Chapter 11
Life-Cycle Energy Consumption and Greenhouse Gas Emissions of Automotive Energy Pathways

Ou Xunmin and Zhang Xiliang

Abstract In this chapter, a life-cycle analysis (LCA) of vehicle-fuel pathways covering the stages of resource extraction, fuel production, and utilization is conducted to examine the macro impact of China's road transport energy supply and related greenhouse gas (GHG) emissions.

Original Chinese data on feedstock extraction and process efficiency, process fuel mix, transportation mode and average distance, fuel production efficiencies, process fuel mix with transport, storage and distribution (TSD) modes, and average distances for oil-, natural gas (NG)- and coal-based fuels, electricity, and H_2 pathways are all listed in the second part.

For different vehicle and fuel technology pathways, the fuel economy situation is presented by using gasoline spark ignition (SI) vehicles as the baseline.

By using a medium-size passenger car with an energy efficiency of 8 l of gasoline consumed per 100 km as the baseline model, the model calculates out the WTW fossil energy input and GHG emissions of the pathways for gas-based fuels, biofuels, coal-based fuels, electric vehicles, and fuel cell vehicles.

Keywords Automotive energy • Life-cycle analysis • China

11.1 Model and Methodology

11.1.1 Overall Introduction

In this chapter, a life-cycle analysis (LCA) of vehicle-fuel pathways covering the stages of resource extraction, fuel production, and utilization is conducted to examine the macro impact of China's road transport energy supply and related

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greenhouse gas (GHG) emissions. Based on the GHG, Regulated Emission and Energy consumption of Transportation (GREET) model, the Tsinghua China automotive energy LCA Model (TLCAM) was constructed. TLCAM was designed as a computing platform for LCA of end-use energy and specific fuel and vehicle pathways in China using a computerized iterative method (Ou and Zhang 2011).

For the vehicle energy pathway in TLCAM, well to pump (WTP) and pump to wheels (PTW) are the two stages included in this well-to-wheels (WTW) energy consumption and GHG analysis. WTP can be used to study upstream production stages, including the exploitation of raw resources and feedstock plantation, feedstock transportation, fuel production, fuel transportation, storage, and distribution (TSD). PTW can be used to study the downstream fuel combustion process in the vehicle's engine (Wang 1999, 2001, 2004; Ou et al. 2009, 2010a, b, c, 2011, 2012).

11.1.2 System Boundary, Substages Divided, and Functional Units

WTP and PTW are the two stages included in this WTW energy consumption and GHG analysis. WTP can be used to study upstream production stages, including the exploitation of raw resources and feedstock plantation, feedstock transportation, fuel production, fuel transportation, storage, and distribution. PTW studies the downstream fuel combustion process in the vehicle's engine (Fig. 11.1).

11.1.3 WTW Calculation Methods

To calculate the WTW results, the two functional units are linked through the fuel economy of the vehicle:

$$E_{\mathrm{WTW}} = E_{\mathrm{WTP}} * \mathrm{FE} + E_{\mathrm{PTW}} \tag{11.1}$$

$$\mathrm{GHG}_{\mathrm{WTW}} = \mathrm{GHG}_{\mathrm{WTP}} * \mathrm{FE} + \mathrm{GHG}_{\mathrm{PTW}} \tag{11.2}$$

where E_{WTW} is the WTW primary fossil energy used per kilometer (MJ/km), E_{WTP} is the WTP primary fossil energy and is used to show the WTP overall conversion efficiency (MJ/MJ fuel), FE is the vehicle-fuel economy (MJ/km), E_{PTW} is the PTW direct primary fossil energy used (MJ/km), $\mathrm{GHG}_{\mathrm{WTW}}$ is the WTW GHG emission (g $CO_{2,e}$/km), $\mathrm{GHG}_{\mathrm{WTP}}$ is the WTP GHG emission (g $CO_{2,e}$/MJ), and $\mathrm{GHG}_{\mathrm{PTW}}$ is the PTW GHG emission (g $CO_{2,e}$/km).

The functional unit in the WTP stage is MJ of fuel supplied in the form of liquid fuel, gas, or electricity and in the PTW stage it is kilometers driven by a city bus.

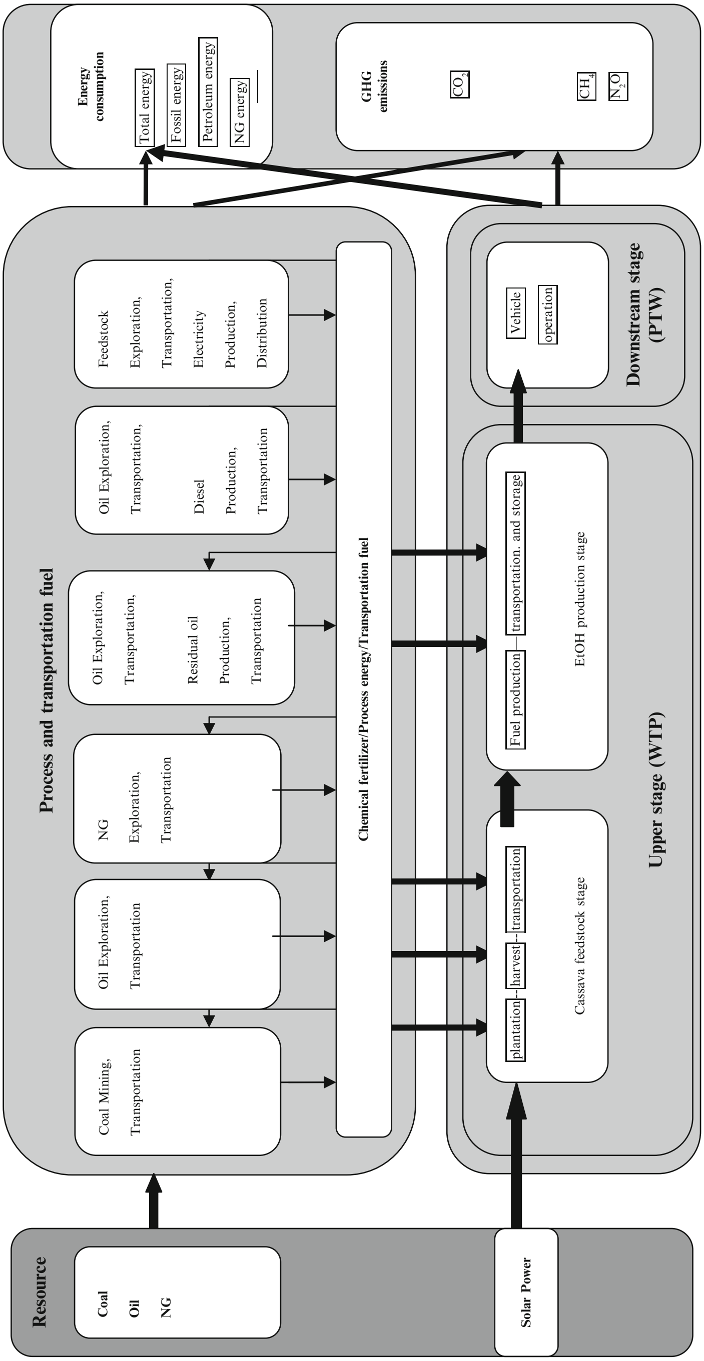

Fig. 11.1 System boundary for energy pathway LCA (cassava case)

Column 11.1 Substages for automotive energy pathways LCA (partial)

Exploitation of raw resources/feedstock plantation	Feedstock transportation	Fuel production	Fuel TSD
Oil exploitation	Oil transportation	Gasoline and oxygenates production, blend	Oxygenated gasoline TSD
Oil exploitation	Oil transportation	Diesel production	Diesel TSD
NG extraction and processing	NG transportation	CNG	CNG TSD
		NG to H_2	H_2 TSD
		LNG	LNG TSD
Coal extraction and processing	Coal transportation	Coal to MeOH	MeOH TSD
		Coal to DME	DME TSD
		Coal to liquid	CtL TSD
Oil, NG, coal, and other feedstock extraction and processing	Feedstock transportation	Power generation	Power TSD and battery charging
Corn plantation	Corn transportation	EtOH production	EtOH TSD
Cassava plantation	Cassava transportation	EtOH production	EtOH TSD
Sweet sorghum plantation	Sweet sorghum transportation	EtOH production	EtOH TSD
Soybean plantation	Soybean transportation	Biodiesel (BD) production	BD TSD
Jatropha plantation	*Jatropha* fruit transportation	BD production	BD TSD
Used cooking oil (UCO) collection	UCO transportation	BD production	BD TSD
Biomass collection	Biomass transportation	Biofuel production	Biofuel TSD

11.1.4 WTP Calculation Methods

11.1.4.1 WTP Energy Use

E_{WTP} is calculated as the sum of the corresponding primary energy (PE) consumption due to the process fuel (PF) directly used during each of the substages of the life cycle:

$$E_{\mathrm{WTP}} = \sum_{p=1}^{4}\sum_{j=1}^{9}\sum_{i=1}^{3}\left(\mathrm{EN}_{p,j} * \mathrm{EF}_{\mathrm{LC},j,i}\right) \tag{11.3}$$

where i is the PE type, j is the PF type, p is the substage number, $\mathrm{EN}_{p,j}$ is the used amount of PF type j during substage p for MJ fuel obtained (MJ/MJ fuel), and $\mathrm{EF}_{\mathrm{LC},j}$, is the LC energy used factor (EF) of PE type i for PF type j (MJ/MJ).

