LIFE-CYCLE IMPACTS OF TESLA MODEL S 85 AND VOLKSWAGEN PASSAT

ENVIRONMENT, CARBON FOOTPRINT, RESOURCE DEPLETION – UNITED STATES

Kimmo Klemola 2016 (updated 31.03.2016)

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GOAL AND SCOPE

The environmental impacts of Volkswagen Passat gasoline-, flexifuel E85- and NExBTL biodiesel-fueled cars and Tesla Model S 85 electric car in the United States are assessed in this report. Volkswagen Passat is about the same size as Tesla Model S.

The environmental impacts assessed in this report are:

- Global warming potential (GWP)
- Depletion potential of the stratospheric ozone layer (ODP)
- Acidification potential (AP)
- Formation potential of tropospheric ozone photochemical oxidants (POCP)
- Eutrophication potential (EP)
- Air toxicity (AT)
- Water toxicity (WT)
- Hazardous waste production (HWP)
- Particulate emissions
- SO_2 emissions
- NO_x emissions
- Methane emissions

TESLA MODEL S 85

The Tesla Model S is a full-sized plug-in electric five-door, luxury liftback, produced by Tesla Motors. (Wikipedia)

VOLKSWAGEN PASSAT

The Volkswagen Passat is a large family car produced by the German manufacturer Volkswagen since 1973 (Wikipedia)

- N_2O emissions
- Non-methane hydrocarbon emissions
- CO emissions
- High-level nuclear waste (HLW)
- Medium- and low-level nuclear waste (MLW+LLW)
- Petroleum consumption
- Energy depletion

Certain important environmental impacts are not quantified in this report. For example, the effect on water tables depends on geographic location. The effect on the loss of biodiversity is also difficult to appraise. For example, increased energy use of biomass decreases fossil fuel combustion, which in the long term mitigates climate change and also loss of biodiversity. However, increased energy use of biomass may lead to deforestation, monocultures and other land-use changes, directly or indirectly, thus promoting the loss of biodiversity.

In allocating combined heat and power production impacts to electricity, the benefit sharing method was used.[1]

The purpose of this inventory report is to characterize resource inputs and environmental impacts and releases associated with different vehicle technologies.

The average distance travelled during the life time of the car in the United States is assumed to be about 305 000 km.

For car manufacturing, the life cycle assessment considers the environmental impacts throughout the entire life cycle, from raw material extraction and acquisition, through energy and material production and manufacturing, to maintenance and end-of-life treatment and final disposal. For fuels and electricity, the whole life cycle from cradle to gate is considered.

PROCESS DESCRIPTION AND SYSTEM BOUNDARIES

The average curb weight of new light-duty vehicles in the United States including over 8500 lb "SUVs" was a couple of years ago 1780 kg and the combined city/highway fuel consumption was 11.3 liters per 100 km (Heavenrich 2005).

For Tesla Model S, the higher greenhouse gas emissions from car materials and manufacturing stage are due to a higher curb weight and more exotic materials. Tesla is an electric vehicle and all its operation stage emissions (fuel/electricity production and tail pipe

[1] Viinikainen S., Ikonen E., Soimakallio S., Lind I., Energy use: Visions and technology opportunities in Finland, VTT-Edita, Helsinki, 2007.

emissions) come from electricity generation. For electric vehicles there are no tail pipe emissions.

The car materials stage or the premanufacturing stage includes the inputs and emissions related to manufacturing the materials (metals, plastics, fluids and other materials) for the cars. Various databases and life cycle analyses were used to create a materials life cycle inventory. Some references are given in the reference list.

The manufacturing stage refers to car assembly. The maintenance stage includes service, infrastructure such as roads, parking lots and insurance company buildings. The end-of-life stage includes car scrapping and recycling.

Biofuels are regarded as being carbon neutral as the carbon dioxide released in combustion is theoretically sequestered back in plantations. Therefore biofuels have no carbon dioxide tailpipe emissions contributing global warming. However, combustion processes generate nitrous oxide and carbon monoxide, which are greenhouse gases, and thus there are some CO_2e tailpipe emissions also for biodiesel and bioethanol cars.

The E85 flexifuel vehicle was developed to run on any mixture of unleaded petrol and ethanol, anywhere from 0% to 85% ethanol by volume. In this analysis, corn bioethanol share is 85 vol-% (E85). Ethanol's energy content (lower heating value LHV is 21.16 MJ/L) by volume is less than two thirds of gasoline's energy content (LHV is 32.92 MJ/L). Based on energy content, the volumetric ethanol (E100) consumption compared to gasoline (E0) would be 55.6% higher. However, the E100 consumption is just 42.2% higher than E0 consumption because of somewhat better efficiency of ethanol in Otto engines.

The data from US Environmental Protection Agency's fuel economy guide (Model year 2007 fuel economy guide, 2007) for flexifuel vehicles and similar gasoline vehicles (51 car models were compared) give the E85-fueled vehicles 37.3% higher fuel consumption by volume than for E0-fueled vehicles.

For gasoline and diesel production, for example Wang’s (1999) report and IPCC data were used. In this report, Volkswagen Passat running on petroleum diesel was not studied.

The specifications of a generic ICEV and EV are presented in Table 1. Table 2 gives the specifications of the Tesla Model S 85 and a similar size ICEV. The vehicle components of the studied cars are given in Tables 3 to 5. The simplified material compositions of the generic ICEV and EV and Tesla Model S 85 are given in Table 6. Table 7 gives the material components of the selected car models. The data are used in the life-cycle analysis. The technical data of the selected car models are given in Table 8. The electricity generation mix (%) of the United States in 2014 is given in Table 9 (EIA 2015). In allocating combined heat and power production impacts to electricity, the benefit sharing method was used.

Similarly as in Table 9, the electricity generation mixes with CHP shares (combined heat and power) of all U.S. states in 2014 were calculated from EIA data (EIA 2015) and the data were used in assessing the life-cycle impacts of driving Tesla Model S in each state. In this report, Tesla's carbon footprint, petroleum use and the high-level nuclear waste "footprint" in each state are presented.

For the analysis of car materials and manufacturing stages, the specific data from the car manufacturers have not been used.

Table 1. Vehicle components of a generic vehicle (ICEV = internal combustion engine vehicle, EV = electric vehicle) (Hawkins *et al.* 2013).

Component group	**All vehicles (kg)**	**ICEV only (kg)**	**EV only (kg)**	**ICEV (kg)**	**EV (kg)**
Body and doors	526.51				
Brakes	12.24				
Chassis	15.53				
Fluids ICEV and EV	5.00				
Vehicle interior and exterior	237.67				
Tyres and wheels	79.36				
Total	876.31				
Engine (ICEV)		170.20			
Fluids (ICEV only)		5.00			
Other ICEV powertrain		92.26			
ICEV transmission		51.86			
ICEV battery		16.47			
Total		335.78			
EV motor and transmission			378.28		
EV differential transmission			25.01		
EV Li-NCM battery			214.00		
Total			617.28		
Car weight				1212.10	1493.59

Table 2. Vehicle components of Tesla Model S 85 and a similar size ICEV (ICEV = internal combustion engine vehicle, EV = electric vehicle) (Hawkins *et al.* 2013). Volkswagen Passat is very close to this ICEV size.

Component group	All vehicles (kg)	ICEV only (kg)	EV only (kg)	ICEV (kg)	EV (kg)
Body and doors	645.18				
Brakes	15.00				
Chassis	19.03				
Fluids ICEV and EV	6.13				
Vehicle interior and exterior	291.23				
Tyres and wheels	97.24				
Total	1073.82				
Engine (ICEV)		208.56			
Fluids (ICEV only)		6.13			
Other ICEV powertrain		113.05			
ICEV transmission		63.55			
ICEV battery		20.18			
Total		411.47			
EV motor and transmission			463.54		
EV differential transmission			30.64		
EV Li-NCM battery			540.00		
Total			1034.18		
Car weight				1485.29	2108.00

Table 3. Vehicle components of Tesla Model S 85 (electric vehicle) based on Hawkins *et al.* (2013).

Component group	All vehicles (kg)	EV only (kg)	EV (kg)
Body and doors	645.18		
Brakes	15.00		
Chassis	19.03		
Fluids ICEV and EV	6.13		
Vehicle interior and exterior	291.23		
Tyres and wheels	97.24		
Total	1073.82		
EV motor and transmission		463.54	
EV differential transmission		30.64	
EV Li-NCM battery		540.00	
Total		1034.18	
Car weight			2108.00

Table 4. Vehicle components of Volkswagen Passat 1.4 TSI (gasoline) based on Hawkins *et al.* (2013).

Component group	All vehicles (kg)	ICEV only (kg)	ICEV (kg)
Body and doors	646.36		
Brakes	15.03		
Chassis	19.07		
Fluids ICEV and EV	6.14		
Vehicle interior and exterior	291.76		
Tyres and wheels	97.42		
Total	1075.78		
Engine (ICEV)		208.94	
Fluids (ICEV only)		6.14	
Other ICEV powertrain		113.25	
ICEV transmission		63.66	
ICEV battery		20.22	
Total		412.22	
Car weight			1487.99

Table 5. Vehicle components of Volkswagen Passat 2.0 TDI (diesel) based on Hawkins *et al.* (2013).

Component group	All vehicles (kg)	ICEV only (kg)	ICEV (kg)
Body and doors	640.71		
Brakes	14.90		
Chassis	18.90		
Fluids ICEV and EV	6.08		
Vehicle interior and exterior	289.22		
Tyres and wheels	96.57		
Total	1066.38		
Engine (ICEV)		207.12	
Fluids (ICEV only)		6.08	
Other ICEV powertrain		112.27	
ICEV transmission		63.11	
ICEV battery		20.04	
Total		408.61	
Car weight			1474.99

Table 6. The simplified material composition of a generic vehicle (ICEV = internal combustion engine vehicle, EV = electric vehicle) and Tesla Model S 85. The battery in this study; cathode: $LiMn_2O_4$, anode: graphite. (Sullivan *et al.* 1998, Hawkins *et al.* 2013, Gaines *et al.* 2011)

Material	ICEV (%)	EV (%)	Tesla Model S 85 (%)
Plastics:	**14.67**	**10.62**	**9.97**
Polyethylene	1.34	0.99	0.86
Polypropylene	6.87	4.21	8.20
Polystyrene	2.81	2.45	0.83
Polyethylene terephthalate	2.42	1.96	0.07
Polyvinylchloride	1.24	1.00	0.00
Metals (non-ferrous):	**9.03**	**30.12**	**32.26**
Aluminum	6.02	17.72	18.24
Copper	3.02	12.41	14.01
Metals (ferrous):	**66.42**	**43.19**	**37.51**
Pig iron	1.98	0.28	0.24
Cast iron	10.85	0.31	0.27
Steel RR	52.25	40.99	36.46
Steel OK	1.34	1.61	0.54
Fluids:	**1.18**	**3.80**	**6.49**
Lubricating oil	0.58	0.07	0.06
Refrigerant	0.33	0.20	0.17
Water	0.00	0.00	0.00
Other materials:	**0.27**	**3.54**	**6.26**
Various plastics	8.70	12.27	13.78
Adhesives	2.78	2.26	1.96
Minerals (clay)	0.33	1.26	1.58
Glass	0.49	0.20	0.17
Wood	2.61	2.31	2.01
Rubber (not tyre)	0.00	1.54	1.34
Rubber (tyre)	0.83	0.58	0.51
Sulphuric acid	1.51	1.23	1.07
Lithium	0.14	0.02	0.02
Graphite	0.00	0.20	0.36

Table 7. The simplified material composition of the studied cars.

Material	Tesla Model S 85 (kg)	Passat 1.4 TSI flexifuel (kg)	Passat 1.4 TSI gasoline (kg)	Passat 2.0 TDI NExBTL (waste) (kg)	Passat 2.0 TDI NExBTL (kg)
Plastics:	210.15	218.25	218.25	216.34	216.34
Polyethylene PE	18.18	19.95	19.95	19.78	19.78
Polypropylene PP	172.89	102.19	102.19	101.30	101.30
Polystyrene PS	17.51	41.74	41.74	41.38	41.38
Polyethyleneterephthalate PET	1.57	35.95	35.95	35.63	35.63
Polyvinylchloride PVC	0.00	18.41	18.41	18.25	18.25
Metals (non-ferrous):	679.95	134.43	134.43	133.26	133.26
Aluminum	384.55	89.55	89.55	88.77	88.77
Copper	295.40	44.88	44.88	44.49	44.49
Metals (ferrous):	790.65	988.37	988.37	979.73	979.73
Pig iron	5.15	29.49	29.49	29.23	29.23
Cast iron	5.69	161.38	161.38	159.97	159.97
Steel RR	768.49	777.49	777.49	770.70	770.70
Steel OK	11.32	20.01	20.01	19.83	19.83
Fluids:	136.83	17.56	17.56	17.41	17.41
Lubricating oil	1.23	8.59	8.59	8.52	8.52
Refrigerant	3.68	4.91	4.91	4.87	4.87
Water	131.93	4.06	4.06	4.02	4.02
Other materials:	290.41	129.39	129.39	128.26	128.26
Various plastics	41.37	41.44	41.44	41.08	41.08
Adhesives	33.28	4.93	4.93	4.89	4.89
Minerals (clay)	3.68	7.24	7.24	7.18	7.18
Glass	42.31	38.89	38.89	38.55	38.55
Wood	28.19	0.00	0.00	0.00	0.00
Rubber (not tyre)	10.65	12.31	12.31	12.21	12.21
Rubber (tyre)	22.47	22.51	22.51	22.31	22.31
Sulphuric acid	0.44	2.06	2.06	2.04	2.04
Lithium	7.56	0.00	0.00	0.00	0.00
Graphite	100.46	0.00	0.00	0.00	0.00
	2108.00	1488.00	1488.00	1475.00	1475.00

Table 8. Technical specifications of the studied cars (model years 2015 and 2016).

