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

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***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].

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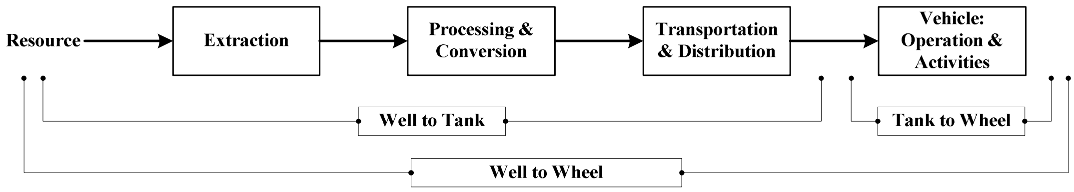

Fig. 1 Scope of Well-to-Wheel for fuel supply chain and vehicle systems

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 interconnected 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.

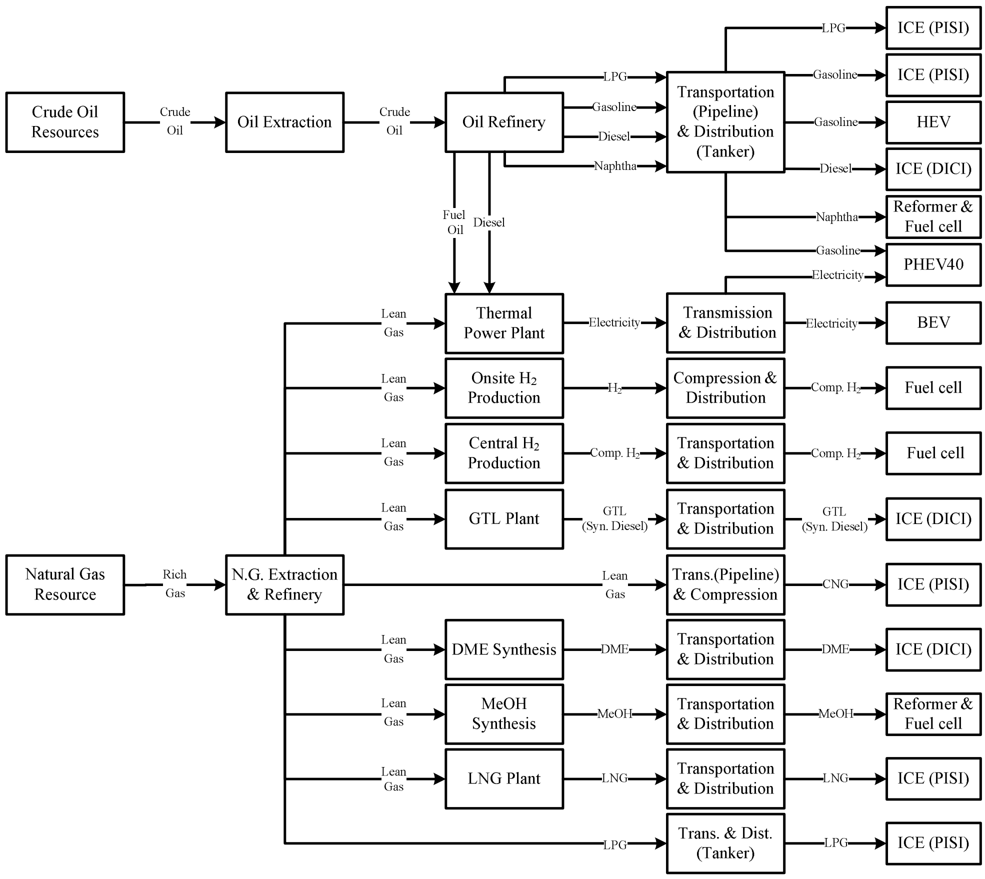

Fig. 2 Reference of energy system in this study

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 retail stations that is distributed by special 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 I
POWERTRAIN TECHNOLOGIES USED IN THE ANALYSIS

Fuel Type	Powertrain
Gasoline/ LPG/ CNG/ LNG	Internal Combustion Engine- Port Injection Spark Ignition (ICE-PISI)
Gasoline	Hybrid Electrical Vehicle (HEV) [a]
Diesel/ DME/ GTL	Internal Combustion Engine- Direct Injection Compression Ignition (ICE-DICI)
Hydrogen	Fuel Cell Vehicle (FCV)
Naphtha/ Methanol	Reformer + Fuel Cell Vehicle
Electricity	Battery Electrical Vehicle (BEV)
Gasoline+ Electricity	Plug in Hybrid Electrical Vehicle (PHEV40)

[a] 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 (η_{WTW}) which consists of extraction (η_e), conversion (η_c), transportation and distribution (η_{td}) and finally powertrain (η_p) efficiencies, is calculated according to the following equation:

$$\eta_{WTW}=\eta_e * \eta_c * \eta_{td} * \eta_p \quad (1)$$

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_2O, 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_2O are 1, 23, and 296, respectively [23].

