Evaluating sustainability of using natural gas as a major transport fuel: A life cycle assessment approach

P. Koltun[1] and M. Kologrivov [2]
1 – CSIRO, Process Science and Engineering, Gate 5, Normanby Road, Clayton, Vic. 3168, Australia; Ph: +613 95457897; Email: paul.koltun@csiro.au
2- State Academy of Refrigeration, 1/3 Dvorianska St., Odessa, 65082, Ukraine; Ph: +38048 7232220; Email: klgrvvmm@rambler.ru

ABSTRACT

For reasons of sustainability, greenhouse gas emissions, and energy security, it becomes necessary to properly evaluate all of possible options for powering transportation fleet for a particular country. When doing this it is equally important to understand all the costs (economic, social, and environmental) and emissions during the fuel extraction, refining and distribution stages as well as the final combustion stage. All steps in the full pathway contribute to the final economic and environmental profile of any given fuel.

The natural gas (NG) family of fuels has to be seriously considered as providing for large-scale transportation. From a combustion point of view, NG derivatives have a lower carbon-to-hydrogen ratio than oil-based fuels and should therefore be cleaner, but the upstream emissions of the fuels need to be properly understood. The supply pathways of gaseous fuels are more diverse than the oil-based fuels pathways, because the sources of gas are varied and can imply substantially different emissions profiles. It is therefore important to understand these various pathways for the country under consideration, so that profiles for each country can be documented and policy formulated accordingly.

This preliminary study is conducted based on a life cycle assessment (LCA) approach to evaluate potential sustainability of using gaseous fuels (CNG/LNG) for light commercial and passenger vehicles based on conditions in Australia and Ukraine, which are quite different, taking into account information on the production, distribution and use of gaseous fuel. Data for this study are mostly sourced from published literature. The results of the study reveal a significant opportunity for

Australia, as well as for Ukraine to increase sustainability of the transport fleet if it takes gaseous fuels on as major source for transport vehicles.

Keywords: transport, sustainability, gaseous fuel, life-cycle approach

1. Introduction

The one of the major task for any country is securing its needs of energy sources and resources conservation. The transportation is one of the major energy using sectors of an economy. And the road transport is the largest user of final energy within the transport sector. The road transport in Australia is accounting for around three quarters of the sector's fuel consumption. Passenger vehicles account for the majority of fuel consumption within the road transport [1]). According data of "AUTO-Consulting" [2] Ukraine had about eight million cars (including trucks) in 2011 and this number is increasing on 1.8% each year. Most of them are using oil-based fuels: 82.1% - gasoline; 17.9% - diesel. Thus, those figures are striking illustration of necessity for substitution of oil-based fuel with more sustainable energy sources.

This study tries to evaluate effect of substitution of oil-based fuels in by NG based fuels on three pillars of sustainability: environmental, economic and social in comparison of two countries Australia and Ukraine. In spite of quite different conditions of production and distribution of transportation fuels in both countries they also have a commonality in adopting alternative fuel technology in comparison with other countries (see, Fig. 1)

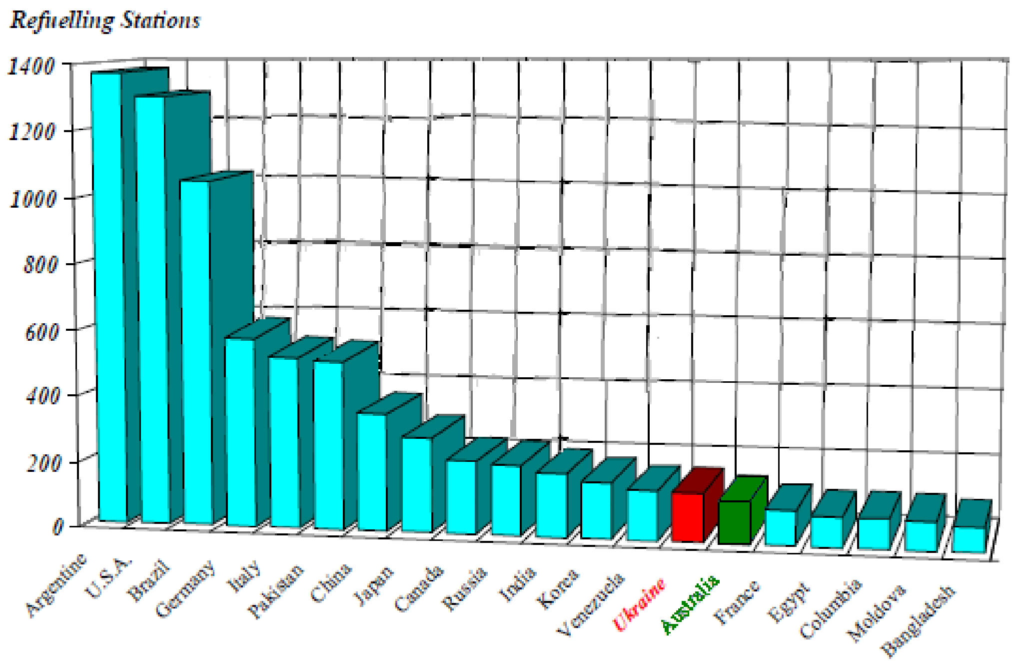


Figure 1. Quantity of NG refuelling stations in Australia and Ukraine in comparison with other countries in the world [3].

Currently the main priority in development of the transport sector in the world is reduction of negative impact of transport fuel on environment taking into account all international agreements and restrictions. Table 1 represents data of energy sources using by Australia and Ukraine (other countries are shown for comparison).

	World	**Ukraine**	**Australia**	**European Union**	**USA**
Natural Gas	21%	41%	19%	22%	24%
Oil	35%	19%	32%	41%	38%
Coal	23%	19%	45%	16%	23%
Nuclear	7%	17%	-	15%	8%
Renewable	14%	4%	4	6%	7%
Total	100%	100%	100%	100%	100%

Table 1. Primary energy consumption by different countries (2009-10) [1]

Considering the source of fuels, the transportation sector is the largest consumer of oil-based fuels (including gasoline, diesel, and other refined products). In fact, Australia is a net importer of crude oil and refined petroleum (oil-based) products [1], as well as Ukraine and this dependence is bound to increase as domestic supplies are unable to meet increasing local demands in the future.

Burning fossil fuels significantly increases the level of carbon dioxide (CO2) and other greenhouse gases (GHG) in the atmosphere, which can have an adverse impact on climate change. There is also great concern about increasing environmental pollution in cities—from the use of oil-based fuels by the transport sector—that that can affect health. The emissions from transport that contribute to this pollution include: particulate matter (PM), carbon monoxide (CO), hydrocarbons (HC), sulphur oxides (SOx), nitrogen oxides (NOx), and other air toxins. Therefore, finding domestic alternatives to gasoline and diesel fuels is a priority.

