel cell buses are expected to remain more efficient than all hybrid solutions, but less efficient than electric buses (due to the lower specific efficiency of fuel cell systems compared to battery)
- However, fuel cell buses are the only solution capable of offering an operational range (and overall productivity potential) close to that of diesel buses, while offering zero TTW emissions

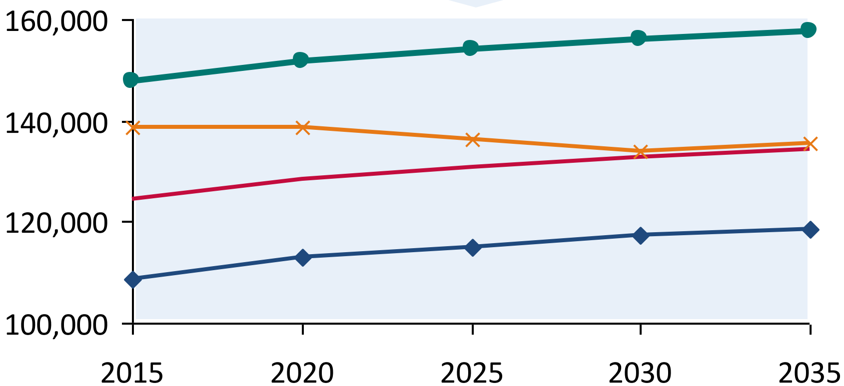
# Cost – comparison between the different powertrain solutions



## Standard Buses – Cost Comparison – Base case




*expanded version below*




## Discussion

- Technical literature suggests diesel ICE will remain the least expensive bus and coach powertrain from 2015-2035.
- R-AEA for CCC 2012 was used to give the baseline diesel ICE cost trend, which increases with time as new efficiency technologies are introduced.
- The cost premiums for hybrids and BEVs were based on TIAX for ICCT 2011, and are consistent with present day real world costs. These premiums are likely to come down with time as technology improves, but this is not captured in the trends presented.
- The trends for FCEVs were taken from Roland Berger for FCH JU 2015, and show that fuel cell buses will remain the most expensive, although their costs are expected to decrease significantly (30%) over the next 10 years.
- The trends for CNG buses were determined from Element Energy's internal analysis.

Diesel ICE
Dedicated CNG ICE
HEV
FHV
HHV
BEV
FCEV

# Contents

# Aviation and Marine

- **Aviation**
- Marine

# There are no strong policy drivers for efficiency improvement yet but a global market based measure is under preparation



## Discussion

### DRIVERS FOR CHANGE

- Efficiency improvements are driven by interest in reducing fuel costs, as well as voluntary $CO_2$ emissions goals, ICAO regulations on local pollutants, and regulations on noise.
- Aviation emissions have been covered in the EU ETS (Emissions Trading Scheme) since 2012. However, because allowances have been over-allocated, no short term impact is expected.
- The International Civil Aviation Organisation is currently developing a market based measure to reduce international aviation emissions and aiming to agree this in autumn 2016.

### BARRIERS TO IMPROVEMENT AT FLEET LEVEL

- **High investment costs**, the **loss of value** from old designs, and **safety risks** inherent in new designs are the main barriers to step change technologies. These can only be overcome with guaranteed high fuel prices for the next twenty years, minimising the risk by guaranteeing a return on investment.
- Increase in demand: DfT projects an increase of 125% by 2050 compared to 2010 (or moderated demand at +90%)
- Low turnover in the fleet, e.g. the British Airways fleet is mostly composed of over 20 year old aircraft (shown later)

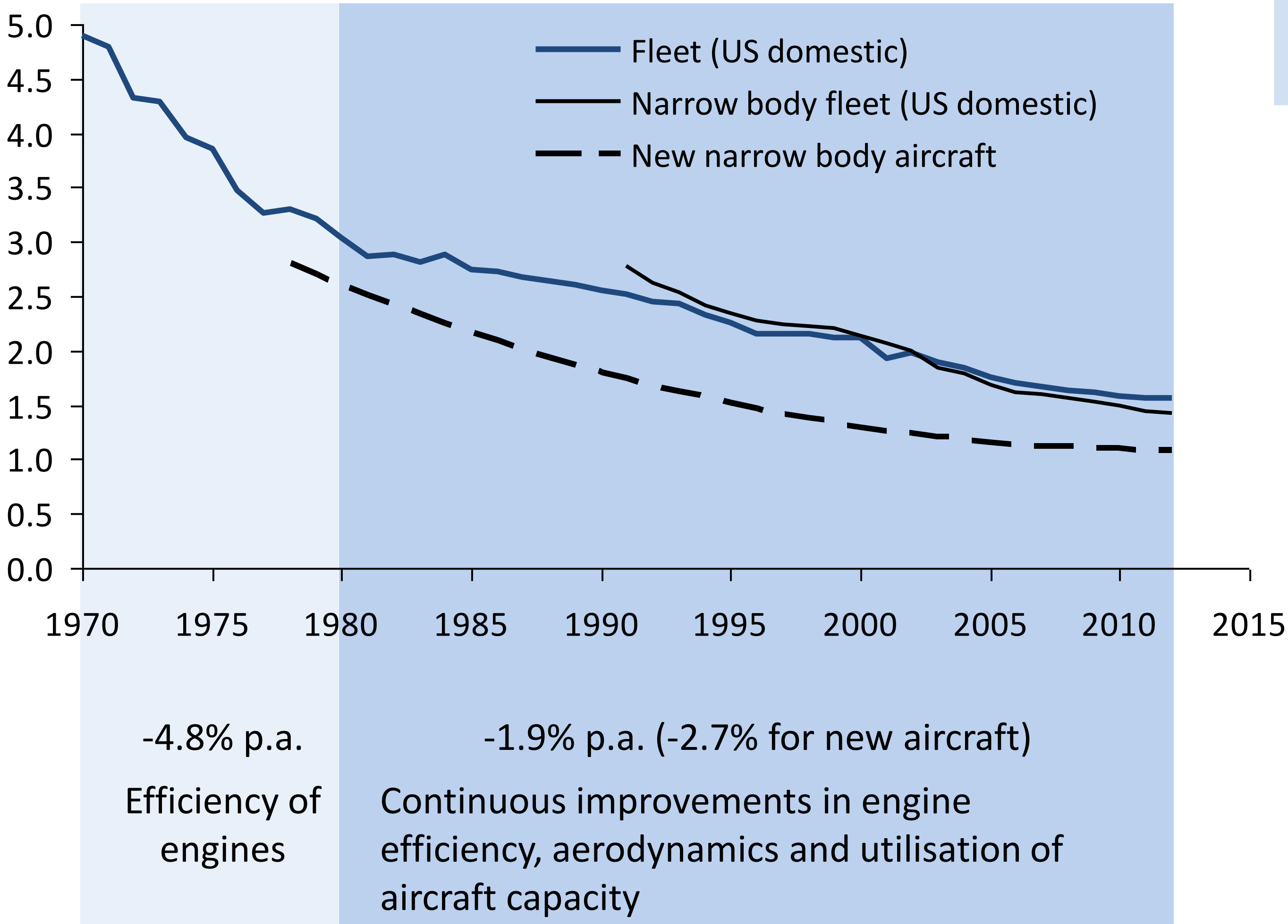
### POTENTIAL FOR IMPROVEMENT (see also next slides)

- After strong annual efficiency increases in the 1970s, changes since 1980 have been of c. 2% p.a. (next slide)
- There are still improvements to be brought, which fall mainly into 3 categories:
  - Incremental technologies, e.g. aerodynamics, use of composites, etc.
  - Step change technologies, e.g. geared turbo fan, open rotor engine, etc.
  - Operational Improvements: e.g. re-routing, more efficient ground operations etc.
  - Modernisation of the fleet, i.e. replacing oldest aircraft with new models
- The use of biofuels is also a way to decrease the carbon intensity of flights, although their use will still be very limited by 2035 (DfT projects 2.5% by 2050 based on purely economic arguments only)

SA 2012, NLR 2005, Qinetiq 2010 ICAO: International Civil Aviation Organisation

# Technology developments, along with seating density, have driven gradual improvements in efficiency per seat-km (c. 2% p.a. since 1980)

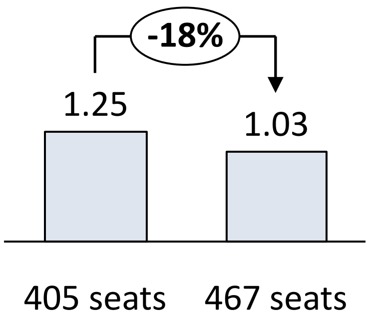
**Historical trends, commercial passenger aircraft, MJ/RPK**




The capacity has a large effect on the per seat-km efficiency within aircrafts of the same model

**Example aircraft, Boeing 747-8, 2011**

**MJ/seat-km**




Sources: Schäfer, Evans et al, 2015 and OEM specifications

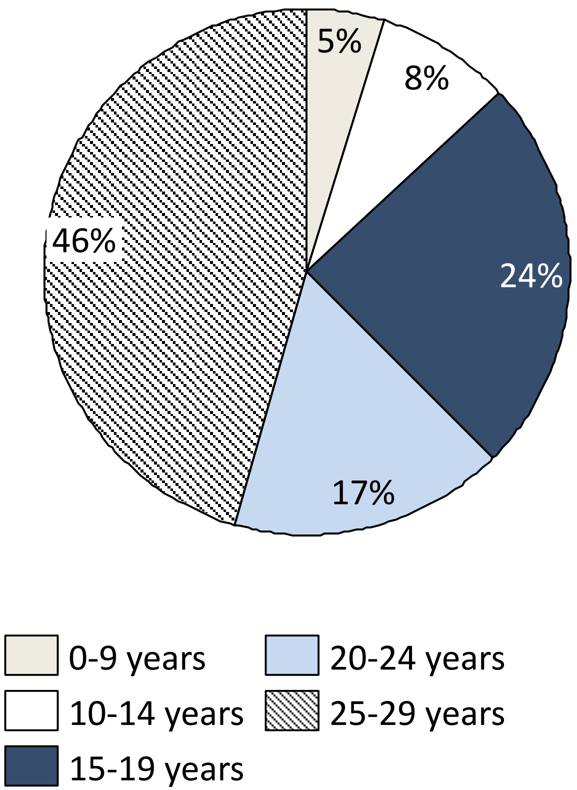
Narrow body: typically up to 300 seats only

RPK: Revenue Passenger Kilometres

# Average fleet efficiencies will only improve gradually over time as new aircraft progressively replace older units

**Example Fleet – British Airways: Age distribution and efficiencies calculated bottom-up from fleet composition data**

## Age distribution of BA fleet (in terms of year of release, rather than purchase)




- BA has an aging fleet, meaning it is less efficient than average. Their transatlantic fleet consumes 51% more fuel than Norwegian airlines, who operate new Boeing 787s (see below)

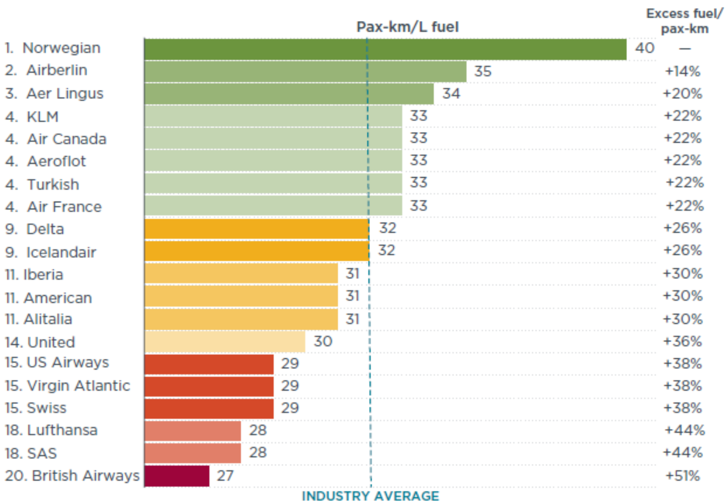



**Figure 1.** Fuel efficiency of the top 20 airlines on transatlantic routes, 2014

Based on published information, BA average fleet performance is as it follows:

- Short Haul efficiency: 1.01MJ/seat-km
- Long Haul efficiency: 1.13MJ/seat-km (or 27 passenger-km/litre, see below)
- Overall efficiency: 1.07MJ/seat-km

ICCT 2015, Manufacturer Specifications

# There is significant scope for improving fleet efficiencies through modernisation and more efficient loading / operations

*Quantified examples are given next*



## Discussion

- **New incremental technology improvements** can be implemented in the 2015-2035 timeframe, and have significant potential for efficiency improvement.
- **Step change technologies** can be implemented to give bigger improvements, but there are significant cost and risk barriers, even for the main OEMs (Airbus and Boeing).
- The biggest scope for efficiency improvements in the short term is in **modernisation of fleets and more efficient loading**:
  - The most efficient available aircraft are not always chosen by operators, who also seek good speed, range, and upfront price. For example, BA is continuing to use its less fuel efficient 747s as they require no capital investment and can be used when needed at busy Heathrow gates.
  - There is currently a 50% difference in efficiency between the most and least efficient transatlantic fleets. This suggests that there is significant potential for improvements to the least efficient fleets, particularly through the replacement of the oldest aircraft.
  - Seating configurations also have a big impact on MJ/seat-km, meaning big improvements could be made by reducing the availability of premium seating and denser seating layouts

**And more efficient operations:**

  - Operational measures can have a significant effect on fuel efficiency of some aircraft, as some flights waste significant amounts of fuel waiting above airports or in stepped ascents and descents. However, total air traffic management efficiency is 92-94%, so there will be a limited total effect.
  - Implementation of improved operations and continuous descent are restricted by ground noise regulations leading to steeper descents and busy skies above airports.