$EN_{p,j}$ can be derived through the direct amount of PF type j used during substage p ($EU_{p,j}$) combined with the product of each of the energy conversion efficiency factors from the following substages (η_p):

$$EN_{p,j} = \frac{EU_{p,j}}{(\eta_{p+1} * \ldots * \eta_4)} \quad \text{for} \quad (p = 1, 2, 3) \tag{11.4}$$

$$EN_{4,j} = EU_{4,j} \tag{11.5}$$

where the units of $EU_{p,j}$ are MJ/MJ feedstock/fuel obtained for $p = 1,3$ and MJ/MJ feedstock/fuel used for $p = 2,4$, respectively; η_p is the result of 1 divided by the sum of 1 plus all PF used for power and process feedstock or transportation fuel during substage p.

11.1.4.2 WTP GHG Emissions

The three key types of GHG emissions are converted to their CO_2 equivalents ($CO_{2,e}$) according to their global warming potential value (IPCC 2007) as shown by the following expression:

$$GHG_{WTP} = CO_{2,WTP} + 23 * CH_{4,WTP} + 296 * N_2O_{WTP} \tag{11.6}$$

where $CO_{2,WTP}$ is WTP CO_2 emissions (g/MJ fuel), $CH_{4,WTP}$ is WTP CH_4 emissions (g/MJ fuel), and N_2O_{WTP} is WTP N_2O emissions (g/MJ fuel).

During each of the substages, the life-cycle (LC) GHG emissions generally include the direct and indirect parts: the former refers to those emissions directly due to PF combustion and PF usage for process feedstock within the system boundary; the latter includes the emissions during the LC upstream stages of those PF utilized directly though they occur outside the entity boundary. For CH_4, an additional indirect part is considered for its LC GHG emissions—some emissions from noncombustion sources, including spills and other fugitive emission losses during the feedstock extraction stage (g/MJ fuel).

$CO_{2,WTP}$ is calculated as the sum of the direct and indirect parts:

$$CO_{2,WTP} = CO_{2,direct} + CO_{2,indirect} = \sum_{p=1}^{4} \sum_{j=1}^{9} EN_{p,j} * \left(CC_j * FOR_j * 44/12 + TCO_{2,j}\right) \tag{11.7}$$

where $CO_{2,direct}$ reflects the WTP direct CO_2 emissions (g/MJ fuel), $CO_{2,indirect}$ corresponds to WTP indirect CO_2 emissions (g/MJ fuel), CC_j is the carbon content factor of PF type j (g/MJ), FOR_j is the fuel oxidation rate of PF type j, $TCO_{2,j}$ is the LC indirect CO_2 emissions factor for PF type j (g/MJ), and 44/12 is the mass conversion rate from C to CO_2. The calculation for $CO_{2,indirect}$ is based on a carbon balance equation (Ou et al. 2008a; Wang and Weber 2001).

Calculations for $CH_{4,WTP}$ and N_2O_{WTP} are similar:

$$CH_{4,WTP} = CH_{4,direct} + CH_{4,indirect} = \sum_{p=1}^{4}\sum_{j=1}^{9} EN_{p,j} * \left(ERCH_{4,j} + TCH_{4,j}\right) + CH_{4,noncomb} \quad (11.8)$$

$$N_2O_{WTP} = N_2O_{direct} + N_2O_{indirect} = \sum_{p=1}^{4}\sum_{j=1}^{9} EN_{p,j} * \left(ERN_2O_j + TN_2O_j\right) \quad (11.9)$$

where $CH_{4,direct}$ is the WTP direct CH_4 emissions (g/MJ fuel), $CH_{4,indirect}$ is the WTP indirect CH_4 emissions (g/MJ fuel), $ERCH_{4,j}$ is the direct CH_4 emissions factor for PF type j (g/MJ), $TCH_{4,j}$ is the LC indirect CH_4 emissions factor for PF type j (g/MJ), $CH_{4,noncomb}$ corresponds to indirect CH_4 emissions from noncombustion sources, including spills and losses during the feedstock extraction stage (g/MJ fuel), N_2O_{WTP} corresponds to the WTP N_2O emissions (g/MJ fuel), N_2O_{direct} is the WTP direct N_2O emissions(g/MJ fuel), $N_2O_{indirect}$ is the WTP indirect N_2O emissions (g/MJ fuel), ERN_2O_j is the direct N_2O emissions factor for type PF j (g/MJ), and TN_2O_j is the LC indirect N_2O emissions factor for type PF j (g/MJ).

For the CH_4 noncombustion calculation:

$$CH_{4,noncomb} = \frac{CH_{4,feedstcok}}{(\eta_2 * \eta_3 * \eta_4)} \quad (11.10)$$

where $CH_{4,feedstock}$ corresponds to the indirect CH_4 emissions from noncombustion sources, including spills and losses during the feedstock extraction stage (g/MJ feedstock obtain).

11.2 Basic Data Collection and Processing

11.2.1 Data on Nonbiofuels

Table 11.1 lists original Chinese data on feedstock extraction and process efficiency, process fuel mix, transportation mode and average distance, fuel production efficiencies, process fuel mix with TSD modes, and average distances for oil-, natural gas (NG)- and coal-based fuels, electricity, and H_2 pathways.

Table 11.1 Basic parameters of oil-, NG-, and coal-based fuel pathways

Oil extraction
Extraction efficiency, 93.0 %
Process fuel mix: electricity (37 %), crude oil (20 %), NG (23 %), coal (10 %), diesel (8 %), residual oil (1 %), and gasoline (1 %)
Oil transportation mode
Sea tanker, 50 % (11,000 km); rail, 45 % (950 km); pipeline, 80 % (500 km); and waterways, 10 % (250 km)
Oil refinery
Process fuel mix: crude oil (50 %), coal (20 %), electricity (12 %), refinery still gas (10 %), residual oil (4 %), diesel (1 %), and gasoline (1 %)
Gasoline production efficiency, 89.1 %; diesel production efficiency, 89.7 %; and LPG production efficiency, 92.0 %
Gasoline and diesel TSD mode
Sea tanker, 25 % (7,000 km); railway, 50 % (900 km); waterways, 15 % (1,200 km); and road (short distance), 10 % (50 km)
LPG TSD mode
Sea tanker, 30 % (7,000 km); railway, 80 % (900 km); pipeline, 0 % (160 km); waterways, 15 % (1,200 km); and road (short distance), 10 % (50 km)
NG extraction and processing
Extraction efficiency, 96.00 %; process fuel mix for NG extraction: electricity (40 %), NG (23 %), residual oil (20 %), diesel (8 %), coal (7 %), and gasoline (2 %); NG processing efficiency, 94.00 %; and process fuel mix for NG processing: residual oil (40 %), NG (28 %), coal (20 %), electricity (10 %), diesel (1 %), and gasoline (1 %)
CNG, LNG, and GTL production
CNG production efficiency, 96.9 %; LNG production efficiency, 90.2 %; and GTL production efficiency, 54.2 %
NG and NG-based fuel transportation mode
For NG: pipeline, 100 % (1,500 km)
For CNG: pipeline, 100 % (300 km)
For LNG: sea tanker, 100 % (6,700 km) and road (short distance), 10 % (50 km)
For GTL: pipeline, 100 % (100 km to production site), similar to diesel TSD
Coal extraction and processing
Coal extraction efficiency, 97 %; coal processing efficiency, 97 %; and process fuel mix for crude coal extraction and processing: coal (80 %), electricity (16 %), diesel (2 %), gasoline (1 %), and NG (1 %)
Coal transportation
Railway, 50 % (1,000 km); waterways, 17 % (650 km); road (long distance), 8 % (310 km); and road (short distance), 100 % (50 km)
Coal-based fuel production
MeOH (50.22 %), DME (47.46 %), direct CTL (50.31 %), and indirect CTL (41.41 %)
Coal-based fuel transportation
Preproduction (50 km road) and postproduction, similar to gasoline and diesel TSD
Electricity supply mix
Coal (80.1 %), oil (1.8 %), NG (0.7 %), and many other sources (17.4 %)
Power-supply efficiency
Coal based (36 %), oil based (32 %), NG based (45 %), and others (assumed to be zero fossil energy input)
CCS will decrease the efficiency at the rate of 10 % with a capture rate of 90 % of CO_2 produced onsite

