Ea Energy Analyses
19-11-2015
cb

Working paper

Vehicle energy use and cost – Methodology used in Grøn Transport Roadmap 2030

Overview

The current paper describes the assumptions undertaken, data utilised, and overall methodology, in calculating the costs and energy usage associated with the various vehicle types. The analysis takes a socioeconomic approach (i.e. costs without taxes, utilises the socioeconomic discount rate prescribed by the Danish Ministry of Finance, etc.), although some aspects of a stringent socio-economic analysis (i.e. some wider implications such as spill over effects) are not included. All costs are in 2015 DKK.

The four primary vehicle types are:

- Personal vehicles
- Light-duty Vehicles (LDVs)
- Heavy-duty Vehicles (HDVs)
- Busses

Within each vehicle category a number of different drivetrains are modelled. For personal vehicles for example, this included:

- Gasoline
- Diesel
- Natural gas / Biogas
- E85 (a type of flexi fuel vehicle)
- Plug-in hybrid
- EV
- Hydrogen

Energy usage

The vehicle energy usage calculated in this analysis is what is commonly referred to as tank to wheel (or socket to wheel for an EV), as it covers the energy usage from the point of filling/charging. A per km energy usage for the years 2015 through to 2050 was calculated for each drivetrain type in the four vehicle categories outlined above. This per km figure was based on assumptions regarding developments in vehicle weights, engine and drivetrain efficiencies, battery density, hybridisation, etc.

Economics

In terms of the economics, a per km transport cost was calculated for each of the drivetrains and fuel types investigated. The main categories of costs were the upfront vehicle cost (with and without battery), operations and maintenance of the vehicle, fuel prices, and externality costs. The latter categories two are covered in other working papers, so the current paper will only describe the upfront and O&M costs. In calculating these, other important variables included the km driven per year, lifetime of the vehicle and battery, and interest rate. All of the costs in the analysis were compiled without taxes.

Standard car vs. fleet average car

For personal vehicles, as a starting point the analysis 'created' a standard car similar to a 2015 Volkswagen Golf for each vehicle drivetrain type. This particular model was selected as it is widely produced vehicle, and is available in gasoline, diesel, CNG, Multi-fuel, and EV versions. As such, it was possible to find data related to energy use, weight, and cost, depending on the drivetrain, and thereby create a standard vehicle for comparison across drivetrain types.

However, when modelling the energy use in the PETRA model, which models energy use for the entire fleet of vehicles, it is necessary to have a vehicle that represents the fleet average. In terms of model year, PETRA takes into account that newer vehicles use less energy, and continually become less efficient as they age. As such, having new vehicle efficiencies upon which to base energy consumption is appropriate. However, it is also important that the modelled vehicle represents the average weight of new vehicles for each drivetrain. In Denmark for example, the average diesel vehicle on the roads is heavier than the Volkswagen Golf, and the average gasoline vehicle is considerably lighter. Therefore, it was necessary to adjust the weight and cost of various vehicle drivetrains accordingly so they match the averages found in Denmark today.

Drivetrains in focus

There are four major types of drivetrains that are covered in the analysis:

- The conventional internal combustion engine (ICE), which utilises gasoline, diesel, bioethanol, and biodiesel. Within this analysis this category also includes combustion engines utilising natural gas and/or biogas as well as parallel hybrid technologies. In parallel hybrids the primary mover is the ICE, however there is also an electric motor coupled to the transmission that makes the overall efficiency of the vehicle higher, and in some models allows for full electric drive for very low speeds and/or short distances.

- Battery electric vehicles (BEVs or EVs) are powered by an electric motor and have a battery as energy carrier.
- Plug-in hybrids (PHEV) in this analysis exclusively entail series hybrids, that is vehicles that are powered by an electric motor, and although they also carry an ICE, it is solely utilised as a generator to produce electricity when the battery is low. These vehicles are essentially EVs with a smaller battery, and an ICE that acts as a range extender. As such, they differ from their parallel hybrid counterparts in that driving distances less than 40-60 km can typically be covered by electricity alone.
- Fuel cell electric vehicles (FCEVs) or hydrogen vehicles (HEVs) are also driven by an electric motor and contain a battery, although the battery is much smaller than in the EV. In addition they have hydrogen fuel cell stacks and a hydrogen tank.

The four main types of drivetrains are depicted below in Figure 1.

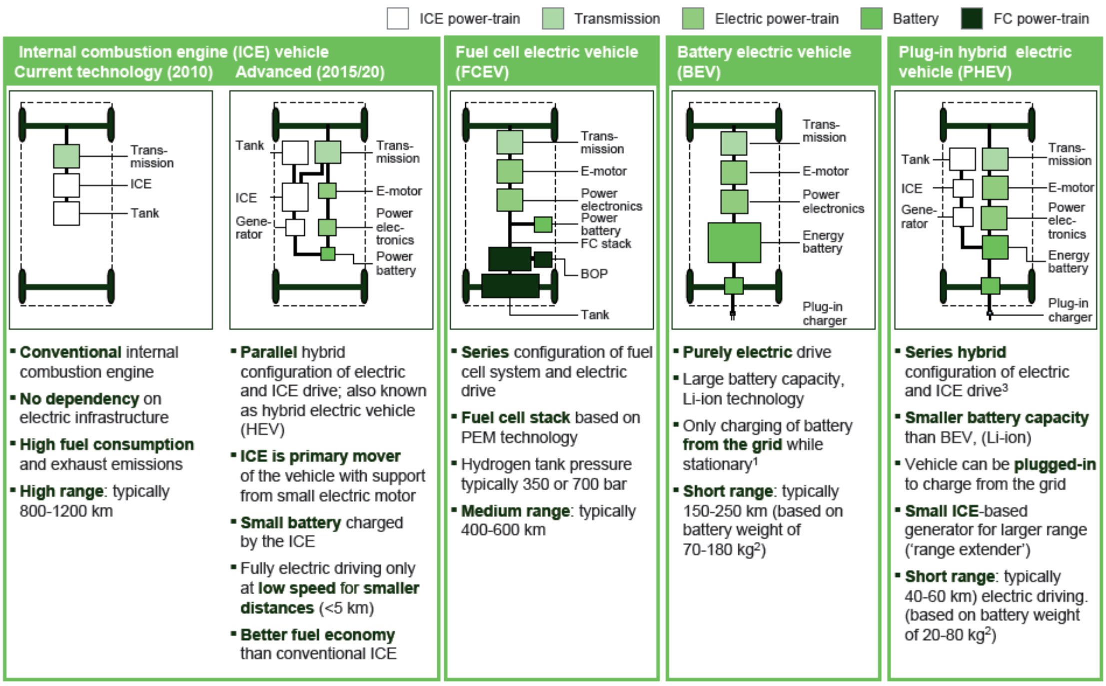

Figure 1: The four primary drivetrain types that are the focus of this study. (McKinsey & Company, 2010)

Energy usage

Real world energy usage

To calculate the 'real world' energy usage for each drivetrain in each vehicle category (as opposed to that stated by vehicle manufactures), the analysis started by estimating the amount of energy required to move a standard sized vehicle 1 km, regardless of the drivetrain type. This was divided into energy related to the vehicle's weight (i.e. overcoming rolling resistance, providing acceleration), and energy not related to the vehicle's weight (i.e. lighting, heating/cooling, etc.). For personal vehicles, various studies indicate that ca. 70% of the energy required to propel a vehicle is directly attributed to the vehicle weight (Transport & Environment, 2008), (Lutsey & German, 2010), and therefore as a vehicle increases/ decreases in weight, it is possible to determine the reduction/addition in energy required to propel the vehicle. Where applicable, energy returned to the vehicle from regenerative braking was then subtracted.