ICCT 2015, Airbus, Ohio University 2014, ICCT 2009, Bloomberg

# A variety of operational and technological measures can be implemented to improve new aircraft efficiency



| Measure: | % Efficiency Improvement | Technology entry into service |
|---|---|---|
| **Incremental Technologies:** | | |
| Aerodynamic improvements (including laminar flow technology) – incremental to 2030 | 12.5 | 2030 |
| Advanced engine technology | 8 | 2025 |
| Increased bypass ratio | 9 | 2025 |
| Increased use of composites | 15 | 2025 |
| Structure optimisation (in conjunction with composites) | 6 | 2025 |
| **Step Change Technologies:** | | |
| Open rotor engines | 21 | 2025 |
| Geared turbofan | 9 | 2015 |
| Blended wing aircraft (2040 or later) | 24 | 2040 |
| **Operational Improvements:** | | |
| Routing optimised to weather conditions | 5 (scope limited as these are already implemented to a significant extent) | |
| More efficient on the ground operations | | |
| Continuous descent | | |
| More direct flightpaths | | |

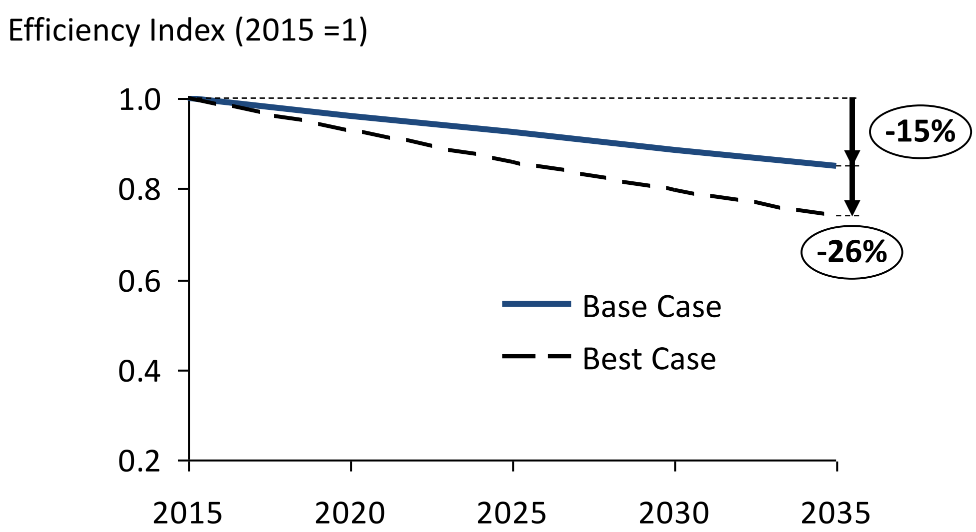
ICAO 2010, Ohio Uni 2014, Qinetiq 2010 (numbers)

# **Literature suggests that average fleet efficiency improvement of 0.8% - 1.5% per year to 2035 is realistic** (based on current fleet replacement practices)

## Discussion

- Fleet efficiency trends are calculated in DfT 2013, taking into account known upcoming efficiency improvement measures, and improved Air Traffic Management and operations, and the improvement potential of each. These are combined assuming that only a proportion will be implemented due to economics. Finally, fleet turnover is also modelled, accounting for the gradual penetration of new aircraft into the fleet.
- The DfT 2013 central demand scenario to 2050 is here taken as the as the **base case** trend, corresponding to a **0.8% per year** fleet efficiency improvement. This is also consistent with the CCC 2009 "likely" scenario, in which efficiency improvement potential is assessed in a similar way as DfT 2013, and aircraft are grouped into generations which enter the fleet at different times. (DfT projects short term improvements of 0.3% per year. It is suggested that this is a modelling construct, and so we take the long term trend to 2050 instead).

## UK Aircraft Fleet Efficiency Trends




- The **best case** trend is taken to give a **1.5% per year** fleet efficiency improvement. This corresponds to the CCC 2009 "speculative" scenario, requiring faster technological development, as well as increased investment and policy intervention. This trend is also consistent with the voluntary industry target of a 1.5% per year fleet fuel efficiency improvement.
- Schäfer, Evans et al 2015 estimates a fleet efficiency improvement of 2% per year in their cost-effective scenario, assuming that all cost-effective measures are implemented. This a faster rate than in other literature, but demonstrates that the best case scenario is achievable.

DfT 2013, CCC 2009, Schäfer, Evans et al 2015, SA 2012

ATM: Air Traffic Management, pkm: passenger km

# Alternative propulsions and fuels (including biofuels and hydrogen fuel cells) are not expected to contribute significantly in the 2035 horizon

**In the long term, biofuels are the best option for significant $CO_2$ emissions reduction**

- Fundamental limits to aircraft efficiency coupled with expected growth in demand mean that efficiency improvements alone are not enough to make significant cuts into total emissions from aviation in regards to the UK 2050 targets
- Airbus and Boeing both have biofuels research programmes, aiming to produce fuels that can be used in standard aircraft engines, and which have no net well-to-motion $CO_2$ emissions.
- **Biofuels** for planes are far from maturity, and are currently not cost competitive. They are expected to make up 2.5% of fuels used in flights from UK airports by 2050 according to DfT 2013, or 25-40% according to SA 2012. The former is based merely on economics, whereas the latter is an ambitious goal as part of a stakeholder roadmap to reduce emissions from aviation .
- While unsuitable as a primary power source, **hydrogen fuel cells** could be used for auxiliary power in the medium term. Airbus are trialling the technology on an A320. This will improve fuel consumption, but not eliminate emissions, as the plan is to generate hydrogen from jet fuel on board.
- Another way to reduce fuel consumption is to power auxiliary systems from land based power sources while stationed at airports. This can save 85% of total APU energy consumption, although this is only a small proportion of the total consumption of a flight.

SA 2012, DfT 2013, Airbus

# Aviation and Marine

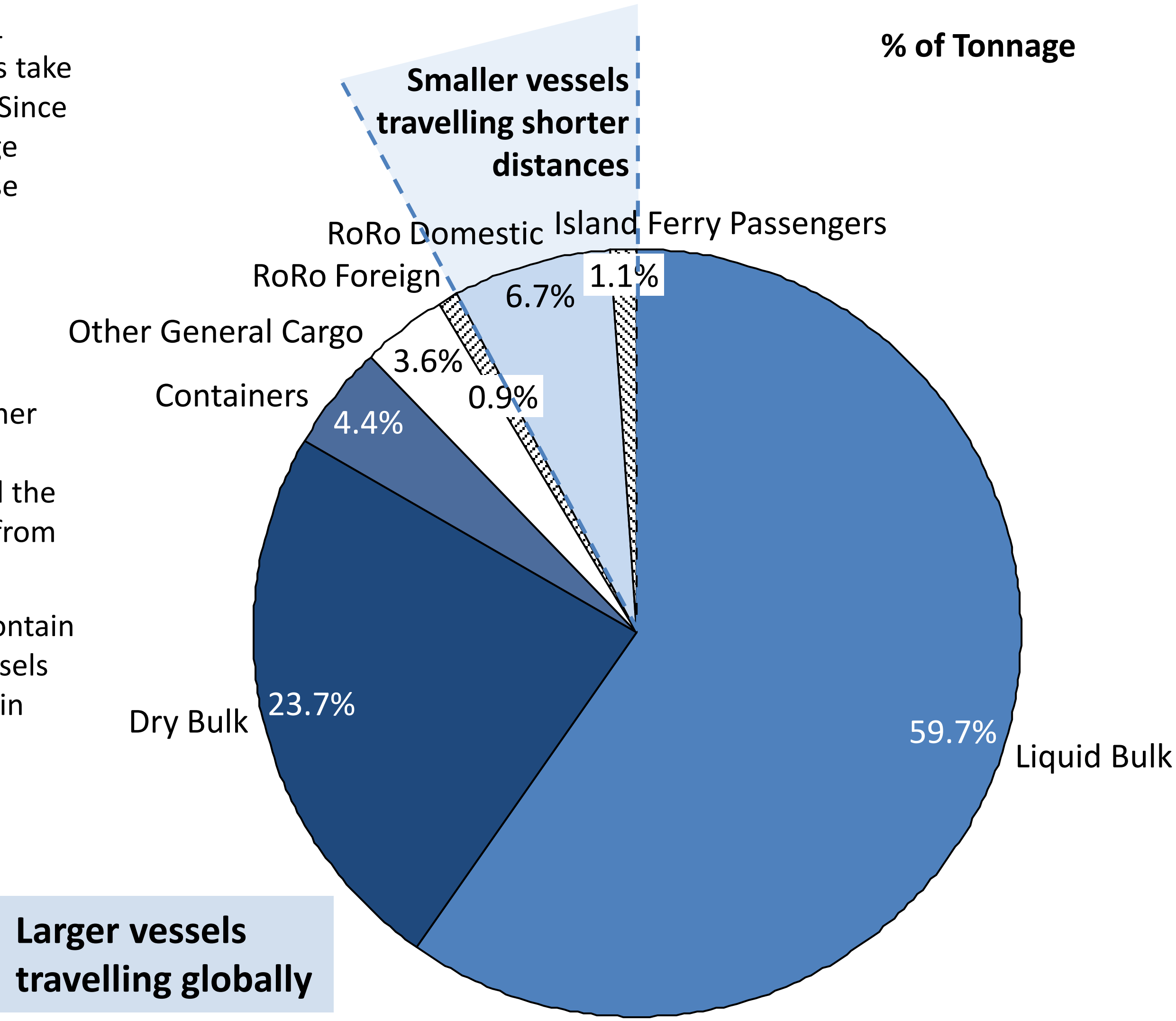
- Aviation
- **Marine**

# Context: Scottish marine emissions are predominantly due to large freight ships, with smaller vessels comprising ~15% of shipping emissions



## Discussion

- Island ferry passengers (assuming 0.1 tonnes/pax) and domestic RoRo ships take up 7.8% of Scottish marine tonnage. Since ferries are less fuel efficient than large freight ships, their emissions comprise ~15% of total marine emissions
- The rest is due to very large vessels travelling between countries and continents
- Smaller vessels have significantly higher potential for deep $CO_2$ reductions (including zero emission options) and the analytical approach will be different from that for large vessels.
- Scottish Transport Statistics do not contain data on fishing vessels, but these vessels are closer to small ferry-type vessels in terms of technology potential.




Scottish Transport Statistics, CMAL 2010

# Different approaches are required for large freight ships and smaller ferries and fishing vessels

## Large Freight Ships

- Efficiency and demand trends are driven by global economics, fuel prices, and international regulation.
- As a result, there is relatively little scope for policy interventions on a national level to drive significant additional progress in large ships, except for e.g. use of on-shore power in particular ports.
- Projected efficiency trends were assessed by considering the range of available technology and operational measures, their technical potential and expected deployment in new ships (similar to approach to diesel truck improvements).
- We also took into account International Maritime Organisation regulations also that drive improvements in fuel efficiency of new ships.
- Fleet efficiency trends were calculated according to assumed rates of new ships into the fleet.

## Smaller Ferries and Fishing Vessels

- Much greater scope for national level measures i.e. franchise conditions for ferries, emissions standards for fishing boats.
- Small vessels also have a higher potential for deep $CO_2$ reductions through hybridisation, electric and $H_2$ powertrains etc.
- We have reviewed the state of the art for these technologies and the status of current demonstration activities to inform projections of low or zero carbon vessels in Scotland.
- Since ferries make up a small percentage of marine tonne-km, measures  such hybridisation have only a small impact. For example, a 50% hybrid ferry procurement policy results in a 1% reduction in marine emissions by 2030 (see main report).

# The marine sector has historically shown relatively low efficiency improvements, although new regulations are beginning to drive improvements in new vessels

## Drivers and barriers of marine efficiency improvements

- The marine industry is characterised by a number of unique factors having a direct impact on its capacity to innovate:
  - *Safety and reliability of the propulsion system is critical* – operations in open sea and under hostile weather could otherwise pose a life-threatening risk to the crew
  - *Most marine vehicles are built in small numbers and designed to be tailored to their specific use* (ferries, container ships, etc.) as well as operators' need (e.g. ferries of different capacity, etc.). Unlike other sectors, prototyping and small-scale testing are thereby rare (economically unfeasible). At the same time, it is unlikely that one alternative propulsion solution will be able to fit all needs.
  - *Reduction in the fuel cost is the key driver* for operators to optimise operations and for ship builders to innovate propulsions. However, ships are often chartered, meaning that the fuel cost can fall on the ship owner or the charterer. In the latter case, there is no incentive for the ship owner to ensure the ship is fuel efficient.
  - Ships have a long commercial life, typically around 30 years, meaning fleet efficiency lags significantly behind new ship efficiency.
  - International maritime emissions are currently *excluded* from any legally-binding GHG reduction targets.

## Environmental and efficiency regulations in the shipping industry

- New ship efficiency is regulated by the Energy Efficiency Design Index (EEDI), adopted by the IMO in 2011. Newly built ships are required to meet efficiency standards, which get stricter over time.
- IMO MARPOL Annex VI came into force in 2005, regulating emissions of local pollutants such as $NO_x$ and $SO_x$ from shipping.
- There is currently no global regulation on the $CO_2$ emissions of shipping, however the IMO is also working on a market-based measure to incentivise emissions reduction.
- There is currently a lack of reliable data on ship efficiency, which is a barrier to adoption of efficiency measures, and to effective legislation. This is being addressed in the EU by Monitoring, Reporting, and Verification regulation requiring ships to publish $CO_2$ data from 2018.

IMO 2014, Nordic Marina

# New ship efficiency is regulated by the Energy Efficiency Design Index, and a market-based measure is being developed



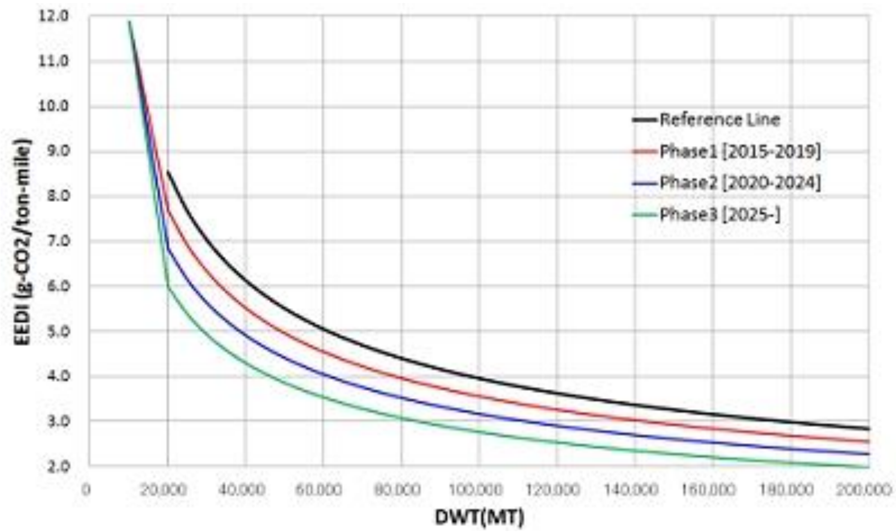
## Discussion

- In July 2011 the IMO adopted the Energy Efficiency Design Index (EEDI) as a means to regulate the efficiency of newly built ships.
- The EEDI is a measure of designed efficiency, and the standard of what index value is allowed gets stricter with time (specific percentage reductions depend on vessel weight and type, see next slide). The reference line is an average of all ship EEDIs between 1999-2009 (see graph on next slide).
- Diesel hybrid and gas turbine powered vessels are excluded from EEDI regulation, as are fishing, offshore, and service vessels.
- Efficiency improvements for new ships on the order of 30% can be expected by 2025 as a result of the EEDI.
- The IMO is also developing a market based measure, likely to be an emissions trading scheme or an emissions levy, in order to further drive efficiency improvements.
- MARPOL Annex VI became effective in 2005, and further amendments came into force in 2010. It regulates air pollutants from ships manufactured or having undergone significant conversion work since 2000.
- Waste incineration, and emissions of $NO_x$, $SO_x$, particulate matter, volatile organic compounds (prohibited), and ozone depleting substances are regulated.
- Stricter $SO_x$ emissions regulations apply in Emissions Control Areas (ECAs; the red zones on the map, see next slide), where the sulphur content of fuel used must be below 0.1%. $NO_x$ emissions in the North American ECA will be more strictly controlled from 2016. Operators can meet the ECA emissions limits through the use of sulphur scrubbers, fuel switching from fuel oil to marine distillate/gas oil (MDO/MGO) or conversion of ships to operate on liquefied natural gas (LNG).

