Comparison of electric cars and different internal combustion engine fuel options – Volkswagen Golf model year 2018

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[1] Cleanfi Oy is a company providing cradle to gate life cycle assessment services for quantifying the carbon footprint and other environmental impacts of various activities, e.g., industry, energy, electricity generation and transportation. Kimmo Klemola is Dr.S. (Tech., oil refining). www.cleanfi.fi

Contents

Example cars

The curb weight, battery pack weight and fuel/electricity consumption data (WTLP[2]) of the following Volkswagen Golf models (2018) were used in comparing different fuel and engine options: Volkswagen Golf Comfortline 1.0 TSI 85 kW, Volkswagen Golf Trendline 1.6 TDI 85 kW, Volkswagen Golf 1.4 TGI 81 kW and Volkswagen e-Golf 100 kW. In calculations, no other factory data were used.

Excerpts

Considering CO2e:

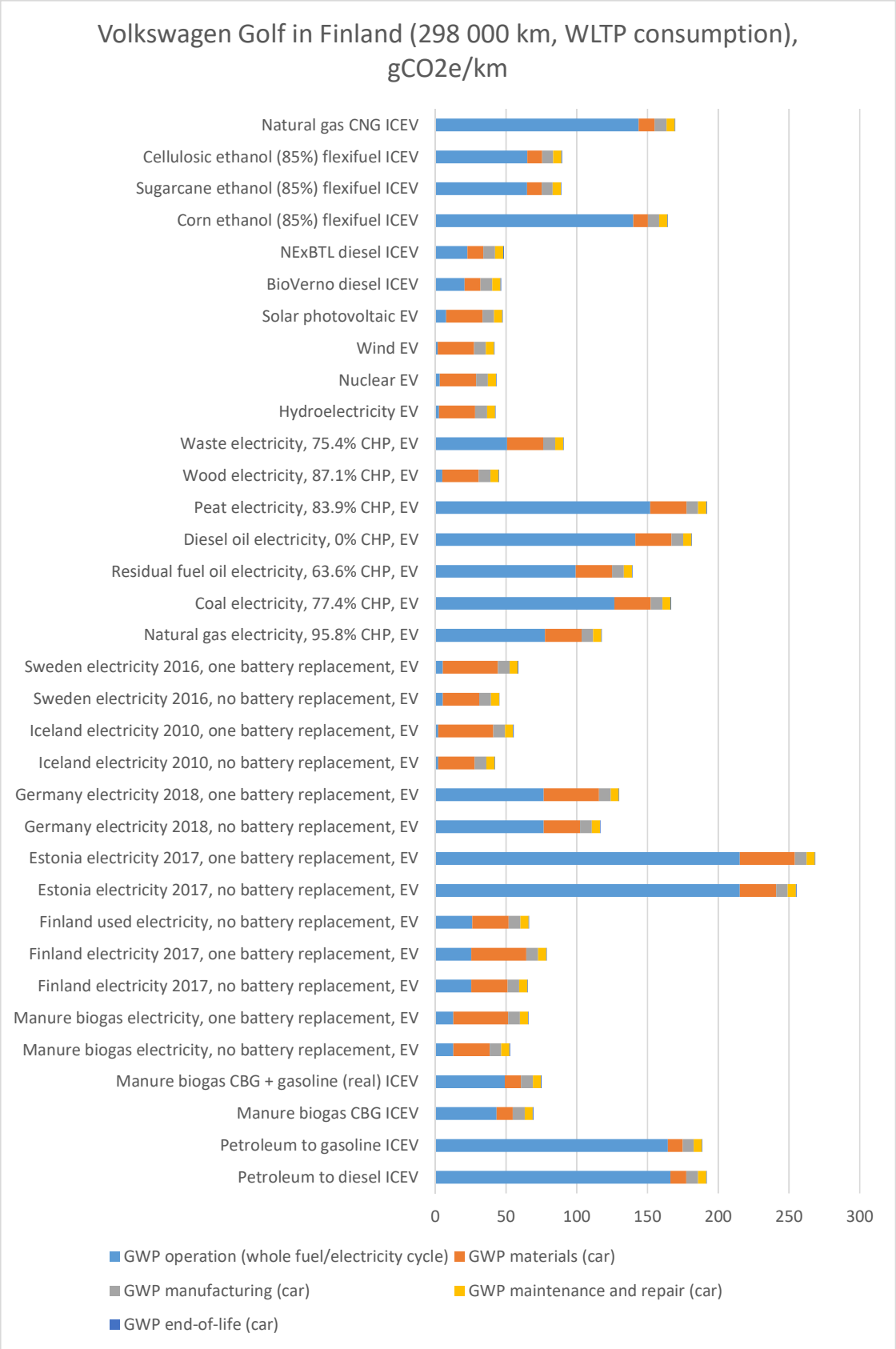
- New electric car beats new diesel car after 28 000 km in Finland.
- New electric car beats new gasoline car after 26 000 km in Finland.
- New electric car beats old diesel car after 72 000 km (old diesel car still has driving, fuel cycle, maintenance and end-of-life emissions – but not the emissions from manufacturing a car) in Finland.
- Electric car in Finland beats biogas car after 203 000 km in Finland (if there is no battery pack replacement)
- Electric car with biogas electricity beats biogas ICE car after 120 000 km.
- Electric car with biogas electricity beats biogas ICE car after 245 000 km, if the battery pack is replaced once.

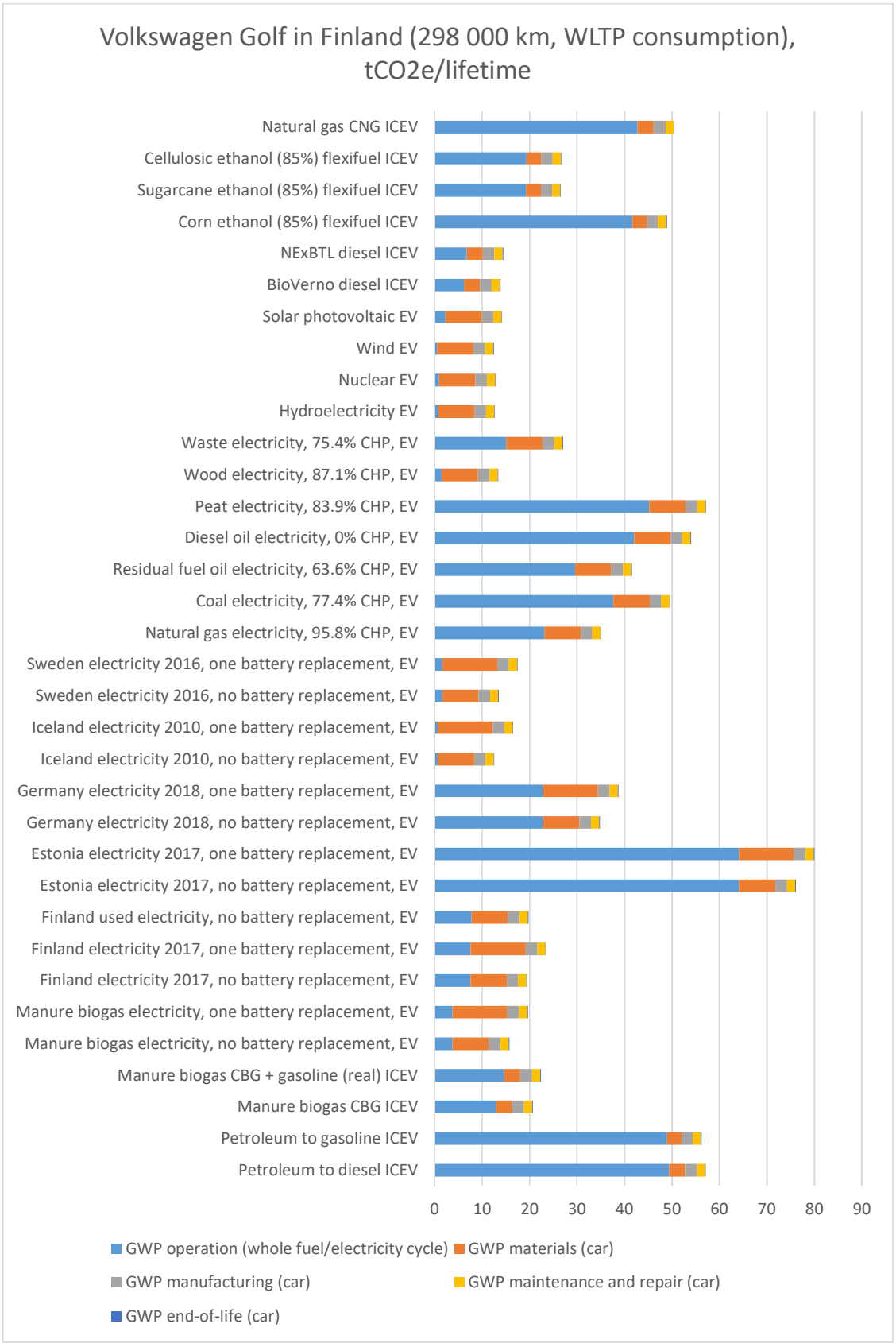
Considering euros:

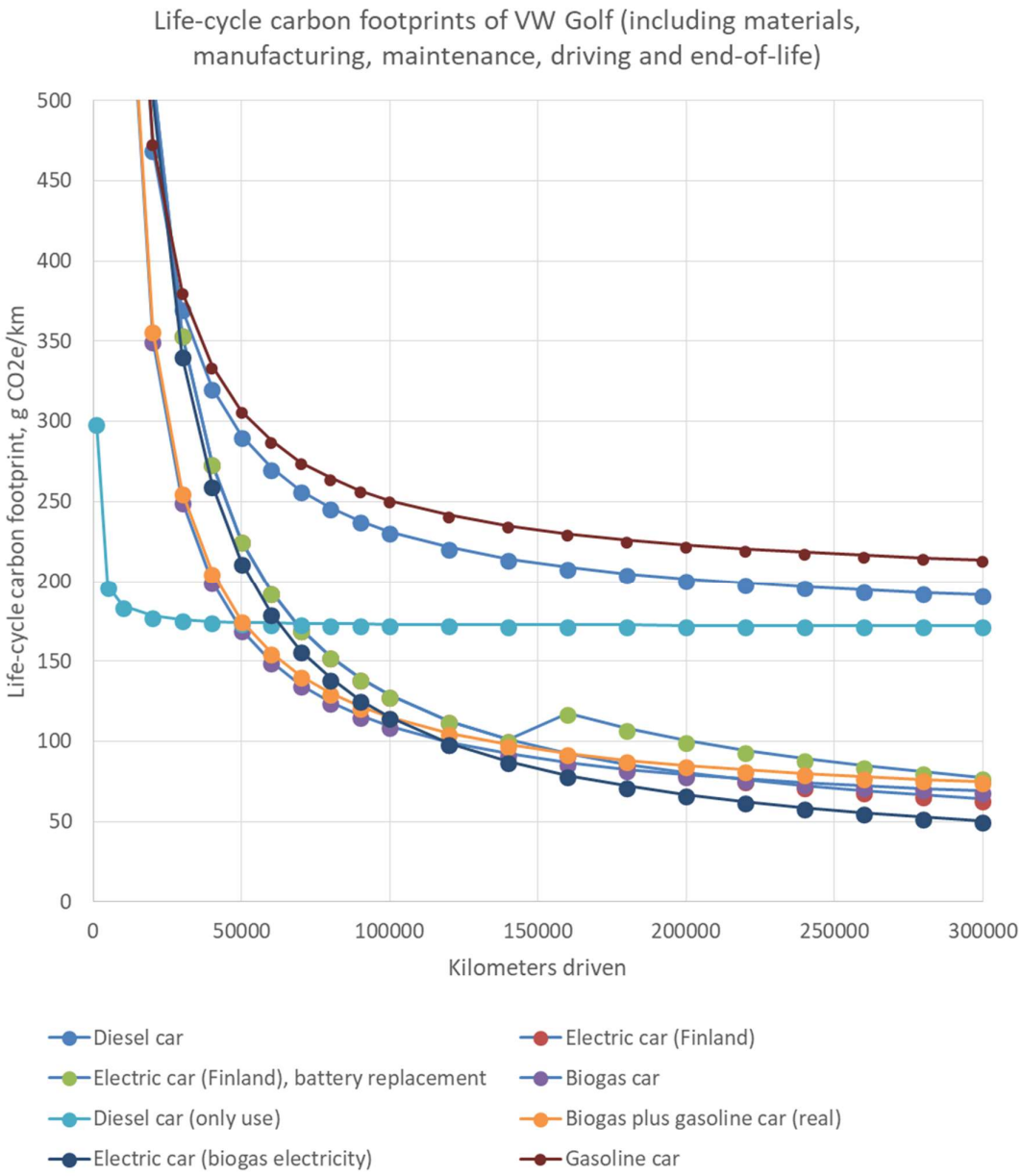
- In Finland, CNG (compressed natural gas) gas car gives cheapest life-time kilometers followed by CBG (compressed biogas).
- In Finland, lifetime costs are about equal for e-Golf, gasoline Golf and diesel Golf.
- January 2019 prices and taxes were used for the whole lifetime of the car.

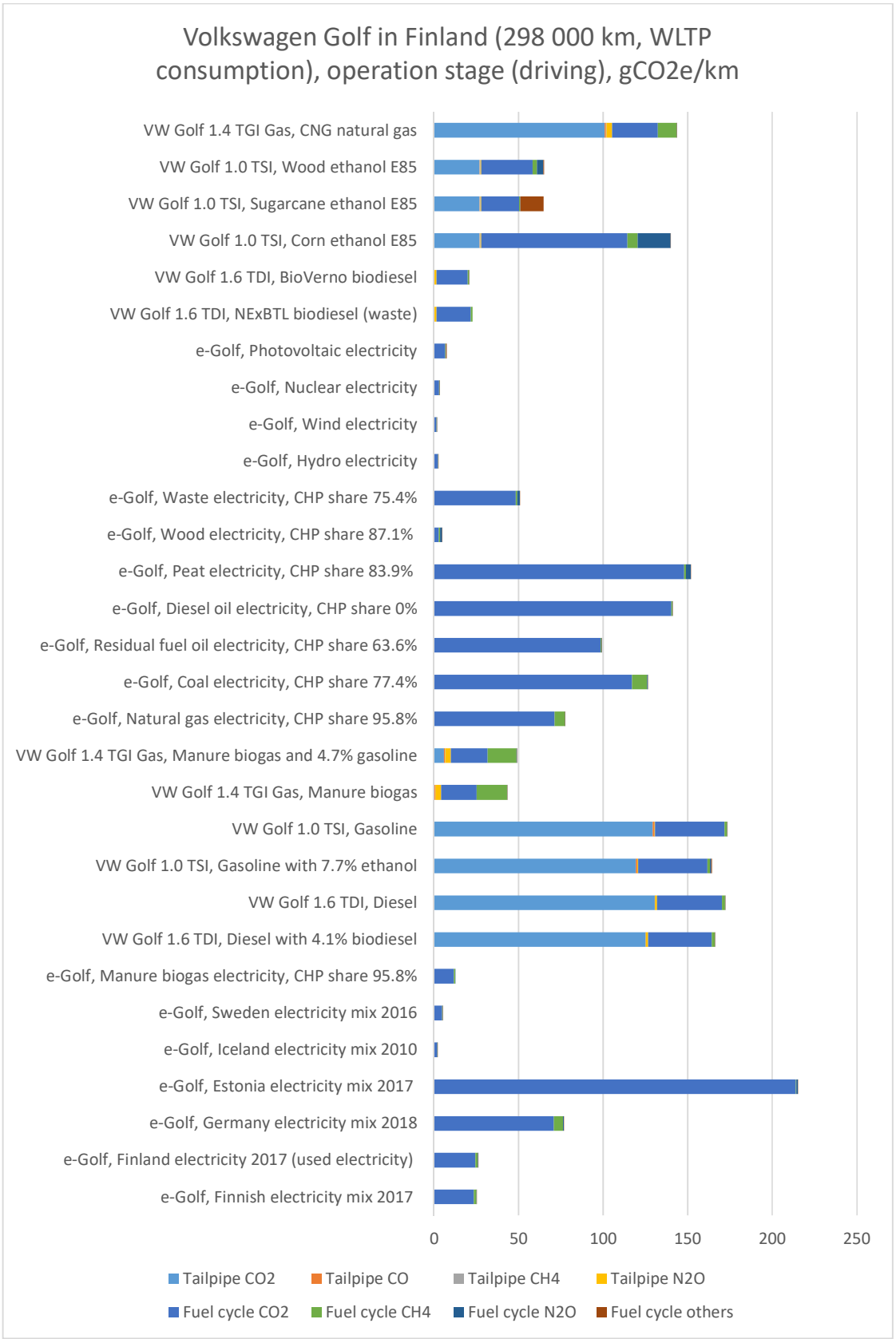
[2] The worldwide harmonized light vehicles test procedure (WLTP) is a global harmonized standard for determining the levels of pollutants and CO2 emissions, fuel or energy consumption, and electric range from light-duty vehicles (passenger cars and light commercial vans). (Wikipedia)

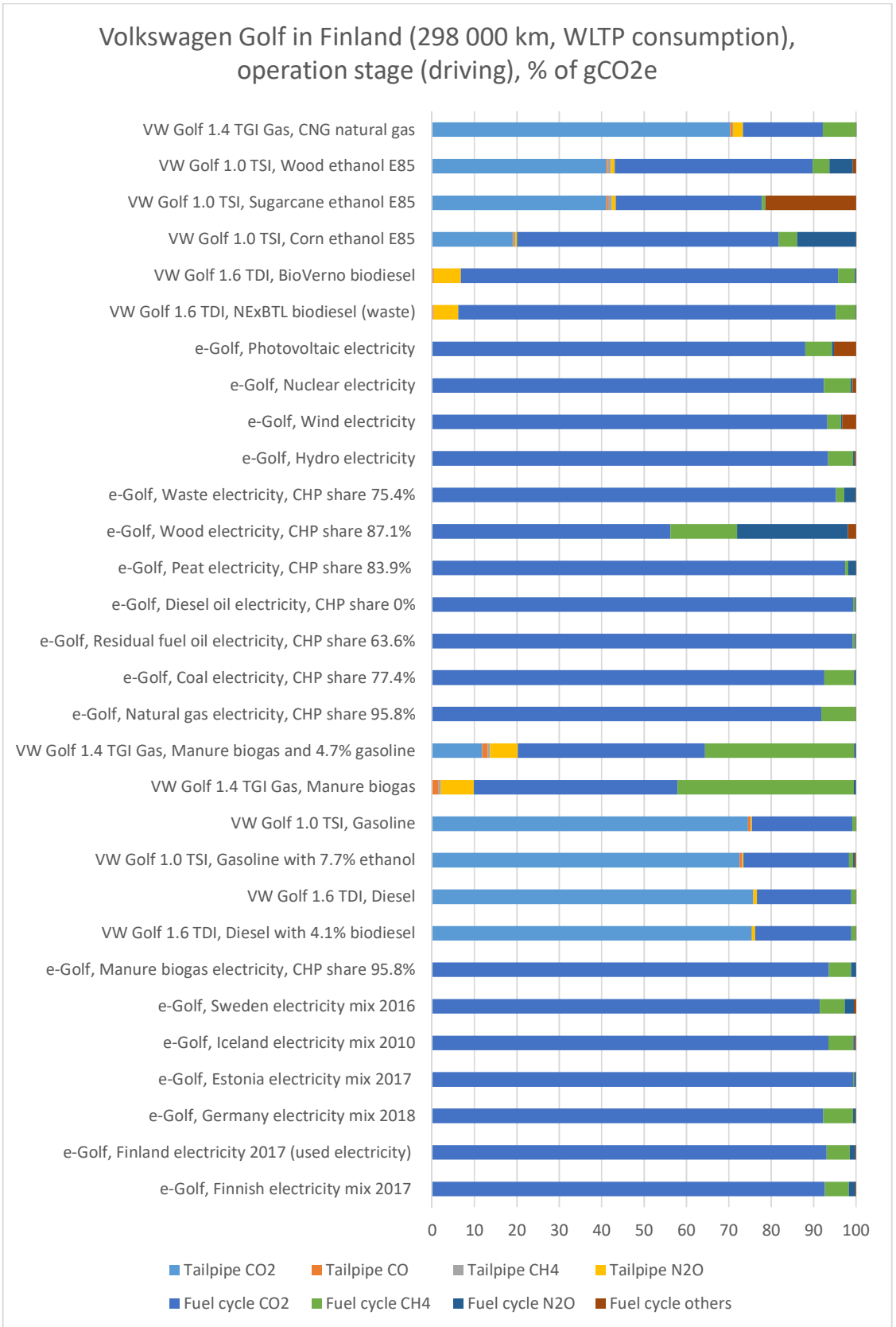
Global warming potential (carbon footprint)




Volkswagen Golf in Finland (298 000 km, WLTP consumption), tCO2e/lifetime
Natural gas CNG ICEV
Cellulosic ethanol (85%) flexifuel ICEV
Sugarcane ethanol (85%) flexifuel ICEV
Corn ethanol (85%) flexifuel ICEV
NExBTL diesel ICEV
BioVerno diesel ICEV
Solar photovoltaic EV
Wind EV
Nuclear EV
Hydroelectricity EV
Waste electricity, 75.4% CHP, EV
Wood electricity, 87.1% CHP, EV
Peat electricity, 83.9% CHP, EV
Diesel oil electricity, 0% CHP, EV
Residual fuel oil electricity, 63.6% CHP, EV
Coal electricity, 77.4% CHP, EV
Natural gas electricity, 95.8% CHP, EV
Sweden electricity 2016, one battery replacement, EV
Sweden electricity 2016, no battery replacement, EV
Iceland electricity 2010, one battery replacement, EV
Iceland electricity 2010, no battery replacement, EV
Germany electricity 2018, one battery replacement, EV
Germany electricity 2018, no battery replacement, EV
Estonia electricity 2017, one battery replacement, EV
Estonia electricity 2017, no battery replacement, EV
Finland used electricity, no battery replacement, EV
Finland electricity 2017, one battery replacement, EV
Finland electricity 2017, no battery replacement, EV
Manure biogas electricity, one battery replacement, EV
Manure biogas electricity, no battery replacement, EV
Manure biogas CBG + gasoline (real) ICEV
Manure biogas CBG ICEV
Petroleum to gasoline ICEV
Petroleum to diesel ICEV
0
10
20
30
40
50
60
70
80
90
GWP operation (whole fuel/electricity cycle)
GWP materials (car)
GWP manufacturing (car)
GWP maintenance and repair (car)
GWP end-of-life (car)


Life-cycle carbon footprints of VW Golf (including materials, manufacturing, maintenance, driving and end-of-life)
Life-cycle carbon footprint, g CO2e/km
500
450
400
350
300
250
200
150
100
50
0
0
50000
100000
150000
200000
250000
300000
Kilometers driven
Diesel car
Electric car (Finland)
Electric car (Finland), battery replacement
Biogas car
Diesel car (only use)
Biogas plus gasoline car (real)
Electric car (biogas electricity)
Gasoline car