Given the aforementioned situation, there is a need to assess the sustainability of predominantly relying on oil-based fuels versus other sources. The most attractive alternative to oil-based fuel currently is NG-based fuels. In fact Australia is well endowed with NG resources and comprises a growing industry to this effect. Although Ukraine doesn't have enough NG resources to cover its needs, however, the divergence of NG resources and possibility of production NG from alternative sources, such as recycling of agriculture waste, waste water processing, etc. makes NG an attractive transportation fuel for Ukraine, as well.

The aim of this study is to make a preliminary comparison of possible sustainability benefits of using NG as a source of fuel for road transport in Australia and Ukraine. Transport vehicles considered are passenger and light commercial vehicles, as they account for the most of all road transport. Comparison of NG and current use of oil fuels is done based on environmental, economic, and social impacts. Environmental impacts include GHG and other pollutants. Economic impacts assess use of gaseous fuels sourced domestically for Australia and supply by Russian Federation for Ukraine - versus oil-refined fuels (imported). Social impacts include pollution, safety, engine operation, as well as a shift of production capacities.

The comparison considers the whole life cycle of fuels (so-called "well-to-wheel") involving a sequence of stages, from the extraction of raw materials through to the combustion of fuel in vehicles. Thus, the study offers a deeper, holistic understanding of the implications from "cradle-to-crave".

2. The scope of the study

There are a number of methods used in presenting quantitative merits for rating the performance of different types of transport [4-6] Life Cycle Assessment (LCA) is currently one of the most popular methods aimed at quantifying the environmental effects related to a given product, process or activity along its life cycle. However, a comprehensive LCA is complex and requires a lot of details at each life cycle stage, including detailed sources of emissions. Therefore, in this study, as a preliminary assessment, a streamlined LCA is used based on the recommendations of a SETAC report [7].

The sustainability assessment for comparison of different systems is an issue. Apart from the well known definition of sustainability given in the Bruntland's Report [8], a more recent definition is given by the US EPA [9]: "Sustainability occurs when we maintain or improve the material and social conditions for human health and the environment over time without exceeding the ecological capabilities that support them". Both definitions lack in terms of being helpful sources when quantifying the sustainability of a system. Although the quantification of sustainability is a problematic task, it is possible to make an assessment about the relative sustainability of comparable systems. To illustrate this statement three metrics have been chosen: environmental or pollution reduction; economic or value-added, and social or societal good. Fig.2 shows sustainability state based on three metrics, for two systems, the "old" and the "new" (the old system is depicted by the smaller triangle and the new system by the larger triangle, i.e. the metrics measure an expansion of advantages in all three dimensions). It is clear that the shape of the outer triangle could be based on an infinite number of possibilities born from improvements made to the system. The improvements in any one aspect can be small or large, thus determining the shape of the triangle.

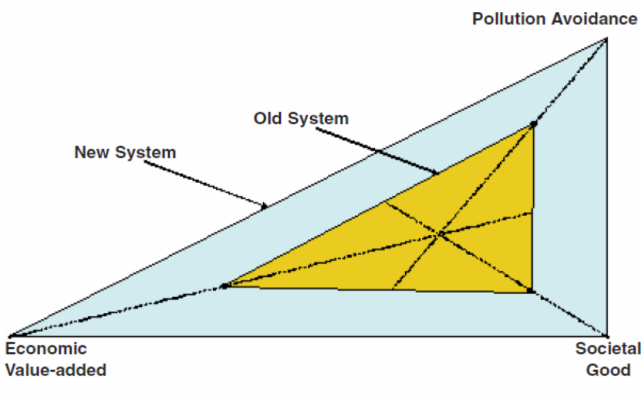


Figure 2. Progress toward sustainability balancing the three aspects of sustainability [9].

Such elaborate analysis requires complex multivariable assessment taking into consideration different aspects in each dimension. In this study a simplified approach is taken to compare the sustainability of road transport in Australia as powered by different type of fuels. A comparison of environmental impacts is made on the basis of GHG emissions, net energy (NE) yield, and non-renewable resource depletion potential

(NRDP). Life cycle costs (LCC) are the basis for the economic comparison. Social impacts are assessed qualitatively.

The geographic scope of this LCA study is largely limited to include only two countries: Australia and Ukraine. However, international scope is also implied in this study, as majority of the oil-based fuel used in for both countries has a foreign origin. A near-term time frame has been selected for this study reflecting current technologies in use. Data on inputs and outputs at each stage of fuel life cycles is sourced from published literature, and simplified models are developed to characterise emissions.

3 Life cycle environmental impact of oil-based fuels vs. NG fuel

Australian primary energy consumption consists mainly of oil-based fuel and coal. Black and brown coal account for the greatest share of the fuel mix, at around 40 per cent, followed by oil-based products (34 per cent), NG (20 per cent) and renewable energy sources (5 per cent) (Fig. 3). Oil-based products compose most transport fuel, whereas NG is mostly used for heating and energy generation. The share of NG in Australian energy consumption has increased in the past 30 years and this trend is likely to continue in the longer term.

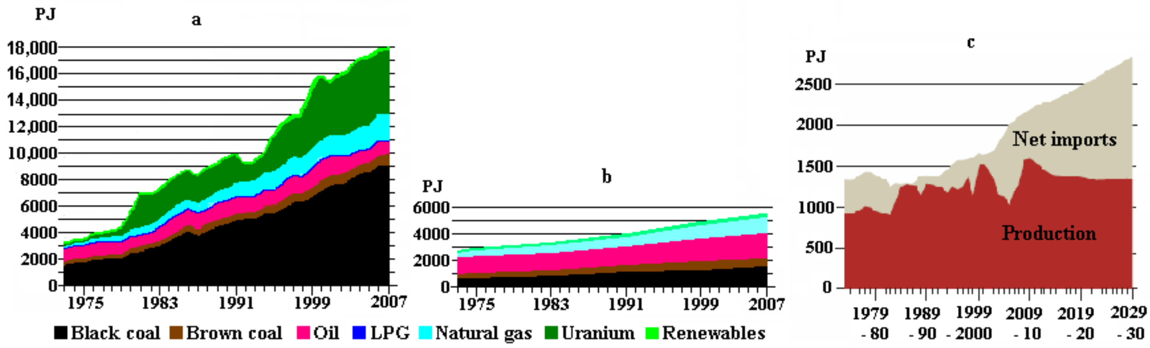


Figure 3. Energy production (a) and consumption (b) and oil production and consumption (c) in Australia [1]

As can be seen in Fig 3a Australia is a stable oil producer (a certain amount of oil is being exported); however, the country consumes more oil than it produces (Fig 3b), and this trend will only increase into the future (Fig 3c).