IMO 2014, RAE 2013

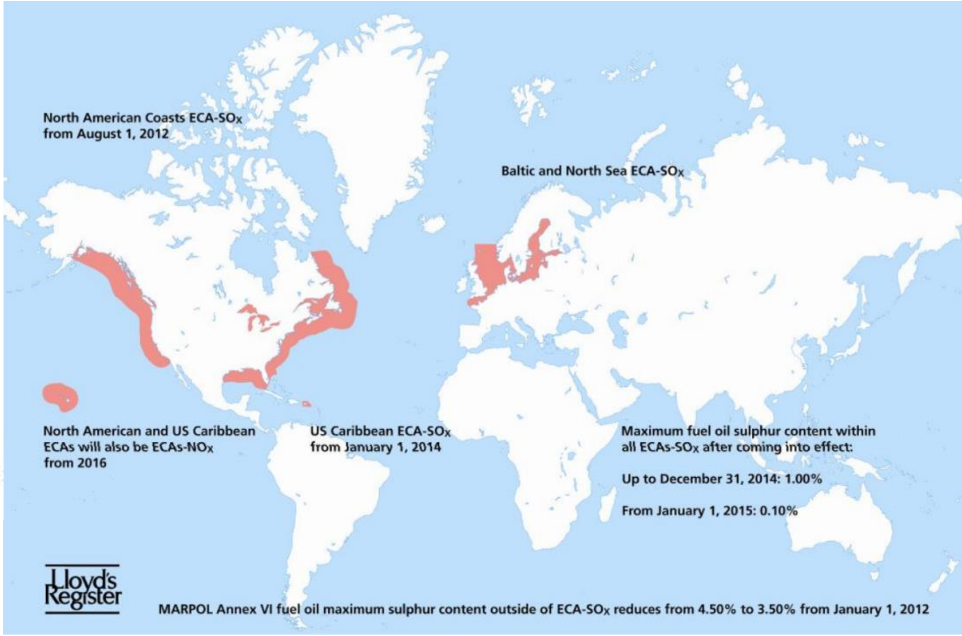
# $CO_2$ emissions are regulated by the IMO's Energy Efficiency Design Index, while local pollution is covered by MARPOL Annex VI

## EEDI % reductions from the reference




| | | Year of entry in the fleet | | | |
|---|---|---|---|---|---|
| | | Phase 0 | Phase 1 | Phase 2 | Phase 3 |
| | | 1 Jan 2013–31 Dec 2014 | 1 Jan 2015–31 Dec 2019 | 1 Jan 2020–31 Dec 2024 | 1 Jan 2025 and onwards |
| Bulk carrier | 20,000–+ dwt | 0 | 10 | 20 | 30 |
| | 10,000–20,000 dwt | na | 0–10 | 0–20 | 0–30 |
| Gas carrier | 10,000–+ dwt | 0 | 10 | 20 | 30 |
| | 2,000–10,000 dwt | na | 0–10 | 0–20 | 0–30 |
| Tanker | 20,000–+ dwt | 0 | 10 | 20 | 30 |
| | 4,000–20,000 dwt | na | 0–10 | 0–20 | 0–30 |
| Container ship | 15,000–+ dwt | 0 | 10 | 20 | 30 |
| | 10,000–15,000 dwt | na | 0–10 | 0–20 | 0–30 |
| General cargo ship | 15,000–+ dwt | 0 | 10 | 20 | 30 |
| | 3,000–15,000 dwt | na | 0–10 | 0–20 | 0–30 |
| Refrigerated cargo carrier | 5,000–+ dwt | 0 | 10 | 20 | 30 |
| | 3,000–5,000 dwt | na | 0–10 | 0–20 | 0–30 |
| Combination carrier | 20,000–+ dwt | 0 | 10 | 20 | 30 |
| | 4,000–20,000 dwt | na | 0–10 | 0–20 | 0–30 |
| LNG carrier | 10,000–+ dwt | na | 10 | 20 | 30 |

## Emissions Control Areas



# Emissions from new vessels can be improved with through technological solutions, operational improvements, and switching to LNG



## Technological Efficiency Improvements

- As shown on the following slide, there is significant scope to **reduce hydrodynamic losses** through cleaning of the hull and propellers, and new, currently unproven, technologies such as air lubrication (pioneered by Mitsubishi Heavy Industries), in which a layer of air is trapped between the hull and the water. Air lubrication is at the trial stage and can be expected to enter the market on a 10 year timescale.

- **Propulsion efficiency** can be improved with a variety of propeller technologies, including counter-rotating propellers.

- **Engine and machinery improvements** can be effected using measures including waste heat recovery and engine de-rating (if the ship can be run safely with lower power).

- Some ship operators are now **switching to LNG** as a way to meet Marpol Annex VI local pollutant regulations, as well as EEDI targets, since LNG has a lower $CO_2$ intensity and near zero SOx and PM emissions compared to marine fuel oil/diesel. However, emissions of unburnt methane must be minimised, otherwise they risk negating any $CO_2$ savings. There are currently ~100 LNG-fuelled ships globally, excluding ~400 LNG carriers. Small scale LNG infrastructure is also being developed, to facilitate the use of LNG to fuel ferries and other smaller vessels.

## Operational Improvements

- **Reducing speed** is a very effective way of improving operational efficiency further. When demand decreases or fuel costs increase, the ships are run at slower speeds in order to deliver freight most efficiently. These “slow-steaming” practices occurred during the recession, resulting in an industry average fuel efficiency improvement of 27% (NCE 2015). Many companies are continuing the practice despite more favourable economic conditions today.

- **Weather routing** can improve efficiency, as bad weather can significantly increase the resistance to the ship’s motion.

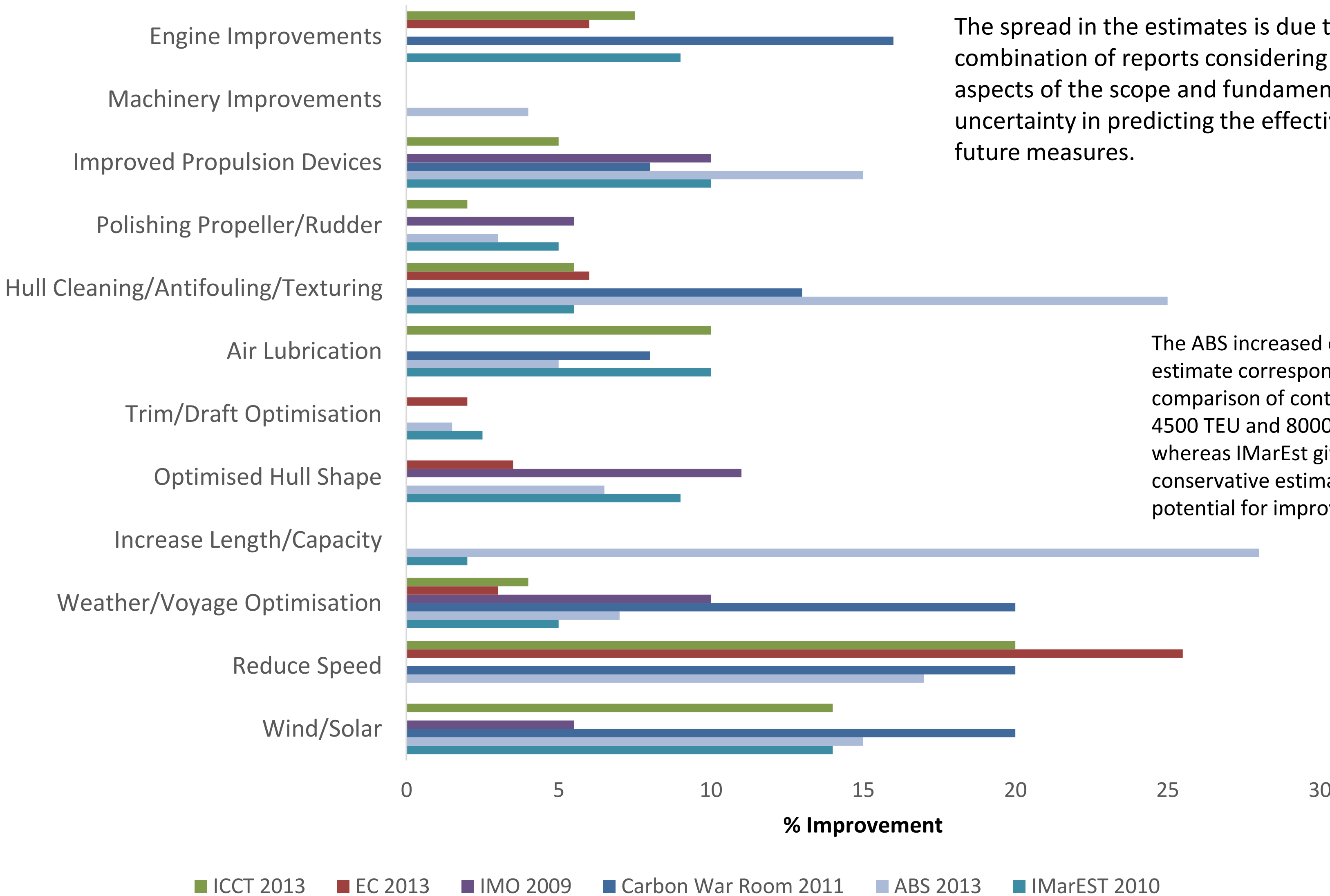
- Improving the **reliability of data** available on the operational efficiency of ships is important, as it will reduce the perceived risk to operators of investing in more efficient vessels. Since 2013 the IMO has required ships to have a Ship Energy Efficiency Management Plan (SEEMP), a tool to aid monitoring and management of a ship’s fuel efficiency. This goes some way towards addressing information gap, but is a full reporting system.

- EU regulation on Monitoring, Reporting and Verification, applicable from 2018, will require ships over 5000 gross tonnes calling at EU ports to **collect and publish verified $CO_2$ data**, as well as other parameters such as time at sea, distance travelled, and cargo carried.

IMarEst 2010, NCE 2015, IMO 2010, DNV 2013

# A variety of operational and technological measures can be implemented






The spread in the estimates is due to a combination of reports considering different aspects of the scope and fundamental uncertainty in predicting the effectiveness of future measures.

The ABS increased capacity estimate corresponds to a comparison of container ships of 4500 TEU and 8000 TEU capacity, whereas IMarEst gives a more conservative estimate of current potential for improvements.

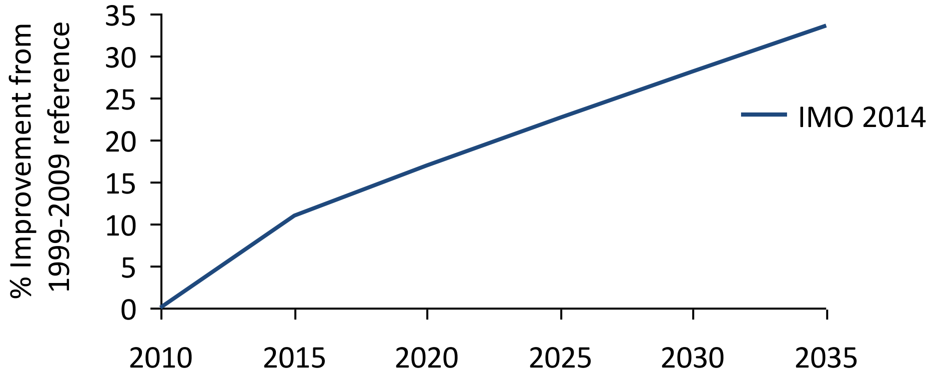
TEU = Twenty-Foot Equivalent unit (number of containers)

# Literature suggests an efficiency improvement for new ships of 28% by 2025 due to the EEDI alone, but only a small fleet improvement due to long vessel replacement cycles

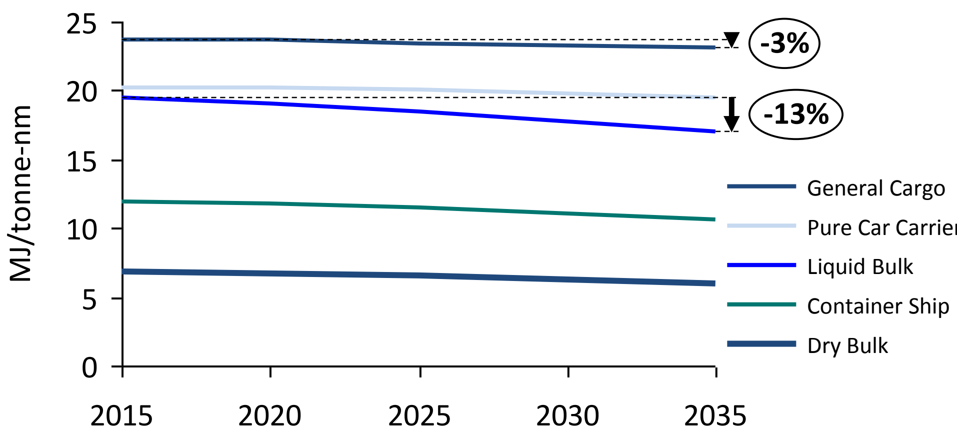
## Discussion

- Analysis in IMO 2014 based on the expected impact of the EEDI predicts efficiency improvement trends depending on ship type and capacity. The trend for the largest capacity ships is shown to the right. The trends are referenced to average ship efficiencies between 1999-2009.
- The EEDI does not regulate beyond 2025, so trends after then are based on the technical potential of efficiency improvements according to IMO 2009.
- New ship efficiency trends were calculated for each ship type using capacity distributions from IMO 2014 and UCL 2013.
- The above efficiency trends were converted to fleet efficiencies by modelling the stock, assuming that historic efficiencies were constant (this is true to within 5-10%, see Delft 2012), and that ships were scrapped at 32 years (taken from IMO 2007).
- This resulted in a 3-14% efficiency improvement by 2035 based on 2015 levels, depending on type. This trend was applied to current operational ship efficiencies by ship type from UCL 2013, calculated from satellite data for global real-world ships. This resulted in the efficiency trends by ship type to the right.
- From these trends it can be seen that there are large differences of up to a factor of three between efficiencies of different ship types. A significant factor in this difference is the variety of load factors and operational speeds between types.