	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Power, kW	278	110	110	110	110
Fuel	Electricity	E85	Petrol	Diesel tallow NExBTL	Diesel tallow NExBTL
Fuel consumption, L/100 km	-	7.55	5.50	4.00	4.00
Electricity consumption, kWh/km	0.24	-	-	-	-
Curb weight, kg	2108	1488	1488	1475	1475
Volume of engine, cm3	-	1395	1395	1968	1968
Transmission	1-speed fixed gear	Automatic	Manual	Manual	Manual

Table 9. The electricity generation mix (%) of the United States in 2014. Exports and imports are not taken into account. (EIA 2015)

Electricity source	**USA Share (%)**	**CHP (%)**
Natural gas	27.81	9.60
Coal	38.64	2.04
Petroleum	0.74	14.30
Wood (biomass)	1.56	54.46
Waste	0.33	52.43
Hydro electricity	6.19	
Wind	4.44	
Nuclear	19.47	
Solar PV	0.43	
Geothermal	0.39	
Electricity mix	100.00	

NEXBTL BIODIESEL

NExBTL biodiesel can be produced via hydrogenation and isomerization of vegetable oils, tall oil fatty acids and animal fats. Hydrogenation and deoxygenation yields *n*-paraffins with high cetane number but poor cold properties. Incomplete skeletal isomerisation yields a mixture of *n*-paraffins and *i*-paraffins with high enough cetane number and good cold properties.

Currently the predominant raw material for NExBTL is palm oil or lower quality residue or waste palm oil. Unknown amounts of tallow are used as a raw material for the production of NExBTL biodiesel. In this report, the life-cycle analysis is made for NExBTL using mutton and lamb tallow raw material from Australia. The detailed process energy, raw material and product data of Neste Oil (2013) from its Singapore plant were used in the analysis.

The sheep tallow to Singapore plant comes from Australia and the NExBTL biodiesel product is exported from Singapore to California. A NExBTL molecule travels about 20 000 km from tallow production site to California fuel station. The electricity needed in the NExBTL process comes from the grid. The Singapore electricity mix has been reported by Energy Market Authority (2015).

The resource use and environmental impacts of NExBTL biodiesel depend heavily on if the raw material tallow is considered as waste or side product. Both of these cases are reported here. Because tallow has a market price, it seems more appropriate to consider tallow as a side product from lamb meat or mutton production.

Sheep meat environmental impacts (Biswas *et al*. 2010) come mostly from nitrous oxide and methane emissions (agriculture, excrement and belching). These emissions were allocated to lamb and mutton tallow using the relative market prices of lamb meat, mutton and tallow in 2012–2014. During this period, tallow price was in average 77% lower than the average price of lamb meat and mutton (Sheep Central 2015, MLA 2014). Thus, 22.9% of sheep meat energy demand and emissions were allocated to tallow.

To carry out life cycle calculations for palm oil raw material is very analogous to tallow raw material. Palm oil production has numerous negative impacts on environment from deforestation to the loss of natural habitat, from huge carbon emissions resulting from burning tropical peatlands to methane emissions of waste ponds. Some of these impacts are direct, some are indirect caused by increased palm oil demand. Palm oil to NExBTL case is not reported here.

Table 10. NExBTL process material and energy balances at Singapore plant. The raw material in this analysis is lamb and mutton tallow. (Neste Oil 2013)

	Material (kg)	Energy (MJ)	Energy (MJ per MJ NExBTL)
INPUT			
Tallow	1.210	46.585	1.086
Tallow after pretreatment	1.180	45.430	1.059
Hydrogen (from steam reforming of natural gas and recycled hydrocarbons)	0.038	4.558	0.106
Electricity (Singapore grid)		0.382	0.009
OUTPUT			
NExBTL biodiesel	1.000	42.910	1.000
Bionaphtha	0.005	0.231	0.005
Biopropane	0.060	2.782	0.065

Table 11. NExBTL process net energy balance at Singapore plant. The raw material in this analysis is lamb and mutton tallow. This energy balance is valid, if tallow is considered as waste. (Neste Oil 2013)

	Net energy (MJ)	Net energy (MJ per MJ NExBTL)
INPUT		
Tallow	46.585	1.0856
Natural gas	4.145	0.0966
Coal	0.046	0.0011
Petroleum	0.011	0.0003
OUTPUT		
NExBTL biodiesel	42.910	1.0000

Table 12. NExBTL product net energy balance at Singapore plant taking into account tallow production from sheep meat. This energy balance is valid, if tallow is considered as side product of sheep meat production. (Neste Oil 2013, Biswas *et al*. 2010)

	Process (net energy) (MJ)	Tallow production (energy) (MJ)	Tallow production (emissions) (g)	Tallow cargo (km)	NExBTL cargo (km)
Tallow	46.585				
Natural gas	4.145	0.069			
Coal	0.046	0.00003			
Petroleum	0.011	0.035			
Methane (CH_4)			1.412		
Nitrous oxide (N_2O)			0.019		
Large cargo vessel				7318	12352
Heavy truck with trailer				1000	530

CORN ETHANOL AND GASOLINE

Refining gasoline from petroleum is an established and relatively efficient process. However, the easiness and efficiency rely on the quality of crude. The energy demand of refining conventional petroleum to reformulated gasoline has been reported by Wang (1999).

In corn ethanol's life cycle assessment, the following energy input and product allocation data were used: Shapouri *et al*. (2002), Pimentel and Patzek (2005), Graboski (2001), Lorenz and Morris (1995), Kim and Dale (2005), Marland and Turhollow (1991) and Hammerschlag (2006). Nitrous oxide emissions from farming have been reported by Kaliyan *et al*. (2013).

Table 13 gives the energy inputs of processing 1 L and 1 MJ of gasoline from conventional petroleum, ethanol from corn and NExBTL biodiesel from tallow.

Table 13. The energy inputs of processing 1 L and 1 MJ of gasoline from conventional petroleum, ethanol from corn and NExBTL biodiesel from tallow, including the energy content of the fuel (Wang 1999, Shapouri *et al*. 2002, Pimentel and Patzek 2005, Graboski 2001, Lorenz and Morris 1995, Kim and Dale 2005, Marland and Turhollow 1991, Hammerschlag 2006, Neste Oil 2013, Biswas *et al*. 2010). Also the global warming potential (GWP) of the fuels is given.

	Petroleum to gasoline		Corn ethanol		NExBTL (tallow is waste)		NExBTL (tallow is side product)	
	MJ per L	MJ per MJ	MJ per L	MJ per MJ	MJ per L	MJ per MJ	MJ per L	MJ per MJ
Petroleum	39.580	1.210	2.162	0.102	2.174	0.060	2.259	0.063
Natural gas	0.428	0.013	13.965	0.656	4.091	0.114	4.158	0.116
Coal	0.018	0.001	1.968	0.093	0.085	0.002	0.113	0.003
Lignite	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hydro power	0.008	0.000	0.123	0.006	0.001	0.000	0.001	0.000
Nuclear power	0.010	0.000	0.320	0.015	0.009	0.000	0.009	0.000
Wind power on-shore	0.001	0.000	0.045	0.002	0.000	0.000	0.000	0.000
Solar PV	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000
Biomass	0.000	0.000	21.275	1.000	35.940	1.000	35.940	1.000
Total input	40.054	1.225	39.864	1.874	42.300	1.177	42.481	1.182
Primary energy input	40.052	1.225	18.537	0.871	6.360	0.177	6.541	0.182
GWP, g CO_2e	2826	86	1485	70	434	12	1724	48

ABOUT ELECTRIC CARS

Electric vehicles store electricity in batteries, which have a limited storage capacity and must be replenished by plugging the vehicle into a recharging unit. The electricity comes from the grid or from decentralized renewable sources such as solar or wind energy. The cost of recharging an electric vehicle is very small, but an electric vehicle is still very expensive. Most electric vehicles have a range of only 100–160 km before recharging is needed.[2]

The electric car is not a new invention. In 1888 there were 24 small batteries in the early electric car of Magnus Volk and Moritz Immisch, enough to give a driving range of 80 km, not much less than today's electric vehicles.[3] In the turn of 20th century, electric cars dominated the emerging U.S. automotive market. In 1903 there were 36 recharging sites in Boston alone.

[2] The energy factbook: a resource for South Carolina, South Carolina Energy Office, September, 2003.

[3] Smil Vaclav, Energy at the Crossroads: Global Perspectives and Uncertainties, "MIT Press, Cambridge, MA", 2003.

Cars equipped with internal combustion engines replaced electric cars in the first decade of the 20th century. More than a century after the first electric cars, oil shocks, global warming and urban pollution have prompted renewed interest in electric vehicles.

In 1995 the California Energy Commission decided that by 1998 two percent of all new vehicles sold in California will have to be electric and that the share of zero-emission vehicles (ZEVs) will rise to 10% of the state's car sales by the year 2003.[3] However, no commercial electric cars were sold during the late 1990s. The ZEV refers to a vehicle with no emission of urban pollutants: CO, NO_x, SO_2, particulates or unburned hydrocarbons.[4] This regulation does not cover greenhouse gases like carbon dioxide, and the objective has always been clean air and personal health.

The first years of the 21st century have been better for electric cars. Environmental regulations have been tightening worldwide and new innovations and materials have made it possible to reduce the production costs.[5]

The internal combustion engine is not an efficient energy converter. Only a small fraction, less than 25% of the energy in gasoline, is available for propulsion. An electric vehicle running on batteries is a much better energy-conversion device. Starting with 11% loss in battery charge, 6% loss in discharge, and another 11% loss in moving the energy from the battery to the wheels, one ends up with 74% conversion efficiency from grid electricity to wheels.[6]

On the other hand, burning coal and other fossil fuels to generate electricity is an inherently inefficient process. The electricity generation efficiency from underground coal to electricity is typically less than 30%, while the well-to-tank efficiency from crude oil to gasoline or diesel is about 85%. Depending on how the electricity is generated for electric vehicles, electric cars either decrease or increase overall emissions. Certainly they cut local emissions.

CHALLENGES AND OPPORTUNITIES OF ELECTRIC VEHICLES

For an electric vehicle, the maintenance expenses (except changing the whole battery pack) and fuel costs are low. Also there are no tailpipe emissions. In many cities, electric vehicle owners are allowed to travel in bus or carpool lanes, they have free access to the congestion charge zones, they are exempt from public parking fees and they may be eligible for tax credits.

[4] Britton Ron, The coming of the hydrogen age, The Chemical Engineer, November, 2004.

[5] Sato Yutaka, Drive to cooperate, ICIS Chemical Business October 18-24, 2010.

[6] Abu-Rub H., Malinowski M., Al-Haddad K., Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications, John Wiley & Sons, 2014.

Electric vehicles have two key limitations:[7]

- Vehicle range.
- Long Battery recharging times.

The electric vehicles are also pricey and the battery packs endure only a limited number of recharging cycles (about a thousand cycles). The battery pack may not last the life of the car.

In hybrid electric vehicles, batteries store energy generated during braking, supply energy during startup and assist the engine during acceleration.[8] Plug-in hybrid electric vehicles allow the battery to be recharged by connection to the electrical grid when the car is parked. They avoid the two main problems of pure electric vehicles: they are not limited in range by the total amount of battery charge and they can be used also in long-distance trips without excessive recharging times.[9]

One big challenge for electric vehicles is that the conventional cars are every year more fuel-efficient releasing less greenhouse gases and air pollutants.

BATTERIES

The batteries of electric vehicles have limited capacity, with a range of about 100 km per charge. Extending the range can be achieved by improving the performance of batteries and by reducing the weight of vehicles.[5]

Lithium-ion batteries pack more energy per unit weight and volume than most other batteries, which is why they are preferred for laptops and mobile devices, even though they are more expensive than other batteries. In electric vehicles, battery packs are scaled up in capacity and used in modes that draw high power. They heat up, and since lithium batteries employ flammable solvents, there is the hazard of fire.[10]

With lithium-ion batteries there are more safety issues than for other electric vehicle battery options. Another major issue with lithium-ion batteries is the battery cost. Cost reduction can be achieved by making the batteries more efficient, increasing the battery life, using less lithium and getting rid of the cobalt.[11] In R&D departments, chemists try to solve these problems.

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[7] Forsberg Charles A., The hydrogen economy is coming – the question is where?, Chemical Engineering Progress, December, 2005.

[8] Kung Harold H., Taylor Kathleen C.", Expanding role of chemical engineers in transportation-motivated R&D, AIChE Journal, "Vol. 48, No. 11, pp. 2422-2425", 2002.

[9] Competing visions of a hydrogen economy, Chemical & Engineering News, August 22, 2005.

[10] Marikar Faruq, Assault with battery, ICIS Chemical Business Americas, February 16-22, 2009.

[11] O'Driscoll Cath, BASF to grow bigger on batteries, Chemistry & Industry, March 21, 2011.

ELECTRICITY GENERATION

Electricity generation has a low efficiency compared to conventional petroleum fuels production. If the electricity is produced from coal or other carbon intensive sources, there is potential for increased CO_2 emissions.

If the electricity is generated by renewable technologies with very low life-cycle emissions, such as wind, solar or geothermal power, then electric vehicles curb greenhouse gas emissions.

LIFE-CYCLE IMPACTS

Environmental impacts of electric vehicles should be compared with those of conventional vehicles on the basis of emissions over the entire fuel-cycle (well-to-wheels). For conventional vehicles, the fuel-cycle emissions include emissions that result from extracting and processing crude oil as well as tailpipe emissions. For electric vehicles, emissions produced by power plants providing the electricity for charging the batteries are taken into consideration. A thorough life-cycle analysis takes also into account the car manufacturing, maintenance and end-of-life stages.

