Alternative fuel buses currently in use in China: Life-cycle fossil energy use, GHG emissions and policy recommendations

Xunmin Oua,b,c, Xiliang Zhangb,c, Shiyan Changb,c

1. Introduction

The transport sector, a major oil consumer and greenhouse gas (GHG) emitter worldwide, accounted for 26% of world’s energy use and 23% of energy-related GHG emissions in 2004 (IPCC, 2007).

With the substantial increase in passenger and freight transportation demand, China’s energy consumption for this sector is soaring upwards. Table 1 indicates that the total energy use per year by all the transportation activities including railway, road, water way, air and pipeline has quadrupled from 2000 to 2007 (Wang, 2009). Correspondingly, transportation has been the most rapidly growing sector in terms of energy and particularly oil demand and GHG emission in China (Yan and Crookes, 2009). In 2005, it accounted for 37% of China’s total oil consumption (121 out of 327 Mt) (IEA, 2008). Though the related GHG emission data have not been officially published, IEA (2003, 2008) made the following estimates and projections: the share of CO₂ emissions from the transportation sector in China is 6% and 8% of all CO₂ emissions in 2000 and 2005, respectively, and Cai (2008) projected this figure to be 12–15% by 2020. IEA (2008) has also forecasted that without aggressive policies and measures to reduce oil demand in the next two decades, Chinese oil demand will reach 808 Mt per year in 2030, and road transport would account for 43% of that value. However, the slow growth of China’s domestic oil supply has increased its dependency on imported oil and this ratio has risen to over 50% in 2007 (EIA, 2008; NBSC, 2008). At the same time, as one of the two largest emitters of CO₂ in the world today, China has received and will continue...
to receive more and more pressure to reduce GHG emissions (He et al., 2007).

The effort of energy-saving (ES) technologies and alternative vehicle fuel (AVF) application in the transport sector is growing in China (Ouyang, 2006; Wang and Huo, 2009; Yan and Crookes, 2009). In 2008, approximately 53.06, 55.85 and 1.64 Mt of gasoline, diesel and bio-ethanol served on-road vehicles, respectively. A certain amount of liquefied petroleum gas (LPG) and natural gas (NG) and more than 2 Mt of methanol was estimated to be used for these vehicles in China (Zhang, 2009).

Due to their large size, which facilitates the inclusion of larger engines and fuel tanks, along with their fixed routes and refueling points, city bus fleets provide excellent opportunities for commercial demonstrations of alternative fuel vehicles (AFVs) (Ally and Pyyor, 2009; Chen et al., 2007; Collantes, 2008; Collantes and Sperling, 2008; Frenette and Forthoffer, 2009; Hekkert et al., 2005; Karamangil, 2007; Kathuria, 2004; Katransnik, 2009; Khillare et al., 2008; Kim and Moon, 2008; Lai et al., 2009; Solomon and Banerjee, 2006; Steenbergen and López, 2008; Tzeng et al., 2005; Wang and Ouyang, 2007; Yeh, 2007; Zhao and Melaina, 2006).

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>carbon content factor of process fuel (g/MJ)</td>
</tr>
<tr>
<td>CH₄.direct</td>
<td>WTP direct CH₄ emissions (g/MJ fuel)</td>
</tr>
<tr>
<td>CH₄.feedstock</td>
<td>WTP indirect CH₄ emissions from non-combustion sources (g/MJ fuel)</td>
</tr>
<tr>
<td>CH₄.indirect</td>
<td>WTP indirect CH₄ emissions from non-combustion sources (g/MJ fuel)</td>
</tr>
<tr>
<td>CH₄.noncomb</td>
<td>WTP CH₄ emissions from non-combustion sources (g/MJ fuel)</td>
</tr>
<tr>
<td>CH₄.WTP</td>
<td>WTP CH₄ emission (g/MJ fuel)</td>
</tr>
<tr>
<td>CO₂.direct</td>
<td>WTP direct CO₂ emissions (g/MJ fuel)</td>
</tr>
<tr>
<td>CO₂.Indirect</td>
<td>WTP indirect CO₂ emissions (g/MJ fuel)</td>
</tr>
<tr>
<td>CO₂.WTP</td>
<td>WTP CO₂ emission (g/MJ fuel)</td>
</tr>
<tr>
<td>EF.LC</td>
<td>life-cycle primary fossil energy use factor for process fuel (MJ/MJ)</td>
</tr>
<tr>
<td>EN</td>
<td>WTP use amount of process fuel for MJ fuel obtained (MJ/MJ fuel)</td>
</tr>
<tr>
<td>E.PTWT</td>
<td>PTW direct fossil energy use (MJ/km)</td>
</tr>
<tr>
<td>ER.CH₄</td>
<td>WTP CH₄ direct emission factor for process fuel (g/MJ)</td>
</tr>
<tr>
<td>ER.N₂O</td>
<td>WTP N₂O emission factor for process fuel (g/MJ)</td>
</tr>
<tr>
<td>EU</td>
<td>WTP direct use amount of process fuel (MJ/MJ)</td>
</tr>
<tr>
<td>E.WTP</td>
<td>WTP primary fossil energy use (MJ/MJ fuel)</td>
</tr>
<tr>
<td>E.WTW</td>
<td>WTW primary fossil energy use (MJ/km)</td>
</tr>
<tr>
<td>FE</td>
<td>vehicle fuel economy (MJ/km)</td>
</tr>
</tbody>
</table>

FOR: the fuel oxidation rate of process fuel (−)
GHG.PTW: PTW direct GHG emission (g CO₂,km)
GHG.WTP: WTP GHG emission (g CO₂,MJ fuel)
GHG.WTW: WTW GHG emission (g CO₂,MJ fuel)
N₂O.direct: WTP direct N₂O emissions (g/MJ fuel)
N₂O.Indirect: WTP indirect N₂O emissions (g/MJ fuel)
N₂O.WTP: WTP N₂O emission (g/MJ fuel)
TCH₄: life-cycle indirect CH₄ emission factor for process fuel (g/MJ)
TCO₂: life-cycle indirect CO₂ emission factor of process fuel (g/MJ)
TN₂O: life-cycle indirect N₂O emission rate for process fuel (g/MJ)

Greek symbol |
η conversion energy efficiency factor

Subscripts |
i primary fossil fuel type
j process fuel type
p life-cycle sub-stage number

Some AVF technologies have already been applied in city bus fleets in China: LPG, compressed NG (CNG), methanol (M100) and dimethyl ether (DME) bus technologies are already in commercial operation in cities where these fuels or their feedstock are abundant, while hybrid electric vehicles (HEV), electric buses (EB) and fuel cell bus (FCB) technologies are in varying stages of demonstration or deployment (Wan, 2008; Wang, 2006; Ouyang, 2006).