## New Large Capacity Ship Efficiency Trends from the EEDI

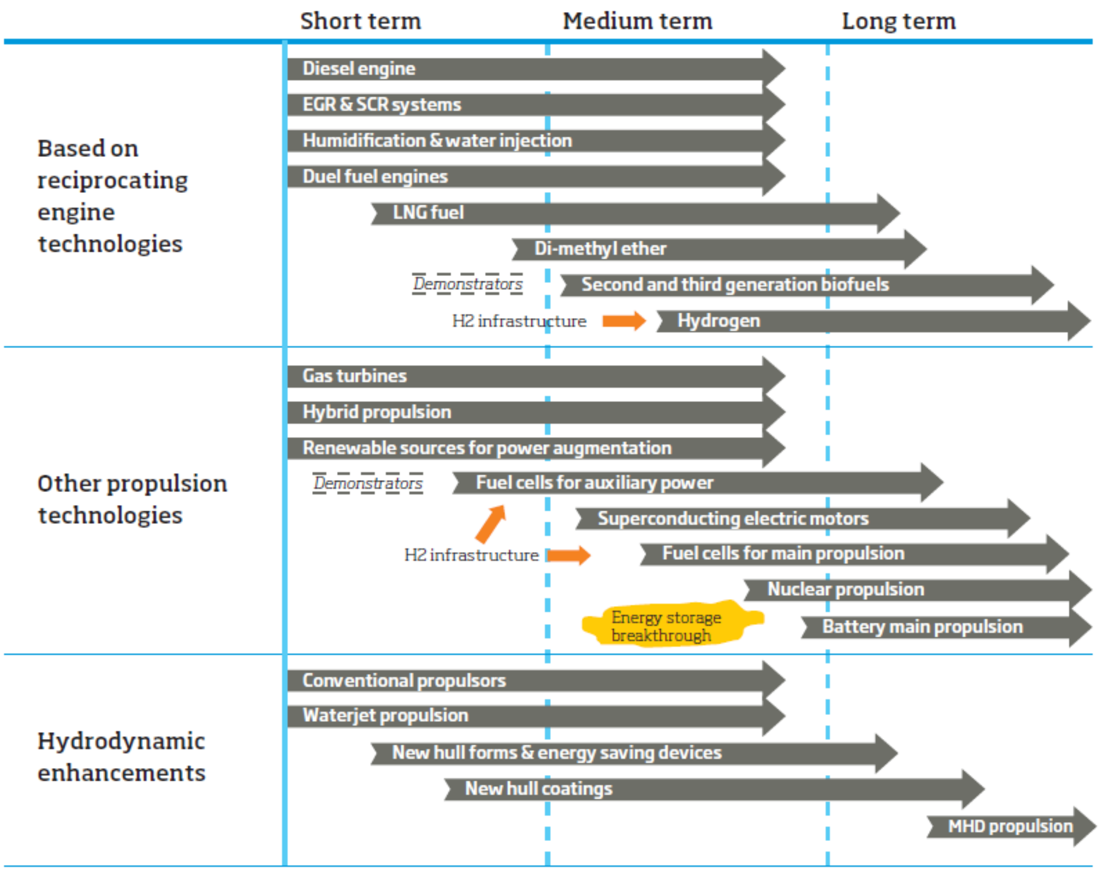



## Ship Efficiency Trends by Ship Type



# A number of alternative propulsion types are available, at varying levels of technological maturity and infrastructure availability






## Discussion

- There is a variety of alternative options available for application to smaller marine vessels.
- There are varying levels of technological maturity, from hybrids and LNG powered vessels which are in the market now, to less well developed technologies such as hydrogen fuel cell primary power.
- Many alternative propulsion types have associated complexities due to a lack of refuelling infrastructure and engineering expertise.
- Power sources such as LNG can use modified current engine technologies, and so are less complicated to implement.
- Some technologies are only useful for certain specific marine applications. This makes prototyping and small-scale testing more of a challenge, as the resultant technology cannot be then rolled out to as large a market.

# Hybrid vessels offer significant fuel consumption savings, and three have been built so far in Scotland

## Description, potential and barriers to introduction

- Diesel-electric hybrids most commonly have an electric motor powered by a battery as the main powertrain. This battery can then be charged by a diesel generator or plugged in at port.
- Currently applicable to smaller vessels only, as the weight of batteries/capacitors required to provide significant power to a heavy vessel would be too great.
- Hybrid systems bring many advantages. The diesel engine can be run continuously to charge the battery, reducing peaking of power and allowing the engine to always work at its most efficient point. The engine can be shut off when near land, eliminating local pollutant emissions there. Charging in ports also allows them to meet some of their power demand with local renewable electricity where available.
- They provide reduced operating costs through lower fuel consumption, but are expensive to manufacture.
- Manufacturers include ABB and Siemens, and are experimenting with battery and capacitor solutions.

## Example

There are three diesel-electric hybrid island ferries operating in Scotland, reported to achieve a 20-38% emissions reduction, assuming the land-charging uses renewable electricity. One of these is the MV Lochinvar, pictured below:


Other hybrid ferries operate in New York, Washington, Alcatraz, and four in Denmark

# A variety of biofuels could be used for marine applications, but all are currently at low levels of technological maturity

## Description, potential and barrier to introduction

- Fatty acid methyl esters (FAME) and bioethanol are the main possible biofuels, and di-methyl ether can also be generated from biomass. One diesel-biofuel blend trial has been performed on the auxiliary engines of the container ship Maersk Kalmar.
- Diesel engines can also be converted to use methanol, which can be generated from biomass, offering the potential for minimal WTM emissions.
- Drop-in fuels (using gasification or hydrotreating processes to create molecules identical to diesel) could remove technical and food competition barriers if produced from non-food sources. However, these very high quality, ultra-low sulphur fuels may used preferentially in aviation where technical requirements are stricter

| Fuel Type | Benefits | Barriers |
|---|---|---|
| DME, FAME, bioethanol | • Can offer zero WTM emissions<br>• Can be used with current engine technology and all ship types | • Inefficient and land intensive to produce<br>• Technical issues including engine corrosion and water absorption in marine environments |
| Methanol | • Engines can be converted from standard diesel<br>• Low emissions of local pollutants | • Minimal refuelling infrastructure<br>• Much less mature option |

## Examples


Viking Grace, large LNG-powered passenger ferry operating in Sweden and Finland


Stena Germanica, a ferry with two out of four engines running on methanol, operating between Kiel, Germany and Gothenburg, Sweden.

# Wind power can be harnessed as a secondary means of propulsion, and solar panels can be used for auxiliary power



## Description, potential and barrier to introduction

- Wind power can be used to provide direct additional propulsion by a number of means. They provide emissions reduction benefits, but are dependent on wind conditions. They also require adjustments to the main propulsion system to account for the variability of wind power.
  - Kites and sails are useful when the wind is behind a vessel. They can provide a 10-40% efficiency improvement when in use. There are currently two operational kite systems.
  - Flettner Rotors , rotating columns which make use of the Magnus effect[1] to provide additional provision, can be added to ships above 10000dwt[2]. The technology is at the trial stage so estimates of efficiency improvement potential vary, with an upper bound of 35%. One operational system and one trial currently.
  - Vindskip is a new concept for a cargo ship whose hull acts like an aerofoil, using wind from any direction for propulsion. Its primary power would come from LNG. It is still at the concept stage, so not likely to be relevant in the short to medium term.
- Solar panels can be used to provide useful auxiliary power, but are not applicable on a sufficient scale to significantly reduce primary power demand.

## Examples

The MS Beluga SkySails is a German cargo ship; the first ship to use a computer-controlled kite to aid propulsion.


The MV Ashington is a cargo ship which uses an experimental wing-sail (rigid sail) for additional propulsion.

The Enercon E Ship 1 was made to transport wind turbine parts from Germany. Flettner rotors aid the ship's propulsion.



1 - Magnus Effect: fluid flow past a rotating body produces a perpendicular force on the body.

2 - dwt = deadweight tonnes, a measure of a ship's capacity

# Battery electric vessels are a zero emission marine solution, but are currently limited by range, and few vessels exist

## Description, potential and barriers to introduction

- All-electric vessels use an electric motor with battery or supercapacitor storage.
- Current battery/supercapacitor technology does not have the required energy density to provide sufficient range for most marine applications.
- The technology is applicable to fishing vessels and car and passenger ferries making short journeys of up to around 30 minutes, after which they can be recharged in port.
- For these applications, they emit no local pollutants, and if powered by renewable electricity can emit zero $CO_2$ on a well to motion basis.

## Examples

The first all-electric car and passenger ferry entered service in May 2015, operated by Norwegian company Norled.


Norwegian boat builder Selfa is supplying an all-electric fishing boat, which is charged overnight via the grid.

Ar Vag Tredan, an electric passenger ferry built by STX France uses supercapacitors for energy storage. It operates in Lorient, France.

# Fuel cells are currently only useful for auxiliary power or short range applications, but could eventually be extended to provide full power

## Status

- Fuel cells convert chemical energy in fuel to DC electrical power. They can be run on hydrogen, which offers potential for zero emissions power if renewably sourced.
- Molten carbonate fuel cells run on other fuels such as LNG, with higher power densities, and are being trialled in primary propulsion

## Opportunities

- Hydrogen fuel cells currently only have the energy density to power small vessels like urban river ferries and house boats.
- They can also be used to provide auxiliary power to ships, although this makes up a small proportion of a ship's overall fuel consumption.
- LNG and similar other fuel cells offer good energy efficiency and low emissions of local pollutants. They are compatible with electric propulsion systems, and so could function as a bridging technology for fuel cell/battery electric marine power.

## Barriers

- Hydrogen fuel cells are unproven for large scale primary propulsion, and currently do not have sufficient energy or power density. Hence they are only relevant in the long term.
- They would require a hydrogen supply infrastructure at ports, which could be implemented given sufficient fuel demand

## Examples

Viking Lady offshore supply ship, built by Eidesvik Offshore and Wärtsilä. Dual fuel diesel/LNG fuel cell power. Also now fitted with an electric hybrid system.



MV Undine car carrier ferry, operated by Wallenius Shipping. Ran a trial route from Germany to the USA with a fuel cell APU.

Alsterwasser passenger ferry, carries up to 100 passengers along the river Alster in Hamburg. Uses hydrogen fuel cells for primary power.

RAE 2013, dnv.nl, Wallenius, Zemships

APU: Auxiliary Power Unit

# Summary of alternative propulsion options

## Near term options

- Marine engines are well-understood and reliable, and so will continue to dominate shipping in the short to medium term. Significant $CO_2$ reductions of ~30% by 2030 can be implemented through efficiency improvements. This will be driven by fuel costs and current and future regulation.
- Using LNG as a fuel offers potential $CO_2$ reductions, provided methane slip is avoided. Adoption of LNG fuel is mainly driven by MARPOL Annex VI local pollutants regulations. However, a lack of refuelling infrastructure is currently a key barrier.
- Use of wind/solar power systems can supplement primary propulsion on large ships, with the potential to reduce fuel consumption and $CO_2$ emissions by 10-40%.
- Hybrid systems can offer 20-40% efficiency improvements, but are only applicable to certain ship types, such as ferries and offshore supply vessels.

## Longer term options

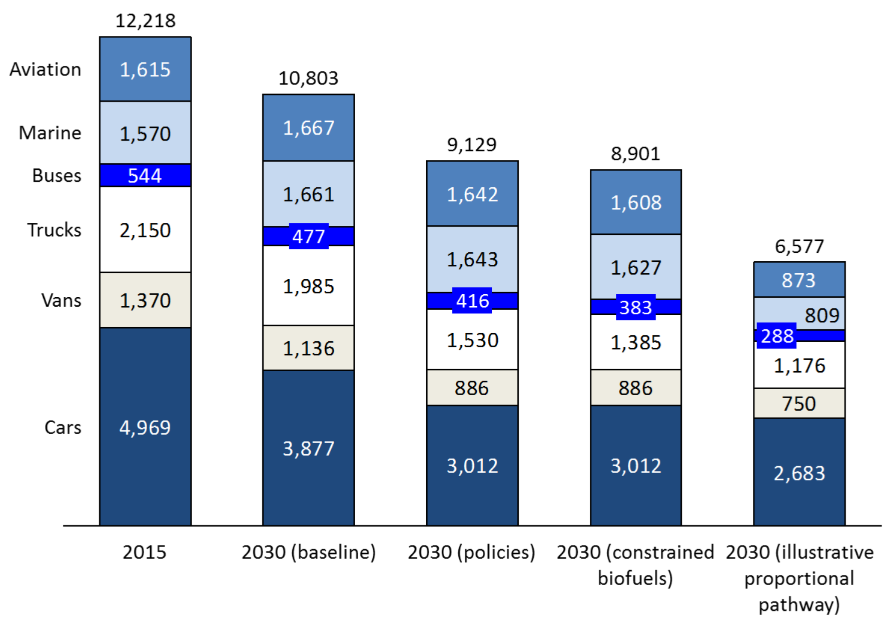
- Biofuels such as FAME and bioethanol could offer modest WTM $CO_2$ emissions, but technical and land use concerns remain for some fuels. 'Drop-in' diesel fuels from crop residues could overcome these issues, but these high quality fuels may be better used in the aviation sector.
- Fuel cells currently only have the energy and power density for small scale applications such as river ferries, or for providing auxiliary power, but could be developed for primary power in the long term. However hydrogen fuel cells have limited specific power, so hydrogen may have to be used in combustion engines to provide sufficient power for use in large scale shipping.
- Battery electric power has issues of energy and power density, but is being developed for small scale applications such as ferries and fishing boats.
- These options would all also require the relevant infrastructure to be developed.

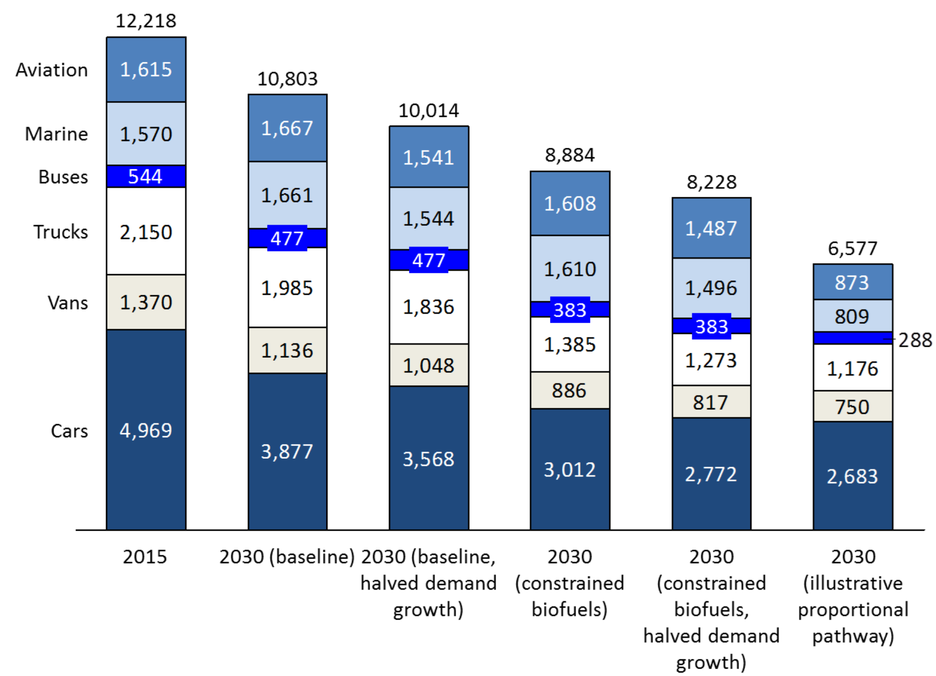
# Contents

# In the main report, 2030 emissions and market shares in multiple scenarios were presented; here we present supplementary figures