The WTW emissions (ε_{WTW}) consists of extraction (ε_e), conversion (ε_c), transportation and distribution (ε_{td}) and finally powertrain (ε_p) emissions, are calculated according to the following equation:

$$\varepsilon_{WTw} = \varepsilon_e + \varepsilon_c + \varepsilon_{td} + \varepsilon_p \quad (2)$$

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:

$$TC = C_k * P + \sum_{t=1}^{N} \frac{C_x * P}{(1+r)^t} + \sum_{t=1}^{N} \frac{C_v * P * f}{(1+r)^t} + \sum_{t=1}^{N} \frac{C_f * \frac{P*f}{\eta}}{(1+r)^t} \quad (3)$$

Where:
P: Capacity of technology (kW)
C_k: Investment cost of technology ($/kW)
C_x: Annual fixed O&M costs ($/kW)
C_v: Annual variable O&M costs ($/kWh)
C_f: Annual fuel costs ($/kWh input)
f: Plant factor (share)
η: Efficiency (share)
N: Plant life (year)
r: Discount rate (share)

Then the average LCOE is calculated as follows:

$$LCOE = \frac{TC}{\sum_{t=1}^{N} \frac{P*f}{(1+r)^t}} \quad (4)$$

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:

$$Fuel\ Cost\ \left(\frac{\$}{km}\right) = LCOE\ \left(\frac{\$}{GJ}\right) * Energy\ Consumption\ \left(\frac{GJ}{km}\right) \quad (5)$$

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:

$$Emissions\ Cost\ \left(\frac{\$}{km}\right) = \quad (6)$$

$$50\left(\frac{\$}{ton_{CO_2}}\right) * 10^{-6}\left(\frac{ton_{CO_2}}{g_{CO_2}}\right) * Energy\ Consumption\left(\frac{MJ}{km}\right) * WTW\ Emissions\left(\frac{g_{CO_2}}{MJ}\right)$$

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:

$$Total\ Cost\ \left(\frac{\$}{km}\right) = Fuel\ Cost\ \left(\frac{\$}{km}\right) + Emissions\ Cost\left(\frac{\$}{km}\right) \quad (7)$$

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

Resource	Fuel Type	Powertrain	WTT (%)			TTW (%)	WTW (%)
			Extraction (η_e)	Processing/ Conversion (η_c)	Transportation & Distribution (η_{td})	Powertrain (η_p) [q]	Total (η_{WTW}) [r]
Crude Oil	LPG	ICE/PISI	97.6 [b]	92.0 [f]	97.8 [i]	18.0	15.8
	Gasoline	ICE/PISI	97.6	92.6 [f]	98.2 [j]	18.0	16.0
	Gasoline	HEV	97.6	92.6 [f]	98.2 [j]	21.2	18.8
	Diesel	ICE/DICI	97.6	90.9 [f]	98.2 [j]	19.9	17.3
	Naphtha	Reformer+FC	97.6	95.1 [f]	98.2 [j]	21.1	19.2
Fossil Fuel	Electricity [a]	BEV	96.2 [c]	39.5 [g]	85.4 [k]	76.0	24.7
	Electricity+ Gasoline	PHEV40	96.2	39.5 [g]	85.4 [k]	42.8	23.3
Natural Gas	Onsite H_2	Fuel Cell	97.7 [d]	68.2 [h]	90.9 [l]	36.4	22.0
	Central H_2	Fuel Cell	97.7	73.4 [h]	92.7 [m]	36.4	24.2
	GTL	ICE/DICI	97.7	65.0 [h]	99.0 [n]	19.9	12.5
	CNG	ICE/PISI	97.7	100	93.6 [o]	18.2	16.6
	DME	ICE/DICI	97.7	70.0 [h]	98.8 [n]	19.9	13.6
	Methanol	Reformer+FC	97.7	68.4 [h]	98.5 [n]	23.1	15.8
	LNG	ICE/PISI	97.7	84.7 [h]	95.1 [n]	18.2	14.3
	LPG	ICE/PISI	94.7 [e]	100	97.7 [p]	18.0	16.7