Vehicle efficiency

Having determined the required energy to propel the vehicle regardless of the drivetrain type, this figure was then combined with the vehicle and drivetrain efficiency to determine the required energy usage per km. For the EV and PHEV, this includes any charger or battery losses.

Personal vehicles

Vehicle weight

As was indicated above, the weight of a vehicle is a vital factor for car manufactures when they look to reduce energy and CO_2 emissions. Current average Danish vehicle fleet weights were based on preliminary 2014 data from the European Environment Agency (EEA, 2015) as displayed in Table 1.

Car type	Sold in EU	% of EU total	Av. mass EU (kg)	Sold in DK	% of DKK total	Av. mass DK (kg)
Diesel	6,646,953	53.0%	1,520	59,482	31.7%	1,475
Diesel-Electric	7,383	0.1%	1,892	5	0.0%	1,841
E85	3,326	0.0%	1,434	-	0.0%	-
Electric	38,028	0.3%	1,510	973*	0.5%	1,428
Hydrogen	7	0.0%	1,921	1	0.0%	1,921
LPG	142,680	1.1%	1,207	-	0.0%	-
NG	91,302	0.7%	1,290	28	0.0%	1,153
Petrol	5,558,685	44.3%	1,210	127,051	67.7%	1,096
Petrol-electric	61,094	0.5%	1,556	77	0.0%	1,406
Total	**12,549,481**		**1,377**	**187,617**		**1,218**

*Table 1: New car sales for the EU and Denmark in 2014, along with average weights for each vehicle type. Some vehicle categories with sales volumes under 0.0% have been omitted. (EEA, 2015). *Please note that the figures from the Danish Electric Vehicle Alliance are higher, as they reported EV sales figures of 1,575 for 2014 (Dansk Elbil Alliance, 2015).*

The weights given above are for a new vehicle 'in running order'[1], and are therefore a somewhat lighter than vehicles used on Danish roads on a daily basis.

In modelling vehicle weights in the future, all vehicle types (without battery where applicable) start with weights relative to a normal gasoline vehicle today, and adjustments to this variable are made based on assumptions regarding how the individual vehicle type will evolve going forward.[2]

Greater number of gasoline vehicles in Denmark
In looking at Table 1 it is interesting to note the differences in both the size and composition of new car sales in Denmark as compared to the EU. While 53% of new vehicles in the EU in 2014 were diesel, this was less than 32% for Denmark. In terms of vehicle weight, the average new diesel vehicle sold in Denmark was roughly 3% lighter than the EU average, whereas for gasoline this figure is over 10%. One of the primary reasons for this is the current Danish registration tax, which provides a strong incentive to purchase small inexpensive vehicles. Often referred to as 'mikrobiler' in Denmark, this includes vehicles such as the Volkswagen UP or Toyota Aygo, which were the #1 and # 4 most sold vehicle in Denmark last year. In fact, in looking at a list of the top 30 passenger vehicles sold in 2014 (which accounted for over 110,000 vehicles, or nearly 60% of new vehicles sales), these mikrobiler stood for over half. (De Danske Bilimportører, 2015).

Energy usage related to vehicle weight

Based on a literature review and an interview with a transport expert in 2011, it was determined that in 2012 it required roughly 100 Wh/kg to propel a new 1350 kg standard vehicle (i.e. regardless of drivetrain type) one km given a standard European test cycle (Kaj, 2011). Vehicle manufactures are under constant pressure to reduce CO_2 emissions (thereby energy usage), and improvements in for example aerodynamics (drag) and tyres (rolling resistance), are anticipated to bring this figure of 100 Wh/kg down in the future. In the current study this figure is estimated to fall to 88 Wh/kg in 2030.

Energy usage to power accessories

In addition to the weight related energy usage, it was estimated that on average a new standard sized vehicle would require roughly 25 Wh/km in

[1] According to regulation (EC) No 443/2009, means "The mass of the car with bodywork, coolant, oils, fuel, spare wheel, tools, and driver as stated in the certificate of conformity and defined in Section 2.6 of Annex I to Directive 2007/46/EC. (EEA, 2014)
[2] For example, an average Danish gasoline vehicle today weighs roughly 1100 kg, while an average diesel is roughly 1475 kg. Diesel vehicles thus weigh 1.35 more than gasoline vehicles today. Such a factor was calculated for each vehicle type and adjusted towards 2050. It is for example assumed that diesel vehicles will see this ratio fall by 2050 as diesel and gasoline vehicles become more similar. Hydrogen vehicles also see a slight decrease in this ratio as technology advancements make them lighter than today.

order to power accessories not related to the vehicle weight (i.e. heating/cooling, music, lights, wipers, etc.). Contrary to the weight related energy usage, due to an ever increasing number of electricity using gadgets (GPS, IPhone chargers, cameras, touch screens, etc.), the modelling has only assumed a slight fall in this 25 Wh/km figure going forward.

Drivetrain efficiencies

While the above two parameters are unchanged in the modelling regardless of drivetrain type, the efficiency of the overall drivetrain varies significantly between vehicle types. Drivetrain efficiency in this regard is essentially the % of energy from the fuel tank/battery that is delivered to the wheels of the vehicle, and therefore comprises losses associated with the motor, transmission, battery, etc. Based on an extensive literature review, initial estimates for drivetrain efficiencies were made. These efficiencies were then calibrated according to figures for new vehicle CO_2 emissions in 2012. At that time there was a growing recognition that real-world emissions were considerably higher than those published by car manufacturers, but the exact extent of this discrepancy was difficult to ascertain. Based on a 2012 study (see figure below) that showed a growing gap when comparing real-world and official CO_2 testing in Germany, it was determined to adjust the 2012 manufacturer results upwards with a 25% 'reality factor'.

