Evaluating Alternative Fuel Vehicles from Technical, Environmental and Economic Perspectives: Case of Light-Duty Vehicles in Iran

Vahid Aryanpur, Ehsan Shafiei

Abstract—This paper presents an environmental and techno-economic evaluation of light duty vehicles in Iran. A comprehensive well-to-wheel (WTW) analysis is applied to compare different automotive fuel chains, conventional internal combustion engines and innovative vehicle powertrains. The study examines the competitiveness of 15 various pathways in terms of energy efficiencies, GHG emissions, and levelized cost of different energy carriers. The results indicate that electric vehicles including battery electric vehicles (BEV), fuel cell vehicles (FCV) and plug-in hybrid electric vehicles (PHEV) increase the WTW energy efficiency by 54%, 51% and 46%, respectively, compared to common internal combustion engines powered by gasoline. On the other hand, greenhouse gas (GHG) emissions per kilometer of FCV and BEV would be 48% lower than that of gasoline engines. It is concluded that BEV has the lowest total cost of energy consumption and external cost of emission, followed by internal combustion engines (ICE) fueled by CNG. Conventional internal combustion engines fueled by gasoline, on the other hand, would have the highest costs.

Keywords—Well-to-Wheel analysis, Energy Efficiency, GHG emissions, Levelized cost of energy, Alternative fuel vehicles.

I. INTRODUCTION

VEHICLE manufacturers and global laboratories have started projects about alternatives to alleviate the multiple threats, including climate change, urban air pollution and oil dependence for both fuels and drivetrains. On the fuel side, possibilities exist to switch from gasoline and diesel to synthetic fuels, hydrogen, bio-fuels or electricity. On the vehicle side, there is possibility to reduce fuel demand by a shift to more efficient hybrid, electric or fuel cell drivetrains [1].

The transportation sector in Iran is the second largest end-use sector which accounts for about a quarter of total final energy consumption [2]. Moreover, it is responsible for at least 23% of greenhouse gas (GHG) emissions in the country [2]. Nearly the entire energy carriers used in this sector consists of petroleum products. Analysis of data on gasoline and diesel consumption in transport sector over the period 1998-2008 shows an average growth rate of 6.2% and 4.4%, respectively [3]. However, the consumption of petroleum products had been a challenge due to the opportunity costs of oil, doubts about of the security of petroleum products supply and environmental pollutants. In recent decades, the country has been suffering from the externalities of high emissions of transportation system. Based on these facts, in the last few years great efforts have been undertaken to reduce the share of petroleum products by supporting alternative automotive fuels and drivetrain technologies.

Since transport sector is integrated with the energy supply system, a comprehensive Well-to-Wheel (WTW) analysis would be required for appropriate policy making. This analysis has been conventionally employed to study the environmental aspects, energy efficiency comparison or both of them (see e.g. [4]-[20]). In this study, different automotive fuel chains, originated from different primary energy sources (crude oil, natural gas and grid electricity), new automotive fuels such as CNG, LNG, GTL, DME, methanol and hydrogen and innovative vehicle powertrains are evaluated from environmental and techno-economic perspectives. To perform this comparison, a WTW analysis is applied.

In this study the methodology is briefly described in section II, then the structure of reference energy system (RES), showing different energy supply chains for transport sector is introduced. In section III the results of WTW energy efficiency analysis, WTW greenhouse gas emissions and levelized cost of various energy carriers are presented and finally in section IV, the main findings, insights and conclusions are presented.

II. METHODOLOGY: WELL-TO-WHEEL ANALYSIS

A comprehensive evaluation of the energy efficiency, economic and environmental effects associated with new vehicle powertrain in relation to those associated with conventional internal combustion engine (ICE) technologies requires a full fuel-chain analysis. In transportation studies, the fuel-chain analysis is commonly referred to as a well-to-wheels (WTW) analysis (see Fig. 1). WTW analyses mainly focus on the process of energy utilization through different technologies and unlike life-cycle analyses, do not take into account the energy and emissions required to construct fuel production infrastructure or those required to produce the vehicles [21].
The analysis is based on the segregation of the whole process of energy flow through various processing and conversion technologies. The rationale behind the analysis is defined according to the Reference Energy System (RES) concept which shows the flow of energy carriers from resources to the end users. In this framework, energy carriers flow from resources through processing, conversion, transport network and distribution to the final consumers. Therefore, the methodology enable us a detailed representation of current and emerging interlinked technologies characterized in terms of their technical indices such as costs, conversion efficiency and emission factors.