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

[b] The average energy consumption is 0.025 $MJ/MJ_{oil\ extracted}$ [26]-[28], $Eff. = \frac{1\ MJ_{Crude\ oil}}{1.025\ MJ_{energy\ input}} = 97.6\%$

[c] 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]

[d] The average energy consumption in natural gas extraction and sweetening processes is $0.024MJ/MJ_{N.G.\ Extracted}$ [27], [31], $Eff. = \frac{1\ MJ_{Crude\ oil}}{1.024\ MJ_{energy\ input}} = 97.7\%$

[e] The average energy consumption in natural gas extraction and LPG separation processes is $1.053MJ/MJ_{LPG}$ [31,32]. Energy consumption in LPG liquefaction is $0.0028MJ/MJ_{LPG}$, $\text{Eff.} = \frac{1\ MJ_{LPG}}{(1.053*0.0028)\ MJ_{energy\ input}} = 94.7\%$

[f] Sources: [26], [28], [33]

[g] Sources: [2], [29]-[30]

[h] Sources: [31], [32]

[i] Assuming 300 km crude oil pipeline transportation and 700 km LPG tanker transportation and distribution.

[j] Assuming 300 km crude oil pipeline transportation, 500 km oil products pipeline transportation and 200 km oil products tanker distribution.

[k] Electricity transmission and distribution losses are 4.1% and 11.0%, respectively [29,30]. Total efficiency is: $(1-0.041)*(1-0.11) = 85.4\%$

[l] Assuming 1000 km natural gas pipeline transportation, H_2 compression and distribution

[m] Assuming 950 km natural gas pipeline transportation, H_2 compression and 50 km tanker distribution

[n] Assuming 800 km natural gas pipeline transportation, 200 km tanker LNG and synthesis fuels (GTL,DME, MeOH) distribution

[o] Assuming 1000 km natural gas pipeline transportation, compression and CNG distribution

[p] Assuming 1000 km LPG tanker transportation and distribution

[q] Sources: [22], [26] and [28]