(continued)

Table 11.1 (continued)

Loss ratio during transmission and distribution
6.97 % in 2008 but 5.5 % in 2020
Hydrogen production efficiency
H_2 from NG, 71 %; H_2 from coal, 51.5 %; H_2 from water electrolysis, 80 %; H_2 from biomass, 42–48 %; and H_2 from high-temperature gas cool nuclear reactor, 50–60 % (2020)
Hydrogen processing and transportation
H_2 compression efficiency, 92.5 % and gaseous H_2 transportation, pipeline (1,000 km)

Notes:
1. The data are for 2007 unless otherwise specified
2. For hydropower, there is 5 g $CO_{2,e}$/MJ of life-cycle fossil energy used
3. For nuclear power, there is 6.506 g $CO_{2,e}$/MJ and 0.063 MJ/MJ of life-cycle fossil energy used and GHG emissions
4. For biomass power, there is 5.846 g $CO_{2,e}$/MJ and 0.064 MJ/MJ of life-cycle fossil energy used and GHG emissions

11.2.2 Data on Biofuels

The basic parameters of China's current biofuel pathways include corn to ethanol (CE), cassava to ethanol (KE), sweet sorghum to ethanol (SE), soybean to biodiesel (SB), Jatropha fruit to biodiesel (JB), and used cooking oil to biodiesel (UB) (Tables 11.2 and 11.3). Second-generation biofuel from agricultural and forestry residues is an important pathway of waste utilization. Thus, the energy used during plantation is not allocated to the energy input for biofuel life-cycle energy use and related GHG emissions. Though a great deal of electricity and heat (greater than with first-generation biofuels) is required for the pretreatment and hydrolysis of cellulosic ethanol, considerable lignin is available for use as fuel. There is thus no need to outsource large amounts of electricity or steam.

Since the biomass can be used for electricity feedstock, the biomass-to-liquid (BTL) pathway does not require external energy input. Data on the cellulosic ethanol and BTL pathways are presented in Table 11.4. The TSD situation is similar to that with EtOH (500 km) and biodiesel (200 km).

11.3 Assumptions for PTW

For different vehicle and fuel technology pathways, the fuel economy situation is presented in Table 11.5 using gasoline spark ignition (SI) vehicles as the baseline. It should be noted that the electric vehicle (EV) and plug-in hybrid electric vehicle (PHEV) pathways are gauged under hypothetical conditions with heating and air-conditioning in use. The fuel consumption in real operating conditions is about 15 % higher than in laboratory tests for inner combustion engine (ICE) vehicles and about 30 % for the electric drive mode.

Table 11.2 Basic parameters of EtOH biofuel pathways

Pathway	CE	Data source	KE	Data source	SE[h]
Production (tons/ha)	6.5	Data for Jilin in NSBC (2007a)	13.3	Dai et al. (2006)	64.5
Planting energy (MJ/ha)	4,047[a]	CATARC (2007)	1,572	Dai et al. (2006)[c]	2,800[i]
N fertilizer inputs (kg/ha)	162	Chai (2008)	100	Dai et al. (2006)	600
P fertilizer inputs (kg/ha)	13.3	Chai (2008)	100	Dai et al. (2006)	150
K fertilizer inputs (kg/ha)	131	Chai (2008)	200	Dai et al. (2006)	0
Pesticide inputs(kg/ha)	8	Chai (2008)	0	Chai (2008)	0
Collection radius (km)	125	Average of Zhang et al. (2008) and CATARC (2007)[b]	250	Dai et al. (2006)[d]	50
Conversion rate (tons of feedstock/tons of fuel)	3.2	CATARC (2007)	3.0	Dai et al. (2006)	18.8
Energy for extraction (GJ/ton)	25	Zhang et al. (2008)	13.9	Dai et al. (2006)[e]	20[j]
Distance transmission and distribution (km)	520	Zhang et al. (2008)	450	Dai et al. (2006)[f]	300
Sharing ratio of the by-product (%)	30.90	Wang (2007)	18.06	Dai et al. (2006)[g]	20

Notes:
[a]The energy mix is gasoline (7.16 %), diesel (86.62 %), and electricity (6.02 %)
[b]The values of Zhang et al. (2008) and CATARC (2007) are 100 and 150 km, respectively
[c]According to Dai et al. (2006), diesel fuel and electricity are 44 $l*ha^{-1}$ and 60,923 $kWh*year^{-1}$(200,000 ha), so the total planting energy can be determined based on LHV and the density of diesel—42.7 $MJ*kg^{-1}$ and 0.837 $kg*l^{-1}$
[d]Including 250 km in truck mode
[e]In Dai et al. (2006) the energy consumption per liter of EtOH is 11.898 MJ and almost 100 % of that is from coal
[f]Including 450 km in truck mode
[g]According to their average results
[h]The data of SE are based on a field visit of 2008 to Inner Mongolia, China
[i]The energy mix is gasoline (10 %), diesel (80 %), and electricity (10 %)
[j]The energy mix is coal (90 %) and electricity (10 %), and the energy efficiency from coal to steam is 80 %

11.4 Results for WTP

As noted above, the conversion efficiency of the WTP stage is defined as the ratio of the calorific value of the fuel to the total fossil energy input during the WTP stage (including the raw material input). This ratio is generally expressed as a percentage; however, it may exceed 100 % for those pathways that use nonfossil energy as feedstock and are therefore expressed as the ratio of output to input. In Table 11.6, all the WTP stage conversion rates are listed with error estimations.

Table 11.3 Basic parameters of biodiesel (BD) pathways

Pathway	SB	Data source	JB[d]	UB[g]
Production (tons/ha)	1.8	Data for Heilongjiang in NSBC (2007)[a]	5.0	–
Planting energy (MJ/ha)	4,494[a]	CATARC (2007)	800	–
N fertilizer input (kg/ha)	88	Chai (2008)	97	–
P fertilizer input (kg/ha)	33	Chai (2008)	27	–
K fertilizer input (kg/ha)	27	Chai (2008)	18	–
Pesticide input (kg/ha)	4	Chai (2008)	0	–
Collection radius (km)	200	Zhang et al. (2008)	250	35[h]
Conversion rate (tons of feedstock/tons of fuel)	5.9	CATARC (2007)	3.3[e]	20.0
Energy for extraction (GJ/ton)	12.9[b]	Chai (2008)	10[f]	7.5
Distance transmission and distribution (km)	200[c]	Field visit	300	100
Sharing ratio of the by-product (%)	27.50	Chai (2008)	40	0

Notes:
[a]The energy mix is gasoline (7.33 %), diesel (88.87 %), and electricity (3.80 %)
[b]The energy mix is coal (90 %) and electricity (10 %), and the energy efficiency from coal to steam is 80 %
[c]Currently in China, most BD is used in agricultural machines and fishing boats because its use as ordinary vehicle fuel is prohibited
[d]The data for JB were based on a field visit of 2009 to Hainan, China
[e]The data were confirmed by CATARC (2007)
[f]The data were confirmed by CATARC (2007)
[g]The data for UB are based on a field visit of 2009 to Beijing and CATARC (2007)
[h]The collection energy used for UCO was 30 MJ/ton (to collection points) and 135 MJ/ton (transported to processing plants)

11.5 Results for WTW

Using a medium-size passenger car with an energy efficiency of 8 l of gasoline consumed per 100 km as the baseline model, we can calculate the WTW fossil energy input and GHG emissions of such pathways as those for gas-based fuels, biofuels, coal-based fuels, electric vehicles, and fuel cell vehicles. The error bars that appear in Figs. 11.2 and 11.3 indicate the uncertainty of the efficiency of oil extraction, crude oil transport distance, and oil-refinery efficiency for gasoline and diesel pathways; they will be explained in detail for other pathways.