Primary energy consumption by transportation sector in Ukraine is much lower than in Australia(see Table 2), due to much higher density of population. However, it doesn’t mean that the substitution of oil-based transportation fuel is not an important problem. Substitution of such fuel is one of the main outlooks for improving ecological conditions in Ukraine. More over there are existing international programs of substitution of oil-based transportation fuels in accordance with the decision of European Commission (the program “Dream-2020”) and European Association of Transportation (“Target 2020”) providing that 10% of oil-based fuels have to be substituted by NG till the year 2020.

To evaluate all advantages (as well as possible disadvantages) of using NG as a transportation fuel the full sustainability analysis has to be conducted including ecological, economical and sociological aspects. The ecological aspect should include a “cradle-to-grave” LCA: NG extraction, processing and storage, transportation and distribution, compression and on-road use.

Consumers	Boiler's Fuel (10^3 ton of equivalent fuel) .		Electrical Energy (10^9 kWh)	
	Years		Years	
	1990	2000	1990	2000
Industry	213,6/ 76,1%	196,0/ 77,4%	188,34/ 47,0%	160,2/ 47,1%
Building & Construction	2,4/ 0,9%	1,2/ 0,5%	3,98/ 1,0%	2,12/ 0,6%
Transportation	**8,8/ 3,1%**	**9,5/ 3,9%**	**145,0/ 36,2%**	**110,4/ 32,4%**
Agriculture	5,7/ 2,0%	3,5/ 1,4%	19,02/ 4,7%	15,6/ 4,6%
Housing & Communal services	50,1/ 17,9%	43,0/ 15,8%	44,60/ 11,1%	51,9/ 15,3%
Total	280,6/ 100%	253,2/ 100%	400,94/ 100%	340,22/ 100%

Table 2. Consumption of Boiler's Fuels and Electrical Energy in Ukraine [10]

(NG is referred as boiler's fuel in Ukraine**;** 10^3 ton of equivalent fuel equals 0,00814*10^9 kWh of electrical energy)**.**

Although the overall conventional reserves of oil and gas are similar worldwide, Australian NG reserves are much bigger than oil (Table 3). Contemporary production volume of NG exceeds current and near future needs even if the entire road fleet would use NG fuel (Table 4). Ukraine has less energy resources than Australia. Those resource are mostly concentrated within three oil-gas regions: Karpaty's reserve Dnepropetrovsk-Pripiatsky reserve, Crimian-Black Sea reserve[10]. Although Ukrainian energy reserves less that Australian, however, gas reserves are much bigger than oil, as well (Table 5) [10].

	World		**Australia**	
	Oil	**N. Gas**	**Oil**	**N. Gas**
Proven reserve (PJ)	5,770,000	5,740,000	8,770	152,000
Reserves to current production ratio (years)	42	60	11	95

Table 3. Proven oil and gas reserves in Australia[11]

State	**Current Production (PJ)**	**Potential consumption by road fleet (PJ)**
NT	22	7.1
NSW +ACT	5*	307
QLD	139*	200
SA	124	71.4
VIC+TAS	312	343
WA	1141	107.1
Total	**1599**	**1035.6**
* Potential production are: 300PJ - for NSW; 700PJ - for QLD		

Table 4. Production and potential consumption of NG as a transport fuel in each Australian state [1]

Except conventional NG resources (Table 3 and 5) there are many other sources of methane in the world, Australia and Ukraine (Fig. 4). For example, gas hydrates have an estimated reserve 10-20,000 times bigger than that of conventional NG [12], i.e. greater than all other fossil fuel reserves put together. Ukraine has potential gas hydrates reserve more than 8 times bigger of others hydro carbon energy reserves all together. Additionally, methane can be obtained from coal-bed methane (so-called coal seam gas–CSG), tight sands, etc., and can even be obtained from landfill waste, agricultural waste and processing of waste water. Therefore using NG as a fuel has substantially less impact on environmental characterisation factors, such as resource depletion potential, when compared with oil-based fuels and the impact is small specifically for Australian and Ukraine conditions.

Hydrocarbon Resources	**Deposits**		**Potential Deposits**
	Mined	**Resources**	
Natural Gas(NG), PJ	5,624	10,238	146,631
NG dissolved in oil, PJ	3, 569	4,362	11, 407
Oil, PJ	4,400	6,688	31,024
Gas Condensates, PJ	5,529	8,290	14,918
Coal Seam Gas (CSG), PJ	2,868	5,664	5,184
Offshore gas hydrates, PJ	-	-	up to 1,756,650

Table 5 Proven oil and gas reserves in Ukraine [10].