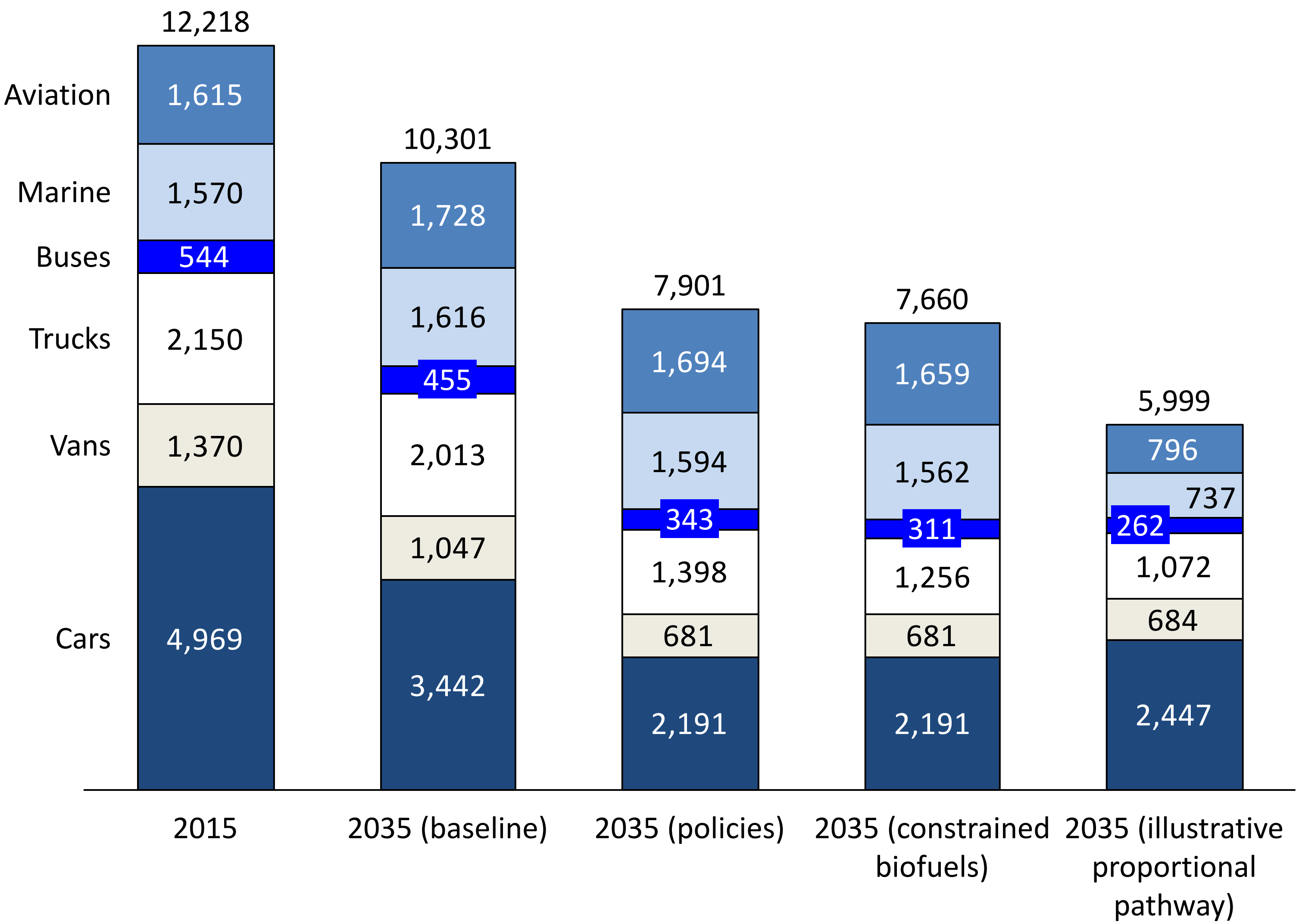
## Summary

- In this study, multiple scenarios were used to represent different levels of policy ambition.
- The main report presented emissions and market shares in 2030 (see the graphs below for examples).
- In the following slides we present similar graphs using 2035 as the year for comparison, as well as market share comparisons in 2035, emissions trajectories from 2015 to 2035, and market shares from 2015 to 2035, for each scenario.
- Refer to the main report for a discussion of the policy measures associated with each scenario.

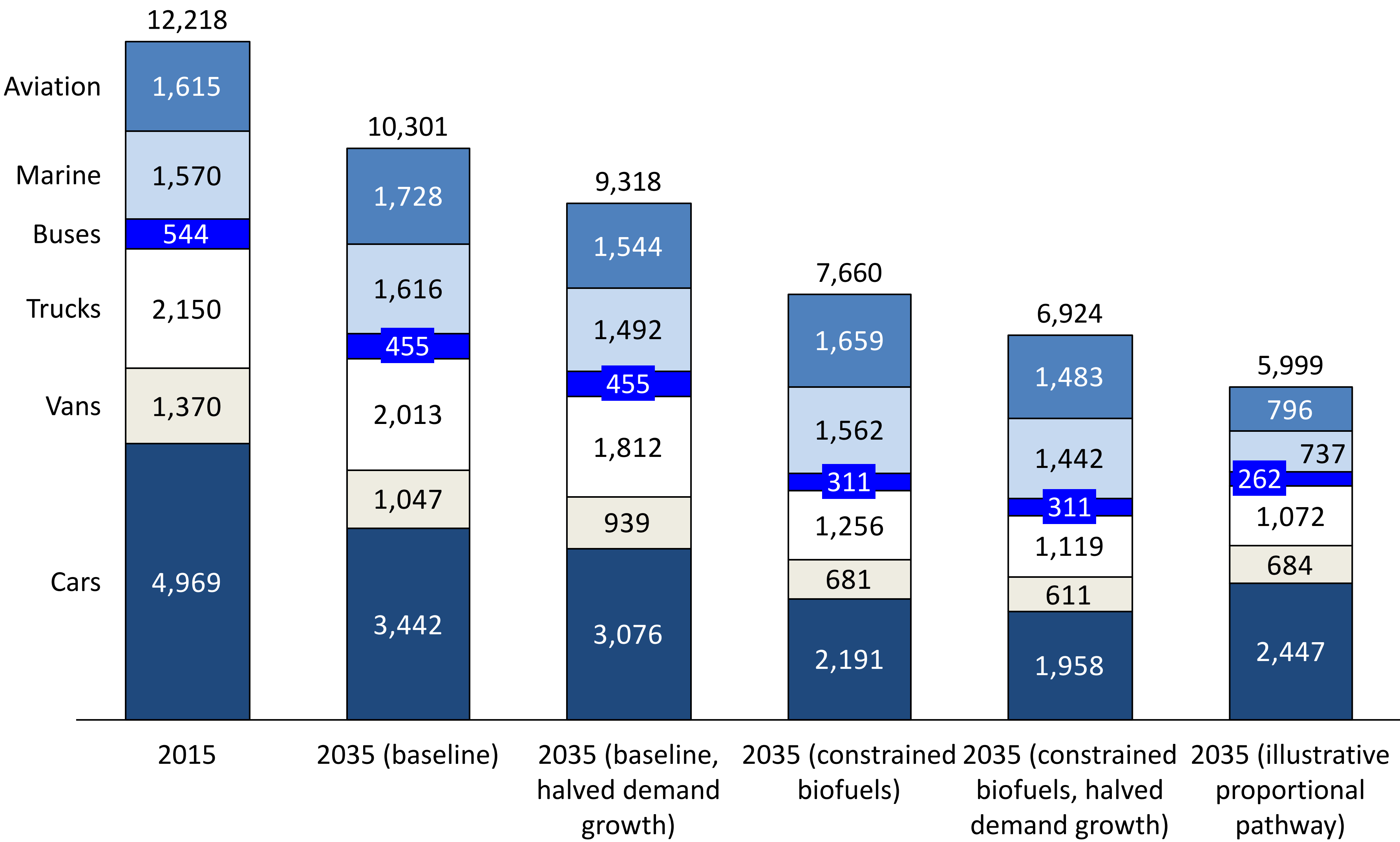


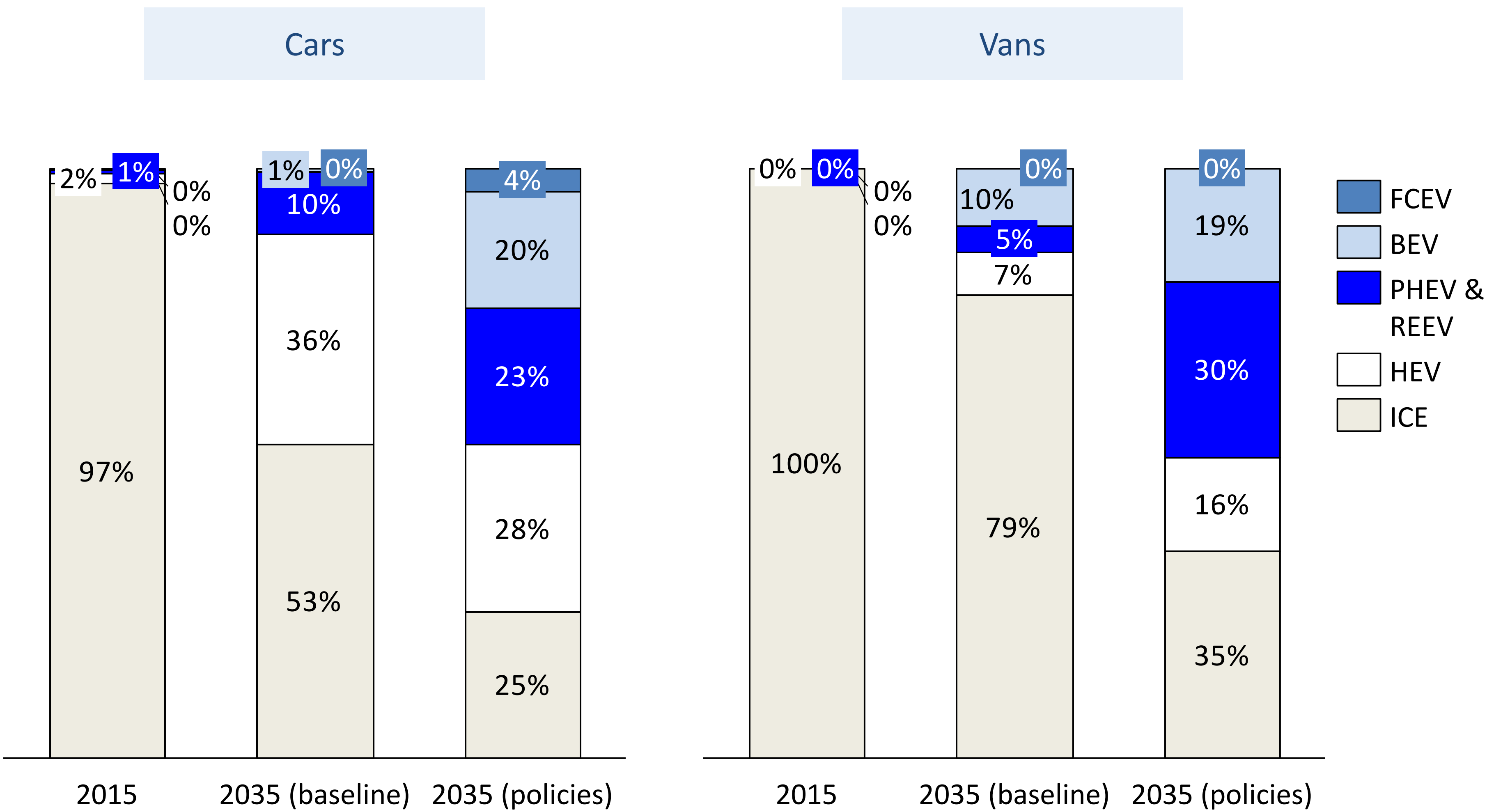
# Emissions comparison in 2035 (1) (cf. Figure 14 of main report)



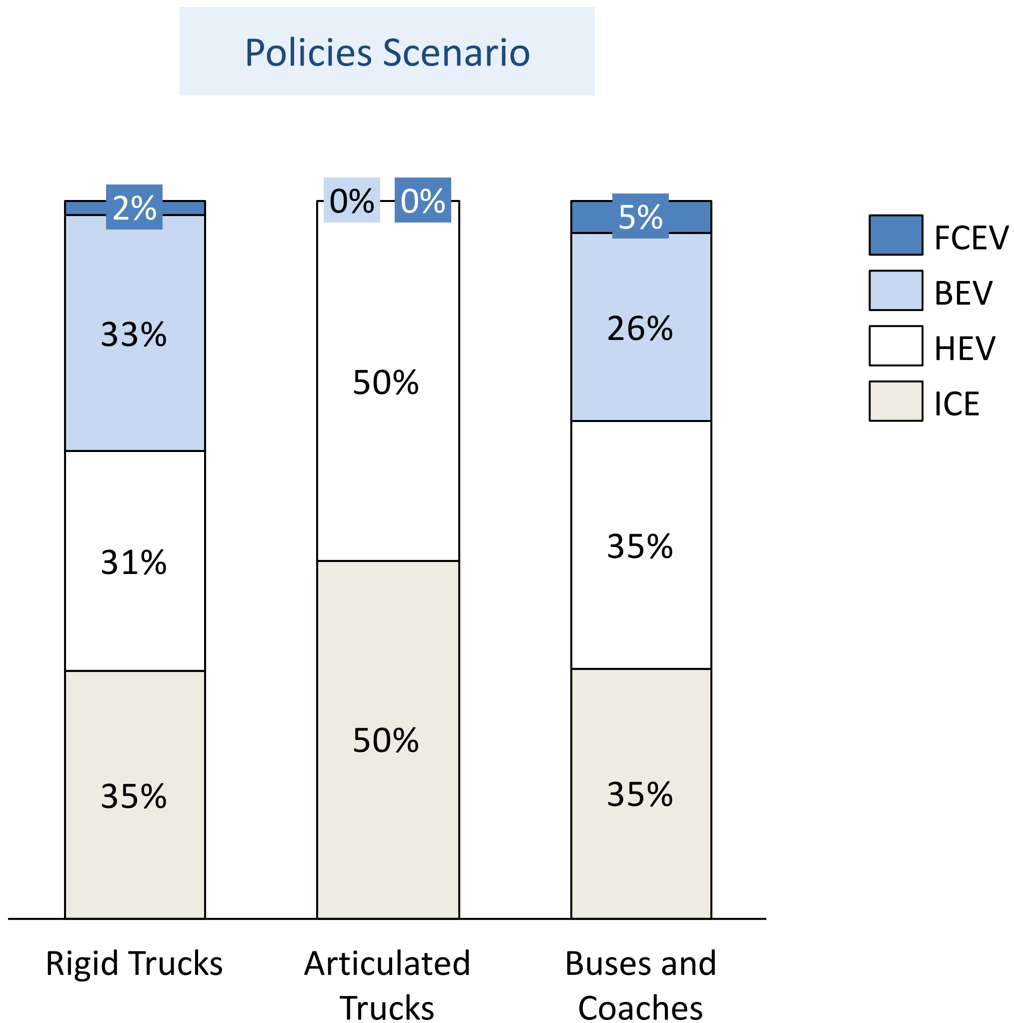
# Emissions comparison in 2035 (2) (cf. Figure 15 of main report)