Volkswagen Golf in Finland (298 000 km, WLTP consumption), operation stage (driving), gCO2e/km
VW Golf 1.4 TGI Gas, CNG natural gas
VW Golf 1.0 TSI, Wood ethanol E85
VW Golf 1.0 TSI, Sugarcane ethanol E85
VW Golf 1.0 TSI, Corn ethanol E85
VW Golf 1.6 TDI, BioVerno biodiesel
VW Golf 1.6 TDI, NExBTL biodiesel (waste)
e-Golf, Photovoltaic electricity
e-Golf, Nuclear electricity
e-Golf, Wind electricity
e-Golf, Hydro electricity
e-Golf, Waste electricity, CHP share 75.4%
e-Golf, Wood electricity, CHP share 87.1%
e-Golf, Peat electricity, CHP share 83.9%
e-Golf, Diesel oil electricity, CHP share 0%
e-Golf, Residual fuel oil electricity, CHP share 63.6%
e-Golf, Coal electricity, CHP share 77.4%
e-Golf, Natural gas electricity, CHP share 95.8%
VW Golf 1.4 TGI Gas, Manure biogas and 4.7% gasoline
VW Golf 1.4 TGI Gas, Manure biogas
VW Golf 1.0 TSI, Gasoline
VW Golf 1.0 TSI, Gasoline with 7.7% ethanol
VW Golf 1.6 TDI, Diesel
VW Golf 1.6 TDI, Diesel with 4.1% biodiesel
e-Golf, Manure biogas electricity, CHP share 95.8%
e-Golf, Sweden electricity mix 2016
e-Golf, Iceland electricity mix 2010
e-Golf, Estonia electricity mix 2017
e-Golf, Germany electricity mix 2018
e-Golf, Finland electricity 2017 (used electricity)
e-Golf, Finnish electricity mix 2017
0
50
100
150
200
250
Tailpipe CO2
Tailpipe CO
Tailpipe CH4
Tailpipe N2O
Fuel cycle CO2
Fuel cycle CH4
Fuel cycle N2O
Fuel cycle others


Volkswagen Golf in Finland (298 000 km, WLTP consumption), operation stage (driving), % of gCO2e
VW Golf 1.4 TGI Gas, CNG natural gas
VW Golf 1.0 TSI, Wood ethanol E85
VW Golf 1.0 TSI, Sugarcane ethanol E85
VW Golf 1.0 TSI, Corn ethanol E85
VW Golf 1.6 TDI, BioVerno biodiesel
VW Golf 1.6 TDI, NExBTL biodiesel (waste)
e-Golf, Photovoltaic electricity
e-Golf, Nuclear electricity
e-Golf, Wind electricity
e-Golf, Hydro electricity
e-Golf, Waste electricity, CHP share 75.4%
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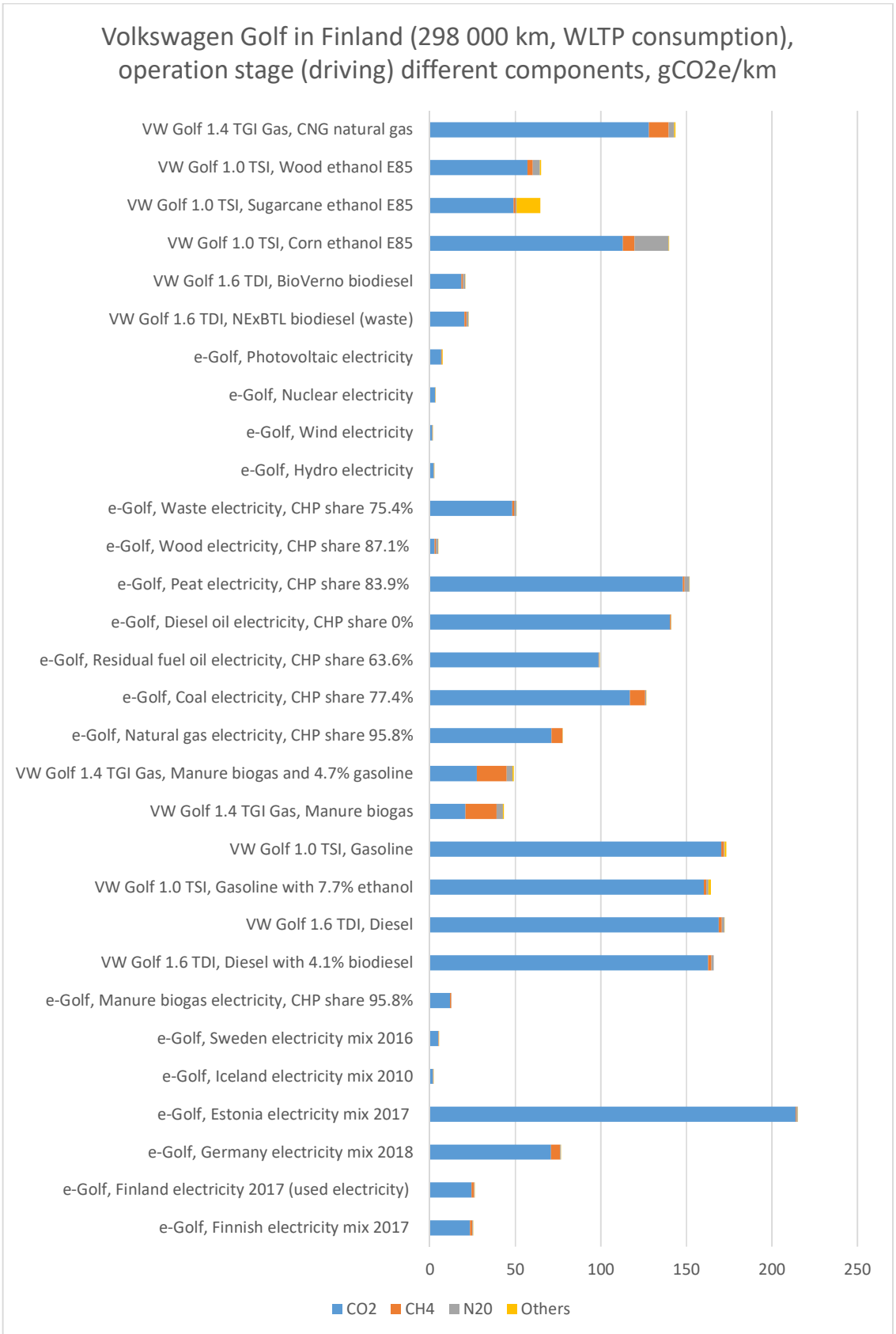
e-Golf, Residual fuel oil electricity, CHP share 63.6%
e-Golf, Coal electricity, CHP share 77.4%
e-Golf, Natural gas electricity, CHP share 95.8%
VW Golf 1.4 TGI Gas, Manure biogas and 4.7% gasoline
VW Golf 1.4 TGI Gas, Manure biogas
VW Golf 1.0 TSI, Gasoline
VW Golf 1.0 TSI, Gasoline with 7.7% ethanol
VW Golf 1.6 TDI, Diesel
VW Golf 1.6 TDI, Diesel with 4.1% biodiesel
e-Golf, Manure biogas electricity, CHP share 95.8%
e-Golf, Sweden electricity mix 2016
e-Golf, Iceland electricity mix 2010
e-Golf, Estonia electricity mix 2017
e-Golf, Germany electricity mix 2018
e-Golf, Finland electricity 2017 (used electricity)
e-Golf, Finnish electricity mix 2017
0
10
20
30
40
50
60
70
80
90
100
Tailpipe CO2
Tailpipe CO
Tailpipe CH4
Tailpipe N2O
Fuel cycle CO2
Fuel cycle CH4
Fuel cycle N2O
Fuel cycle others


Volkswagen Golf in Finland (298 000 km, WLTP consumption), operation stage (driving) different components, gCO2e/km
VW Golf 1.4 TGI Gas, CNG natural gas
VW Golf 1.0 TSI, Wood ethanol E85
VW Golf 1.0 TSI, Sugarcane ethanol E85
VW Golf 1.0 TSI, Corn ethanol E85
VW Golf 1.6 TDI, BioVerno biodiesel
VW Golf 1.6 TDI, NExBTL biodiesel (waste)
e-Golf, Photovoltaic electricity
e-Golf, Nuclear electricity
e-Golf, Wind electricity
e-Golf, Hydro electricity
e-Golf, Waste electricity, CHP share 75.4%
e-Golf, Wood electricity, CHP share 87.1%
e-Golf, Peat electricity, CHP share 83.9%
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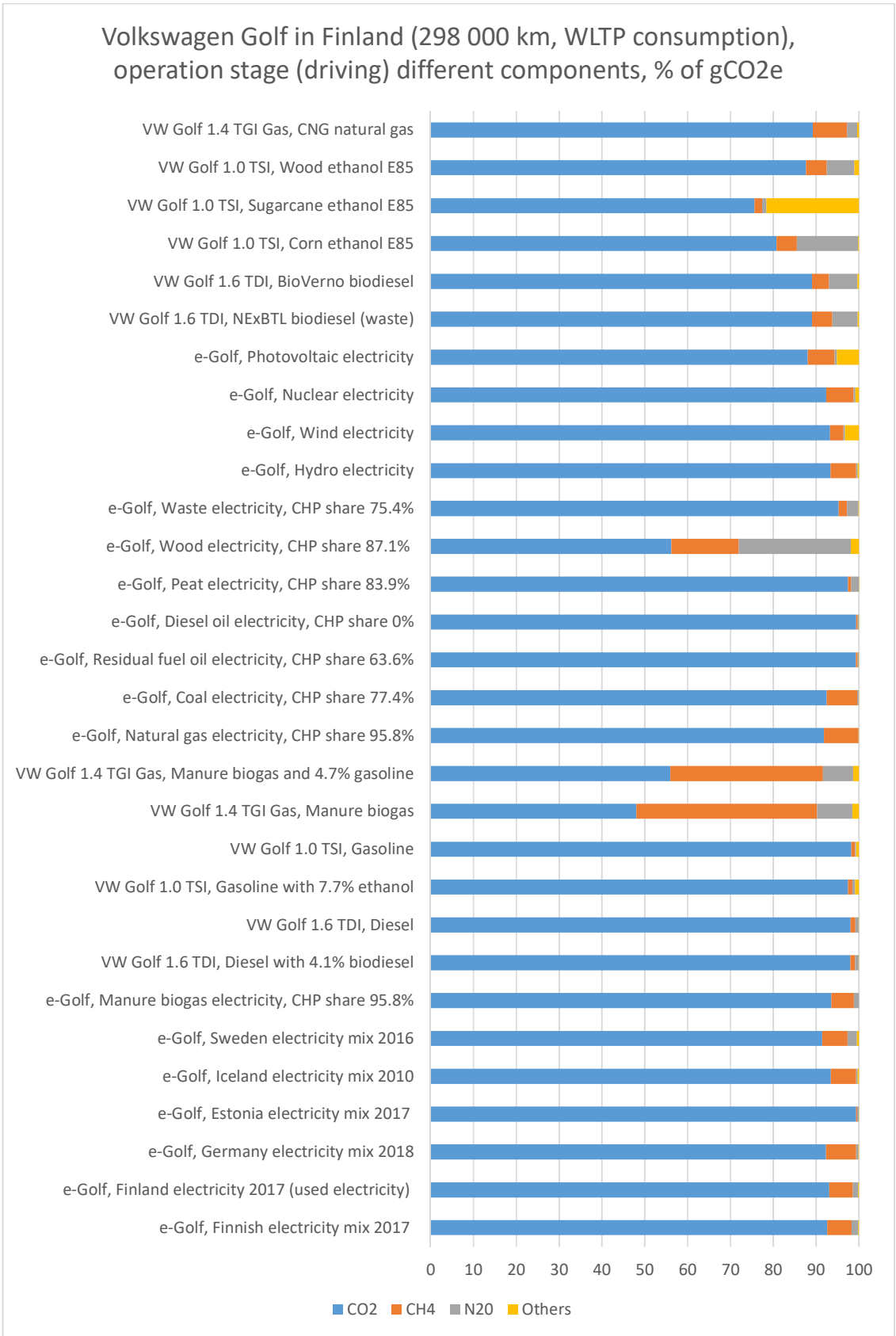
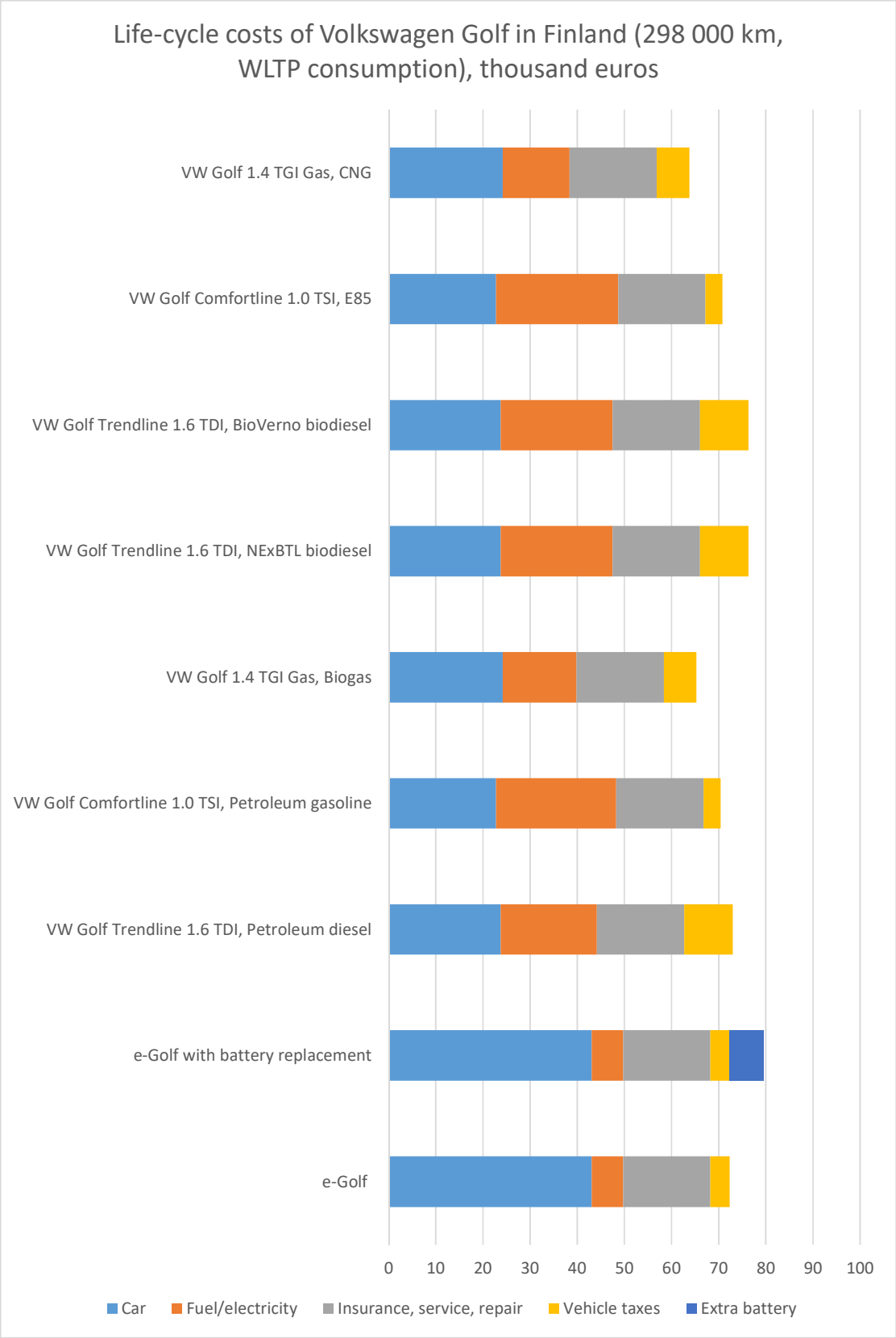
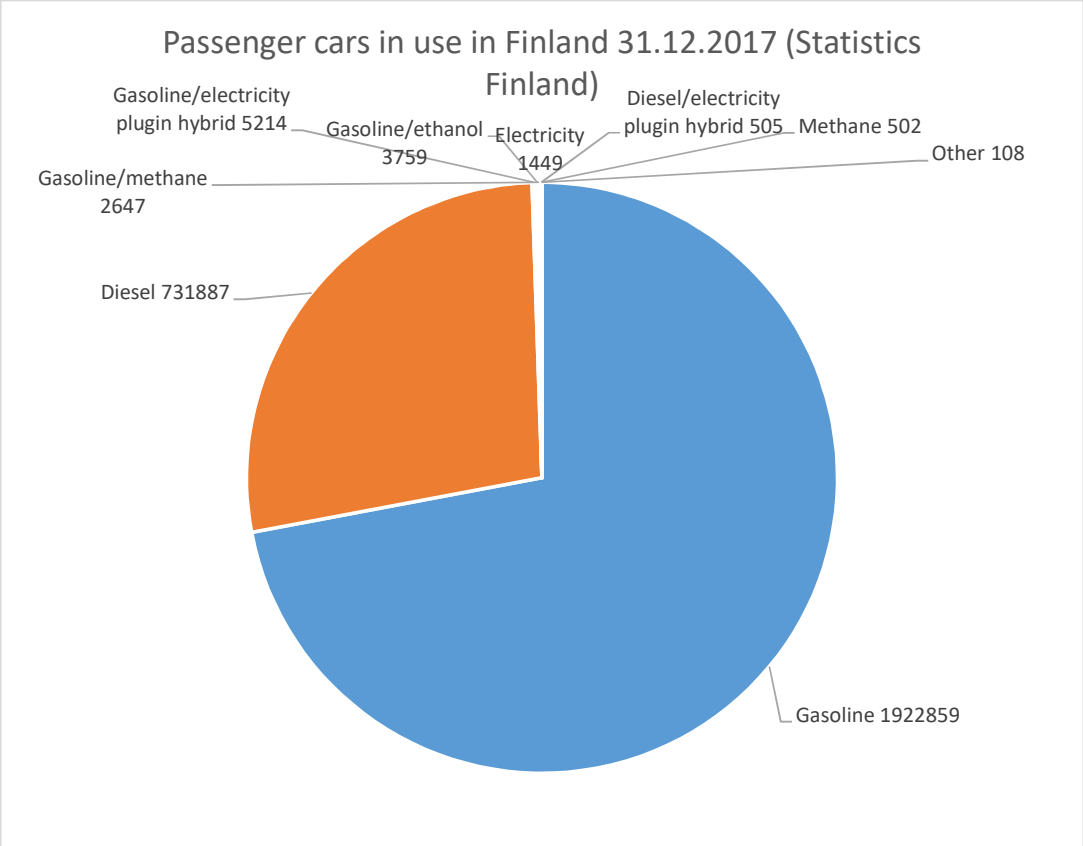
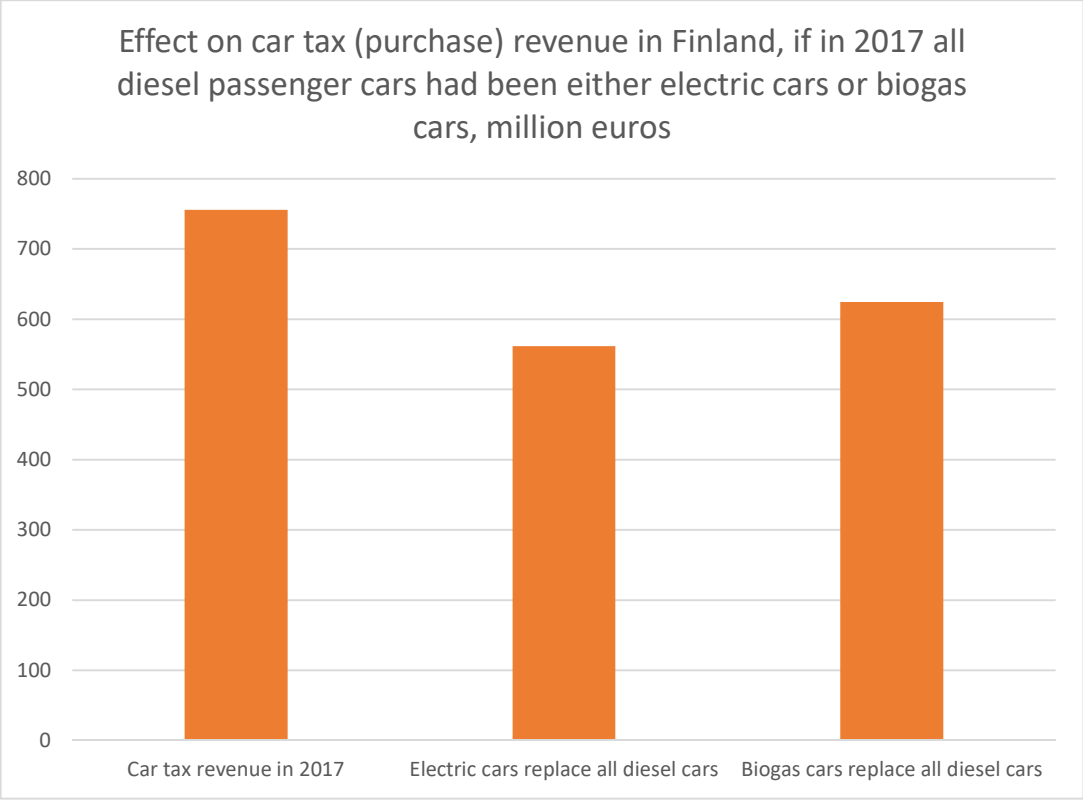
VW Golf 1.4 TGI Gas, Manure biogas and 4.7% gasoline
VW Golf 1.4 TGI Gas, Manure biogas
VW Golf 1.0 TSI, Gasoline
VW Golf 1.0 TSI, Gasoline with 7.7% ethanol
VW Golf 1.6 TDI, Diesel
VW Golf 1.6 TDI, Diesel with 4.1% biodiesel
e-Golf, Manure biogas electricity, CHP share 95.8%
e-Golf, Sweden electricity mix 2016
e-Golf, Iceland electricity mix 2010
e-Golf, Estonia electricity mix 2017
e-Golf, Germany electricity mix 2018
e-Golf, Finland electricity 2017 (used electricity)
e-Golf, Finnish electricity mix 2017
0
50
100
150
200
250
CO2
CH4
N20
Others