According to Fig. 1, we use the WTW analysis in two stages: well-to-tank (WTT) and tank-to-wheel (TTW). Then, in each stage, energy efficiency, cost and GHG emissions are evaluated for the different pathways within the energy system.

**A. Structure of Transportation Energy System**

The proposed structure for WTW analysis of light-duty transportation system in Iran is illustrated in Fig. 2. We consider the entire fuel supply system from resources (crude oil, natural gas and grid electricity from fossil resources) to different end-users of passenger transport sector. According to the system boundaries we have chosen in our study, we can evaluate various alternatives for passenger vehicles: gasoline, diesel, LPG and naphtha from crude oil, Hydrogen, LPG, CNG, LNG, Methanol, DME and GTL from natural gas and electricity from grid. These energy carriers are the most important feasible options to meet the present and future demand for passenger transportation.

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**Fig. 1 Scope of Well-to-Wheel for fuel supply chain and vehicle systems**

**Fig. 2 Reference of energy system in this study**
The oil-derived fuel chain starts with crude oil extraction. The crude oil is then transported by oil pipeline to oil refineries, where different petroleum products including gasoline, diesel, LPG, Fuel oil and naphtha are produced. Petroleum products are then transported and distributed to retail stations by pipelines and road tanker trucks.

Rich gas is extracted from natural gas resources and transported to gas refinery, where lean gas and LPG are produced. LPG can be transported and distributed by road tanker trucks directly, while lean gas is transported by natural gas pipelines. In this chain, CNG can be produced by compression of lean gas at the retail stations. LNG is also produced near the consumption market and then is distributed by special trucks. Methanol, GTL and DME can be synthesized from natural gas near the consumption market and finally distributed by tanker trucks. Hydrogen is assumed to be produced from natural gas centrally, at a large-scale plant near the consumption market and then is distributed by tanker trucks. The other option for hydrogen could be distributed production at the retail stations.

Electricity can be generated from natural gas, fuel oil and diesel oil and then is transmitted and distributed.

Finally, fuel consumption by different powertrain technologies shall be analyzed in terms of energy use and carbon emissions. Table I presents the different vehicle technologies considered in this study.

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Powertrain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline/LPG</td>
<td>Internal Combustion Engine- Port Injection Spark Ignition (ICE-PISI)</td>
</tr>
<tr>
<td>CNG/ LPG</td>
<td>Hybrid Electrical Vehicle (HEV) a</td>
</tr>
<tr>
<td>Gasoline</td>
<td>Internal Combustion Engine- Direct Injection Compression Ignition (ICE-DICI)</td>
</tr>
<tr>
<td>Diesel/ DME/ GTL</td>
<td>Fuel Cell Vehicle (FCV)</td>
</tr>
<tr>
<td>Naphtha/ Methanol</td>
<td>Reformer + Fuel Cell Vehicle</td>
</tr>
<tr>
<td>Electricity</td>
<td>Battery Electrical Vehicle (BEV)</td>
</tr>
<tr>
<td>Gasoline+</td>
<td>Plug in Hybrid Electrical Vehicle (PHEV)</td>
</tr>
</tbody>
</table>

* The parallel hybrid configuration is considered.

### B. Energy Efficiency

In order to compare different pathways from an energetic perspective, the overall efficiency of each fuel chain is calculated. The overall energy efficiency \( \eta_{WTO} \) which consists of extraction \( \eta_e \), conversion \( \eta_c \), transportation and distribution \( \eta_{td} \) and finally powertrain \( \eta_p \) efficiencies, is calculated according to the following equation:

\[
\eta_{WTO} = \eta_e \times \eta_c \times \eta_{td} \times \eta_p
\]

(1)

The efficiencies of various WTT pathways are determined based on lower heating value by dividing the total energy output (GJ) by the total energy input (GJ) [22].

### C. GHG Emissions

GHG emissions are the sum of emissions of CO\(_2\), CH\(_4\), and N\(_2\)O, weighted by their global warming potentials in every stage from WTW. Other GHG emissions are not emitted in significant quantities in any of the WTW considered. According to intergovernmental panel on climate change (IPCC), the global warming potentials of CO\(_2\), CH\(_4\), and N\(_2\)O are 1, 23, and 296, respectively [23].