[r] $\eta_{WTW} = \eta_e * \eta_c * \eta_{td} * \eta_p$

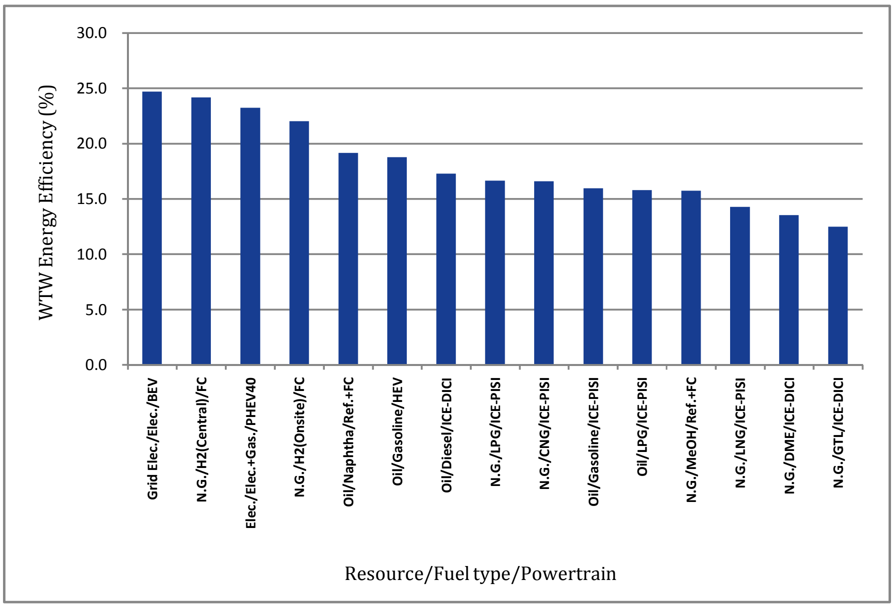

Fig. 3 Comparison of WTW energy efficiency

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
WELL TO WHEEL GHG EMISSION

Resource	Fuel Type	Powertrain	WTT (gCO_{2eq}/MJ_{Fuel}) Extraction (ε_e)	WTT (gCO_{2eq}/MJ_{Fuel}) Processing/ Conversion (ε_c)	WTT (gCO_{2eq}/MJ_{Fuel}) Transportation & Distribution (ε_{td})	TTW (gCO_{2eq}/MJ_{Fuel}) Powertrain (ε_p)	WTW (gCO_{2eq}/MJ_{Fuel}) Total [c] (ε_{WTW})	WTW (gCO_{2eq}/km) Total
Crude Oil	LPG	ICE/PISI	3.6	7.0	2.7	65.7	79.0	150.1 [d]
	Gasoline	ICE/PISI	3.6	7.0	1.9	73.4	85.9	163.2
	Gasoline	HEV	3.6	7.0	1.9	73.4	85.9	138.9
	Diesel	ICE/DICI	3.6	8.6	1.9	73.3	87.4	150.3
	Naphtha	Reformer+FC	3.6	4.4	1.9	71.2	81.1	131.7
Fossil Fuel	Electricity	BEV	5.4	183.3 [a]	0.0	0.0	188.7	84.9
	Elec.+ Gasoline	PHEV40	-	125.9 [b]	-	26.2	157.5	126.0
Natural Gas	Onsite H_2	Fuel Cell	3.4	96.4	1.9	0.0	101.7	95.6
	Central H_2	Fuel Cell	3.4	84.0	2.5	0.0	89.9	84.5
	GTL	ICE/DICI	3.4	16.5	5.2	70.8	95.9	165.0
	CNG	ICE/PISI	3.4	2.8	2.5	56.2	64.9	122.3
	DME	ICE/DICI	3.4	10.6	5.2	67.4	86.6	149.0
	Methanol	Reformer+FC	3.4	11.7	5.2	69.1	89.4	132.3
	LNG	ICE/PISI	3.4	7.9	3.6	56.2	71.1	134.0
	LPG	ICE/PISI	3.4	0.7	3.2	65.7	73.0	138.7

[a] Sources: [29], [30]

[b] In every 100 km: Electricity Share= 40mile*1.609km/mile=64.36km and Gasoline share=100-64.36=35.64km, So emission equals to:

$$\left(188.7\,\frac{gCO_{2eq}}{MJ_{Out}} * 0.6436\right)_{electricity} + \left(12.5\,\frac{gCO_{2eq}}{MJ_{Out}} * 0.3564\right)_{gasoline} = 125.9\,\frac{gCO_{2eq}}{MJ_{Out}}$$

[c] $\varepsilon_{WTW} = \varepsilon_e + \varepsilon_c + \varepsilon_{td} + \varepsilon_p$

[d] $79.0\,\frac{gCO_{2eq}}{MJ} * 190\,\frac{MJ}{100km} = 150.1\,\frac{gCO_{2eq}}{km}$

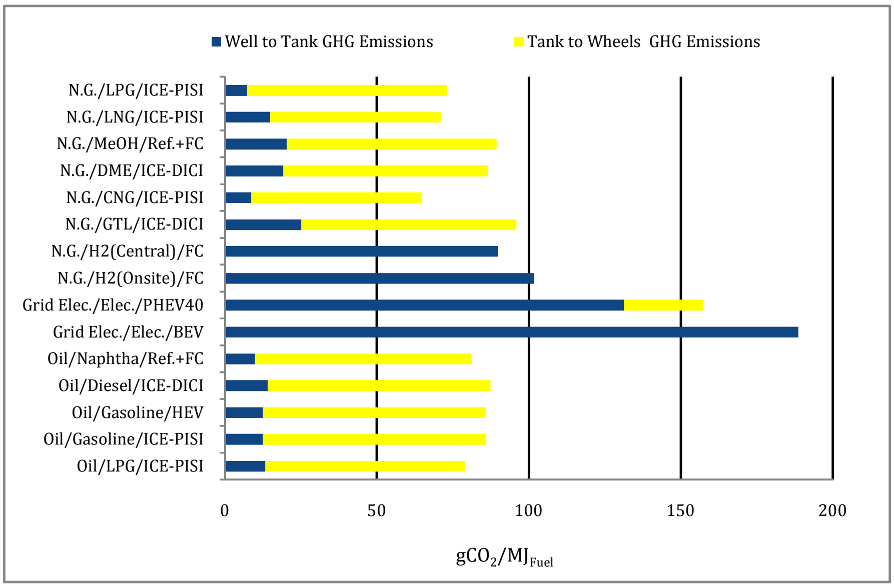

Fig. 4 Comparison of WTW GHG emissions

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_{2eq} [29]. Accordingly, the average direct GHG emissions of electricity generation system were 183.3 gCO_{2eq} 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_{2eq} 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.