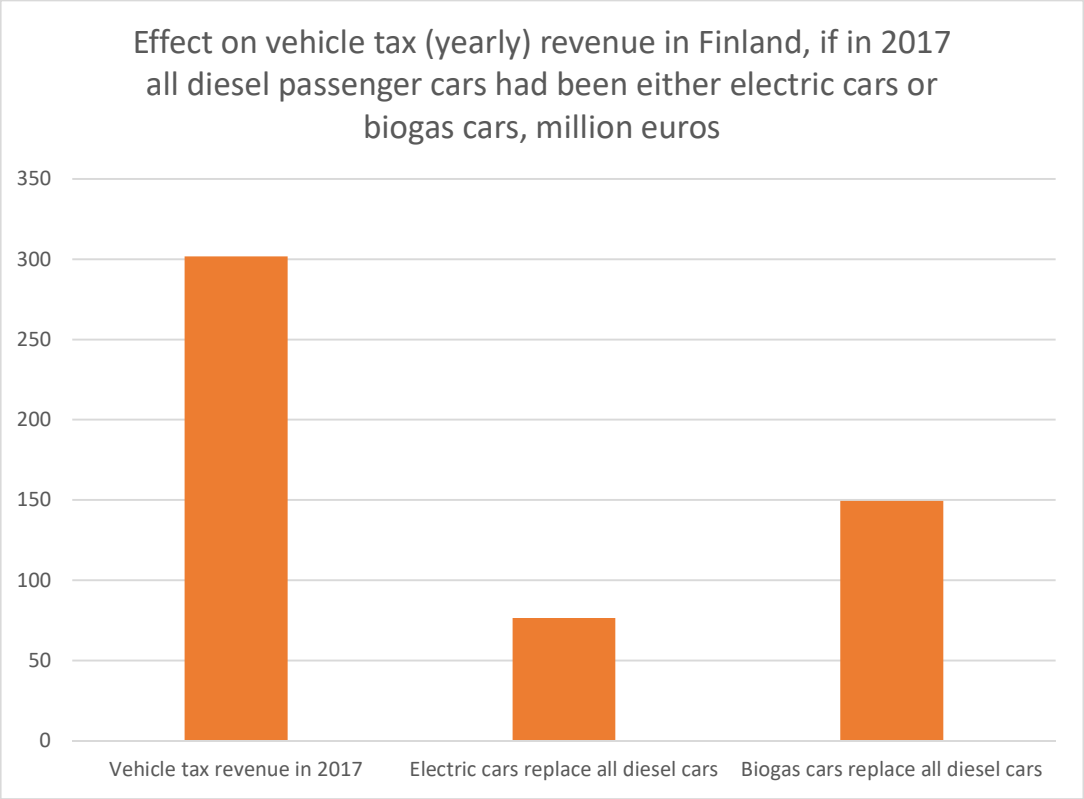

Volkswagen Golf in Finland (298 000 km, WLTP consumption), operation stage (driving) different components, % of gCO2e
VW Golf 1.4 TGI Gas, CNG natural gas
VW Golf 1.0 TSI, Wood ethanol E85
VW Golf 1.0 TSI, Sugarcane ethanol E85
VW Golf 1.0 TSI, Corn ethanol E85
VW Golf 1.6 TDI, BioVerno biodiesel
VW Golf 1.6 TDI, NExBTL biodiesel (waste)
e-Golf, Photovoltaic electricity
e-Golf, Nuclear electricity
e-Golf, Wind electricity
e-Golf, Hydro electricity
e-Golf, Waste electricity, CHP share 75.4%
e-Golf, Wood electricity, CHP share 87.1%
e-Golf, Peat electricity, CHP share 83.9%
e-Golf, Diesel oil electricity, CHP share 0%
e-Golf, Residual fuel oil electricity, CHP share 63.6%
e-Golf, Coal electricity, CHP share 77.4%
e-Golf, Natural gas electricity, CHP share 95.8%
VW Golf 1.4 TGI Gas, Manure biogas and 4.7% gasoline
VW Golf 1.4 TGI Gas, Manure biogas
VW Golf 1.0 TSI, Gasoline
VW Golf 1.0 TSI, Gasoline with 7.7% ethanol
VW Golf 1.6 TDI, Diesel
VW Golf 1.6 TDI, Diesel with 4.1% biodiesel
e-Golf, Manure biogas electricity, CHP share 95.8%
e-Golf, Sweden electricity mix 2016
e-Golf, Iceland electricity mix 2010
e-Golf, Estonia electricity mix 2017
e-Golf, Germany electricity mix 2018
e-Golf, Finland electricity 2017 (used electricity)
e-Golf, Finnish electricity mix 2017
0
10
20
30
40
50
60
70
80
90
100
CO2
CH4
N20
Others

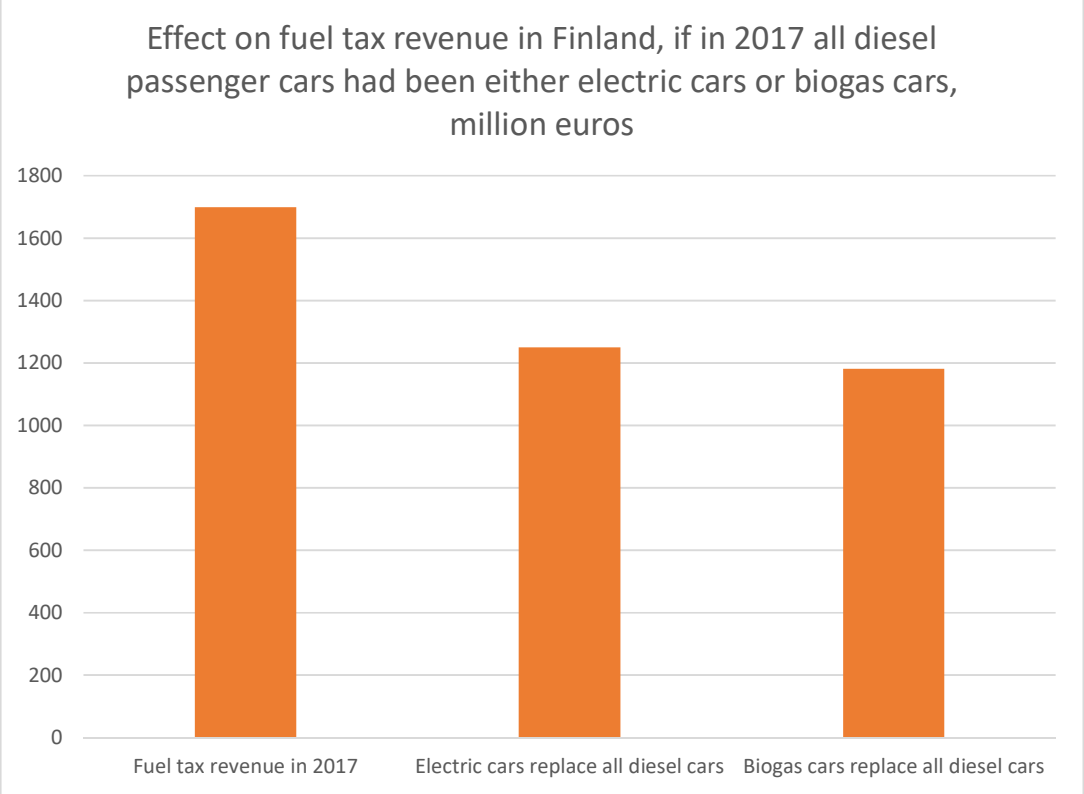
Economics and tax revenues

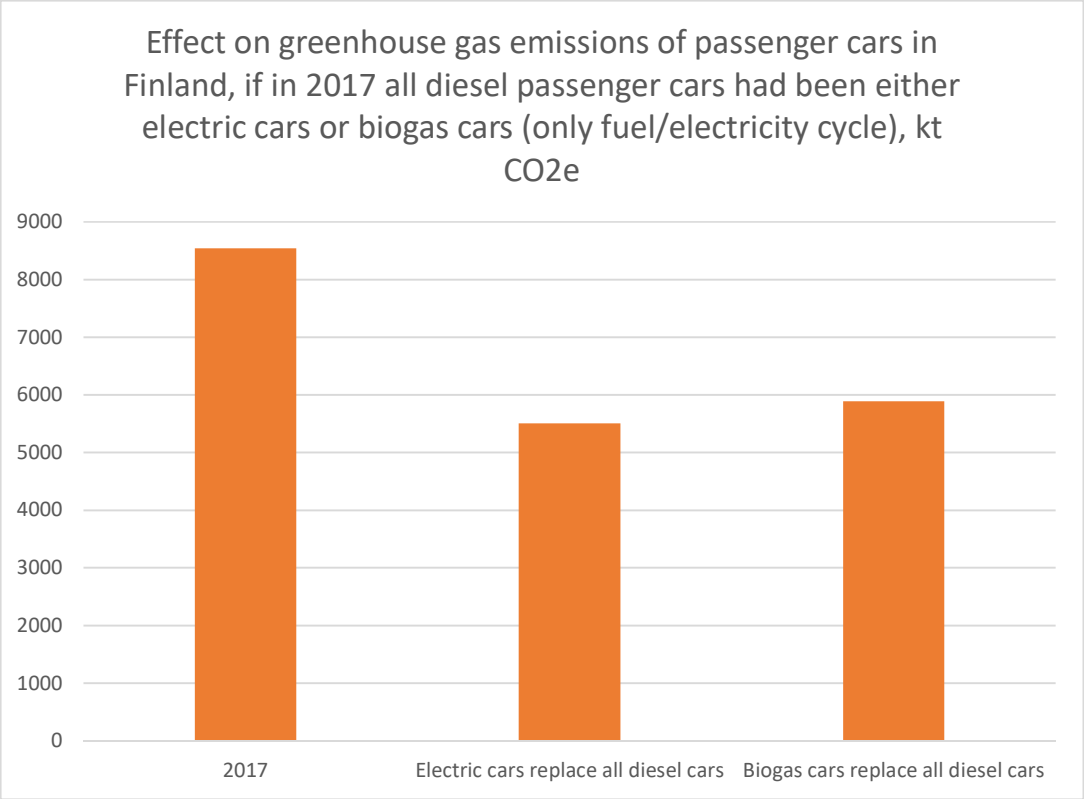


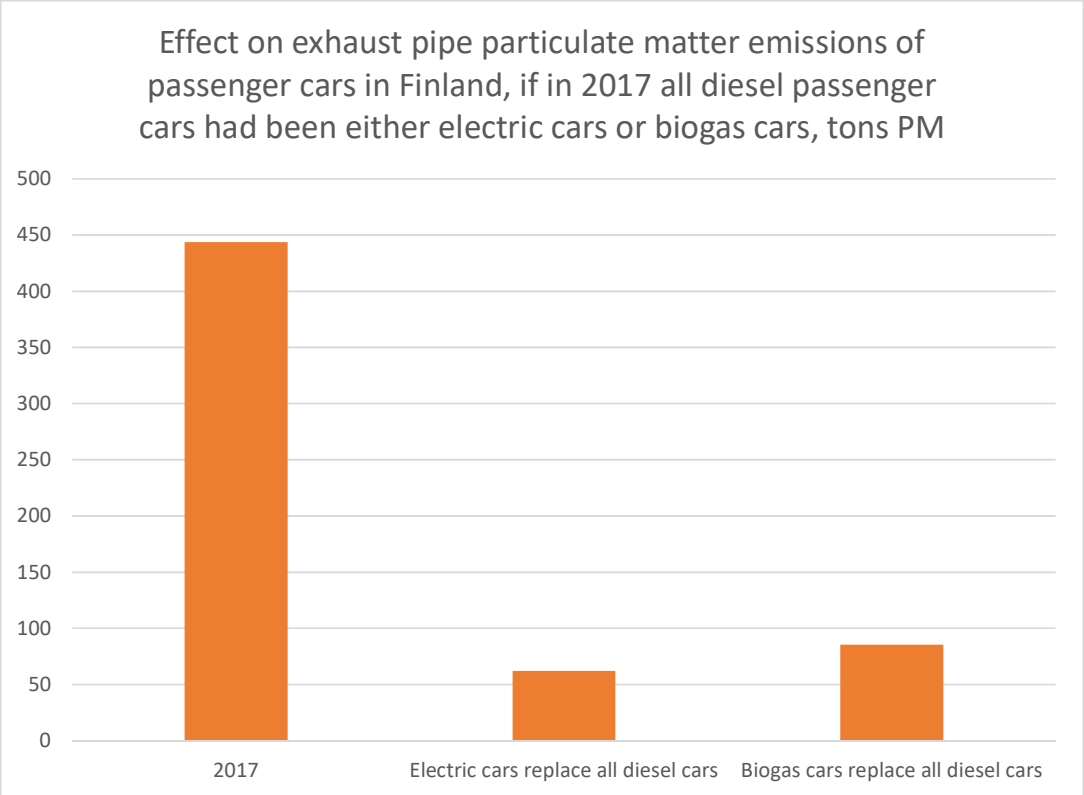

Passenger cars in use in Finland 31.12.2017 (Statistics Finland)
Gasoline/electricity plugin hybrid 5214
Gasoline/ethanol 3759
Electricity 1449
Diesel/electricity plugin hybrid 505
Methane 502
Other 108
Gasoline/methane 2647
Diesel 731887
Gasoline 1922859

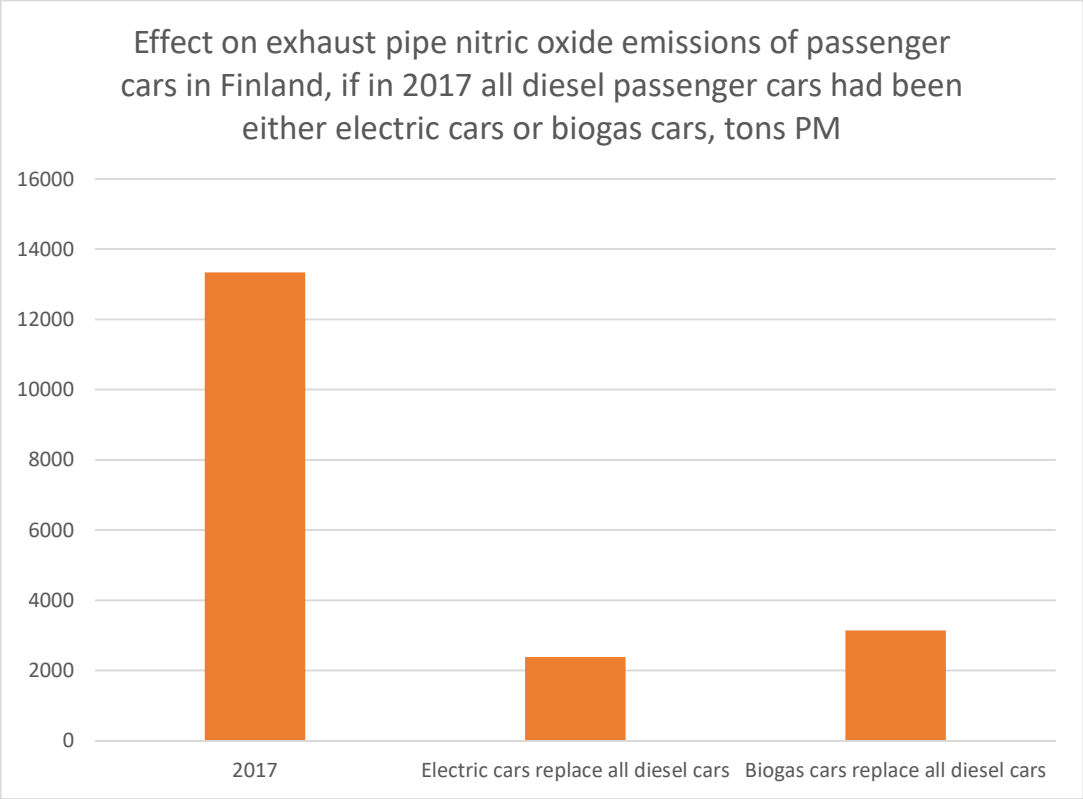

Effect on car tax (purchase) revenue in Finland, if in 2017 all diesel passenger cars had been either electric cars or biogas cars, million euros
800
700
600
500
400
300
200
100
0
Car tax revenue in 2017
Electric cars replace all diesel cars
Biogas cars replace all diesel cars


Effect on vehicle tax (yearly) revenue in Finland, if in 2017 all diesel passenger cars had been either electric cars or biogas cars, million euros
350
300
250
200
150
100
50
0
Vehicle tax revenue in 2017
Electric cars replace all diesel cars
Biogas cars replace all diesel cars

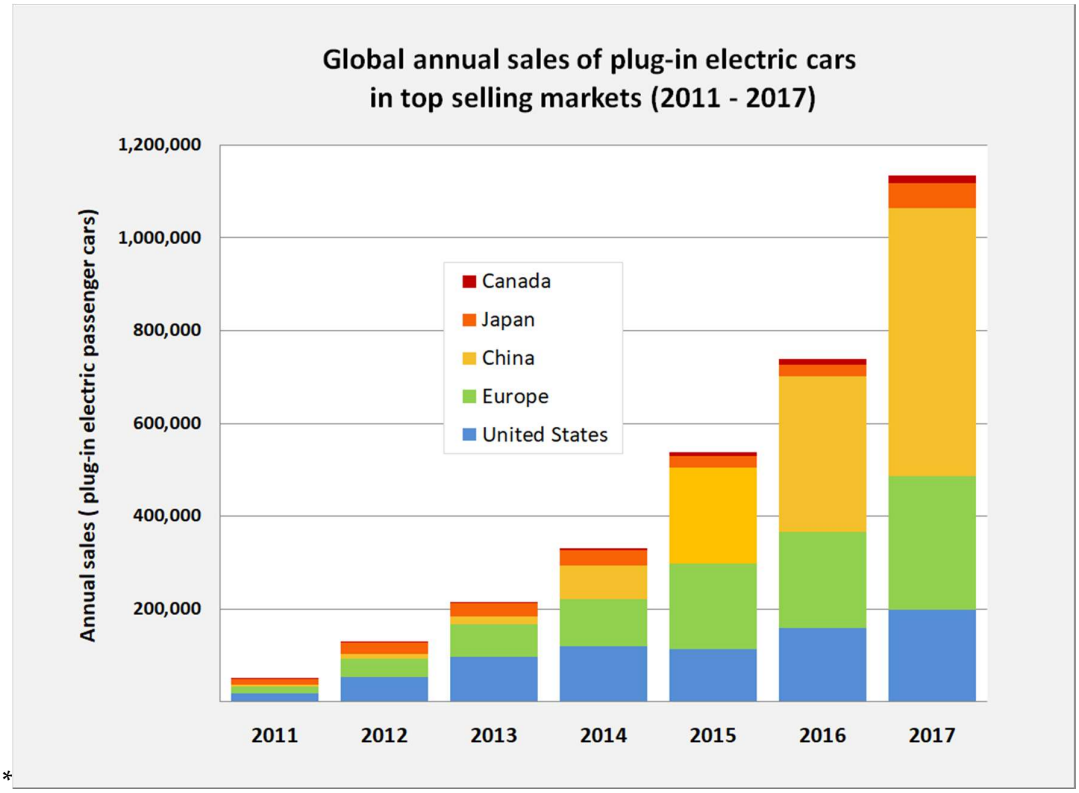

Effect on fuel tax revenue in Finland, if in 2017 all diesel passenger cars had been either electric cars or biogas cars, million euros
1800
1600
1400
1200
1000
800
600
400
200
0
Fuel tax revenue in 2017
Electric cars replace all diesel cars
Biogas cars replace all diesel cars


Effect on greenhouse gas emissions of passenger cars in Finland, if in 2017 all diesel passenger cars had been either electric cars or biogas cars (only fuel/electricity cycle), kt CO2e
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
2017
Electric cars replace all diesel cars
Biogas cars replace all diesel cars


Effect on exhaust pipe particulate matter emissions of passenger cars in Finland, if in 2017 all diesel passenger cars had been either electric cars or biogas cars, tons PM
500
450
400
350
300
250
200
150
100
50
0
2017
Electric cars replace all diesel cars
Biogas cars replace all diesel cars



Electric car sales globally and battery cell patent indicators



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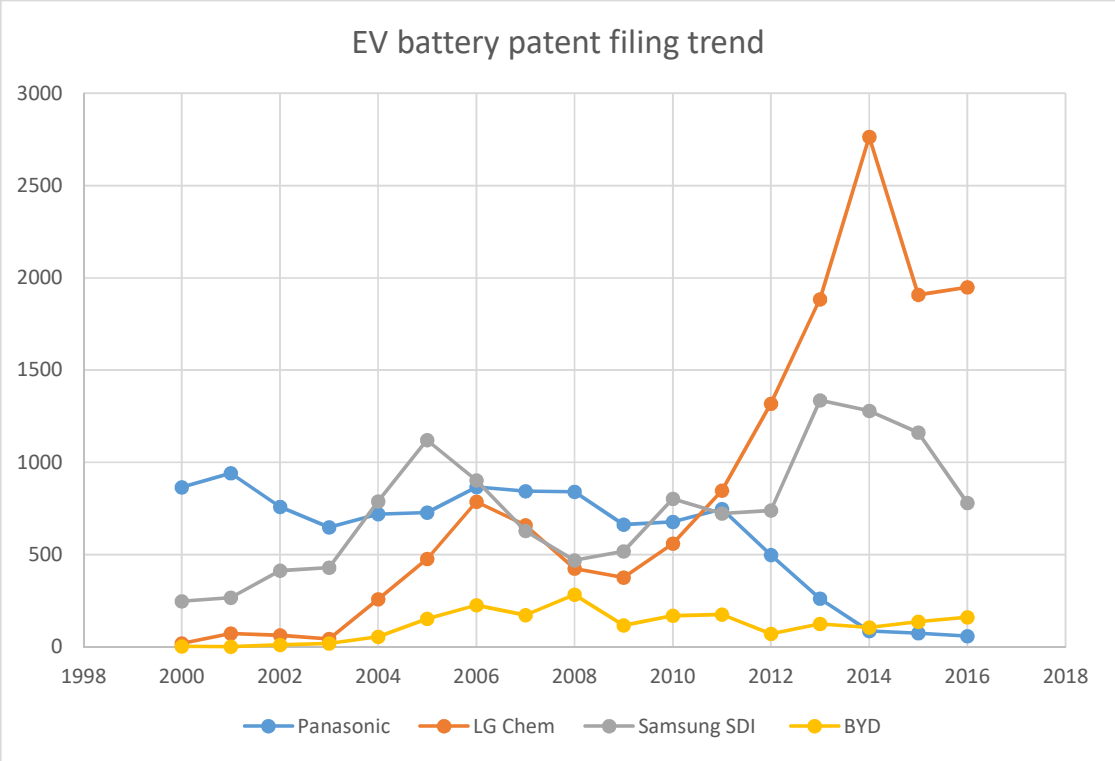
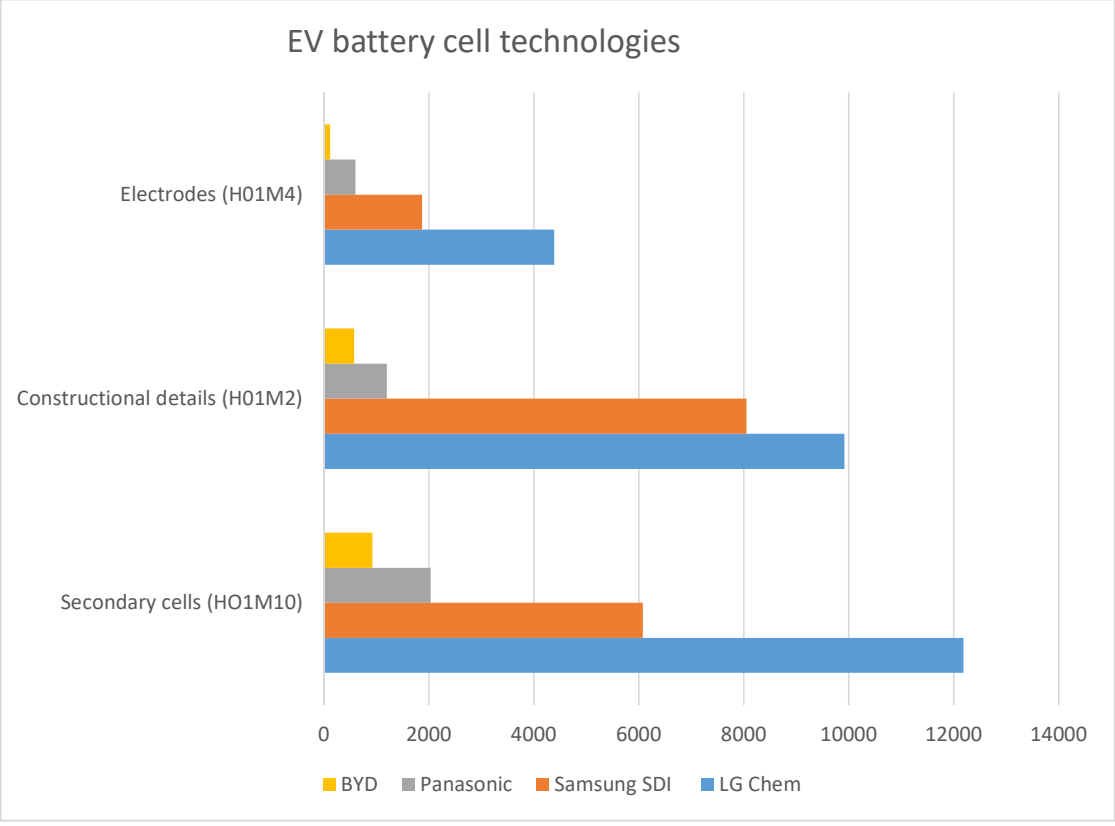
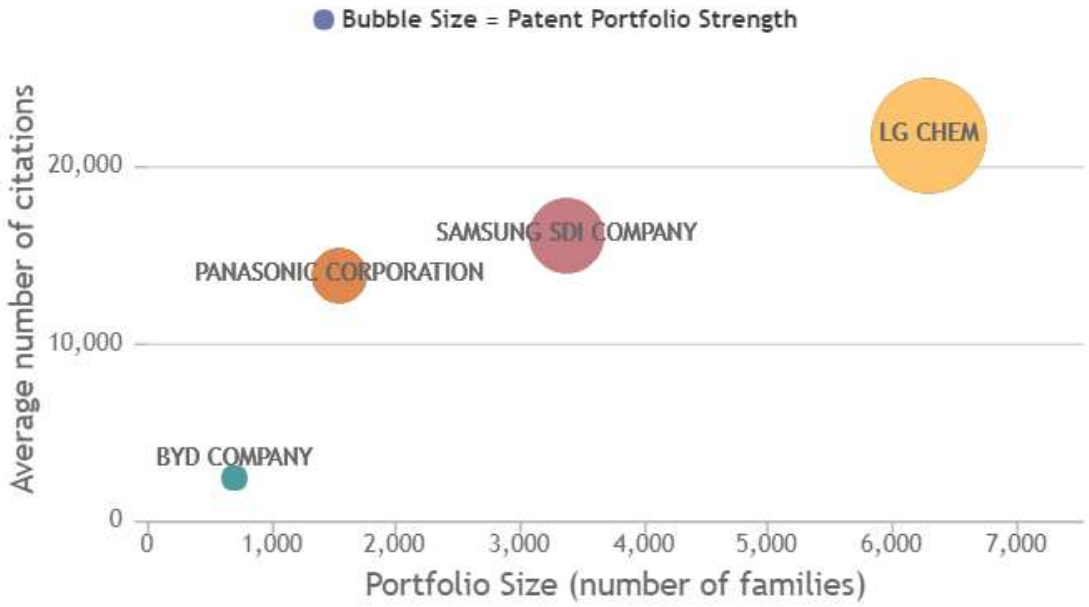