The Chinese government has taken a number of actions for AVF/AVF technology improvement and market creation, including AVF/AVF promotion policies, funding for R&D and market demonstrations of technology (Ouyang, 2006; Wan, 2008; Yan and Crookes, 2009; Zhao and Melaina, 2006). In 2009, more intensive policies and initiatives have been initiated, including the implementation of a demonstration project introducing 1000 electric vehicles (EVs) in 10 cities (Xinhuanet, 2009a) and providing financial subsidies for energy-saving vehicles and AFVs buyers (Xinhuanet, 2009b).

As Jaramillo et al. (2009) observed, actual life-cycle (LC) energy inputs and GHG emissions of these technologies are critical factors informing policy decisions regarding their implementation or abandonment.

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Published Chinese life-cycle analysis (LCA) studies of AVF/AFV technologies to date have primarily been based on unique single fuel/vehicle scenarios (Huang and Zhang, 2006; Zhang and Huang, 2005, 2007), or have compared multiple technologies, but explored only one stage of the fuel production or vehicle operation cycles (Di et al., 2002; Song et al., 2008; Wei et al., 2008; Xiao, 2002; Zhang, 2007). Due to the shortage of actual data, some of the previous conclusions were based on laboratory studies of vehicle engine rigs or on projections lacking supporting data (Hu et al., 2007a, 2007b; Zhang et al., 2005). Therefore, it is not possible to use such results for comparisons among multiple technologies in a way that reflects recent AVF implementation projects including full LC comprehension (Chai, 2008; Shen et al., 2006; Zhang et al., 2008).

The well-to-wheels (WTW) module of the Tsinghua-CA3EM model (China Automotive Energy, Environmental and Economic Model) (Ou et al., 2008a, 2008b, 2009) is employed here to
analyze the LC energy consumption (EC) and GHG emissions of China’s current dominant alternative fuel bus (AFB) in detail, using the same platform, and actual China data. By parallel comparison with gasoline and diesel buses, LC EC, GHG reduction (GR) and oil/gas substitution effects of the AFB technology have been explored. Through key factor analysis and comparative studies, some potential approaches for improving these dual effects have also been discussed. Finally, based on a quick scan of the AVE/AEV promotion policy history, status and trends in China, and combined with the analysis of the actual LC behaviors of these AFBs, some suggestions are presented for future policy decisions and implementation.

2. Methodology

2.1. Tsinghua-CA3EM employed

Tsinghua-CA3EM is an integrated computerized model for China’s automotive energy supply and demand balance calculation and analysis which is based on China’s national conditions and integrates the widely used transportation energy micro-level computing GREET (GHG, Regulated Emissions and Energy use of Transportation fuel model) (Wang, 2007). Parts of the GREET model structure have been adjusted to be specific to China, such as reflecting the dominance of coal utilization. A majority of the parameters have also been modified with local Chinese data (Ou et al., 2008a, 2008b, 2009).

2.2. System boundary and sub-stages divided

Well-to-Pump (WTP) and Pump-to-Wheels (PTW) are the two stages included in this well-to-wheels (WTW) EC and GHG analysis: WTP comprehends both EC and GHG during the upstream fuel production stage, including raw resource extraction, feedstock transportation, fuel production, and fuel transportation, storage and distribution (TSD), while PTW comprehends both EC and GHG during the downstream fuel combustion process in the vehicle’s engine. The WTP stage is divided to four sub-stages: (1) feedstock production for the fossil energy source; (2) feedstock transportation; (3) fuel production; and (4) fuel TSD.

2.3. Covered primary fossil energy, process fuel and GHG types

Three types of primary fossil energy (PE) and nine types of process fuel (PF) are considered in this study. The former includes coal, natural gas and oil, and the latter includes crude coal, crude NG, crude oil, coal, NG, diesel, gasoline, residual oil and electricity. The first three types of PF are just extracted and transported but not processed to secondary energy. Three key types of GHG emissions (CO$_2$, CH$_4$ and N$_2$O) are considered.

2.4. Functional units and WTW calculation methods

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 km driven for the city bus. To calculate the WTW results, the two units are linked through the fuel economy (FE) of the AFB:

\[ E_{\text{WTW}} = E_{\text{WTP}} \cdot FE + E_{\text{PTW}} \]  
\[ GHG_{\text{WTW}} = GHG_{\text{WTP}} \cdot FE + GHG_{\text{PTW}} \]  

where $E_{\text{WTW}}$ is the WTW primary fossil energy use per km (MJ/km), $E_{\text{WTP}}$ 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), $E_{\text{PTW}}$ is the PTW direct primary fossil energy use (MJ/km), $GHG_{\text{WTP}}$ is the WTP GHG emissions (gCO$_2$/km), $GHG_{\text{WTW}}$ is the PTW GHG emissions (gCO$_2$/MJ), and $GHG_{\text{PTW}}$ is the PTW GHG emissions (gCO$_2$/km).

2.5. Pathways selected

China’s current dominant six AFB pathways are selected with the gasoline bus (GB) and diesel bus (DB) as the baselines: LPG bus (LPGB), CNG bus (CNGB), NG-derived H$_2$ FCB (NGHFCB), coal-derived methanol bus (CM100B), coal-derived DME bus (CDMEB) and EB.

2.6. WTP calculation methods

2.6.1. WTP energy use

$E_{\text{WTP}}$ is calculated as the sum of the corresponding PE consumption due to the PF directly used during each of the sub-stages of the life cycle:

\[ E_{\text{WTP}} = \sum_{p=1}^{4} \sum_{j=1}^{9} (EN_{pj} \cdot EF_{ij}) \]  

where $i$ is the PE type, $j$ is the PF type, $p$ is the sub-stage number, $EN_{pj}$ is the use amount of PF type $j$ during the sub-stage $p$ for MJ fuel obtained (MJ/MJ fuel), $EF_{ij}$ is the LC energy use factor (EF) of PE type $i$ for PF type $j$ (MJ/MJ).