Former U.S. senator Richard Lugar and CIA chief James Woolsey[12] stated in 1999: "For electric vehicles it is both good and bad that electricity is commonly produced by burning fossil fuels at another location. The local air quality is improved, but total carbon dioxide emissions are not curtailed."

Urban air pollution is a serious issue in the world. Massive amounts of carbon dioxide, carbon monoxide, sulphur dioxide, nitrogen dioxide, aromatic hydrocarbons and particulates are released from internal combustion engine vehicles every day, threatening people's health and the environment.

Electric vehicles have the advantage that they produce no air pollution at the point of use. If the electricity is generated in a distant place, electric cars are a means of switching the location of emissions. Electric vehicles can move emissions to less crowded and less polluted locations. Centralized electric generation plants may also cause fewer emissions per kilometer than the internal combustion engine vehicles do.[13]

GLOBAL WARMING POTENTIAL (GWP)

Energy use, manufacturing processes, agriculture and other activities release greenhouse gases to atmosphere, thus strengthening the greenhouse effect and warming up the planet.

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[12] Lugar Richard G., Woolsey R. James, The new petroleum, Foreign Affairs, January–February, 1999.

[13] Lave Lester B., Hendrickson Chris T., McMichael Francis Clay, Environmental implications of electric cars, Science, Vol. 268, May 19, 1995.

Although the energy generation processes may be zero emission – such as nuclear electricity, photovoltaic and wind electricity – construction, maintenance and fuel processing cause greenhouse gas emissions.

In this analysis, the following greenhouse gases are taken into account: carbon dioxide, methane, nitrous oxide (N_2O), carbon monoxide and Freons. The global warming effect of aerosols and carbon black is location and time dependent and difficult to quantify, thus they are not included in calculations.

For example, uranium industry has used Freon CFC-114 in the enrichment process and this process is a significant source of Freon emissions. CFC-114 has a global warming impact 10,000 times higher than carbon dioxide. In the analysis, all the emissions are converted to carbon dioxide equivalents and summed together.

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

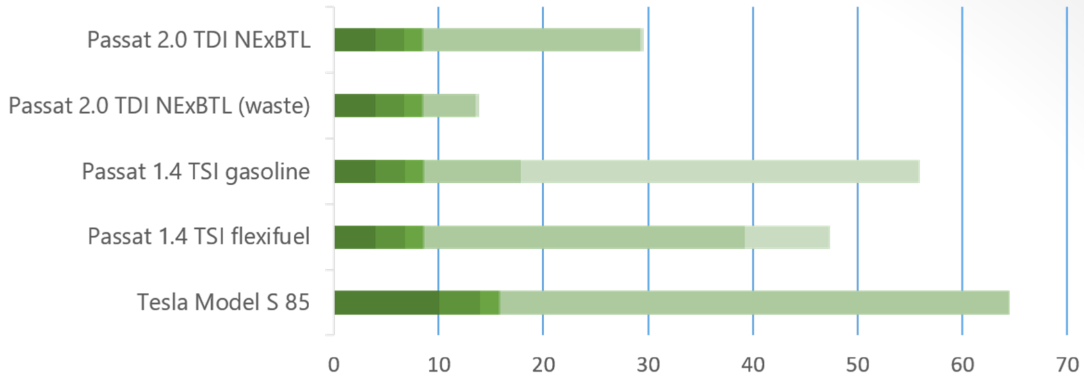
The uncertainties of global warming potential are related to other gases than carbon dioxide (the typical variability is ±35% relative to the CO_2 reference) and aerosols.

Global warming potential is considered highly reliable.

Life-cycle greenhouse gas emissions in different electricity generation stages (well-to-fuel and fuel-to-electricity) and the contributions of various gases to global warming are presented in figures below. The gases are:

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Others
    - Carbon monoxide (CO)
    - CFC compounds
    - HCFC compounds
    - Dichloromethane

The other life-cycle environmental impacts are divided in very much a similar way in different electricity generation stages.

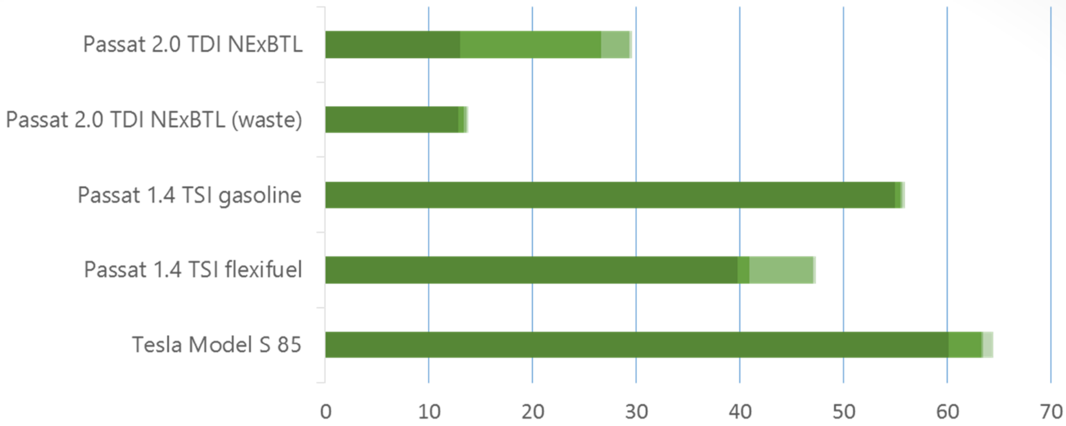


	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	1.01E+01	4.01E+00	4.01E+00	3.97E+00	3.97E+00
Manufacturing	3.92E+00	2.77E+00	2.77E+00	2.74E+00	2.74E+00
Maintenance	1.70E+00	1.70E+00	1.70E+00	1.70E+00	1.70E+00
End-of-life	2.02E-01	1.43E-01	1.43E-01	1.41E-01	1.41E-01
Fuel/electricity production	4.86E+01	3.06E+01	9.24E+00	4.96E+00	2.07E+01
Tail pipe	0.00E+00	8.16E+00	3.81E+01	3.29E-01	3.29E-01

Car materials Manufacturing Maintenance End-of-life Fuel/electricity production Tail pipe

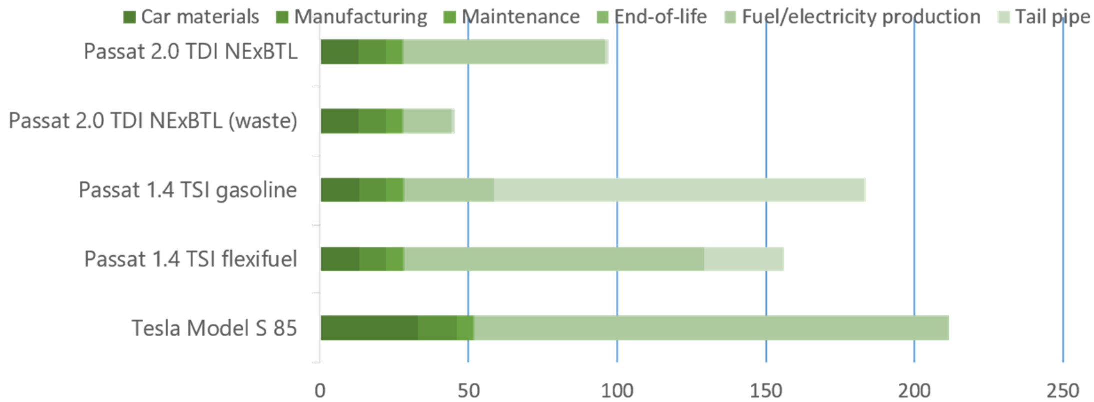
Unit: t CO_2e

Note: If NExBTL is not considered as waste, the agricultural emissions are not counted such as methane emissions caused by belching of the sheep. The USA electricity mix is carbon intensive and thus the electric vehicle life-cycle carbon dioxide emissions are high. Electric vehicles are heavier and they contain more exotic materials. Consequently emissions from the premanufacturing and manufacturing stages are higher.



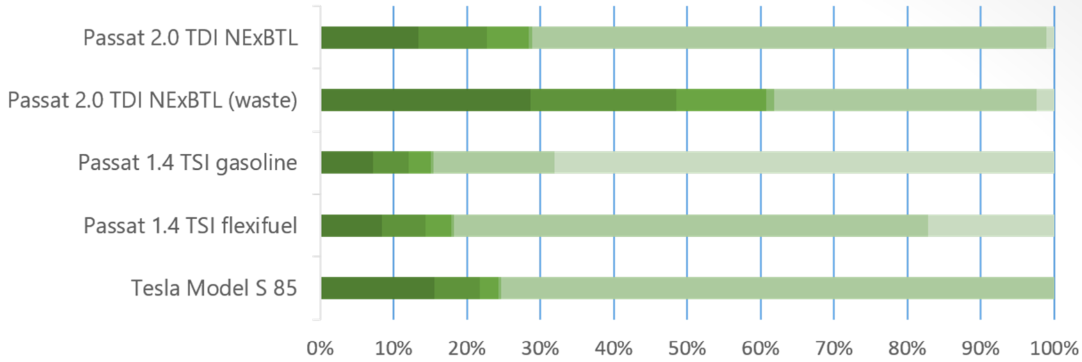
	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
CO2	6.02E+01	3.98E+01	5.50E+01	1.28E+01	1.30E+01
CH4	3.09E+00	1.10E+00	5.18E-01	5.81E-01	1.36E+01
N2O	2.21E-01	6.20E+00	1.53E-01	1.98E-01	2.77E+00
Others	9.80E-01	2.67E-01	2.55E-01	2.61E-01	2.61E-01

Unit: t CO_2e



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	3.30E+01	1.32E+01	1.32E+01	1.30E+01	1.30E+01
Manufacturing	1.29E+01	9.08E+00	9.08E+00	9.00E+00	9.00E+00
Maintenance	5.57E+00	5.57E+00	5.57E+00	5.57E+00	5.57E+00
End-of-life	6.64E-01	4.68E-01	4.68E-01	4.64E-01	4.64E-01
Fuel/electricity production	1.59E+02	1.01E+02	3.03E+01	1.63E+01	6.79E+01
Tail pipe	0.00E+00	2.68E+01	1.25E+02	1.08E+00	1.08E+00

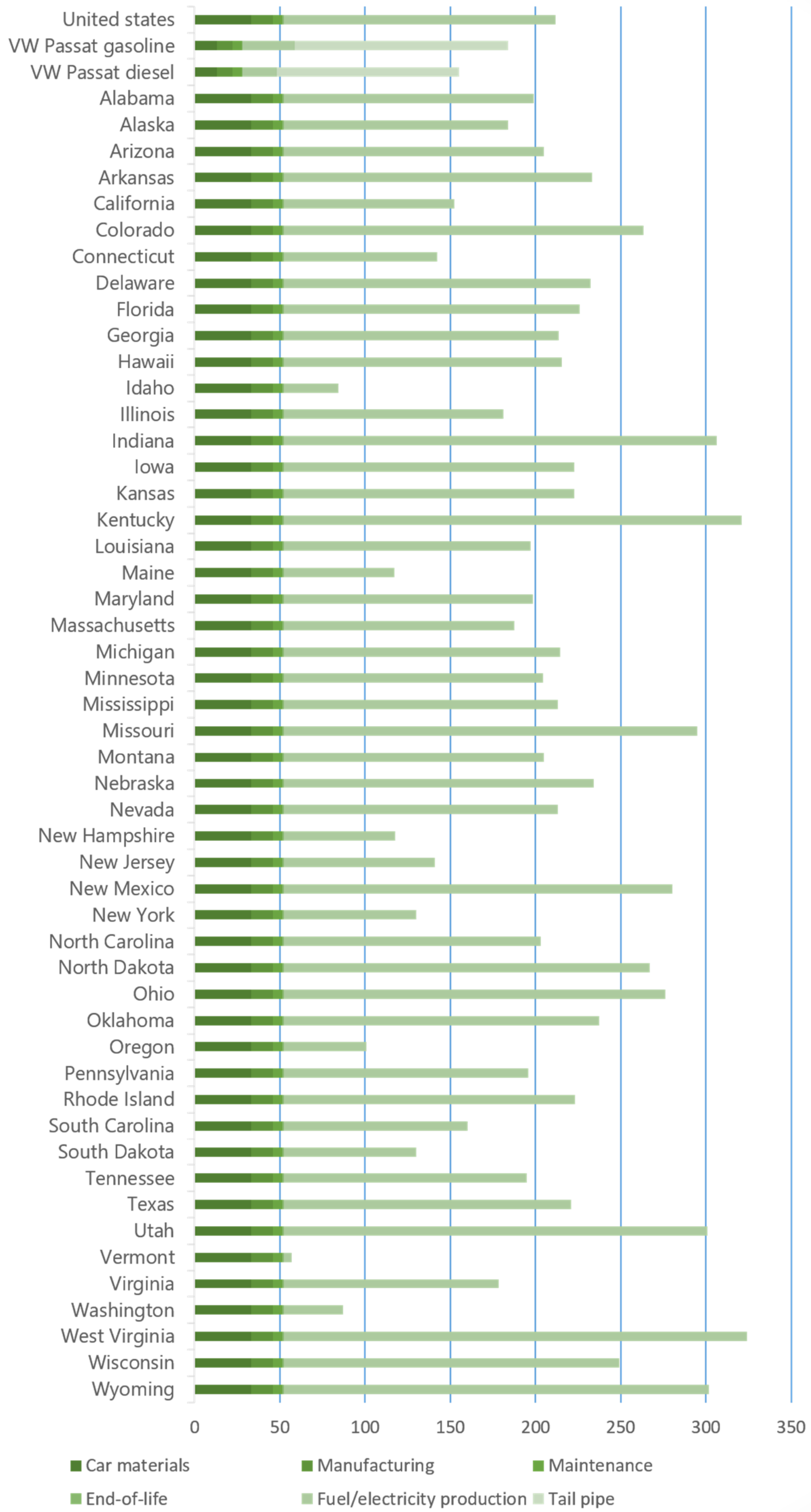
Unit: g CO_2e/km



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
■ Car materials	15.61%	8.45%	7.16%	28.70%	13.40%
■ Manufacturing	6.08%	5.84%	4.94%	19.80%	9.28%
■ Maintenance	2.63%	3.58%	3.03%	12.30%	5.74%
■ End-of-life	0.31%	0.30%	0.26%	1.02%	0.48%
■ Fuel/electricity production	75.37%	64.60%	16.50%	35.80%	70.00%
■ Tail pipe	0.00%	17.20%	68.10%	2.37%	1.11%

■ Car materials ■ Manufacturing ■ Maintenance ■ End-of-life ■ Fuel/electricity production ■ Tail pipe

Unit: CO_2e-%


United states
VW Passat gasoline
VW Passat diesel
Alabama
Alaska
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
Florida
Georgia
Hawaii
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
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Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
0
50
100
150
200
250
300
350
Car materials
Manufacturing
Maintenance
End-of-life
Fuel/electricity production
Tail pipe

Unit: g CO_2e/km, Tesla S Model S in different U.S. states

Note: in 39 of the 50 states, the carbon footprint of Tesla Model S is higher than for equal-size diesel car.