The WTW emissions \( \epsilon_{WTW} \) consists of extraction \( \epsilon_e \), conversion \( \epsilon_c \), transportation and distribution \( \epsilon_{td} \) and finally powertrain \( \epsilon_p \) emissions, are calculated according to the following equation:

\[
\epsilon_{WTW} = \epsilon_e + \epsilon_c + \epsilon_{td} + \epsilon_p
\]

(2)

Furthermore, the global climate-change damage cost in dollars per metric ton carbon ($/tC) is assumed to be $5/tC in the low case, $16/tC in the medium case, and $150/tC in the high case [24], [25]. In this study global warming external cost assumption is $50 per ton carbon.

### D. Levelized Cost of Energy

The levelized cost of energy output (LCOE) is here used to evaluate the economic aspects of each alternative. The costs have included annualized investment costs, fixed O&M costs and fuel costs. The total generation cost of energy (TC) for each technology over its lifetime can be computed using the following equation:

\[
TC = C_e * P + \sum_{i=1}^{N} \frac{C_{s+P+I}}{1+r^i} + \sum_{i=1}^{N} \frac{C_{s+P+I}}{(1+r)^i} + \sum_{i=1}^{N} \frac{C_f}{(1+r)^i}
\]

(3)

Where:

- \( P \): Capacity of technology (kW)
- \( C_e \): Investment cost of technology ($/kW)
- \( C_s \): Annual fixed O&M costs ($/kW)
- \( C_f \): Annual variable O&M costs ($/kWh)
- \( f \): Plant factor (share)
- \( \eta \): Efficiency (share)
- \( N \): Plant life (year)
- \( r \): Discount rate (share)

Then the average LCOE is calculated as follows:

\[
LCOE = \frac{TC}{N \times \frac{1}{(1+r)^N}}
\]

(4)

### E. Total Cost of Energy Consumption and WTW Emissions Cost

Total cost of energy supply for transportation system accounts for the cost of fuel per kilometer and the cost of GHG emissions. The fuel cost per kilometer is calculated as follows:

\[
Fuel\ Cost\ \left( \frac{\$}{km} \right) = LCOE\ \left( \frac{\$}{GJ} \right) \times Energy\ Consumption\ \left( \frac{GJ}{km} \right)
\]

(5)

A value of $50 per ton carbon is assumed to quantify the external cost of GHG emissions. So the GHG emissions cost per kilometer is:

\[
Emissions\ Cost\ \left( \frac{\$}{km} \right)
\]

(6)
50 \left( \frac{s_{\text{ton}CO_2}}{s_{\text{ton}CO_2}} \right) \times 10^{-6} \left( \frac{s_{\text{ton}CO_2}}{s_{\text{ton}CO_2}} \right) \times \text{Energy Consumption} \left( \frac{MJ}{km} \right) \times WTW \ Emissions \left( \frac{\text{gCO}_2}{\text{km}} \right)

As a result, based on equation (7), the total cost of fuel consumption and WTW emissions cost as another index to compare alternative fuel/powertrain options is expressed as:

\[
\text{Total Cost} = \frac{1}{k} \times \text{Fuel Cost} + \frac{1}{k} \times \text{Emissions Cost}
\]

III. RESULTS

A. WTW Energy Efficiency

Table II shows the overall energy efficiency for 15 different pathways identified by resources and fuel types. The results show that even with medium energy efficiency in electricity generation and low energy efficiency in electricity distribution, electric vehicles (i.e., BEV, PHEV) would have the maximum overall WTW efficiency (see Fig. 3 for the ranking). This is due to the high TTW efficiency of BEV efficiency must be considered as no fuel conversion occurs onboard the vehicle, instead occurring during the WTT stages.