$EN_{pj}$ can be derived through the direct amount of PF type $j$ used during sub-stage $p$ ($EU_{pj}$) combined with the product of each of the energy conversion efficiency factors from the following sub-stages ($\eta_p$):

\[ EN_{pj} = EU_{pj} / (\eta_1 \cdot \eta_2 \cdot \eta_3) \] for $(p = 1, 2, 3) \]  
\[ EN_{pj} = EU_{pj} \] for $(p = 1, 3) \]  

where the unit of $EU_{pj}$ is MJ/MJ feedstock/fuel obtained for $p = 1, 3$ and MJ/MJ feedstock/fuel used for $p = 2, 4$, respectively; $\eta_p$ is the result of one divided by the sum of one and all PE used for power and process feedstock or transportation fuel during sub-stage $p$.

2.6.2. WTP GHG emission

The three key types of GHG emissions are converted to their CO$_2$ equivalents (gCO$_2$/MJ) according to their global warming potential value (IPCC, 2007) as shown by the following expression:

\[ GHG_{\text{WTP}} = \text{CO}_2_{\text{WTP}} + 23\text{CH}_4_{\text{WTP}} + 296\text{N}_2\text{O}_{\text{WTP}} \]  

where CO$_2_{\text{WTP}}$ is WTP CO$_2$ emissions (g/MJ fuel), CH$_4_{\text{WTP}}$ is WTP CH$_4$ emissions (g/MJ fuel) and N$_2$O$_{\text{WTP}}$ is WTP N$_2$O emissions (g/MJ fuel).

During each of the sub-stages, 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, and the latter includes the emissions during their 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 emission: some emissions from non-combustion sources, including spills and other fugitive emission losses during the feedstock extraction stage (g/MJ fuel).
\[ \text{CO}_2 \text{WTP} = \text{CO}_2 \text{direct} + \text{CO}_2 \text{indirect} = \sum_{p=1}^{9} \sum_{j=1}^{4} E_{pj}(C_j \text{FOR}_j/44/12 + \text{TCO}_2) \]

where \( \text{CO}_2 \text{direct} \) reflects WTP direct \( \text{CO}_2 \) emissions (g/MJ fuel), \( \text{CO}_2 \text{indirect} \) corresponds to WTP indirect \( \text{CO}_2 \) emissions (g/MJ fuel), \( C_j \) is the carbon content factor of PF type \( j \) (g/MJ), \( \text{FOR}_j \) is the fuel oxidation rate of PF type \( j \), \( \text{TCO}_2 \) is the LC indirect \( \text{CO}_2 \) emissions factor for PF type \( j \) (g/MJ) and 44/12 is the mass conversion rate from C to \( \text{CO}_2 \). The calculation for \( \text{CO}_2 \text{indirect} \) is based on a carbon balance equation (Ou et al., 2008a; Wang and Weber, 2001).

Calculations \( \text{CH}_4 \text{WTP} \) and \( \text{N}_2\text{O}_\text{WTP} \) are similar:

\[ \text{CH}_4 \text{WTP} = \text{CH}_4 \text{direct} + \text{CH}_4 \text{indirect} = \sum_{p=1}^{9} \sum_{j=1}^{4} E_{pj}((E_{CH}_4 j + TCH_4 j) + \text{CH}_4_{\text{noncomb}}) \]

\[ \text{N}_2\text{O}_\text{WTP} = \text{N}_2\text{O}_\text{direct} + \text{N}_2\text{O}_\text{indirect} = \sum_{p=1}^{9} \sum_{j=1}^{4} E_{pj}(E_{\text{RN}_2\text{O}_j} + T\text{N}_2\text{O}_j) \]

where \( \text{CH}_4 \text{direct} \) is WTP direct \( \text{CH}_4 \) emissions (g/MJ fuel), \( \text{CH}_4 \text{indirect} \) is WTP indirect \( \text{CH}_4 \) emissions (g/MJ fuel), \( E_{\text{RH}_4 j} \) is the direct \( \text{CH}_4 \) emissions factor for PF type \( j \) (g/MJ), \( \text{TCH}_4 \) is the LC indirect \( \text{CH}_4 \) emissions factor for PF type \( j \) (g/MJ). \( \text{CH}_4_{\text{noncomb}} \) corresponds to indirect \( \text{CH}_4 \) emissions from non-combustion sources, including spills and losses during the feedstock extraction stage (g/MJ fuel), \( \text{N}_2\text{O}_\text{direct} \) corresponds to the WTP \( \text{N}_2\text{O} \) emissions (g/MJ fuel), \( \text{N}_2\text{O}_\text{indirect} \) is the WTP direct \( \text{N}_2\text{O} \) emissions (g/MJ fuel), \( \text{ER}_{\text{RN}_2\text{O}_j} \) is the direct \( \text{N}_2\text{O} \) emissions factor for PF type \( j \) (g/MJ), \( \text{TN}_2\text{O} \) is the LC indirect \( \text{N}_2\text{O} \) emissions factor for PF type \( j \) (g/MJ).

For the \( \text{CH}_4 \text{noncomb} \) calculation:

\[ \text{CH}_4_{\text{noncomb}} = \text{CH}_4 \text{feedback}/(\eta_2 \eta_4) \]

where \( \text{CH}_4 \text{feedback} \) corresponds to the indirect \( \text{CH}_4 \) emissions from non-combustion sources, including spills and losses during the feedstock extraction stage (g/MJ feedstock obtained).

### 3. Data and assumptions

Based on Eqs. (1)–(10), for WTP LCA of all AFV pathways (excluding electricity) two parts of the data are essential: (1) the energy conversion efficiency factors of each sub-stage (\( \eta \)) and direct use amount of each type of PF during each sub-stage (EU); and (2) the direct and indirect PE use and GHG emission factors for each type of PF (\( E_{\text{EffC}}, C, \text{FOR}, \text{TCO}_2, E_{\text{RH}_4}, \text{TCH}_4, E_{\text{ER}_2\text{N}_2\text{O}}, \text{TN}_2\text{O} \) and \( \text{CH}_4_{\text{noncomb}} \)). The intermediate data for MJ fuel obtained (\( E_{\text{NE}} \)) can be calculated based on the former part (\( \eta \) and EU), and provided for the calculation of WTP when combined with the latter part. Due to a wide variety of feedstock for its generation, WTP data of the electricity pathway will be described in a separate section.

For the PTW stage, the essential data are vehicle fuel economy (\( F_E \)) and the corresponding PE use (\( E_{\text{PTW}} \)) and their associated GHG emissions (\( \text{GHG}_{\text{PTW}} \)).

#### 3.1. \( \eta \), EU and \( EN \)

##### 3.1.1. Original data and source

Table 2 lists original Chinese data on feedstock extraction and processing efficiency, process fuel mix, transportation mode and average distance, fuel production efficiencies, and process fuel emission factors for oil-, NG- and coal-based fuel.