EV battery patent filing trend
3000
2500
2000
1500
1000
500
0
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
Panasonic
LG Chem
Samsung SDI
BYD


EV battery cell technologies
Electrodes (H01M4)
Constructional details (H01M2)
Secondary cells (HO1M10)
0
2000
4000
6000
8000
10000
12000
14000
BYD
Panasonic
Samsung SDI
LG Chem


Bubble Size = Patent Portfolio Strength
Average number of citations
20,000
10,000
0
LG CHEM
SAMSUNG SDI COMPANY
PANASONIC CORPORATION
BYD COMPANY
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Portfolio Size (number of families)

Data

Below car component and material data and electricity/fuel data are given in detail.

Car components and materials

Table 1. Volkswagen Golf Comfortline 1.0 TSI 85 kW, gasoline, 5.7 L/100 km. Car components (generic data).

Component group	All vehicles (kg)	ICEV only (kg)	ICEV (kg)
Body and doors	528.21		
Brakes	12.28		
Chassis	15.58		
Fluids ICEV and EV	5.02		
Vehicle interior and exterior	238.43		
Tyres and wheels	79.61		
Total	879.13		
Engine (ICEV)		170.75	
Fluids (ICEV only)		5.02	
Other ICEV powertrain		92.55	
ICEV transmission		52.03	
ICEV battery		16.52	
Total		336.86	
Car weight			1216.00

Table 2. Volkswagen Golf Trendline 1.6 TDI 85 kW, diesel, 4.9 L/100 km. Car components (generic data).

Component group	All vehicles (kg)	ICEV only (kg)	ICEV (kg)
Body and doors	565.13		
Brakes	13.14		
Chassis	16.67		
Fluids ICEV and EV	5.37		
Vehicle interior and exterior	255.10		
Tyres and wheels	85.18		
Total	940.58		
Engine (ICEV)		182.69	
Fluids (ICEV only)		5.37	
Other ICEV powertrain		99.02	
ICEV transmission		55.66	
ICEV battery		17.68	
Total		360.41	
Car weight			1301.00

Table 3. Volkswagen Golf 1.4 TGI 81 kW, methane, 3.6 kg/100 km. Car components (generic data).

Component group	All vehicles (kg)	ICEV only (kg)	ICEV (kg)
Body and doors	572.08		
Brakes	13.30		
Chassis	16.88		
Fluids ICEV and EV	5.43		
Vehicle interior and exterior	258.24		
Tyres and wheels	86.22		
Total	952.15		
Engine (ICEV)		184.93	
Fluids (ICEV only)		5.43	
Other ICEV powertrain		100.24	
ICEV transmission		56.35	
ICEV battery		17.89	
Total		364.84	
Car weight			1317.00

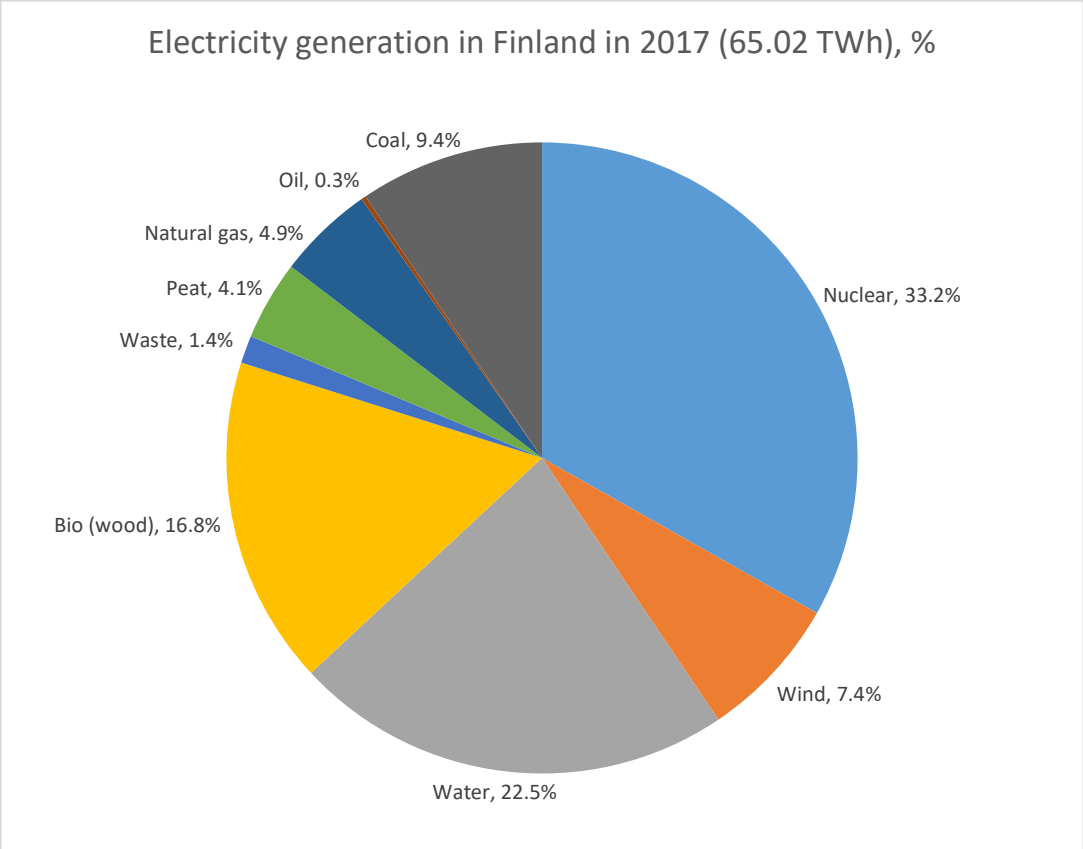
Table 4. Volkswagen e-Golf 100 kW, electricity, 15.6 kWh/100 km (grid electricity consumption). Car components (generic data).

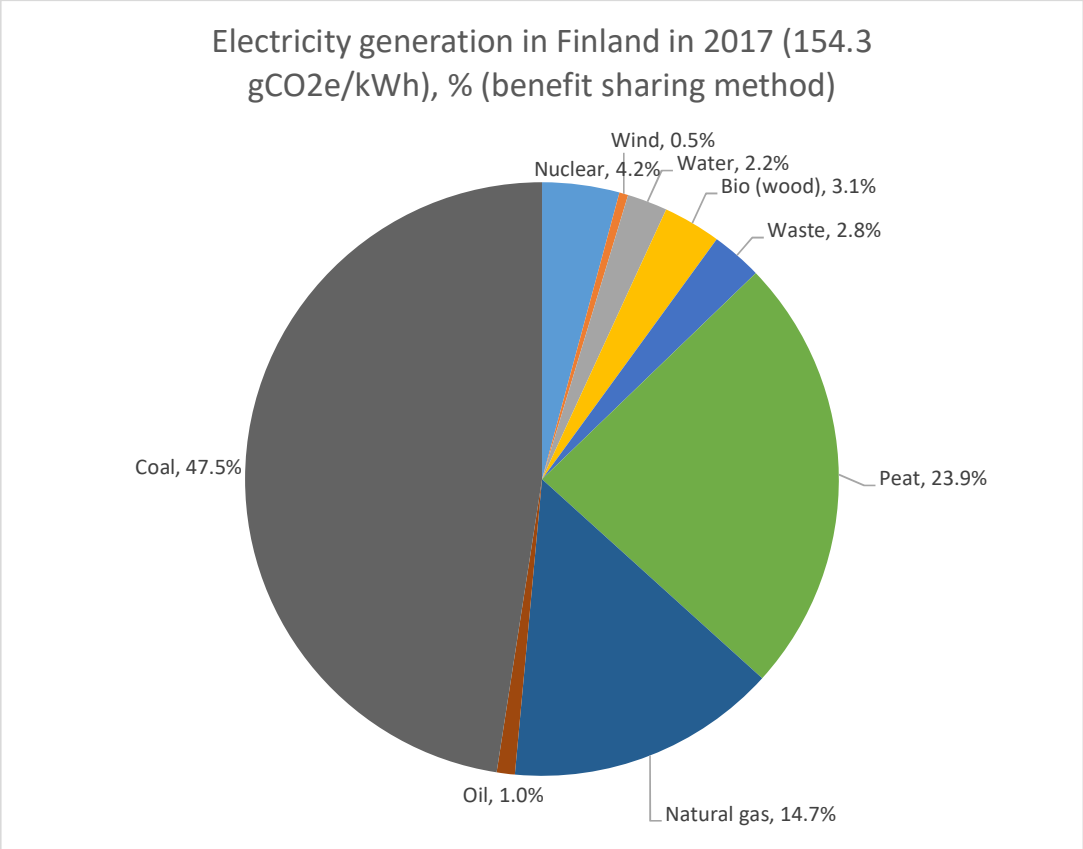
Component group	All vehicles (kg)	EV only (kg)	EV (kg)
Body and doors	566.03		
Brakes	13.16		
Chassis	16.70		
Fluids ICEV and EV	5.38		
Vehicle interior and exterior	255.51		
Tyres and wheels	85.31		
Total	942.09		
EV motor and transmission		304.36	
EV differential transmission		38.56	
EV Li-NCM battery		330.00	
Total		672.92	
Car weight			1615.00

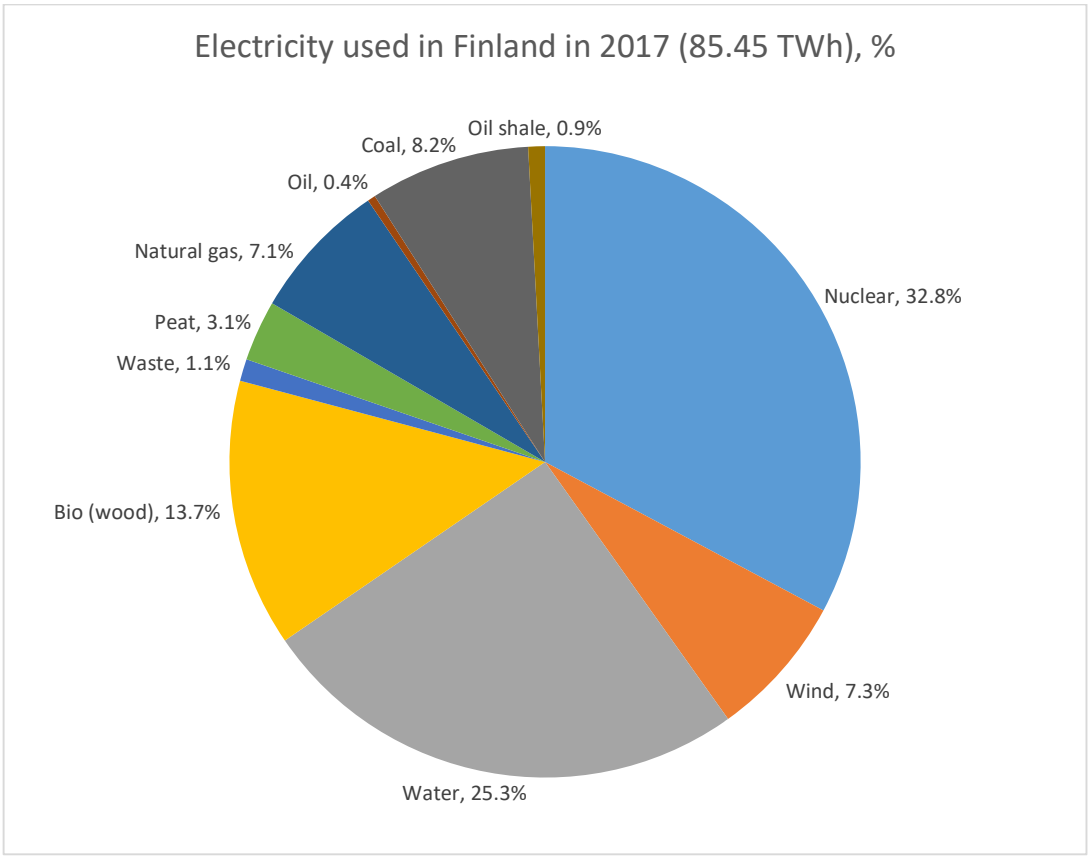
Table 5. Volkswagen Golf, car materials. Some materials are lumped together (generic data).

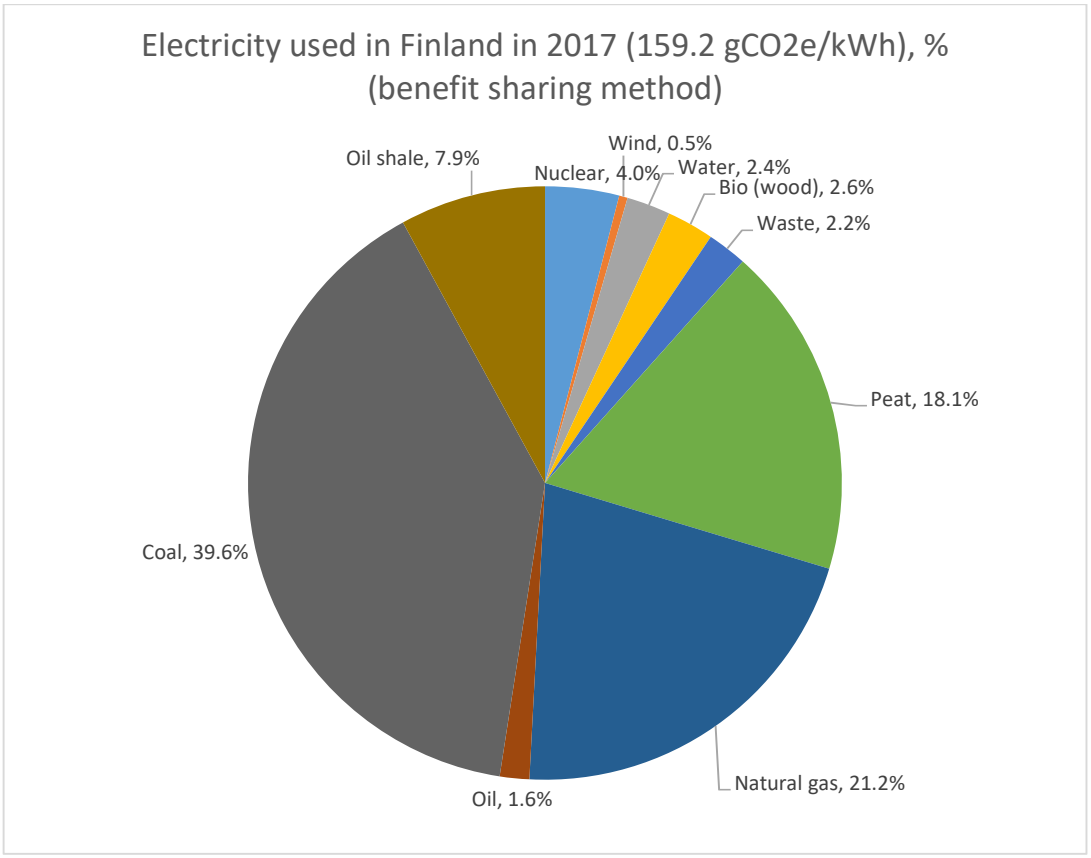
Material	Volkswagen Golf Comfortline 1.0 TSI 85 kW (kg)	Volkswagen Golf Trendline 1.6 TDI 85 kW (kg)	Volkswagen Golf 1.4 TGI 81 kW Gas (kg)	Volkswagen e-Golf 100 kW (kg)	Volkswagen e-Golf 100 kW with extra battery pack (kg)
Plastics:	178.35	190.82	193.17	183.37	202.18
Polyethylene	16.31	17.45	17.66	13.43	13.43
Polypropylene	83.51	89.35	90.45	76.96	91.81
Polystyrene	34.11	36.50	36.95	42.91	46.87
Polyethylene terephthalate	29.38	31.43	31.82	33.10	33.10
Polyvinylchloride	15.05	16.10	16.30	16.96	16.96
Metals (non-ferrous):	109.86	117.54	118.98	299.24	452.03
Aluminum	73.18	78.30	79.26	167.89	239.50
Copper (manganese, cobalt, nickel)	36.68	39.24	39.72	131.35	212.53
Metals (ferrous):	807.70	864.16	874.78	835.49	835.82
Pig iron	24.10	25.78	26.10	3.54	3.54
Cast iron	131.88	141.10	142.83	5.25	5.25
Steel RR	635.37	679.78	688.14	799.13	799.13
Steel OK	16.35	17.49	17.71	27.57	27.90
Fluids:	14.35	15.35	15.54	95.93	175.79
Lubricating oil	7.02	7.51	7.61	1.13	1.13
Refrigerant	4.01	4.29	4.35	3.39	3.39
Water	3.32	3.55	3.59	91.40	171.26
Other materials:	105.74	113.13	114.52	200.98	279.19
Various plastics	33.86	36.23	36.68	38.16	38.16
Adhesives	4.03	4.31	4.37	18.43	30.64
Minerals (clay)	5.92	6.33	6.41	3.39	3.39
Glass	31.78	34.01	34.42	35.44	35.44
Wood	0.00	0.00	0.00	0.00	0.00
Rubber (not tyre)	10.06	10.77	10.90	9.82	9.82
Rubber (tyre)	18.39	19.68	19.92	20.73	20.73
Sulphuric acid	1.68	1.80	1.82	0.41	0.41
Lithium	0.00	0.00	0.00	5.22	9.84
Graphite	0.00	0.00	0.00	69.38	130.76