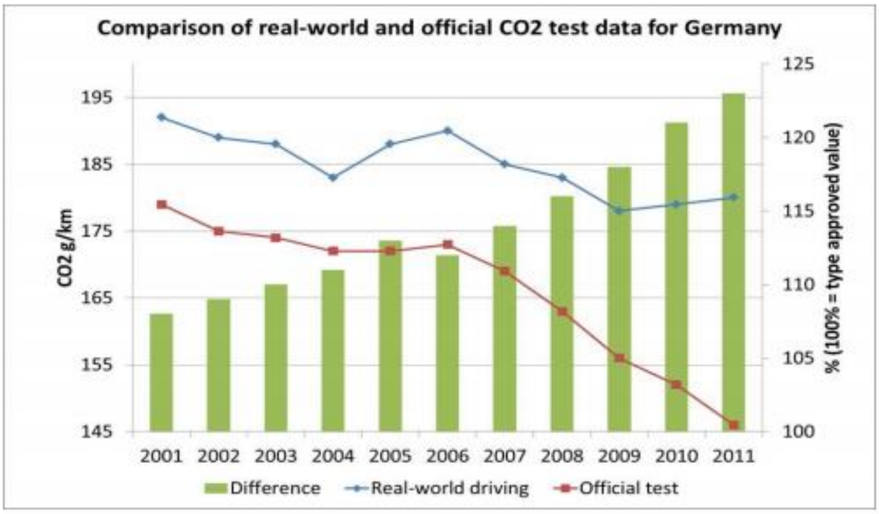

Figure 2: Comparison of average real world and official test results for Germany (derived from Mock et al, 2012). (Transport and Environment, 2013).

With the given vehicle weights, assumed energy usage per km regardless of drivetrain type, and adjusted real world energy usage for new vehicles it was possible to fine-tune the assumed vehicle efficiencies for each drivetrain type.

Regenerative braking

The last energy component is the energy that can be captured via regenerative braking. There are numerous forms of 'brake energy recuperation strategy systems', with varying levels of complexity, cost and effectiveness, but simply speaking, regenerative braking allows vehicles to recover kinetic energy as the vehicle slows. Generally speaking regenerative braking involves an electric motor that acts as a generator when the brakes are applied, and this electric energy is then stored in a battery or capacitor for later use. (Automotive IQ, 2011). As a general rule, the larger the electric motor and battery, the larger amount of energy that can be re-captured. As such, the amount that can be captured is greatest for EVs, followed by PHEVs, hydrogen vehicles, and finally conventional vehicles. The majority of conventional vehicles today do not employ regenerative braking, but many hybrid vehicles do, and it is assumed that with a growing degree of hybridisation in the years ahead, the number of conventional vehicles that will utilise this technology will continue to grow.

Total energy use for personal vehicles

The table below displays the vehicle weights, drivetrain efficiencies, and resulting energy usage for new vehicles in 2015 and 2030. Figures are for the average size of new vehicles for each category. For example, the average new Danish gasoline vehicle sold today is considerably lighter than the average new diesel vehicle.

Car type	Weight (kg)		Energy use attributable to car weight (Wh/km)		Energy from regenerative braking (Wh/km)		Overall efficiency (%)		Energy use (MJ/km)		CO_2 (g/km)		Range (km)	
	2015	2030	2015	2030	2015	2030	2015	2030	2015	2030	2015	2030	2015	2030
Gasoline*	1100	1020	84	73	0	3	20	26	1.9	1.3	137	86	890	940
Diesel*	1460	1290	103	85	0	3	24	27	1.9	1.4	133	97	990	970
Natural gas	1300	1190	94	81	0	3	20	25	2.1	1.5	121	84	440	510
E85*	1100	1020	84	73	0	3	21	27	1.9	1.3	39	27	680	750
Plug-in hybrid*	1380	1120	98	77	6	8	44	60	1.0	0.6	40	16	450	660
EV	1400	1130	99	78	8	10	73	84	0.6	0.4	0	0	160	290
EV – large	2090	1650	134	102	10	12	73	84	0.8	0.5	0	0	420	600
Hydrogen	1870	1340	123	88	5	6	39	43	1.4	0.9	0	0	330	730

*Table 2: Personal vehicle weights, efficiencies and resulting energy use per km for the selected drivetrains in the study. Please note that the figures are for the average size of new vehicles for each category. The column 'overall efficiency' takes into consideration energy from regenerative braking, battery and charger losses for vehicles with batteries, as well as the assumed amount of km that will be driven based on electricity/gasoline for plug-in hybrids. *Includes biofuel blends.*

Towards 2030 it is assumed that gasoline vehicles will continue to get lighter, but not to the same extent as diesel vehicles, which are likely to face greater difficulty in reducing their CO_2 emissions via improvements in engine efficiency alone. One example of this is the recent VW scandal, which, amongst other things, has highlighted the fact that for passenger diesel vehicles there is often a trade-off between fuel economy and NO_x reduction (Bredsdorff, 2015). For ICE vehicles it is assumed that a greater degree of hybridisation will take place, particularly for gasoline vehicles, which will result in gasoline vehicles achieving a similar overall efficiency by 2030.[3]

Additional considerations and notes

Gap between manufacture CO_2 tests and real-world driving

The issue regarding the discrepancy between real world energy use and that reported from manufacture tests has garnered increased attention since 2012 (and will likely receive even more attention in the wake of the Volkswagen scandal in September of 2015). A number of recent reports have indicated that this gap is likely now between 35-45%, deepening on the vehicle size, manufacturer, and owner type (see below).

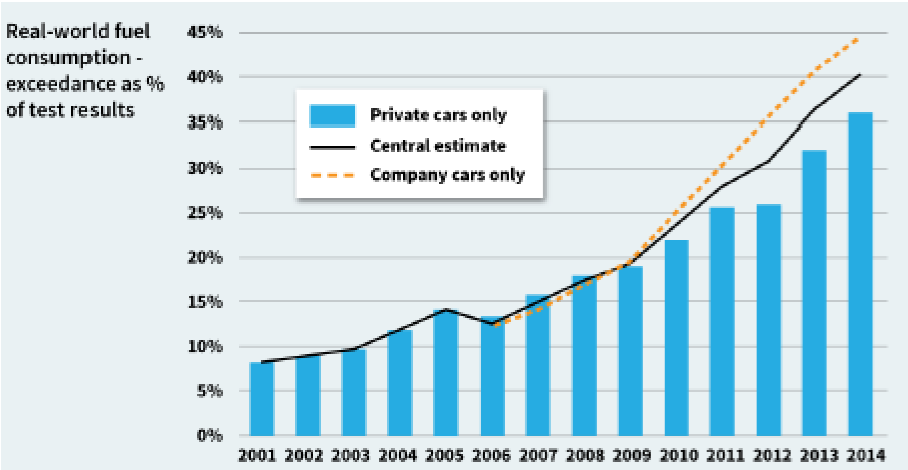

Figure 3: The gap between official fuel economy and CO_2 tests and real-world driving 2014 (derived from ICCT, 2015) (Transport & Environment, 2015)

The above figure indicates that the 25% upwards adjustment made to 2012 figures may have been on the conservative side (as the 2012 figure now appears to have been over 30%), and that any future calibrations should likely use a value of roughly 40%. Other recent reports (ICCT, 2015) have indicated that there are variances in this 'reality factor' according to vehicle segment and drivetrain type (amongst others), and any future 'recalibrating' of the modelling should therefore strongly consider taking this into consideration.