### Table 2

<table>
<thead>
<tr>
<th>Type of Fuel</th>
<th>Process Type</th>
<th>Extraction Emissions Factor</th>
<th>Processing Emissions Factor</th>
<th>Fuel Use</th>
<th>Transportation Mode</th>
<th>GHG Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>Oil</td>
<td>93.00%</td>
<td>94.00%</td>
<td>95.00%</td>
<td>100%</td>
<td>90.00%</td>
</tr>
<tr>
<td>Gas</td>
<td>Gas</td>
<td>90.00%</td>
<td>90.00%</td>
<td>95.00%</td>
<td>90.00%</td>
<td>95.00%</td>
</tr>
<tr>
<td>Coal</td>
<td>Coal</td>
<td>90.00%</td>
<td>90.00%</td>
<td>95.00%</td>
<td>90.00%</td>
<td>95.00%</td>
</tr>
</tbody>
</table>

Note: (1) While refinery still gas is produced onsite from crude oil inputs, no additional PE inputs are necessary for production of this by-product (Wang, 2009), which is characterized by a CO2 emission factor of 65 g/MJ fuel and has a production energy efficiency of 100%. (2) Transportation mode: % share (average distance). (3) Some data sources directly from Ou et al. (2008a), containing a comprehensive and detailed LCA study of China’s transportation sector compiled by the China Automotive Energy Research Center (CAERC). CAERC is a university- and education-based research center targeting sustainable transportation energy pathways for China. It is jointly supported by Tsinghua University, the GM Corporation and the China Shanghai Automotive Industry Company. The CAERC has conducted site investigations, held expert panel meetings and conducted extensive literature reviews to create a full and detailed picture of China’s automotive energy issues including LCA (Ou et al., 2008a, 2008b).
mix with TSD modes average distances for oil-, NG- and coal-based fuels (CATARC, 2007; CTTA, 2008; NBSC, 2008; Ou et al., 2008a). Although H₂ has many production pathways, this study assumes all H₂ was produced by steam reforming of NG (Ou, 2009).

Table 3 lists the data for transportation energy intensity (kJ/t km) and the fuel mix for each mode. These data can serve for the calculation of direct amount of PF used (EU) during feedstock transportation and fuel TSD sub-stages when the low heat values (MJ/kg) of these transportation fuels are known (Ou et al., 2008a).

3.1.2. Z and EU

Based on the original data in Section 3.1.1, all the energy conversion efficiency factors (Z) and amount of direct use PF (EU) for each sub-stage for the oil-, NG- and coal-based fuel can be calculated. The former is listed in Table 4 and the latter is used directly to calculate ENₚᵢ.

3.1.3. EN

According to Eqs. (4) and (5), EN is based on the inputs of η and EU, and the results are listed in Table 5.

3.2. Direct and indirect energy use and GHG emission factors for WTP

The factors for both direct and indirect energy use and GHG emissions are shown in Table 6 (Ou et al., 2008a). The non-combustion CH₄ emission values (CH₄,feedstock) are 0.009, 0.072 and 0.406 g for each MJ of crude oil, crude NG and crude coal obtained in China, respectively (3E-THU, 2003), and their CH₄,noncomb values are calculated based on Eq. (10) and listed in Table 7.

3.3. Original data for electricity WTP

The energy use and GHG emission effects of electricity are highly dependent on feedstock utilized and should be calculated accordingly and then converted to accommodate mixed scenarios (Wang and Huo, 2009). The original data about power supply mix, transmission and distribution loss ratio, generation supply efficiency and LCA behaviors of each pathway are listed in Table 8.

3.4. Original data for PTW

While precise vehicle fuel efficiencies are extremely important to WTW analysis, many of these values are difficult to determine, and wide ranges of estimates currently exist (Ally and Pryor, 2009; Wang and Huo, 2009). Here we use recent FE data and GHG emission factors for AFVs currently in use, either on a demonstration or on a commercial basis as shown in Table 9.

Table 3
Transportation mode and fuel mix.

<table>
<thead>
<tr>
<th>Energy intensity (kJ/t km)</th>
<th>Fuel mix and percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea tanker</td>
<td>23</td>
</tr>
<tr>
<td>Rail</td>
<td>240</td>
</tr>
<tr>
<td>Pipeline: oil</td>
<td>300</td>
</tr>
<tr>
<td>Pipeline: NG</td>
<td>372</td>
</tr>
<tr>
<td>Waterway</td>
<td>148</td>
</tr>
<tr>
<td>Road: short distance</td>
<td>1362</td>
</tr>
<tr>
<td>Road: long distance</td>
<td>1200</td>
</tr>
</tbody>
</table>

Note: (1) Source: Ou et al. (2008a).

Table 4
Energy conversion efficiency factors (η) of each sub-stage [%].

<table>
<thead>
<tr>
<th>Sub-stage</th>
<th>Gasoline</th>
<th>Diesel</th>
<th>LPG</th>
<th>CNG</th>
<th>H₂</th>
<th>M100</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedstock production</td>
<td>93.0</td>
<td>93.0</td>
<td>93.0</td>
<td>90.2</td>
<td>94.1</td>
<td>94.1</td>
<td></td>
</tr>
<tr>
<td>Feedstock transportation</td>
<td>99.4</td>
<td>99.4</td>
<td>99.4</td>
<td>99.4</td>
<td>99.8</td>
<td>99.8</td>
<td></td>
</tr>
<tr>
<td>Fuel production</td>
<td>89.1</td>
<td>97.6</td>
<td>91.1</td>
<td>96.1</td>
<td>42.8</td>
<td>39.0</td>
<td></td>
</tr>
<tr>
<td>Fuel TSD</td>
<td>99.7</td>
<td>99.7</td>
<td>99.7</td>
<td>99.8</td>
<td>99.5</td>
<td>99.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 5
Type of PF used during each sub-stage (EN) (kJ/MJ fuel).