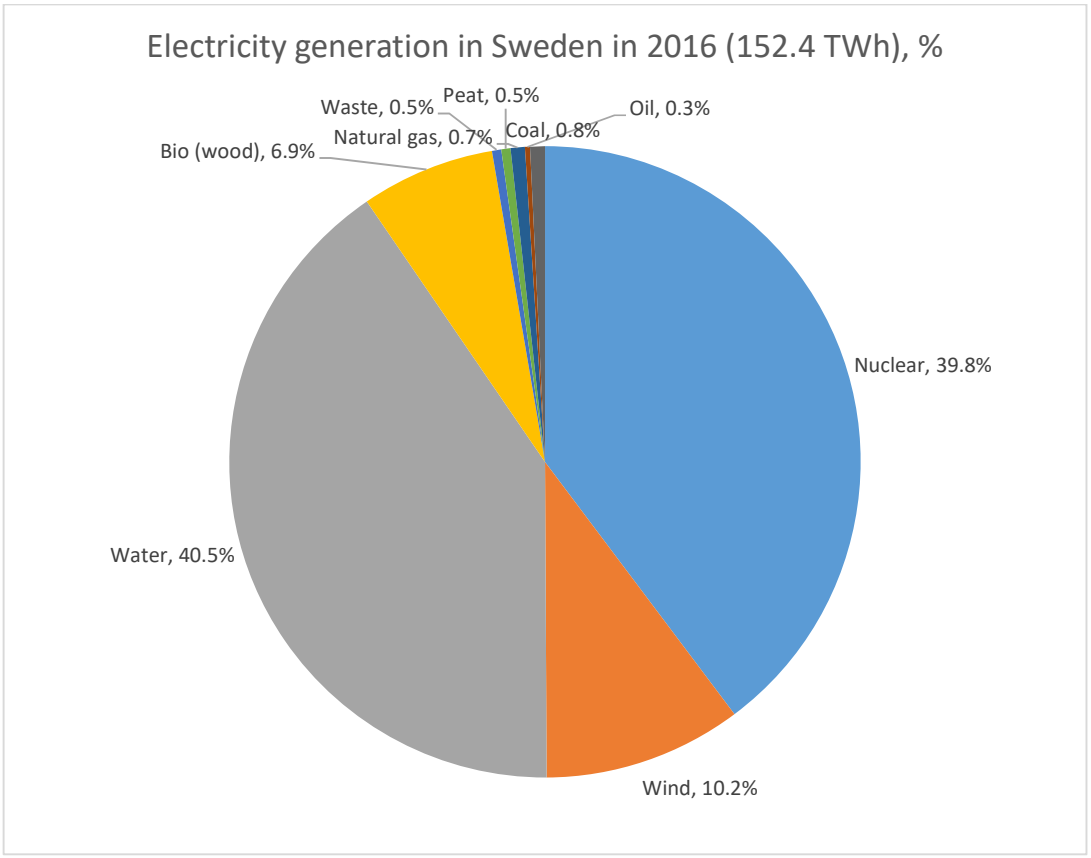
Electricity generation and use

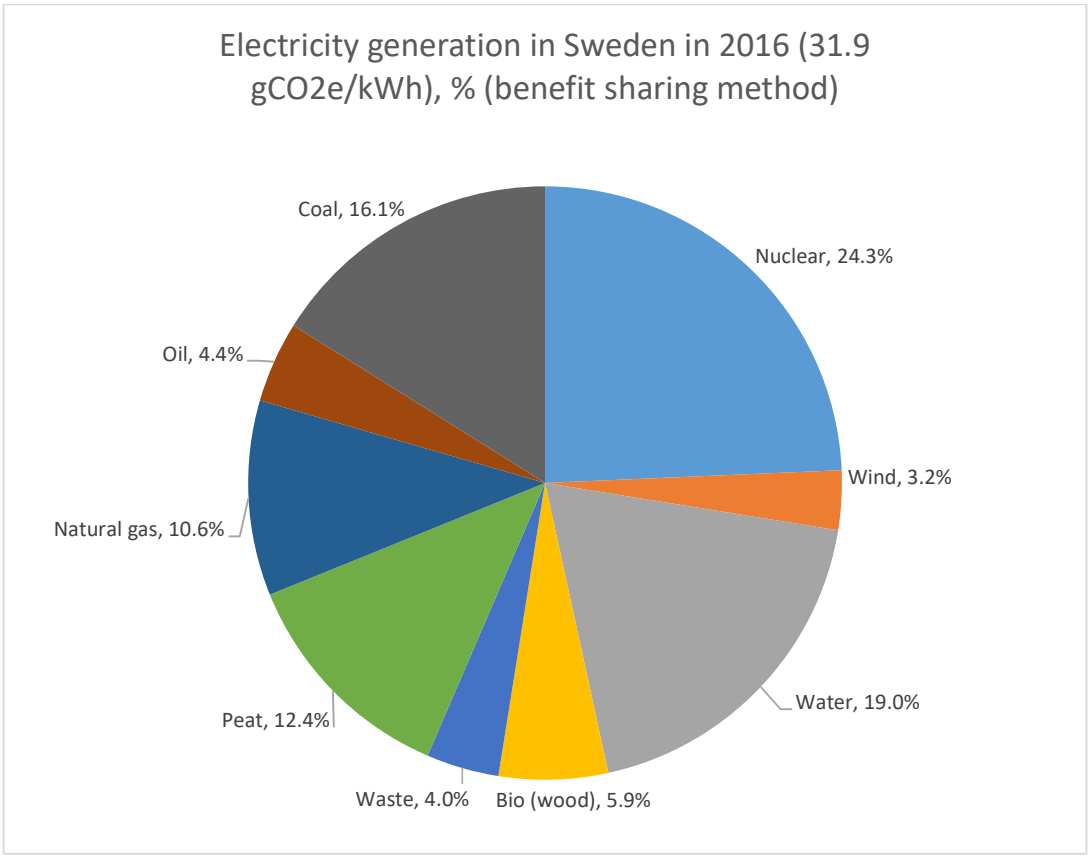


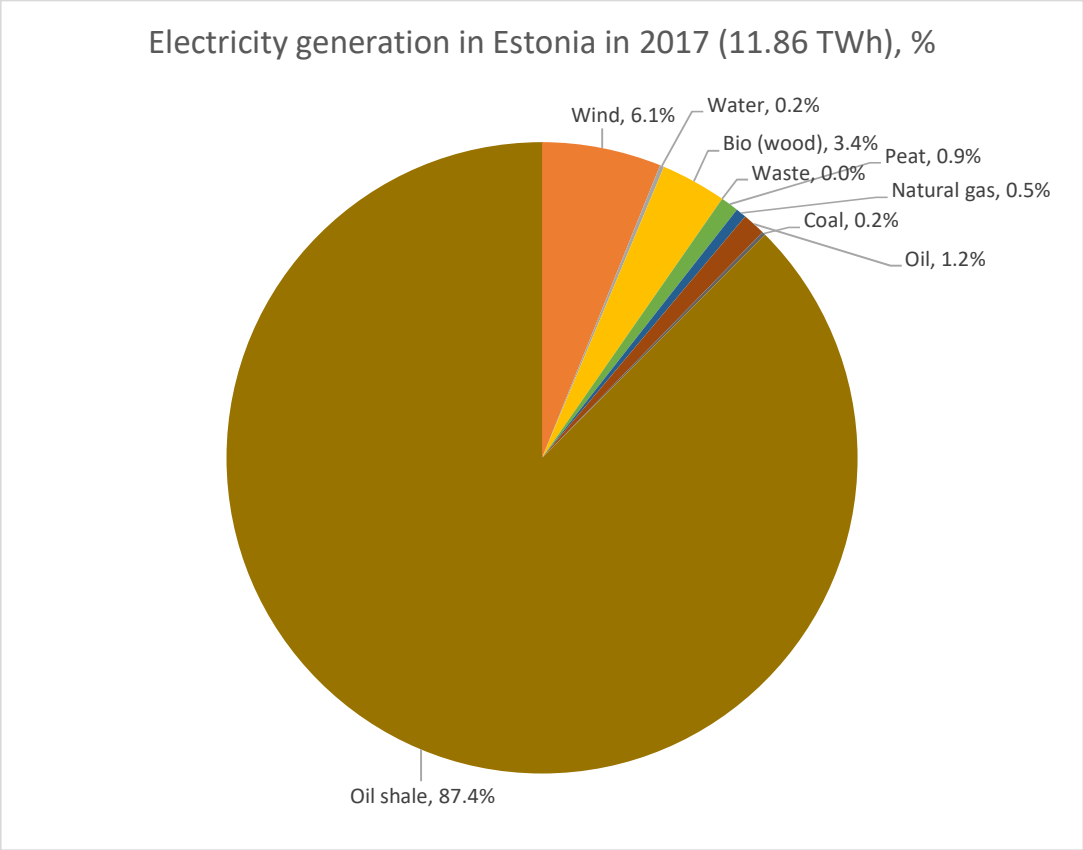


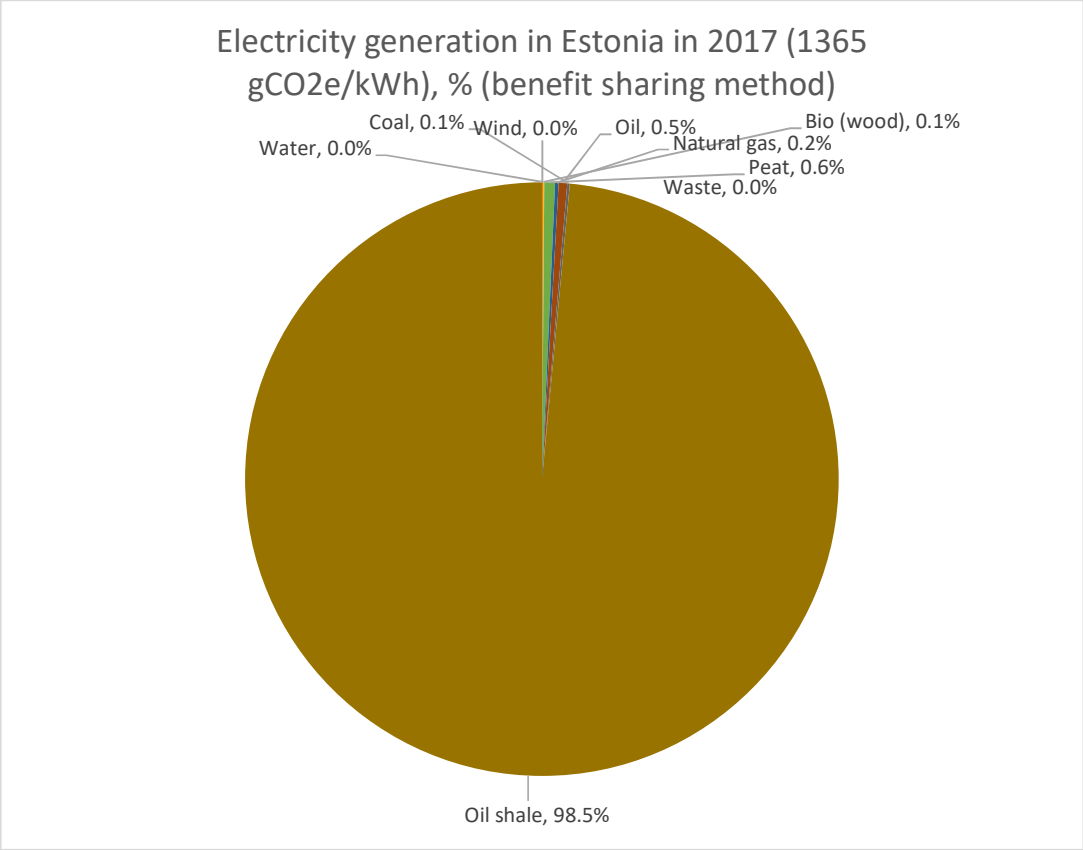

Electricity used in Finland in 2017 (85.45 TWh), %
Oil shale, 0.9%
Coal, 8.2%
Oil, 0.4%
Natural gas, 7.1%
Peat, 3.1%
Waste, 1.1%
Bio (wood), 13.7%
Water, 25.3%
Wind, 7.3%
Nuclear, 32.8%

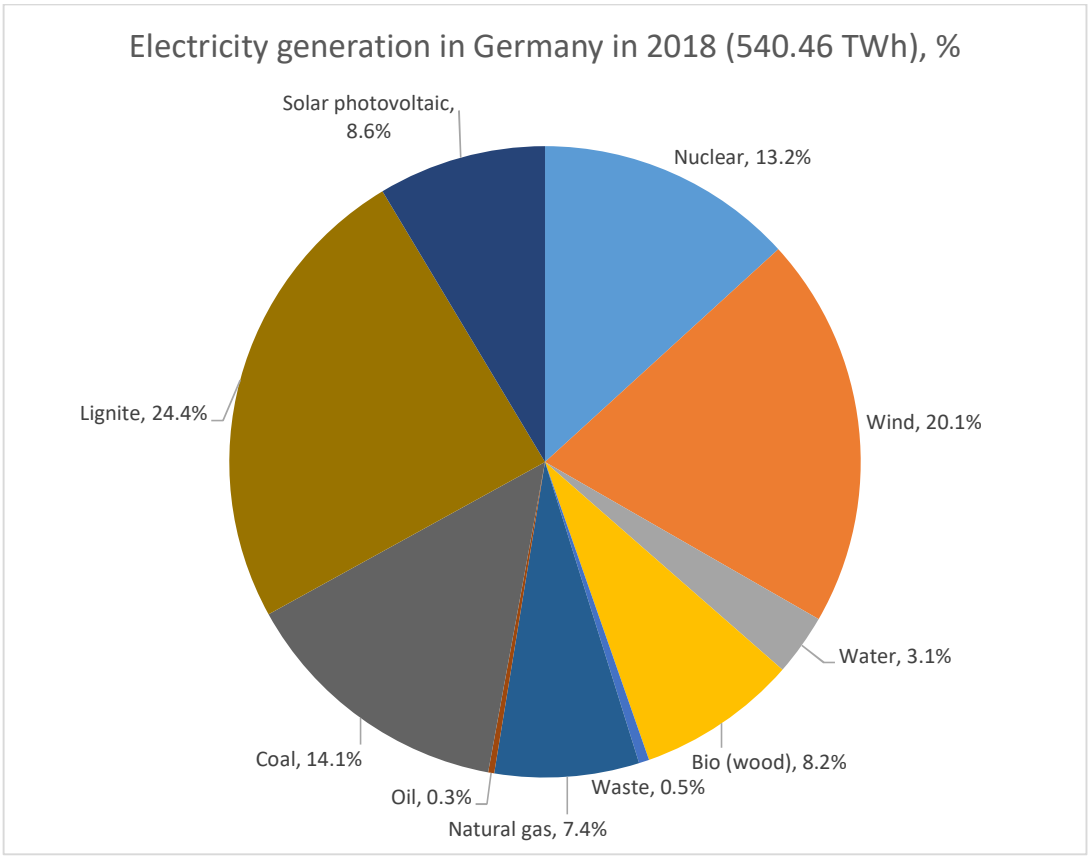

Electricity used in Finland in 2017 (159.2 gCO2e/kWh), %
(benefit sharing method)
Oil shale, 7.9%
Wind, 0.5%
Nuclear, 4.0%
Water, 2.4%
Bio (wood), 2.6%
Waste, 2.2%
Peat, 18.1%
Coal, 39.6%
Oil, 1.6%
Natural gas, 21.2%

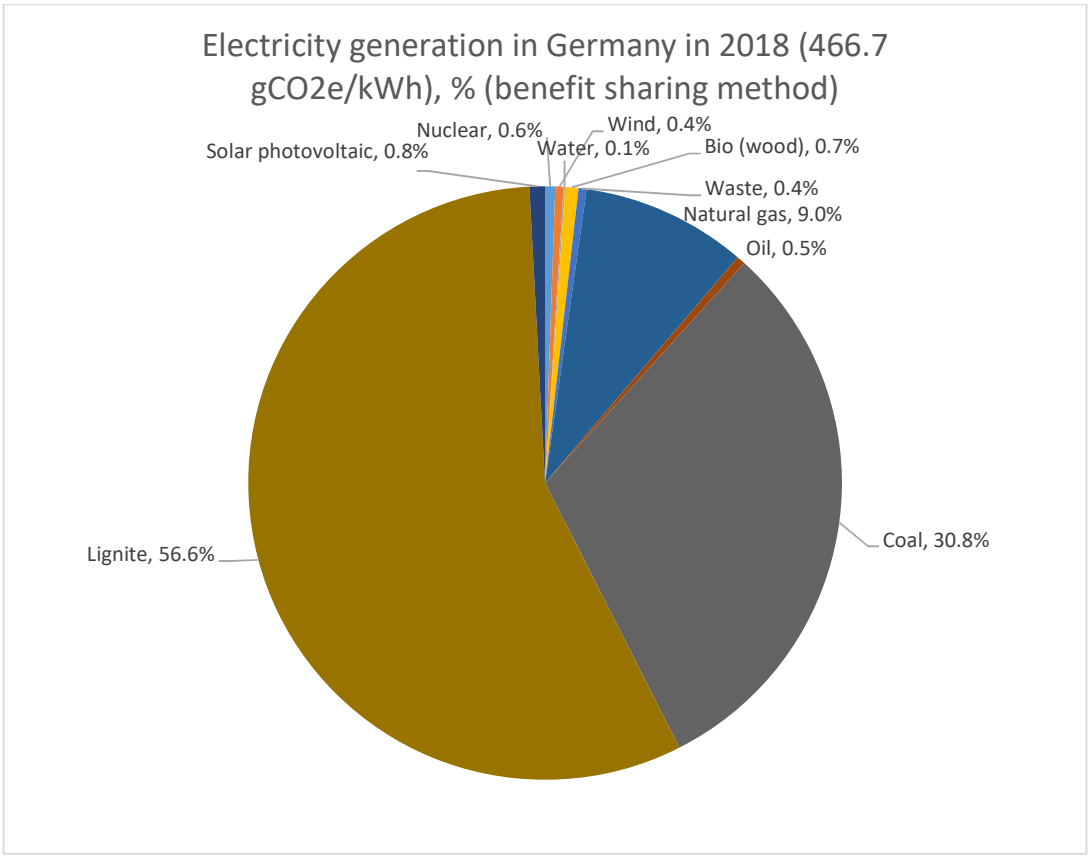

Electricity generation in Sweden in 2016 (152.4 TWh), %
Waste, 0.5%
Peat, 0.5%
Oil, 0.3%
Natural gas, 0.7%
Coal, 0.8%
Bio (wood), 6.9%
Nuclear, 39.8%
Water, 40.5%
Wind, 10.2%

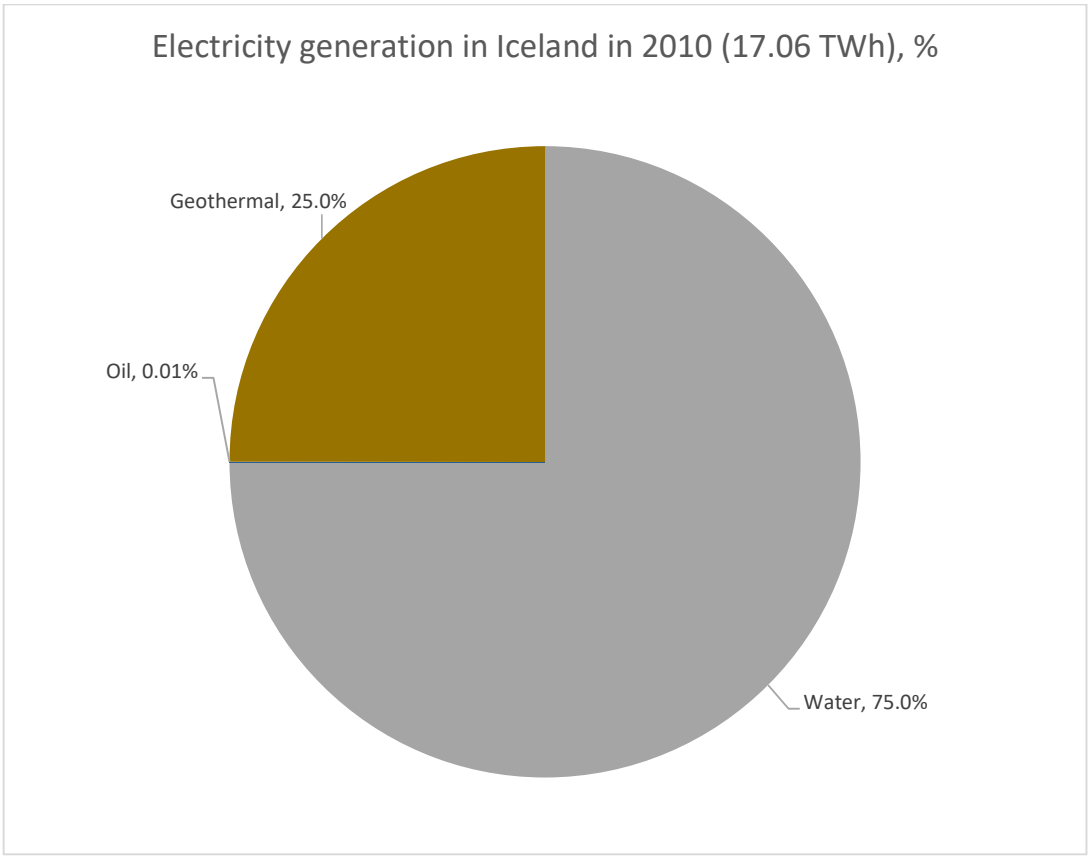

Electricity generation in Sweden in 2016 (31.9 gCO2e/kWh), % (benefit sharing method)
Coal, 16.1%
Nuclear, 24.3%
Oil, 4.4%
Wind, 3.2%
Natural gas, 10.6%
Water, 19.0%
Peat, 12.4%
Waste, 4.0%
Bio (wood), 5.9%

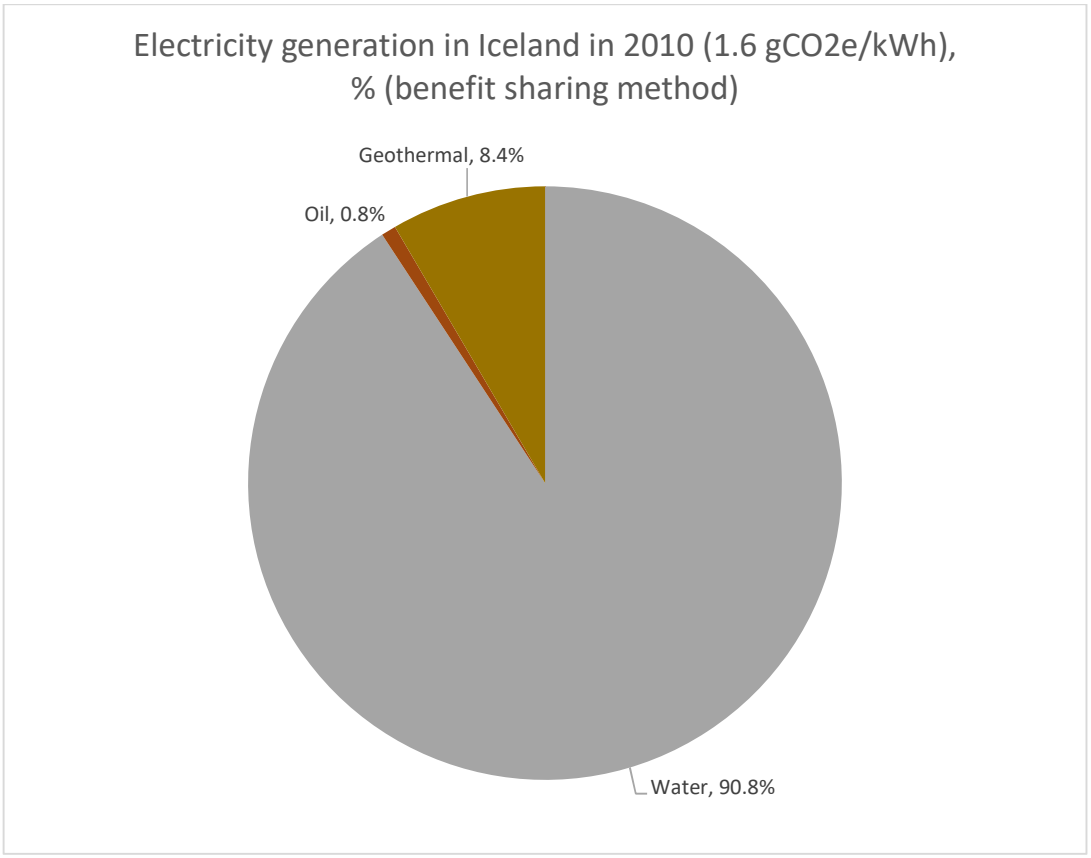

Electricity generation in Estonia in 2017 (11.86 TWh), %
Wind, 6.1%
Water, 0.2%
Bio (wood), 3.4%
Peat, 0.9%
Waste, 0.0%
Natural gas, 0.5%
Coal, 0.2%
Oil, 1.2%
Oil shale, 87.4%


Electricity generation in Estonia in 2017 (1365 gCO2e/kWh), % (benefit sharing method)
Coal, 0.1%
Wind, 0.0%
Oil, 0.5%
Bio (wood), 0.1%
Water, 0.0%
Natural gas, 0.2%
Peat, 0.6%
Waste, 0.0%
Oil shale, 98.5%