OZONE DEPLETION POTENTIAL (ODP)

The ozone layer in the stratosphere is an essential component of the Earth's atmosphere. It protects humans, animals and plants from damaging shortwave ultraviolet (UV) radiation. Ozone is produced in the upper stratosphere by the interaction of shortwave solar UV radiation with oxygen. It is destroyed by reactions with certain ozone-depleting substances in the presence of somewhat longer wavelength UV radiation.[14]

The dynamic balance between production and destruction determines the concentration and total amount of ozone in the stratosphere. Anthropogenic emissions of ozone depleting substances that contain chlorine and bromine disturb this balance.

Ozone layer depletion is caused by anthropogenic emissions of:

- Chlorofluorocarbons (CFCs)
- Carbon tetrachloride
- Methyl chloroform
- Halons
- Hydrochlorofluorocarbons (HCFCs)
- Hydrobromofluorocarbons (HBFCs)
- Methyl bromide (CH_3Br)
- Nitrous oxide (N_2O)

These substances are used as solvents, refrigerants, foamblowing agents, degreasing agents, aerosol propellants, fire extinguishers (halons) and agricultural pesticides (CH_3Br). According to new research, nitrous oxide is today top ozone-layer damaging emission and this is projected to remain the case for the rest of this century.[15,16]

These substances are used as solvents, refrigerants, foamblowing agents, degreasing agents, aerosol propellants, fire extinguishers (halons) and agricultural pesticides (CH_3Br).

ODP is expressed as CFC-11-equivalent, g CFC-11-eq.

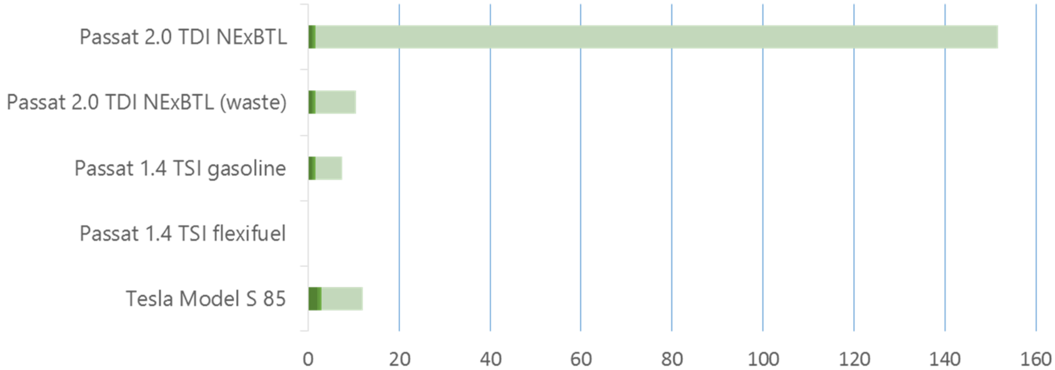
[14] Velders Guus, Stratospheric ozone depletion, Europe's environment: the third assessment, Environmental assessment report No 10, European Environment Agency, 2002.

[15] Ravishankara A.R., Daniel J.S., Portmann R.W., Nitrous oxide (N_2O): the dominant ozone-depleting substance emitted in the 21st century, Science, Vol. 326, No. 5949, pp. 123–125, 2009.

[16] Nitrous oxide is now top ozone-layer damaging emission, European Commission DG ENV, News Alert Issue 178, December 2009.

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

Uncertainties exist in the observations and the models of the depletion of stratospheric ozone layer.



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	1.92E+00		8.02E-01	7.95E-01	7.95E-01
Manufacturing	7.26E-01		5.13E-01	5.08E-01	5.08E-01
Maintenance	2.40E-01		2.40E-01	2.40E-01	2.40E-01
End-of-life	3.24E-02		2.29E-02	2.27E-02	2.27E-02
Operation	9.17E+00		5.80E+00	8.96E+00	1.50E+02

Car materials Manufacturing Maintenance End-of-life Operation

Unit: g CFC-11-eq

Note: ODP was not calculated for corn ethanol. The high ODP of NExBTL is caused by agricultural nitrous oxide emissions.

ACIDIFICATION POTENTIAL (AP)

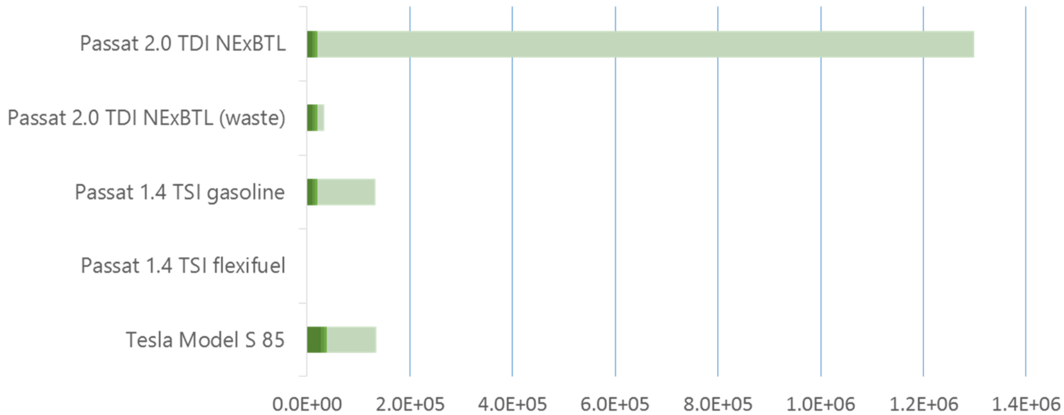
Incineration processes in energy generation and fuel combustion in transportation release sulphur oxide (SO_2) and nitric oxides (NO_x) into the atmosphere. Acid rain is produced when sulphur dioxide and nitrogen oxides are present in moisture in the atmosphere. Sulphur oxides and nitrous oxides are removed from the atmosphere through wet and dry deposition, causing acidification of water and soil. Ammonia, hydrogen sulphide and hydrogen chloride are also causing acidification of the environment.

Industrial processes, energy generation, transportation and agriculture are the most significant sources of acidification. Acidification affects human health, wildlife and vegetation and causes damage to anthropogenic structures and materials.

AP is expressed as SO_2 equivalent, g SO_2e.

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

Acidification potential is considered reliable.



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	2.62E+04		1.03E+04	1.02E+04	1.02E+04
Manufacturing	7.97E+03		5.62E+03	5.57E+03	5.57E+03
Maintenance	3.60E+03		3.60E+03	3.60E+03	3.60E+03
End-of-life	4.46E+02		3.15E+02	3.12E+02	3.12E+02
Operation	9.69E+04		1.14E+05	1.41E+04	1.28E+06

Car materials Manufacturing Maintenance End-of-life Operation

Unit: g SO_2e

Note: AP was not calculated for corn ethanol. The high AP of NExBTL is caused by agricultural nitrous oxide emissions.

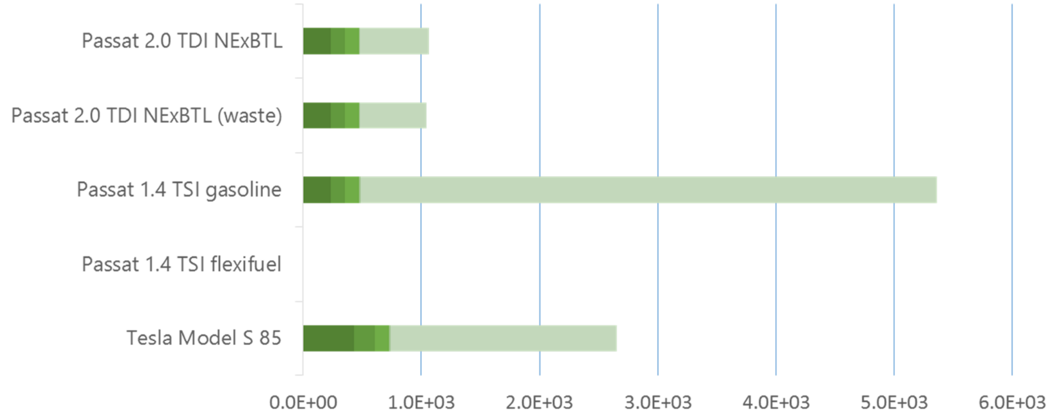
PHOTOCHEMICAL OZONE CREATION POTENTIAL (POCP)

Photochemical smog is formed when primary pollutants react with ultraviolet light to create a variety of toxic and reactive compounds. The two major primary pollutants, nitrogen oxides and VOCs (volatile organic compounds), combine to change in sunlight in a series of chemical reactions to create secondary pollutants. The secondary pollutant that causes the most concern is the ozone that forms at ground level.

Photochemical smog is harmful to human health, ecosystems, materials, vegetation and crops. Emissions that lead to photochemical smog are measured in g ethylene equivalents (C_2H_4e).

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

Photochemical ozone creation potential is a very coarse approximation of the actual phenomena. It has very low reliability.



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	4.32E+02		2.34E+02	2.32E+02	2.32E+02
Manufacturing	1.75E+02		1.23E+02	1.22E+02	1.22E+02
Maintenance	1.19E+02		1.19E+02	1.19E+02	1.19E+02
End-of-life	1.62E+01		1.14E+01	1.13E+01	1.13E+01
Operation	1.92E+03		4.87E+03	5.62E+02	5.78E+02

Car materials   Manufacturing   Maintenance   End-of-life   Operation

Unit: g ethylene-eq

Note: POCP was not calculated for corn ethanol.

AIR TOXICITY (AT)

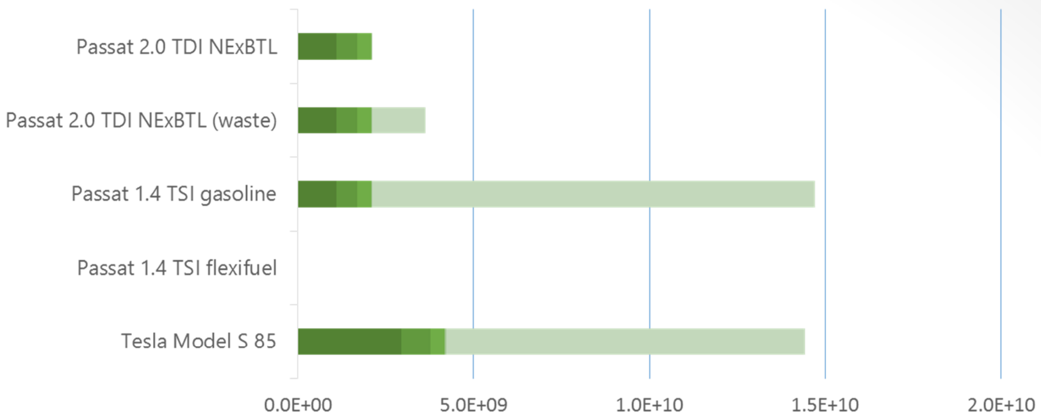
The air toxicity indicator (AT) is representing the air toxicity in a human environment, taking into account the usually accepted concentrations tolerated for several gases and the quantity released. The given indication corresponds to the air volume necessary to dilute "contaminated air".[17]

A gram of CO_2 requires 125 m^3 to dilute to an acceptable level while a gram of mercury requires 1.4 million m^3.

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

This method has limitations. Acceptable levels vary from country to country and are subject to public opinions and political decisions.

[17] EIME, Environmental Improvement Made Easy, Life cycle analysis and ecodesign software, Indicators manual, Bureau Veritas CODDE, July 2009.