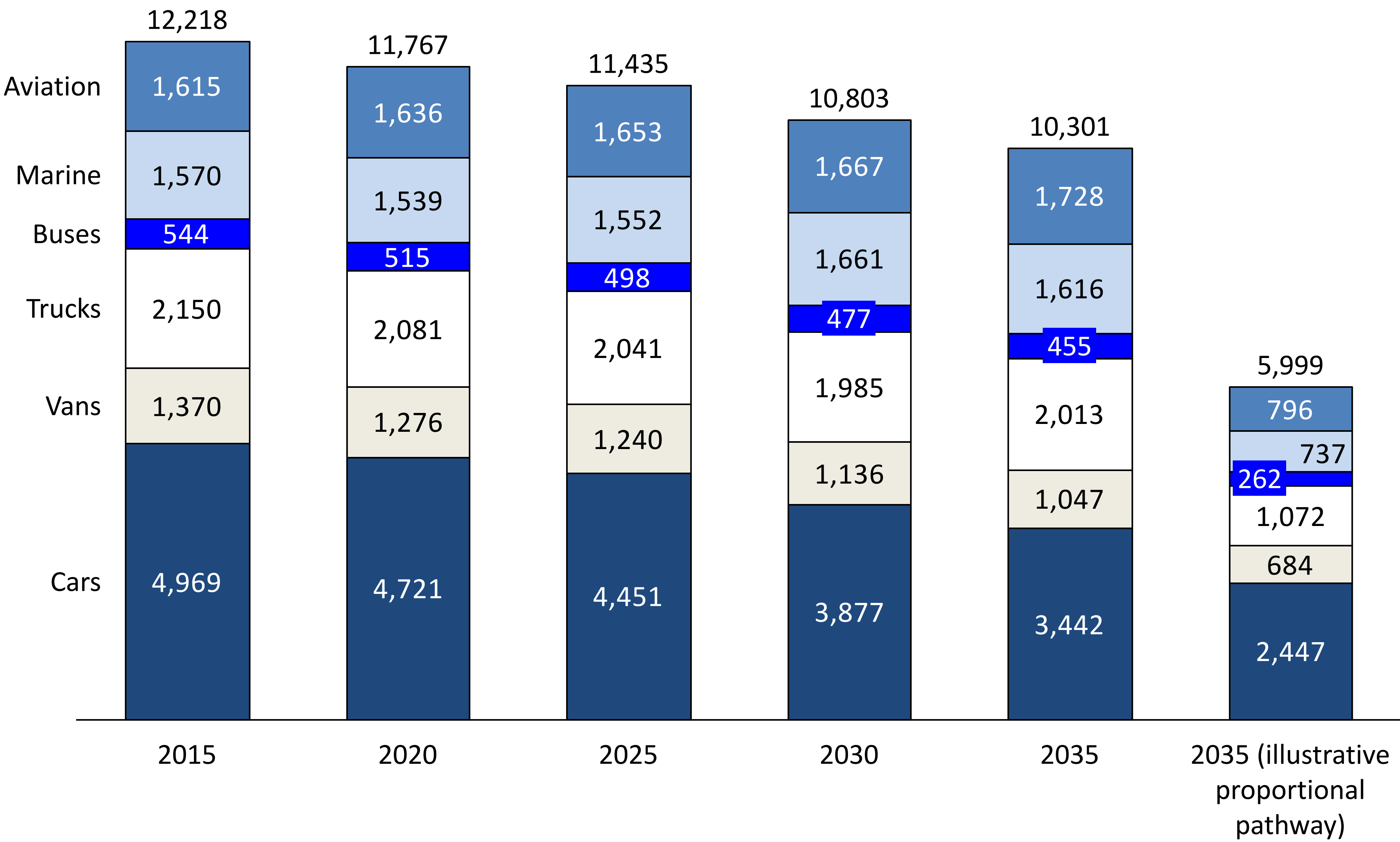
# Market share comparison in 2035 – Cars and Vans (cf. Figure 9 of main report)



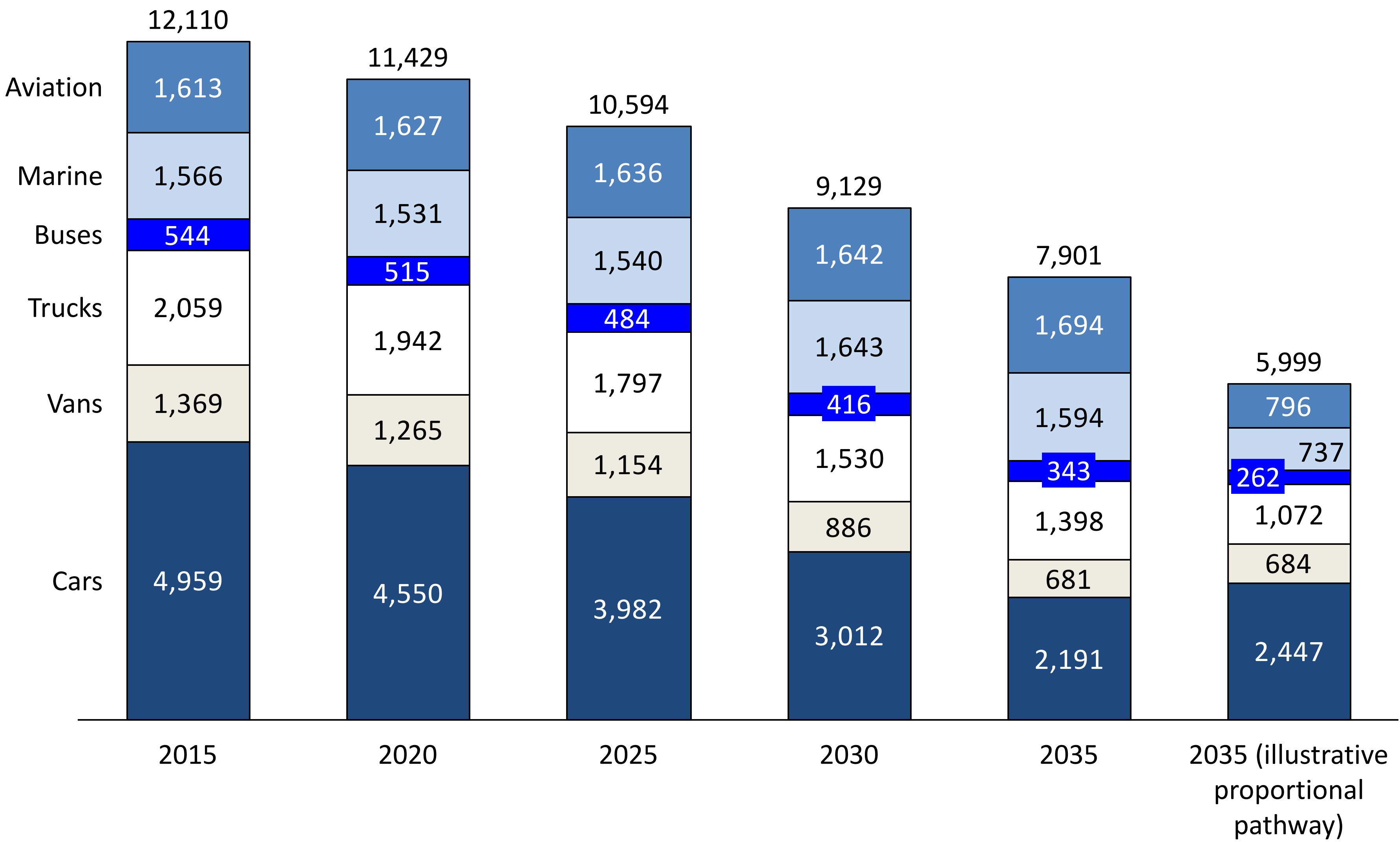
# Market share comparison in 2035 – Trucks and buses (cf. Figure 11 of main report)



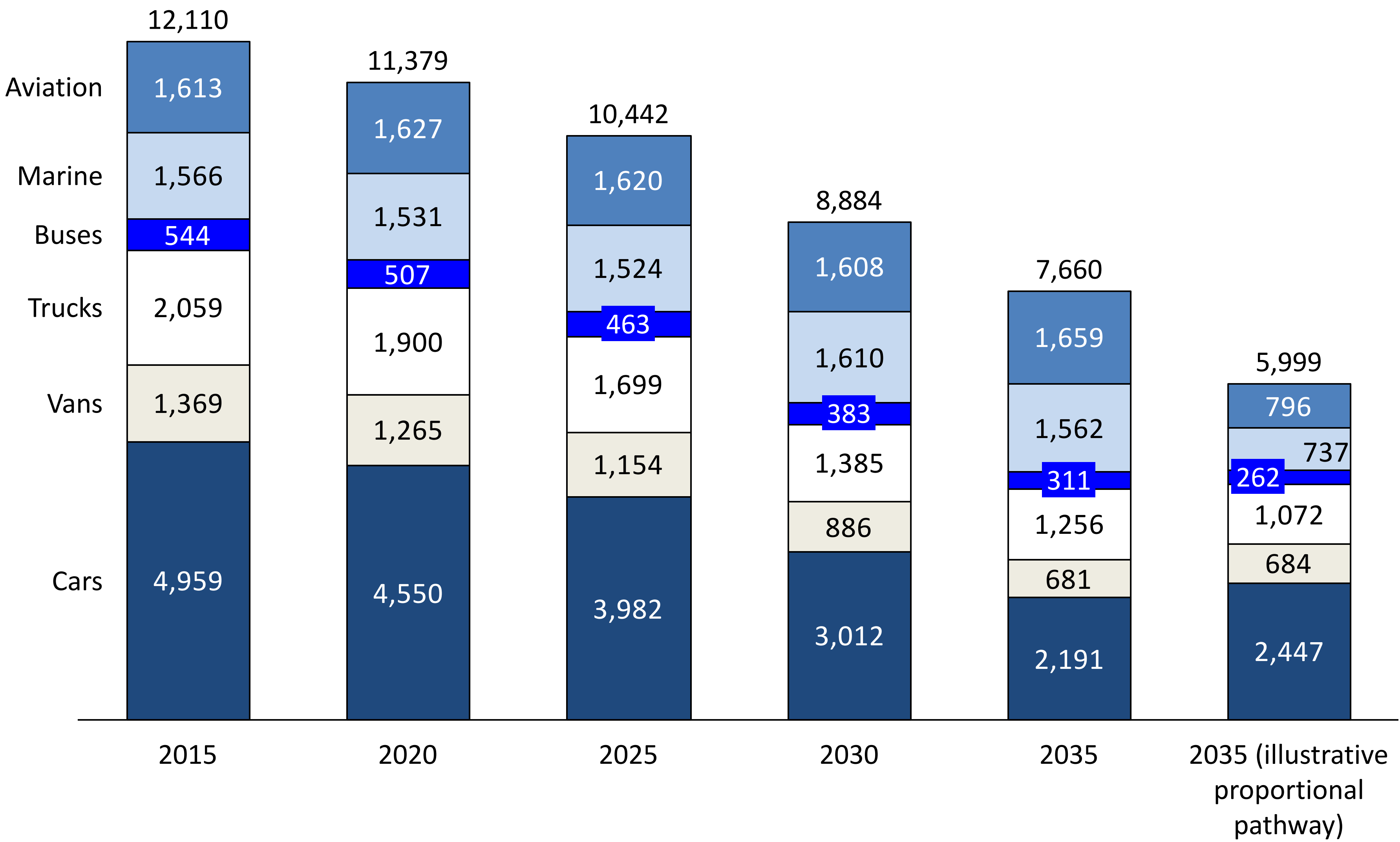
# Emissions trajectories – Baseline



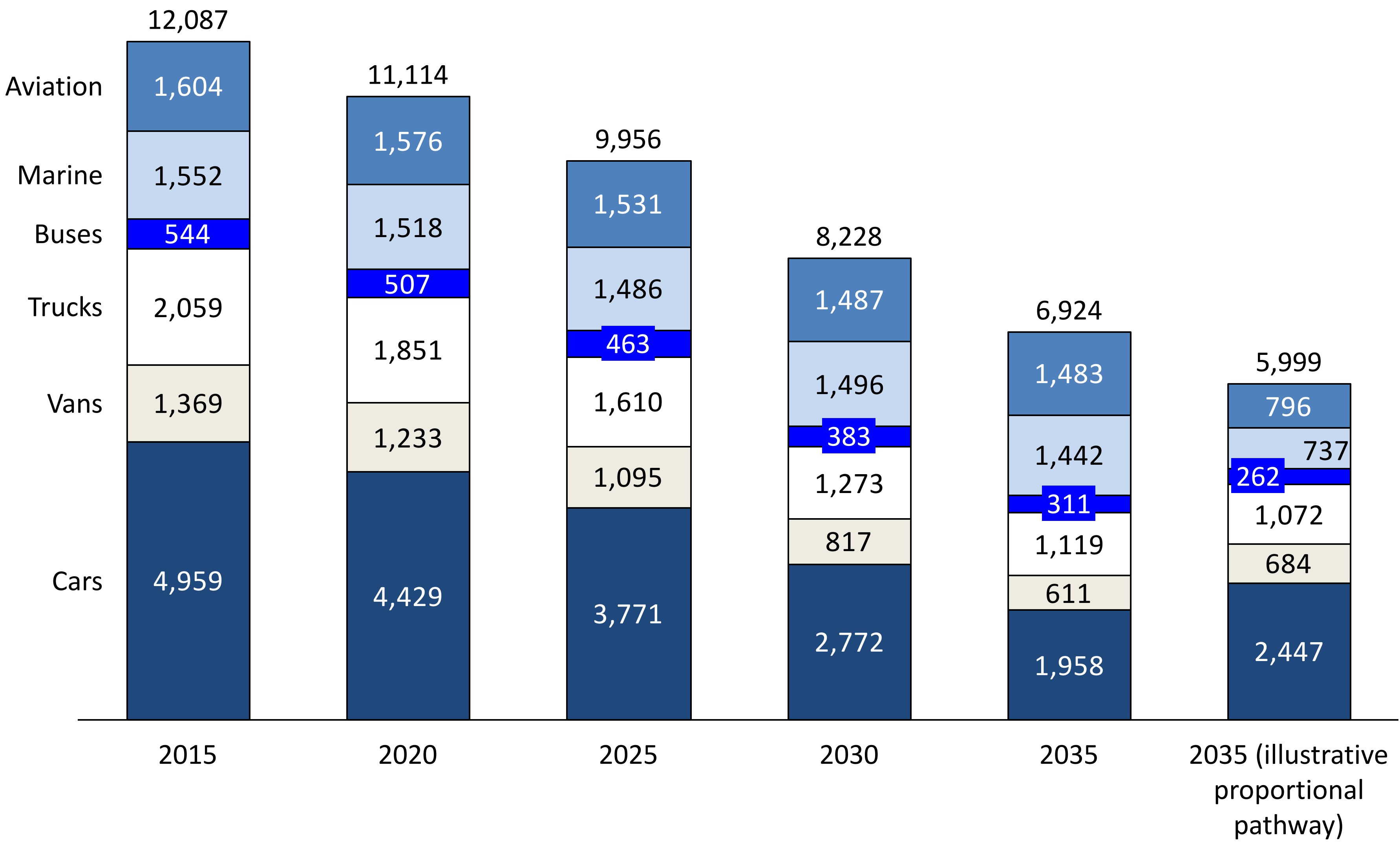
# Emissions trajectories – Policies



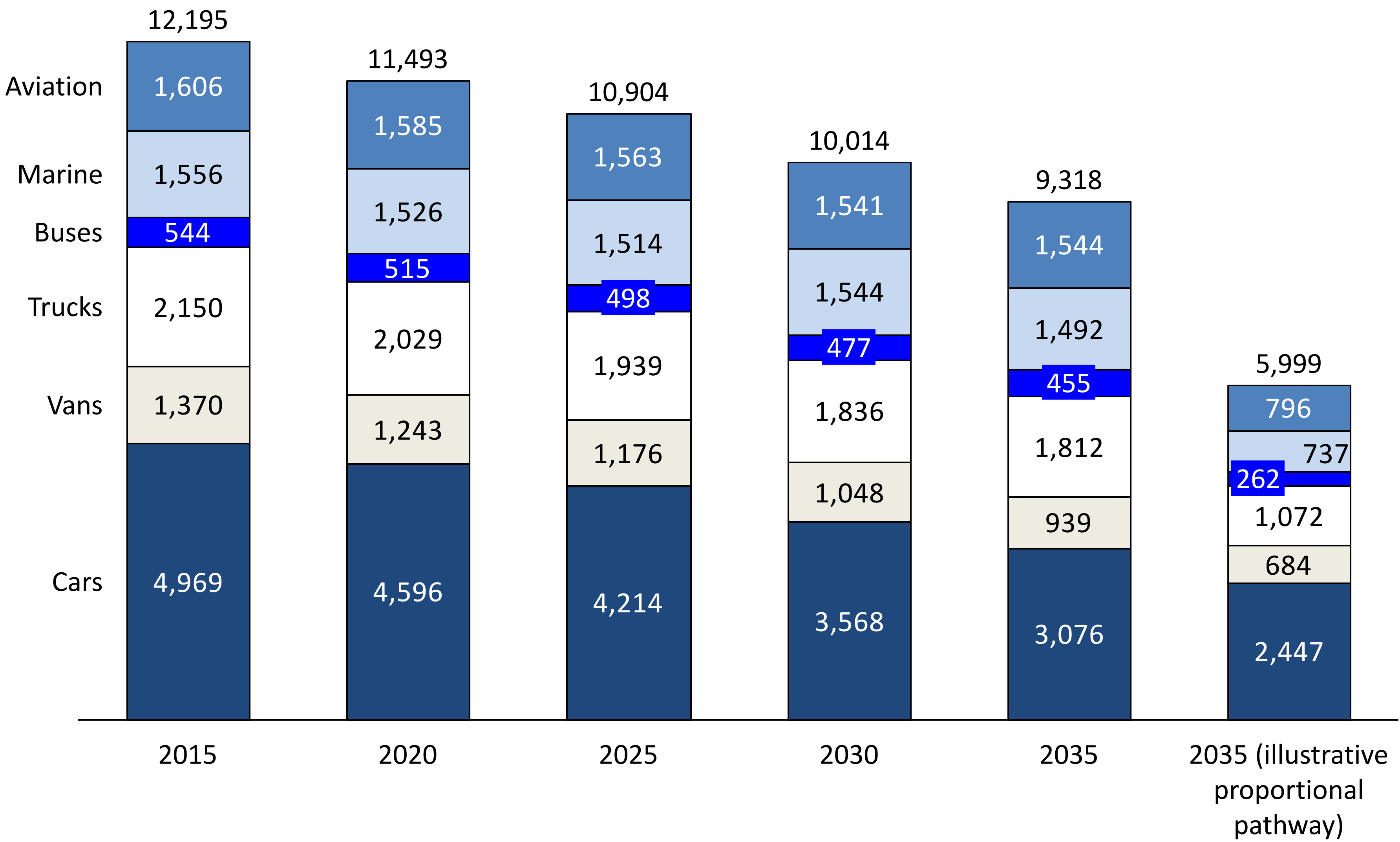
# Emissions trajectories – Constrained Biofuels