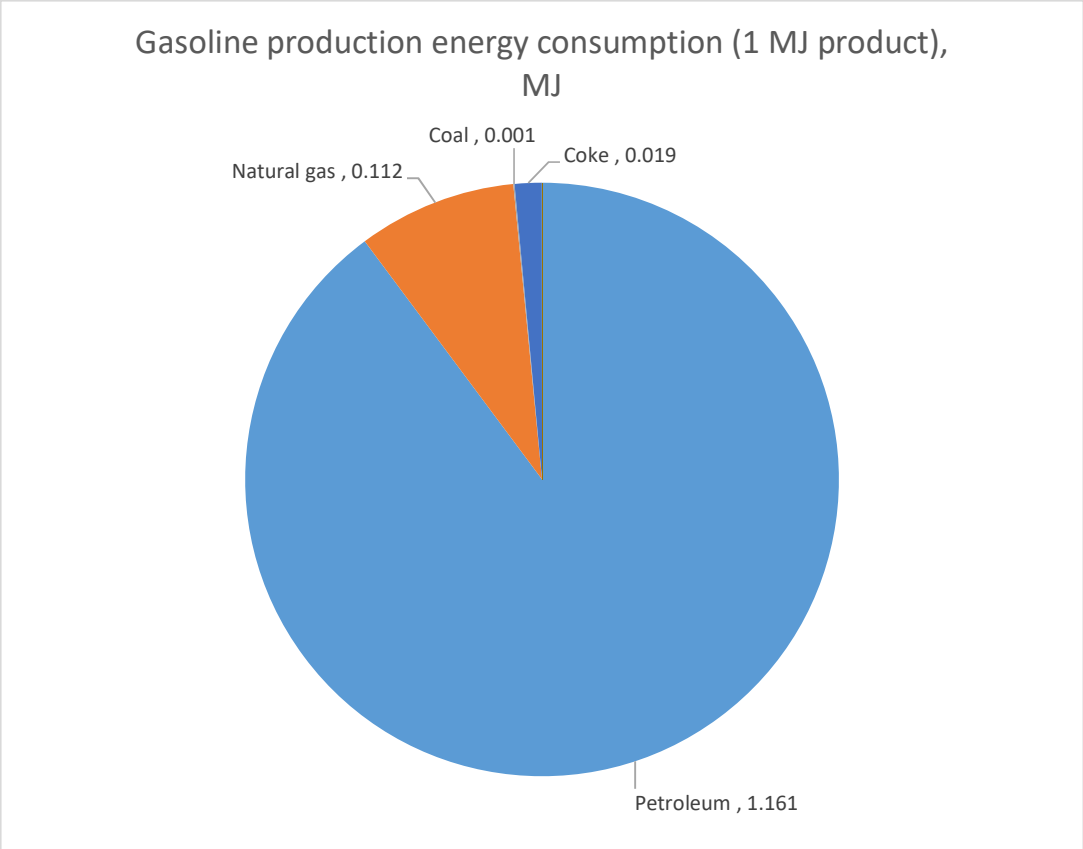

Electricity generation in Germany in 2018 (540.46 TWh), %
Solar photovoltaic, 8.6%
Nuclear, 13.2%
Wind, 20.1%
Water, 3.1%
Bio (wood), 8.2%
Waste, 0.5%
Natural gas, 7.4%
Oil, 0.3%
Coal, 14.1%
Lignite, 24.4%

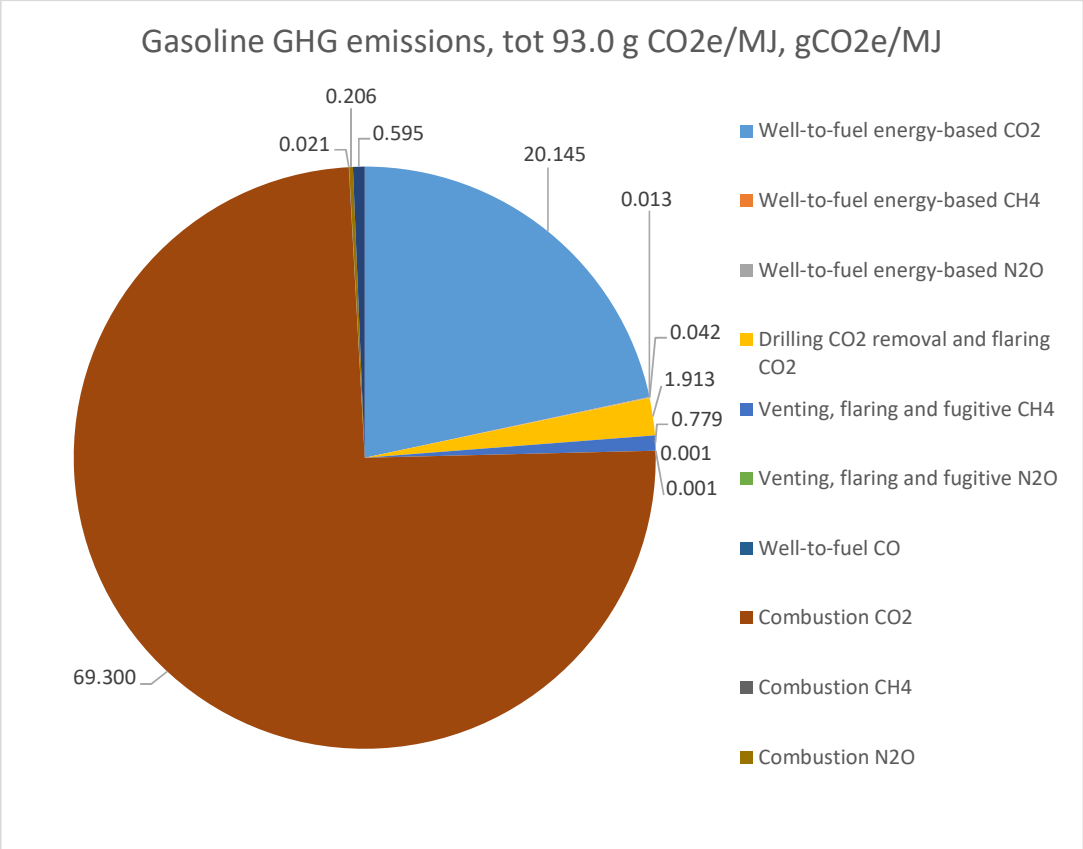

Electricity generation in Germany in 2018 (466.7 gCO2e/kWh), % (benefit sharing method)
Nuclear, 0.6%
Wind, 0.4%
Solar photovoltaic, 0.8%
Water, 0.1%
Bio (wood), 0.7%
Waste, 0.4%
Natural gas, 9.0%
Oil, 0.5%
Coal, 30.8%
Lignite, 56.6%

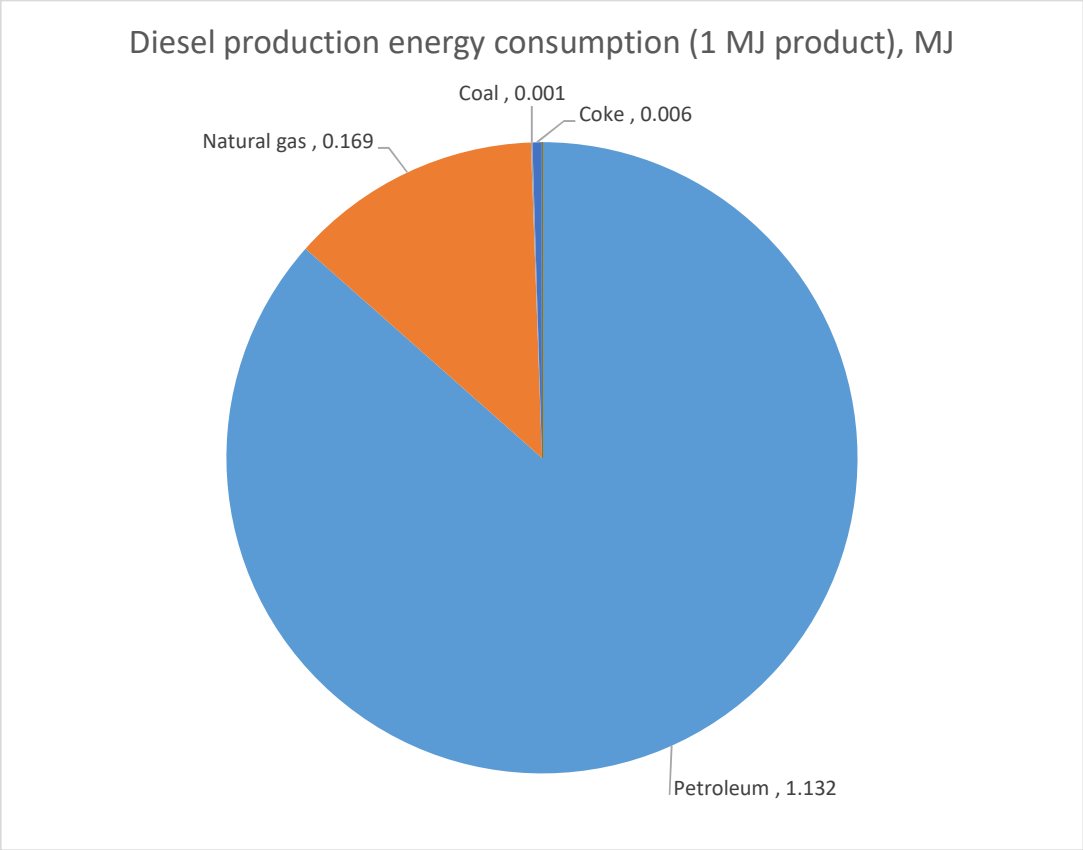

Electricity generation in Iceland in 2010 (17.06 TWh), %
Geothermal, 25.0%
Oil, 0.01%
Water, 75.0%

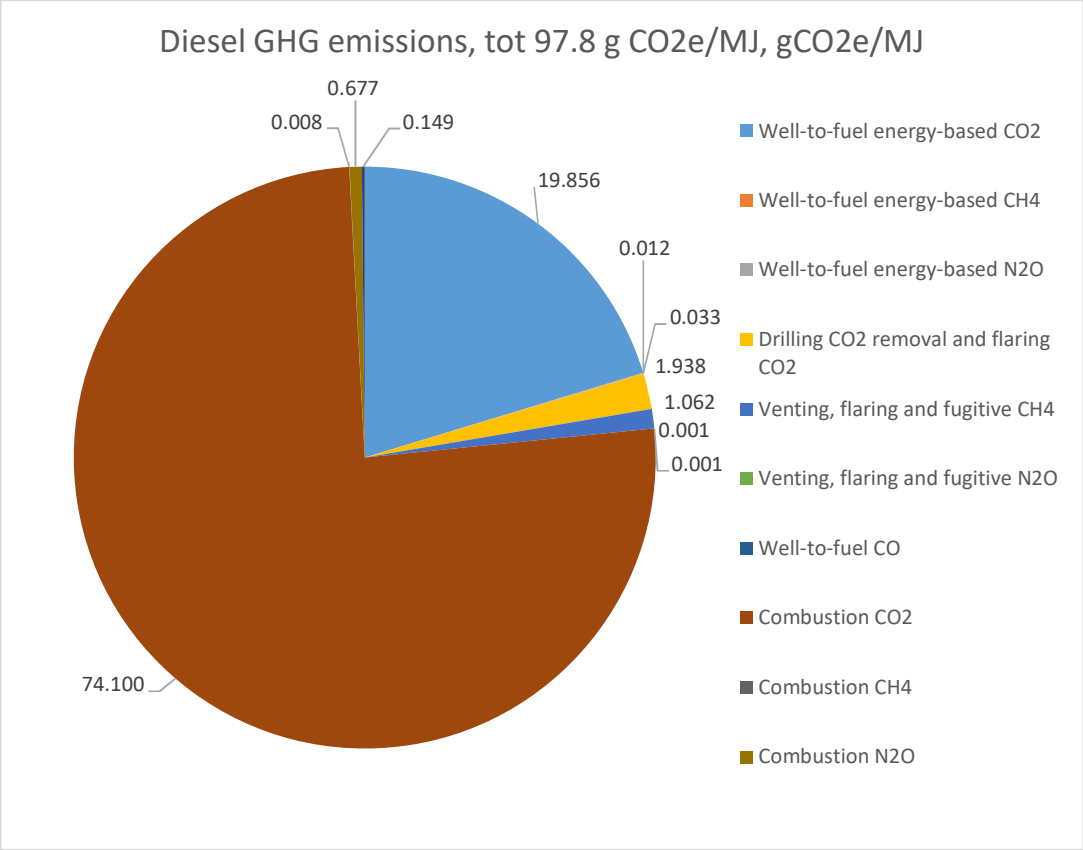

Electricity generation in Iceland in 2010 (1.6 gCO2e/kWh), % (benefit sharing method)
Geothermal, 8.4%
Oil, 0.8%
Water, 90.8%

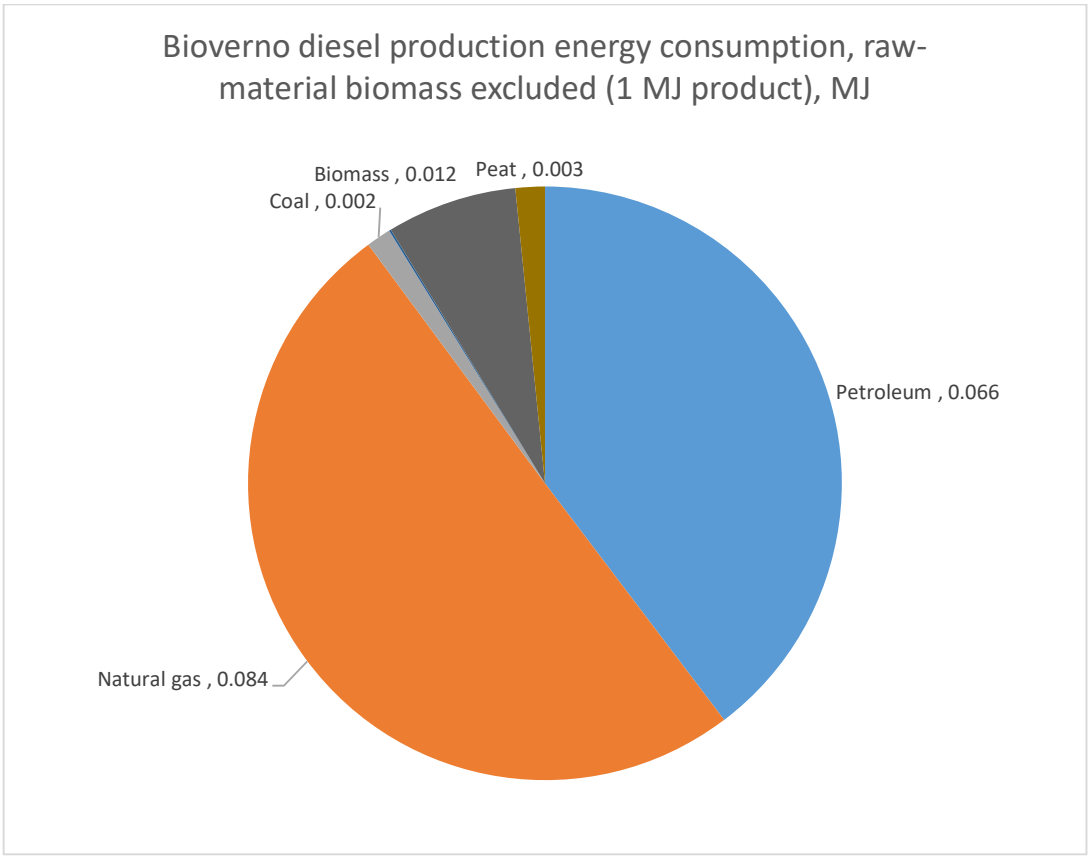
Fuels production and use

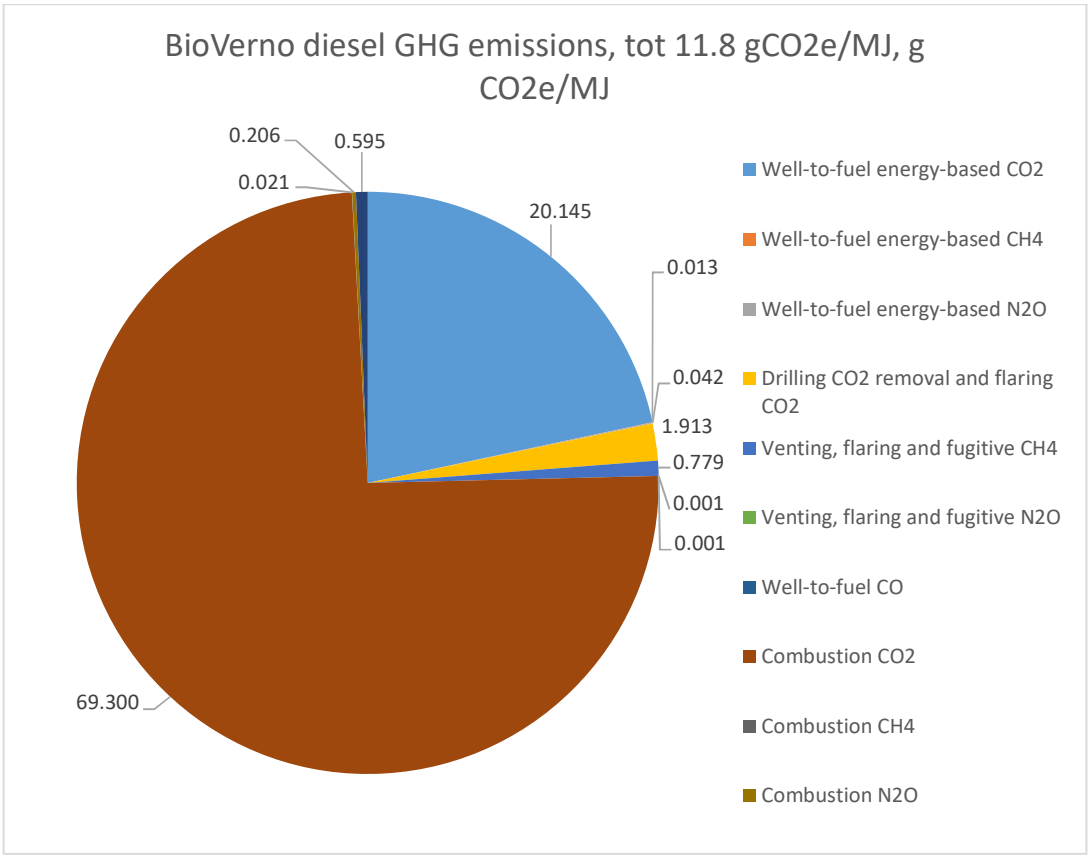


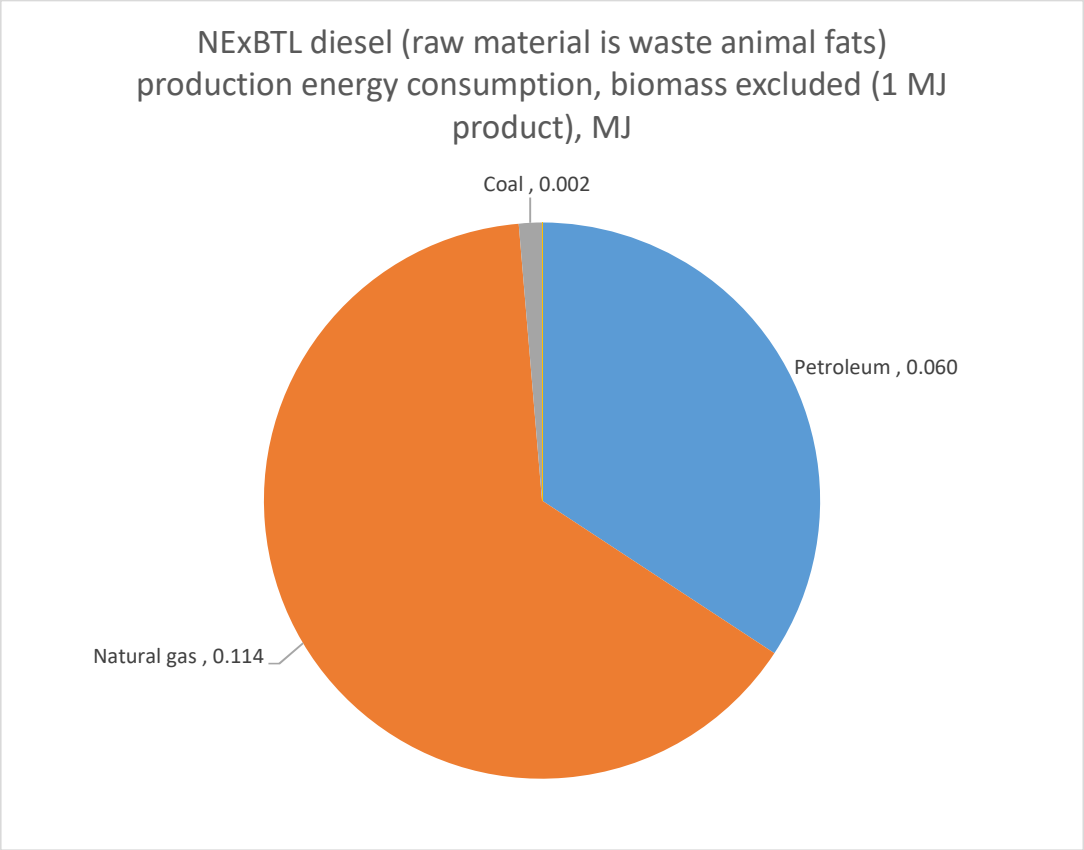


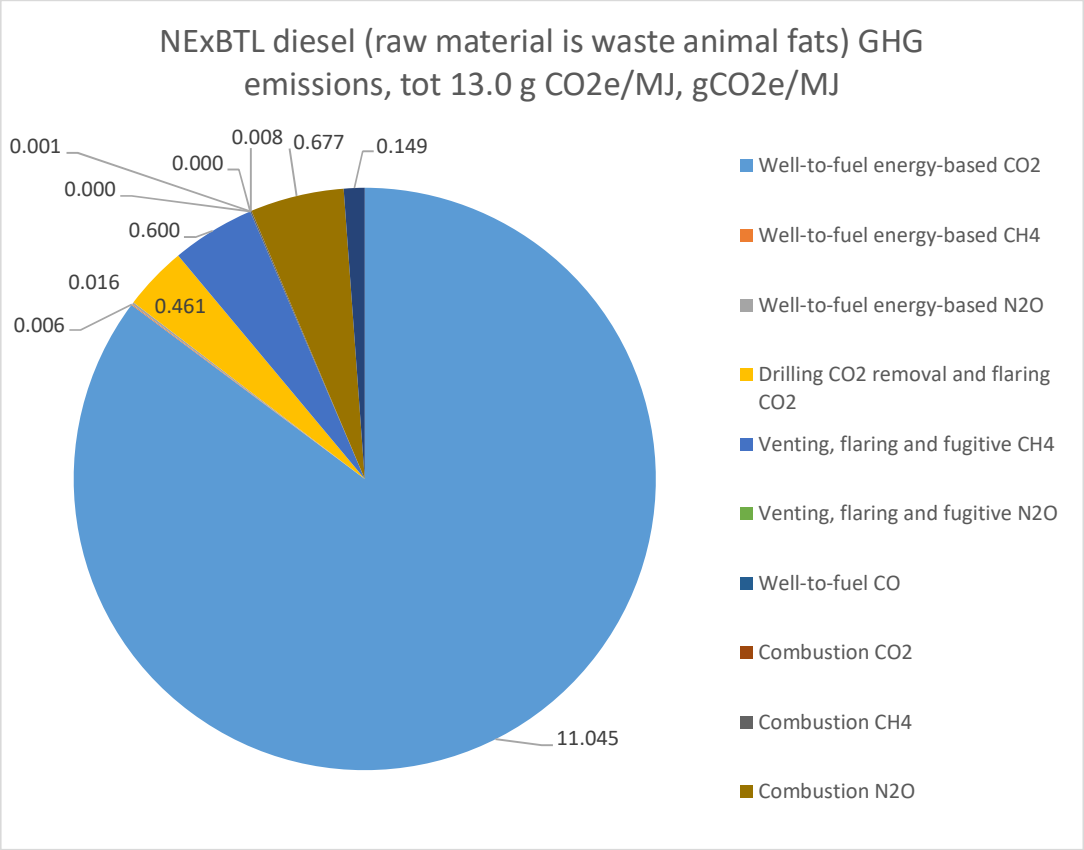

Diesel production energy consumption (1 MJ product), MJ
Coal , 0.001
Coke , 0.006
Natural gas , 0.169
Petroleum , 1.132