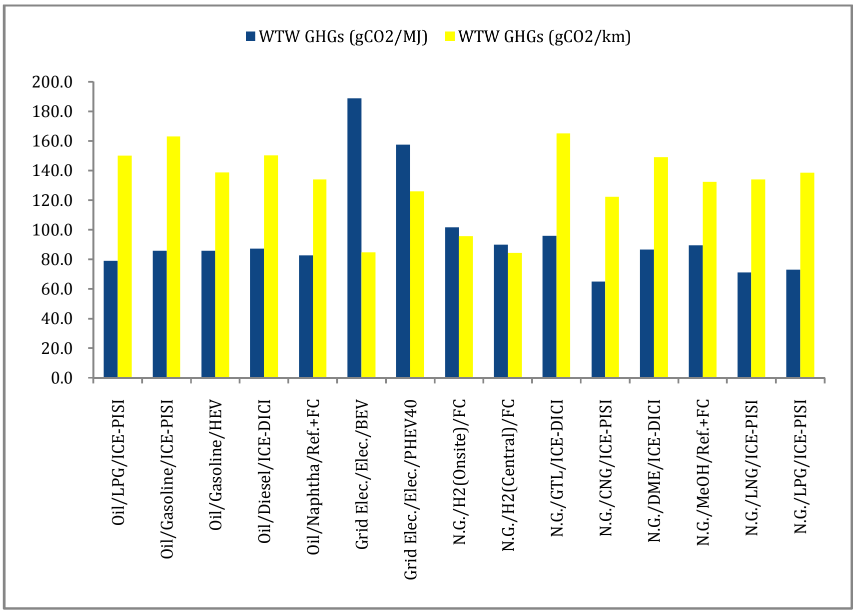

Fig. 5 WTW emissions per MJ energy and WTW emissions per kilometer

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
LEVELIZED COST OF ENERGY

Resource	Fuel Type	Extraction ($/GJ)	Processing/ Conversion ($/GJ)	Transportation &Distribution ($/GJ)
Crude Oil	LPG	1.05 [a]	13.0	13.5
	Gasoline	1.05	13.0	13.3
	Gasoline	1.05	13.0	13.3
	Diesel	1.05	13.0	13.2
	Naphtha	1.05	12.9	13.2
Fossil Fuel	Electricity	-	-	24.0 [c]
	Electricity + Gasoline	-	-	20.2 [d]
Natural Gas	Onsite H_2	1.1 [b]	24.6	24.8
	Central H_2	1.1	20.8	27.1
	GTL	1.1	13.7	14.0
	CNG	1.1	1.1	7.9 [e]
	DME	1.1	12.4	13.5
	Methanol	1.1	14.0	15.2
	LNG	1.1	11.8	13.3
	LPG	1.1	11.6	12.3

[a] Refers to production cost of oil [34].
[b] Refers to production cost of natural gas (1 $/GJ) and gas sweetening (0.11$/GJ) [34].
[c] Cost of electricity generation, transportation and distribution in Iran is 86.3 $/MWh ($86.3 \frac{\$}{MWh} * \frac{MWh}{3.6\ GJ} = 24.0 \frac{\$}{GJ}$) [35]
[d] Assuming 0.6436% drive on electricity and 0.3564% drive on gasoline $\left(0.6436 * 24.0 \frac{\$}{GJ}\right)_{electricity} + \left(0.3564 * 13.3 \frac{\$}{GJ}\right)_{gasoline} = 20.2 \frac{\$}{GJ}$
[f] Natural gas is compressed at the retail station.