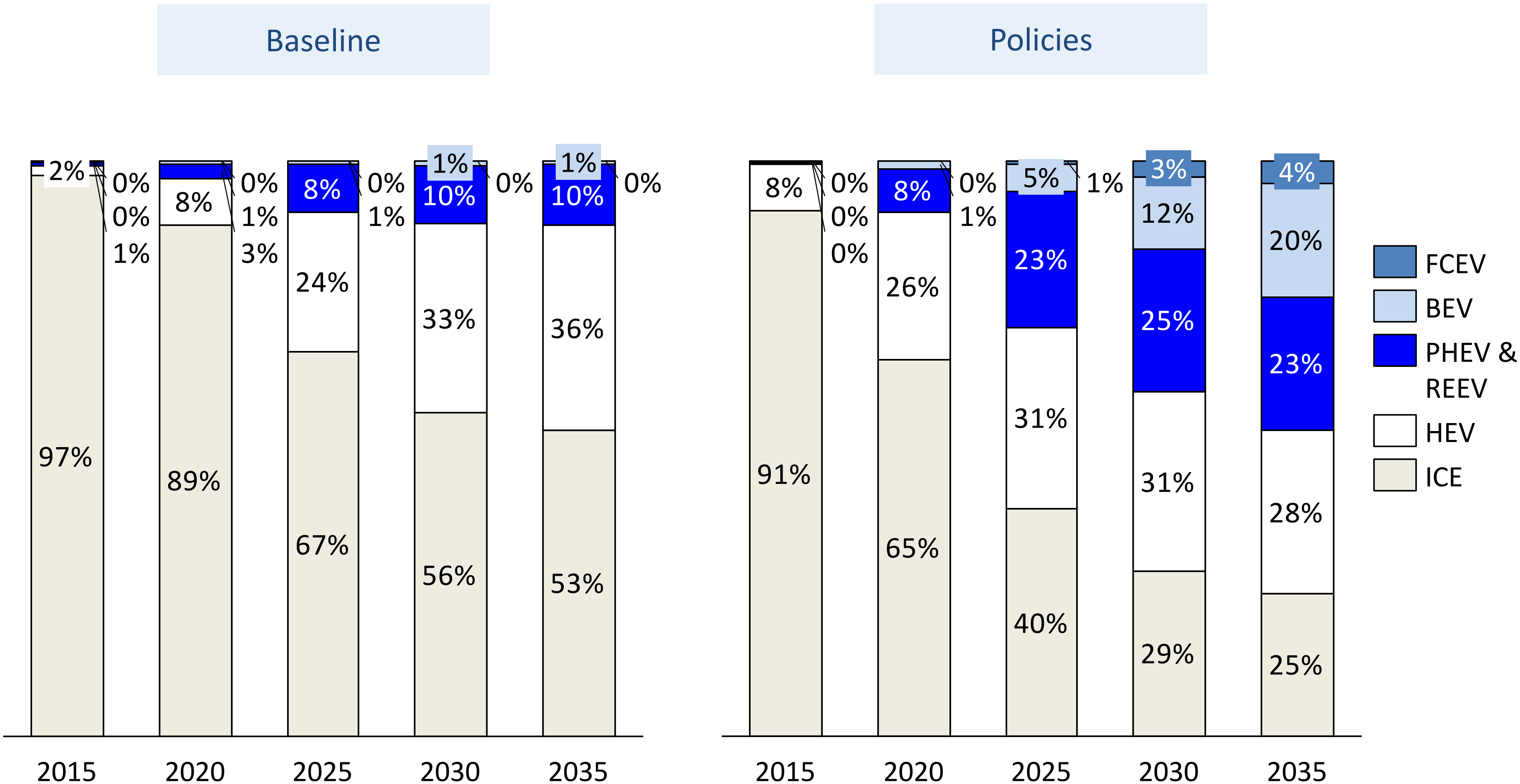
# Emissions trajectories – Halved Demand Growth (relative to Constrained Biofuels)



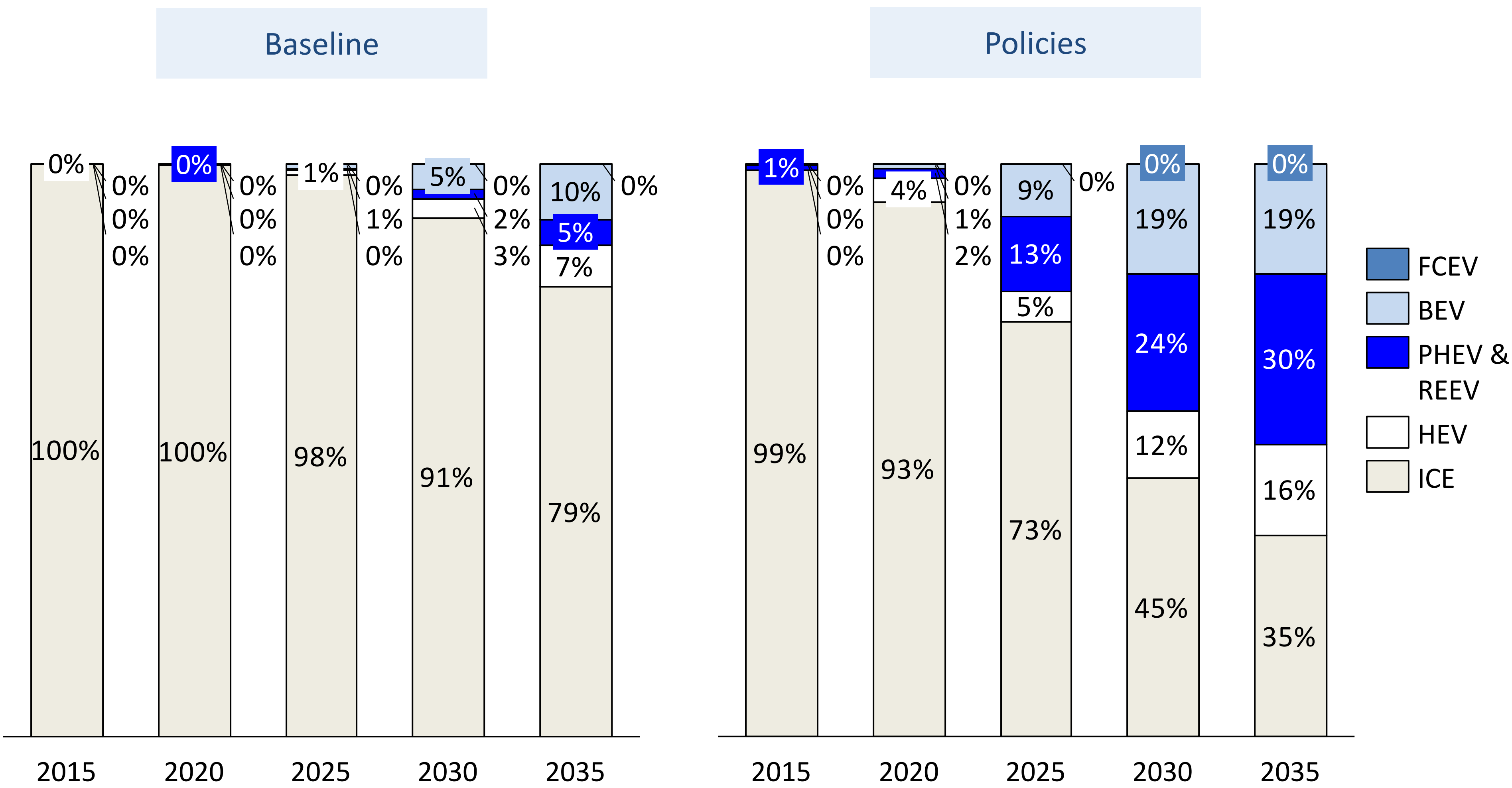
# Emissions trajectories – Halved Demand Growth (relative to Baseline)



