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Well-to-wheel assessment for informing transition strategies to low-carbon fuel-vehicles in developing countries dependent on fuel imports: A case-study of road transport in Lebanon

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Title

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Abstract

Road transportation worldwide is undergoing a rapid transition to more sustainable alternative fuel vehicle (AFV) technologies as an effective means of dealing with climate change and related challenges. Several well-to-wheel (WTW) studies have been done in mostly industrialized countries to assess the environmental impacts of these technologies as compared to conventional fuel vehicles, but few studies exist for the developing countries. This study is a WTW case assessment of the energy use, GHG and criteria pollutant emissions and economic costs for conventional and potentially feasible alternative fuel vehicle pathways in Lebanon designed to inform transition strategies over the near, medium and long-terms for the Lebanese case and similar fuel-importing countries with comparable levels of infrastructure development. Results show that electric vehicles are the most beneficial but require a costly charging infrastructure and a clean electricity mix. Plug-in hybrid electric vehicles are more attractive for the medium term, with gasoline or diesel hybrid electric vehicles the most feasible and beneficial technologies in the short-term. A sensitivity analysis showed that natural gas-based vehicles offer the most benefits for high driving mileage, while locally produced biodiesel from waste cooking oil proved to be beneficial if emission controls are enforced.

1. Introduction

The general awareness about the unsustainability of relying on non-renewable energy resources and the serious need to reduce green-house gas (GHG) and other pollutant emissions continues to build up from year to year. The global transportation sector is responsible for a large share of these challenges, which has propelled the transition to cleaner alternative fuel-vehicles (AFV) and dual, or flexible, fuel-vehicles (FFV) as replacements of conventional gasoline and diesel vehicles.

In order to better inform this complex transition involving a variety of upstream fuel-related processes as well as technology and market processes on the vehicle side, the use of lifecycle assessment (LCA) studies is commonly adopted. Well-to-wheel (WTW) analysis is the LCA method used for evaluating the energy and environmental impacts of transport fuels from the well (or where the fuel is obtained) to the vehicle tank (WTT), and then onboard the vehicle from the tank to the wheels (TTW). A comparative analysis is typically done for different fuel pathways and their corresponding vehicle technologies in terms of the total energy consumption and cumulative GHG emissions of each option. This helps to develop country-specific strategies for future vehicle use, including the development of new markets for alternative fuels and vehicles and the planning of necessary infrastructure.

This study consists of a WTW assessment in the country of Lebanon where the road transport system faces serious sustainability challenges [1], but where recent discovery of offshore natural gas (NG) resources has opened the debate in favor of a national strategy to transition to alternative fuels in the energy and transport sectors [2–4]. The transportation sector in Lebanon is currently dominated by gasoline internal combustion engine vehicles (ICEV) which continue to increase at a high rate, from

450,000 vehicles in 1994 to 1,350,000 in 2012 [5], with automotive gasoline consumption seeing an increase of approximately 25% since 2006 [6]. This sector is responsible for almost 40% of total oil consumption and is the second largest contributor to GHG emissions nationally after the power sector, accounting for over 23% of annual emissions in 2012, in addition to a significant share of air-pollutant emissions [7].

In its efforts to deal with this unsustainable reality, Lebanon signed the Paris agreement in April 2016 where it committed to GHG mitigation targets under the Intended Nationally Determined Contribution (INDC) of the United Nations Framework Convention on Climate Change (UNFCCC). The first target represents the country's own contribution of GHG emission reduction of 15% compared to the business-as-usual (BAU) scenario in 2030, and the second offering a more ambitious target of 30% conditional on receiving international support [8]. The latter target involves a number of infrastructure initiatives such as reviving the role of public transport and achieving a share of 20% fuel efficient vehicles by 2030. The expected impacts of these commitments on the current GHG emission trends are illustrated in Figure 1

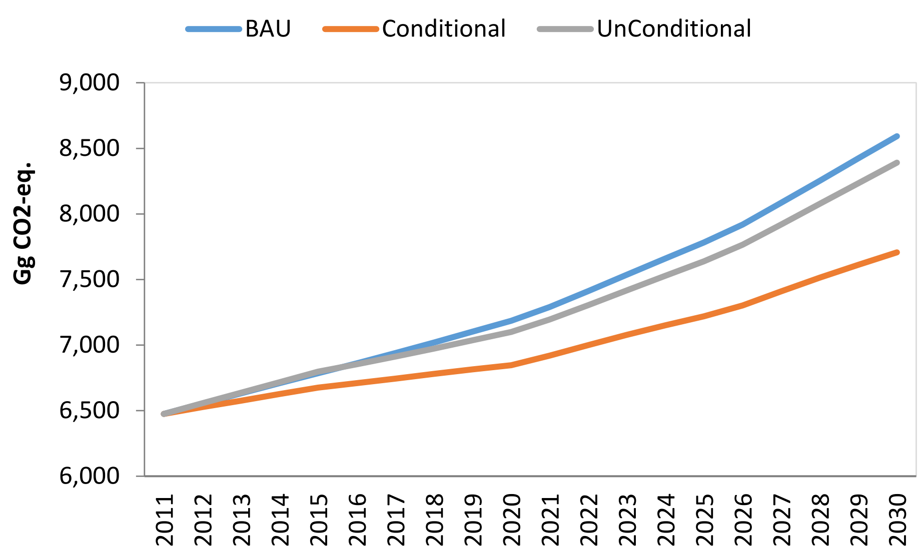

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Figure 1: CO2 trends for the Lebanese transport sector.

Lebanon currently imports 98% of its energy requirements in the form of conventional gasoline and diesel fuels, similar to other neighboring Mediterranean and Middle Eastern countries which heavily rely on petroleum imports, such as Jordan (97%), Cyprus (94%) and Morocco (90%) [9]. Some studies found evidence that energy importing countries have a similar dynamic for energy use and economic growth which is different than for energy exporters [10]. A previous WTW comparative analysis found very similar levels of energy use and GHG emissions when comparable fuel-vehicle pathways in different energy importing countries were evaluated [11]. This means that a WTW assessment in one context can potentially be informative for other comparable contexts. Other studies further found evidence that countries in comparable stages of development can adopt similar energy policies and strategies since the level of a nation's development determines the patterns of its energy consumption [12,13].

Building on the aforementioned findings, this study will attempt to provide a WTW framework for developing countries where infrastructures are typically underdeveloped and related processes are characterized by low efficiencies and lacking environmental controls. The study will define existing and potentially feasible pathways for conventional and alternative fuels in Lebanon, and will evaluate the associated environmental and financial impacts for the defined pathways. The WTW assessment of energy consumption and GHG emissions is done for all activities from the point of import to the point of use of the fuel in the corresponding vehicle technology. Since passenger cars (PC) and light duty vehicles (LDV) constituted 92.3% of the total fleet in 2012 and since these vehicles accounted for nearly 76% of GHG emissions in this sector in 2010 [14], this study will only consider this category of vehicles in the assessment.

Twenty-six fuel-vehicle pathways will be evaluated, eighteen of which are based on imported fuels (gasoline, diesel, natural gas, biofuels and electricity from imported fuel), and six based on potentially feasible local production of biofuels. Specifically, the biofuels considered are gasoline blends of 10% ethanol (E10) and 85% ethanol (E85), and diesel blends of 20% biodiesel (B20). The vehicle technologies which have been considered include the internal combustion engine vehicle (ICEV), hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV20 and PHEV60 reflecting the range of electric drive autonomy of 20km or 60km, respectively), and the electric vehicle (EV) with the appropriate local electricity generation mix over the near (2015-2020), medium (2020-2030) and long terms (2030-2040).

Table 1 lists the fuel-vehicle technologies considered as viable in this context and which will be evaluated in this study using local data and assumptions adapted to the Lebanese case.

Table 1: Applicable fuels and vehicle technologies for the WTW analysis.

Fuel Feedstock Category	Fuels in Use	Vehicle Technology
Oil-based	Gasoline	ICEV, HEV, PHEV
	Diesel	ICEV, HEV, PHEV
Biofuel-based	E10 from import only	ICEV, HEV
	E10 from sugar cane	ICEV, HEV
	E85 from import only	ICEV, HEV
	E85 from sugar cane	ICEV, HEV
	B20 from import only	ICEV, HEV
	B20 from waste cooking oil	ICEV, HEV
Gas-based	LPG (liquefied petroleum gas)	ICEV
	CNG (compressed natural gas) from import only	ICEV
Electricity-based	PP10 (electricity from current resource mix as of 2010)	EV, PHEV
	PP20 (electricity from 2020 resource mix per government policy paper)	EV, PHEV
	PP30 (electricity from 2030 resource mix per government policy paper)	EV, PHEV

Biofuel production from imported sugar cane and locally procured waste cooking oil are included in this study as the most likely production pathways to be feasible in the Lebanese context, and the most promising in terms of energy and GHG reduction for the least infrastructure investment [15–17].

For gas-based fuels, only ICEV vehicle technologies are considered, since no hybrid vehicles are commercially available. The use of liquefied natural gas (LNG) in passenger cars is not yet commercially viable due to technical and economic factors, and therefore this fuel-vehicle option was not considered.

Fuel-cell vehicles (FCV) fueled with hydrogen are also excluded from this study as they are not yet feasible for developing countries over the near and medium terms due to the extensive challenges of providing the hydrogen infrastructure and the still early level of vehicle commercialization [18–21].

The year 2015 is chosen as the base year against which all comparisons will be done, and the base vehicle is the 2015 conventional gasoline ICEV midsize passenger car.

The study will answer the following questions: first, what are the potential fuel-vehicle pathways that can be viable and efficient over the next 25 years for the case of Lebanon and similar fuel-importing countries with developing infrastructure? Second, what are the fuel-vehicle technologies which offer the best environmental-to-cost performance over the near, medium and long terms in this context?

This study is novel in three ways: First, it is the first WTW study on a country in the Middle East region. This is significant since it is important to have representative studies for different regional contexts. Second, it defines a number of possible alternative fuel pathways with clearly delineated system boundaries that make them generically applicable for the case of fuel-importing countries with developing infrastructures. And third, the study provides a comprehensive comparative analysis which covers energy consumption, GHG and pollutant emissions as well as economic costs from the perspective of users, the government and the private sector. This is done for a variety of fuel-vehicle technologies and electricity generation mixes over three future planning horizons, along with a sensitivity analysis over annual mileage driven and fuel price.

The rest of this paper is structured as follows: Section 2 presents an overview of the recent literature on well-to-wheels studies. Section 3 defines the existing and potentially feasible pathways, including all industrial and commercial activities and processes for conventional and alternative fuels as adapted to the case of Lebanon. These pathways are then modeled in the software GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) developed by Argonne National Laboratory [22] in order to perform the WTW assessment of the emissions and energy use of each fuel pathway for the selected fuel-vehicle technologies. The results are reported in Section 4 in terms of CO2 emissions versus energy consumption for each fuel-vehicle technology. An economic cost-benefit analysis is presented in Section 5 where these technologies are ranked by their environmental-to-cost performance over the lifetime use of each vehicle type. A sensitivity analysis is used to evaluate the impact of the annual mileage driven and price of fuel on the performance of different vehicle technologies. A discussion of the final results along with concluding remarks and proposed directions for future research are reported in Section 6.

2. Review of the Literature

There have been numerous WTW studies published over the past decade in the academic literature, as will be reviewed here, and in publically available professional reports [23–25]. These studies have covered a multitude of fuel-vehicle pathways in different geographical regions for a variety of vehicle characteristics and driving conditions.