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	2.93E+09		1.10E+09	1.10E+09	1.10E+09
Manufacturing	8.36E+08		5.90E+08	5.85E+08	5.85E+08
Maintenance	3.98E+08		3.98E+08	3.98E+08	3.98E+08
End-of-life	4.82E+07		3.40E+07	3.37E+07	3.37E+07
Operation	1.02E+10		1.26E+10	1.51E+09	1.71E-01

Car materials, Manufacturing, Maintenance, End-of-life, Operation

Unit: m^3 air

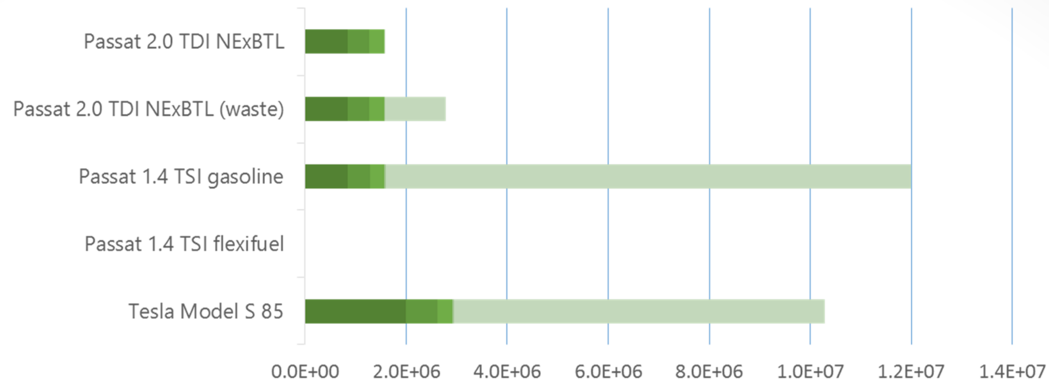
Note: AT was not calculated for corn ethanol.

WATER TOXICITY (WT)

The water toxicity indicator (WT) is representing the water toxicity. This indicator takes into account the usually accepted concentrations tolerated for several substances and the quantity released. The given indication corresponds to the water volume necessary to dilute "contaminated water".

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

Water toxicity indicator is reliable/very reliable.



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	2.00E+06		8.46E+05	8.38E+05	8.38E+05
Manufacturing	6.26E+05		4.42E+05	4.38E+05	4.38E+05
Maintenance	2.83E+05		2.83E+05	2.83E+05	2.83E+05
End-of-life	3.97E+04		2.80E+04	2.78E+04	2.78E+04
Operation	7.34E+06		1.04E+07	1.20E+06	2.54E-04

Car materials · Manufacturing · Maintenance · End-of-life · Operation

Unit: L water

Note: WT was not calculated for corn ethanol.

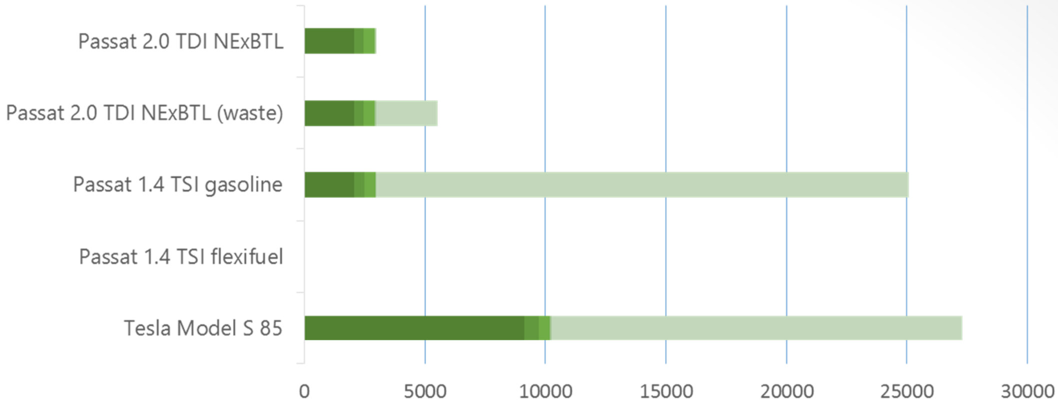
HAZARDOUS WASTE PRODUCTION (HWP)

Hazardous waste production (HWP) calculates the quantity of hazardous waste produced for a given product during its life cycle. It is expressed as kg hazardous waste.

In figure, the “Finland electricity” is the only one, in which there is considerable amount of waste incineration. This is why HWP is so high for “Finland electricity”.

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

Hazardous waste production indicator has low reliability.



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	9.13E+03		2.07E+03	2.05E+03	2.05E+03
Manufacturing	5.77E+02		4.07E+02	4.04E+02	4.04E+02
Maintenance	4.59E+02		4.59E+02	4.59E+02	4.59E+02
End-of-life	7.13E+01		5.03E+01	4.99E+01	4.99E+01
Operation	1.71E+04		2.21E+04	2.55E+03	7.03E-08

Car materials Manufacturing Maintenance End-of-life Operation

Unit: g

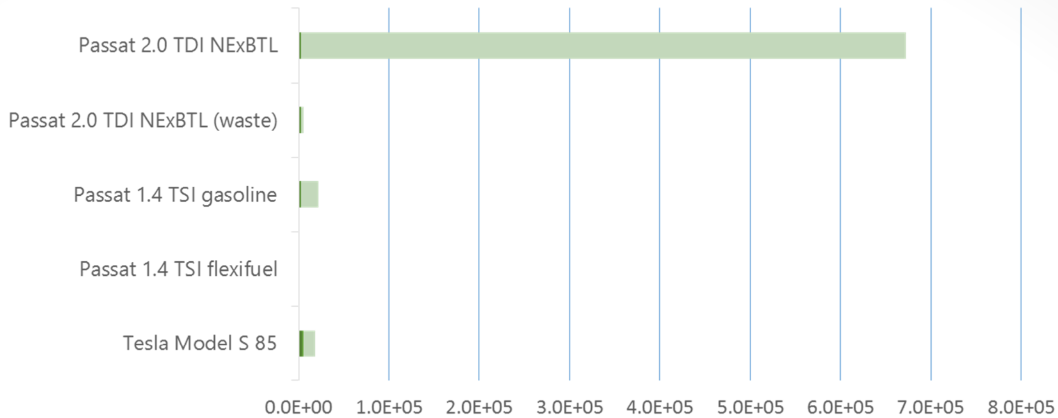
Note: HWP was not calculated for corn ethanol.

EUTROPHICATION POTENTIAL (EP)

Human activities – industry, energy generation, transportation, silviculture, agriculture and land use changes – have accelerated the rate and extent of eutrophication.

Emissions of ammonia, nitrates, nitrogen oxides and phosphorous to air or water all have an impact on eutrophication. The eutrophication potential is expressed using the reference unit, g PO4 equivalents.

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	3.74E+03		1.46E+03	1.45E+03	1.45E+03
Manufacturing	1.09E+03		7.69E+02	7.63E+02	7.63E+02
Maintenance	5.48E+02		5.48E+02	5.48E+02	5.48E+02
End-of-life	6.95E+01		4.90E+01	4.86E+01	4.86E+01
Operation	1.29E+04		1.88E+04	2.86E+03	6.70E+05

Car materials Manufacturing Maintenance End-of-life Operation

Unit: g PO4-eq

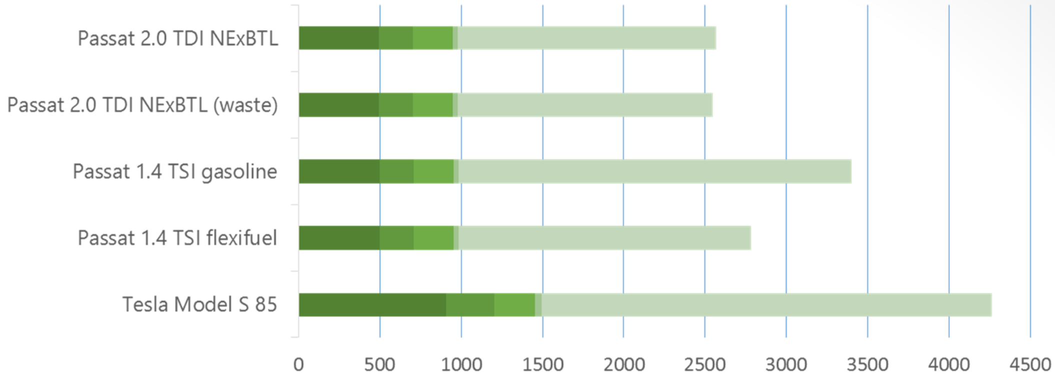
Note: EP was not calculated for corn ethanol.

Eutrophication potential has very low reliability.

EFFECT ON PARTICULATE EMISSIONS

Air pollution is caused by the presence of polluting substances such as fine particulates, sulphur compounds, nitrous oxides, volatile hydrocarbons and ground-level ozone. At high concentrations, these substances have effects on health and environment.

Burning fossil fuels and biomass has increased the concentrations of particulate matter in the air. Particulate matter is a mixture of solid particles and liquid droplets that are suspended in the air. Particulate matter is composed of a mixture of particles directly emitted into the air and particles formed in the air from the chemical transformation of gaseous pollutants (secondary particles). Particle size can range from 0.001 to 500 µm. Size of fine particulate is less than 2.5 µm.



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	9.08E+02	4.97E+02	4.97E+02	4.93E+02	4.93E+02
Manufacturing	2.97E+02	2.10E+02	2.10E+02	2.08E+02	2.08E+02
Maintenance	2.48E+02	2.48E+02	2.48E+02	2.48E+02	2.48E+02
End-of-life	3.97E+01	2.80E+01	2.80E+01	2.78E+01	2.78E+01
Operation	2.77E+03	1.80E+03	2.42E+03	1.57E+03	1.59E+03

■ Car materials ■ Manufacturing ■ Maintenance ■ End-of-life ■ Operation

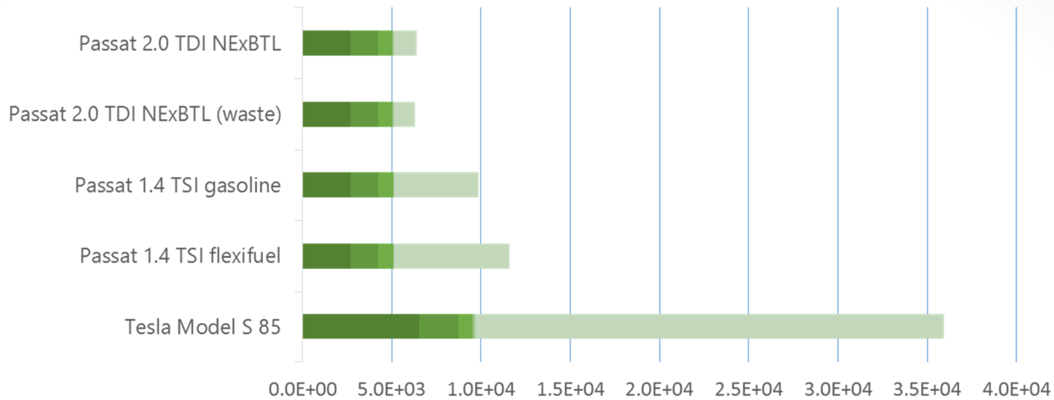
Unit: g

Note: High particulate emissions of an electric vehicle are caused by coal-fired electricity generation. These emissions are in operation stage. Local emissions of an electric vehicle are very low.

EFFECT ON SO_2 EMISSIONS

Fuels contain varying amounts of sulphur. In combustion processes sulphur is converted into sulphur dioxide (SO_2). In the atmosphere, sulphur dioxide reacts with moisture in the air to form sulphurous acid (H_2SO_3) or sulphuric acid (H_2SO_4) causing acid rain.

Sulphur dioxide emissions have adverse effects on human health, environment and anthropogenic constructions and materials. Sulphur dioxide emissions can be reduced by reducing energy consumption, switching to cleaner and more efficient energy production technologies and fuels and cleaning fuel gases.



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	6.53E+03	2.71E+03	2.71E+03	2.69E+03	2.69E+03
Manufacturing	2.22E+03	1.56E+03	1.56E+03	1.55E+03	1.55E+03
Maintenance	8.09E+02	8.09E+02	8.09E+02	8.09E+02	8.09E+02
End-of-life	1.11E+02	7.81E+01	7.81E+01	7.74E+01	7.74E+01
Operation	2.63E+04	6.45E+03	4.73E+03	1.19E+03	1.26E+03

Car materials   Manufacturing   Maintenance   End-of-life   Operation

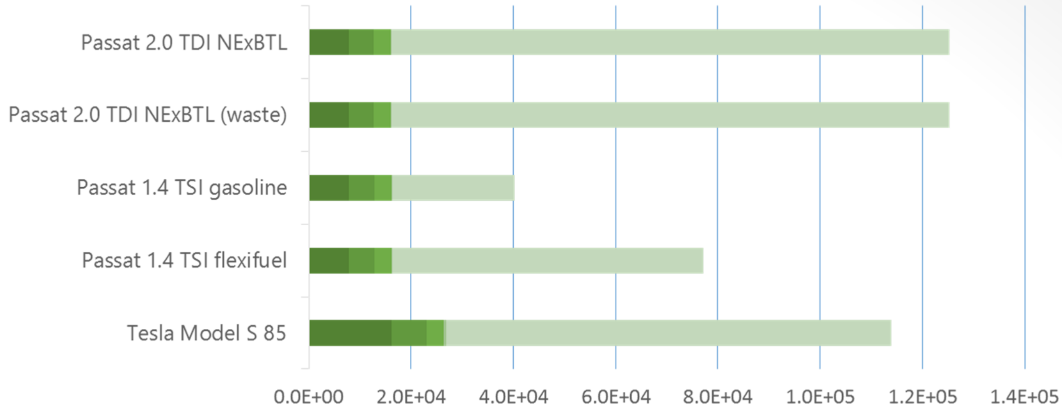
Unit: g

Note: High SO_2 emissions of an electric vehicle are caused by coal-fired electricity generation. These emissions are in operation stage. Local emissions of an electric vehicle are very low.