<table>
<thead>
<tr>
<th>Fuel/sub-stage no.</th>
<th>Gasoline</th>
<th>Diesel</th>
<th>LPG</th>
<th>CNG</th>
<th>H₂</th>
<th>M100</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude coal</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Crude NG</td>
<td>0.0</td>
<td>0.0</td>
<td>2.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Crude oil</td>
<td>21.8</td>
<td>0.0</td>
<td>73.6</td>
<td>0.0</td>
<td>21.1</td>
<td>0.0</td>
<td>69.1</td>
</tr>
<tr>
<td>Coal</td>
<td>10.9</td>
<td>0.0</td>
<td>24.5</td>
<td>0.0</td>
<td>10.5</td>
<td>0.0</td>
<td>69.1</td>
</tr>
<tr>
<td>NG</td>
<td>25.1</td>
<td>0.0</td>
<td>24.3</td>
<td>0.0</td>
<td>24.1</td>
<td>0.0</td>
<td>24.1</td>
</tr>
<tr>
<td>Diesel</td>
<td>8.7</td>
<td>1.0</td>
<td>12.1</td>
<td>1.0</td>
<td>8.4</td>
<td>1.0</td>
<td>8.4</td>
</tr>
<tr>
<td>Gasoline</td>
<td>1.1</td>
<td>0.0</td>
<td>1.2</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Residual oil</td>
<td>1.1</td>
<td>3.4</td>
<td>4.9</td>
<td>1.0</td>
<td>1.3</td>
<td>4.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Electricity</td>
<td>40.4</td>
<td>1.9</td>
<td>147.0</td>
<td>0.7</td>
<td>39.0</td>
<td>1.9</td>
<td>138.0</td>
</tr>
</tbody>
</table>

Table 6
Type of PF used during each sub-stage (EN) (kJ/MJ fuel).

<table>
<thead>
<tr>
<th>Fuel/sub-stage no.</th>
<th>CNG</th>
<th>H₂</th>
<th>M100</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude coal</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Crude NG</td>
<td>41.7</td>
<td>0.0</td>
<td>42.8</td>
<td>4.3</td>
</tr>
<tr>
<td>Crude oil</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Coal</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>NG</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.0</td>
<td>0.0</td>
<td>6.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Gasoline</td>
<td>0.0</td>
<td>0.0</td>
<td>2.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Residual oil</td>
<td>0.0</td>
<td>0.0</td>
<td>52.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.1</td>
<td>0.1</td>
<td>36.8</td>
<td>0.1</td>
</tr>
</tbody>
</table>


Table 6
LCA PE use factors and direct and indirect GHG emission factors for PFs.

<table>
<thead>
<tr>
<th>PF</th>
<th>( E_{FC} )</th>
<th>PE: coal (MJ/MJ)</th>
<th>PE: NG (MJ/MJ)</th>
<th>PE: oil (MJ/MJ)</th>
<th>( TCO_2 ) (g/MJ)</th>
<th>( TCH_4 ) (g/MJ)</th>
<th>( TN_2O ) (mg/MJ)</th>
<th>( ERCH_4 ) (g/MJ)</th>
<th>( ERN_2O ) (mg/MJ)</th>
<th>CC (gC/MJ)</th>
<th>FOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude coal(^b)</td>
<td>1.05</td>
<td>0.00</td>
<td>0.00</td>
<td>4.26</td>
<td>0.42</td>
<td>0.06</td>
<td>0.001</td>
<td>0.001</td>
<td>24.08</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>Crude NG(^b)</td>
<td>0.08</td>
<td>1.01</td>
<td>0.06</td>
<td>11.91</td>
<td>0.07</td>
<td>0.15</td>
<td>0.001</td>
<td>0.001</td>
<td>15.30</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Crude oil(^b)</td>
<td>0.10</td>
<td>0.02</td>
<td>1.05</td>
<td>16.00</td>
<td>0.05</td>
<td>0.27</td>
<td>0.002</td>
<td>0.000</td>
<td>20.00</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>1.06</td>
<td>0.00</td>
<td>0.11</td>
<td>5.73</td>
<td>0.43</td>
<td>0.17</td>
<td>0.001</td>
<td>0.001</td>
<td>24.74</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>NG</td>
<td>0.11</td>
<td>1.04</td>
<td>0.05</td>
<td>16.58</td>
<td>0.05</td>
<td>0.12</td>
<td>0.001</td>
<td>0.001</td>
<td>15.32</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>0.18</td>
<td>0.03</td>
<td>1.12</td>
<td>27.87</td>
<td>0.08</td>
<td>0.44</td>
<td>0.004</td>
<td>0.002/0.028(^c)</td>
<td>20.20</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>Gasoline</td>
<td>0.18</td>
<td>0.03</td>
<td>1.12</td>
<td>28.83</td>
<td>0.09</td>
<td>0.47</td>
<td>0.080</td>
<td>0.002</td>
<td>18.90</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>Residual oil</td>
<td>1.14</td>
<td>0.03</td>
<td>0.36</td>
<td>265.22</td>
<td>1.01</td>
<td>3.92</td>
<td>0</td>
<td>0</td>
<td>21.10</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>2.86</td>
<td>0.03</td>
<td>0.36</td>
<td>265.22</td>
<td>1.01</td>
<td>3.92</td>
<td>0</td>
<td>0</td>
<td>21.10</td>
<td>0.98</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Source from Ou et al. (2008a).
\(^b\) These fuels are mined and transported but not refined.
\(^c\) For vehicles, the utilization value is 0.002, while for other applications this value is 0.028.

Table 7
Non-combustion CH\(_4\) emission (CH\(_4\)\(_{noncomb}\)) (g/MJ fuel).

<table>
<thead>
<tr>
<th></th>
<th>Gasoline</th>
<th>Diesel</th>
<th>LPG</th>
<th>CNG</th>
<th>H(_2)</th>
<th>M100</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH(<em>4)(</em>{noncomb})</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td>0.076</td>
<td>0.110</td>
<td>0.955</td>
<td>1.049</td>
</tr>
</tbody>
</table>

Table 8
Input data for electricity pathway WTP.

Electricity supply mix
- Coal (80.1%), oil (1.8%), NG (0.7%), nuclear energy (1.9%), biomass (0.1%) and many other sources (14.7%) (CEC, 2008; NBCS 2008)
- Loss ratio during transmission and distribution: 6.97% in 2007 (CEC, 2008; NBCS 2008)
- Power supply efficiencies
  - Coal (36%), oil (32%), NG (45%), nuclear energy (32%) and others (100%) (Ou et al., 2008a)
- Fuel LCA
  - Fossil energy use: 3.894 MJ/MJ, including coal (3.527), NG (0.007) and oil (0.361); GHG emissions: 322.311 g CO\(_2\)/MJ (Ou et al., 2008a)
  - Oil LCA
    - Fossil energy use: 4.098 MJ/MJ, including coal (0.467), NG (0.087) and oil (3.544); GHG emissions: 334.633 g CO\(_2\)/MJ (Ou et al., 2008a)
- Nuclear power LCA
  - Fossil energy use: 3.329 MJ/MJ, including coal (0.522), NG (2.572) and oil (0.235); GHG emissions: 270.338 g CO\(_2\)/MJ (Ou et al., 2008a)
  - Nuclear LCA
    - Fossil energy use: 0.063 MJ/MJ, including coal (0.052), NG (0.005) and oil (0.006); GHG emissions: 6.506 g CO\(_2\)/MJ (Ou et al., 2008a)
  - Nuclear LCA
    - Energy use can be neglected, while GHG emissions are approximately 5 g CO\(_2\)/MJ (Weisser, 2007)
  - Hydroelectric LCA
    - Case of cotton stalks: 0.075 MJ/MJ, including coal (0.010), NG (0.002) and oil (0.064); GHG emissions: 5.846 g CO\(_2\)/MJ (Ou et al., 2008a)