Some publications provided a historical overview of WTW studies [26–28] with a summary of their objectives or the methods used, and a reporting of some of the main results. There have only been a few detailed but now dated review papers of WTW studies which compared results from major developing countries [29,30]. However, there has not been a systematic and comprehensive synthesis of the important insights and the similarities and differences in results between studies in the recent literature, which we present in this section in a summary table and the ensuing discussion.

Several WTW studies have been surveyed and a wide sample of the most relevant and well-cited studies since 2005 were selected to identify the focus of each study, the modeling tools used in performing the WTW analysis, as well as the main results and any potentially important insights for this work, as presented in Table 2.

Table 2: Summary overview of the recent literature on well-to-wheel studies.

Reference	Focus	WTW Tools	Main Results	Relevant Insights
Orsi, Muratori et. al (2016) [26]	Comparing the WTW energy use, CO2 emissions and economic costs of passenger vehicles in Brazil, China, France, Italy and USA	GREET for WTT, AVL Cruise and proprietary models for TTW	CNG vehicles have the lowest energy and cost, but high emissions. HEVs offer the best performance-to-cost ratio, followed by PHEVs	Liquid fuel vehicles show similar energy use and emissions across countries. Only performance of EVs varies due to different national electricity mixes
Rahman, Canter and Kumar (2015) [31]	Assessing GHG emissions of transport fuels from 5 North American conventional crudes	FUNNEL-GHG-CCO	The biggest portion of WTW GHG emissions comes from combustion of transport fuels in engines (TTW)	The transportation of crude oil and refined fuel contributes less than 2% of the total WTW GHG emissions
Karimi, Ansari et. al (2014) [32]	Assessing EVs energy cost, load on grid and WTW emissions	Own calculations	Introducing EVs without adding renewable energy resources to the electricity mix may increase emissions and energy costs	The degree of improvement in WTW energy costs and emissions depends on the type and extent of renewable energy in the mix
Choi and Song (2014) [11]	Assessing WTW energy use and GHG emissions for CNG city bus in Korea with comparisons to Japan and USA	GREET	Combustion of natural gas in the vehicle is responsible for around 3/4th of the total WTW energy use and 2/3rd of the total WTW GHG emissions	Energy use and GHG emissions for natural gas importing countries are higher than for fuel producers due to the additional processes needed to transform and distribute the fuel
Yazdanie, Noembrini et. al (2014) [33]	Comparing energy use and GHG emissions from different drivetrain and production pathways in Switzerland	Own calculations and other studies	EVs and PHEVs are preferred, followed by AFV's powered by ICE drivetrains	Electricity mix is critical for deciding optimal drivetrain strategy
Zhou, Ou and Zhang (2013) [34]	Investigating the development of EVs and PHEVs in China based on WTW energy use and GHG emissions	GREET	EVs can reduce energy use and GHG emissions by 45% - 60% in the medium and long-terms, but high purchase price is a barrier to adoption	Develop EVs in those regions with clean power. Promote biofuel and other alternative fuel-vehicles in regions with a dirty electricity mix
Elgowaini, Rousseau et. al (2013) [35]	Comparing WTW energy use, GHG emissions and costs of advanced LDVs for 2035 and 2050 scenarios in US, Asia and non-OECD Americas	GREET, Autonomie	Ownership costs of advanced powertrains likely to converge by 2035. Robust infrastructure is needed before EVs, FCEVs and NG vehicles are adopted	Deploy different fuel-vehicles types for different regions. Use PHEVs in regions with clean electricity mix, and biofuel vehicles in regions with abundant biomass

Shen, Han et. al (2012) [36]	Comparing WTW energy use and GHG emissions of passenger vehicles in China	GREET	BEVs offer highest reductions of energy use and GHG emissions, even on current electricity mix based mostly on coal, followed closely by HEVs and PHEVs	Energy use and emissions of biofuel vehicles are similar or worse than gasoline due to inefficient upstream processes in China
van Vliet, Kruithof et. al (2010) [37]	Comparing energy use, GHG emissions, and ownership cost for 4 fuel-vehicle types in the Netherlands	Own calculations	PHEVs are cost competitive when driving large distances on electricity, and offer lowest GHG emission on Dutch electricity mix	The current generation of hybrid cars cannot compete strictly on cost with regular diesel or petrol cars without additional support
Torchio and Santarelli (2010) [28]	Developing an index for fuel-vehicle options in Europe based on WTW cost of energy and emissions	Own calculations	Natural gas-based fuels are very promising, while conventional fueled hybrids are an effective option already available	The high energy costs and GHG external costs of biofuel-vehicles and EVs means they cannot compete with diesel and gasoline
Huo, Wu and Wang (2009) [38]	Comparing total versus urban WTW emissions for 5 criteria pollutants from 9 fuel-vehicle types in US driving conditions	GREET, Mobile and EMFAC	HEVs reduce total and urban emissions. E85 FFVs increase total emissions but reduce urban emissions	The location and source of pollutant emissions have an equally important impact as the total amount of those emissions
Ou, Xiliang et. al (2009) [39]	Comparing WTW energy use and GHG emissions of six biofuel pathways in China	GREET	Only 3 biofuels (cassava ethanol, jatropha and used cooking oil biodiesel) offer energy and GHG savings over conventional fuels	Dirty electricity mix, inefficient production processes and polluting agricultural practices are main contributors to energy use and GHG
Shen, Zhang and Han (2006) [40]	Developing strategy for passenger AFVs in China based on WTW energy use and GHG emissions	GREET	Conventional fuel HEV is the best and most feasible technology for the near-term in China, followed by CNG and Diesel vehicles	Ethanol-blended gasoline, Methanol, Dimethyl Ether and Fischer-Tropsch Diesel offer no energy or emissions savings over petroleum fuels
Williamson and Emadi (2005) [41]	Comparing WTW energy use and GHG emissions of HEV and FCV technologies	GREET and ADVISOR	HEVs are the most viable technology for the next 10-20 years, and 1.5-2 times more energy efficient than FCVs	FCV technology is far from commercial readiness and requires high cost distribution infrastructure
Hekkert, Hendriks et. al (2005) [27]	Developing transition strategies to natural gas for	Own calculations	Diesel-HEVs are preferred for short-term, with biofuel-HEVs	LNG/CNG ICEVs are good transition technologies over the medium term

	passenger cars based on WTW energy use and GHG emissions	expected to maintain HEV dominance over medium term	only since they require extensive infrastructure, and EVs for long term

The survey of the literature on WTW analysis confirms that while most industrialized countries have been well covered, no studies have been done on countries in the Middle East region. One comparative study [11] involving Korea and Japan, which share similar energy import needs and infrastructures, found that WTT values for energy use and GHG emissions were "very close to each other". This is an indication that while WTW results are country-specific and even region-specific, they can however serve to inform energy and emissions-related strategies in other similar contexts. However, no framework of fuel-vehicle pathways has been proposed yet in the literature for WTW studies in countries sharing similar energy and infrastructure characteristics.

A majority of studies used GREET, which shows that it is currently one of most widely adopted software tools for WTW analysis. The vast majority of studies have modeled both energy use and GHG emissions, but only a small minority have considered pollutant emissions [19,22]. It was found that while AFVs can generally reduce the overall energy use and emissions over conventional fuels, they do however displace the location of emissions, such as from urban to rural areas for electric and biofuel vehicles since power plants are typically located outside cities and biomass is grown and transformed in the countryside [38].

Along those lines, a number of studies agreed that the national electricity mix is the most influential factor in determining the performance and viability of EVs [26,32–34,36,39,43]. In the case of China where ambitious pilot programs for launching electrified vehicles were started in 2009, some studies have advocated that it would be more effective to deploy EVs in the most polluted cities first but only if these cities have clean power. For regions powered by coal and heavy fuel oil (HFO), it would be more beneficial to focus on NG-based and biofuel vehicles, especially where land for biomass cultivation is abundant [34,35].

Another related conclusion is that biofuel-vehicles will not reduce energy and GHG emissions if agricultural practices are polluting, as in the excessive use of chemical pesticides, or if upstream production processes are inefficient [36,39].

Few of the studies considered economic costs [26,28,32,35,37], and of those none considered the costs of transitioning to AFVs on the government or the private sector, in terms of infrastructure costs or subsidy costs for example. Economics were considered from the user's perspective, consisting mostly of vehicle ownership costs, with one study including the cost of emissions on society [28]. It was found that biofuel-vehicles are the least cost-competitive, and that EVs are at a disadvantage from a cost perspective due to the high purchase price of the vehicle [34,37]. Natural-gas based vehicles can serve as a transition strategy towards electric-based vehicles, but not in the short-term since they require extensive infrastructure first [27,35].

One of the main conclusions that the majority of studies agreed on is that HEV's are the most efficient and feasible technology in the short-term and likely over the medium term, even outperforming FCVs in terms of TTW efficiency and WTW GHG emissions [41], as well as cost [26,28] and commercial readiness. These vehicles require no new infrastructure, and their energy and emissions performance is consistently near the top, right behind electric vehicles powered by clean electricity [33,36].

Overall, we identified the following main gaps and limitations in the recent WTW literature:

- There is no comprehensive WTW analysis which includes energy use, GHG emissions, criteria pollutants and economic costs together in one study.
- Economic costs have only been accounted for from the user's perspective, with no consideration of costs on the government or private sector.
- There are no published WTW studies on countries in the Middle East region, or studies focusing on developing countries which are typically characterized by overdependence on fuel imports and limited energy infrastructure.
- There is no defined set of clearly delineated fuel pathways which can serve as a template for countries sharing similar energy needs and infrastructure characteristics.

Based on the above synthesis of the insights and gaps in the literature, this study will propose a framework of fuel-vehicle pathways appropriate for developing countries having limited infrastructure capabilities and which rely on fuel imports for their energy needs. While the results of WTW studies are very geographically dependent, such a framework can still provide these countries with general guidance about the environmental, energy and cost performance of fuel-vehicle pathways for this context. This is because in the fuel-importing case there are no major processes for fuel production and transformation upstream, and when having an underdeveloped infrastructure the remaining processes will tend to have similarly low efficiencies and dirty electricity mix [36,39]. In addition, the contribution of fuel transportation processes to energy consumption and GHG emissions is very small, such that the impact of having different transport distances for each country on the WTW results will tend to be minimal [31].

In summary, this study proposes a WTW energy use and GHG emissions comparison, adding criteria pollutants and a detailed economic analysis under a comprehensive framework of fuel-vehicle pathways for fuel-importing countries with developing infrastructure. This will be accomplished through a case-study of the transport sector in Lebanon based on local data and assumptions. The results of this study will be compared with those of the surveyed literature in order to derive the appropriate conclusions and recommendations.

3. Methodology

In order to assess the energy consumption and environmental impacts of fuel and vehicle systems currently existing, and those potentially applicable in Lebanon, the different fuel-vehicle pathways were modeled and analyzed using the commonly adopted well-to-wheels (WTW) approach. The methodology for modeling and analyzing the different pathways is discussed in this section, and the modeling results are presented in section 4.