TABLE V
TOTAL COST OF ENERGY CONSUMPTION AND GHG EMISSIONS

Resource	Fuel Type	Powertrain	Consumption (MJ/100km) [a]	Fuel Cost (Cent/km)	Emission Cost (Cent/km)	Total Cost (Cent/km) [d]
Crude Oil	LPG	ICE/PISI	190.0	2.6 [b]	0.8 [c]	3.3
	Gasoline	ICE/PISI	190.0	2.5	0.8	3.3
	Gasoline	HEV	161.7	2.2	0.7	2.8
	Diesel	ICE/DICI	172.1	2.3	0.8	3.0
	Naphtha	Reformer+FC	162.4	2.1	0.7	2.8
Fossil Fuel	Electricity	BEV	45.0	1.1	0.4	1.5
	Elec.+ Gasoline	PHEV40	80.0	1.6	0.6	2.2
Natural Gas	Onsite H_2	Fuel Cell	94.0	2.3	0.5	2.8
	Central H_2	Fuel Cell	94.0	2.5	0.4	3.0
	GTL	ICE/DICI	172.1	2.4	0.8	3.2
	CNG	ICE/PISI	188.3	1.5	0.6	2.1
	DME	ICE/DICI	172.1	2.3	0.7	3.1
	Methanol	Reformer+FC	148.0	2.2	0.7	2.9
	LNG	ICE/PISI	188.3	2.5	0.7	3.2
	LPG	ICE/PISI	190.0	2.3	0.7	3.0

[a] Source: [36]
[b] From equation (5): $13.5 \frac{\$}{GJ} * 100 \frac{Cent}{\$} * \frac{GJ}{1000MJ} * 190 \frac{MJ}{100km} = 2.6 \frac{Cent}{km}$
[c] From equation (6): $50 \frac{\$}{ton_{CO2}} * 100 \frac{Cent}{\$} * \frac{ton_{CO2}}{10^6 g_{CO2}} * 190 \frac{MJ}{100\ km} * 79.0 \frac{g_{CO2}}{MJ} = 0.8 \frac{Cent}{km}$
[d] Due to rounding, in some cases total cost may not equal sum of component.
[e] From equation (7): $2.57 \frac{Cent}{km} + 0.75 \frac{Cent}{km} = 3.3 \frac{Cent}{km}$

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

[1] O. V. Vliet, M. V. Broek, W. Turkenburg and A. Faaij, "Combining hybrid cars and synthetic fuels with electricity generation and carbon capture and storage," *Energy Policy*, vol. 39, pp. 248–268, Jan. 2011.

[2] Ministry of Energy of Iran, Office of Energy and Power Affairs, "Energy balance of Iran in 2008 (Available in Persian)," 2010.

[3] Iranian Fuel Conservation Company (IFCO), "Transportation and energy data book (Available in Persian)," 2009.

[4] J. Barkenbus, "Our electric automotive future: CO_2 savings through a disruptive technology," *Policy and Society*, vol. 27, pp. 399–410, 2009

[5] International Energy Agency (IEA), "Technology roadmap: electric and plug-in hybrid vehicles," 2009.

[6] C. Samaras and K. Meisterling, "Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: implications for policy," *Environ. Sci. Technol.*, vol. 42, pp. 3170-3176, Apr. 2008.

[7] Energy Independence Now, "How do hydrogen fuel cell vehicles compare in terms of emissions and energy use? A well-to-wheel analysis,"
Available at: www.hydrogenhighway.ca.gov/facts/einwelltowheel.pdf, Last accessed Aug. 2011.

[8] S. Soimakallio, T. Makinen, T. Ekholm, K. Pahkala, H. Mikkola and T. Paappanen, "Greenhouse gas balances of transportation biofuels, electricity and heat generation in Finland- Dealing with the uncertainties," *Energy Policy*, vol. 37 pp. 80–90, Jan. 2009.

[9] M. A. Kromer and J. B. Heywood, "Electric powertrains: Opportunities and challenges in the U.S. light-duty vehicle fleet," Sloan Automotive Laboratory, Laboratory for Energy and the Environment, Massachusetts Institute of Technology (MIT), May 2007.

[10] C.E. Sandy Thomas, "Transportation options in a carbon-constrained world: Hybrids, plug-in hybrids, biofuels, fuel cell electric vehicles, and battery electric vehicles," *International journal of hydrogen energy*, vol. 34, pp. 9279–9296, 2009.

[11] R. T. Doucette and M. D. McCulloch, "Modeling the prospects of plug-in hybrid electric vehicles to reduce CO_2 emissions," *Applied Energy*, vol. 88, pp. 2315–2323, 2011.