11.5.1 Gas-Based Fuel Pathways

The results for gas-based fuel pathways are shown in Figs. 11.2 and 11.3. The WTW fossil energy inputs for LPG, CNG, and LNG vehicles are about 2–7 % lower than

Table 11.4 Data for second-generation biofuels

Pathway	Cellulosic EtOH		BTL
Feedstock	Woody feedstock	Herbal feedstock	Mixed feedstock
Heat value (MJ/kg)	15.89	14.63	15.55
Energy used for collection (–)	Ignored	Ignored	Ignored
Feedstock transport distance (km)	100	100	100
Energy used during transportation (L diesel/100 ton km)	7.45	7.45	7.45
Conversion rate (ton feedstock/ton fuel)	4.1	3.7	6
External electricity used (GJ/ton fuel)	1.00	0.85	0
Process fuel	Coal (100 %)	Coal (100 %)	Biomass feedstock (100 %)
Electricity coproduct (kWh/ton fuel)	400	200	0
Distribution distance (km)	500	500	200

Table 11.5 Data for fuel economy of a combination of fuel and vehicle pathways

	Fuel economy (kilometers traveled per unit energy) (%)	Energy consumption per unit distance	Note
SI ICE-gasoline	100.0	1.00	
SI ICE-CNG	95.0	1.05	
SI ICE-LNG	95.0	1.05	
SI ICE-LPG	100.0	1.00	
SI ICE-methanol	107.0	0.93	
FFV-methanol	100.0	1.00	
SI ICE-ethanol	107.0	0.93	
FFV-ethanol	100.0	1.00	
SI ICE-hydrogen	120.0	0.83	
SI HEV-liquid fuel-gasoline	143.0	0.70	Energy-saving rate is 30 % of gasoline vehicles
SI HEV-hydrogen	160.0	0.62	Energy-saving rate is 25 % of H_2 SI vehicles
CI ICE-diesel	120.0	0.83	
CI ICE-DME	120	0.83	
CI ICE-biodiesel	120	0.83	
CI HEV-liquid fuel-diesel	170.0	0.59	Energy-saving rate is 30 % of diesel vehicles
EV-electricity	350.0	0.29	
SI PHEV-electricity	300.0	0.33	
SI PHEV-ICE mode-gasoline	143.0	0.70	
FCV-hydrogen	230.0	0.43	

Table 11.6 WTP efficiency

Pathway	Unit	WTP efficiency	Positive error	Negative error	Note
Part I: Fossil fuel as feedstock					
ICE-gasoline	%	73.60	3.68	3.68	Current situation; will not vary much in future
ICE-diesel	%	76.03	3.80	3.80	Current situation
ICE-LPG	%	78.84	3.94	3.94	Current situation
ICE-CNG	%	82.50	8.25	8.25	Current situation
ICE-LNG	%	78.99	3.95	3.95	Current situation
ICE-GTL	%	51.51	7.73	7.73	Current situation
ICE-MeOH	%	44.90	8.98	6.74	Current situation
ICE-DME (coal)	%	42.45	8.49	6.37	Current situation
ICE-CDL	%	44.99	6.75	4.50	Current situation
ICE-CTL	%	37.06	5.56	3.71	Current situation
ICE-MeOH (CCS)	%	35.30	8.83	7.06	When the technology is mature
ICE-DME (coal) (CCS)	%	35.00	8.75	7.00	When the technology is mature
ICE-CDL (CCS)	%	40.96	8.19	6.14	When the technology is mature
ICE-CTL (CCS)	%	33.24	6.65	4.99	When the technology is mature
EV-electricity (grid)	%	34.20	3.42	3.42	Current situation
EV-electricity (coal)	%	28.56	2.86	2.86	Current situation
EV-electricity (oil)	%	24.40	2.44	2.44	Current situation
EV-electricity (gas)	%	35.08	3.51	3.51	Current situation
EV-electricity (coal) (IGCC+CCS)	%	29.72	4.46	4.46	When the technology is mature
Part II: Nonfossil fuel as feedstock					
EV-electricity (nuclear)	Ratio of output to input	15.87	1.59	1.59	Current situation
EV-electricity (hydraulic)	Ratio of output to input	–	–	–	Current situation
EV-electricity (biomass)	Ratio of output to input	13.16	1.32	1.32	Current situation
ICE-EtOH (corn)	Ratio of output to input	0.65	0.13	0.13	Current situation
ICE-EtOH (cassava)	Ratio of output to input	1.15	0.23	0.23	Current situation
ICE-EtOH (sweet sorghum)	Ratio of output to input	1.38	0.14	0.69	Current situation
ICE-EtOH (herbs)	Ratio of output to input	7.29	0.73	1.46	When the technology is mature
ICE-EtOH (wood)	Ratio of output to input	4.55	0.45	0.91	When the technology is mature

(continued)

Table 11.6 (continued)

Pathway	Unit	WTP efficiency	Positive error	Negative error	Note
ICE-BD (waste oil)	Ratio of output to input	1.03	0.31	0.10	Current situation
ICE-BD (*Jatropha* oil)	Ratio of output to input	1.33	0.13	0.13	Current situation
ICE-BTL	Ratio of output to input	17.24	3.45	3.45	Current situation
FCV-H_2 (NG)	Ratio of output to input	0.53	0.05	0.05	Current situation
FCV-H_2 (coal)	Ratio of output to input	0.40	0.04	0.04	Current situation
FCV-H_2 (water electrolysis)	Ratio of output to input	0.26	0.03	0.03	Current situation
FCV-H_2 (biomass)	Ratio of output to input	3.37	0.34	0.34	When the technology is mature
FCV-H_2 (Nuclear)	Ratio of output to input	3.53	0.35	0.35	When the technology is mature
FCV-H_2 (coal) (CCS)	Ratio of output to input	0.37	0.06	0.06	When the technology is mature
FCV-H_2 (NG)	Ratio of output to input	0.33	0.03	0.03	Current situation
FCV-H_2 (coal)	Ratio of output to input	0.27	0.03	0.03	Current situation
FCV-H_2 (water electrolysis)	Ratio of output to input	0.20	0.02	0.02	Current situation
FCV-H_2 (biomass)	Ratio of output to input	0.67	0.07	0.07	When the technology is mature
FCV-H_2 (nuclear)	Ratio of output to input	0.68	0.07	0.07	When the technology is mature
FCV-H_2 (coal) (CCS)	Ratio of output to input	0.25	0.06	0.06	When the technology is mature

those of conventional vehicles; the rate of decrease is related to the gas-based fuel-transport distance. Since the carbon content of natural gas is lower than that of oil, the GHG emissions of gas-based fuels vehicles are 15 % lower than those of conventional vehicles. The analysis error of such gas-based fuel (LPG, CNG, and LNG) pathways arises from the transport distance.

It should be noted that since the production efficiency of gas to liquid (GTL) is relatively low, the WTW fossil energy input of the GTL pathway increases by 50 % compared with that of conventional diesel vehicles. The GHG emissions with the GTL pathway show a slight increase compared with those of conventional diesel vehicles owing to the low carbon content in natural gas. The future uncertainty related to production efficiency of GTL produces a significant analysis error interval.

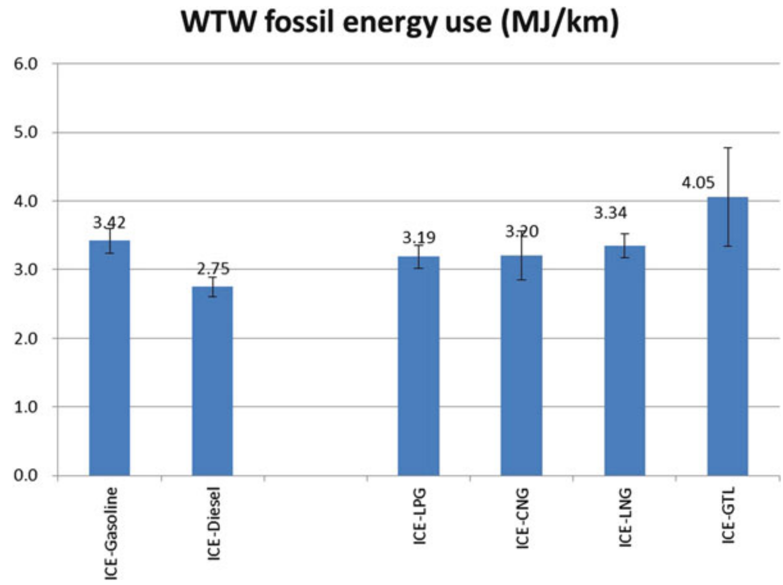

Fig. 11.2 WTW fossil energy input for gas-based fuel (MJ/km)