EFFECT ON NO_X EMISSIONS

In combustion processes, nitrogen of the fuel and also of the combustion air reacts to a certain amount with oxygen of the combustion air and forms nitric oxides (NO_x). The amount of nitric oxides formed can be affected by controlling the combustion process.

Nitric oxides form nitric acid when dissolved in atmospheric moisture, forming a component of acid rain and causing acidification and eutrophication of soils and waters.



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	1.61E+04	7.82E+03	7.82E+03	7.75E+03	7.75E+03
Manufacturing	7.02E+03	4.95E+03	4.95E+03	4.91E+03	4.91E+03
Maintenance	3.33E+03	3.33E+03	3.33E+03	3.33E+03	3.33E+03
End-of-life	3.78E+02	2.67E+02	2.67E+02	2.64E+02	2.64E+02
Operation	8.72E+04	6.08E+04	2.38E+04	1.09E+05	1.09E+05

Car materials Manufacturing Maintenance End-of-life Operation

Unit: g

Note: High NO_x emissions of an electric vehicle are caused fossil fuel--fired electricity generation. These emissions are in operation stage. Local emissions of an electric vehicle are very low.

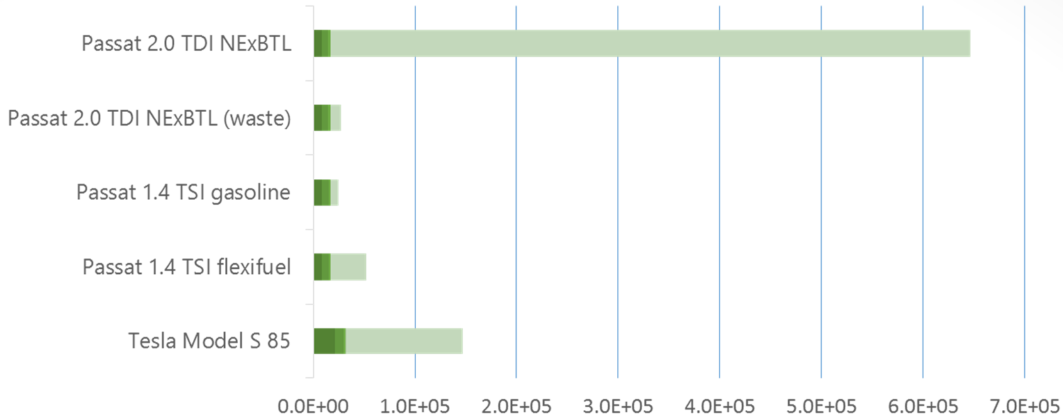
EFFECT ON METHANE EMISSIONS

Methane (CH_4) is emitted by natural sources such as wetlands. Globally, over 60% of total methane emissions come from human activities. Methane is emitted from natural gas systems and other industries, agriculture (such as the raising of livestock) and waste management activities.[18]

Gram for gram, the comparative impact of methane on climate change is 21 times greater than carbon dioxide over a 100-year period.[19] Methane emissions also affect ground-level ozone formation.

[18] Methane emissions, U.S. Environmental Protection Agency, Washington, DC, USA, [http://epa.gov/climatechange/ghgemissions/gases/ch4.html], 11.06.2014.

[19] Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H.L. (eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	2.11E+04	8.59E+03	8.59E+03	8.52E+03	8.52E+03
Manufacturing	8.93E+03	6.30E+03	6.30E+03	6.25E+03	6.25E+03
Maintenance	1.89E+03	1.89E+03	1.89E+03	1.89E+03	1.89E+03
End-of-life	1.74E+02	1.23E+02	1.23E+02	1.22E+02	1.22E+02
Operation	1.15E+05	3.48E+04	7.39E+03	1.07E+04	6.30E+05

Car materials ■ Manufacturing ■ Maintenance ■ End-of-life ■ Operation

Unit: g

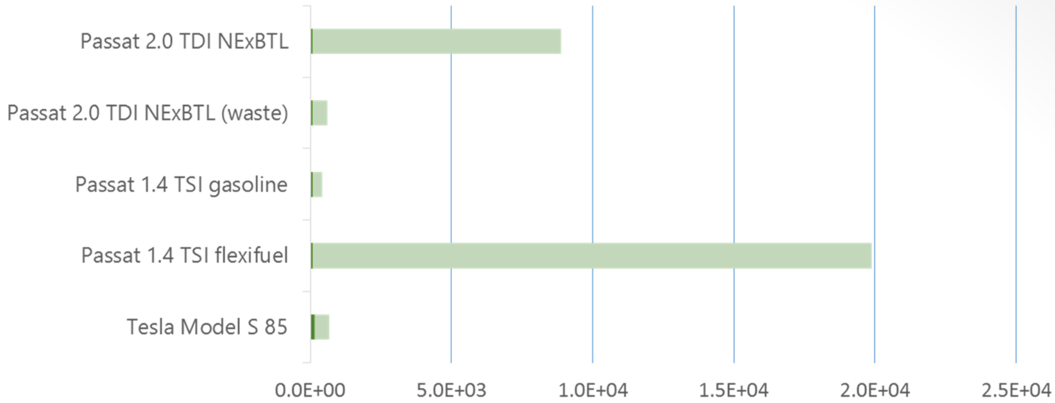
Note: High methane emissions of NExBTL are caused by sheep meat production emissions (excrement, belching).

EFFECT ON N_2O EMISSIONS

Nitrous oxide (N_2O) is a major greenhouse gas and air pollutant. Over a 100-year period, it has 298 times more impact per unit mass than carbon dioxide[19].

Human activities have more than doubled the global nitrogen inputs to ecosystems and accelerated the nitrogen cycle. Also N_2O emissions have increased substantially over the last century because of human actions. Human-related sources are responsible for 38% of total N_2O emissions.

Energy generation, transportation, agriculture and industry are major sources of N_2O. Nitric acid and adipic acid production are the main industrial sources of N_2O emissions.



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	1.11E+02	4.61E+01	4.61E+01	4.57E+01	4.57E+01
Manufacturing	3.97E+01	2.80E+01	2.80E+01	2.78E+01	2.78E+01
Maintenance	1.38E+01	1.38E+01	1.38E+01	1.38E+01	1.38E+01
End-of-life	1.82E+00	1.28E+00	1.28E+00	1.27E+00	1.27E+00
Operation	5.19E+02	1.98E+04	3.30E+02	5.26E+02	8.81E+03

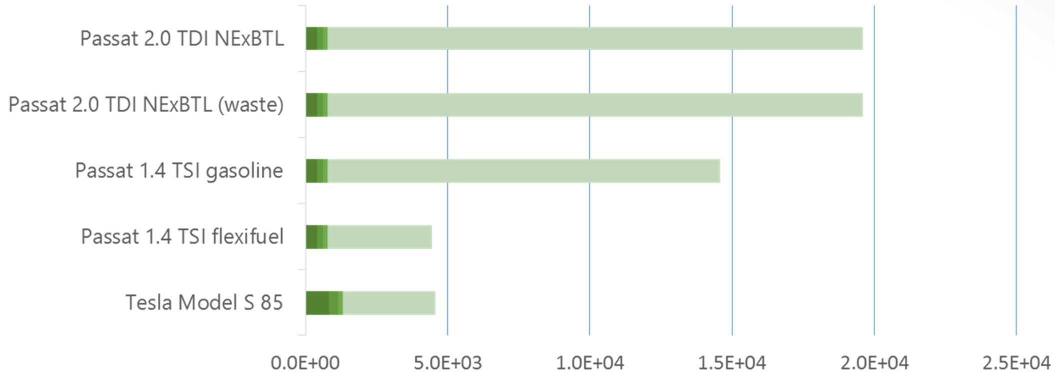
■ Car materials ■ Manufacturing ■ Maintenance ■ End-of-life ■ Operation

Unit: g

Note: Agricultural emissions cause the high nitrous oxide emissions of tallow biodiesel (NExBTL) and corn ethanol.

EFFECT ON NON-METHANE HYDROCARBON EMISSIONS

Hydrocarbon emissions affect both air and water quality. Many volatile reactive hydrocarbons facilitate the photochemical creation of ground-level ozone.



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	8.45E+02	4.07E+02	4.07E+02	4.03E+02	4.03E+02
Manufacturing	2.98E+02	2.11E+02	2.11E+02	2.09E+02	2.09E+02
Maintenance	1.60E+02	1.60E+02	1.60E+02	1.60E+02	1.60E+02
End-of-life	2.41E+01	1.70E+01	1.70E+01	1.69E+01	1.69E+01
Operation	3.24E+03	3.65E+03	1.38E+04	1.88E+04	1.88E+04

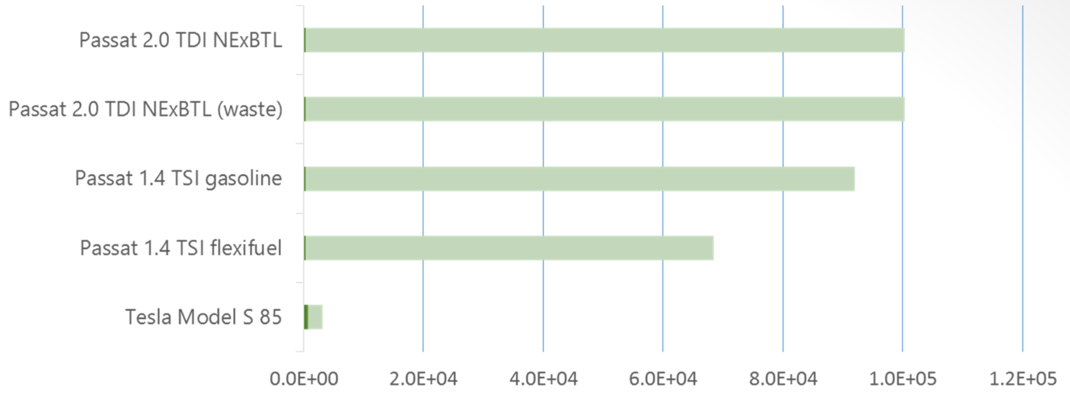
Car materials Manufacturing Maintenance End-of-life Operation

Unit: g

Note: High non-methane hydrocarbon emissions of NExBTL are related to the emissions of diesel combustion.

EFFECT ON CO EMISSIONS

Carbon monoxide (CO) is formed by incomplete combustion. It affects air quality and contributes to global warming. Carbon monoxide is 1.9 times more potent greenhouse gas than carbon dioxide (gram for gram).



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	5.47E+02	1.87E+02	1.87E+02	1.86E+02	1.86E+02
Manufacturing	1.34E+02	9.48E+01	9.48E+01	9.40E+01	9.40E+01
Maintenance	6.09E+01	6.09E+01	6.09E+01	6.09E+01	6.09E+01
End-of-life	8.14E+00	5.74E+00	5.74E+00	5.69E+00	5.69E+00
Operation	2.45E+03	6.81E+04	9.17E+04	1.00E+05	1.00E+05

Car materials Manufacturing Maintenance End-of-life Operation

Unit: g

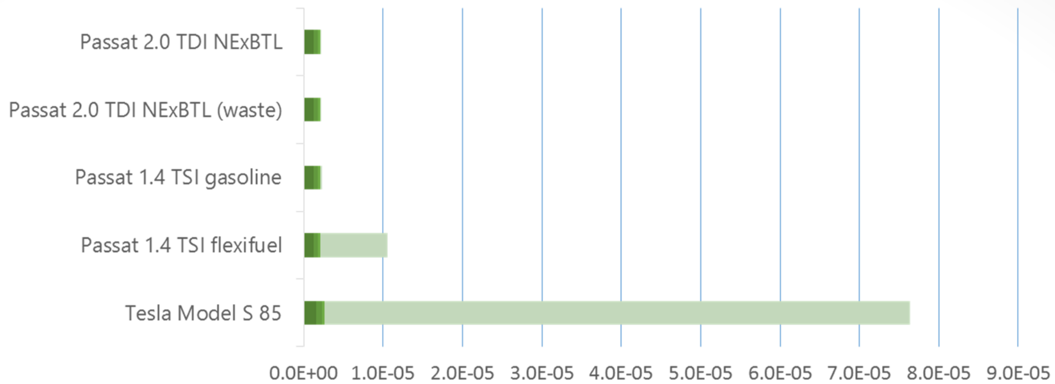
Note: High carbon monoxide emissions of NExBTL are related to the emissions of diesel combustion.

EFFECT ON CREATION OF HIGH-LEVEL RADIOACTIVE WASTE (HLW)

Radioactive waste is created at every step of the nuclear fuel cycle from uranium mining to nuclear fission in reactors. The high-level radioactive waste (HLW) is mostly spent nuclear fuel from commercial power plants.

High-level radioactive wastes are hazardous to humans and other life forms because of their high radiation levels that are capable of producing fatal doses during short periods of direct exposure.[20] The amount of time high-level waste remains dangerous is thousands to hundreds of thousands of years. Deep geological repositories are being considered for the long-term management of the high-level radioactive wastes.

[20] Radioactive Waste, The U.S. Nuclear Regulatory Commission, http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/radwaste.html, 11.06.2014.