[12] C. Thiel, A. Perujo and A. Mercier, "Cost and CO_2 aspects of future vehicle options in Europe under new energy policy scenarios," *Energy Policy*, vol. 38, pp. 7142–7151, 2010.

[13] X. Ou, X. Zhang and S. Chang, "Scenario analysis on alternative fuel/vehicle for China's future road transport: Life-cycle energy demand and GHG emissions," *Energy Policy*, vol. 38, pp. 3943–3956, 2010.

[14] A. Veziroglu and R. Macario, "Fuel cell vehicles: State of the art with economic and environmental concerns," *International journal of hydrogen energy*, vol. 36, pp. 25–43, 2011.

[15] M. Wang, Argonne National Laboratory, "Fuel Cycle analysis of conventional and alternative fuel vehicles," *Encyclopedia of Energy*, vol. 2, 2004.

[16] C.E. Thomas, "Fuel cell and battery electric vehicles compared," *International journal of hydrogen energy*, vol. 34, pp. 6005-6020, 2009.

[17] M. Eberhard and M. Tarpenning, "The 21st centuty electric car," *Tesla Motors Inc.*, Oct. 2006.

[18] G.J. Offer, M. Contestabile, D.A. Howey, R. Clague and N.P. Brandon, "Fuel Cycle analysis of conventional and alternative fuel in a future sustainable road transport system in the UK," *Energy Policy*, vol. 39, pp. 1939–1950. 2011.

[19] O. P.R. van Vliet and T. Kruithof, W. C. Turkenburg and A. P.C. Faaij, "Techno-economic comparison of series hybrid, plug-in hybrid, fuel cell and regular cars," *Journal of Power Sources*, vol. 195, pp. 6570–6585, 2010.

[20] A. Simpson, "Full-cycle assessment of alternative fuels for light-duty road vehicles in Australia", Proc. World Energy Congress, Sydney, Sep. 2004, Updated Apr. 2005.

[21] N. Brinkman, M. Wang, T. Webber and T. Darlington , "Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems - A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions," May 2005.

[22] M. P. Hekkert, Franka H. J. F. Hendriks, Andre P. C. Faaij and M. L. Neelis, "Natural gas as an alternative to crude oil in automotive fuel chains Well-to-Wheel analysis and transition strategy development," *Energy policy, vol. 33*, pp. 579-594, 2005.

[23] J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson, "Climate change 2001: The scientific bases," Contribution of working group I to the third assessment report of the intergovernmental panel on climate change; published for the Intergovernmental Panel on Climate Change (IPCC).

[24] Y. Sun, "Societal lifetime cost comparison of hydrogen fuel cell vehicles and gasoline vehicles," Office of Graduate Studies of the University of California, 2010.

[25] R. S. J. Toll, "The marginal damage costs of carbon dioxide emissions: An assessment of the uncertainties, *Energy Policy*, vol. 33 pp. 2064-2074., Jun. 2005.
[26] 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, Mar. 2007.
[27] R. Choudhury, T. Weber, J. Schindler, W. Weidorf and R. Wurster, "GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems- A European Study – Results, Sep. 2002.
[28] 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: http://ies.jrc.ec.europa.eu/uploads/media/Input%20data%20OIL%20&%20COAL%20181108.xls, Last accessed June 2011.
[29] Ministry of Energy of Iran, Office of Energy and Power Affairs, "Energy Balance of Iran in 2009 (Available in Persian)," 2011.
[30] Iran Power Generation, Transmission and Distribution Management Company (TAVANIR), "Electric power industry in Iran" 2010.
[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: http://ies.jrc.ec.europa.eu/uploads/media/Input%20data%20NG%20181108.xls, Last accessed Jun. 2011.
[32] 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 2: Description and detailed energy and GHG balance of individual pathways, Mar. 2007.
[33] C. Stiller, P. Schmidt, W. Weindorf and Z. Matra, "CNG and LPG for transport in Germany environmental performance and potentials for GHG emission reductions until 2020," Sep. 2010.
[34] International Energy Agency- Energy Technology Systems Analysis Program (IEA-ETSAP), Conventional oil and gas technologies, 2010.
[35] Iran Power Generation, Transmission and Distribution Management Company (TAVANIR).
[36] European Commission Joint Research Center (JRC), Well-to-wheels analysis of future automotive fuels and powertrains in the European context, Tank-to-wheels report, Version 2c, Mar. 2007.