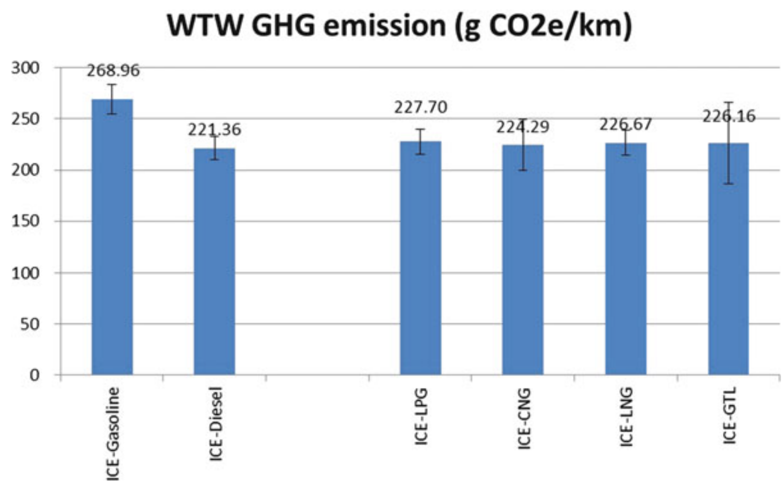

Fig. 11.3 WTW GHG emission for gas-based fuel (g $CO_{2,e}$/km)

11.5.2 Biofuel Pathways

The results for biofuel pathways appear in Figs. 11.4 and 11.5. As noted above, in terms of biofuel pathways (except for the waste cooking oil pathway), plants can absorb carbon dioxide during their growing period. As a consequence, the

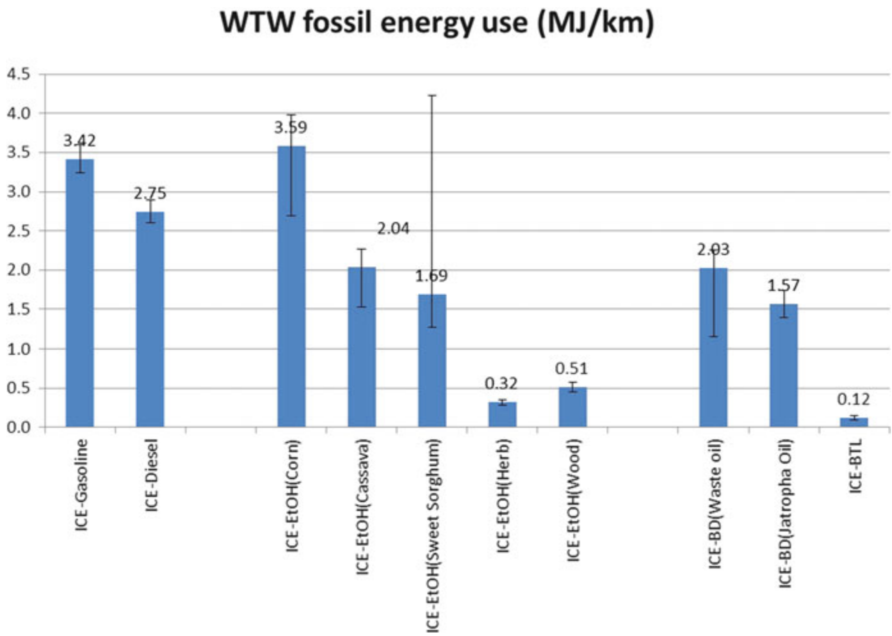

Fig. 11.4 WTW fossil energy input for biofuels (MJ/km)

carbon dioxide that derives from the fuel combustion stage can be regarded as carbon being recycled into the atmosphere from absorption during the growing period.

Although the raw material is not fossil fuels but biomass, the WTW fossil energy input and GHG emissions of the current first-generation biofuel-powered vehicles are high. This is a result of high gasoline and diesel consumption in the transport of raw materials and the large amount of coal consumed in fuel-processing plants for fermenting and distilling. Whether the energy consumption and GHG emissions can be reduced depends on the raw material pathways compared with conventional vehicle pathways. The corn-based ethanol pathway has 5 % more energy consumption and 82 % more GHG emissions; this is because a large amount of fertilizer is applied in plantations, and the high energy consumption in fertilizer production has to be considered in the LCA. The cassava-based ethanol pathway has 40 % less energy consumption and 17 % less GHG emissions. The sweet sorghum-based ethanol pathway has 50 % less fossil energy consumption and 40 % less GHG emissions compared with gasoline vehicles. This is because the sweet sorghum stalk residues in ethanol plants can produce the necessary amount of steam and electricity; they thus act as a substitute for external coal steam for electricity production.

It should be noted that there are great uncertainties in this analysis as a result of differences in factory processes, management levels, and whether or not by-products are synthetically used. Taking the sweet sorghum pathway as an example,

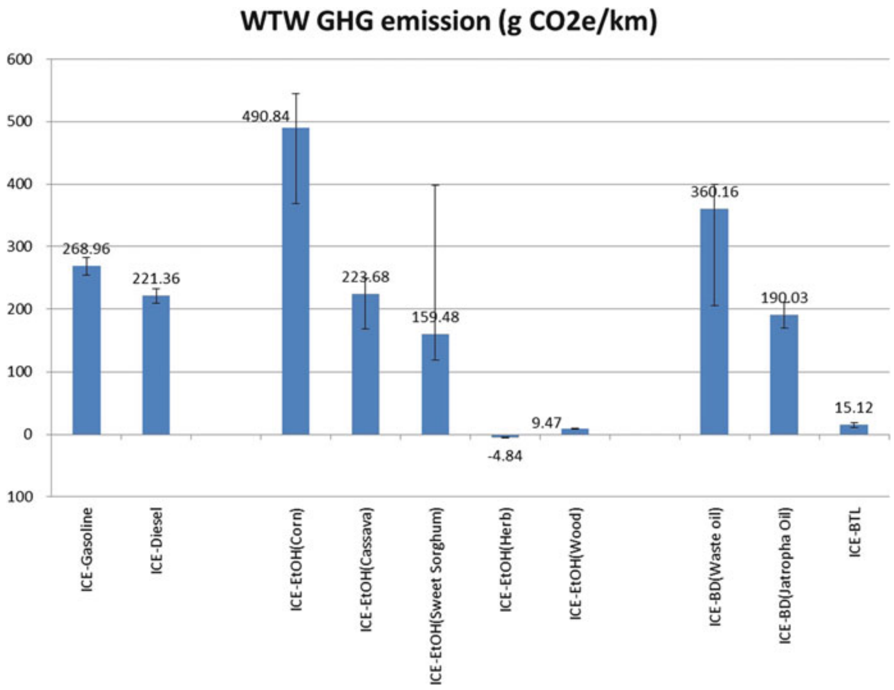

Fig. 11.5 WTW GHG emissions for biofuels (g $CO_{2,e}$/km). *Note*: It is assumed that the waste cooking oil pathway can store carbon and has no alternative usage

its energy consumption and GHG emissions are very high if this pathway has no comprehensive utilization of stalk. In such a case, this pathway operates poorly; the situation is exacerbated in the fuel ethanol pathways, as shown in Figs. 11.4 and 11.5.

The WTW fossil energy input of first-generation biodiesel fuel-powered vehicles is 26–43 % lower than that of conventional diesel vehicles. However, there is a high carbon content (g C/MJ) per calorific unit in waste cooking oil, and no planting process is involved, as it is with the other biofuel pathways. Thus, the WTW GHG emissions of biofuels based on waste cooking oil are 30 % lower than with the diesel pathway if oxidation of disposed waste cooking oil to carbon dioxide is assumed. The WTW GHG emissions of biofuels based on waste cooking oil are 63 % greater than with the diesel pathway if waste cooking oil is unused and simply put directly into the sewage system. The WTW GHG emissions of biofuels based on waste cooking oil are higher than with the diesel pathway since more GHG emissions result from the manufacturing of other products (such as glycerol and soap). Here, we take it that waste cooking oil is unused and simply discharged directly into the sewage system with no oxidation. In addition, the transport distance of the raw materials is the main factor in producing erroneous results regarding waste cooking oil. For example, the results may be reduced by 30 % if the transport distance decreases from the current average of 1,000 to 100–200 km.