3.1. Modeling methodology and assumptions

A well-to-wheels (WTW) assessment of the environmental impacts of different fuel-vehicle options consists of two components: a well-to-tank (WTT) assessment of the energy use and emissions associated with fuel production and distribution activities; and, a tank-to-wheels (TTW) assessment of the energy use and emissions associated with vehicle operation activities. However, for the case of fuel importing countries, such as Lebanon which reports regularly its national emissions and energy use to the Conference of Parties of the UNFCCC, the WTT assessment is carried out based on the revised 1996 IPCC guidelines for national greenhouse gas inventories, where fuels consumed by international transportation (i.e. marine and aviation) for fuel delivery to these countries are excluded from national total emissions and energy use; consequently, emissions and fuel use are only reported from the country entry point (e.g. ports) to their final use in vehicles.

WTW calculations were based on the most widely adopted fuel lifecycle model for WTW studies, namely the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model developed by Argonne National Laboratory, specifically adapted to the case of Lebanon. The inputs to the WTW analysis are the process data in terms of energy consumption and emissions for all applicable processes under each fuel-vehicle pathway, including fuel or feedstock storage, transportation, processing and production, and distribution at the pump. These processes can be classified as either stationary or transportation processes. For stationary processes, the principal data consist of process efficiencies. For transportation processes, the principal data consist of their energy intensities. These required data were specifically developed for the case of Lebanon based on data collection obtained from the concerned local stakeholders such as concerned government ministries, oil importing companies and governmental oil authorities. Results relative to each of the local stationary and transportation processes are reported on its corresponding fuel pathway as represented in figures 2 to 8.

Since the current vehicle fleet in Lebanon is made up of almost exclusively gasoline-ICEV vehicles, the 2015 gasoline ICEV is chosen as the base vehicle against which all other alternative fuel-vehicle types are compared.

Table 3 presents a summary of the TTW energy consumption figures for the considered fuel-vehicle technologies. These values were determined from simulation on the software ADVISOR [44] of vehicle performance under local driving conditions [45]. They are used in the GREET modeling along with the WTT figures for the corresponding fuel-vehicle pathways discussed in the next section in order to determine the total WTW energy use and exhaust emissions.

Table 3: Evaluated vehicle technologies energy consumption.

Technology	Fuel Consumption (lge/100km)	Electricity Consumption (Wh/km)	Electric Drive Share
Gasoline/E10/E85 ICEV	8.6/ 8.6/ 8.6	-	-
Gasoline/E10/E85 HEV	6.2/ 6.2/ 6.2	-	0%
Diesel/B20 ICEV	7.2/ 7.2	-	-
Diesel/B20 HEV	5.1/ 5.1	-	0%
CNG/LPG ICEV	9.6/ 9.1	-	-
Gasoline PHEV20/60	6.2/ 6.2	203.7/206.5	28%/ 61%
Diesel PHEV20/60	5.1/ 5.1	206.1/210.2	28%/ 61%
EV PP10/ PP20/ PP30	-	183.0 / 168.1/ 132.9	100%

Note that for all fuel feedstock including imported feedstock, the energy and emission impacts of upstream processing at the source (outside Lebanon) and during transportation by sea to the Lebanese market are not considered in the WTW analysis, as they do not count towards the local impacts.

3.2. Modeling of existing pathways

The existing fuel pathways in Lebanon are for gasoline, diesel and liquefied petroleum gas. All fuel types are imported by sea into the country and stored at various locations along the coastline, as summarized in Table 4 below.

Table 4: Gasoline, diesel and LPG fuel storage locations and terminal capacities in Lebanon.
Source: Association of Petroleum Importing Companies (APIC), 2015

Region	Gasoline and Diesel Storage Location(s)	Gasoline Terminal Capacity (liters)	LPG Storage Location(s)	LPG Terminal Capacity (m^3)
Beirut	Karantina	69,385,993	N/A	--
Mount Lebanon	Dora, Bauchrieh, Antelias	188,424,304	Nahr El Mot, Dora	33,870
North	Amchit, Anfeh, Beddawi	16,648,580	Tripoli	3,313
South	Jiyyeh	50,640,390	Zahrani - Jiyyeh	7,485
Other	Unspecified locations	105,557,164	N/A	--

The annual import of gasoline typically ranges between 1.8 and 2.0 million tons in total, all of which is consumed in the transportation sector. The 2014 annual import of diesel fuel amounted to 1.45 million tons in total, of which only 20% is consumed in the transportation sector (primarily trucks and buses, with some passenger cars still illegally operating on diesel). The annual import of LPG amounted to 220,000 tons in 2015, with main uses in heating, cooking, and illegal retrofitting in transport. The regional spread of petrol stations in Lebanon is summarized in Table 5.

Table 5: Geographical spread of petrol stations by region in Lebanon.
Source: Association of Petroleum Importing Companies (APIC), 2015

Region	Number of Stations	% of Total	% of gasoline distribution to stations
Beirut	108	3.5	65
Mount Lebanon	1,185	38.9	
North	603	19.8	12.5
South (including Nabatieh)	568 (233)	18.6	10
Bekaa (including Baalbeck-Hirmel)	586 (241)	19.2	12.5

Based on the above and other relevant stakeholder data, the existing pathways for gasoline, diesel and LPG, are represented in Figure 2.

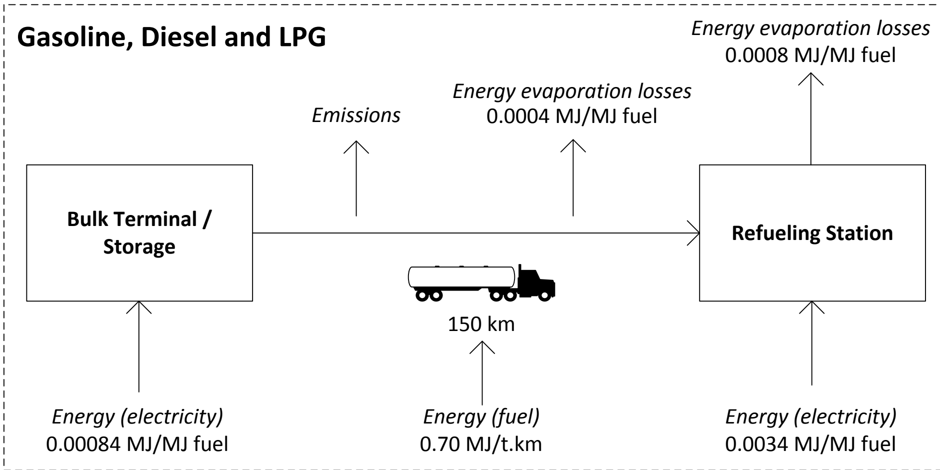

Figure 2: Gasoline, diesel and LPG pathways in Lebanon.

The figure represents the main processes of storing, transporting and dispensing the corresponding fuels. The fuel storage process does not produce any notable emissions or losses; however, it consumes energy to power fuel pumps and other loading devices, and this data is used in the GREET model as the amount of energy (MJ) needed to load/unload 1 MJ of the corresponding fuel. The transportation process is done by truck (over an average distance of 150 km as per analysis of the stakeholder data), which also consumes energy and produces various emissions and losses, expressed as MJ per 1 ton of fuel transported over 1 km. Finally, and similar to the storage process, the refueling process at the station consumes energy but in this case there are evaporation losses due to various leaks and inefficiencies at the pump.

3.3. Modeling of potential pathways

The potential fuel pathways for alternative fuels in Lebanon (natural gas, electricity and biofuels) were modeled using assumptions developed with the concerned stakeholders.

3.3.1. Natural gas pathways

The proposed pathways for natural gas include the import and distribution of liquefied natural gas (LNG) and compressed natural gas (CNG) to refueling stations, and to power plants for electric recharging stations.

Figure 3 presents a potentially feasible pathway for LNG which would be distributed by truck from the import terminal on the coast to L-CNG refueling stations in the inland regions such as the Bekaa and Nabatieh regions where a pipeline connection would not be feasible due to cost and land use considerations.

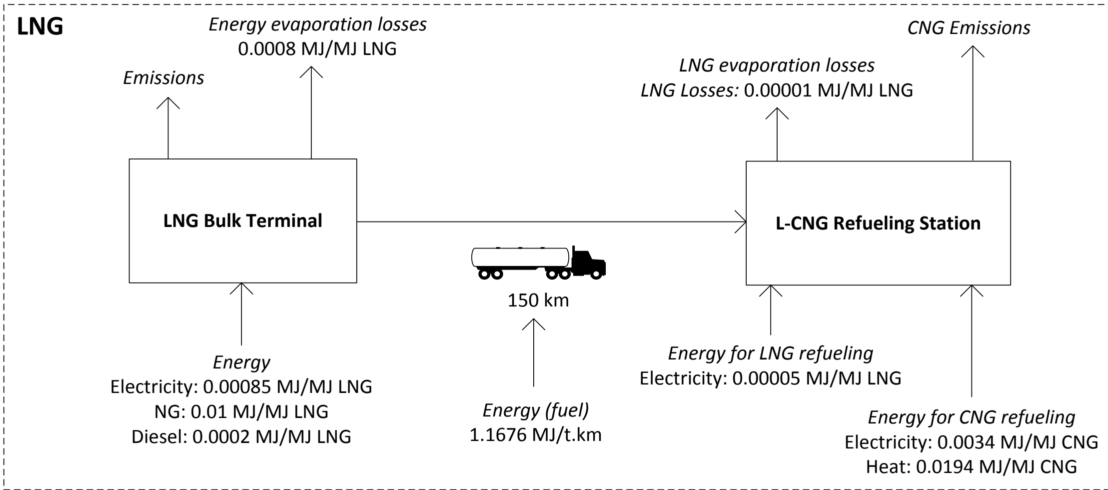

Figure 3: Potential pathway for liquefied natural gas (LNG) in Lebanon.

Figure 4 presents a potentially feasible pathway for CNG, which depends on importing LNG and processing it in the off-shore floating, storage and regasification unit (FSRU), proposed to be located in the Beddawi region, and transporting it in its gaseous form by high pressure pipeline to existing petrol stations which can be retrofitted to dispense CNG to vehicles.

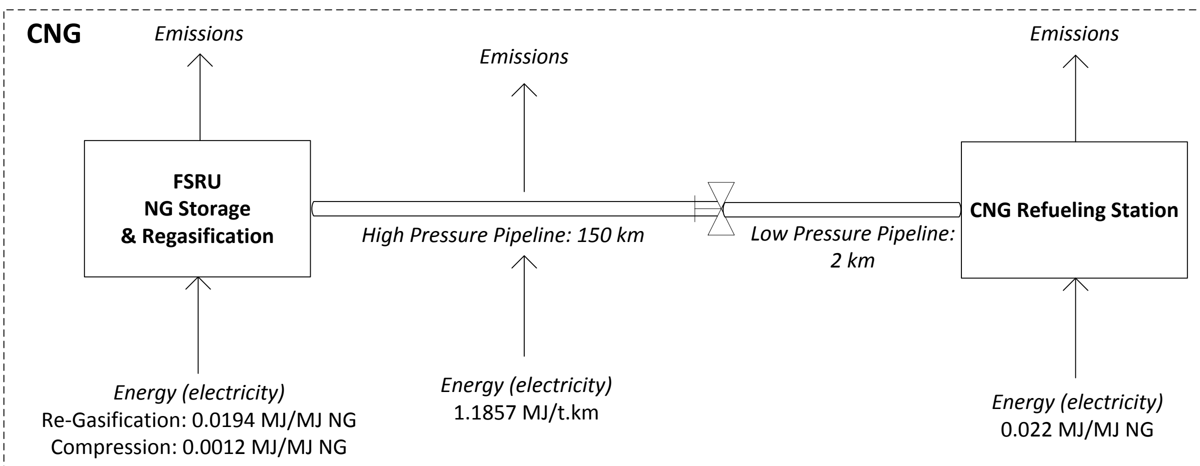

Figure 4: Potential pathway for compressed natural gas (CNG) in Lebanon.