From individual tech model to PETRA model

After the modelled figures based on a 25% increase (which in retrospect should likely have been 30-35%) for new vehicle energy use from the

[3] For a more extensive discussion of the degree of hybridisation for conventional vehicle types, their costs, and the additional costs associated with implementing them on diesel vehicles, please see the interview notes with FDM.

individual technology model were transferred to the PETRA model (which calculates the fleet energy use), the fleet energy use resulted in a lower total energy usage than reported in Danmarks Statistik. In order to eliminate this discrepancy, each vehicle was deemed to use 10% more energy. Given that the initial new vehicle correlation assumed a gap of 25% in 2012, but it has later been deemed to be over 30% on average (and even higher for smaller vehicle segments), this additional 10% energy use applied in PETRA seems quite reasonable.

EV and Plug-in Hybrid battery characteristics

As batteries become cheaper and increase in battery density it is assumed that they will increase in capacity (kWh), thereby increasing the vehicle range, which is currently a limiting factor for EVs in particular. The energy density of the battery cells alone are assumed to increase from roughly 140 Wh/kg in 2015 to 250 Wh/kg in 2030. These figures were arrived at in collaboration with Dansk Energi (Dansk Energi, 2015), and relied on a number of sources including the US Department of Energy (DOE, 2015), EIA, IEA (IEA, 2012), Bloomberg (Bloomberg, 2015) and McKinsey (ARF & McKinsey, 2014).

It is worth noting that in calculating the range of EV and Plug-in Hybrid vehicles it was assumed that 85% and 75% of the battery capacity was available for EVs and Plug-in Hybrids respectively. This is due to the fact that the entire battery capacity is not made available for discharge, thus improving the performance and lifetime of the battery. The portion of the battery that is available for discharge is often referred to as the depth of discharge (DOD) window. This window is lower for Plug-in hybrids than EVs as a higher power to energy ratio in these vehicles makes the power requirement more difficult to meet at low states of charge. (Element Energy, 2012).

Light-duty Vehicles

For the most part, Light-duty vehicles (LDVs) in Denmark have similar drivetrains to that of personal vehicles, but are larger, heavier, and drive more km per year. As such, the energy usage for LDVs was modelled in a similar fashion to personal vehicles and the same figures were used for drivetrain efficiencies and energy usage related to accessories, from regenerative braking, and vehicle weight (i.e. 70% of the energy required to propel a vehicle is directly attributed to the vehicle weight).

Vehicle weight

To determine the average running weight of LDVs, initial estimates where made regarding their: weight without load, maximum carrying capacity, and % of this maximum that was utilised (in terms of weight). According to the EU Commission, the average weight without load for LDVs in the EU is 1,835 kg, while the maximum gross weight is 3,500 kg (ICCT, 2004). However, in Denmark the LDV category also contains larger vehicles than those in the EU Commission category. As such, the figures for Demark were estimated to be roughly 2,200 kg and 5,000 kg respectively. Lastly, it was estimated that on average, 50% of the maximum load is utilised (including when driving empty). Transport experts at the initial workshop indicated that for goods and heavy transport the focus is on decreasing the amount of energy per tonne of goods transported (Larsson, 2015). It has been assumed that this will likely be the case for LDVs as well, and therefore the modelling has assumed that the average LDV weight and maximum gross weight will only increase very slightly towards 2030, whereas the utilisation rate will increase to 55%.

Iterative process via comparison with historic fleet data

The actual average running weight of LDVs is highly dependent on the average weight of the load carried by the LDV vehicle fleet, a figure that is difficult to accurately pinpoint. Therefore, the methodology used involved an iterative process where the modelled energy use for a new diesel LDV was compared to the historical diesel LDV energy usage. It was possible to do so because past figures indicate that a new LDV is roughly 5% more efficient than the fleet average. The resulting energy usage for a modelled new LDV diesel, the modelled LDV diesel fleet usage, as well as the historic LDV diesel fleet usage are displayed in Figure 4.

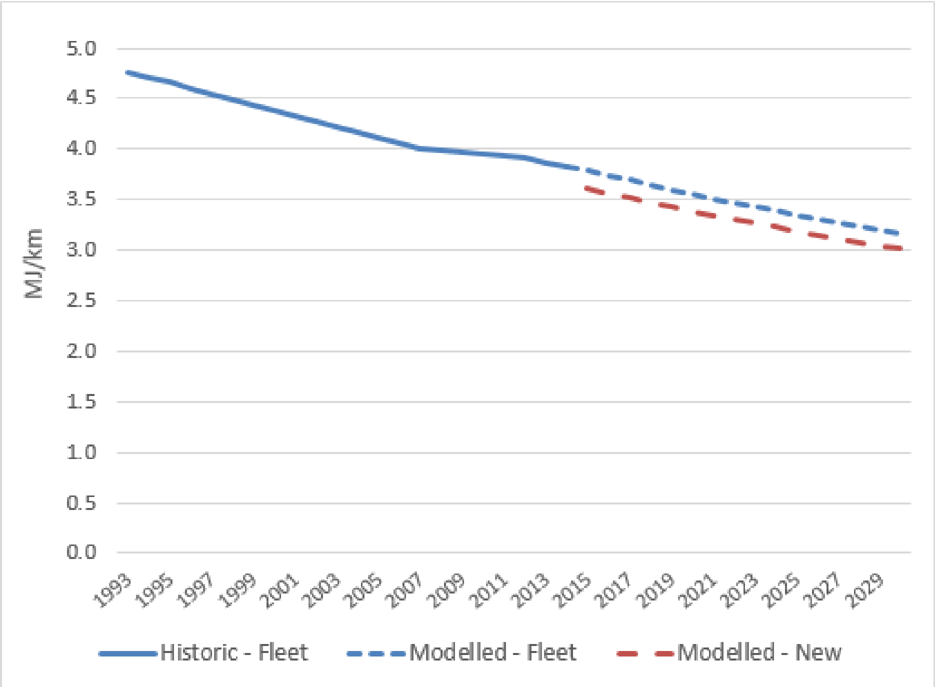

Figure 4: Historic energy usage for the Danish LDV diesel fleet, along with modelled energy usage for new diesel LDVs and the LDV diesel fleet.

Total energy use for LDVs

The table below displays the vehicle weights, drivetrain efficiencies, and resulting energy usage for new LDVs in 2015 and 2030. Figures are for the average size of new vehicles for each category, but unlike those for passenger vehicles, there is not a large variance between drivetrain types.