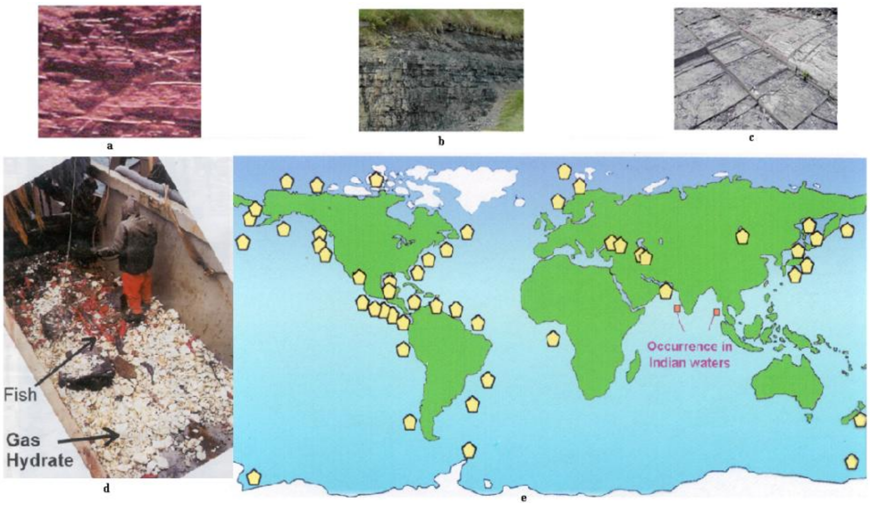


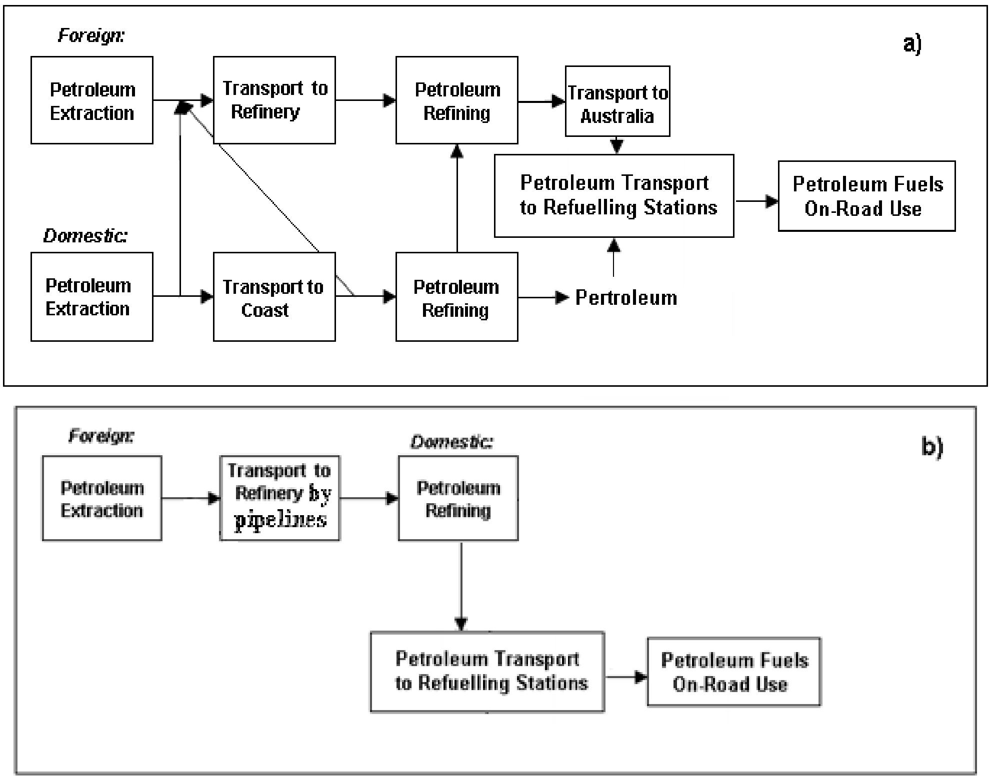
Figure 4. Non conventional reserves of NG: a) tight sands; b) coal-bed methane and coal mine gas; c) gas shales; d) gas hydrates; e) known occurrences of gas hydrates in offshore sediments

To make a quantitative comparison of the global warming (GW) impacts of oil-based with NG transport fuels in Australia and Ukraine, the all stages of 'LCA - well-to-wheel" are modelled.

The model for oil-based fuel includes crude oil extraction (worldwide for Australia; East part of Russia for Ukraine – only 15-18% of consumed oil is mined within Ukraine and the rest is imported from Russia and Kazakhstan [10]). It's also includes local (for Ukraine) and mostly foreign refinery operations (for Australia [1]) and petroleum transportation, transportation to refuelling stations (in both countries) and end-use petroleum as a fuel in vehicles. Energy consumption and emissions relating to production, refining and transportation of imported oil are based on an average data from different sources [13 - 16]. The model for Australia involves a half-and-half mix of oil produced domestically and overseas and 18% extraction and 100% refining domestically for Ukraine. It is also assumed that 75 percent of all energy consumption and emissions due to refinery operations are allocated to oil-based fuels according to results presented in [17]. The model for transportation of petroleum to Australia and its delivery to refuelling stations is similar to the model used for petroleum transportation within the USA [18], but it has been adapted for Australian conditions. The system boundaries for the oil-based model are shown in Fig 5a. The model for transportation of oil to refining plants is based on pipelines transportation (Fig. 5b). All other stages of LCA for oil- based fuels are similar for both countries (Fig 5a and 5b). The figures for energy consumption and GHG emissions are worked out for a functional unit of 1GJ of energy carried by the fuel and presented in Tables 6a and 6b.

The model for NG used as a transportation fuel includes gas extraction and purification, transportation and storage within the gas hubs, and delivery to refuelling stations (Fig 5c). This model is based on assumptions for Australia that each state in Australia has its own NG resources (Table 4). Extracted gas will be transported and delivered to refuelling stations by pipelines and compressed there. The results of the NG model using the same functional unit are presented in (Table 6c). The model for NG used in Ukraine is similar to the previous one. The only differences are that NG is extracted mostly on shore and the distance for NG transportation by pipelines about two times longer on average (The obtained results are presented in Table 6d).

Comparison emissions for oil-based and NG fuels (Tables 6), from the front end of the fuel cycle - “well-to-tank” shows that emissions for NG fuel are less for Australia by about 25%. The same emissions in Ukraine are even higher than for oil-base fuels (mostly due higher emissions from the extraction processes). However, overall emissions from the whole life cycle are less for NG in Ukraine by about 25% (from 86.20 to 64.16 CO_2 kg eq.). The GHG emissions for the whole life cycle in Australia are reduced by 30 percent (from 88.67 to 61.01 CO_2 kg eq.) for the NG fuel (see Tables 6).



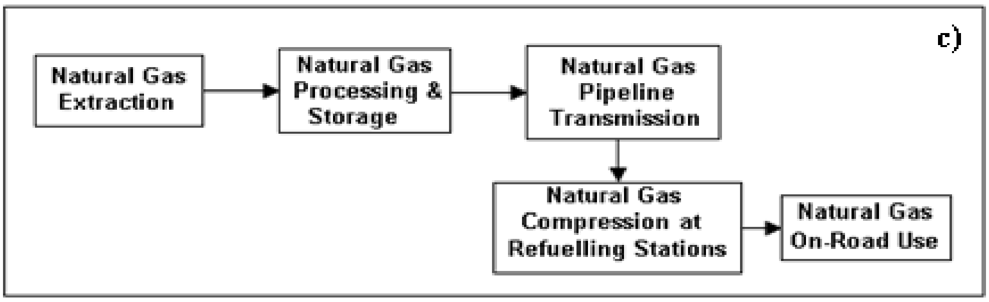


Figure 5. System boundaries for the life cycle model of oil-based fuels in Australia (a), oil-based fuel in Ukraine (b) and NG fuel in both countries (c)

It's possible to estimate the overall reduction of GHG emissions due to replacement of oil-based fuels with NG using figures presented in Table 6. To calculate such GHG emissions reduction it must be taken into account the overall oil-based fuel consumed annually by a country (it's approximately 1000 PJ of oil-based fuels for Australia- about 300PJ of diesel and 700 PJ of gasoline; and – is approximately 400 PJ of oil-based fuels for Ukraine with about the same proportion diesel and gasoline: 1 to 1 [10]. In addition it's assumed that: a) NG as a transport fuel improves vehicle efficiency by approximately 13 percent (this is conservative figure as vehicle efficiency actually may be improved by 16 percent, as octane number of compressed NG is higher than for gasoline [9] b) a vehicle carrying NG will be slightly heavier, as a typical fuel tank carrying oil-based fuel weighs 0.08kg/l, and gaseous fuel has to be stored in a pressurized vessel with a weight ratio of approximately 0.55kg/l [22]. The LCA software SimaPro 7.1 [21] is used to compute global warming impact for different stages of the fuel's life cycle. The results for GHG emissions reduction are presented in Table 7 for two scenarios: a) 50% and b) 100% replacement of oil-based fuel with NG.