Apart from the electricity chain, the most efficient fuel chains are those that are connected to the innovative end-use technologies (i.e. FCV and HEV). The results show that the efficiency of innovative vehicles has a considerable impact on the overall WTW efficiency. The direct hydrogen FCV has 24.2% WTW energy efficiency, while the naphtha and methanol ones have 19.2% and 15.8% WTW efficiency, respectively. From the WTW perspective, BEV would consume 54% less energy than the conventional gasoline ICES. The corresponding value for HEVs is around 18%.

| TABLE II | WTW ENERGY EFFICIENCY
<table>
<thead>
<tr>
<th>Resource</th>
<th>Fuel Type</th>
<th>Powertrain</th>
<th>Extraction (\eta_e)</th>
<th>Processing/Conversion (\eta_p)</th>
<th>Transportation &amp; Distribution (\eta_d)</th>
<th>Powertrain (\eta_p)</th>
<th>Total (\eta_{WTT})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude Oil</td>
<td>LPG</td>
<td>ICE/PISI</td>
<td>97.6</td>
<td>92.0</td>
<td>97.8</td>
<td>18.0</td>
<td>15.8</td>
</tr>
<tr>
<td></td>
<td>Gasoline</td>
<td>ICE/PISI</td>
<td>97.6</td>
<td>92.6</td>
<td>98.2</td>
<td>18.0</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>ICE/DICI</td>
<td>97.6</td>
<td>90.9</td>
<td>98.2</td>
<td>19.9</td>
<td>17.3</td>
</tr>
<tr>
<td></td>
<td>Naphtha</td>
<td>Reformer+FC</td>
<td>97.6</td>
<td>95.1</td>
<td>98.2</td>
<td>21.1</td>
<td>19.2</td>
</tr>
<tr>
<td>Fossil Fuel</td>
<td>Electricity</td>
<td>BEV</td>
<td>96.2</td>
<td>39.5</td>
<td>85.4</td>
<td>76.0</td>
<td>24.7</td>
</tr>
<tr>
<td></td>
<td>Electricity+Gasoline</td>
<td>PHEV40</td>
<td>96.2</td>
<td>39.5</td>
<td>85.4</td>
<td>42.8</td>
<td>23.3</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>Onsite H2</td>
<td>Fuel Cell</td>
<td>97.7</td>
<td>68.2</td>
<td>90.9</td>
<td>36.4</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>Central H2</td>
<td>Fuel Cell</td>
<td>97.7</td>
<td>73.4</td>
<td>92.7</td>
<td>36.4</td>
<td>24.2</td>
</tr>
<tr>
<td></td>
<td>GTL</td>
<td>ICE/DICI</td>
<td>97.7</td>
<td>65.0</td>
<td>99.0</td>
<td>19.9</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>CNG</td>
<td>ICE/PISI</td>
<td>97.7</td>
<td>100</td>
<td>93.6</td>
<td>18.2</td>
<td>16.6</td>
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<td></td>
<td>DME</td>
<td>ICE/DICI</td>
<td>97.7</td>
<td>70.0</td>
<td>98.8</td>
<td>19.9</td>
<td>13.6</td>
</tr>
<tr>
<td></td>
<td>Methanol</td>
<td>Reformer+FC</td>
<td>97.7</td>
<td>68.4</td>
<td>98.5</td>
<td>23.1</td>
<td>15.8</td>
</tr>
<tr>
<td></td>
<td>LNG</td>
<td>ICE/PISI</td>
<td>97.7</td>
<td>84.7</td>
<td>95.1</td>
<td>18.2</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>LPG</td>
<td>ICE/PISI</td>
<td>94.7</td>
<td>100</td>
<td>97.3</td>
<td>18.0</td>
<td>16.7</td>
</tr>
</tbody>
</table>

Electricity is generated from fossil fuels (natural gas, fuel oil, diesel oil)

1 The average energy consumption is 0.025 MJ/MJ

2 Including crude oil and natural gas extraction, sweetening natural gas, fuel oil and diesel oil production (natural gas: 76%, fuel oil: 16.4% and diesel oil: 7.6%) [29,30]

3 The average energy consumption in natural gas extraction and sweetening processes is 0.024MJ/MJ

4 The average energy consumption in natural gas extraction and sweetening processes is 1.053MJ/MJ

5 Energy consumption in LPG liquefaction is 0.0028MJ/MJ

Sources: [26, 28, 33]

Sources: [2], [29,30]

Sources: [31],[32]
B. GHG Emissions

Estimation of GHG emissions in every stage of energy supply system and for various propulsion systems are presented in Table III. Fig. 4 summarizes the comparison of GHG emissions in different pathways.