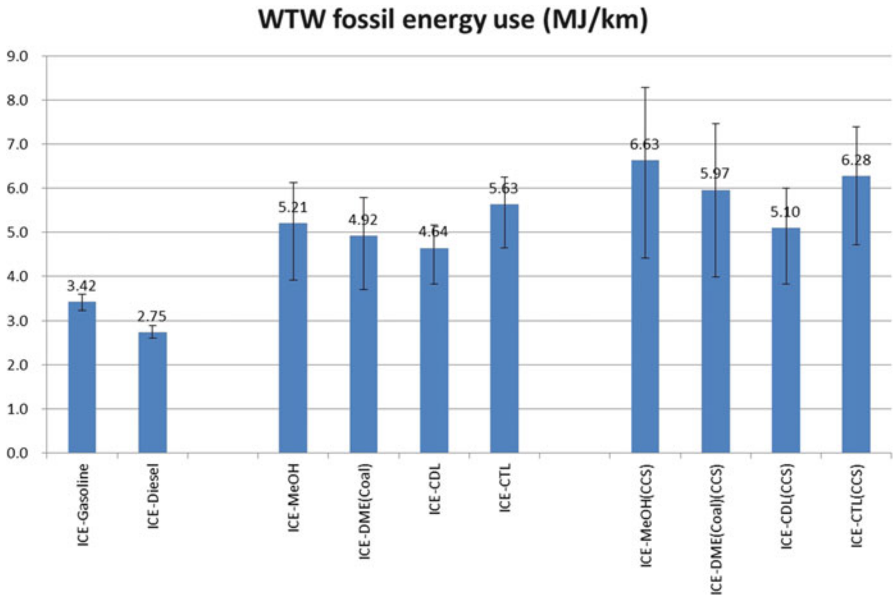

Fig. 11.6 WTW fossil energy input for coal-based fuel (MJ/km)

In terms of second-generation fuel ethanol and biodiesel pathways, there are both good energy-saving and good emission-reduction effects with less energy input in the production process: some lignin and residues can be used to produce electricity as fuel instead of large amounts of coal being consumed. Compared with the baseline vehicle, the fossil energy consumption input can be reduced by over 80 %, and the GHG reduction rate may be above 90 %—or even result in zero emissions.

11.5.3 Coal-Based Fuel Pathway

The results for coal-based fuel pathways appear in Figs. 11.6 and 11.7. Compared with the baseline vehicle, the WTW fossil energy input and GHG emissions in the coal-based fuel pathways without adopting CO_2 capture and storage (CCS) technology increase dramatically: a 50–105 % increase in fossil energy input and a 126–174 % increase in GHG emissions. The main reason is the relatively low conversion rate of coal-based fuel plants and the high carbon content of coal. Since the methanol and DME plants in China are quite dispersed and there is a great diversity in the technology level, errors in the analysis results are quite large.

The WTW fossil energy input in coal-based pathways increases by 90–129 % if CCS technology is adopted, whereas the GHG emission rate is reduced by 50–137 % compared with conventional gasoline and diesel vehicles. With the CCS technology

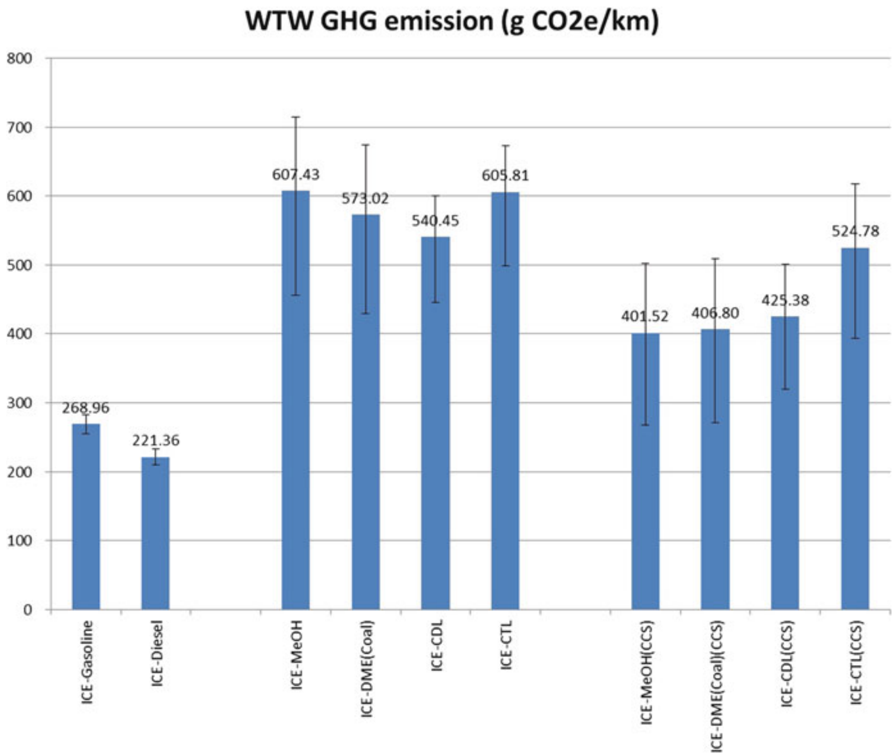

Fig. 11.7 WTW GHG emission for coal-based fuel (g $CO_{2,e}$/km)

pathway, the error bar is expanded owing to uncertainty in CCS technology energy consumption and the carbon capture rate. However, even with the most optimistic interpretation, the WTW fossil energy input and GHG emissions with coal-based fuel pathways are both greater than with the gasoline and diesel pathways.

There are two reasons for the application of CCS technology being unable to change the fact that coal-based fuels have greater GHG emissions than petroleum-based fuels: (1) GHG emissions in coal mining, disposing, and transport are higher than with the oil pathway, and (2) coal-based fuel plants have relatively low efficiency and high energy consumption, whereas the carbon content of the main fuel, coal, is higher than that of oil in oil-refining plants. As a result, the GHG emissions from plants are at a high level even though a carbon dioxide capture rate of 90 % is achieved.

11.5.4 EV Pathways

The results for EV pathways are shown in Figs. 11.8 and 11.9. The WTW fossil energy consumption with EVs adopting grid electricity as the power source is 62 %

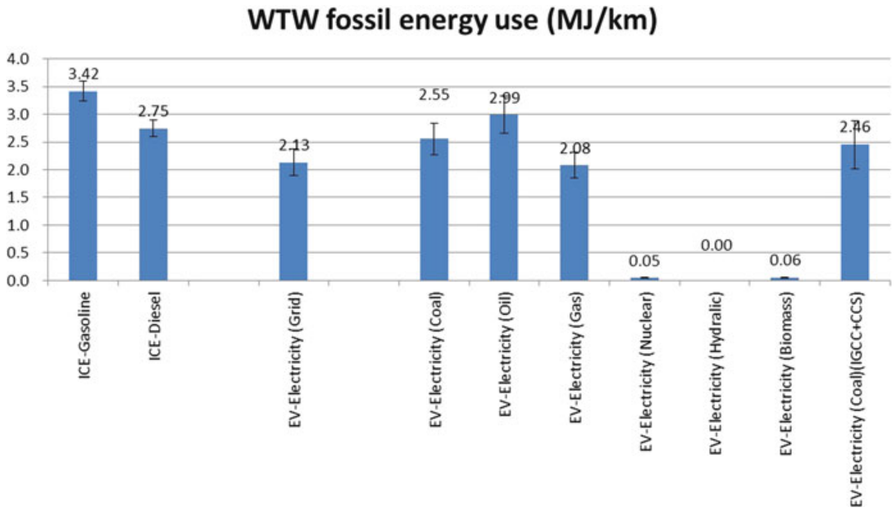

Fig. 11.8 WTW fossil energy input for EVs (MJ/km)

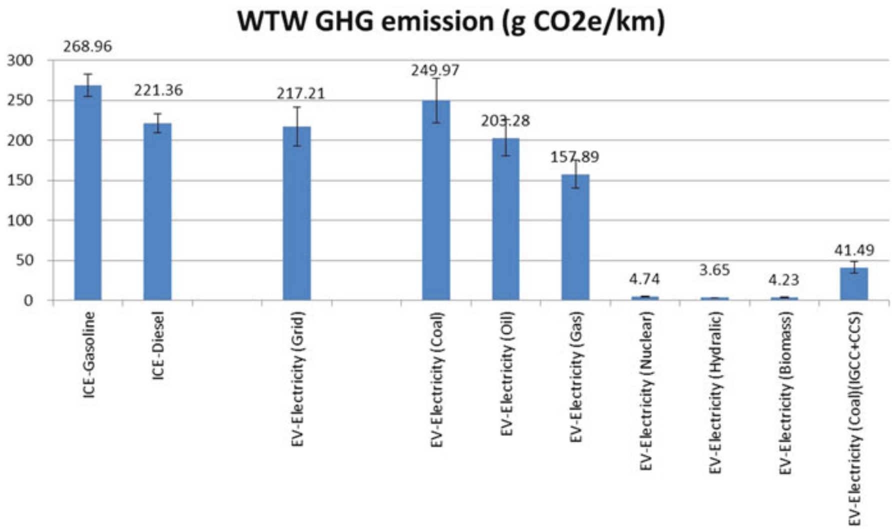

Fig. 11.9 WTW GHG emissions for EVs (g $CO_{2,e}$/km)

that of gasoline vehicles and 75 % that of diesel vehicles. This is because the energy efficiency of EVs is much higher than that of internal combustion engine vehicles. However, since the proportion of coal in China's power supply is over 80 %, the decline in GHG emissions with the EV pathway is only 20 % lower than with gasoline vehicles and under 10 % lower than that of diesel vehicles.