The pipeline would run along the coast from Beddawi to the south through Beirut in order to connect the majority of power plants in the country. Local connections to stations must be through low pressure pipelines off of the main high pressure line, and these are expected to be a short distance away from the main pipeline (2km on average) since the majority of refueling stations are located in Beirut and Mount Lebanon, as noted in Table 5.

Figure 5 presents a potentially feasible pathway for natural gas from the FRSU to electrified vehicle recharging stations, which consists of importing LNG and processing it in the FSRU for transportation to power plants in order to generate electricity, followed by distribution through power lines to electric charging units which are considered to produce negligible emissions.

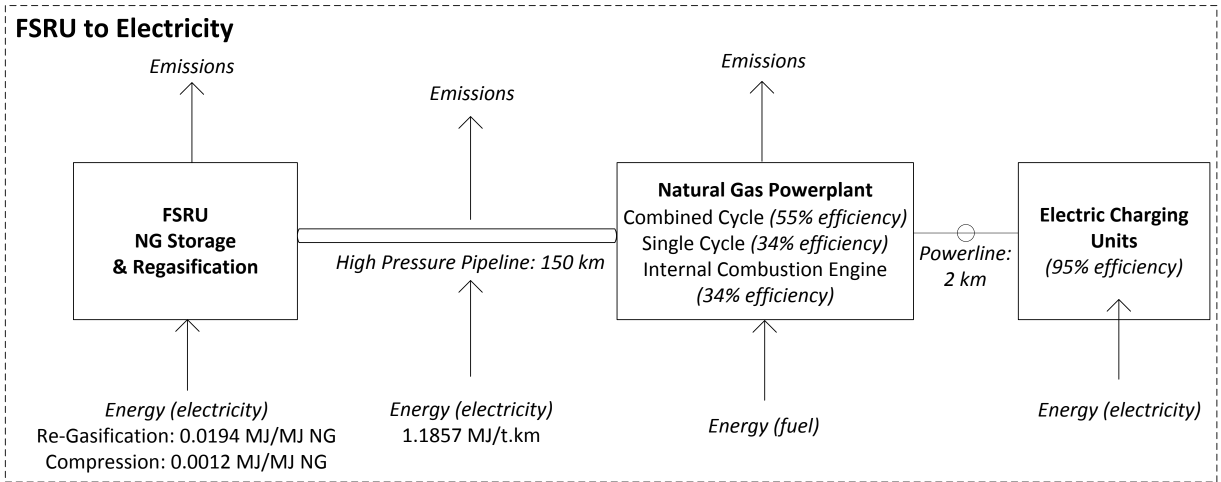

Figure 5: Potential natural gas to electricity pathway in Lebanon.

3.3.2. Ethanol pathway

The proposed pathway for ethanol biofuel is presented in Figure 6. The process starts with the import of feedstock, where Brazilian sugar cane is chosen as one of the most attractive due to the abundance of supply, relative ease of processing at market, and the relatively lower emissions from growing the crop at the source. This is true for both direct (pollutant) and indirect (land-use change, impact on the soil) emissions [15]. Sugar cane is transported by shipment truck for processing (fermentation and distillation), and the resultant ethanol liquid fuel is transported by tanker truck for blending with gasoline into E10 and E85 biofuels. These final products are finally transported by tanker truck to refueling stations. Note that electricity to power the processing plant is not considered in our energy calculations due to lack of data.

The above pathway can be simplified to directly import E10 and E85 biofuels for direct distribution to refueling stations (similar to the existing gasoline pathway); this possibility is also considered in the environmental modeling and cost-benefit analysis. The proposed pathway for imported E10 and E85 would be identical to the existing pathway for gasoline, diesel and LPG.

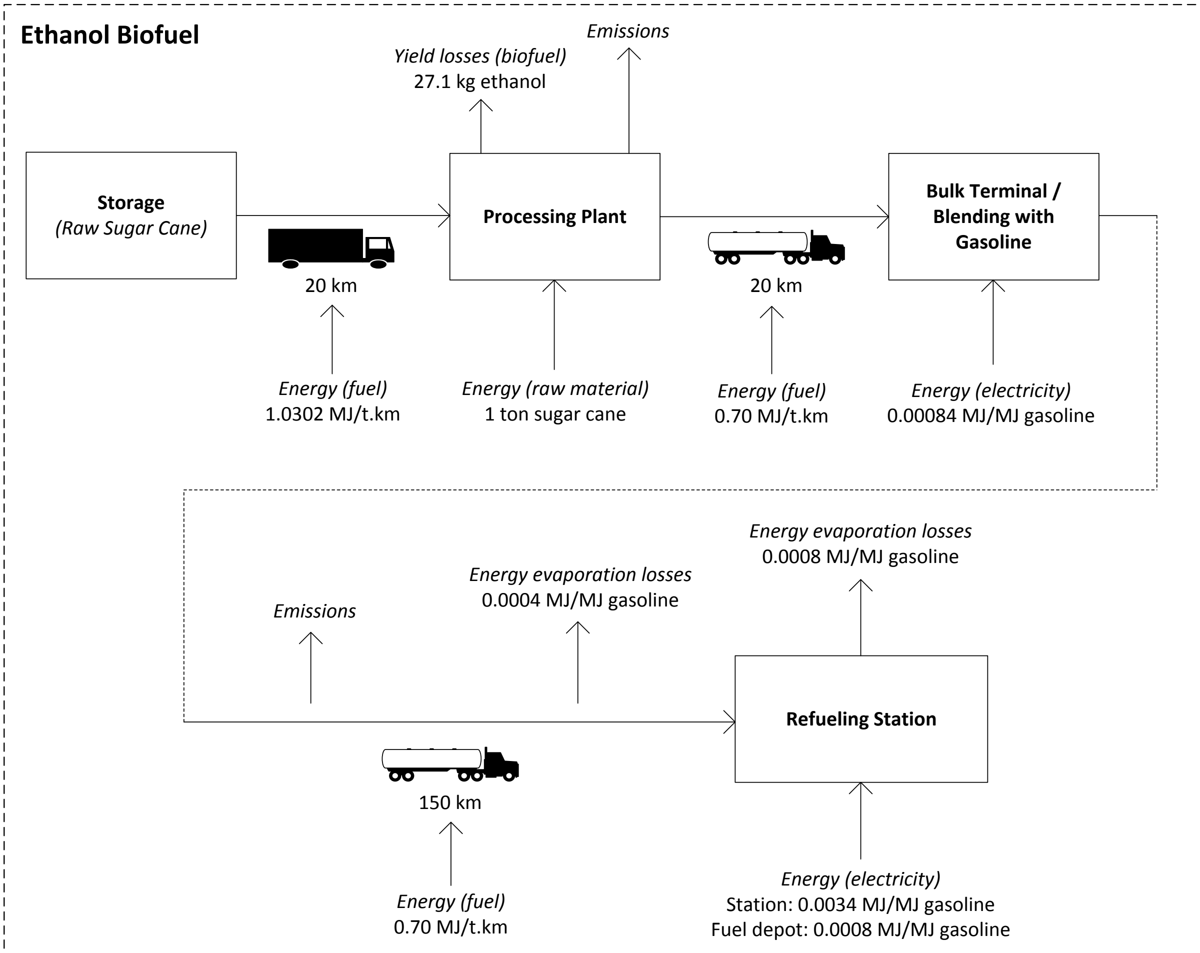

Figure 6: Potential ethanol biofuel pathway in Lebanon.

3.3.3. Biodiesel pathway

The proposed pathway for biodiesel fuel is presented in Figure 7. Similar to Ethanol, feedstock can be imported for processing at market; however, in the case of Lebanon and since biodiesel production from waste-cooking oil already exists, this possibility is selected for modeling instead. Processing of waste cooking oil consists of cleaning, refining and esterification, before transportation for blending and finally to the refueling stations as B20 and lower blends.

Note that the above pathway can be simplified to directly import B20 and lower biodiesel blends for direct distribution to refueling stations (similar to the existing diesel pathway); this possibility will also be considered in the environmental modeling and cost-benefit analysis.

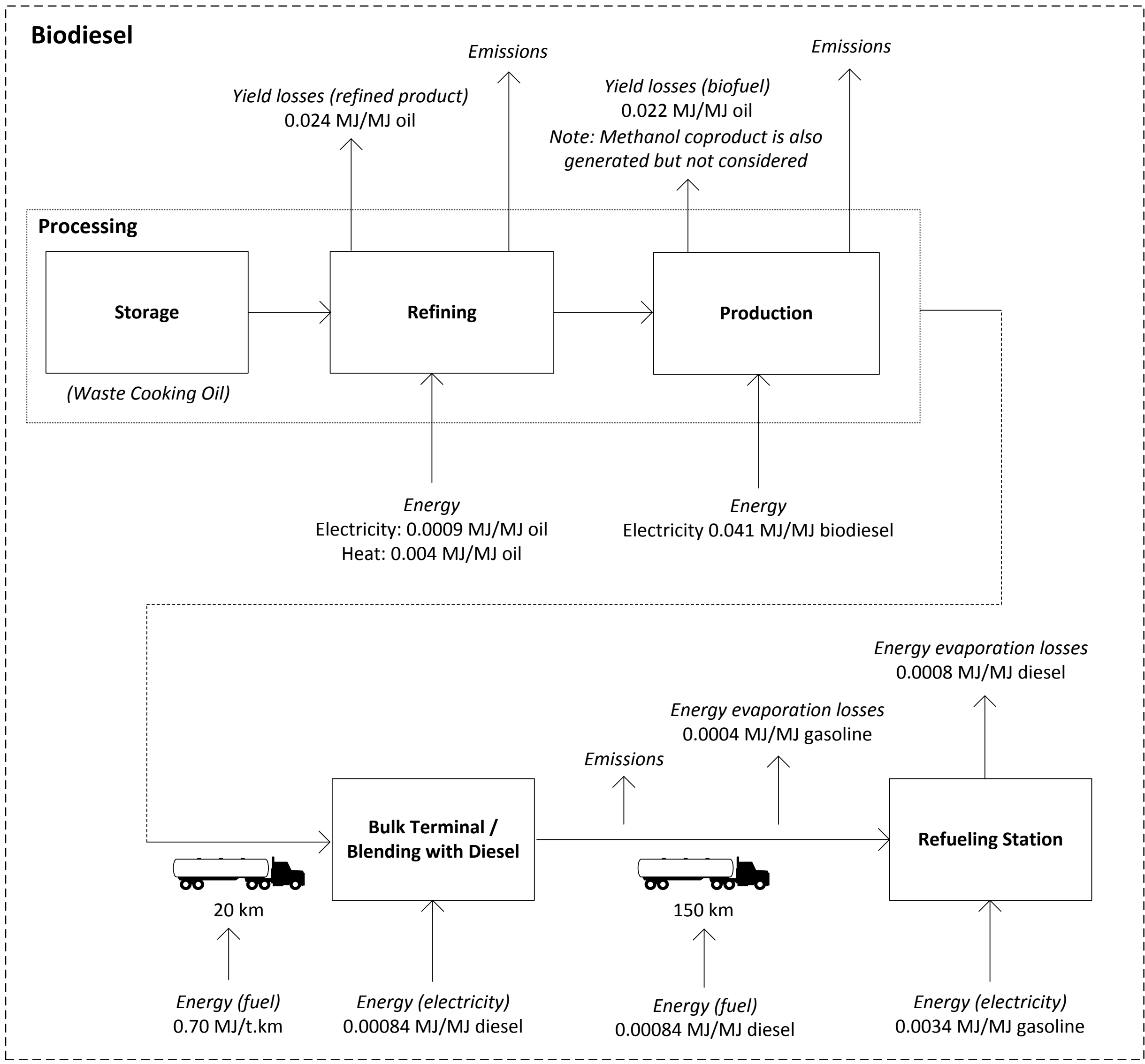

Figure 7: Potential biodiesel fuel pathway in Lebanon.