Car type	Average running weight (kg)		Energy use attributable to car weight (Wh/km)		Energy from regenerative braking (Wh/km)		Overall efficiency (%)		Energy use (MJ/km)		CO_2 (g/km)	
	2015	2030	2015	2030	2015	2030	2015	2030	2015	2030	2015	2030
Gasoline*	3,650	3,790	212	199	1	7	20	26	4.2	3.0	298	198
Diesel*	3,690	3,830	214	201	1	7	24	27	3.6	3.0	250	200
Natural gas	3,760	3,900	218	204	1	7	20	25	4.4	3.2	247	184
E85*	3,650	3,790	212	199	1	7	21	27	4.1	2.9	86	62
Plug-in hybrid*	3,864	3,930	223	206	12	17	44	60	2.0	1.4	81	37
EV	4,020	4,070	231	212	17	23	73	84	1.3	1.0	0	0

*Table 3: LDV weights, efficiencies and resulting energy use per km for the selected drivetrains. The column 'overall efficiency' takes into consideration energy from regenerative braking, battery and charger losses for vehicles with batteries, as well as the assumed amount of km that will be driven based on electricity/gasoline for plug-in hybrids. *Includes biofuel blends.*

Heavy-duty Vehicles

The methodology for calculating the energy use from Heavy-duty vehicles (HDVs) consisted of combining findings from Dansk Energi's report on future road transport (Dansk Energi, 2015), with adjustments that reflected the needs of this particular study. Dansk Energi utilised the same approach outlined above for personal vehicles and LDVs, namely calculating the energy required to propel a truck given a particular weight 1 km regardless of the drivetrain type, and then applying the engine and drivetrain efficiency to arrive at a total energy usage per drivetrain type.

Vehicle efficiencies

Based on feedback with market actors and COWI's 2014 report on gas in heavy transport (COWI, 2014), Ea Energy Analysis made slight adjustments to the drivetrain efficiency assumptions utilised by Dansk Energi. It was assumed that diesel trucks had a drivetrain efficiency of 39% in 2015, growing to 43% by 2035, whereas the figures were 33% and 41% for natural gas. Adjustments in the 2030 figures were based on the COWI report, which found that there is significant improvement potential for natural gas motors (perhaps up to 15 percent points), and the current extra energy use when compared to diesel trucks (15-20%), could fall to roughly 4% in the future (COWI, 2014).

Vehicle weight

The other adjustment to the Dansk Energi findings was in relation to the vehicle weight. Ea Energy Analyses utilised Dansk Energi's figures for the vehicle weights without load (7,450 kg for diesel and 7850 kg for natural gas), and maximum total load (26,000 kg), but as was the case with LDVs, for trucks there was again made an assumption regarding the % of the maximum capacity that was utilised. Through the iterative process outlined below, this figure was assumed to be roughly 50% throughout the study period.

Iterative process via comparison with historic fleet data

Once again the modelled energy use for a new diesel HDV was compared to the historical diesel HDV energy usage. As HDVs have a shorter economic lifetime (assumed to be six years in this study), the energy efficiency of a new HDV is only roughly 2% higher than the fleet average. The energy usage for a modelled new HDV diesel, modelled new natural gas vehicle, modelled HDV diesel fleet usage, as well as the historic HDV diesel fleet usage are displayed below.

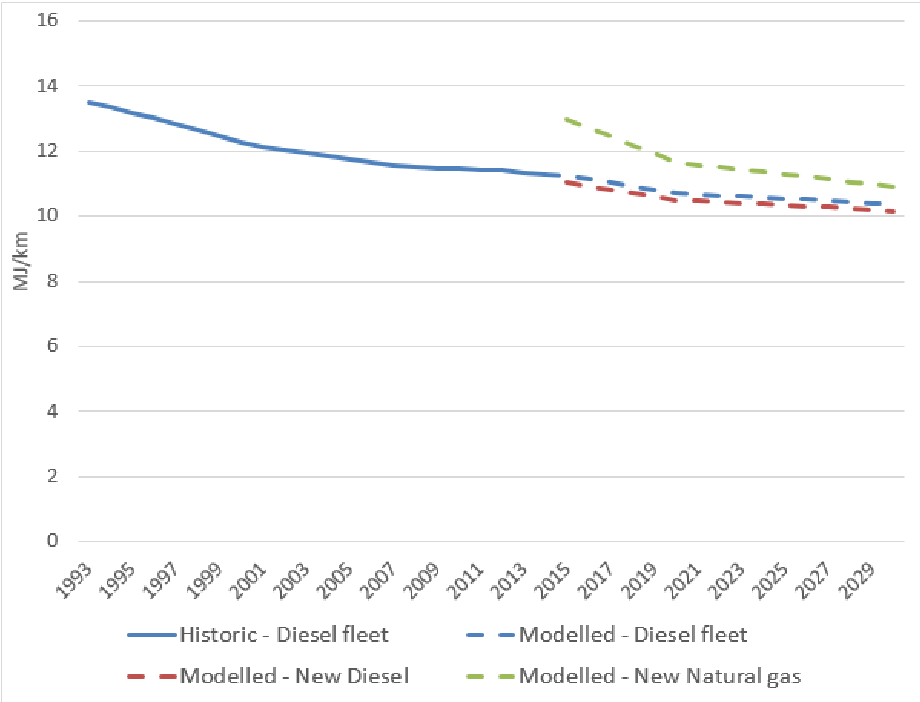

Figure 5: Historic energy usage for the Danish HDV diesel fleet, along with modelled energy usage for new diesel and natural gas HDVs and a modelled HDV diesel fleet.

Busses

The methodology for calculating the energy use from busses was very similar to that of HDVs, as it utilised Dansk Energi's findings as a starting point, and once again made minor adjustments. Similar to the case for HDVs, the efficiencies of natural gas busses were adjusted in the same manner, and once again, an iterative estimate of the average utilisation of busses maximum carrying capacity was made. The resulting modelled energy usage for new diesel, natural gas, and electric buses is displayed in the figure below.

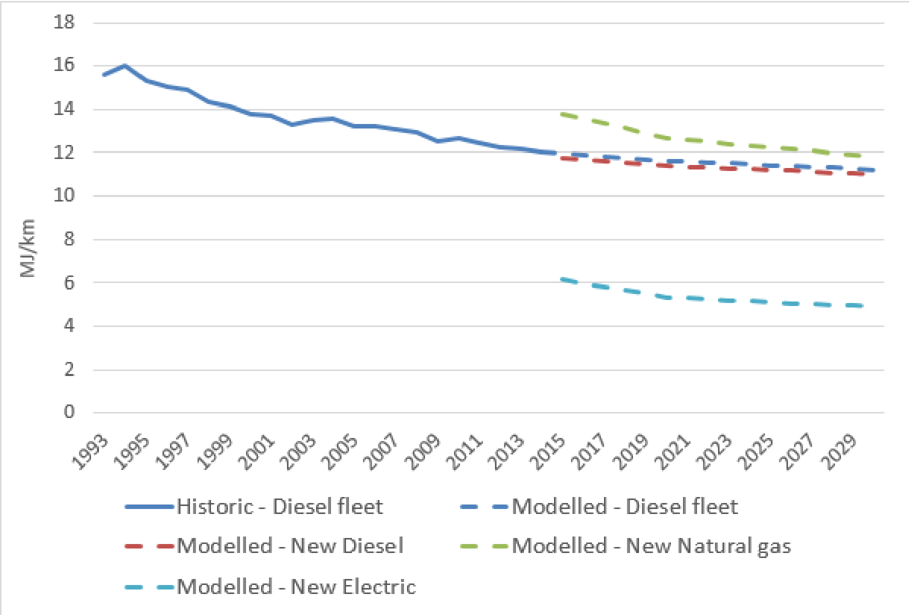

Figure 6: Modelled energy usage for new natural gas, diesel and electric buses, along with that for the historic and modelled diesel fleet.