a)

	Primary Energy input (MJ)	**GHG emissions (kg of CO2 eq.)**	**Short description**	**Source**
Exploration & extraction	79.7	2.08	Domestic (50%) + Foreign (50%)	[17]
Transportation to refinery	19.8	1.44	Domestic (50%) + Foreign (50%)	[17]
Refining	66.5	8.74	75% allocated to vehicles depending on oil-based fuel	[17]
Distribution to refuelling stations	30	2.61	10,000 Tanker (50%) + 1,000 km rail (50%) + 250km truck (100%)	[17]
Combustion in vehicles	1000	73.8		[18]
Total (without use stage)	**1196.0 (196.0)**	**88.67 (14.87)**		

b)

	Primary Energy input (MJ)	GHG emissions (kg of CO2 eq.)	Short description	Source
Exploration & extraction	62.0	1.75	Domestic (20%) + Foreign (80%)	[16]
Transportation to refinery	4.72	0.34	Pipelines (20% - 300 km; 80% – 4000km)	[19]
Refining	66.5	8.74	75% allocated to vehicles depending on oil-based fuel	[17]
Distribution to refuelling stations	18	1.57	300 km rail (50%) + 150km truck (50%)	[17]
Combustion in vehicles	1000	73.8		[20]
Total (without use stage)	**1151.2 (151.2)**	**86.20 (12.40)**		

c)

	Primary Energy input (MJ)	GHG emissions (kg of CO2 eq.)	Short description	Source
Exploration & extraction	74.9	5.29	Off shore extraction (Australia)	[20]
Reforming & storage	9.5	0.57	On shore processing	[21]
Distribution to refuelling stations	8.4	2.61	1500km on shore pipeline (pipelines installation, NG lost during extraction and transportation are included)	[20]
Compression for refuelling vehicles	60.0	3.04	Compression done by: engines 75%; turbines 25%	[18]
Combustion in specifically designed engines	1000	49.50		[15]
Total (without use stage)	**1152.8 (152.8)**	**61.01 (11.51)**		

d)

	Primary Energy input (MJ)	GHG emissions (kg of CO2 eq.)	Short description	Source
Exploration & extraction	30.0	4.1	On shore extraction	[20]
Reforming & storage	9.5	0.57	On shore processing	[21]
Distribution to refuelling stations	22.4	6.95	4000km on shore pipeline (pipelines installation, NG lost during extraction and transportation are included)	[20]
Compression for refuelling vehicles	60.0	3.04	Compression done by: engines 75%; turbines 25%	[18]
Combustion in specifically designed engines	1000	49.50		[15]
Total (without use stage)	**1121.9 (121.9)**	**64.16 (14.66)**		

Table 6 Energy and GHG emissions from "well-to-wheel" LCA per 1GJ of petroleum fuels in Australia (a) and Ukraine (b), and NG as a transportation fuel in Australia (c) and Ukraine (d)

The actual reduction of GHG emissions could be higher than presented in Table 7 if consideration of unconventional sources of NG would be included. For example, combustion NG (methane) from agricultural waste and some other sources, instead of venting it into the atmosphere, reduces the level of CO2 emissions. Venting 1kg of methane produces GHG equivalent to 20kg CO2 eq, while burning the same amount of methane produces only that equivalent to 2.75kg kg eq. The global warming potential (GWP) of methane is more than 20 times higher than carbon dioxide based on a 100-year time horizon [23], mainly adopted for LCA studies [21].

Replacement of petroleum with NG (%)	**Australia**		**Ukraine**	
	50	**100**	**50**	**100**
GHG emissions reduction, Mt	17.8	35.6	4.4	8.8
GHG emissions reduction, (% of overall emissions)	4.5	9.0	1.4	2.8

Table 7. GHG emissions reduction due to replacement of petroleum with NG as a major transportation fuel in Australia and Ukraine [24].

Although composition of NG depends upon gas field and usually is a mixture of different gases (the average composition of NG presented in Table 8), however, this mixture predominantly consists from hydrocarbon gases and burning by motors fuel emits mostly only carbon dioxide (CO2) thus, used as transportation fuel leads to reduction in other emissions, as well and as follows from Table 9.

Component	**Molar (volume) part,%**	**Range of values, %**
Methane	95.2	75.0 – 98%
Ethane	2.5	1.5 – 15.1
Propane	0.2	0.1 – 1.5
Isobutane («butane»)	0.03	0.01 – 0.3
n-butane (also «butane»)	0.03	0.01 – 0.3
Isopentane («pentane»)	0.01	trace quantity – 0.04
n-pentane («pentane»)	0.01	trace quantity – 0.04
Hexanes	0.01	trace quantity – 0.06
Nitrogen	1.3	0.7 – 5.6
Carbon dioxide	0.7	0.1 – 1.0
Oxygen	0.01	0.01 – 0.1
Hydrogen	trace quantity	trace quantity
Hydrogen sulphide	trace quantity	trace quantity – 0.02
Helium	trace quantity	trace quantity

Table 8. Average composition of natural gas (NG) [25].

Emission	Petroleum	Natural Gas
Volatile organic compounds (VOC)	48.8	20.5
Total particulate matter	79.8	5.81
SOx	346	100.9
NOx	1,865	200

Table 9. Comparison of major air emission substances from "well-to-wheel" life cycle of petroleum and NG [15, 26]

4 Estimation of economic impacts

Table 10 presents tariffs for different energy sources and associated cost per 1GJ of consumed energy in Australia and Ukraine (Shown in Table 10 prices include also government taxes). Presented figures show that 1GJ of CNG in Australia is approximately three times cheaper than 1GJ of oil. This difference between oil-based and NG energy sources is even bigger for Ukraine (more than 4.5 times). The figures presented in Table 11 for international prices for oil and LNG (the figures are based on conservative oil price of US$80 per barrel and US$217 per tonne of LNG [12]) show the similar trend.