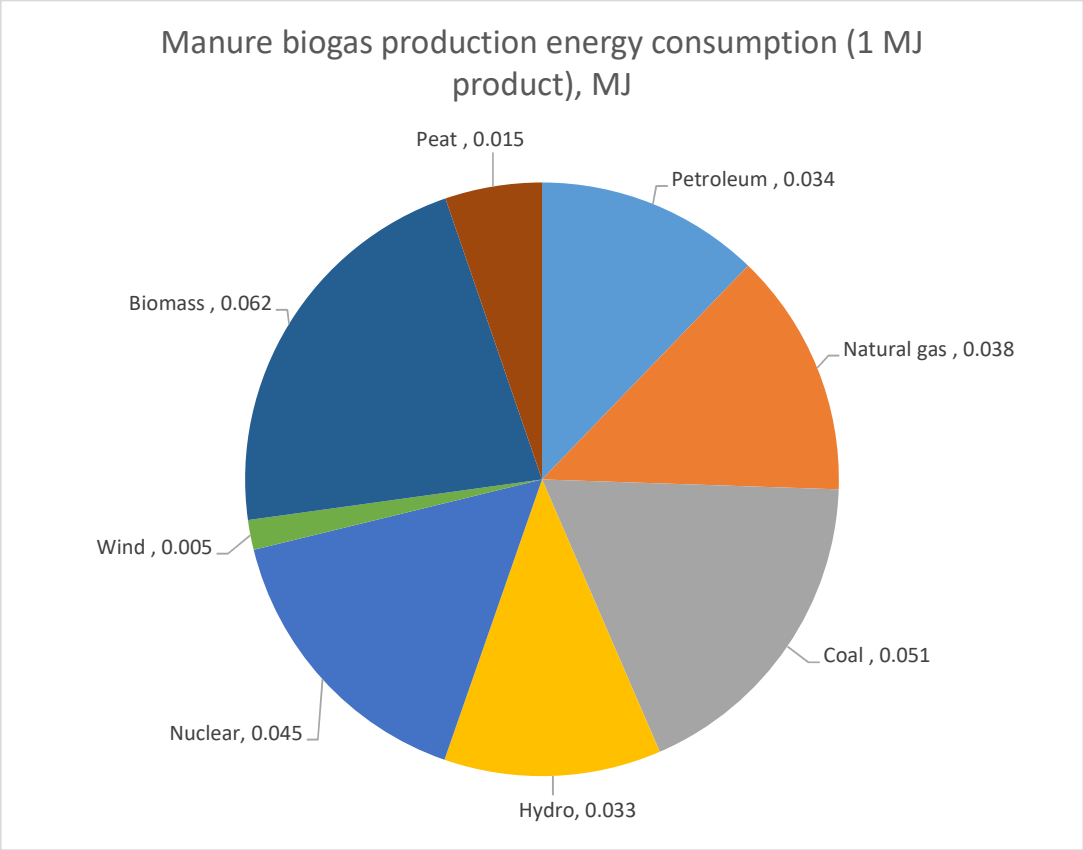

Diesel GHG emissions, tot 97.8 g CO2e/MJ, gCO2e/MJ
0.677
0.008
0.149
19.856
0.012
0.033
1.938
1.062
0.001
0.001
74.100
Well-to-fuel energy-based CO2
Well-to-fuel energy-based CH4
Well-to-fuel energy-based N2O
Drilling CO2 removal and flaring CO2
Venting, flaring and fugitive CH4
Venting, flaring and fugitive N2O
Well-to-fuel CO
Combustion CO2
Combustion CH4
Combustion N2O

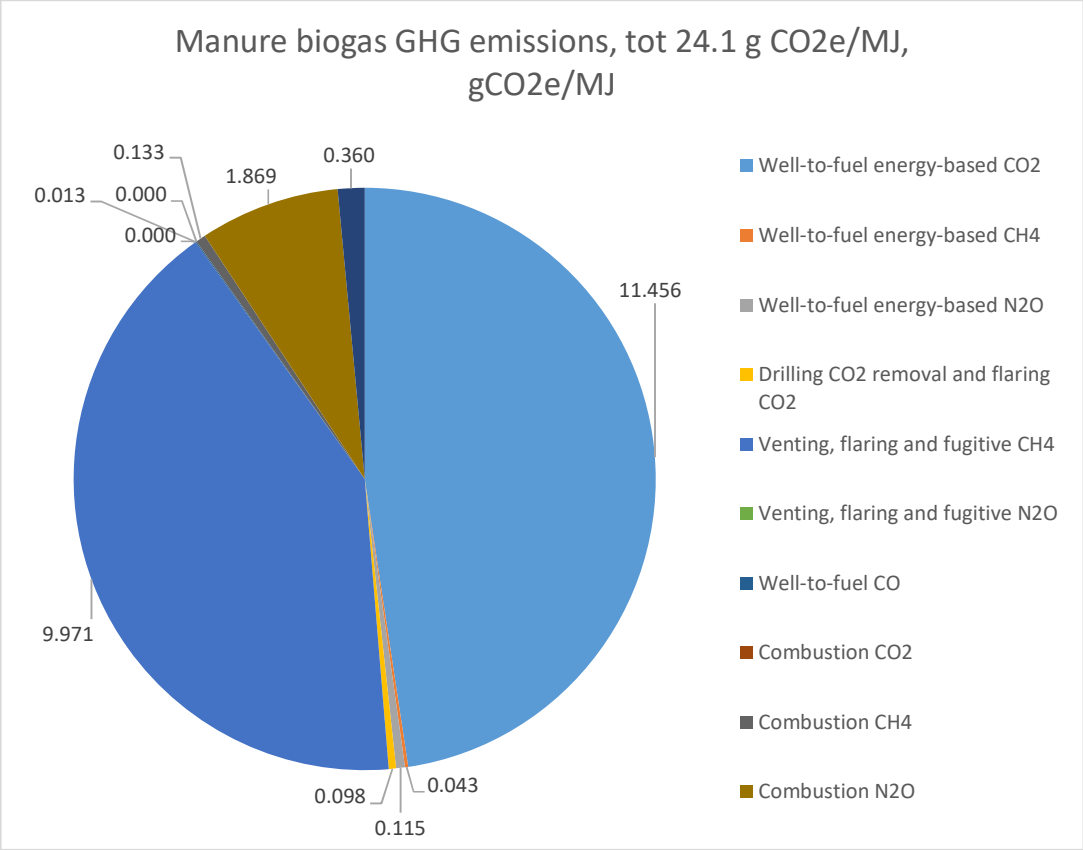

Bioverno diesel production energy consumption, raw-material biomass excluded (1 MJ product), MJ
Biomass , 0.012
Peat , 0.003
Coal , 0.002
Petroleum , 0.066
Natural gas , 0.084

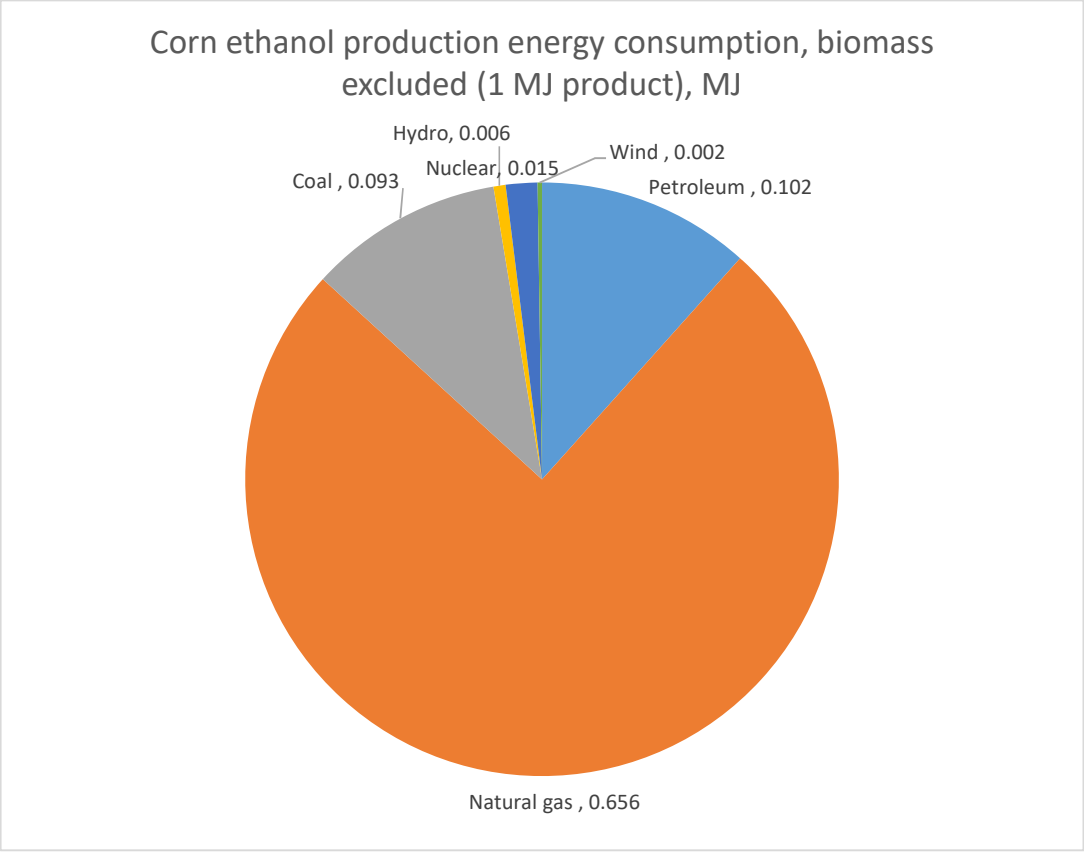

BioVerno diesel GHG emissions, tot 11.8 gCO2e/MJ, g CO2e/MJ
0.206
0.595
0.021
20.145
0.013
0.042
1.913
0.779
0.001
0.001
69.300
Well-to-fuel energy-based CO2
Well-to-fuel energy-based CH4
Well-to-fuel energy-based N2O
Drilling CO2 removal and flaring CO2
Venting, flaring and fugitive CH4
Venting, flaring and fugitive N2O
Well-to-fuel CO
Combustion CO2
Combustion CH4
Combustion N2O

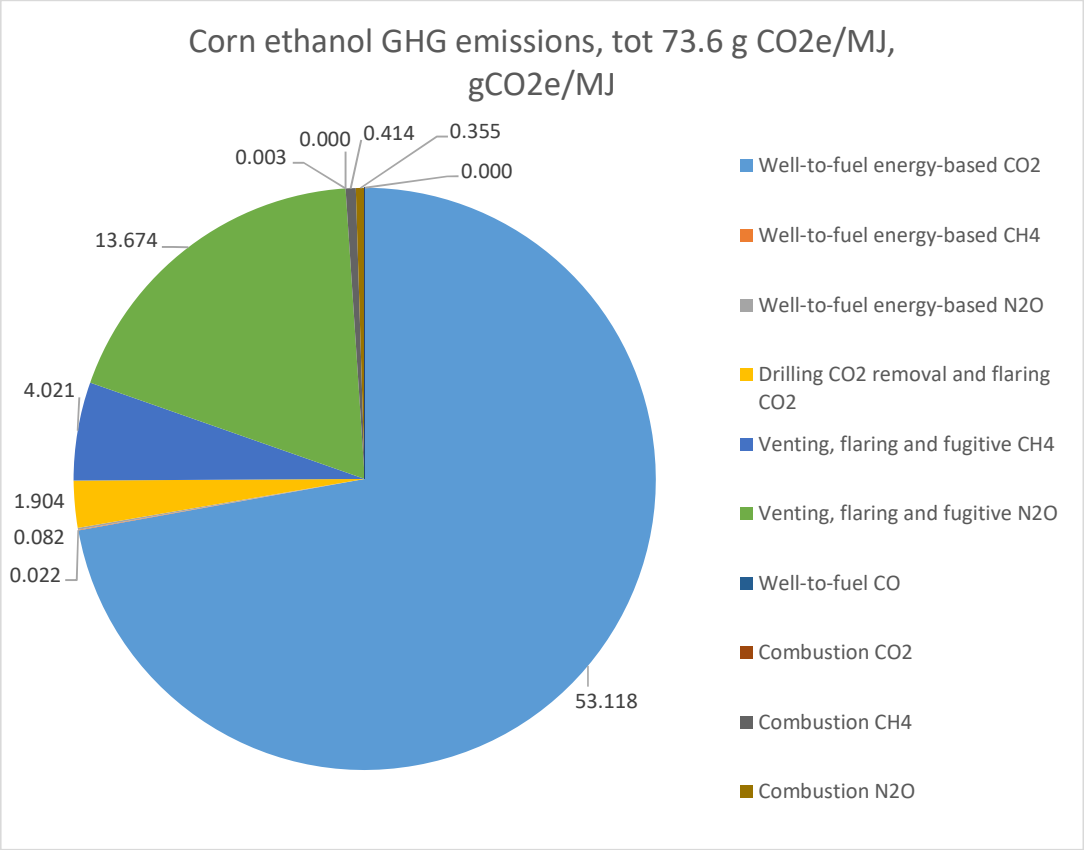

NExBTL diesel (raw material is waste animal fats) production energy consumption, biomass excluded (1 MJ product), MJ
Coal , 0.002
Petroleum , 0.060
Natural gas , 0.114

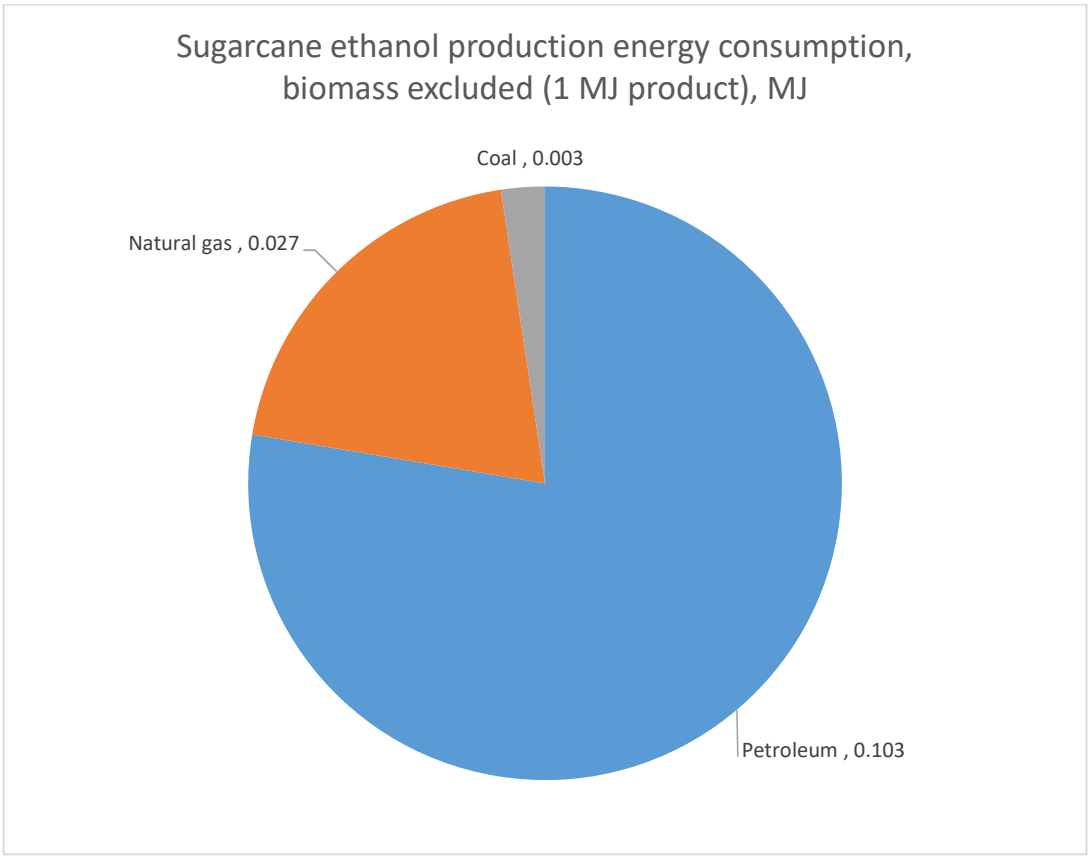

NExBTL diesel (raw material is waste animal fats) GHG emissions, tot 13.0 g CO2e/MJ, gCO2e/MJ
0.001
0.000
0.000
0.008
0.677
0.149
0.600
0.016
0.461
0.006
11.045
Well-to-fuel energy-based CO2
Well-to-fuel energy-based CH4
Well-to-fuel energy-based N2O
Drilling CO2 removal and flaring CO2
Venting, flaring and fugitive CH4
Venting, flaring and fugitive N2O
Well-to-fuel CO
Combustion CO2
Combustion CH4
Combustion N2O

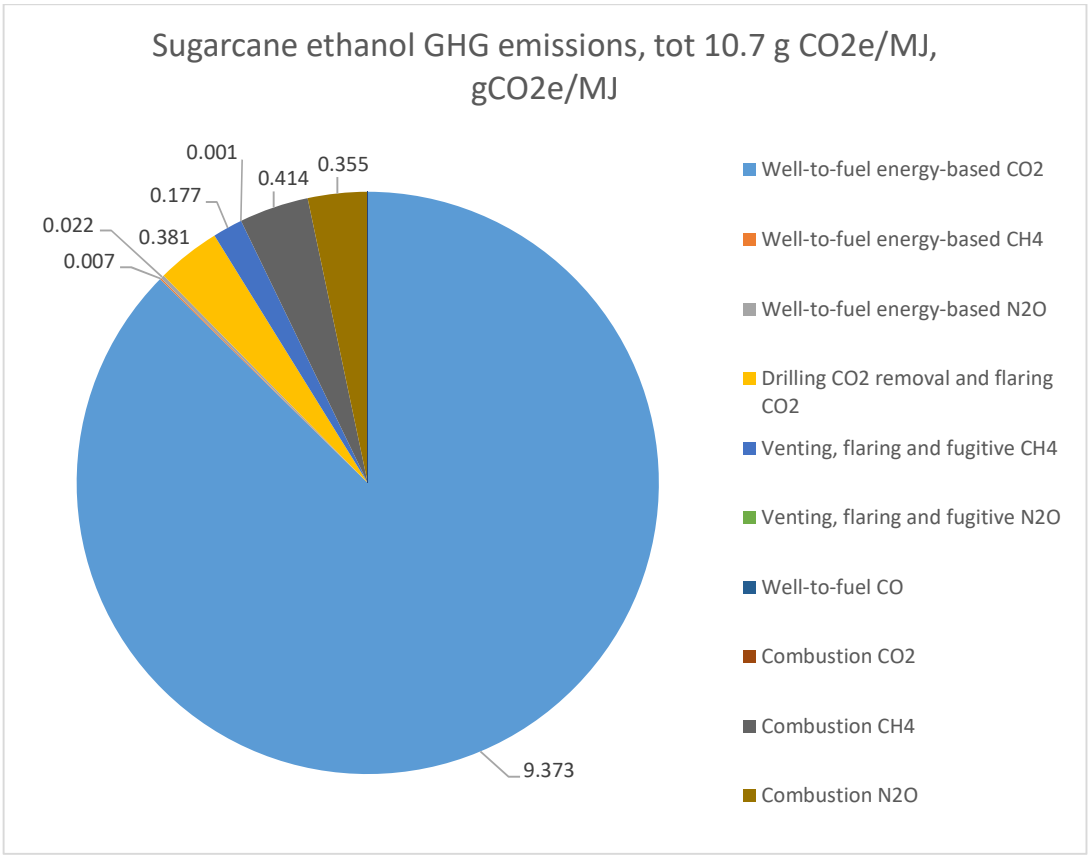

Manure biogas production energy consumption (1 MJ product), MJ
Peat , 0.015
Petroleum , 0.034
Biomass , 0.062
Natural gas , 0.038
Wind , 0.005
Coal , 0.051
Nuclear, 0.045
Hydro, 0.033

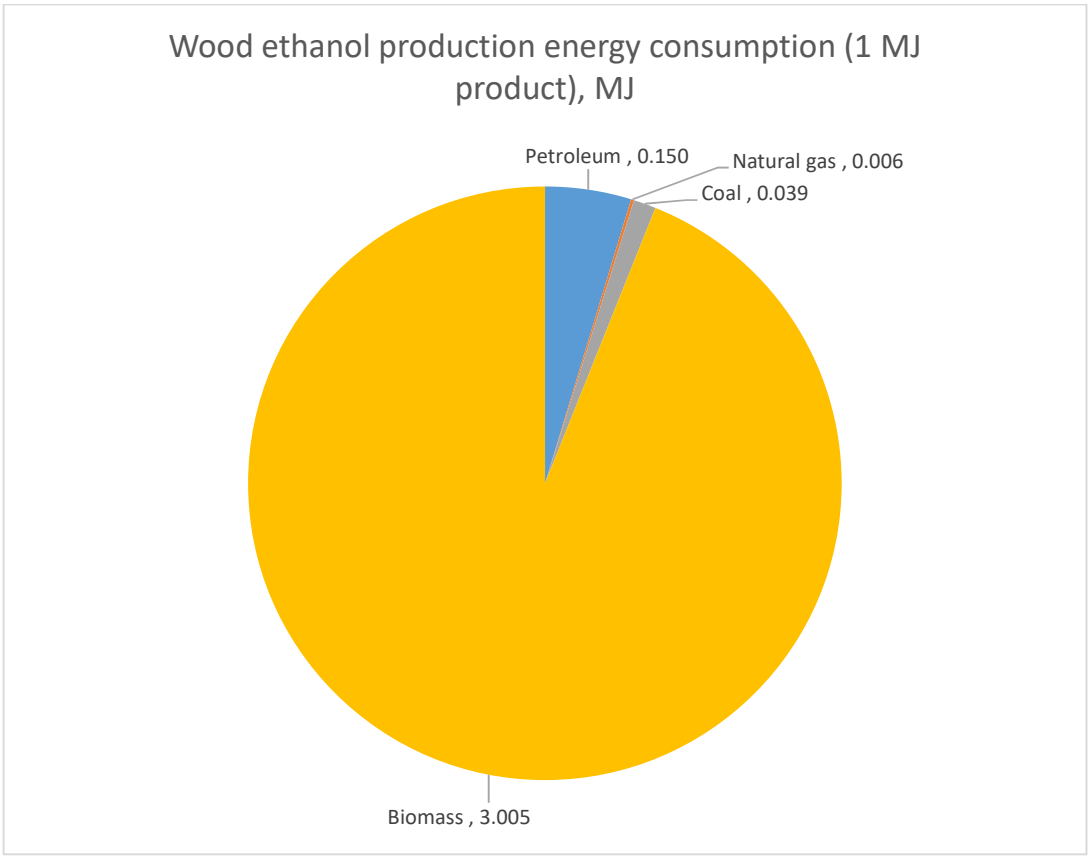

Manure biogas GHG emissions, tot 24.1 g CO2e/MJ, gCO2e/MJ
0.133
0.360
1.869
0.013
0.000
0.000
11.456
9.971
0.098
0.043
0.115
Well-to-fuel energy-based CO2
Well-to-fuel energy-based CH4
Well-to-fuel energy-based N2O
Drilling CO2 removal and flaring CO2
Venting, flaring and fugitive CH4
Venting, flaring and fugitive N2O
Well-to-fuel CO
Combustion CO2
Combustion CH4
Combustion N2O