The relatively larger fall in energy usage for natural gas buses is due to the aforementioned improvement potential in their drivetrain efficiency. Meanwhile, electric busses realise a larger fall in their energy usage primarily because it is assumed that the energy density of batteries increases from 140 Wh/kg to 250 Wh/kg,

Economics

A per km transport cost was calculated for each of the drivetrains and fuel types investigated with all costs being without taxes. The costs described in this report are the upfront vehicle cost (with and without battery), and operations and maintenance. Other important costs such as fuel prices, fuel infrastructure & distribution, and externality costs are covered in other working papers.

Personal vehicles

Standard car

In determining the cost of personal vehicles, as a starting point the analysis 'created' a standard car similar to a 2015 Volkswagen Golf for each vehicle drivetrain type. This particular model was selected as it is a widely produced vehicle, and is available in gasoline, diesel, CNG, Multi-fuel, and EV versions.

Vehicle costs in 2015 for 'standard' vehicle

In collaboration with Dansk Energi, 2015 vehicle prices were collected for a VW Golf of each drivetrain type, with motor effect and performance kept as even across the drivetrain types as possible. Where certain models came with fewer/additional accessories, the prices were adjusted accordingly. For VW Golf models with market prices in Denmark (gasoline, diesel, electric, and plug-in hybrid[4]), it was possible to estimate the vehicle cost without taxes by working backwards from the list price using the registration and VAT taxes from the Danish Ministry of Taxation (Skatteministeriet, 2015). For models that were not available in Denmark, but were available in neighbouring countries (flexi-fuel in Sweden, and natural gas in Germany[5]), these vehicle prices were compared to vehicle models available in both countries, thus allowing for price estimates given the assumption that a significant demand for these type of vehicles would develop in Denmark. Lastly, the price of a hydrogen vehicle was based on the Honda Mirai, which is anticipated to be available in the United States in late 2015 with a price of $57,500 (Toyota, 2015).

Future vehicle costs: Relative to gasoline vehicle without battery

In modelling the future vehicle costs, as was the case with vehicle weights, all vehicle types now had a 2015 cost relative to the gasoline vehicle (without battery where applicable). The reason for modelling the future costs in this fashion is because the price of batteries is such a significant cost component for PHEVs and EVs, and this approach allows for adjustments in the size of the car battery over time and/or between scenarios. For each vehicle type, assumptions were made regarding how this price would evolve going forward.

It is assumed that the EU will continue to apply increasingly stringent CO_2 emission requirements on ICE vehicles up to 2030, requirements that have proven to be very effective in increasing vehicle efficiency in the recent past. An example of improvement potential is a continued move to hybridisation of all ICE vehicles, which involves the utilisation of a highly efficient electric motor in addition to the traditional ICE engine. According to various sources, this will be more cost-effective for gasoline as opposed to diesel, and therefore greater efficiency gains (and slightly higher costs) will be realised by gasoline vehicles (Rasmussen, 2015).

Given the assumption that ICE vehicle manufactures will have a strong incentive to continue to innovate and utilise new technologies, it is assumed that cost of new ICE vehicles will remain roughly the same for gasoline, and fall slightly for diesel and natural gas. For EVs and PHEVs large price reductions are anticipated to come about partly due to larger production volumes, but primarily as a result of lower battery costs (Rasmussen, 2015).

[4] Gasoline: Golf 1.2 TSI 105 hk, Diesel: Golf 1.6 TDI 105 hk (VW Danmark, 2015a), Electric: eGolf 115 hk (VW Danmark, 2015b), Plug-in hybrid: Golf GTE 204 hk (VW Danmark, 2015c)
[5] Multifuel: Golf TSI 125 hk (VW Sweden, 2015), Natural gas: TGI BlueMotion 110 (VW Germany, 2015)

For hydrogen vehicles, large price falls are also assumed, but it is not anticipated that they will become cost competitive with the other technologies prior to 2030 (Godwin, 2015).

Vehicle and battery lifetime

The new vehicle lifetime for all vehicle types in all scenarios was assumed to be 15 years, while batteries produced in 2015 were assumed to have a lifetime of 8 years, with this growing to 10 years by 2030. In calculating the total capital costs for use in the PETRA model, EV and PHEV owners were assumed to purchase a replacement battery if the life of the vehicle surpassed the battery life, and if the replacement battery outlived the vehicle life, then the residual value of this battery was deducted. The discount rate used for vehicles and batteries was 4%.

Battery costs

Current and future battery costs were arrived at in collaboration with Dansk Energi (Dansk Energi, 2015), and relied on a number of sources (DOE, 2015), (IEA, 2012), (Bloomberg, 2015), (ARF & McKinsey, 2014), (Element Energy, 2012) (McKinsey, 2011), (IEA, 2012) (COWI, 2013) and cover the battery cells alone. Other costs associated with the battery back are included in the EV/Plug-in hybrid price cost.[6] The battery assumptions utilised in the primary scenarios are displayed in Table 4.

Car type	2015	2020	2030
Battery capacity (kWh)			
Plug-in hybrid	15	16	18
EV	26	30	35
EV - large	90	90	90
Amount of battery capacity used (%)[7]			
Plug-in hybrid	75	75	77
EV	85	85	87
EV - large	87	87	89
Other battery characteristics			
Density (Wh/kg)*	140	200	250
Cost (DKK/kWh)*	2,150	1,500	1,120
Lifetime (years)	8	9	10

*Table 4: Battery assumptions utilised in the study. *Battery cells alone.*

[6] Including the battery cell costs alone in the battery costs, and allocating the rest of the battery back in the cost of the EV or plug-in hybrid was done to allow for scaling up and down of the battery size in different scenarios and years.

[7] In order to improve the cycle life of their batteries, EVs and PHEVS are set up to use less than 100% of the battery capacity. The exact figure relates to the depth of discharge (DOD) for the battery, which varies according to the battery chemistry and thermal management. Generally speaking, it the DOD window is lower for PHEVs, as the higher power to energy ratio makes the power requirement more difficult to meet at low state of charge. (Element Energy, 2012).