Fuel	Australia		Ukraine	
	Fuel price (US$)	Price per 1GJ (US$)	Fuel price (US$)	Price per 1GJ (US$)
Firewood Domestic (Air dry)	250/ton	17.0	102/t	6.9
Black Coal	100/ton	7.0	100/t	7.0
Liquefied Petroleum Gas (LPG)	0.67/L	26.8	0.39/L	15.6
Compressed Natural Gas (CNG)	11.1/GJ	11.1	11.1/GJ	11.1
Petroleum	1.30/L	34.0	1.16/L	30.3
Electricity (tariffs)	0.18/kWh	50.0*	0.046/kWh	12.8*
Natural gas (tariffs)	0.013/MJ	13.0*	0.0028/MJ	2.8*

(*All tariffs include supply charges for NG and electricity)

Table 10. Prices of different energy source in Australian (August, 2009) [27-30]

Fuel	Fuel price (US$)	Price per 1GJ (US$)
Oil	$578/ton	$13.6
LNG	$217/ton	$4.5

Table 11. International price of oil and liquefied NG [12]

It also should be mentioned that in case of oil-based fuel additional costs are incurred to convert oil to petrol and fuel distribution, hence its price will increase. The figure for NG presents LNG price. Natural gas is converted to LNG by cooling the gas to –161°C to reduce its volume for storage and transportation (say by sea ships). This process requires a lot of energy and hence adds cost to LNG, which isn't required for NG distribution. Although, costs of distribution and compression of NG also have to be added to the NG figures presented in Table 11, however, those additional costs from "well-to-tank" for NG will be much lower than for oil-based fuels. The cost of distribution of CNG is lower than respective cost of oil-based fuels for two reasons. First, distribution of NG in Australia and Ukraine will be done though pipelines, which is much cheaper than by rails and roads. The pipeline infrastructure for NG already exists in Australia and Ukraine (Fig. 6). Secondly, NG compression at refuelling stations mostly will be done by effective compression engines using NG as source of energy. Natural gas should be compressed to about 20MPa (3,000psi). The sketch of possible gas refuelling station is shown in Fig 7.

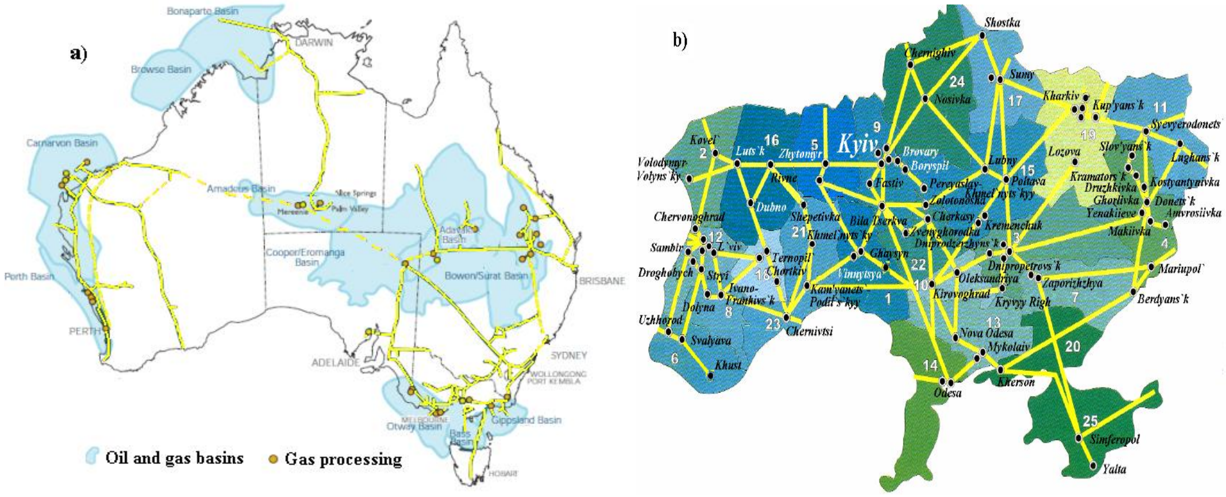


Figure 6. Gas pipelines network in Australia (a) and Ukraine (b) [3, 12]

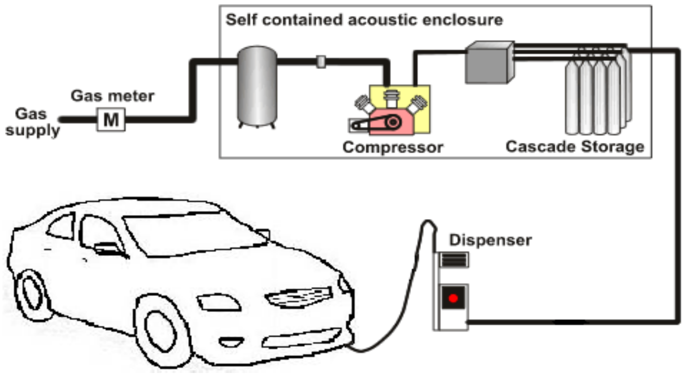


Figure 7. Refuelling system for CHG station [31]

Although oil-based fuels and NG prices are affected by many different factors it is possible to roughly estimate economic advantage due to replacement of oil-based fuels. The possible economic benefit has been calculated using the following models (cost figures for both models are based on figures presented in Tables 11 and 12):

1. Oil-based fuel: a) price of crude oil; b) cost of oil refining; c) cost of oil transportation to Australia by ships (for 50 per cent of oil-based fuel according to adopted model in section 3); d) cost of fuel distribution among refuelling stations (50 per cent by road and 50 per cent by rail).
2. Natural gas-based fuel: a) price of NG; b) cost of gas distribution among refuelling stations by pipelines (distribution distance is based on figures presented in Tables 6) and existing pipeline infrastructure (Fig 5); c) cost of compression and storage of NG at refuelling stations including cost of necessary equipment. There is no need to build new refuelling stations as current stations can be partially or fully converted by replacing storage vessels and some refuelling equipment.
3. Cost factors for transportation are based on Australian and Ukrainian data, all other cost factors are based on Australian data due to unavailability of reliable Ukrainian data.

The benefits of fuel replacement are presented in Table 13 using previous scenarios (Tables 6) and annual consumption of the oil-based fuels for both countries. Although presented figures are very much different by absolute values, but their relative contribution for cost saving due to adoption of NG based fuel are similar for both countries (see Table 13).

Presented in Table 13 figures do not take into account the cost of the transportation fleet (cars and trucks) — which can be slightly higher (for example, currently the Honda Civic Sedan powered by gasoline costs around $22,255 in the USA and the Honda Civic GX powered by CNG is priced at $24,590 [31])—this cost can be offset by lower maintenance costs. It is well known that NG burns clean and does not leave residue or deposits in the engine. Recent surveys found that NG engines require check-ups only after 160,000km and last up to 800,000km [40].