3.3.4. Electricity pathway

The proposed pathway for electricity as a fuel is presented in Figure 8.

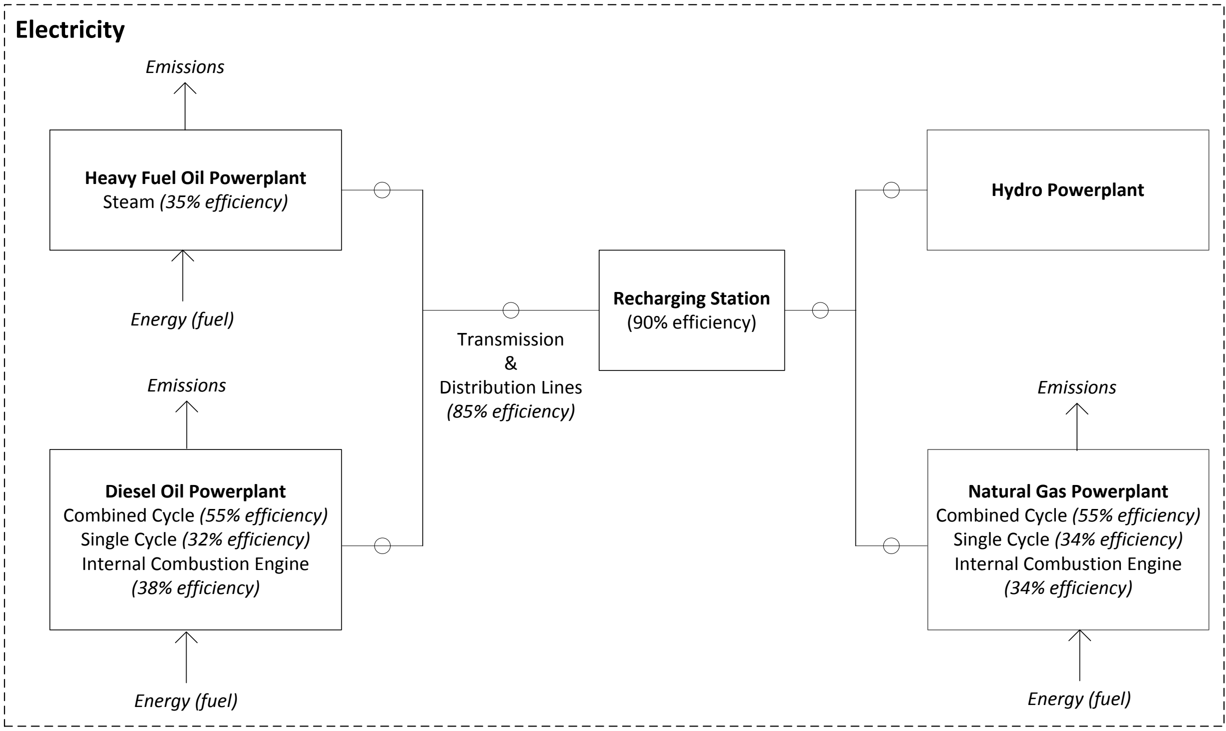

Figure 8: Electricity pathways in Lebanon.

The figure includes the existing pathways using the current power plant infrastructure and fuel resource mix, which are divided as 31.3% HFO, 64% diesel oil (DO) and 4.7% renewable (hydroelectric), as per the 2010 policy paper of the Lebanese Ministry of Energy and Water Resources (MOEW). A different power generation mix for future scenarios in 2020 and 2030 were considered according to forecasts from the same source, as illustrated in figure 9. Future renewable energy technologies are expected to include hydroelectric, photovoltaic and wind.

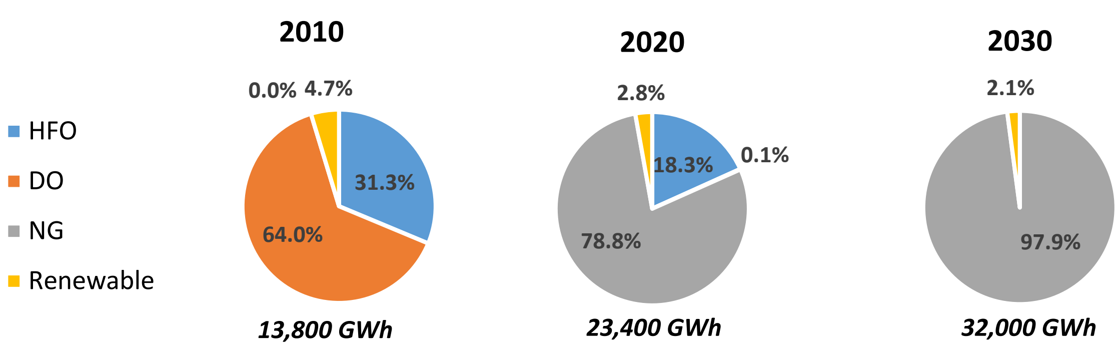

Figure 9: Electricity mix assumptions.

4. Well-to-Wheel results and analysis by pathway

A WTW analysis was done for each of the fuel pathways and corresponding vehicle technologies described in section 3. Results for WTW emissions of air pollutants and greenhouse gases as well as energy consumption are discussed next. Since CH4 and N2O emissions are almost negligible compared with those of CO2, the discussion of GHG emissions will be restricted to the levels of CO2 only.

4.1 Pollutant emissions results

The six criteria air pollutants were examined, namely volatile organic compounds (VOC), nitrogen oxide (NOx), sulfur oxides (SOx), particulate matter with diameters of 10 micrometers or less (PM10), and 2.5 micrometers or less (PM2.5), and carbon monoxide (CO). Pollutant emission results are shown in Figure 10 for representative fuel-vehicles from each technology type.

The reported emission levels are compared to applicable emission standards to determine if any of the results are in violation of the allowed thresholds. U.S. National Ambient Air Quality Standards (NAAQS) for light duty low emitting vehicles (LEV-LDV) have been adopted for VOC (25.48 g/100km), CO (211.27 g/100km) and NOx (12.43 g/100km) since no local standards are available for Lebanon. No vehicle emission standards are available for PM and SOx, however a threshold of 5.0 g/100km for PM10 is used as per California emission standards for LEV technology.

It is important to note that the standards used are only for vehicle emissions (i.e. the TTW portion only), while the reported emissions are for the entire WTW assessment for each fuel-vehicle technology, which includes the emissions of the WTT portion from upstream processes. In this respect, the comparison of the WTW numbers against the vehicle emission standards is a very conservative assessment of the polluting performance of each technology.

Results show that all fuel-vehicle technologies are compliant for VOC emissions. EV's are the lowest polluters (<5 g/100km), with equivalent performance by HEV's and PHEV's for all fuel types (< 10 g/100km).

The picture for CO emissions is similar to the one for VOC, with EVs showing very low CO levels followed by diesel and biodiesel vehicles well below the allowable standard. It is important to keep in mind however that the performance of diesel-based vehicles for CO and other pollutants is contingent on the mandated use and regular maintenance of on-board emission control systems (e.g. the diesel particulate filter DPF), as well as the use of low-sulfur fuels and the ban of unauthorized vehicle retrofitting. In the case of Lebanon and the context of similar developing countries, this typically requires enacting new laws and regulations along with stringent enforcement in the field.

Gas-based fuels have much higher CO emissions, primarily due to upstream WTT processes, but remain below the threshold. Ethanol-based vehicles are close to the standard, with locally converted E85 exceeding the standard due to the significant contribution of upstream WTT processes. Slightly exceeding the standard for CO are gasoline-HEVs and newer model gasoline-ICEVs, which is characteristic of the global performance for these technologies.

The picture for NOx is different than for the previous two pollutants, as HEVs and ICEVs become the least polluting vehicle technologies for almost all fuels, especially imported biofuels, diesel and gasoline. Only locally converted E85 biofuel exceeds the standard, which is again due to the contribution of emissions from upstream WTT processes. In addition, EV's and PHEV's become the least performing technologies, with most being in violation of the standard due to the WTT emissions.

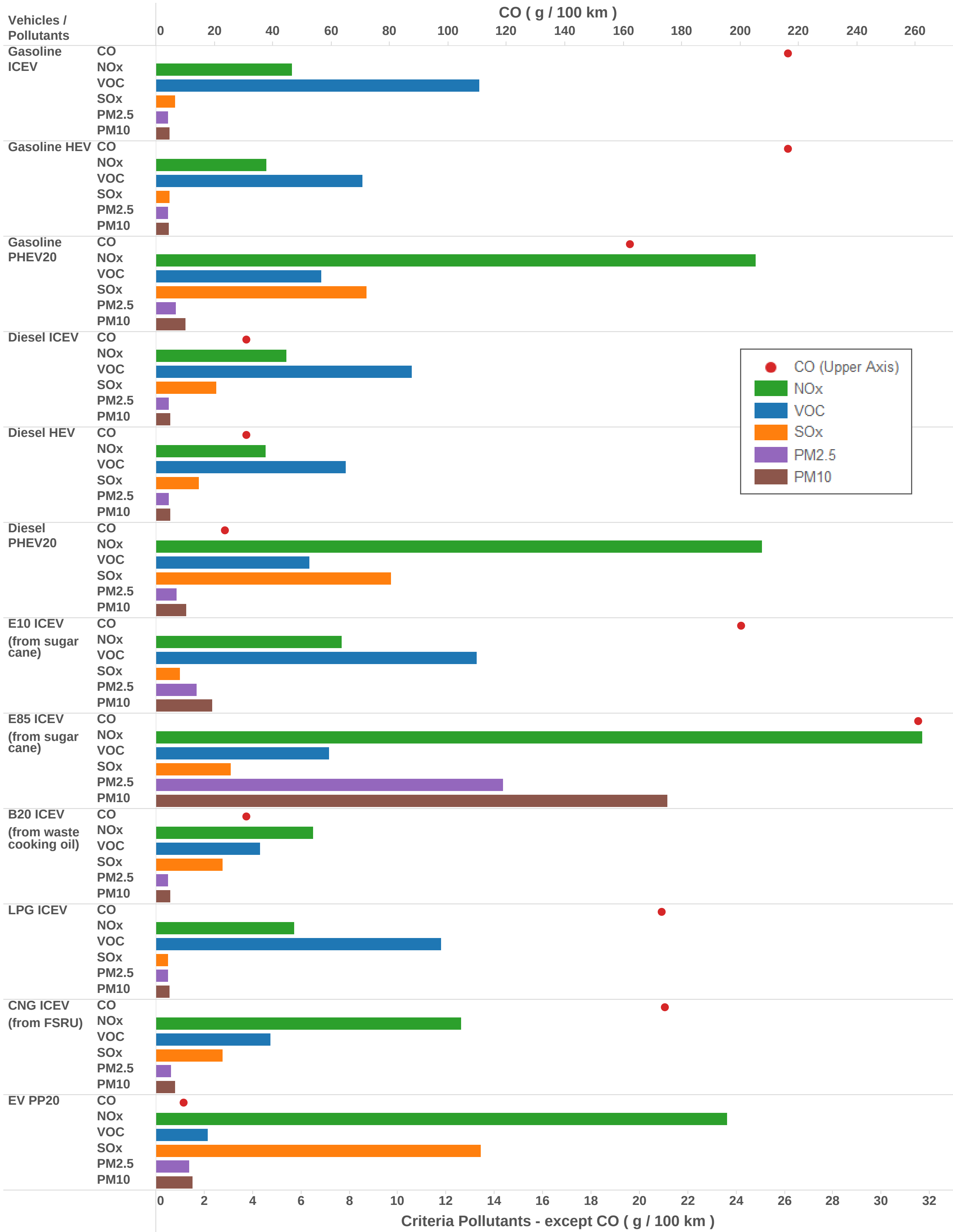

Figure 10: Well-to-wheel pollutant emissions by fuel-vehicle technology.