Note: (1) Nuclear power LCA mainly covers uranium mining, processing and transportation sub-stages. (2) Hydroelectric power is primarily non-fossil energy power used in China. (3) Biomass power LCA is based on the following values: the heat value of feedstock is 15.89 MJ/kg; feedstock transportation distance is set to 100 km; and fuel economy for feedstock transportation (by diesel truck) is 0.0745 l/t km.

4. Results and discussion

4.1. WTW results
The complete benefits of fuels are compared on a WTW basis including differences in vehicle system efficiency (CATARC, 2007; Ou et al., 2008b; Wang and Huo, 2009). WTW results are presented on a per-km basis in Fig. 1. In general AVFs achieved reductions in petroleum use, but coal-based fuels faced major challenges in terms of GHG emissions. CM100Bs and CMDEMs emit 120% more GHGs, use 100% more fossil fuel (primarily coal) but use 97% less oil than DBs. Because EBs achieve significant gains in fuel economy over conventional ICE buses, these vehicles showed a 20% reduction in fossil energy use and a 13% reduction in GHG emissions compared to DBs. Noticeable differences between WTP and WTW results are found for hydrogen FCs and EBs. This finding illustrates the importance of including vehicle efficiencies in evaluating transportation fuels (CATARC, 2007; Ou et al., 2008b; Wang and Huo, 2009). Because the actual efficiencies of operational FCs are lower than might be desired, they do not present significant benefits over DBs in terms of ES and GR, and have fossil energy use and GHG emissions that are 33% and 16% greater, respectively, than those of DBs; CNG buses use approximately the same amount of fossil energy as DBs, but primarily use NG, and consequently emit 26% less GHGs. Among buses using petroleum-based fuels, the ranking of energy use and GHG emissions follows the order of GB > DB > LPGb, with each pathway differing from the next by approximately 10% in both categories.

4.2. General sensitivity analysis
Generally, AVF/AFV LCA results can be impacted by the following factors: fuel characteristics, location of feedstock extraction/production sites, fuel/feedstock transportation mode and distance, conversion efficiency and utilization efficiency (Jaramillo et al., 2009; Shen et al., 2006; Weisser, 2007). For the AVFs considered, there are no obvious differences in energy extraction efficiency (CATARC, 2007; Hekkert et al., 2005; Wang and Huo, 2009), but there are potentially significant differences in fuel transportation and distribution distances and small variations in fuel production efficiency and vehicle fuel economy (CATARC, 2007; Ou et al., 2009).

Fig. 2 presents the impact on WTW fossil energy use and GHG emissions of the variations of the above-mentioned factors. Interestingly, a 50% variation in transportation and distribution distances results in only a 0.15–2.25% difference in WTW results for all AFVs. Differences in fuel production efficiency can substantially impact WTW results for vehicles using fuel sources with relatively low transformation efficiencies, including hydrogen produced from NG, M100 and DME from coal, as well as for EBs. Changes in vehicle fuel economy result in proportional changes in WTW efficiency and emissions.
4.3. Key impact factors analysis

Based on the sensitivity analysis in Section 4.3, several key factors affecting LCA results can be identified, including fuel production efficiency, vehicle fuel economy, and fuel/feedstock transportation and distribution distances. By identifying opportunities to modify these factors for the different classes of AFBs studied, we can further analyze the potential to realize greater gains in AFB ES and GR and define future scenarios including the introduction of new coal-to-liquid (CTL) and corresponding CTL bus (CTLB) pathways, and a new CO₂ capture and storage (CCS) method to reduce GHG emissions, as shown in Table 10. The WTW results under different future scenarios are shown in Fig. 3.

Due to substantial improvements in fuel production efficiency, FCBs use only 15% more energy and have roughly comparable GHG emissions compared to DBs, while buses using coal-based fuels use about 50% more energy and have 60% greater GHG emissions, respectively. Only with the application of CCS, the latter fuel (CTL) can compete with petroleum-based fuel with a 25% GHG emissions reduction. However, the resulting energy use is 40% more than that of DB.

For LPGB and CNGB pathways, the reduction of feedstock and fuel transportation distances can strengthen their obvious benefits in terms of both ES and GR. For EB, CCS is a potential method to reduce about 65% of GHG emissions when compared to DBs. Even if this relatively ideal technology is not employed, the dual benefits of EBs can be enhanced by introducing the new clean power mix where ES and GR are increased to the values that are 20–30% lower than those for DBs.

Table 9
Key parameters for operating AFBs.