Additional cost factors	Cost (US$)	Source
Refinery (petroleum)	2.412 / GJ	[32]
Transportation by tanker (for Australia only)	0.000019 / (GJ*km)	[33]
Transportation by rail in Australia {in Ukraine}	0.000647 / (GJ*km) 0.00113 / (GJ*km)	[34] {[35]}
Transportation by road in Australia {in Ukraine}	0.00133 / (GJ*km) 0.0096 /(GJ*km)	[34] {[36]}
Pipelines transportation oil {in Ukraine}	{0.000203/(GJ*km)}	{[37]}
Pipelines transportation NG in Australia {in Ukraine}	0.000256/ (GJ*km) 0.00021 / (GJ*km)	[38] {[39]}
Compression (NG)	0.257 / GJ	[18]
Liquefaction (NG) [1]	1.000 / GJ	[38]

(1- Liquefaction cost has to be subtracted from cost of NG if it will be distributed within Australia)

Table 12. Major additional cost factors and their cost for different type of fuels (based on years 2007-2008 prices)

	Australia		Ukraine	
Replacement of petroleum with NG (%)	**50**	**100**	**50**	**100**
Estimated economic benefit in Australia, BUS$	7.5	15.0	2.53	5.12
Estimated reduction of fuel cost (%)	39.0	78.0	35.5	71.03

Table 13. Estimated annual economic benefit in Australia and Ukraine due to replacement of petroleum fuels with NG

Additional economic advantages for NG as a transportation fuel may come from: a) use of unconventional sources of NG (such as agricultural waste), which are cheaper than conventional NG sources and in most cases require less transportation due to local production; b) unlike prices for oil-based fuels, which are highly volatile, the price of NG has been rather stable during past three years (Table 14) and it’s likely to remain stable into the future due to much wider availability and diversified sources; and c) a reduction of road-based delivery fleet since NG will be mostly transported by pipelines.

Year	Oil (US$/GJ)[1]	NG (U$$/GJ)[2]
2009	10.12	3.69
2010	12.99	4.16
2011	15.54	3.80

1. Prices from West Texas Intermediate; 2 –Prices from US Henry Hub

Table 14. Oil and Natural gas prices for the last three years [41]

5 Evaluation of social impacts

Social considerations are also very important factors (Fig 2.), which influence the success or failure of adopting NG as an alternative transportation fuel. Quantitative evaluation of social factors requires substantial scientific research that is far beyond the scope of this study. Hence, a qualitative estimation of the benefits of introducing NG-based fuel is examined. For a new vehicle technology, two key areas have been identified by [42], which require consumer acceptance: vehicle performance and refuelling. Table 15 presents some key performance criteria for passenger cars run by CNG fuel as compared with oil-based fuel.

Other two important social factors demanding attention are employment and safety. Employment will tend to increase as local companies get involved in developing new technologies. Additionally, other employment opportunities arise related to the construction of new refuelling stations and/or the expansion of current ones, as well as the diversification of NG supplies routes. Regarding safety: NG is an inherently safe fuel compared with gasoline, as leaks rapidly disperse into the air, and rapid combustion (explosion) is extremely unlikely. Although, there are few statistics in relation to the use of NG as a transport fuel, its storage systems have been operating for many years, and the technology is in place to assure the fuel distribution infrastructure is as safe as any other competitive technology. Since NG delivery through pipelines will tend to remove (or at least reduce) the number of fuel delivery trucks on the roads, reliance on NG has the potential to contribute to safer road conditions as well.

Performance Criteria		Performance of NG fuel vs. oil-based fuels
Operation	Acceleration	Comparable performance
	Maintenance	Tends to be lower
	Distance between refuelling	Comparable with gasoline / Tends to be less than diesel
	Noise	Comparable performance
Safety	Toxic to skin and lungs	No
	Ingestion risk	No
	Temp required for spontaneous ignition	2.5 times higher
	Limits of flammability	Higher
Refuelling	Equipment	More complex
	Possibilities	Broader

Table 15. Comparison of CNG vehicle performance against gasoline vehicle [42]

Natural gas is neither corrosive nor toxic and does not contaminate soil or water [42]. As a hydrocarbon gas (predominantly methane), NG is lighter than air and odourless. A distinctive odorant, such as butylmercaptan, is added to the fuel and allows NG to be detected at 0.5 per cent concentration in air, well below the weakest concentration that can support [43]. Further, replacement of oil-based fuels in Australia and Ukraine with NG promises to improve the energy security for both countries (Australia currently imports around 40 per cent of its supply and this portion will only tend to increase in the future [1]; Ukraine currently imports 80% of its oil supply). Decreasing dependence on oil also may allow both countries under consideration in this study to improve its transportation networks, as well.

6 Conclusions

The results presented in this work demonstrate the relative benefits of using of NG as a transportation fuel in Australia and Ukraine. Natural gas vehicles have much lower life-cycle GHG emissions than oil-based internal combustion engine (ICE) vehicles. Compared to gasoline and diesel, NG has fewer air pollutants of concern and is not toxic or corrosive, and does not contaminate soil or water. Although NG is a greenhouse gas pollutant fuel, however, GHG its emissions are much lower than from oil-based fuels for both countries under consideration in this study. It can be also used in hybrid electric vehicles (HEV) presenting an opportunity for further reduction of vehicles life-cycle impacts.

Since NG as transportation fuel shows a substantially better performance relative to oil-based fuels—in all three dimensions of sustainability: environmental, economic and social—it can be the nexus to hydrogen technology, i.e. fuel cell vehicles (FCV). These vehicles will require infrastructure similar to NG (chemically NG is 80 per cent hydrogen). Although, hydrogen technology is not yet commercially mature, it has great potential.

This work demonstrates that a life-cycle approach is necessary to effectively evaluate the overall performance of vehicle and component design, fuel supply systems and infrastructure. Such an approach enables designers to identify multiple reasons for implementing NG as a wide-spread transportation fuel. Vehicles depending on NG have the potential to be cost-competitive; however, this will require changes to storage and supply infrastructure.

This preliminary study does not discuss policy issues surrounding the introduction of an NG-based transport sector. Nevertheless, it invariably shows the possible benefits of using NG-based fuels to reduce environmental impact by the transport sector whilst being cost competitive with current oil-based fuel use.

References

1. ABARE (2009, May). The Australian Bureau of Agricultural and Resource Economics, *Energy in Australia 2009*, Report, Retrieved from http:/www.abare.gov.au.

2. “Quantity of road transport in Ukraine,

   http://www.auto.bigmir.net/autonews/autoworld/152015-skol-ko-v-Ukraine-i-v-mire-mashin-na-tysjachu-zhitelej

3. Orlov I., Kozak V. (2006) *Use of Compressed Natural Gas (CNG) as Motor Fuel in Ukraine, Prosoects and Problems*, 23-rd World Gas Conference, Amsterdam.

4. Manzini, F. and Martinez, M. (1999). *Choosing an energy future: the environmental impact of end-use technologies*, Energy Policy, 27, 401–14.

5. Wackernagel, M. and Yount, J. (1998). *The ecological footprint: an indicator of progress toward regional sustainability*, Environment Monitoring Assess, 51, 511–29.

6. Afgan, N.H., Carvalho, M.G., G Hovanov, N.V. (2000). *Energy system assessment with sustainability indicators*, Energy Policy, 28, 603–612.