O&M

The operation and maintenance for a standard gasoline vehicle was assumed to be roughly 700 €/year, a figure based on those in *Alternative drivmidler* (COWI, 2013). For EVs it was assumed that the O&M costs are roughly 60% of this, due to EVs having less moving parts in the engine, not requiring oil changes, etc. Meanwhile, for hydrogen vehicles these costs were roughly estimated to be 20% higher, based on an assumption that as there are so few hydrogen vehicles on the road, their maintenance will require staff with relevant training.

The resulting CAPEX and OPEX figures for the 'standard' passenger vehicles are displayed in Table 5.

Car type	Weight (kg)		Vehicle cost without battery (DKK)		Initial battery cost (DKK)		Vehicle cost with battery (DKK)		Annual O&M (DKK)	
	2015	2030	2015	2030	2015	2030	2015	2030	2015	2030
Gasoline*	1,210	1,100	111,000	111,000			111,000	111,000	5,200	5,200
Diesel*	1,230	1,120	124,000	123,000			124,000	123,000	5,200	5,200
Natural gas	1,320	1,200	126,000	126,000			126,000	126,000	5,600	5,600
E85*	1,210	1,100	115,000	114,000			115,000	114,000	5,700	5,700
Plug-in hybrid*	1,450	1,160	202,000	117,000	33,000	20,000	235,000	137,000	5,200	5,200
EV	1,490	1,200	156,000	111,000	57,000	39,000	213,000	150,000	3,100	3,100
EV – large	2,120	1,550	234,000	167,000	194,000	100,000	428,000	267,000	3,400	3,400
Hydrogen	1,380	1,190	373,000	156,000			373,000	156,000	6,700	6,100

Table 5: CAPEX and OPEX for the 'standard' new passenger vehicles in Denmark, excluding taxes and delivery fees. (2015 DKK)

Standard car vs. fleet average car

After vehicle costs for each drivetrain version of the standard vehicle were calculated, these figures were then scaled up or down in order to reflect their relation to the average vehicle size of their drivetrain type. For example, the gasoline powered VW Golf used as the 'standard' vehicle has a running weight of 1210 kg (VW Danmark, 2015a), whereas the average new gasoline vehicle purchased in Demark in 2014 weighed under 1100 kg, and the average diesel roughly 1460 kg (EEA, 2015). Therefore, the 2015 cost for the average new gasoline vehicle was estimated to be 105,000 DKK, which is 6,000 DKK less than the 'standard' new gasoline vehicle. Meanwhile, for the average new diesel vehicle in 2015, the cost was estimated to be 133,000 DKK, or roughly 9,000 DKK more than that for the 'standard' diesel vehicle. Scaling up/down from the standard vehicle was of course not an exact science, and took into account a number of factors, including: the effect of the aforementioned micro vehicles, which are quite inexpensive vehicles without many of the extras found in the 'standard' vehicle based on VW Golf, assumptions regarding which vehicle classes were likely to be larger or smaller than the average going forward, the Danish vehicle fleet relative to the European vehicle fleet, etc. The resulting figures are displayed in the table below.

Car type	Weight (kg)		Vehicle cost without battery (DKK)		Initial battery cost (DKK)		Vehicle cost with battery (DKK)		Annual O&M (DKK)	
	2015	2030	2015	2030	2015	2030	2015	2030	2015	2030
Gasoline*	1,100	1,020	105,000	105,000			105,000	105,000	5,200	5,200
Diesel*	1,460	1,290	133,000	128,000			133,000	128,000	5,200	5,200
Natural gas	1,370	1,220	132,000	131,000			132,000	131,000	5,600	5,600
E85*	1,100	1,020	109,000	108,000			109,000	108,000	5,700	5,700
Plug-in hybrid*	1,380	1,120	193,000	116,000	33,000	20,000	226,000	136,000	5,200	5,200
EV	1,400	1,130	150,000	109,000	57,000	39,000	207,000	148,000	3,100	3,100
EV – large	2,120	1,550	234,000	167,000	194,000	100,000	428,000	267,000	3,400	3,400
Hydrogen	1,380	1,190	373,000	156,000			373,000	156,000	6,700	6,100

Table 6: CAPEX and OPEX for the fleet average of Danish passenger vehicles, excluding taxes and delivery fees. (2015 DKK)

Light-duty Vehicles

The capital cost of Light-duty vehicles (LDVs) was modelled in a similar fashion to that of personal vehicles, i.e. a list price was found for gasoline and diesel models, from which the cost price without taxes could be derived based on the Danish taxes and fees levied on LDVs (Skat, 2015). Based on a sample of list prices, the average cost without taxes was estimated to be in the range of 150,000-160,000 DKK.[8] Thereafter, the cost for the other drivetrain types were estimated accordingly. For example, it was estimated that the cost of an electric LDV, excluding battery cost, would be roughly the same as that of a gasoline vehicle, with this ratio falling slightly as electric LDVs start to be produced in greater quantities. Meanwhile, the battery cost (on a per kWh basis) would evolve in the same fashion as for passenger EVs. With respect to battery size, the modelling assumed that an average all-electric LDV would have a battery capacity of roughly 50 kWh in 2015, growing to 70 in 2030, while the average plug-in hybrid LDV would have a battery 30 kWh battery today, growing to 36 kWh in 2030. Within the study, the average economic lifetime of LDVs was estimated to be 10 years. The resulting figures are displayed in the table below.

[8] Prices without taxes for for the LDV Maxus, Ford Transit Van 470 - L4 H3, and Ford Transit Van 350 - L2 H2, for example ranged from 130,000 to 190,000 DKK, with an average of 158,000.

Car type	Average running weight (kg)		Vehicle cost without battery (DKK)		Initial battery cost (DKK)		Vehicle cost with battery (DKK)		Annual O&M (DKK)	
	2015	2030	2015	2030	2015	2030	2015	2030	2015	2030
Gasoline	3,650	3,790	149,000	149,000			149,000	149,000	7,800	7,800
Diesel	3,690	3,830	163,000	161,000			163,000	161,000	7,800	7,800
Natural gas	3,760	3,900	166,000	164,000			166,000	164,000	8,400	8,400
E85	3,650	3,790	153,000	152,000			153,000	152,000	8,600	8,600
Plug-in hybrid	3,864	3,930	181,000	141,000	66,000	40,000	247,000	181,000	7,800	7,800
EV	4,020	4,070	147,000	134,000	114,000	78,000	261,000	212,000	4,700	4,700

Table 7: Modelled CAPEX and OPEX for new Danish LDVs excluding taxes and delivery fees (2015 DKK)

Heavy-duty Vehicles

CAPEX and OPEX costs for Heavy-duty Vehicles (HDVs) were based on figures from a 2014 report on gas in heavy transport, *Rammevilkår for gas til tung vejtransport* (COWI, 2014), and supplemented with discussions with market actors that indicated that a similar natural gas truck would cost roughly 200,000 DKK more than its diesel counterpart today, with this figure likely to fall to roughly 100,000 DKK by 2035. Lastly, the economic lifetime for HDVs was assumed to be 6 years.