<table>
<thead>
<tr>
<th>Pathway no.</th>
<th>Propulsion system</th>
<th>Fuel type</th>
<th>Fuel consumption/100 km</th>
<th>FE (MJ/km)</th>
<th>$E_{PTW}$ (MJ/km)</th>
<th>GHG$_{PTW}$ (g CO₂, e/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB</td>
<td>SI ICE</td>
<td>Gasoline</td>
<td>55 l</td>
<td>17.53</td>
<td>17.53</td>
<td>1191.78</td>
</tr>
<tr>
<td>DB</td>
<td>CI ICE</td>
<td>Diesel</td>
<td>45 l</td>
<td>16.12</td>
<td>16.12</td>
<td>1171.32</td>
</tr>
<tr>
<td>LPGB</td>
<td>SI ICE</td>
<td>LPG</td>
<td>30 kg</td>
<td>15.56</td>
<td>15.56</td>
<td>963.18</td>
</tr>
<tr>
<td>CNGB</td>
<td>SI ICE</td>
<td>CNG</td>
<td>45 kg</td>
<td>16.02</td>
<td>16.02</td>
<td>893.9</td>
</tr>
<tr>
<td>NGHFCB</td>
<td>FCB</td>
<td>Hydrogen</td>
<td>10.76 kg</td>
<td>13.02</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CM100B</td>
<td>SI ICE</td>
<td>M100</td>
<td>901</td>
<td>16.23</td>
<td>16.23</td>
<td>1072.41</td>
</tr>
<tr>
<td>CDMEB</td>
<td>CI ICE</td>
<td>DME</td>
<td>801</td>
<td>15.18</td>
<td>15.18</td>
<td>1039.9</td>
</tr>
<tr>
<td>EB</td>
<td>EB</td>
<td>Electricity</td>
<td>150 kWh</td>
<td>5.40</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: (1) Data sources are Ou et al. (2008a, 2008b) and site investigations. (2) SI: spark-ignition; ICE: internal combustion engine; CI: compression-ignition. (3) Fuel use data are based on actual in-city operation of buses with a 12-m vehicle length and 70-passenger capacity using heat and air conditioning as needed.
Fuel economy is critical to realizing ES and GR gains (Ou et al., 2008b; Wang and Huo, 2009). When HEV is applied to DBs, only modest dual effects are achieved. In the case of FCBs, when the long-term objective of an efficiency ratio of 2.4 times that of DB is achieved, dramatic ES and GR gains of about 30–40% are projected. Finally, by optimizing the battery performance of EBs, a 10% improvement in fuel economy can be realized, with concomitant improvements in ES and GR.

4.4. Comparative studies

Due to different vehicle fuel economy data used, the comparison across the WTW results using the same fuel type in different studies should be based units of per MJ fuel obtained and utilized in order to avoid inevitable errors when comparing to the WTW unit of per km traveled.

4.4.1. Oil-based fuels

As Fig. 4 shows, the oil-based fuel WTW EC results for China (Huang and Zhang, 2006; Hu et al., 2007a, 2007b; Shen et al., 2006) are close to the worst in the world (Campanari et al., 2009; Granovskii et al., 2006; Hekkert et al., 2005). Among studies focusing on China, the current study reports some of the most pessimistic GHG emissions figures.

4.4.2. NG-based fuels

As Fig. 5 shows, the CNG WTW EC results for China (Shen et al., 2006) are close to the values reported for Italy (Campanari et al., 2009), but the values for hydrogen produced from NG for China (Huang and Zhang, 2006) are higher than the levels reported for Canada (Granovskii et al., 2006). Among studies focusing on China, the present work reports some of the most pessimistic GHG emissions results.

4.4.3. Coal-based fuels

As Fig. 6 shows, there are not many studies for coal-based M100 and DME pathways, and the results for China show that as this technology improves, efficiency increases (Hu et al., 2007b; Shen et al., 2006; Wei et al., 2008; Zhang and Huang, 2007). Vehicles using NG-based fuels in the US (Steenberghen and López, 2008) showed better performance than buses running on coal-based DME in China.

4.4.4. Electricity generation

As Fig. 7 shows, electricity generation WTW EC results for China are among the worst in the world (Weisser, 2007). Even among studies focusing on China, the present work reports some of the most pessimistic energy use and GHG emissions results (Di et al., 2002; Xiao et al., 2006).

4.4.5. Causal analysis of differences across various LCA studies

Differences between results in life-cycle energy use from studies of transportation fuel in China and other countries can be largely attributed to: (1) low efficiencies of feedstock extraction/processing, for example, oil extraction efficiency in

Table 10

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>DB@HEV10</td>
<td>DB fuel economy gets an improvement of 10% in currently operating fleets with HEV technology (Ou et al., 2008b)</td>
</tr>
<tr>
<td>DB@HEV20</td>
<td>DB fuel economy gets an improvement of 20% according to research projections (MOST, 2008)</td>
</tr>
<tr>
<td>LPGB@D50</td>
<td>LPG feedstock and fuel transportation distance is greatly reduced to 50 km for the LPG in the districts adjacent to large-scale oil refineries such as Changchun city in Jilin</td>
</tr>
<tr>
<td>CNGB@D100</td>
<td>CNG feedstock and fuel transportation distance is greatly reduced to 100 km for CNGB in locally gas abundant areas such as Sichuan and Chongqing</td>
</tr>
<tr>
<td>NGHCFB@FE15</td>
<td>Hydrogen production efficiency from NG is improved substantially by 15% in the future according to estimates by Huang and Zhang (2006) and Wang and Huo (2009)</td>
</tr>
<tr>
<td>NGHCFB@FE24</td>
<td>Extensive efforts have been made to raise the efficiency of FCBs to be 2.4 times that of diesel buses (Concawe and ELCAR, 2007) from the value of 1.24 for the current study</td>
</tr>
<tr>
<td>CM100@FE25</td>
<td>M100 production efficiency from coal is improved substantially by 25% when considering the optimistic projections of Song et al. (2008) and Zhang and Huang (2007)</td>
</tr>
<tr>
<td>CDMEB@EF35</td>
<td>DME production efficiency from coal is improved substantially by 35% when considering the optimistic projections of Song et al. (2008) and Zhang and Huang (2007)</td>
</tr>
<tr>
<td>CTLB@CCS</td>
<td>CTL would be supplied commercially to fuel the bus in the future based on current success of production tests on the 1 Mt oil scale. Additional 80–160 kWh is consumed to capture 80% of CO₂ produced in the factory when CCS is applied according to Jaramillo et al. (2005). Based on that the aforementioned, CTL (with CCS) results in WTP fossil energy use of 2.965 MJ/MJ and GHG emissions of 14.7 g CO₂/e/km</td>
</tr>
<tr>
<td>EB@CCS</td>
<td>The electricity is supplied from coal-fired power plants with CCS technology to capture 80% of CO₂ produced on-site with the penalty of the conversion efficiency reduction to 32% (IPCC, 2005)</td>
</tr>
<tr>
<td>EB@CE</td>
<td>The ratios of nuclear and renewable energy are increased to 15% and 10%, respectively, in the future (Ou et al., 2008a)</td>
</tr>
<tr>
<td>EB@FE10</td>
<td>A 10% improvement in fuel economy of EB can be realized by optimizing battery performance (Ou et al., 2008a)</td>
</tr>
</tbody>
</table>

Fig. 3. WTW fossil energy use and GHG emissions under different future scenarios.
China is only 93.0% while this value is 98% for US as used in the GREET model (Wang, 2007); (2) China’s relatively high energy consumption in the process of fuel production (NBSC, 2008; Ou et al., 2008a), particularly in the case of widely used steam boilers mainly fueled with coal, which achieve low efficiency levels of 80%, compared to the global average of 90% (IPCC, 2006); (3) high energy intensity for China’s transportation sector, which are higher than the corresponding North American values (Wang, 2007). As Fig. 8 shows, for the same diesel pathway, based on the above-mentioned factors, the WTP fossil energy use is one time higher than US results.