The results for PM10 show that the vast majority of fuel-vehicle technologies are well within the standard, with the only concern coming again from the WTT emissions for locally converted E85. The same picture is observed for PM2.5 which, despite the absence of a standard, shows a similar pattern.

Finally, for SOx emissions where no standard for vehicle emissions is available, the assessment results show that emissions are very low for all fuel-vehicle technologies, with the exception of EV's and PHEV's under all but the 2030 clean resource mix. This demonstrates again that the high emission levels are primarily due to the contribution from the WTT emissions.

4.2. WTW results for energy use and CO2 emissions

Since the WTW levels of pollutant emissions did not demonstrate any significant exceedances beyond the TTW standards that would force the elimination of particular categories of fuel-vehicle technologies, the down-selection of the most beneficial technologies was done on the basis of energy use-to-CO2 emissions, shown in Figure 11, where all fuel-vehicle technologies are compared against the 2015 model gasoline ICEV technology.

Figure 11: CO2 emissions versus energy use savings of the assessed fuel-vehicle technologies.

Note that E85-based vehicles (with ethanol produced from sugar cane) are not included in the figure due to their excessively high emissions-to-energy figures.

Fuel-vehicle technologies with the lowest energy use-to-CO2 emissions are those in the upper right quadrant of Figure 11, with the best performing being the EV under the 2030 clean energy resource mix. This result is in general agreement with findings in other studies [33,34,36,46].

Electrified hybrids are the next preferred technologies, namely PHEVs and HEVs. Compared to the 2015 gasoline ICEV baseline vehicle and under the current resource mix, the diesel-PHEV20 has the lowest WTW energy use (192.9 MJ/100km), on par with the gasoline-HEV (196.6 MJ/100km), but more energy consuming than the diesel-HEV (163.8 MJ/100km). This is due to the low efficiency of the WTT power generation in Lebanon which currently relies on a dirty resource mix. However, the 2020 and 2030 future scenarios show significant improvements in energy use for all electricity-based vehicles. In the 2030 scenario, the EV becomes the absolute lowest energy consuming vehicle compared with all other fuel-vehicle technologies.

At similar performance levels of diesel and gasoline HEVs are the imported biofuel-HEVs, namely imported B20 and E10 HEVs, as these biofuels achieve reduced emissions for the same energy use. B20 HEVs were found to be more energy efficient than E10 HEVs, which is explained by the fact that diesel engines have a higher efficiency than gasoline engines. A notable mention is the locally produced B20 from waste cooking oil which has only slightly higher energy use-to-CO2 emissions than the imported B20 on the same HEV technology, making it an attractive option for local fuel production. The promising potential of locally produced biodiesel is confirmed in other studies [16,47]

Less performing technologies are ICEV vehicles, with gas-based ICEV's having some of the highest energy use, while ethanol-based ICEV's have CO2 emissions as high as the newer model gasoline cars. As expected, E10-ICEV shows only a small improvement in energy use-to-CO2 emissions as compared with the baseline gasoline vehicle.

As figure 11 also illustrates, the gas-based vehicles are more energy consuming (12% on average) than the baseline vehicle for relatively moderate improvements (5-20%) in CO2 emissions. This is due to a number of factors, mainly: the lower energy density of these fuels, the fact that they are used on the same conventional ICEV technology as for gasoline, and the WTT energy losses. Even in the medium term, they remain at a disadvantage relative to HEV and PHEV technologies which may require similar investment but offer much higher energy use-to-CO2 emissions benefits. Nonetheless, gas-based vehicles remain an attractive technology relative to conventional fuel vehicles, especially in countries with natural gas resources. This is also the case for developing countries where the electricity infrastructure tends to be underdeveloped and the power mix dirty, or where governments are simply not willing to invest in electric mobility.

Based on the preceding analysis, the most beneficial technologies in this context are listed in Table 6.

Table 6: Applicable fuel-vehicle technologies under near, medium and long-term scenarios.

Scenario	Fuel Feedstock	Vehicle Technology
Near-term	Gasoline	HEV

(2015-2020)	Diesel	HEV
	E10 from import only	HEV
	B20 from import only	HEV
Medium-term (2020-2030)	B20 from waste cooking oil	HEV
	E85 from import only	HEV
	CNG/LPG	ICEV
Long-term (beyond 2030)	Electricity from resource mix for 2030 per government policy paper	EV, PHEV

5. Cost benefit analysis for selected fuel-vehicle technologies

A cost-benefit analysis (CBA) is performed in order to support setting a beneficial transport policy, favoring cleaner and lower-cost transport technologies over more polluting and higher-cost transport technologies.

5.1. Cost analysis framework and assumptions

The CBA in this study consists of two main parts: the user's perspective which is based on a comparison of the emissions-to-cost performance (USD/veh.km) for owning and operating each fuel-vehicle technology relative to the model 2015 gasoline ICEV considered as the baseline vehicle, where benefits are measured in terms of the cost of GHG reductions; and, the government and private sector perspective which relies on the corresponding costs of the infrastructure for fuel distribution and the foregone government revenues for each fuel-vehicle technology.

The fixed and variable cost components considered include the vehicle ownership costs defined as the vehicle purchase cost minus its salvage value, the insurance fees, custom and excise fees, registration fees, road-usage fees and loan financing charges; the vehicle operating costs defined as the cost of consumed fuel, maintenance and tires; the infrastructure and subsidy costs on the government defined as the costs of alternative fuel distribution networks in addition to the financial subsidies for implementing required measures to deploy the technology; the investment costs on the private sector defined as the costs of alternative fuel stations.

Table 7 summarizes the total vehicle costs for a mid-size passenger car for each of the different fuel-vehicle technologies.

Table 7: Evaluated vehicle technologies ownership and operating costs.

Technology	Ownership cost (USD)	Operating cost (USD/year)
Gasoline/E10/E85 ICEV	29,640/ 29,640/ 31,350	1437/ 1437/ 1437
Gasoline/E10/E85 HEV	39,900/ 39,900/ 41,610	1,160/ 1,160/ 1,160
Diesel/B20 ICEV	37,335/ 37,335	1,409/ 1,409
Diesel/B20 HEV	45,030/ 45,030	1,160/ 1,160
CNG/LPG ICEV	35,625/ 35,625	1,016/ 986
Gasoline PHEV20/60	46,030/ 52,015	1,072/ 995
Diesel PHEV20/60	52,015/ 57,145	984/ 953
EV PP10/ PP20/ PP30	48,595/ 48,595/ 48,595	836/ 795/ 698

Vehicle purchase costs were estimated from a Lebanese market survey for conventional fuel-vehicle technologies, and from worldwide industry data adapted to the Lebanese market for alternative fuel-vehicle technologies. Financing charges for car loans were estimated locally at 4% average bank interest rate after a 20% down payment of the total vehicle purchase price over a standard 5 year loan period. Vehicle depreciation was estimated at 20% for the first year and 12% for the following years, with a vehicle service life of 10 years. Insurance fees were computed according to the locally adopted formula of 14.5% of the vehicle purchase cost for the 5-year loan period, plus an average of 150 USD/year for the remaining life of the vehicle. Custom and excise fees were computed according to the locally used formulas, which for custom fees is equal to 5% of the vehicle estimated value (considered in this study similar to the vehicle purchase cost), and for excise fees is equal to 15% on the first 13,333 USD of the vehicle purchase price, plus 45% of the vehicle's value above that initial value [48]. Car registration fees were computed according to the locally used formula of 4% of the vehicle's estimated value. Road-usage fees were computed based on the 11-20 horsepower category and taking into consideration that new cars are exempted from this fee for the first 3 years. The standard value-added tax (VAT) of 10% was used.

Energy consumption costs were computed under local driving conditions, with an annual mileage estimated at 12,000 km and an appropriate average fuel cost for each fuel type (1.0 USD/liter for gasoline; 0.5 USD/liter gasoline equivalent (lge) for natural gas; and, 0.23 USD/kWh for electricity). Vehicle maintenance and repair costs were estimated from worldwide professional databases in 2016 as no local data is available. Diesel particulate filter (DPF) costs were estimated from professional associations at 1,500 USD for every 160,000 km. Battery costs were estimated from 2015 industry data at 450 USD/kWh every 8 years or 240,000 km.

5.2. CBA Methodology

The individual cost component estimates are computed over a comprehensive timeframe to emulate the phased deployment of the fuel-vehicle technologies over time, namely under the following three scenarios: short-term (up to 2020), medium-term (up to 2030) and long-term (up to 2040). These estimates are based on extensive research of the real local ownership and operating conditions in Lebanon.

Considering the total costs of ownership and operation for the vehicle service life of 10 years and the average driving distance of 12,000 km per year, vehicle ownership costs per vehicle.km were computed and ranged from 0.338 USD/vehicle-kilometer (veh.km) for gasoline and E10 ICEVs to 0.635 USD/veh.km for diesel PHEV60. Similarly, vehicle operating costs per vehicle-kilometer were computed and ranged from 0.058 USD/veh.km for EVs under the 2030 electricity mix to 0.120 USD/veh.km for gasoline, E10 and E85 ICEVs. Note that these costs are borne by the user.

The cost of infrastructure for alternative fuels is primarily covered by the government, such as the cost of storage reservoirs and distribution pipelines for natural gas, or transmission lines for electricity. It is considered that this infrastructure is built and made available for the energy sector and other sectors of industry and the economy at large, and as such the corresponding costs cannot be attributed solely to the transportation sector in the CBA. Therefore, the only infrastructure costs that will be considered are the capital and operating costs of the distribution stations (natural gas and electric) where the private sector is assumed to take up much of the provisioning role, as is currently the case for gasoline and diesel fuels. The cost components considered include the storage, compression, dispensing and metering equipment for gas, and the charging equipment (electric vehicle supply equipment or EVSE) for electricity. The cost of land is not considered. The average cost of a station for each fuel type, shown in Tables 8 and 9, was used along with the estimated values for demand in order to calculate the average total cost of the distribution infrastructure needed for the near, medium and long-terms. This provides an indicative value for the cost of infrastructure to transition to any particular fuel.

Table 8: Average cost and capacity of medium-size CNG, L-CNG and LPG refueling stations.