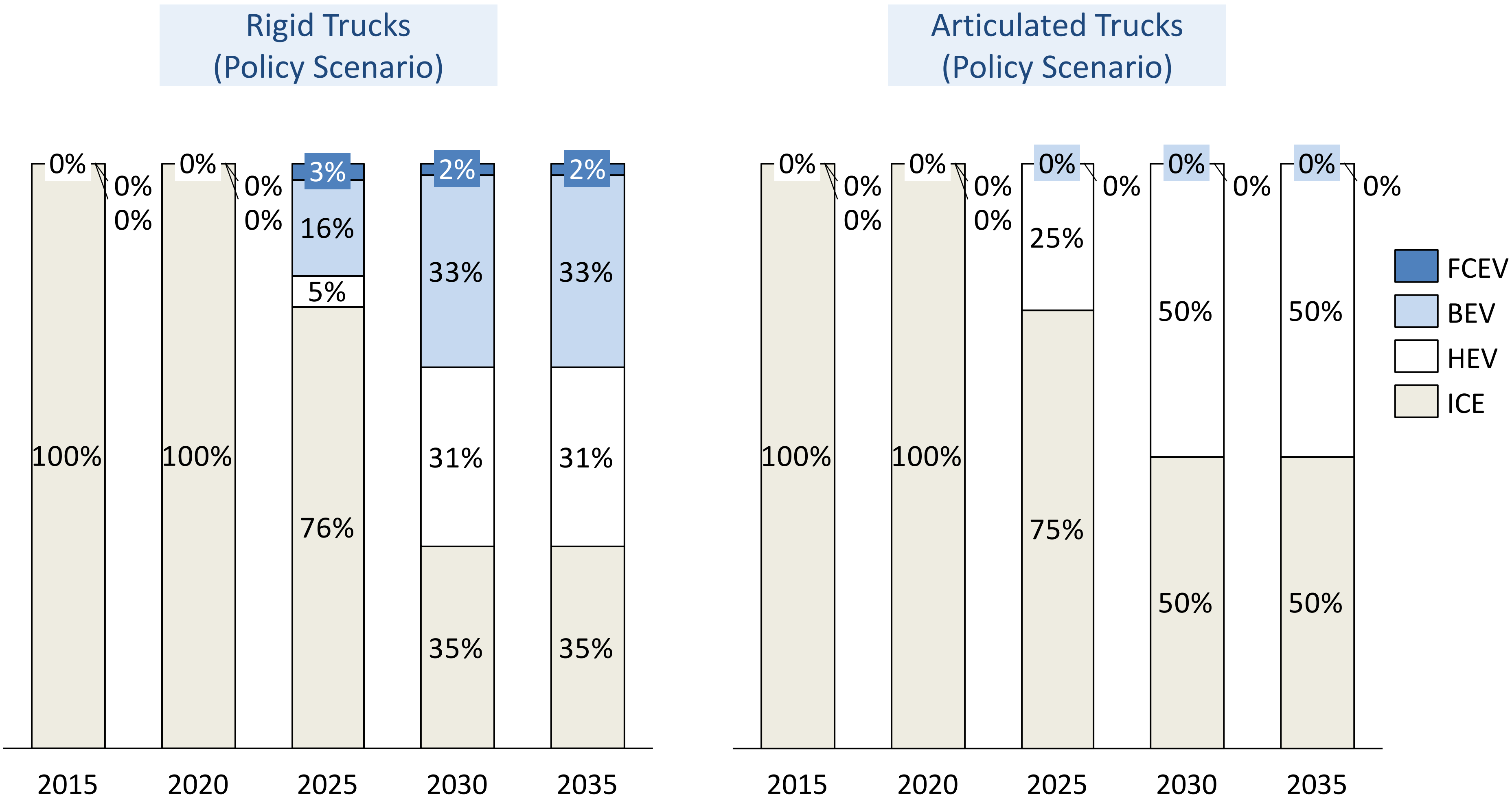
# Market Shares by Scenario – Cars



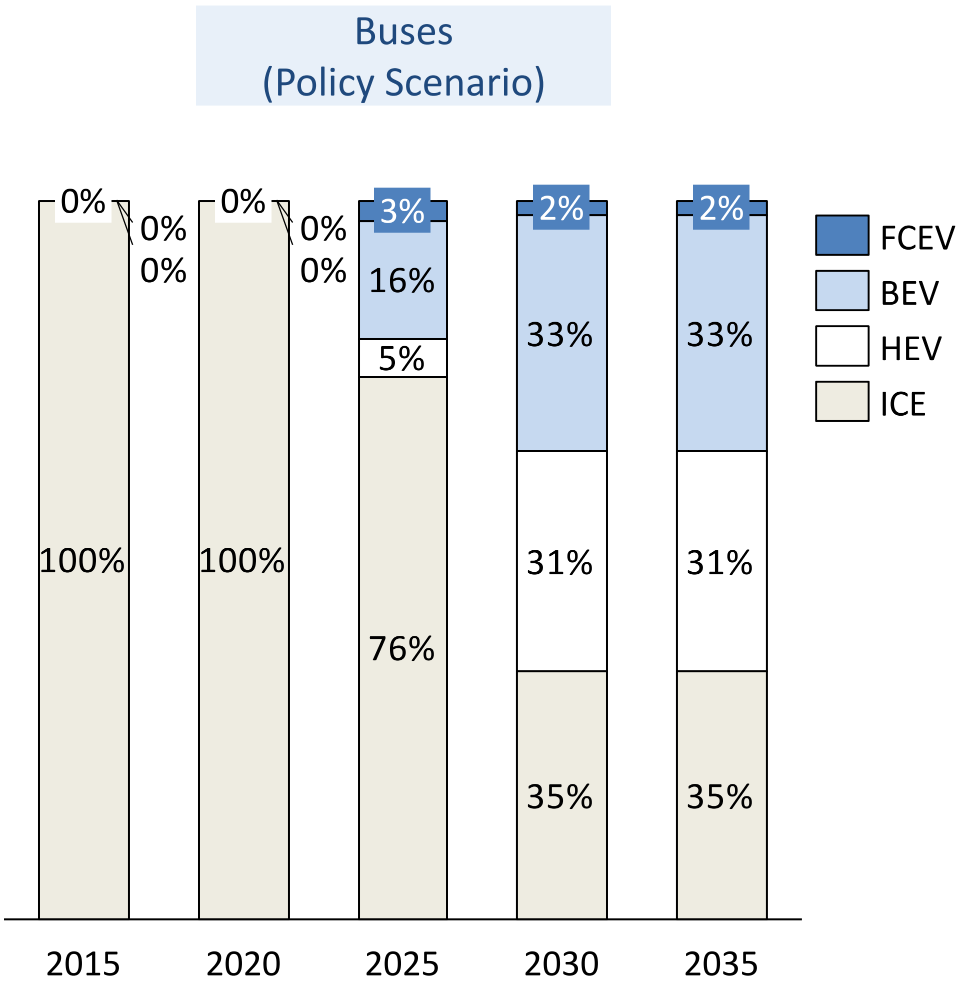
# Market Shares by Scenario – Vans



# Market Shares – Trucks (Policy Scenario)



# Market Shares – Buses (Policy Scenario)



# Contents

# List of recent techno-economical reports used to populate data for the main car components

| Report | Data relevant to our work |
|---|---|
| **WhatCar, SMMT** (2015 access) | • Characterisation of 2015 base vehicle archetypes |
| **TNO 2011** - Support for the revision of Regulation (EC) No 443/2009 on $CO_2$ emissions from cars | • ICE efficiency improvement, technology costs and $CO_2$ reduction potential |
| **EE for LowCVP 2011** – Influences on the Low Carbon Car Market from 2020 – 2030 | • ICE cost trends<br>• Electric motor cost |
| **EE for CCC 2012** – Cost and performance of EV batteries | • Battery cost (BEV- PHEV differentiated)<br>• Battery Depth of Discharge (DoD) and density |
| **R-AEA for CCC 2012** - A review of the efficiency and cost assumptions for road transport vehicles to 2050 | • ICE cost trends<br>• Electric motor cost |
| **R-AEA for ICCT 2012** - Analysis of Greenhouse Gas Emission Reduction Potential of Light Duty Vehicle Technologies in the European Union for 2020–2025 | • ICE efficiency improvement and $CO_2$ reduction potential |
| **FEV for ICCT 2012** - Light-Duty Vehicle Technology Cost Analysis – European Vehicle Market, Additional Case Studies | • ICE efficiency improvement and technology costs |
| **R-AEA for ECF 2013** – Fuelling Europe's Future | • ICE cost trends<br>• Electric motor cost |
| **PwC 2013** - Battery update Can the Lithium-ion industry satisfy the growing demands of the auto market? (Nov 2013); | • Battery cost trends |

# A similar exercise was conducted to update our assumptions about main ICE vehicle components for vans



| Report | Data relevant to the modelling |
|---|---|
| **Vansa2z, SMMT** (2015 access) | • Characterisation of 2015 base vehicle archetypes |
| **TNO 2011** - Support for the revision of Regulation (EC) No 443/2009 on $CO_2$ emissions from cars | • ICE eff. impr. tech. cost<br>• ICE eff. impr. tech $CO_2$ reduction |
| **EE for LowCVP 2011** – Influences on the Low Carbon Car Market from 2020 – 2030 | • ICE cost<br>• Electric motor cost |
| **EE for CCC 2012** – Cost and performance of EV batteries | • Battery cost (BEV- PHEV differentiated)<br>• Battery Depth of Discharge (DoD) and density |
| **R-AEA for CCC 2012** - A review of the efficiency and cost assumptions for road transport vehicles to 2050 | • ICE cost<br>• Electric motor cost |
| **R-AEA for ICCT 2012** - Analysis of GHG Emission Reduction Potential of Light Duty Vehicle Technologies in the EU for 2020–2025 | • ICE eff. impr. tech $CO_2$ reduction |
| **FEV for ICCT 2012** - Light-Duty Vehicle Technology Cost Analysis – European Vehicle Market, Additional Case Studies | • ICE eff. impr. tech. cost |
| **R-AEA for ECF 2013** – Fuelling Europe's Future | • ICE cost<br>• Electric motor cost |
| **PwC 2013** – Battery update Can the Lithium-ion industry satisfy the growing demands of the auto market? (Nov 2013); | • Battery cost trends |
| **EE 2012** – Element Energy, *Ultra Low Emission Vans study*, report for the DfT for vans, Jan 2012 | • TCO assumptions |
| **TNO 2012** - Support for the revision of regulation on $CO_2$ emissions from light commercial vehicles | • ICE eff. impr. tech. cost<br>• ICE eff. impr. tech $CO_2$ reduction |

# Battery and fuel cell-related costs (for all vehicles)

| Report | Data relevant to the modelling |
|---|---|
| **PwC**, November 2013. Battery update Can the Lithium-ion industry satisfy the growing demands of the auto market? | • Battery performance and cost trends |
| **Peter Miller**, 2015. Automotive Li-ion batteries. State of the art and future developments in Li-ion battery packs for passenger car applications. Johnson Matthey Technol. Rev., 2015, 59, (1), 4–13 | |
| **Björn Nykvist and Måns Nilsson**, 2015. Rapidly falling costs of battery packs for electric vehicles. Nature, DOI: 10.1038/NCLIMATE2564 Referred as 'Nature article' in the rest of the presentation | |
| **BATTERIES Avicenne conference**, Nice, Oct 2015 | |
| **UK Energy Storage conference**, Birmingham, November 2015 | |
| **IDTechEx webinar**, Oct 2015. Advanced and post lithium-ion batteries 2016-2026 | |
| Other consulted **websites**: charged EVs, US Energy Efficiency and Renewable Energy website, chemical and engineering news | |
| **DOE Fuel Cell Technologies Office Record**, Fuel Cell System Cost – 2013 | • Fuel cell performance and cost trends |
| **Oak Ridge National Laboratory**, Status and Prospects of the Global Automotive Fuel Cell Industry [..] (July 2013) | • Fuel cell, H2 tank and BoP performance and cost trends |
| **Strategic Analysis**, Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications (2013) | • Fuel cell performance and cost trends<br>• BoP trends |
| **DOE Fuel Cell Technologies Office Record**, Fuel Cell System Cost – 2014 | • Fuel cell performance and cost trends |
| **International Energy Agency**, Technology Roadmap – Hydrogen and Fuel Cells (2015) | • Fuel cell performance and cost trends<br>• Hydrogen tank cost trends |
| **FCH JU**, A portfolio of power-trains for Europe (2011) | • Fuel cell performance and cost trends<br>• Hydrogen tank cost trends |
| **Element Energy** for the European Climate Foundation (2015) and industry consultations (2012-2015) | • Fuel cell, H2 tank and BoP performance and cost trends |

# List of recent techno-economical reports used to populate data for trucks of different sizes



| Report | Data relevant to our work |
|---|---|
| **University of Delft for EC 2012** – Marginal Abatement Cost Curves for Heavy Duty Vehicles | • Efficiency improvement measures and potential |
| **IEA 2012** – Technology Roadmap: Fuel Economy of Heavy Duty Vehicles | • Efficiency improvement measures and potential |
| **R-AEA for EC 2011** – Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy | • Efficiency improvement measures and potential |
| **ICCT 2015 (1)** – Advanced Tractor Trailer Efficiency Technology Potential in the 2020-2030 Timeframe | • Efficiency improvement measures and potential |
| **R-AEA for DfT 2009** – Review of Low Carbon Technologies for Heavy Goods Vehicles | • Efficiency improvement measures and potential |
| **ICCT for IEA 2015** – Heavy Duty Vehicle Technology Potential around the World | • Sources of losses in different ICE trucks |
| **R-AEA for CCC 2012** - A review of the efficiency and cost assumptions for road transport vehicles to 2050 | • Vehicle cost and efficiency future trends |
| **DECC 2010** – 2050 Pathways Analysis | • Vehicle efficiency trends |
| **Transport Environment 2015** – Lorry $CO_2$ - why Europe needs standards | • Drivers and barriers to improved fuel efficiency |
| **ICCT 2015 (2)** – Assessment of Heavy-Duty Natural Gas vehicle emissions | • Comparison of natural gas and diesel emissions |
| **R-AEA for Low CVP 2012** - Opportunities to overcome the barriers to uptake of low emission technologies for each commercial vehicle duty cycle | • ICE and hybrid efficiency improvements |
| **Gas Vehicle Hub** – gasvehiclehub.org | • UK available gas vehicles |
| **National Petroleum Council (NPC) 2012** – Advancing Technology for America's Transportation | • Vehicle efficiency trends |
| **ICCT 2015 (3)** – Overview of the HDV market and $CO_2$ emissions in the EU | • Historic EU efficiency trends<br>• Share of emissions by truck type |
| **TIAX for ICCT 2011** – European Union Greenhouse Gas Reduction Potential for Heavy-Duty Vehicles | • Alternative powertrain cost trends |

# List of recent techno-economical reports used to populate data for buses and coaches



| Report | Data relevant to the modelling |
|---|---|
| **R-AEA for LowCVP 2012** – Preparing a low $CO_2$ technology roadmap for buses | • ICE efficiency improvement measures and potential, timescales, costs<br>• Alternative powertrain potential, timescales, costs |
| **University of Delft for EC 2012** – Marginal Abatement Cost Curves for Heavy Duty Vehicles | • ICE efficiency improvement measures and potential |
| **R-AEA for EC 2011** – Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy | • ICE efficiency improvement measures and potential |
| **IEA 2012** – Technology Roadmap: Fuel Economy of Heavy Duty Vehicles | • ICE efficiency improvement measures and potential |
| **R-AEA for CCC 2012** - A review of the efficiency and cost assumptions for road transport vehicles to 2050 | • Vehicle cost and efficiency baseline trends |
| **DECC 2010** – 2050 Pathways Analysis | • Vehicle efficiency best case future trends |
| **Civitas 2013** – Smart choices for cities: Clean buses for your city | • Drivers and challenges for powertrain options |
| **Transport and Travel Research Ltd (TTR) for Low CVP 2014** – Barriers and opportunities to expand the low carbon bus market in the UK | • Drivers for adoption of efficiency improvement technologies |
| **FCH JU 2012** – Urban Buses - Alternative Powertrains for Europe | • Fuel Cell bus performance |
| **Clean Fleets 2014** – Clean Buses - Experience with Fuel and Technology Options | • Natural gas drivers |
| **OLEV 2013** – A strategy for ultra low emission vehicles in the UK | • Hybrid buses in the UK |
| **Element Energy 2015 –** West Midland low emission bus delivery plan | • All bus technologies and market data |
| **TIAX for ICCT 2011** – European Union Greenhouse Gas Reduction Potential for Heavy-Duty Vehicles | • Alternative powertrain cost trends |
| **Roland Berger for FCH JU 2015** – Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe | • Fuel cell bus cost projections |

# List of recent techno-economical reports used to analyse potential aviation efficiency trends



| Report | Data relevant to our work |
|---|---|
| **DfT 2013** – UK Aviation Forecasts | • Projected UK aviation efficiency trends<br>• Projected biofuels penetration |
| **ICCT 2009** – Efficiency trends for new commercial aircraft 1960-2008 | • Historic efficiency trends and drivers |
| **ICAO 2010** – Environmental Report | • Description of efficiency improvement measures |
| **CCC 2009** – Meeting the UK aviation target – options for reducing emissions to 2050 | • Fleet efficiency projections |
| **Ohio State University 2014** – What does the future bring? A look at the technologies for commercial aircraft in the years 2035-2050 | • Analysis of efficiency improvement technologies and drivers<br>• Efficiency projections for 2030-2035 |
| **Qinetiq for DfT 2010** – Future Aircraft Fuel Efficiencies | • Efficiency improvement potential of future technologies |
| **ICCT 2015** – Transatlantic airline fuel efficiency ranking, 2014 | • Comparison of efficiencies of different fleets |
| **Pew Center 2009** – Greenhouse gas emissions from aviation and marine transportation: Mitigation potential and policies | • Efficiency improvement potential of future technologies |
| **Sustainable Aviation 2012** – Sustainable Aviation $CO_2$ Roadmap | • Projected biofuels penetration<br>• Proportion of costs to airlines due to fuel |
| **Canso and Boeing 2012** – Accelerating air traffic management efficiency: A call to industry | • Air traffic management efficiencies |
| **Airbus** - http://www.airbus.com/innovation/future-by-airbus/future-energy-sources/fuel-cells/ | • Fuel cell auxiliary power |
| **Bloomberg** – bloomberg.com/news/articles/2015-08-28/boeing-747-dethronement-on-hold-as-british-airways-extends-reign | • BA continuing to use 747s |
| **Schäfer, Evans et al, 2015** – Nature Climate Change – Costs of mitigating $CO_2$ emissions from passenger aircraft | • Fleet efficiency projections<br>• Available efficiency improvement measures |
| **NLR 2005** - Fuel efficiency of commercial aircraft: An overview of historical and future trends | • Historic efficiency trends |

# List of recent techno-economical reports used to analyse potential marine efficiency trends



| Report | Data relevant to the modelling |
|---|---|
| **American Bureau of Shipping (ABS) 2013** – Ship Energy Efficiency Measures | • Efficiency improvement technologies and potential |
| **Carbon War Room 2011** – Shipping Report | • Efficiency improvement technologies and potential |
| **EC 2013** – Time for international action on $CO_2$ emissions from shipping | • Efficiency improvement technologies and potential (2020 timeframe) |
| **ICCT 2013** – Long-term potential for increased shipping efficiency through the adoption of industry-leading practices | • Efficiency improvement technologies and potential (2020 timeframe) |
| **IMO 2009** – 2nd IMO Greenhouse Gas Study | • Efficiency improvement technologies and potential |
| **IMO 2014** – 3rd IMO Greenhouse Gas Study | • Efficiency improvement trends based on EEDI |
| **IMarEst 2010** - Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures | • Efficiency improvement technologies and potential |
| **UCL for ICCT 2013** – Assessment of Shipping's Efficiency using AIS Data | • Current ship efficiency by segment |
| **CMAL Hybrid Ferries Project** –www.cmassets.co.uk/project/hybrid-ferries-project/ | • Hybrid ferries emissions reduction |
| **Delft 2012** – The Fuel Efficiency of Maritime Transport | • Alternative fuels analysis |
| **New Climate Economy (NCE) 2015** – Raising ambition to reduce International Aviation and Maritime Emissions | • Efficiency improvement through speed reduction |
| **IMO 2010** – Market-Based Measures Proposals under consideration within the Market Based Measure Expert Group | • Proposed market-based efficiency measures |
| **DNV 2013** – LNG for Shipping - Current Status | • Global LNG fleet |
| **Nordic Marina 2015** – Pushing the green transport movement out to sea | • Alternative power projects in Scandinavia |
| **Royal Academy of Engineers (RAE) 2013** – Future Ship Powering Options | • Alternative power analysis |
| **IMO 2007** – A statistical overview of ship recycling | • Ship scrappage age |
| **CMAL 2010 –** Scottish Scottish Government Ferry Review Work Package 6 – Vessels | • Emissions from ferries |

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