It is clearly the case that coal and oil power pathways deteriorate the energy-saving advantages of EVs if this kind of power source is used. This is particularly

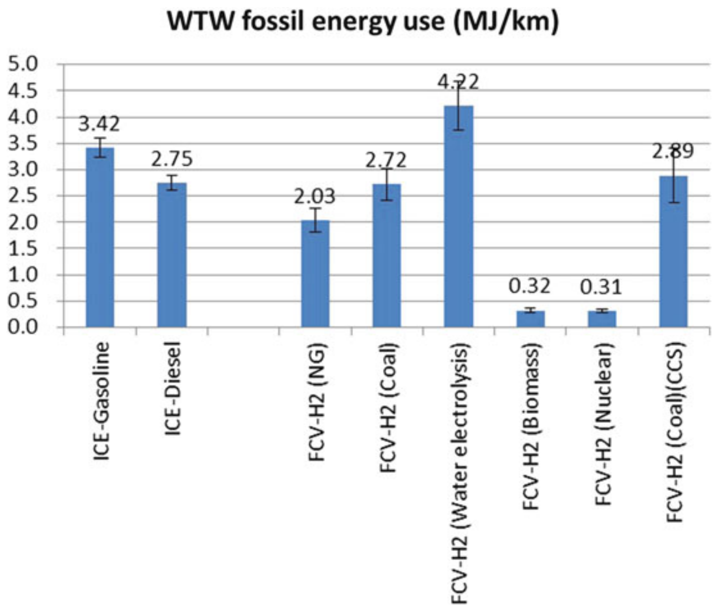

Fig. 11.10 WTW fossil energy input for FCVs (MJ/km)

true if the WTW fossil energy consumption of oil-based EV is 10 % more than that with the diesel pathway. Although the WTW GHG emissions with the coal power pathway are slightly lower than with the gasoline vehicle pathway (7 %), they are somewhat higher than with the diesel pathway (13 %).

If both integrated gasified cycling combustion (IGCC) and CCS technology are adopted in new coal-fired power plants, the WTW fossil energy input and GHG emissions with EV pathways are better than with the conventional gasoline and diesel vehicle pathways. There is the advantage of IGCC and CCS technology being efficient at capturing the carbon dioxide produced by power plants, with energy savings of 10–30 % and emission reductions of 80 %.

In terms of nuclear, hydro-, and biomass power, the WTW fossil energy input and GHG emissions are only 1–2 % lower than with the traditional gasoline and diesel pathways. The difference is thus almost negligible.

11.5.5 FCV Pathways

The results for the FCV pathways are shown in Figs. 11.10 and 11.11. Since the efficiency of FCVs is much higher than that of internal combustion engine vehicles, the WTW fossil energy consumption with the FCV pathway that uses hydrogen produced from natural gas is 40 % lower than with the gasoline pathway and 26 %

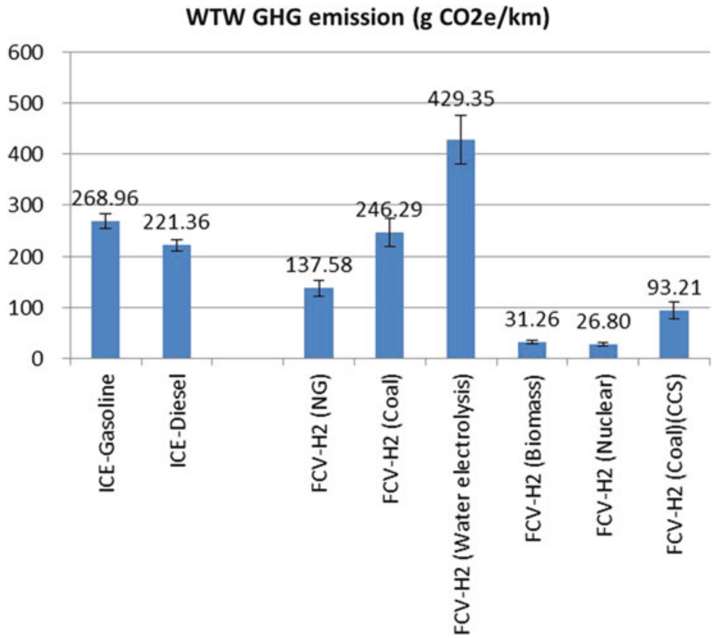

Fig. 11.11 WTW GHG emission for FCVs (g $CO_{2,e}$/km)

lower than with the diesel pathway; GHG emissions decrease by 49 and 38 %, respectively. In the FCV pathway that uses hydrogen produced from coal, the WTW fossil energy consumption is 20 % lower than with the gasoline pathway though the consumption is the same as with the diesel pathway; the GHG emissions decrease by 10 % and increase by 10 %, respectively. If the hydrogen is produced from biomass and future nuclear commercialization can be achieved, the WTW fossil energy consumption and GHG emissions with these two FCV pathways are only 1–2 % that of the traditional gasoline and diesel vehicles.

If coal-derived hydrogen plants adopt CCS technology in the future, the WTW fossil energy consumption in the hydrogen FCV pathway will decline by 15 % and increase by 5 %, respectively, compared with the gasoline and diesel pathways. The respective decline in GHG emissions will be 65 and 60 %.

11.6 Outlook for Vehicle-Fuel Combination LCA

Following the definition of the reference scenario and integrated policy scenario, this section will examine the LCA results for vehicle-fuel pathways in China. The WTP results for the energy pathways presented here will be used in Chap. 12; only the LC energy and future GHG emission levels are examined in this section. In combination

Table 11.7 LC fossil energy intensity for biofuels (MJ/MJ)

	2010	2015	2020	2030	2040	2050
Reference scenario						
First-generation EtOH	1.08	1.08	1.08	1.08	1.08	1.08
First-generation biodiesel	0.80	0.80	0.80	0.80	0.80	0.80
Second-generation EtOH			−0.01	−0.01	−0.01	−0.01
Second-generation biodiesel			0.07	0.07	0.07	0.07
Integrated policy scenario						
First-generation EtOH	1.08	1.05	1.03	0.97	0.92	0.86
First-generation biodiesel	0.80	0.78	0.76	0.72	0.68	0.64
Second-generation EtOH			−0.01	−0.01	−0.01	−0.01
Second-generation biodiesel			0.07	0.07	0.07	0.07

Note: Because of electricity coproduction as a substitute for coal-derived power, energy credit accrues for the second-generation EtOH pathway

Table 11.8 LC GHG emission intensity for biofuels (g $CO_{2,e}$/MJ)

	2010	2015	2020	2030	2040	2050
Reference scenario						
First-generation EtOH	115.0	115.0	115.0	115.0	115.0	115.0
First-generation biodiesel	79.0	79.0	79.0	79.0	79.0	79.0
Second-generation EtOH			−3.0	−3.0	−3.0	−3.0
Second-generation biodiesel			6.0	6.0	6.0	6.0
Integrated policy scenario						
First-generation EtOH	115.0	112.1	109.3	103.5	97.8	92.0
First-generation biodiesel	79.0	77.0	75.1	71.1	67.2	63.2
Second-generation EtOH			−3.0	−3.0	−3.0	−3.0
Second-generation biodiesel			6.0	6.0	6.0	6.0

Note: Because of electricity coproduction as a substitute for coal-derived power, GHG credits accrue for the second-generation EtOH pathway

with the prospects for future propulsion system technologies, the WTW results are presented to predict LC energy consumption and GHG emissions in future vehicle-fuel pathways.

11.6.1 WTP Results

For the period 2010–2050, the WTP results are assumed to be constant for the pathways for conventional gasoline, diesel, LPG, CNG, LNG, and GTL. However, the results differ for those pathways of bio- and coal-derived electricity and hydrogen is included. The results are presented in Tables 11.7, 11.8, 11.9, 11.10, 11.11, and 11.12.