What is more, due to China’s coal-dominated energy mix (Jiang, 2008), coal use accounts for 54% of WTP fossil energy use for diesel production while it is only 18% in the US, as shown in Fig. 8. Moreover, with its higher carbon content than that of NG and oil, coal emits more CO₂ when it is used to supply the same energy service. There are also more CH₄ emissions associated within China’s coal mining and crude oil and NG exploration stages, resulting in higher GHG emissions in WTP results.

Therefore, the following measures have been taken to rationalize the difference across all Chinese AFVs’ LCA studies: (1) collection of additional actual Chinese data, including EC and...
GHG emissions of all the life-cycle stages as suggested by Zhang et al. (2008); (2) a more comprehensive analysis of CO₂ and CH₄ emissions associated within China’s coal mining and crude oil and NG exploration stages as suggested by Chai (2008).

5. China’s alternative fuel/vehicle policy

This section briefly reviews China’s AFV and AVF policy history, status and trends, and considers the LC ES and GR implications with respect to future policy recommendations.

5.1. Main current policy frameworks and key initiatives

As noted by Yeh (2007) and Stepp et al. (2009), there are two principal types of policies commonly employed to stimulate AVF/AFV development: technology-pushing and demand-pulling policies. Both types of policies have been pursued by the Chinese government since as early as the 1990s (Gan, 2003; Zhao and Melaina, 2006), resulting in initiatives such as the Clean Vehicles Initiative and the Deployment of 1000 EVs in Ten Cities (Ouyang, 2006; Wan, 2008; Wang, 2006). Moreover, national-level policy frameworks have been established to guide central- and provincial-governments in supporting these initiatives as well.
We can define key functions in terms of Setting Policy Frameworks, Subsidizing Technology R&D and Supporting Market Creation. For these three key functions there are seventeen related policy documents and initiatives; nine for Setting Policy Frameworks, four relating to Subsidizing Technology R&D and four Supporting Market Creation.

5.2. Policy trends: strategic synergies between energy-saving and GHG reduction efforts

Three priority principles have been suggested for developing effective AVF/AFV policies in China: (1) keeping the role of AVFs as important as vehicle energy-saving technology; (2) shaping the results of national-level diversification and district-level focus for AVFs; and (3) promoting the domestic automotive industry (Ouyang, 2006; Wan, 2008; Wang, 2006; Wang and Ouyang, 2007).

GHG reduction consensus is playing an increasingly important role in China, and it is publicly recognized that low-carbon or climate-friendly energy policies should support the following activities: more efficient fossil energy utilization, shifting to low-carbon fossil fuels, using more nuclear energy and renewable energy, and applying CCS technologies (NDRC, 2007).

In combination with the current LCA of fossil energy use and GHG emissions, additional policy milestones should be incorporated into technology-pushing and demand-pulling policies and implementations for the transportation sector. These include: (1) a long-term strategy to commercialize EVs or the so-called PICVs (plug-in capable vehicles) and support FCB technology innovation; and (2) a short- and medium-term strategy to utilize AVFs such as LPG, coal-based fuels and NG-based fuels as petroleum substitutes.

Additional issues require increased attention and study, including: (1) the effectiveness in the past and the feasibility in future for those policy tools currently in use; (2) further research into the toxicity and human health impacts of coal-based fuel such as M100; and (3) additional analysis of obstacles restricting AVF/AFV development, such as the issues of high cost and lack of infrastructure, along with innovations to overcome these barriers through public–private partnerships between AVF manufacturers and governments.

5.3. Policy tools on discussion

Besides the above-mentioned methods including subsidizing technology R&D and support for market creation, other market-based tools, such as carbon pricing mechanisms, have been researched in depth by domestic scholars (BGSRI, 2009; Fen, 2009; Zhang and Lu, 2009) and are expected to expand the scale of low-carbon AVF development and promote AFV technology innovation.

Carbon pricing and trading mechanisms are being developed and/or deployed in certain markets within the industrialized world. Currently, Chinese companies are actively involved in providing (selling) certified emission reduction projects (credits) in accordance with the Clean Development Mechanism within the framework of the Kyoto Protocol. However, there are considerable issues to be studied in depth for domestic carbon trading to become actualized, like quota assignment (the allocation of allowances), supervision mechanisms and the formation of a trading platform before creating a possible GHG reduction commitment for China. These policy mechanisms take time and global coordination to develop, deploy and manage. Therefore, enactment of these kinds of tools to aid in China’s energy policy implementation will not happen in the near-term. That being said, the official energy-saving targets for China are in line with global efforts to reduce GHG emissions (NDRC, 2007; Zeng et al., 2008).

6. Concluding remarks

(1) Current alternative fuel/vehicle technologies differ substantially in their life-cycle fossil energy use and GHG emissions profiles, and only half of the six alternative fuel bus pathways studied, currently realize energy savings and GHG emission reductions relative to conventional technologies, as shown in Fig. 9.

(2) All technologies, excluding fuel cell buses, are currently feasible in China today due to the benefits of oil/NG substitution, though most lack obvious energy savings and GHG reductions.

(3) Current energy use and GHG emission scenarios can be improved by a series of measures: (a) improving fuel economy for non-ICE vehicles such as fuel cell buses and EVs, while incorporating HEV technology for ICEs or employing PICVs; (b) improving fuel production efficiency for coal-based fuels and NG-based H2; (c) developing some AVF/AFVs based on local resource abundance; and (d) employing low-carbon methods such as renewable energy and CCS technologies for both electricity generated and coal-based fuel production.

(4) Integrated policies should be implemented to pave the way for promoting alternative fuel/vehicles. These might include: (a) supporting energy-saving technologies for conventional

Fig. 9. Quadrant chart of WTW fossil energy use and GHG emissions of AFB.
ICES, HEVs or PICVs to begin capturing large-scale dual benefits immediately; (b) supporting R&D and the application of gaseous and coal-based fuels by accelerating infrastructure development; (c) supporting EV demonstration projects and creating markets to catalyze large-scale commercialization; (d) jumping-starting innovation in fuel cell bus technology, including solutions to H2 feedstock and fuel production issues; and (e) addressing critical issues such as the potential human toxicity of Methanol fuels, and the application of CCS and other clean coal technologies.

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Appendix. Supplementary materials

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2009.09.031.

References