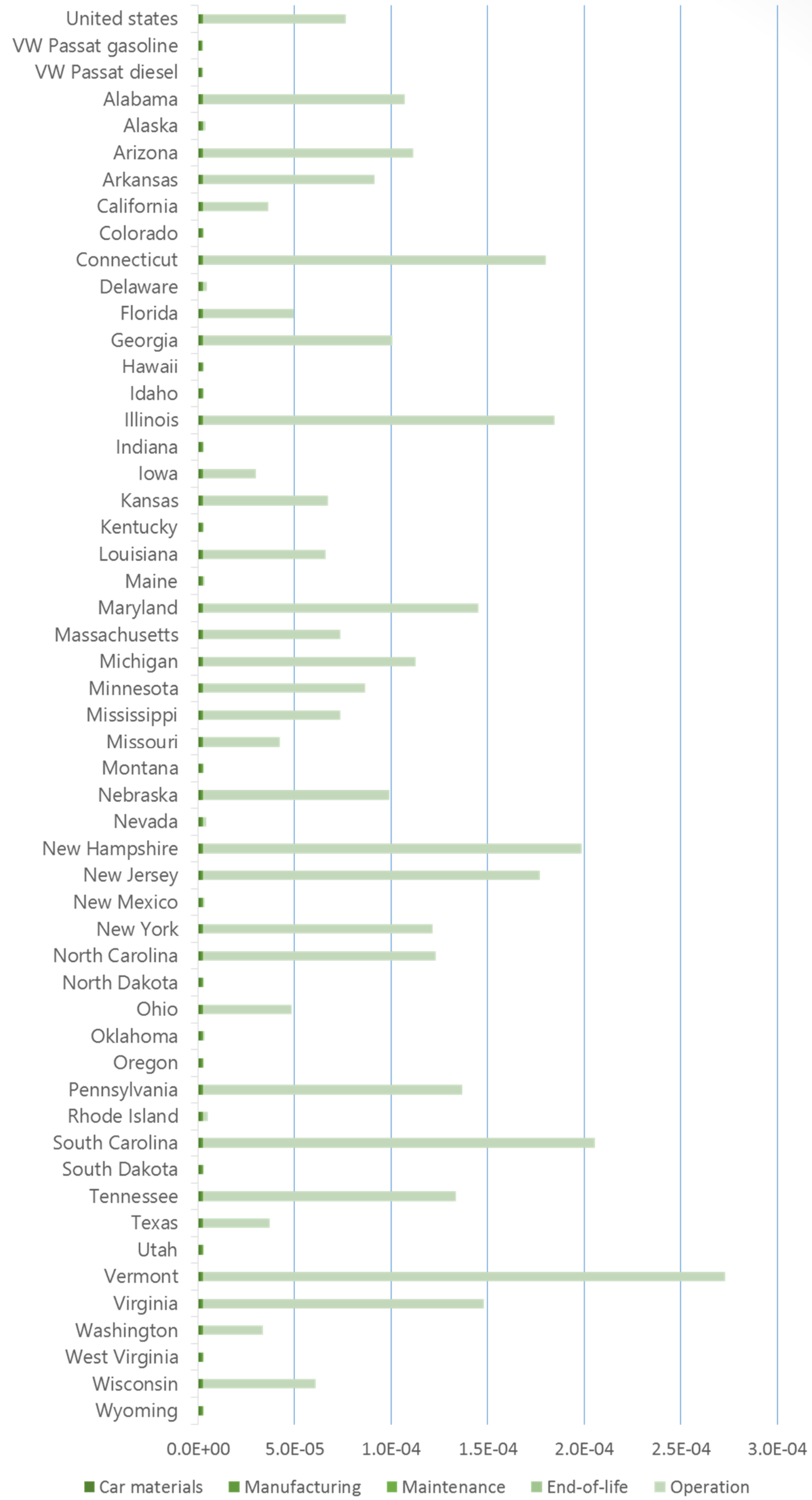


	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	1.52E-06	1.27E-06	1.27E-06	1.26E-06	1.26E-06
Manufacturing	7.88E-07	5.57E-07	5.57E-07	5.52E-07	5.52E-07
Maintenance	2.74E-07	2.74E-07	2.74E-07	2.74E-07	2.74E-07
End-of-life	1.52E-08	1.08E-08	1.08E-08	1.07E-08	1.07E-08
Operation	7.38E-05	8.43E-06	2.34E-07	1.45E-07	1.47E-07

Car materials   Manufacturing   Maintenance   End-of-life   Operation

Unit: m^3

Note: Also nuclear power powers electric vehicles. In ethanol production, grid electricity is used and thus also nuclear power.

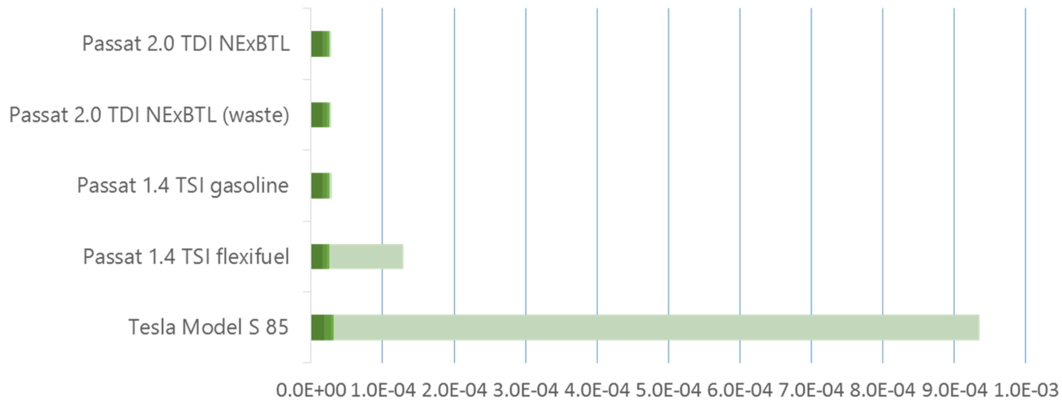


Unit: m^3 high-level radioactive waste Tesla S Model S in different U.S. states

EFFECT ON CREATION OF MEDIUM- AND LOW-LEVEL RADIOACTIVE WASTE (MLW+LLW)

Medium-level radioactive waste (MLW) (containing higher concentrations of beta/gamma contamination and sometimes alpha emitters) originates from routine power station maintenance operations, for example used ion exchange resins and filter cartridges.

Low-level radioactive waste (LLW) consists of trash and debris from routine nuclear facility operations and decommissioning.



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	1.86E-05	1.56E-05	1.56E-05	1.54E-05	1.54E-05
Manufacturing	9.65E-06	6.81E-06	6.81E-06	6.75E-06	6.75E-06
Maintenance	3.36E-06	3.36E-06	3.36E-06	3.36E-06	3.36E-06
End-of-life	1.87E-07	1.32E-07	1.32E-07	1.31E-07	1.31E-07
Operation	9.04E-04	1.03E-04	2.86E-06	1.77E-06	1.80E-06

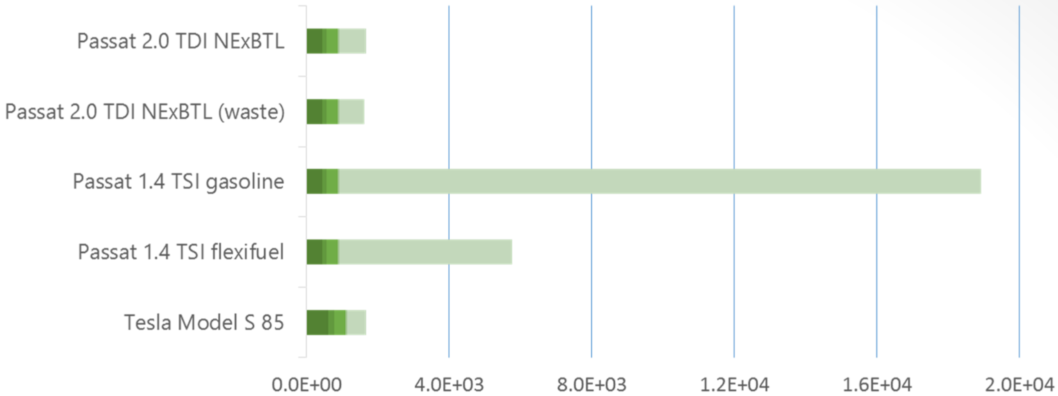
Car materials · Manufacturing · Maintenance · End-of-life · Operation

Unit: m^3

Note: Also nuclear power powers electric vehicles. In ethanol production, grid electricity is used and thus also nuclear power.

EFFECT ON PETROLEUM CONSUMPTION

Petroleum is a nonrenewable resource that is used in practically every human activity. For about 150 years, the consumption of petroleum has increased year after year. This will not be possible forever, and we must decrease our petroleum intensity in all sectors of our society. The petroleum intensities of the energy systems vary significantly.

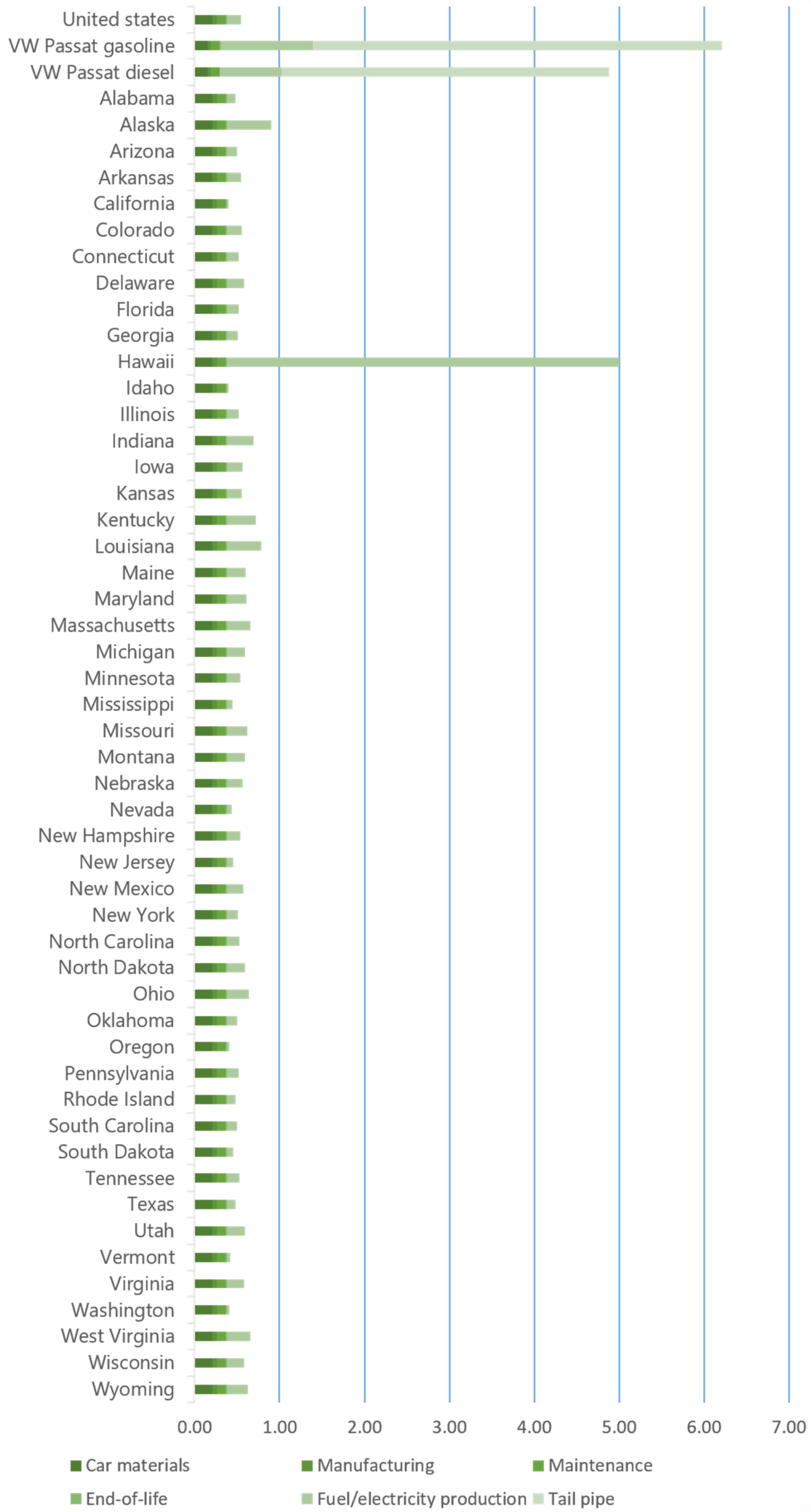


	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	6.27E+02	4.58E+02	4.58E+02	4.54E+02	4.54E+02
Manufacturing	1.59E+02	1.12E+02	1.12E+02	1.11E+02	1.11E+02
Maintenance	3.17E+02	3.17E+02	3.17E+02	3.17E+02	3.17E+02
End-of-life	5.39E+01	3.80E+01	3.80E+01	3.77E+01	3.77E+01
Operation	5.10E+02	4.86E+03	1.80E+04	7.19E+02	7.47E+02

Car materials Manufacturing Maintenance End-of-life Operation

Unit: L (whole life cycle)

Note: In flexifuel vehicles, at least 15 vol-% of the fuel is petroleum gasoline.


United states
VW Passat gasoline
VW Passat diesel
Alabama
Alaska
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
Florida
Georgia
Hawaii
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
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Nebraska
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Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
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Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
Car materials
Manufacturing
Maintenance
End-of-life
Fuel/electricity production
Tail pipe

Unit: L/100 km, Tesla S Model S in different U.S. states

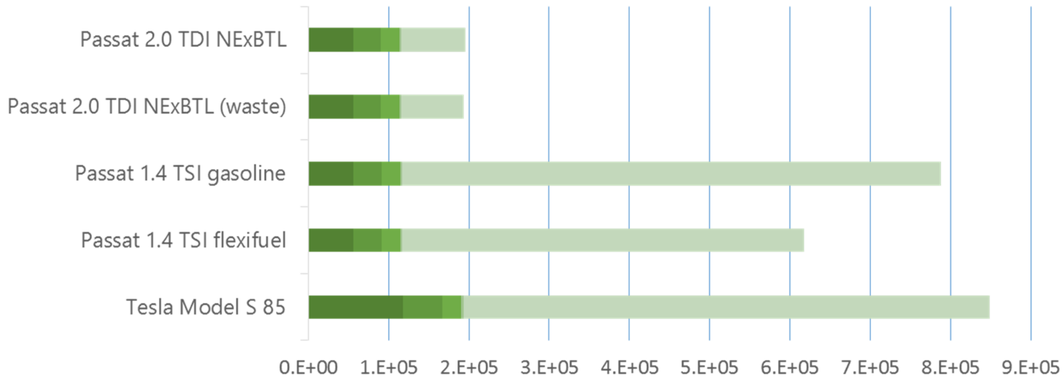
Note: in Hawaii, driving Tesla electric car consumes more petroleum than driving equal-size Volkswagen Passat diesel car.