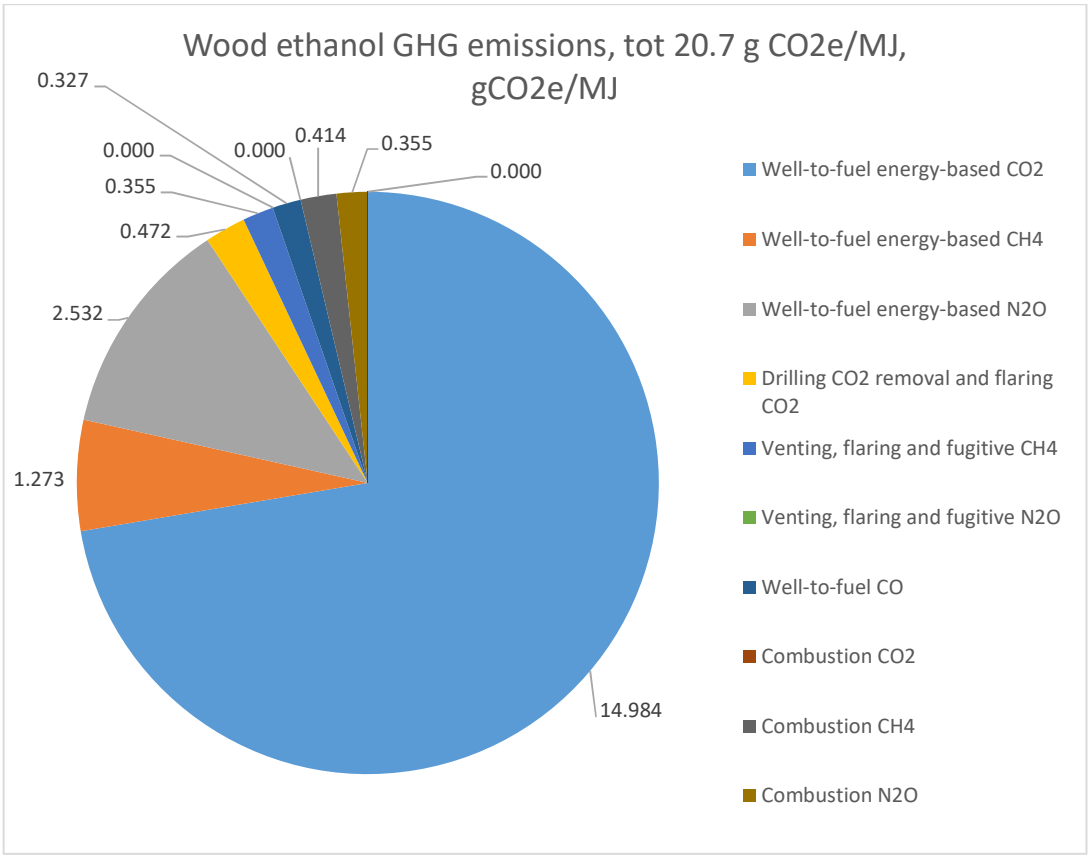

Corn ethanol production energy consumption, biomass excluded (1 MJ product), MJ
Hydro, 0.006
Wind , 0.002
Nuclear, 0.015
Coal , 0.093
Petroleum , 0.102
Natural gas , 0.656

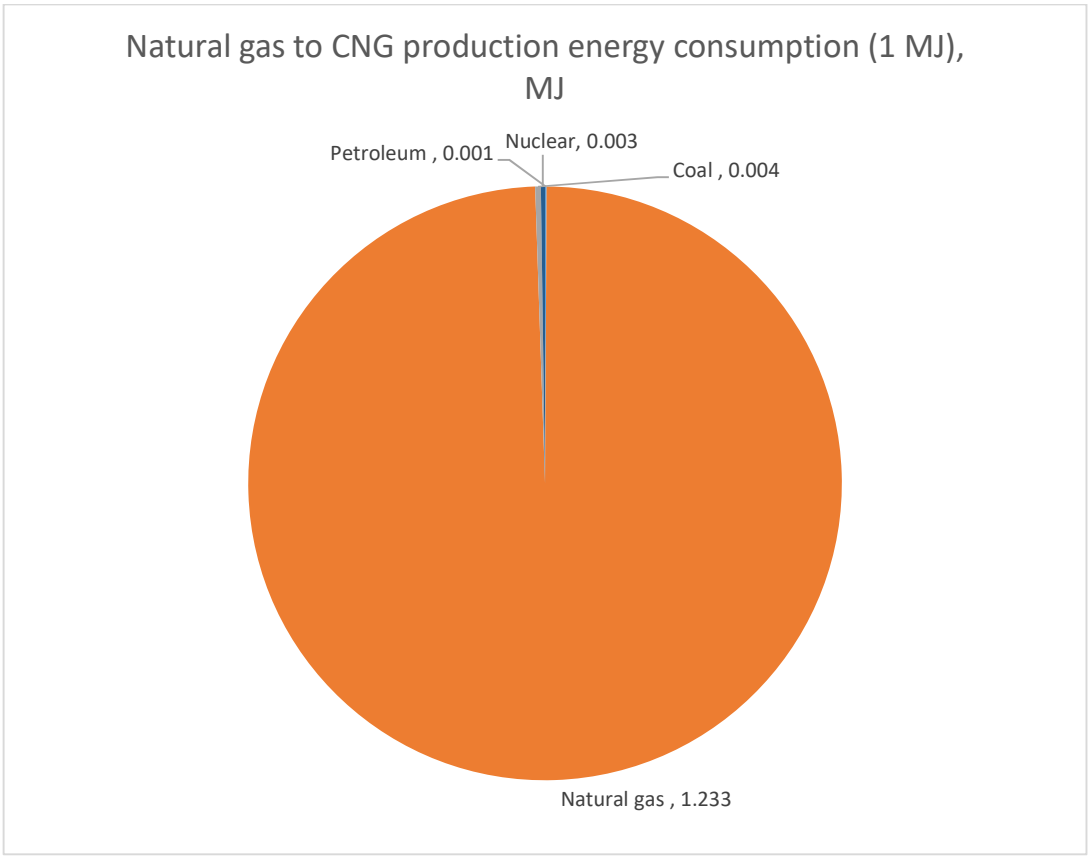

Corn ethanol GHG emissions, tot 73.6 g CO2e/MJ, gCO2e/MJ
0.000
0.414
0.355
0.003
0.000
13.674
4.021
1.904
0.082
0.022
53.118
Well-to-fuel energy-based CO2
Well-to-fuel energy-based CH4
Well-to-fuel energy-based N2O
Drilling CO2 removal and flaring CO2
Venting, flaring and fugitive CH4
Venting, flaring and fugitive N2O
Well-to-fuel CO
Combustion CO2
Combustion CH4
Combustion N2O

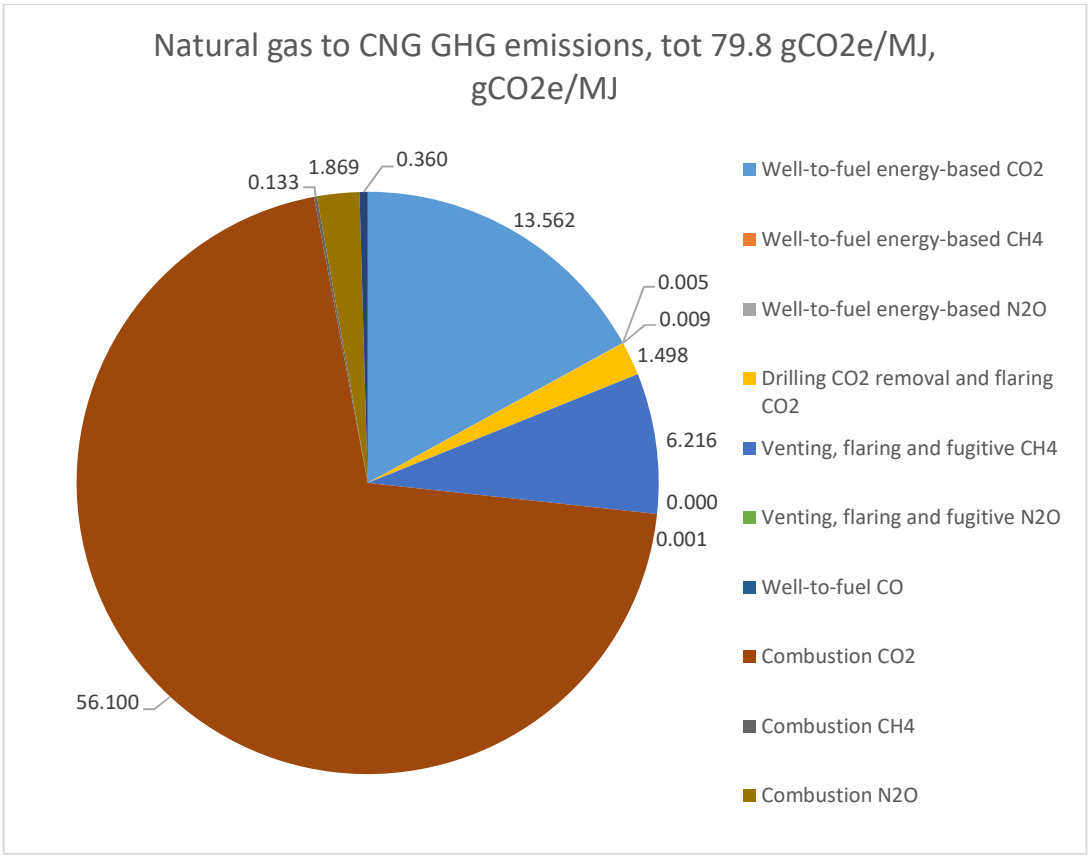

Sugarcane ethanol production energy consumption, biomass excluded (1 MJ product), MJ
Coal , 0.003
Natural gas , 0.027
Petroleum , 0.103


Sugarcane ethanol GHG emissions, tot 10.7 g CO2e/MJ, gCO2e/MJ
0.001
0.414
0.355
0.177
0.022
0.381
0.007
9.373
Well-to-fuel energy-based CO2
Well-to-fuel energy-based CH4
Well-to-fuel energy-based N2O
Drilling CO2 removal and flaring CO2
Venting, flaring and fugitive CH4
Venting, flaring and fugitive N2O
Well-to-fuel CO
Combustion CO2
Combustion CH4
Combustion N2O

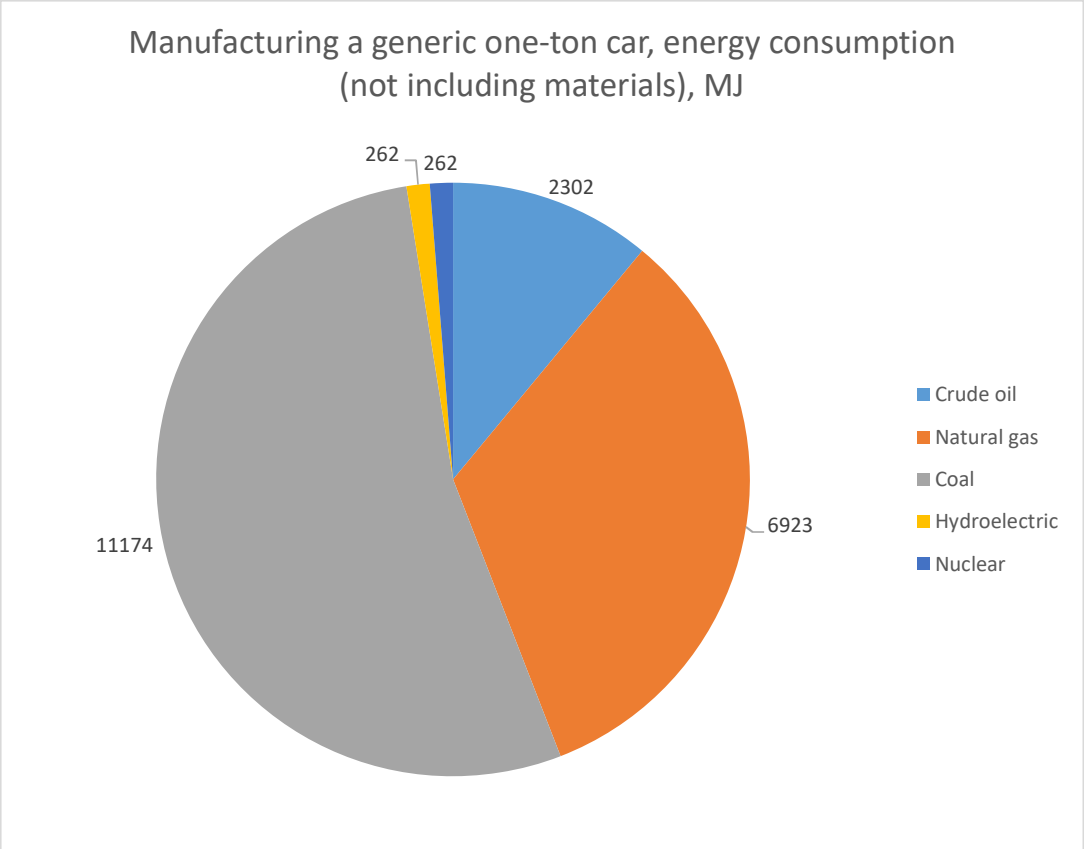

Wood ethanol production energy consumption (1 MJ product), MJ
Petroleum , 0.150
Natural gas , 0.006
Coal , 0.039
Biomass , 3.005


Wood ethanol GHG emissions, tot 20.7 g CO2e/MJ, gCO2e/MJ
0.327
0.000
0.000
0.414
0.355
0.000
0.355
0.472
2.532
1.273
14.984
Well-to-fuel energy-based CO2
Well-to-fuel energy-based CH4
Well-to-fuel energy-based N2O
Drilling CO2 removal and flaring CO2
Venting, flaring and fugitive CH4
Venting, flaring and fugitive N2O
Well-to-fuel CO
Combustion CO2
Combustion CH4
Combustion N2O


Natural gas to CNG production energy consumption (1 MJ), MJ
Petroleum , 0.001
Nuclear, 0.003
Coal , 0.004
Natural gas , 1.233


Natural gas to CNG GHG emissions, tot 79.8 gCO2e/MJ, gCO2e/MJ
0.133
1.869
0.360
13.562
0.005
0.009
1.498
6.216
0.000
0.001
56.100
Well-to-fuel energy-based CO2
Well-to-fuel energy-based CH4
Well-to-fuel energy-based N2O
Drilling CO2 removal and flaring CO2
Venting, flaring and fugitive CH4
Venting, flaring and fugitive N2O
Well-to-fuel CO
Combustion CO2
Combustion CH4
Combustion N2O

Manufacturing a car



Principles and parameters

Volkswagen Golf models' weight and fuel/electricity consumption (WTLP) were used in calculations, not the real material and energy use data from Volkswagen manufacturing plants. The scientific literature data are used in the calculations. Volkswagen Golf is an average-size car in Finland.

In combined heat and power (CHP) generation, the energy inputs and emissions are allocated between heat and power outputs. The principles of the allocation methods are explained by Soimakallio and Manninen[3]:

- ***Energy method: primary energy is allocated to heat and power on the basis of the energy (enthalpy) content of those products.*** Burning 100 MJ fuel in a CHP plant generates 36 MJe usable electricity and 51 MJ heat. These values are used in this analysis. In power generation, the power station losses are taken into account.
- ***Exergy method: primary energy is allocated to power and heat on the basis of the exergy content of those products.*** The exergy of power is higher than the exergy of heat and thus e.g. the CO_2e emissions per kWh for power are higher than in energy method. The exergy factors used for power and heat are 1 and 0.24, respectively. These values were used by Soimakallio and Manninen.

[3] Soimakallio Sampo, Manninen Jussi, Chapter 2: Energy efficiency and the Finnish energy system, in Energy Use – Visions and Technology Opportunities in Finland, VTT, Edita, 2007.

- ***Price method: primary energy is allocated to power and heat on the basis of the difference between the prices of those products.*** The price of power is higher than the price of heat and thus e.g. the CO_2e emissions per kWh for power are higher than in energy method. The average household prices for electricity and district heat were calculated from 2015 to 2017 and were found to be 16.99 cent/kWh and 7.80 cent/kWh, respectively[4].
- ***Benefit sharing method: primary energy is allocated to heat and power on the basis of the fuel consumption of the forms of heat and power production replaced by CHP.*** The benefit for power is higher than the benefit for heat and thus e.g. the CO_2e emissions per kWh for power are higher than in energy method. The efficiencies of the replaced heat and power production plants used here equal to 89 % and 36 %, respectively. In power generation, the power station losses are taken into account. **Benefit sharing method is used in this analysis.**
- ***Partial benefit sharing method: primary energy is allocated to heat on the basis of the fuel consumption of alternative heat production, and the remaining share is allocated to power.*** Not calculated in this analysis.
- ***No sharing method: primary energy is allocated without sharing, i.e. allocated to one product only.*** If all primary energy is allocated to electricity, e.g. all CO_2e emissions are allocated to power.

For electricity generated in Finland:

- 90% steam generator efficiency
- 44% turbine efficiency
- 99% electrical generator efficiency
- 3.8% power station losses (Finnish Energy statistics 2017)
- 3.24% transmission losses (Finnish Energy statistics 2017)

Battery packs:

- The carbon footprint of manufacturing a 330 kg and 35.8 kWh battery pack (e-Golf) is about 4 ktCO2e. In calculations, it has been assumed that the battery is lithium manganese oxide battery that contains no nickel and cobalt. Lithium manganese cobalt oxide batteries contain nickel and cobalt, but manufacturing these metals for a 330 kg battery is not a major source of greenhouse gases (about 260 kg CO2e).
- There is not yet any second-life applications for the electric car batteries, so all life-cycle emissions have to be allocated to electric car use.
- The most energy (electricity) intensive part of battery pack manufacturing is the manufacturing of battery cells. They are manufactured in countries with high carbon intensity in electricity generation (China, Japan, South Korea, Poland). In this analysis, South-Korean electricity mix was used.

Notifications (figures)

Electricity generation and consumption data for Finland are from Finnish Energy statistics. Peat LULUCF and emissions from the field are taken into account for peat (Statistics

[4] Statistics Finland's PX-Web databases, Price of district heating by type of consumer, Price of electricity by type of consumer.

Finland's data for years 2010–2014). Export and import data are also from Finnish Energy statistics, and the electricity generation data for Sweden, Russia, Norway and Estonia are from Energimyndigheten, World Bank, IEA Statistics and Statistics Estonia, respectively. Germany electricity generation data is from Fraunhofer Institute for Solar Energy Systems ISE and Iceland electricity generation data is from IEA Statistics.

The carbon footprints i.e. global warming potential life-cycle analyses are carried out from cradle to gate. All life-cycle stages and all greenhouse gases are taken into account. This is also the case for gasoline and diesel, natural gas and biofuels.

Figure "Life-cycle carbon footprints of VW Golf (including materials, manufacturing, maintenance, driving and end-of-life) as a function of driving distance":

- New electric car beats new diesel car after 28 000 km in Finland.
- New electric car beats new gasoline car after 26 000 km in Finland.
- New electric car beats old diesel car after 72 000 km (old diesel car still has driving, fuel cycle, maintenance and end-of-life emissions – but not the emissions from manufacturing a car) in Finland.
- Electric car in Finland beats biogas car after 203 000 km in Finland (if there is no battery pack replacement)
- Electric car with biogas electricity beats biogas ICE car after 120 000 km.
- Electric car with biogas electricity beats biogas ICE car after 245 000 km, if the battery pack is replaced once.

Figures "Volkswagen Golf in Finland (298 000 km, WLTP consumption), gCO2e/km" and "Volkswagen Golf in Finland (298 000 km, WLTP consumption), tCO2e/lifetime":

- The CHP share values are from Finland 2017 electricity mix.
- Lifetime distance of an average car used in calculations is 298 000 km.[5]
- In Finland in 2017, diesel fuel contained 4.1 vol-% HVO biodiesel (assumption 2.05 vol-% NExBTL biodiesel and 2.05 vol-% BioVerno biodiesel).
- In Finland in 2017, gasoline contained 7.71 vol-% ethanol (assumption 3.76 vol-% Brazilian sugarcane ethanol, 3.76 vol-% U.S. corn ethanol and 0.19 vol-% Finnish cellulosic ethanol).
- In real life (own two-year experiment with gas Touran), 4.7% of fuel is gasoline (by energy content).
- NExBTL and BioVerno biodiesels have 4.9% higher fuel consumption by volume than petroleum diesel due to lower volumetric energy content of HVO diesel.
- E85 has 37.3% higher fuel consumption by volume than petroleum gasoline.[6]

Figure "Life-cycle costs of Volkswagen Golf in Finland (298 000 km, WLTP consumption), thousand euros":

- Fuel price
    - Gasoline 1.50 e/L
    - Diesel 1.40 e/L

[5] Klemola Kimmo, Life-cycle energy consumption and carbon dioxide emissions of world cars, Lappeenranta University of Technology, 2006.

[6] Model year 2007 fuel economy guide, U.S. Environmental Protection Agency.

    - Compressed biogas 1.45 e/L
    - Compressed natural gas 1.32 e/L
    - Electricity 0.14 e/kWh
    - Today's prices are assumed for the whole lifetime.
- Insurance, service, repair etc. 1000 e/year
- Vehicle tax
    - Volkswagen Golf Comfortline 1.0 TSI 85 kW: 194.18 e/year
    - Volkswagen Golf Trendline 1.6 TDI 85 kW: 558.08 e/year
    - Volkswagen Golf 1.4 TGI 81 kW Gas: 375.95 e/year
    - Volkswagen e-Golf 100 kW (136 hp) automatic: 221.18 e/year
    - Today's taxes are assumed for the whole lifetime.
- In Finland, CNG (compressed natural gas) gas car gives cheapest life-time kilometers followed by CBG (compressed biogas).
- In Finland, lifetime costs are about equal for e-Golf, gasoline Golf and diesel Golf.
- January 2019 prices and taxes were used for the whole lifetime of the car.

Figure "Global annual sales of plug-in electric passenger cars in world's top markets 2011–2017" is from https://en.wikipedia.org/wiki/Electric_car. In 2017, the sales of electric cars was about 1.15 million globally. In 2018, the number of sold electric cars was probably over 2 million. About 71 million passenger cars were sold in the world in 2017, and in total about 97 million motor vehicles (International Organization of Motor Vehicle Manufacturers).

Japanese Panasonic, South-Korean LG Chem and Samsung SDI and Chinese BYD are the four major manufacturers in EV battery cell technologies. The patent trend analyses for this report were provided by TurnIP (http://www.turnip.co.in).

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The life-cycle analysis tool consists of model library and inventory with thousands of references. Only selected references are presented here.

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