7. Todd J.A. and Curran M.A., (eds) (1999, June). *Streamlined Life Cycle Assessment*, A Final report from the SETAC North America Streamlined LCA Workgroup, SETAC.

8. Brundtland Commission (1987). World Commission on Environment and Development, Report.

9. Sikdar S.K. (2003). *Sustainable Development and Sustainability Metrics*, AIChE Journal, 49, 1928 – 1932.

10. Michaylov V.A. et. al. (2009), *Energy commodity in Ukraine*, Handbook, Kyiv, 379 pp (Ukr.)

11. Schlumberger J.C. (2010). *The New Energy Mix*, Geo-science Australia, Retrieved from http://www.ga.gov.au/servlet/BigObjFileManager?bigobjid=GA16759.

12. Malcolm K. (1994). *Natural gas hydrates: Energy for the future*, Marine Pollution Bulletin, 29, 307-311.

13. ECJRC (2006). European Commission Joint Research Centre, *Well-to-Wheel Analysis of Future Automotive Fuels and Power Trains in the European Context: Well-to-Tank*, Report, Version 2b, May 2006, Retrieved from http://ies.jrc.ec.europa.eu/WTW.

14. Frischknecht, R., et. al. (1996). Report, 3rd ed., BEW, Bern, Swisszerland.

15. Granovskii, M., Dincer, I., Rosen, M.A. (2006). *Life cycle assessment of hydrogen fuel cell and gasoline vehicles*, International Journal of Hydrogen Energy, 31, 337 – 352.

16. Yan, X. and Crookes, R.J. (2009). *Life cycle analysis of energy use and greenhouse gas emissions for road transportation fuels in China*, Renewable and Sustainable Energy Reviews, 13, 2505–2514.

17. NREL (1998, May). National Renewable Energy Laboratory, *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus*, U.S. Department of Energy (DoE), Final Report.

18. López, J.M., Gómez, A., Aparicio, F., Sánchez, F.J. (2009). *Comparison of GHG emissions from diesel, biodiesel and natural gas refuse trucks of the City of Madrid*, Applied Energy, 86, 610–615.

19. Pootakham T., Kumar A. (2010) *A comparison of pipeline versus truck transport of bio-oil,* Bioresource Technology, v. 101, 414–421

20. Meier P.J. et al. (2005). *US Electric Industry Response to Carbon Constraint: A Life-Cycle Assessment of Supply Side Alternatives*, Energy Policy, 33, 1099–1108.

21. Pre Consultans (2009). *SimaPro 7.1 – The software tool to analyse and develop environmentally sound products*, Amersfoort, The Netherlands.

22. Röder A. (2001). *Integration of Life-Cycle Assessment and Energy Planning Models for the Evaluation of Car Power-Trains and Fuels*, Ph.D. Thesis, Swiss Federal Institute of Technology, Zürich 2001, Diss. ETH No. 14291.

23. Working Group I (2007). The Physical Science, *Basis Climate Change 2007*, IPCC Fourth Assessment Report.

24. Wikipedia, *List of countries by carbon dioxide emissions (year 2008)*, http://en.wikipedia.org/wiki/List_of_countries_by_carbon_dioxide_emissions (visited 2012)

25 Lushko V.A. et. al. (2011), *Evaluation of natural gas as transportation fuel*, Transport with alternative fuel, v.3 4-9 (Ukr.)

26. Heather, L. MacLean, H.L. and Lave, L.B. (2000). *Environmental Implications of Alternative-Fueled Automobiles: Air Quality and Greenhouse Gas Tradeoffs*, Environ. Sci. Technol., 34, 225–231. http://pubs.acs.org/doi/abs/10.1021/es9905290 - es9905290AF3

27. Eco-friendly Solutions (2011). Retrieved from http://www.ecofriendlysolutions.com.au/pages/fuelcosts.asp.

28. NG Australia (2011). Retrieved from http://www.natural-gas.com.au/business/fuelcost.htm.

29. Hi-Chun Park (2010) Towards Cost-reflective Energy Pricing in Ukraine, International Association for Energy Economics,

30. UNECE Gas Centre (January, 2012) *Actual Development of the Ukrainian Gas Industry in 2011*, Working Party on Gas, http://www.unece.org/fileadmin/DAM/energy/se/pp/wpgas/22WPG_Jan2012/25Jan/7_4_Ukr_e.pdf, Visited - August, 2012

31. CNG Fuelling (2011). Retrieved from http://www.cngstations.com/cng-fueling-stations.

32. Zeninskii, A. M. and Nurmukhametova, I. Z. (1971). *Methods for Determining Factors in Growth of Labour Productivity*, in Petroleum Refineries [in Russian], BashNII NP, Ufa.

33. Wikipedia (2011). *Oil Tanker*, Retrieved from http://en.wikipedia.org/wiki/Oil_tanker., Visited - August, 2012

34. ADITRD (2008). Australian Department of Infrastructure, Transport, Regional Development and Local Government, *Freight rates in Australia from 1964–65 to 2007–08*, Information Sheet 28, Nov. 2008, **ISSN** 1440–9593.

35. *Ukraine: Trade and Transit Facilitation Study* (2010) Report , prepared under the Netherlands financed World Bank executed Trust Fund “Ukraine: Support Competitiveness through Capital Budgeting, Public Financial Management and Trade and Transit Facilitation, Kyiv. http://siteresources.worldbank.org/UKRAINEEXTN/Resources/TTF_April2010.pdf, Visited - August, 2012

36. http://www.della-ua.com/cost/local/, Visited - August, 2012

37. Wikipedia, *Druzhba pipeline*, http://en.wikipedia.org/wiki/Druzhba_pipeline, Visited – August, 2012

38. Cornot-Gandolphe, S., et. al. (2003). *The Challenges of Further Cost Reductions for New Supply Options (Pipeline, LNG, GTL)*, 22nd World Gas Conference, 1-5 June 2003, Tokyo, Japan

39. Tariff for Russian gas transit across Ukraine increases to $3.11 in Q2, KyivPost, http://www.kyivpost.com/content/business/tariff-for-russian-gas-transit-across-ukraine-incr-310454.html, Visited - August, 2012

40. NG Vehicles (2011). Retrieved from http://www.ehow.com/about_4568279_natural-gas-vehicles.html#ixzz16vkjzKIc. Visited - August, 2012

41. BP historical data, http://www.bp.com/sectiongenericarticle800.do?categoryId=9037181&contentId=7068643, Visited – August, 2012

42. Row J. et. al. (June, 2002). Life-*Cycle Value Assessment (LCVA) of Fuel Supply Options for Fuel Cell Vehicles in Canada*, Report, Pembina Institute, Canada, Retrieved from http://www.p2pays.org/ref/37/36488.pdf.

43. AFDC (2002). Alternative Fuels Data Centre, *Natural Gas Training and Safety*, U.S. Department of Energy.