Station Type	Station Size	Station Capacity (lge/day)	CNG Station Cost (USD)	L-CNG station cost (USD)	Station Capacity (lge/day)	LPG Station Cost (USD)
Fast-fill	Medium	3,000	900,000	1,100,000	6,900	220,000

Table 9: Average cost of electricity public charging stations.

EVSE Type	EVSE/EV Ratio	EVSE Cost (USD)
Curbside (AC slow charger)	0.2	3,000
Fast charging station (DC fast charger)	0.01	35,000

Note that "EVSE/EV Ratio" is the number of charging stations per EVs served, assumed similar to the US with 0.2 for slow AC public charging stations (0.5 is the highest ratio worldwide) and 0.01 for fast DC public charging stations (0.03 is the highest ratio worldwide).

The cost treatment of GHG emissions in this cost-benefit analysis did not involve the assignment of a carbon cost, in order to avoid the subjective and sometimes controversial approach of monetizing this cost component. Instead, the Tank-to-Wheel (TTW) GHG emissions for each fuel-vehicle technology were compared to the GHG emissions of the 2015 baseline gasoline ICEV, and the resultant GHG savings were attributed to the total vehicle ownership and operating costs. This allows the determination of the relative emissions-to-cost performance of all fuel-vehicle technologies, as presented in the results section. The estimates ranged from zero grams CO2 equivalent per vehicle kilometer (g CO2 eq./veh.km) for EVs to 193 g CO2 eq./veh.km for gasoline ICEV.

A separate cost assessment was also done for the total Well-to-Wheel (WTW) GHG emissions for all fuel-vehicle technologies, thereby accounting for the additional emissions from the storage, transportation and distribution infrastructure for a particular fuel. It is common in this case to consider government mechanisms for subsidizing the vehicle ownership costs of cleaner technologies. Such mechanisms are accounted for in this CBA by considering the corresponding foregone government revenues in the near-term (when the incentives and subsidies are given) in the total cost evaluation of the WTW GHG emissions for the entire assessment period (i.e. over the long-term).

Several government incentive schemes were reviewed and evaluated for the case of Lebanon. The most applicable incentives are mainly those intended to reduce the vehicle purchase and ownership costs in the near term, thereby encouraging the creation of a market for alternative fuel technologies. These consist of exemptions from customs and excise fees on vehicle purchase cost and registration fees, and reduction of car loan interest rates. Such subsidies were estimated to amount to a minimum of 0.151 USD/veh.km for gasoline and E10 HEVs, and a maximum of 0.226 USD/veh.km for diesel PHEV60.

5.3. Cost benefit analysis results

The CBA results presented in figure 12 show the emissions-to-cost performance for all fuel-vehicle technologies compared to the baseline 2015 gasoline vehicle from the user's perspective. The financial liability from the government perspective in terms of foregone revenues after cost subsidy and the magnitude of infrastructure investment are later discussed.

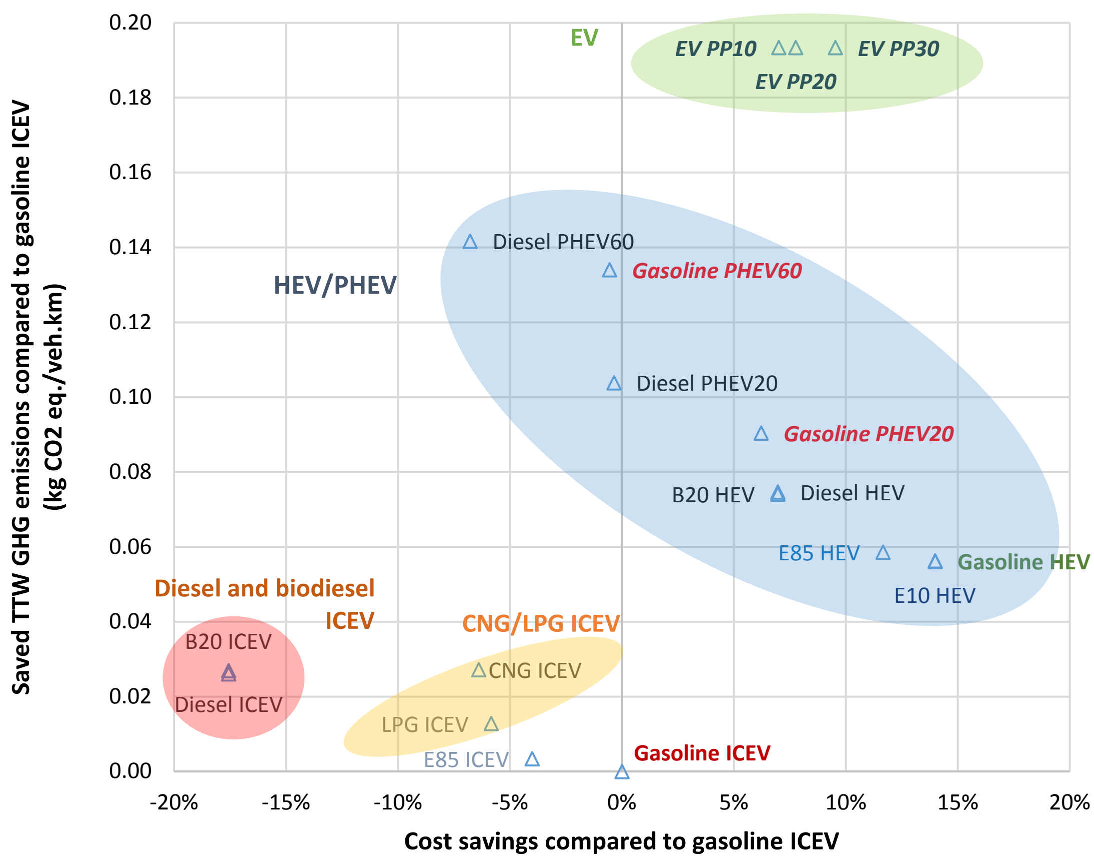

Figure 12: Emissions-to-cost performance of fuel-vehicle technologies relative to gasoline ICEV for yearly mileage of 12,000 km.

The results show that EVs provide the highest CO2 emission savings at a lower cost than the baseline, and the only factor that prevents them from being the most cost-effective of all clean technologies at this yearly mileage range is the higher purchase cost of the vehicle.

Behind EVs are the PHEV20 and PHEV60, but at widely varying cost-performance levels since the purchase cost of PHEVs increases significantly with the level of electric autonomy, making PHEV60 more costly than the baseline ICEV. This is added to the higher operating and maintenance costs of these vehicles, which keeps their gasoline counterparts more attractive from a cost perspective.

The gasoline and diesel HEVs, while not as efficient in terms of emission savings as the PHEVs, are however much more cost-effective than almost all other fuel-vehicle technologies due to the lower purchase cost of the vehicle. The results show that biofuel HEVs provide little environmental and cost savings relative to gasoline and diesel hybrids. Similarly, alternative ICEV technologies offer relatively minor improvement in CO2 emissions for higher costs than the baseline gasoline ICEV due to their higher ownership costs. Specifically, diesel and biodiesel ICEVs are the lowest performers.

A sensitivity analysis was done on two key parameters related to the fuel and the vehicle, namely the price of fuel and the vehicle yearly mileage. The price of fuel was varied between values considered as extremes in the case of Lebanon, from 0.1 to 1 USD/lge for natural gas, from 1 to 25 USC/kWh for electricity tariff, and from 0.25 to 2.5 USD/lge for gasoline. Results showed that at low fuel prices, electric-based and hybrid vehicles (EVs, PHEVs and HEVs) are consistently the preferred choice for the regular user (12,000 km annual driving mileage), while at high fuel prices HEVs are the preferred choice.

Varying the vehicle yearly mileage, gas-based ICEVs become cost-effective at low fuel prices only for the high mileage users above 30,000 km per year, typical of taxis and similar public transport and service vehicles, with CNG having superior performance to LPG. At this mileage and over the service life of the vehicle, additional costs are incurred by EVs, such as for battery replacement, which reduce their cost performance (EVs shift horizontally to the left in figure 12, however they retain their top position in terms of the highest emission savings).

The foregone government revenues due to the incentive schemes identified for the case of Lebanon are estimated for low and high market penetration scenarios of the most promising alternative fuel-vehicle technologies over the near, medium and long-terms. Abatement costs corresponding to the forgone revenues incurred by the government in the near term are then calculated and added to the initial vehicle ownership costs. The abatement costs are presented in figure 13.

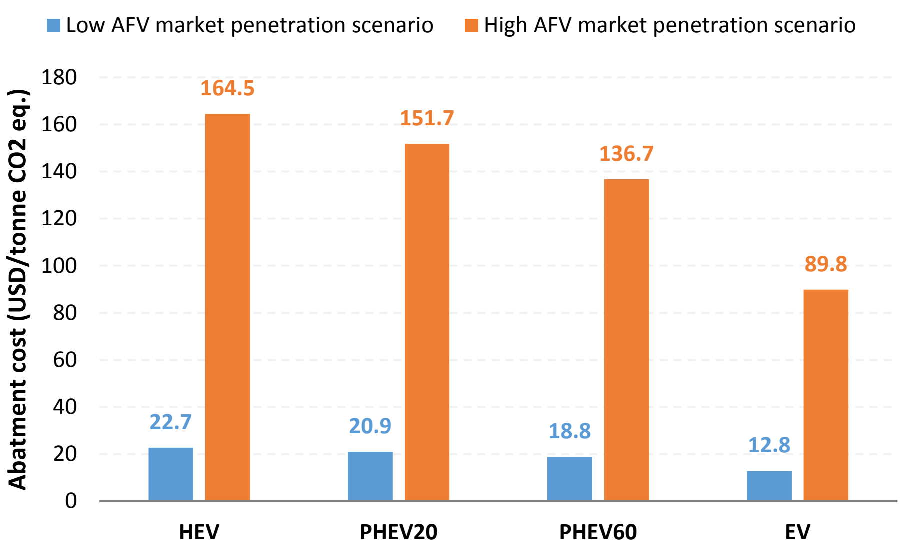

Figure 13: Abatement cost incurred by the government in the near term (2018-2020) in the form of forgone revenues in exchange for the total saved WTW GHG emissions over the entire long-term period (2018-2040).

Lastly, the cost of distribution infrastructure for each fuel-vehicle technology is also considered in the CBA. This cost was estimated using forecasted total energy demand for each fuel type for low and high market penetration scenarios. The cost of transportation infrastructure was only considered for LNG fuel transport to the inland regions (e.g. Bekaa and Nabatieh) from the FSRU offshore, since the infrastructure for all other fuel types is considered to be made available for the energy sector and the economy at large. The long-term infrastructure investment costs and saved WTW GHG emissions are presented in Figures 14 and 15.