ENERGY DEPLETION

Energy depletion gives all the energy inputs needed during the whole life cycle. Energy inputs may be either renewable or nonrenewable.

Typically the energy inputs have a direct effect on the quantities of many environmental impacts, such as global warming or acidification.

Primary energy (MJ)

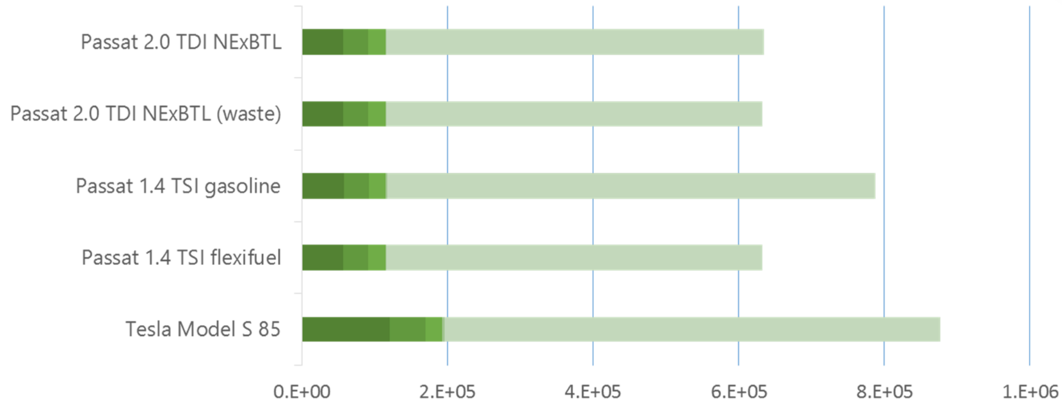


	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	1.18E+05	5.67E+04	5.67E+04	5.62E+04	5.62E+04
Manufacturing	4.91E+04	3.47E+04	3.47E+04	3.44E+04	3.44E+04
Maintenance	2.32E+04	2.32E+04	2.32E+04	2.32E+04	2.32E+04
End-of-life	2.64E+03	1.86E+03	1.86E+03	1.85E+03	1.85E+03
Operation	6.55E+05	5.01E+05	6.71E+05	7.75E+04	7.97E+04

■ Car materials ■ Manufacturing ■ Maintenance ■ End-of-life ■ Operation

LIFE-CYCLE IMPACTS OF TESLA MODEL S 85 AND VOLKSWAGEN PASSAT

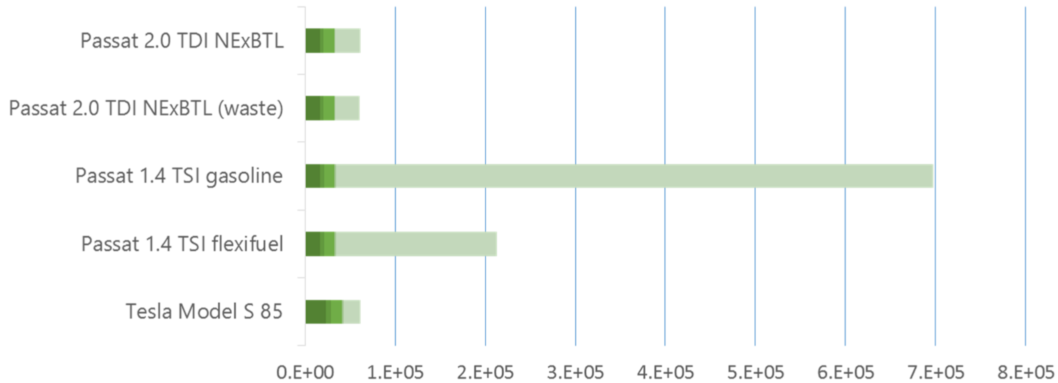
Total energy (MJ)



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	1.20E+05	5.65E+04	5.70E+04	5.65E+04	5.65E+04
Manufacturing	4.91E+04	3.44E+04	3.47E+04	3.44E+04	3.44E+04
Maintenance	2.32E+04	2.32E+04	2.32E+04	2.32E+04	2.32E+04
End-of-life	2.64E+03	1.85E+03	1.86E+03	1.85E+03	1.85E+03
Operation	6.82E+05	5.16E+05	6.71E+05	5.16E+05	5.18E+05

■ Car materials ■ Manufacturing ■ Maintenance ■ End-of-life ■ Operation

Petroleum (MJ)

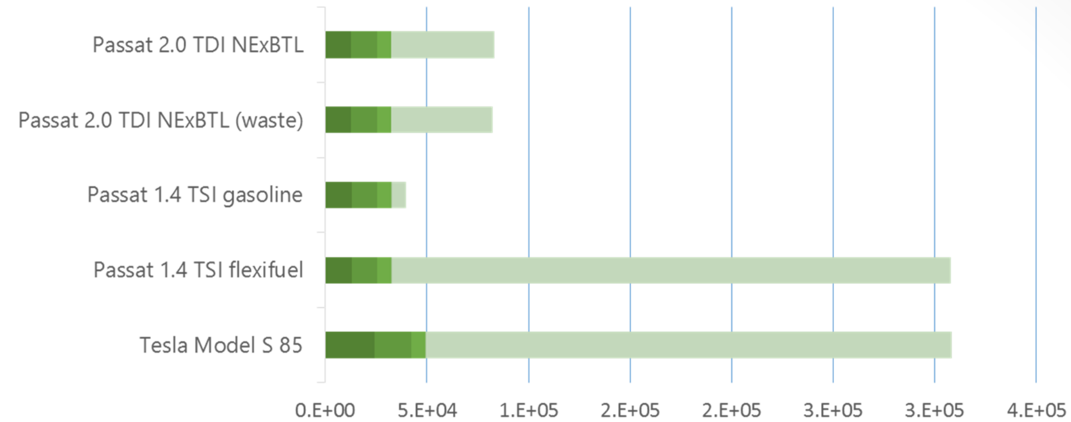


	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	2.31E+04	1.69E+04	1.69E+04	1.67E+04	1.67E+04
Manufacturing	5.85E+03	4.13E+03	4.13E+03	4.09E+03	4.09E+03
Maintenance	1.17E+04	1.17E+04	1.17E+04	1.17E+04	1.17E+04
End-of-life	1.98E+03	1.40E+03	1.40E+03	1.39E+03	1.39E+03
Operation	1.88E+04	1.79E+05	6.63E+05	2.65E+04	2.75E+04

■ Car materials ■ Manufacturing ■ Maintenance ■ End-of-life ■ Operation

Note: In flexifuel vehicles, at least 15 vol-% of the fuel is petroleum gasoline.

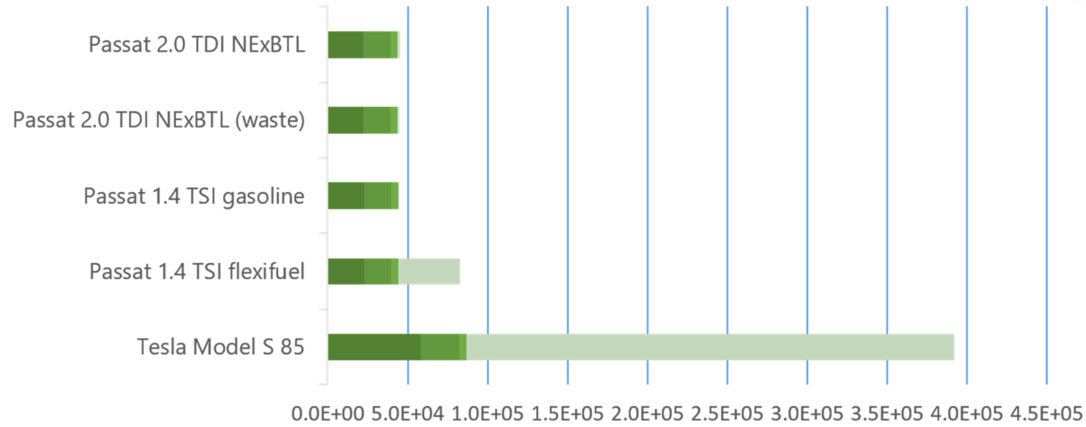
Natural gas (MJ)



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	2.42E+04	1.29E+04	1.29E+04	1.28E+04	1.28E+04
Manufacturing	1.82E+04	1.28E+04	1.28E+04	1.27E+04	1.27E+04
Maintenance	6.87E+03	6.87E+03	6.87E+03	6.87E+03	6.87E+03
End-of-life	2.06E+02	1.45E+02	1.45E+02	1.44E+02	1.44E+02
Operation	2.59E+05	2.75E+05	7.17E+03	4.99E+04	5.07E+04

Note: Natural gas has a 23% share in U.S. electricity mix (Tesla). Corn is a nitrogen-intensive crop. It requires a lot of fertilizer, which requires a lot of natural gas to produce.

Coal/lignite (MJ)

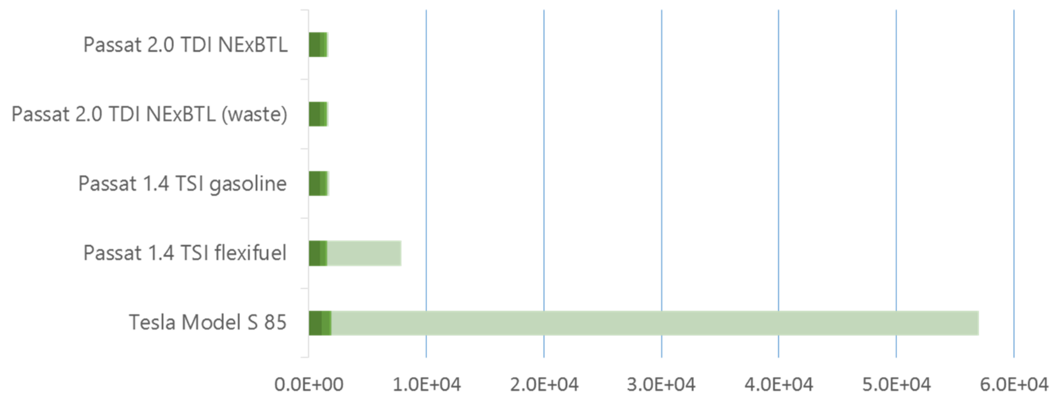


	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	5.83E+04	2.26E+04	2.26E+04	2.24E+04	2.24E+04
Manufacturing	2.39E+04	1.69E+04	1.69E+04	1.68E+04	1.68E+04
Maintenance	4.30E+03	4.30E+03	4.30E+03	4.30E+03	4.30E+03
End-of-life	4.26E+02	3.01E+02	3.01E+02	2.98E+02	2.98E+02
Operation	3.05E+05	3.87E+04	3.07E+02	1.03E+03	1.38E+03

Car materials Manufacturing Maintenance End-of-life Operation

Note: Coal has almost 50% share in the U.S. electricity mix (Tesla).

Nuclear (MJ)



	Tesla Model S 85	Passat 1.4 TSI flexifuel	Passat 1.4 TSI gasoline	Passat 2.0 TDI NExBTL (waste)	Passat 2.0 TDI NExBTL
Car materials	1.14E+03	9.50E+02	9.50E+02	9.42E+02	9.42E+02
Manufacturing	5.88E+02	4.15E+02	4.15E+02	4.12E+02	4.12E+02
Maintenance	2.05E+02	2.05E+02	2.05E+02	2.05E+02	2.05E+02
End-of-life	1.14E+01	8.03E+00	8.03E+00	7.96E+00	7.96E+00
Operation	5.51E+04	6.29E+03	1.75E+02	1.08E+02	1.10E+02

Car materials Manufacturing Maintenance End-of-life Operation

Note: Also nuclear power powers electric vehicles. In ethanol production, grid electricity is used and thus also nuclear power.

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UNCERTAINTIES IN LIFE-CYCLE ANALYSIS

Generally the reliability of the results from a life-cycle analysis depends on the accuracy and reliability of the calculation models and data banks.

In practice, every case is a special case. The feed data and consequently the results are dependent on time, location, raw material, company, political decisions, legislation etc. These factors can be taken into account by changing models and inventory parameters. However, in practice for example country-dependent average models and parameters are used.

For example, crude oil is produced in thousands of locations globally, and the quality of oil differs widely. Good-quality light oil from an easy well can be pumped, transported and refined easily, while bituminous oil requires much more severe processing. Consequently the well-to-fuel emissions are higher in the latter case.

In the future, oil and other raw materials must be extracted from more difficult reserves and the emissions will grow. On the other hand, more efficient production methods may lower the environmental impacts. Political decisions, such as lower sulphur content limits in fuels and exhaust gases and the ban of CFC compounds, have also an effect on emissions.

Some actions that are intended to decrease certain emissions may have contradictory effects on other emissions. For example, flue-gas desulphurization and electrostatic precipitators decrease the emissions of sulphur dioxide and particulates, but at the same time more energy is used and carbon dioxide emissions increase.