It is observed that for ICE, TTW clearly dominate the picture. However, for FCV, BEV and PHEV, the main share of emission is devoted to the production of hydrogen and electricity. The option with the lowest WTW emissions (per MJ energy), is ICE vehicles fueled by CNG (64.9 gCO$_2$ MJ$^{-1}$), followed by LNG (71.1 gCO$_2$ MJ$^{-1}$) and LPG (73.0 gCO$_2$ MJ$^{-1}$).

**TABLE III**

<table>
<thead>
<tr>
<th>Resource</th>
<th>Fuel Type</th>
<th>Powertrain</th>
<th>Extraction (WTT) (gCO$_2$/MJ)</th>
<th>Processing/Conversion (WTT) (gCO$_2$/MJ)</th>
<th>Transportation &amp; Distribution (WTT) (gCO$_2$/MJ)</th>
<th>Powertrain (WTW) (gCO$_2$/MJ)</th>
<th>WTW (gCO$_2$/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude Oil</td>
<td>Gasoline</td>
<td>ICE/PISI</td>
<td>3.6</td>
<td>7.0</td>
<td>1.9</td>
<td>73.4</td>
<td>79.0</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>ICE/DICI</td>
<td>3.6</td>
<td>7.0</td>
<td>1.9</td>
<td>73.4</td>
<td>79.0</td>
</tr>
<tr>
<td></td>
<td>LPG</td>
<td>ICE/PISI</td>
<td>3.4</td>
<td>8.6</td>
<td>1.9</td>
<td>73.3</td>
<td>81.1</td>
</tr>
<tr>
<td>Fossil Fuel</td>
<td>Electricity</td>
<td>BEV</td>
<td>5.4</td>
<td>83.3$^d$</td>
<td>0.0</td>
<td>0.0</td>
<td>188.7</td>
</tr>
<tr>
<td></td>
<td>Elec. + Gasoline</td>
<td>PHEV40</td>
<td>-</td>
<td>125.9$^b$</td>
<td>-</td>
<td>26.2</td>
<td>157.5</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>Onsite H$_2$</td>
<td>Fuel Cell</td>
<td>3.4</td>
<td>96.4</td>
<td>1.9</td>
<td>0.0</td>
<td>101.7</td>
</tr>
<tr>
<td></td>
<td>Central H$_2$</td>
<td>Fuel Cell</td>
<td>3.4</td>
<td>84.0</td>
<td>2.5</td>
<td>0.0</td>
<td>89.9</td>
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<tr>
<td></td>
<td>GTL</td>
<td>ICE/DICI</td>
<td>3.4</td>
<td>16.5</td>
<td>5.2</td>
<td>70.8</td>
<td>95.9</td>
</tr>
<tr>
<td></td>
<td>CNG</td>
<td>ICE/PISI</td>
<td>3.4</td>
<td>2.8</td>
<td>2.5</td>
<td>56.2</td>
<td>64.9</td>
</tr>
<tr>
<td></td>
<td>DME</td>
<td>ICE/DICI</td>
<td>3.4</td>
<td>10.6</td>
<td>5.2</td>
<td>67.4</td>
<td>86.6</td>
</tr>
<tr>
<td></td>
<td>Methanol</td>
<td>Refomer+FC</td>
<td>3.4</td>
<td>11.7</td>
<td>5.2</td>
<td>69.1</td>
<td>89.4</td>
</tr>
<tr>
<td></td>
<td>LNG</td>
<td>ICE/PISI</td>
<td>3.4</td>
<td>7.9</td>
<td>3.6</td>
<td>56.2</td>
<td>71.1</td>
</tr>
<tr>
<td></td>
<td>LPG</td>
<td>ICE/PISI</td>
<td>3.4</td>
<td>0.7</td>
<td>3.2</td>
<td>65.7</td>
<td>73.0</td>
</tr>
</tbody>
</table>

*Sources: [29], [30]