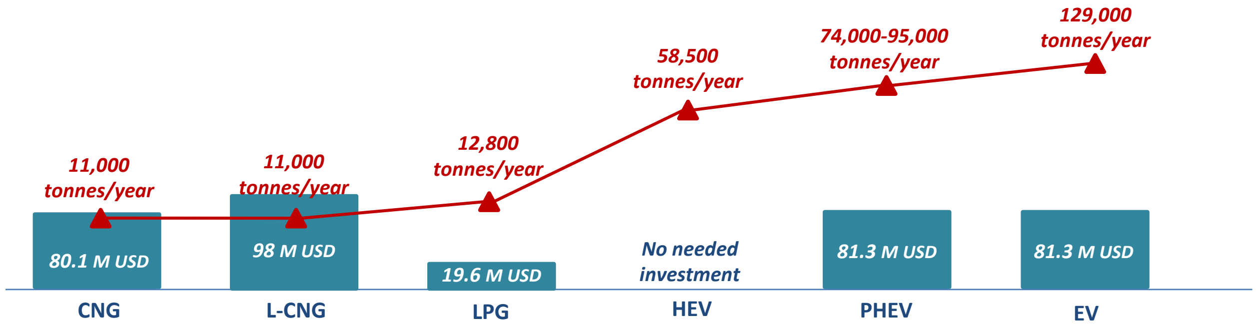

Figure 14: Infrastructure investment costs and saved WTW GHG emissions over the long term for low alternative fuel vehicles market penetration scenario.

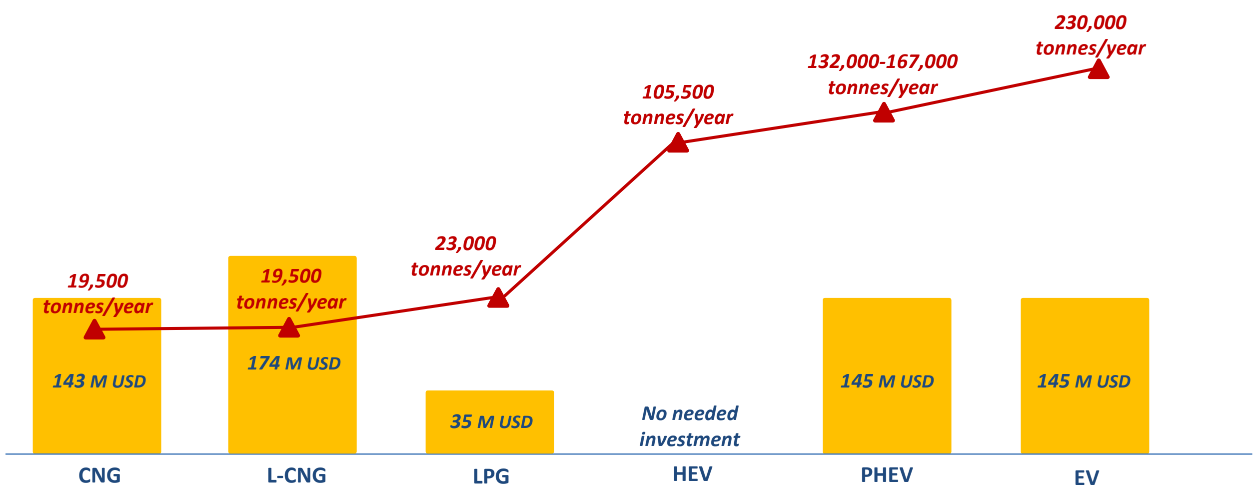

Figure 15: Infrastructure investment costs and saved WTW GHG emissions over the long term for high alternative fuel vehicles market penetration scenario.

The main conclusions which can be drawn from the above cost analysis are as follows:

- HEVs are the vehicle technology of choice if no infrastructure investment is to be made
- EVs and PHEVs with extended electric drive autonomy are preferred when it comes to maximizing emission savings, making them the preferred fuel-vehicle technology in the medium and long terms.

It is noteworthy to mention that the infrastructure costs for natural-gas based vehicles and electricity-based vehicles are of comparable scale, which means it is more effective to develop an infrastructure for electricity-based vehicles since they provide superior GHG emission savings for the same cost.

6. Policy Recommendations

Combining the preceding insights about the benefits and limitations of the selected fuels, vehicles, infrastructure requirements for these fuels, and the corresponding financial and market considerations in terms of fuel price, vehicle and infrastructure costs, the study is concluded with the following heuristics and policy recommendations:

- Biofuel ICEVs offer only moderate energy use-to-CO2 emissions improvements (<20%) relative to the 2015 model gasoline ICEV technology, leaving gasoline, diesel and biofuel HEVs as the preferred technologies for the near term due to their commercial readiness at no additional infrastructure cost. The government is therefore in front of an opportunity to achieve significant environmental benefits quickly and affordably. This can readily be done by providing financial incentives to create a market for hybrid vehicles through exemption mechanisms to remove custom and excise fees, registration fees, and/or road usage fees at registration.

  By contrast, natural gas-based vehicles are at a disadvantage from the standpoint of energy use, infrastructure costs and local market readiness in the near-to-medium term. However, at high driving range CNG vehicles become feasible, while LPG becomes attractive as an alternative fuel if infrastructure investment is limited. In fact, in the absence of planning and a comprehensive strategy as is currently the case in Lebanon, the market will tend to evolve in an ad-hoc manner towards the more easily accessible technologies such as LPG. It is in this way that a black market for LPG has recently evolved in Lebanon through illegal retrofitting of taxis and minivans by operators seeking to reap some of the energy-saving benefits, in order to reduce their fuel costs. This is why the government would be well-served to intervene and regulate the gradual introduction of these fuels rather than banning them. This could be achieved by leveraging the resourcefulness of the private sector in creating a local service provider industry, as in public-private partnerships to build infrastructure for dispensing natural gas to taxis and service vehicles.

- Over the medium term, electricity-based vehicles appear to hold the most promise; however, the local infrastructure for these technologies is unlikely to be ready in time in Lebanon and other developing countries. As a result, high-blending ethanol and locally converted biodiesel become attractive options. It is also possible for natural gas vehicles to become more attractive from a cost perspective if the infrastructure is expanded over the medium term; however, plug-in hybrid electric vehicles still rank better than gas-based vehicles with higher CO2 savings for comparable investment costs. It should be noted that the infrastructure needed for electricity-based vehicles is complementary but separate from that for natural gas-based vehicles, which means that one choice should normally be adopted over the other depending on cost, market readiness and related factors. This is why a national government strategy across key sectors of the economy should be elaborated based on overall needs and capabilities in order to avoid being locked-in by near-to-medium term choices which may not be optimal for the long-term.

- For the long-term scenario, the electricity-based vehicles offer much higher benefits than all other technologies and become the dominant choice under the future 2030 clean resource mix (which would consist of natural gas and renewable energies), assuming the power generation and distribution infrastructures are ready as planned. This result serves as clear indication that for countries such as Lebanon where alternative fuels have not yet been introduced, the long-term strategy for the use of natural gas should be to evolve an infrastructure that can serve electric mobility instead of promoting the widespread use of natural gas vehicles for the larger public.

Taking the costs, benefits and barriers facing the adoption of each fuel type in the Lebanese transport sector and similar developing countries, some heuristics for the near to long terms can be concluded as shown in Figure 16.

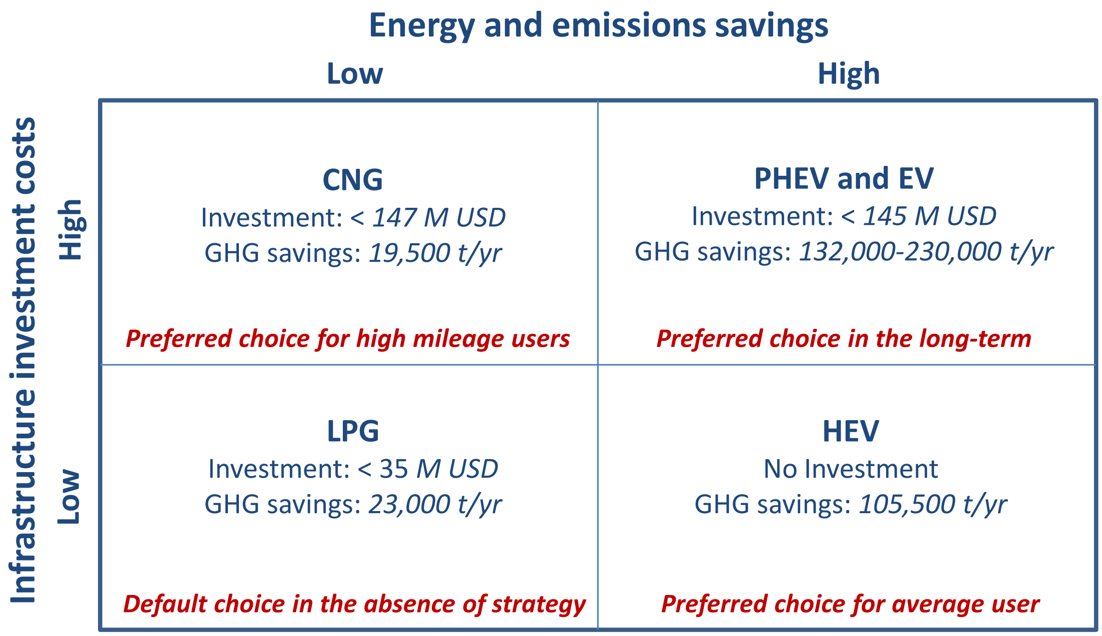

Figure 16: Heuristics for alternative fuel-vehicle technology strategy by environmental-to-cost performance

7. Conclusion

This paper presented the results of a well-to-wheel study for 26 fuel-vehicle pathways applicable to Lebanon and similar developing countries with limited road transport and energy infrastructures, in order to help inform transition strategies over the near, medium and long-terms to sustainable alternative fuels. The study assessed the impacts from the point of fuel import into the country to the point of use on the vehicle, based on the commonly adopted GREET lifecycle assessment tool for energy use, GHG and criteria pollutant emissions. In addition, an economic cost-benefit assessment for the most beneficial 19 of the 26 selected fuel vehicle technologies was performed.

Results showed that electric vehicles are the most beneficial but require a charging infrastructure and a clean electricity mix that are not feasible in the near and medium terms due to high construction costs and time requirements. Plug-in hybrid electric vehicles become feasible over the medium term, with gasoline or diesel hybrid electric vehicles the most feasible and beneficial technologies in the near-to-medium terms. A sensitivity analysis on price of fuel and vehicle yearly mileage showed that at low fuel prices and a typical 12,000 km annual driving mileage, electric-based and hybrid vehicles are the preferred choice for the regular user, while at high fuel prices hybrid electric vehicles become the preferred technology. Natural gas vehicles become beneficial at an annual mileage of 30,000 km typical of taxis and service vehicles, while locally produced biodiesel from waste cooking oil proved to be beneficial if strict emission controls are enforced.

When taking the cost of infrastructure for fuel distribution and dispensing into consideration, the cost-benefit analysis results showed that electric and plug-in hybrid electric vehicles are preferred over natural gas vehicles as they provide better emission savings for comparable to lower infrastructure costs. If no infrastructure investment is to be made as is currently the case in Lebanon and many developing countries, a market for hybrid electric vehicles can be created with government incentives to achieve environmental benefits without the need for new infrastructure.

Finally, some concluding remarks are in order about the limitations of this study and potential future work. In particular, the proposed framework of potentially feasible pathways for developing fuel-importing countries remains a theoretical framework which needs to be validated in order to confirm that WTW results can indeed be used to inform strategies across similar contexts. This can be accomplished through case studies in other fuel-importing countries with similar states of economic and infrastructure development. An extension of this study would be to identify the most beneficial vehicle fleet mix over future planning horizons in order to meet the commitments for reducing GHG emissions under the UNFCCC agreement. This can be done by building on the results and recommendations in this study. A model is under development to test the effects of the government policies and incentives considered here on fleet mix parameters such as user adoption of the different types of AFVs.

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