Truck type	Vehicle cost (DKK)		Annual O&M (DKK)	
	2015	2030	2015	2030
Diesel	949,000	949,000	67,400	67,400
Natural gas	1,148,000	1,074,000	69,900	69,900

Table 8: CAPEX and OPEX figures for HDVs utilised in the study, excluding taxes (2015 DKK) (COWI, 2014).

Busses

Natural gas and diesel bus costs largely based on Dansk Energi's report on future road transport (Dansk Energi, 2015). The cost of an electric bus without a battery has been assumed to be roughly that of a diesel bus, with the additional cost therefore determined by the size and per kWh cost of the battery.

Truck type	Vehicle cost (DKK)		Annual O&M (DKK)	
	2015	2030	2015	2030
Diesel	1,240,000	1,240,000	150,100	150,100
Natural gas	1,400,000	1,400,000	154,300	154,300
Electric	2,497,000	1,861,000	147,800	108,700

Table 9: CAPEX and OPEX figures for buses utilised in the study, excluding taxes (2015 DKK) (Dansk Energi, 2015 & own calculations)

References

ARF & McKinsey. (2014). *EVolution - Electric vehicles in Europe: gearing up for a new phase?* Amsterdam: Amsterdam Roundtable Foundation.

Automotive IQ. (2011, March 31). *Brake energy recuperation strategy systems*. Retrieved from Automotive IQ: https://automotiveiq.wordpress.com/2011/03/31/brake-energy-recuperation-strategy-systems/

Bloomberg. (2015, April 8). *Clean Energy Revolution Is Ahead of Schedule*. Retrieved from BloombergView: http://www.bloombergview.com/articles/2015-04-08/clean-energy-revolution-is-way-ahead-of-schedule

Bredsdorff, M. (2015, September 25). *Kun kostbar rensning kan sikre ren luft fra dieselbiler*. Retrieved from Ingeniøren: http://ing.dk/artikel/kun-kostbar-rensning-kan-sikre-ren-luft-fra-dieselbiler-178994

COWI. (2013). *Alternative drivmidler.* Kongens Lyngby: COWI A/S.

COWI. (2014). *Rammevilkår for gas til tung vejtransport.* Kongens Lyngby: COWI.

Dansk Elbil Alliance. (2015, September 17). *Årlige salgstal for elbiler i Danmark*. Retrieved from Dansk Elbil Alliance: http://www.danskelbilalliance.dk/Statistik/Salgstal_Aar.aspx

Dansk Energi. (2015). *Analyse nr. 18 - Fremtidig vejtransport.* København: Dansk Energi.

De Danske Bilimportører. (2015, September 15). *Statistik*. Retrieved from De Danske Bilimportører: http://www.bilimp.dk/statistics/index.asp

DOE. (2015). *Vehicle technologies office: Batteries*. Retrieved from Department of Energy: http://energy.gov/eere/vehicles/vehicle-technologies-office-batteries

EEA. (2014). *Monitoring CO2 emissions from passenger cars and vans in 2013.* Luxembourg: European Environment Agency.

EEA. (2015, August 20). *Monitoring of CO2 emissions from passenger cars - Data 2014 - Provisional data*. Retrieved from European Environment Agency: http://www.eea.europa.eu/data-and-maps/data/co2-cars-emission-8

Element Energy. (2012). *Cost and performance of EV batteries.* Cambridge: Element Energy Limited.

European Environment Agency. (2013). *Monitoring CO2 emissions from new passenger cars in the EU: summary of data for 2012.* Copenhagen: European Environment Agency.

Godwin, S. (2015). Electricity, gas and biofuels: which road to take? Copenhagen.

ICCT. (2004). *EU CO2 emission standards for passenger cars and light-commerical vehicles.* Berlin: International Council on Clean Transportation.

ICCT. (2015). *From laboratory to road - A 2015 update of official and 'real world' fuel consumption and CO2 values for passenger vehicles.* Berlin: International Council on Clean Transportation Europe.

IEA. (2012). *Energy Technology Perspectives 2012.* Paris: International Energy Agency.

Kaj. (2011). Road transport energy use. (C. L. Bang, Interviewer)

Larsson, S. (2015, April 30). Reducing CO2 from Road Freight Transport . Copenhagen.

Lutsey, N., & German, J. (2010). *Size or Mass? The technical rationale for selecting size as an attribute for vehicle efficiency standards.* Washington, DC: The International Council on Clean Transportation.

McKinsey & Company. (2010). *The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles.* McKinsey & Company.

McKinsey. (2011). *Boost! Transforming the powertrain value chain - a portfolio challenge.* McKinsey & Company.

Rasmussen, S. W. (2015, September 16). Hybridiserings omkostninger. (J. H. Skjold, & C. Bang, Interviewers)

Skat. (2015, July 31). *Last- og varebiler med en tilladt totalvægt på ikke over 4 tons*. Retrieved from Skat: https://www.skat.dk/SKAT.aspx?oId=1947292&chk=211047

Skatteministeriet. (2015, May 15). *Registreringsafgiftsloven*. Retrieved from Skatteministeriet: http://www.skm.dk/skattetal/satser/satser-og-beloebsgraenser/registreringsafgiftsloven

Toyota. (2015, Oct 5). *Mirai Fuel cell Vehicle*. Retrieved from Toyota: https://ssl.toyota.com/mirai/fcv.html

Transport & Environment. (2008, April). *Background briefing: Weight vs Footprint.* Retrieved from Transport & Environment: http://www.transportenvironment.org/sites/te/files/media/2008_04_footprint_background_briefing.pdf

Transport & Environment. (2015). *Mind the Gap 2015.* Brussels: Transport & Environment.

Transport and Environment. (2013). *Mind the Gap! Why official car fuel economy figures don't match up to reality.* Brussels: Transport and Environment.

VW Danmark. (2015a, 6 15). *Priser og Brochure for Golf*. Retrieved from Voklswagen Denmark:

http://www.volkswagendanmark.dk/Modeller/Golf/Priser-og-Brochure/

VW Danmark. (2015b, June 18). e-Golf - Detailprisliste. Copenhagen: Volkswagen Danmark.

VW Danmark. (2015c, October 5). *Oplev Golf GTE*. Retrieved from Volkswagen Danmark: http://www.volkswagen.dk/da/models/Golf_GTE/udstyrsvariant.html

VW Germany. (2015). Der Golf: Technik unde Preise - Gültig für das Modelljar 2016. Volkswagen Germany.

VW Sweden. (2015, August). Cirkaprislista Augisti 2015. Volkswagen Sweden.