$^a$ In every 100 km: Electricity Share= 40mile*1.609km/mile=64.36km and Gasoline share=100-64.36=35.64km. So emission equals to:

\[
(188.7 \text{ gCO}_2\text{ MJ}^{-1} + 0.6436 \text{ gCO}_2\text{ MJ}^{-1}) = 125.9 \text{ gCO}_2\text{ MJ}^{-1}
\]

\[
\varepsilon_{\text{WTW}} = \varepsilon_e + \varepsilon_f + \varepsilon_{\text{sd}} + \varepsilon_p
\]

\[
\varepsilon_e = \frac{\text{WTT (gCO}_2\text{MJ) }}{\text{WTW (gCO}_2\text{MJ) }}
\]

\[
\varepsilon_f = \frac{\text{WTT (gCO}_2\text{MJ) }}{\text{WTW (gCO}_2\text{MJ) }}
\]

\[
\varepsilon_{\text{sd}} = \frac{\text{WTT (gCO}_2\text{MJ) }}{\text{WTW (gCO}_2\text{MJ) }}
\]

\[
\varepsilon_p = \frac{\text{WTT (gCO}_2\text{MJ) }}{\text{WTW (gCO}_2\text{MJ) }}
\]

\[
\varepsilon_{\text{WTW}} = \frac{\text{WTT (gCO}_2\text{MJ) }}{\text{WTW (gCO}_2\text{MJ) }}
\]

\[
\varepsilon_{\text{WTW}} = \frac{\text{WTT (gCO}_2\text{MJ) }}{\text{WTW (gCO}_2\text{MJ) }}
\]

\[
\varepsilon_{\text{WTW}} = \frac{\text{WTT (gCO}_2\text{MJ) }}{\text{WTW (gCO}_2\text{MJ) }}
\]

\[
\varepsilon_{\text{WTW}} = \frac{\text{WTT (gCO}_2\text{MJ) }}{\text{WTW (gCO}_2\text{MJ) }}
\]
WTW emissions per MJ energy will be different from WTW emissions per kilometer (see Fig. 5). Although electricity consumption does not emit GHG emissions, however electricity generation emits significant amount of GHG emissions. The amount of electricity generation in Iran was about 195 billion kWh in 2009 [29]. The corresponding generated GHG emissions were 129 million ton CO$_2$eq [29]. Accordingly, the average direct GHG emissions of electricity generation system were 183.3 gCO$_2$eq per MJ of generated electricity. GHG emissions arising from the upstream activities including extraction, processing and transportation of oil and natural gas for power generation increase the above value by 5.4 gCO$_2$eq per MJ of electricity. As a result, electricity used to charge BEV and PHEV has the highest WTW emissions per MJ electricity; even more than different ICEs. However, the WTW emissions from electric vehicles per kilometer are lower than those of all types of ICEs. ICE vehicles fueled by GTL is the worst chain in terms of WTW emissions per kilometer, followed by ICE vehicles fueled by gasoline and diesel.
C. Levelized Cost of Energy

Comparison of levelized cost of each energy carrier is summarized in Table IV. It can be seen that the lowest cost option is CNG and the highest one is assigned to hydrogen.

D. Total Cost of Energy Consumption and GHG Emissions and

The results of well-to-wheel cost analysis have been summarized in Table V. The fuel cost, emissions cost and total costs are calculated from equation (5) to equation (7), respectively.

Among 15 different pathways, BEVs followed by ICEs fueled by CNG and PHEVs have the lowest total cost per kilometer. Despite medium emission cost of CNG ICEs, it could be considered as an economically attractive alternative, as its fuel cost is very low in Iran. In comparison with ICE fueled by petroleum products (i.e. gasoline and LPG), HEVs could reduce the total cost by 15%.

### Table IV

<table>
<thead>
<tr>
<th>Resource</th>
<th>Fuel Type</th>
<th>Extraction ($/GJ)</th>
<th>Processing/Conversion ($/GJ)</th>
<th>Transportation &amp; Distribution ($/GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude Oil</td>
<td>LPG</td>
<td>1.05</td>
<td>13.0</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>Gasoline</td>
<td>1.05</td>
<td>13.0</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>Gasoline</td>
<td>1.05</td>
<td>13.0</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>1.05</td>
<td>13.0</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>Naphtha</td>
<td>1.05</td>
<td>12.9</td>
<td>13.2</td>
</tr>
<tr>
<td>Fossil Fuel</td>
<td>Electricity</td>
<td>-</td>
<td>-</td>
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<td>24.8</td>
</tr>
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<td>Central H₂</td>
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<td>27.1</td>
</tr>
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<td>13.7</td>
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<td>CNG</td>
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<td>7.9</td>
</tr>
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<td>DME</td>
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<td>12.4</td>
<td>13.5</td>
</tr>
<tr>
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<td>LPG</td>
<td>1.1</td>
<td>11.6</td>
<td>12.3</td>
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</table>