Table 11.9 LC fossil energy intensity for coal-derived fuel (MJ/MJ)

	2010	2015	2020	2030	2040	2050
Reference scenario						
Coal to methanol	2.38	2.19	2.00	2.00	2.00	2.00
Coal to DME	2.56	2.34	2.11	2.11	2.11	2.11
Direct CTL	1.98	1.91	1.83	1.83	1.83	1.83
Indirect CTL	2.42	2.35	2.29	2.29	2.29	2.29
Integrated policy scenario						
Coal to methanol	2.38	2.19	2.00	1.90	1.81	1.76
Coal to DME	2.56	2.34	2.11	2.00	1.91	1.86
Direct CTL	1.98	1.91	1.83	1.74	1.65	1.61
Indirect CTL	2.42	2.35	2.29	2.17	2.07	2.02

Note: Under the integrated policy scenario, CCS is applied gradually from 2025 to 2050 (100 % of the application rate) for these coal-derived fuel pathways; the capture rates are all assumed to be 90 %

Table 11.10 LC GHG emission intensity for coal-derived fuel (g $CO_{2,e}$/MJ)

	2010	2015	2020	2030	2040	2050
Reference scenario						
Coal to methanol	238.0	232.0	225.9	225.9	225.9	225.9
Coal to DME	293.4	267.6	241.8	241.8	241.8	241.8
Direct CTL	236.3	227.2	218.1	218.1	218.1	218.1
Indirect CTL	285.5	278.0	270.4	270.4	270.4	270.4
Integrated policy scenario						
Coal to methanol	238.0	232.0	225.9	189.1	145.7	95.8
Coal to DME	293.4	267.6	241.8	202.4	156.0	102.5
Direct CTL	236.3	227.2	218.1	182.5	140.7	92.5
Indirect CTL	285.5	278.0	270.4	226.3	174.4	114.6

Note: Under the integrated policy scenario, CCS is applied gradually from 2025 to 2050 (100 % of the application rate) for these coal-derived fuel pathways; the capture rates are all assumed to be 90 %

Table 11.11 LC fossil energy intensity for electricity (MJ/MJ)

	2010	2015	2020	2030	2040	2050
Reference scenario	2.83	2.68	2.50	2.40	2.30	2.20
Integrated policy scenario			2.50	2.69	2.58	2.46

Notes:
1. Under the reference scenario, both the coal-to-power efficiency and low-carbon pathways improve in the future
2. under the integrated policy scenario, CCS is applied gradually from 2025 to 2035 (100 % of the application rate) for new-built coal power plants; up to 2050, CCS is applied for all running coal power plants; the capture rates are all assumed to be 90 %

Table 11.12 LC GHG emission intensity for electricity (g $CO_{2,e}$/MJ)

	2010	2015	2020	2030	2040	2050
Reference scenario	286.0	266.5	243.1	230.1	217.1	204.1
Integrated policy scenario			243.1	199.0	143.4	87.8

Notes:
1. Under the reference scenario, the coal-to-power efficiency and low-carbon pathways improve in the future
2. Under the integrated policy scenario, CCS is applied gradually from 2025 to 2035 (100 % of the application rate) for these newly built coal power plants; up to 2050, CCS is applied to all running coal power plants; the capture rates are all assumed to be 90 %

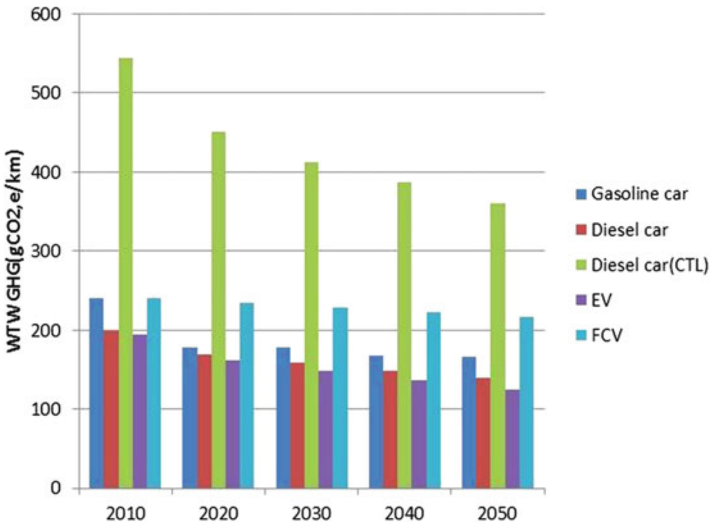

Fig. 11.12 WTW outlook under the reference scenario

11.6.2 WTW Results

With the combination of vehicle technology development (energy efficiency) in the future, the WTW results are examined under the reference scenario and integrated policy scenario. Here, the representative vehicle is a new passenger car with a fuel economy of 8 l of gasoline per 100 km.

11.6.2.1 Reference Scenario

As shown in Fig. 11.12, with technological improvement under the reference scenario, GHG emissions decrease for all pathways. With the gasoline passenger car

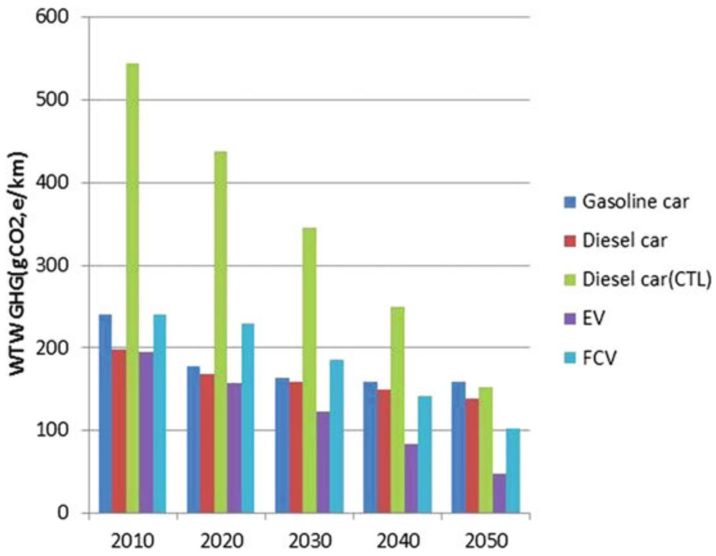

Fig. 11.13 WTW outlook in integrated policy scenario

pathway, GHG emissions decline from 240 g $CO_{2,e}$/km in 2010 to 170 g $CO_{2,e}$/km in 2050. With the EV pathway, since the technological improvement is smaller than with gasoline cars, the overall energy saving and GHG reduction advantage become progressively smaller. For FCV pathway, GHG emissions remain high throughout the whole period from 2010 to 2050. For the coal-derived pathways as coal to liquid (CTL), 100 % of GHG emissions will be more than that from gasoline cars, though the absolute level gradually decreases.

11.6.2.2 Integrated Policy Scenario

As shown in Fig. 11.13, with technological improvement under the integrated policy scenario, GHG emissions for all pathways decrease faster than under the reference scenario. With the gasoline passenger car pathway, GHG emissions decrease from 240 g $CO_{2,e}$/km in 2010 to 160 g $CO_{2,e}$/km in 2050; for EV pathway, through the application of CCS technology, the overall energy saving and reduction in GHG emissions increase, and there is a 70 % emission reduction compared with the gasoline car pathway by 2050; for FCV pathway, the disadvantage of GHG emissions are affected by the application of CCS technology in coal-derived hydrogen processes, and there is a 35 % reduction in emissions compared with the gasoline car pathway by 2050; for the coal-derived pathway as CTL, the absolute level of GHG emissions decreases quickly, and only about 10 % of GHG will be emitted than gasoline cars by 2050.

11.7 Overall Concluding Remarks

(a) China's current alternative fuel pathways are geographically unique. The pathways behave differently from LCA energy consumption and GHG emission analysis and conclusions reached for such places as the United States, the European Union, and Brazil.

(b) All current pathways are feasible in China in terms of energy security since they offer petroleum substitution, though they do not all have a clear energy-saving or GHG reduction effect.

(c) The present energy consumption and GHG situation can be improved by increasing productivity, reducing the use of resources, efficient energy conversion, and optimizing by-product use.

(d) A package of measures is required to achieve the potential of lower energy consumption and GHG emissions offered with alternative pathways. These measures include the following: speeding up improvements in battery technology for electric vehicles and establishing a charging infrastructure; finding solutions to the problems of high water consumption and high pollution emissions from coal chemical plants; and speeding up the R&D and commercial operation of low-carbon technologies, such as CCS.

(e) With the combination of vehicle technology development (energy efficiency) in future, the WTW results show that GHG emissions decrease with all pathways. With the gasoline passenger car pathway, GHG emissions are reduced from 240 g $CO_{2,e}$/km in 2010 to 160–170 g $CO_{2,e}$/km in 2050.

(f) Some policy measurements are suggested to promote efficient energy usage and reduce GHG emissions from a life-cycle perspective: (1) introduce measures to further enhance the energy efficiency of conventional gasoline and diesel vehicles to significantly reduce GHG emissions; (2) support the accelerated development of second-generation biofuels, the development of nonfossil energy sources of hydrogen production, and CCS technology; (3) improve the technology and promote demonstration projects for electric vehicles and fuel cell vehicles as well as supply options for effective energy-efficient vehicles with low GHG emissions; (4) make natural gas an option for use in vehicles; and (5) use coal-based fuel just as a short-term alternative fuel.

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