- Refers to production cost of oil [34].
- Refers to production cost of natural gas (1 $/GJ) and gas sweetening (0.11$/GJ) [34].
- Cost of electricity generation, transportation and distribution in Iran is 86.3 $/MWh (86.3 $/MWh = 24.0 $/GJ) [35].
- Assuming 0.6436% drive on electricity and 0.3564% drive on gasoline 80.6436 $/MWh <= 24.0 $/GJ; 80.3564 $/MWh <= 13.3 $/GJ + 0.3564 * 13.3 $/GJ_gasoline = 20.2 $/GJ.
- Natural gas is compressed at the retail station.

### Table V

<table>
<thead>
<tr>
<th>Resource</th>
<th>Fuel Type</th>
<th>Powertrain</th>
<th>Consumption (MJ/100km) a</th>
<th>Fuel Cost (Cent/km) b</th>
<th>Emission Cost (Cent/km) c</th>
<th>Total Cost (Cent/km) d</th>
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<tr>
<td>Crude Oil</td>
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<td>0.8</td>
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<td>ICE/PISI</td>
<td>190.0</td>
<td>2.3</td>
<td>0.7</td>
<td>3.0</td>
</tr>
</tbody>
</table>

- Source: [36]
- From equation (5): 13.5 $/GJ + 100 Cent $/MJ * 190 MJ_en = 2.6 Cent $/km
- From equation (6): 50 Cent $/MJ * 190 MJ_en = 79.0 Cent $/km
- Due to rounding, in some cases total cost may not equal sum of component.
- From equation (7): 2.57 Cent $/km + 0.75 Cent $/km = 3.3 Cent $/km

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IV. CONCLUSION

In this study we focused on techno-economic and environmental aspects of energy supply pathways and different powertrain technologies with the potential to be used as the light duty vehicles in Iran. A comprehensive WTW analysis was applied to compare alternative fuel vehicles. In this framework, a comparative assessment of the potential energy supply pathways in Iran was performed, taking into account energy efficiencies, GHG emissions and levelized cost of different energy carriers. The most important findings are summarized as follows:

- BEVs followed by FCVs and PHEVs are the best alternatives in terms of WTW energy efficiency and GHG emissions per kilometer.
- BEVs, ICEs fueled by CNG and PHEVs have the lowest fuel cost per kilometer.
- The comparative advantage of BEVs, FCVs and PHEVs with respect to gasoline ICE is that they increase WTW energy efficiency by 54%, 51% and 45%, respectively. BEVs and FCVs may also reduce WTW greenhouse gas emissions per kilometer by up to 48%, compared with the current conventional ICE based vehicle fleet. The corresponding value for ICEs fueled by CNG is about 25%.
- Synthesized fuels from natural gas including LNG, methanol and DME have a little potential to reduce GHG emissions; however, due to the high investment cost of the technologies considered in their energy pathways, they are not attractive compared to other innovative vehicles.
- The main reasons for attractiveness of electric vehicles are the high efficiency of electric powertrains as well as their low emissions. However, the results showed that due to the domination of fossil power plant with the high level of emissions in Iran, the WTT environmental cost of electric vehicle is undesirable. Promoting the existing electricity supply system to enjoy the advanced combustion power plants with higher efficiencies and lower emissions, can ensure the attractiveness of electric vehicles in various environmental scenarios.

Although, the results show the attractiveness of innovative powertrain technologies, but their drawback is that they are not currently economically competitive with conventional ICEs. The batteries used in BEVs and PHEVs have limited range; take hours to charge and vehicle charging infrastructures are not available. FCVs also are facing with the problems in hydrogen production, storage and distribution. As a result consumers may hesitate to accept new technologies. Therefore, consumers' preferences and vehicles' attributes such as price, operation and maintenance costs and range should be taken into account in the future study.

REFERENCES


[31] European Commission Joint Research Center (JRC), “Well-to-wheels analysis of future automotive fuels and powertrains in the European context,” Well-to-tank report version 2c, WTT Appendix 4: Available at:


