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Well-to-wheel analysis of direct and indirect use of natural gas in passenger vehicles

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ABSTRACT

The abundance of natural gas in the United States because of the number of existing natural gas reserves and the recent advances in extracting unconventional reserves has been one of the main drivers for low natural gas prices. A question arises of what is the optimal use of natural gas as a transportation fuel. Is it more efficient to use natural gas in a stationary power application to generate electricity to charge electric vehicles, compress natural gas for onboard combustion in vehicles, or re-form natural gas into a denser transportation fuel? This study investigates the well-to-wheels energy use and greenhouse gas emissions from various natural gas to transportation fuel pathways and compares the results to conventional gasoline vehicles and electric vehicles using the US electrical generation mix. Specifically, natural gas vehicles running on compressed natural gas are compared against electric vehicles charged with electricity produced solely from natural gas combustion in stationary power plants. The results of the study show that the dependency on the combustion efficiency of natural gas in stationary power can outweigh the inherent efficiency of electric vehicles, thus highlighting the importance of examining energy use on a well-to-wheels basis.

1. Introduction

Recent forecasts for natural gas resources in the United States suggest that this fuel will be abundant and low cost for many decades [1], giving reason to study efficiencies and the environmental impact of the multiple paths for its use. For example, growth of natural gas use in transportation can be achieved by directly fueling combustion engines in trucks and cars, by conversion to a liquid fuel for combustion, or by conversion to electricity for use in the expanding number of electric vehicles in the United States. Consideration of longer-range options might include conversion of natural gas to hydrogen for fuel cell vehicles.

Besides its lower cost, natural gas is an attractive fuel for stationary power applications as well as for transportation due to its reduced criteria air pollutants compared to petroleum-derived fuels such as gasoline and diesel for mobile applications and coal for stationary applications. The lower carbon content of methane (CH_4), the primary constituent of natural gas, has increased interest in natural gas as a low-carbon fuel [2] and provides the additional benefit of lower GHG (greenhouse gas) emissions compared to transportation fuels or coal. To assess the overall GHG impacts of numerous paths for natural gas use, a so-called well-to-wheels analysis is needed.

Methane, the primary component in natural gas, has a high octane number (120) and low boiling point (−161.5 °C), making it an applicable fuel for SI (spark ignition) ICEs (internal combustion engines) [3]. To achieve an acceptable vehicle range between refueling, it is necessary to densify natural gas because CH_4 in its gaseous form has a density of 15.4 g/m^3 at standard temperature and pressure compared to gasoline, which has a density of 744,000 g/m^3. For light-duty vehicle applications, natural gas is typically carried as CNG (compressed natural gas) in tanks pressurized to 3600 psi (248 bar), which brings its energy density to about 26% of that of gasoline. Natural gas has been used as a transportation fuel in the form of CNG for many years in the United States and around the world, though in the United States only approximately 0.1% of the total natural gas consumption is in the form of a transportation fuel [4].This is equivalent to less than ½ billion gallons of gasoline per year. Natural gas compression is often done at a refueling station using industrial compressors and storage tanks, although home refueling compressors have been available for CNGVs (CNG vehicles). In the United States there are currently 112,000 CNGVs on the road, with approximately 574 public CNG filling stations [5]. This is in contrast to the nearly 14.8 million

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natural-gas-powered vehicles around the world [5]. For heavy-duty vehicle applications, cryogenically cooling natural gas to LNG (liquefied natural gas) at −162 °C increases the density but adds substantially to the cost [4]. It is also possible to chemically convert natural gas into a liquid fuel such as DME (dimethyl ether), which has autoignition characteristics similar to diesel fuel, or through a FT (Fischer-Tropsch) or gas-to-liquid process for a fuel that has ignition characteristics more similar to either gasoline or diesel fuel depending on the process. Other possible conversions of natural gas to a transportation fuel include reforming CH_4 into hydrogen for use in hydrogen fuel cells either onboard the vehicle or beforehand in a reforming plant. Natural gas can also be used indirectly as a transportation fuel by firing a power plant to generate electricity for charging EVs (electric vehicles). This is not an exclusive list of natural gas to transportation fuel pathways but serves to illustrate the range of possible fuel pathways.

Both EVs and CNGVs have additional energy storage requirements compared to the standard liquid hydrocarbon fueling system common to conventional gasoline or diesel vehicles. For EVs, considerable additional weight is added to the vehicle with the electric ESS (energy storage system), electric motor, and PEs (power electronics). With HEVs (hybrid electric vehicles), the vehicle has the conventional ICE and hydrocarbon fueling system with the addition of an ESS and PEs. In the case of the HEV, the weight penalty is usually somewhat minimized with the selection of smaller ICE and smaller ESS and PE-electric motor systems. With CNG vehicles, there is an SI ICE with a high-pressure natural gas cylinder in the vehicle. For bi-fuel systems, both a natural gas cylinder and a liquid hydrocarbon fueling system are in place. Besides the additional weight incurred by both EVs and CNGVs, the range of both is markedly smaller than that of a conventional gasoline or diesel vehicle. The vehicle range for a CNG passenger vehicle is about 402 km (250 mi), and the range for a similarly sized EV is about 161 km (100 mi), depending on conditions and driving style [6].

Because the use of natural gas for transportation requires compressing, liquefying, or conversion, it is important to determine the best use of natural gas as a transportation fuel. Specifically, to minimize GHG emissions and total energy use, is it better to use natural gas in a stationary power application to generate electricity to charge EVs, to compress natural gas for onboard combustion in vehicles, or to reform natural gas into a denser transportation fuel? To perform a comprehensive analysis of vehicle platforms with varying upstream fuel pathways, a modified cradle-to-grave lifecycle analysis, known as a WTW (well-to-wheels) analysis, is often performed [7–9]. The WTW analysis is broken down by upstream and downstream energy use, criteria air pollutants, and GHG emissions, as shown in Fig. 1. The upstream or WTP (well-to-pump) part captures the fuel production energy costs and emissions, including T&D (transmission and distribution) pathways, from the point of fuel feedstock extraction to the point where the fuel is transferred to a vehicle in units of kilojoules or grams per megajoule of fuel at the pump for energy use and emissions, respectively. The TTW (tank-to-wheels) part of the analysis only considers the vehicle use energy and emissions in units of kilojoules or gallons per kilometer, respectively.

With pending national and international policies concerning the regulation of GHGs from power generation, transportation, and industrial processes, including proposed rules on GHG limits on vehicles, more attention is being paid to carbon dioxide (CO_2) and other GHG emissions than ever before [10–12]. There are three widely accepted GHGs that result from stationary power generation from combustion: CO_2, CH_4, and nitrous oxide (N_2O) [13].The greatest bulk contributor to GHG emissions is CO_2, which results from the combustion of any hydrocarbon fuel. CO_2 emissions make up between 87% and 99% of the total GHG emissions from stationary power, assuming proper emissions controls are in place. The GWPs (global warming potentials) of CH_4 and N_2O are greater than that of CO_2 over a given time scale (often 100 years). Commonly agreed upon GWP values for CH_4 and N_2O for use in regulations come from the IPCC (Intergovernmental Panel on Climate Change) [13]. For example CH_4, which has a strong role in atmospheric chemistry, has a GWP that is 21 times greater than that of CO_2. Nitrous oxide, which is only produced in very small amounts from combustion, has a GWP that is 310 times greater than that of CO_2, meaning that even small amounts of N_2O can have a very strong effect on GHG emissions. GHG emissions values are presented in terms of CO_2 equivalent (CO_{2eq}), taking into account all of the generated GHGs and their GWPs, which are shown in Table 1. To report GHG emissions on a CO_{2eq} basis, the resultant emissions for each of the GHGs are multiplied by their individual GWP and added.

The primary sources of CH_4 emissions from using power generation from natural gas are small leaks in the natural gas infrastructure, known as CH_4 leakage, or from incomplete combustion during engine operation, known as CH_4 slip. The GHG benefits of using natural gas as a fuel depend on minimizing CH_4 leakage and slip during the entire fuel pathway [13–15]. GHG emissions from centralized stationary power depend on the electrical generation mix, which varies regionally depending on the service provider. In the United States, the electrical generation mix varies considerably

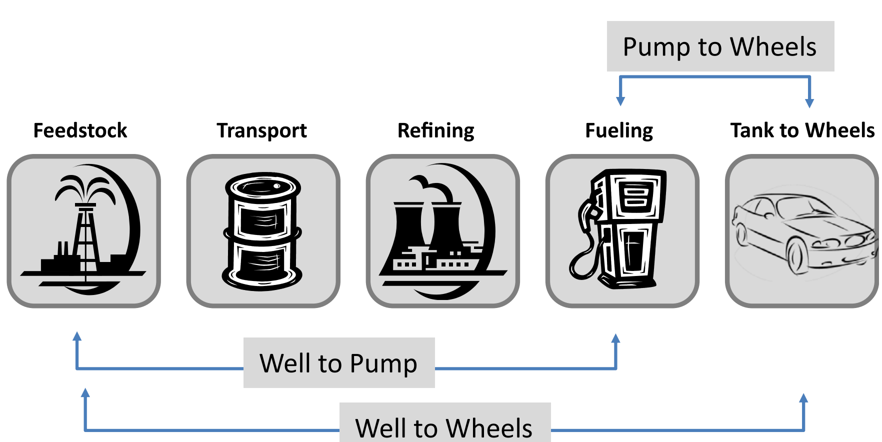

Fig. 1. WTW fuel pathway.

Table 1
IPCC GWP potentials [13].

Greenhouse gas	Common sources	GWP
Carbon dioxide	Combustion	1
Methane	CH_4 slip	21
Nitrous oxide	Combustion	310

for the different subregions as defined by the eGRID (Emissions & Generation Resource Integrated Database) [16]. According to eGRID, GHG emissions from stationary power in the United States range from roughly 245 kg/MWh in the AKMS (Alaska) region, which has 63% hydropower, to a maximum of about 870 kg/MWh in the RMPA (Rocky Mountain) region, which uses 71% coal and 24% natural gas. Fig. 2 shows the average electrical generation mix assumed for the United States (US mix), which is about 45% coal, with a nearly even mix of nuclear and natural gas at around 20% each and the remainder being produced from hydroelectric, oil, biomass, wind, solar, and geothermal (listed in order of percentage of the mix) [16].

A WTW energy and emissions analysis can be used to make a direct comparison between the total energy costs and emissions of the different vehicle technologies taking into account fuel cycle aspects. This study takes advantage of the WTW analysis tool known as the GREET (Greenhouse Emissions and Energy Use in Transportation) model developed for the US Department of Energy by Argonne National Laboratory. The total energy for each scenario by type as well as GHG emissions and criteria air pollutants are estimated to make a complete comparison. Though previous studies have compared the WTW energy use and GHG emissions of CNGVs to EVs and both conventional and advanced powertrains including various HEV architectures [17–20], they have not specifically addressed the use of natural gas in an apples-to-apples comparison of currently available technologies. As part of the GREET development, there was a detailed look at the fuel-cycle analysis of transportation fuel produced from natural gas in 1999 by Wang et al. [21]. The Wang et al. paper examined the various natural gas to transportation fuel pathways, including modeling results for many long-term vehicle technologies, but did not specifically address the question of what is optimal use of natural gas in currently available vehicles.

This study investigates the WTW energy and emissions from various natural gas to transportation fuel pathways and compares the results to conventional gasoline vehicles and EVs using the US mix and conventional gasoline SI ICE vehicles. Specifically, natural gas vehicles with CNG are compared against EVs charged with electricity produced solely from natural gas combustion in stationary power plants. Calculations are performed using the GREET model (GREET1_2012 rev 1) [9, 22].

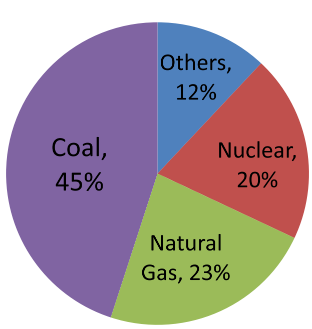

Fig. 2. Sources of electrical generation for US mix [15].

2. WTW analysis method

The GREET model used for this study is designed for WTW analysis for transportation systems and as such has a backbone of stationary power calculations to accurately account for electricity's role in transportation, including upstream emissions for electrical power generation. GREET is a Microsoft Excel-based calculation tool that has referenced or assumed values for emissions factors and energy use for stationary power generation to more accurately determine life-cycle criteria and GHG emissions and energy use for mobile applications. For both stationary and transportation use there are default electricity generation mixes for the US regions as well as user-defined mixes. The mixes allow inputs for the percentage of electricity generated by residual oil, natural gas, coal, nuclear, biomass, and others. The latter category is broken down into hydroelectric, wind, solar photovoltaic, and undefined others. The assumptions used for this study are outlined in the next section.

3. Key assumptions

Using GREET, key assumptions were modified as outlined in the following sections. In both cases of CNG for CNGVs and natural-gas-fired stationary power for EVs, both systems are fed from the same North American natural gas pipeline and as such have the same upstream energy use and emissions to the point of the pipeline. This includes the energy and emissions associated with natural gas recovery for North American natural gas, North American shale gas recovery, natural gas processing, as well as transmissions and distribution.

3.1. Stationary power generation

As stated previously, the analysis assumes the US mix for sources of electrical generation in which natural gas is used in a number of different ways. For stationary power for EVs the fuel mix is varied in this study, for all other calculations including upstream refinery operations, the US mix is assumed. Electricity generation has 8% T&D loss [23]. The share of conventional natural gas and shale gas is assumed to be 77% and 23%, respectively.

For electricity generation in the United States, natural gas is commonly used in both simple-cycle natural gas turbines and combined-cycle natural gas turbines, which use waste heat recovery to increase electrical generating efficiency. According to the 2011 US Energy Information Administration *Annual Electric Generator Report* [24], 112 new power plants were commissioned in the United States in 2011. Of those, the largest net summer capacity was 523 MW and the average was 86.3 MW. The average efficiency of these new power plants is 34% for the simple-cycle turbines and ranges from 52% to 58% for the NGCC (Natural gas combined-cycle) turbines. Other sources show NGCC units to have efficiencies on the order of 50.2% [25]. Though natural gas reciprocating ICEs and fuel cells are also used in industry, they are not commonly used for centralized electricity generation and therefore are not considered in this study. Previous studies have, however, looked at the GHG benefits of distributed energy from these technologies [8]. The default values used for natural gas stationary power generation in GREET are averaged over the United States from the various regions for the different combustion technologies. For example, the efficiency for combined-cycle natural gas turbines ranges from to 36%–50.7% [20].

3.2. Vehicles

The vehicles investigated in this study are separated into two categories: current vehicles, based on US EPA (Environmental

Protection Agency)-reported fuel economy and manufacturers' data, and future technologies that are not currently in the market but are conceptually valid. This latter category includes vehicles such as CNG hybrid electric concepts. There is no option in GREET for accounting explicitly for additional vehicle weight other than manually adjusting the fuel economy values. Vehicle weight for the hybrid vehicle architectures is accounted for in the drive cycle fuel economy results or simulations performed in the vehicle systems simulation tool, Autonomie [26], which was used to provide the default values in GREET over the city and highway federal driving cycles [27]. EPA fuel economy data assume a split of 45% city driving and 55% highway driving. It should be noted that the driving schedule, the particular vehicle used, and driver behavior all have a significant impact on fuel economy and can result in real-world driving fuel economy that differs as much as 40% from the EPA estimate [28]. The midsize passenger vehicles examined in this study are shown in Table 2 and include a conventional gasoline SI ICE vehicle, a dedicated CNGV, and an EV. All vehicles have similar passenger volumes of between 2.55 and 2.69 m^3 (90 and 95 ft^3) [6]. The baseline comparison against a midsize SI gasoline vehicle is based on a 2012 2.4 L Chevrolet Malibu with a combined fuel economy of 26 mpg [29], which is higher than the EPA-reported average fuel economy for passenger vehicles for the entire in-use fleet as of July 2009, which is 24.1 mpg [30]. EV fuel economy is based on a 2012 Nissan LEAF, with a combined EPA label fuel economy of 99 mpg gasoline equivalent (mpgge) [6]. The CNGV is based on a 2012 Honda Civic natural gas vehicle with a combined EPA label fuel economy of 30.9 mpgge [6]. It should be noted that the EPA label fuel economies are aggregated based on a 5-cycle test that also includes additional modifying factors. In the case of the Nissan LEAF, the EPA label fuel economy of 99 mpgge, assuming 45% city driving and 55% highway driving, is lower than the uncorrected "city" and "highway" cycle fuel economies and also includes an assumed charger efficiency and additional correction factors [31].

3.3. Natural gas compression

In the case of CNG, the natural gas pipeline is fed directly into a refueling compressor station. The modeling approach in GREET assumes that the natural gas is initially compressed to a pressure of 276 bar to allow for pressure losses caused by cooling during vehicle refueling to a tank at 248 bar. The key assumption with refueling stations is the compressor efficiency, which Argonne found to range between 91.7% and 97% [22]. For this study the key assumptions are that the CNG is stored in the vehicle at 248 bar, the natural gas compressor is located at the refueling station, and the average compressor efficiency is 93.1%.

3.4. EV charger efficiency

EV battery charging equipment is categorized as AC or DC and is defined by the SAE J11772 standard for EV supply equipment by level [32]. Details for the different AC and DC levels can be found in Ref. [33]. In each case there are losses during charging that must be accounted for in the WTW analysis. The EPA fuel economy label rulemaking requires that the measured AC watt-hours of energy consumption from an EV take into account the charger losses [33].The driver of an EV would not see any difference on the TTW fuel economy on the EV but would notice a difference in the electricity use, which would result in very different upstream emissions, as shown on the WTP analysis. GREET accounts for the EV charger losses by applying the efficiency to the per-mile fuel consumption of vehicle operations (TTW), giving an EV with charger value instead of associating with the WTP portion. GREET embeds this number into the vehicle efficiency assumption with the default grid-connected (plug-in) HEV and EV charger efficiency of 85%. For this study, an EV charger efficiency of 88% is assumed to account for the range of charging levels [34]. For an EV that has an EPA label–rated fuel economy of 99 mpgge with an EV charger efficiency of 88%, the actual battery-to-wheel EV fuel economy would be 112.5 mpgge.

Table 2
Current vehicles used in WTW analysis.

Type	Make/ model	City (mpgge)	Highway (mpgge)	Combined (mpgge)
SI ICE	Chevy Malibu	22	33	26
CNGV	Honda Civic	24	36	31
EV	Nissan LEAF	105	92	99

3.5. Methane slip and leakage

Modern light-duty vehicles sold in the United States are required to meet EPA regulations for criteria air pollutants: NOx, CO, particulate matter, and non-methane hydrocarbons [35]. For stoichiometric vehicles, emissions compliance is accomplished through engine management, along with a three-way catalyst that effectively reduces these pollutants to levels under the drive-cycle limits. These catalysts are also effective at reducing methane slip emissions that can result from unburned methane fuel or reformation of partially hydrocarbon combustion products. The GREET analysis uses the default assumption that a gasoline vehicle has 0.015 g/mile of methane slip, while a dedicated CNGV has 0.146 g/mile. It is worth noting that Argonne chassis dynamometer testing of a 2012 Honda Civic CNGV showed similar post-catalyst methane values of 0.120 g/mile over the urban dynamometer driving schedule [36].

Fugitive methane emissions associated with natural gas transmission, distribution, and storage are termed methane leakage here. GREET accounts for methane leakage in the upstream portion of the model. The amount of methane leakage assumed for all of the natural gas scenarios presented in this study come from the default values in GREET 2012. These leakage values are reported in addition to the methane slip associated with combustion, which is accounted for in the vehicle emission factors. Details of these assumptions can be found in Burnham et al. [37]. The values assumed for the various stages of recovery (398.7 g/mmBtu), processing (31.0 g/mmBtu), and T&D (124.0 g/mmBtu) are used here. The values assumed in GREET for natural gas transmission and distribution leakage are a function of distance where 0.387 vol % methane leakage is assumed for transmission and storage while a 0.278 vol % leakage is assumed in distribution [27]. The default GREET assumptions for transmission distances to CNG refueling stations and to NGCC power plants are used. These assumptions are fixed for this analysis, but the importance of the role methane leakage has on the results should be noted.

4. Results

Using GREET, key assumptions were modified in accordance with the references discussed in the assumptions section. Vehicle fuel economies were normalized to the energy content of gasoline using the miles per gallon gasoline equivalent unit (mpgge)—the mixed unit is used to orient the reader accustomed to fuel economies expressed using the miles per gallon (mpg) unit. GHG emissions are presented in grams per CO_2 equivalent as described previously. This WTW study investigated the use of natural gas in CNGVs with a range of CNGV fuel economy and natural gas

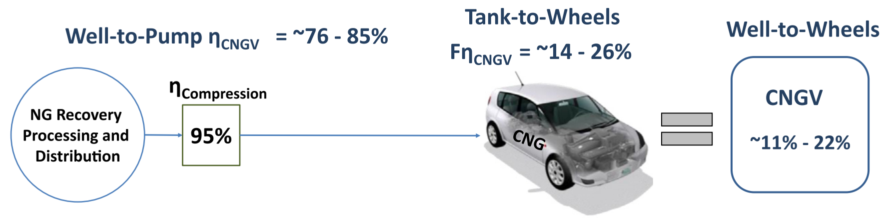

Fig. 3. WTW efficiency for CNGVs.

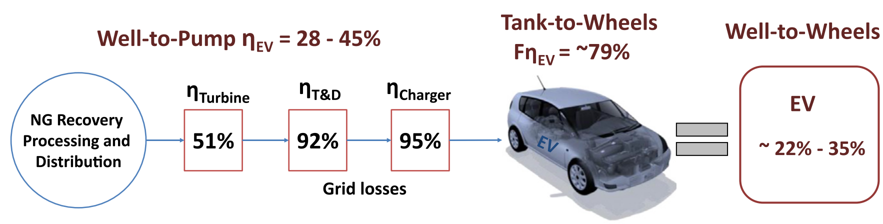

Fig. 4. WTW efficiency for EVs.

compressor efficiency. These results are compared to a range of fuel economies from an EV that was charged from electricity produced from the US mix and a range of natural gas turbines with varying efficiencies. To understand the differences in WTW energy use between the two pathways, the WTW efficiency was examined for each vehicle type. The WTP efficiency is a GREET function that examines energy embedded in the upstream portion of the fuel cycle. The TTW efficiency can be examined by calculating the energy demand over a drive cycle divided by the fuel energy consumed. It should be noted that the TTW efficiency is a function of vehicle system efficiency and includes vehicle-speed-dependent terms over the drive cycle [38–41]. The next section presents diagrams to illustrate the differences in using natural gas directly in the CNGV or upstream in an EV, and the TTW efficiencies presented are for the range of highway and city driving. It should be noted that these WTW efficiencies are not used directly for WTW calculations but instead are presented to give insight into the differences in WTW energy use for the two fuel pathways.

4.1. *Results for currently available technologies*

Considering WTW efficiency breakdown for CNGVs and EVs, we assumed the same natural gas recovery, processing, and distribution. For the CNGV case as shown in Fig. 3, natural gas is compressed from a pipeline feed in a commercial compressor. CNG is then pumped to the vehicle. The TTW efficiency of an ICE burning CNG depends on the speed and load conditions over the drive cycle, which in general ranges from 14% to 26% [41]. Therefore, the total WTW efficiency of natural gas used in a CNGV ranges from about 11% to 22%.

The WTW efficiency for EVs running electricity derived from a stationary power plant is shown in Fig. 4. Natural gas from the pipeline is fed into the stationary power plant, which has an electrical generating efficiency that depends on the type of power plant. The electricity is then distributed to the grid, where it is subject to T&D losses resulting in a WTP efficiency of between 28% and 45% depending on the power plant technology. Electricity is transferred to the EV via a charging station, which is on the order of 85–95% efficiency. The battery-to-wheel efficiency of an EV over a drive cycle can range from about 79 to 91% depending on how regenerative breaking is accounted for [41]. This gives an overall WTW efficiency of between 22% and 35%.

4.1.1. *Electric vehicles*

Holding charger efficiency (88%), T&D losses (8%), and EV with charger fuel economy (99 mpgge) constant, the impact of natural gas turbine efficiency on WTW energy use and GHG emissions can be examined. Fig. 5 shows that varying the natural gas turbine efficiency from 30% to 65% results in half the amount of WTW energy use and GHG emissions with constant EV fuel economy. The WTP efficiency varies from 25.64% at an NGCC efficiency of 30% to a WTP efficiency of 55.6% at an NGCC efficiency of 65%.

The effect of EV fuel economy on WTW energy use and GHG emissions was examined by holding the NGCC combined-cycle natural gas turbine efficiency at 45% along with the same assumptions as the previous case for a charger efficiency of 88% and standard T&D losses. The results, shown in Fig. 6, indicate that when battery-to-wheels EV fuel economy is varied from 80 mpgge to 160 mpgge (70.4 mpgge to 149.6 mpgge w/charger), the WTW energy use and GHG emissions are reduced by about 53%. This range of fuel economy is representative of the reported uncorrected actual cycle energy consumption measured over the various EPA driving cycles [32].

The effect of EV charger efficiency on WTW energy use and GHG emissions was isolated by holding the NGCC combined-cycle natural gas turbine efficiency at 45%, EV battery-to-wheel fuel economy at 112.5 mpgge, along with the same assumptions as the

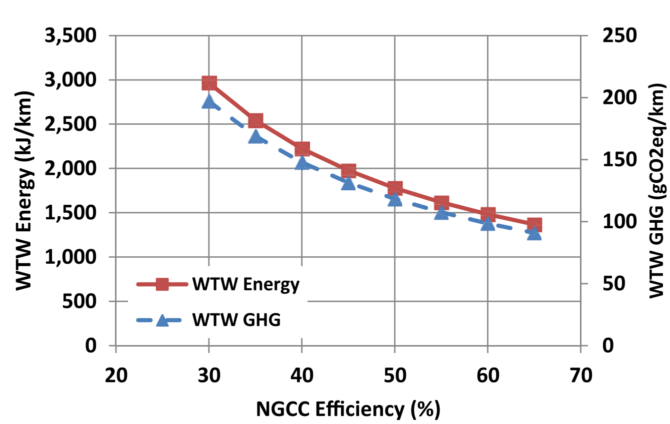

Fig. 5. NGCC (Natural gas combined-cycle) turbine efficiency impact on WTW energy and GHG emissions.

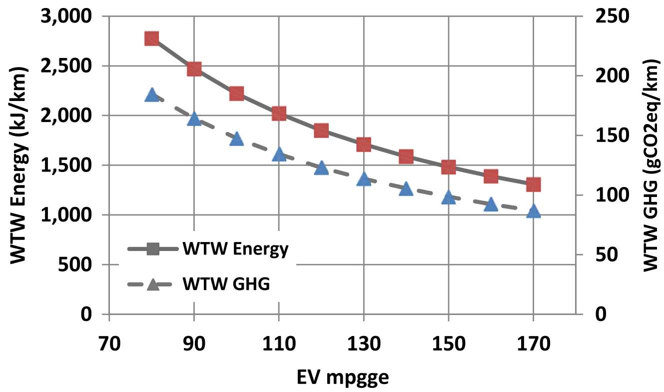

Fig. 6. EV fuel economy impact on WTW energy and GHG emissions.

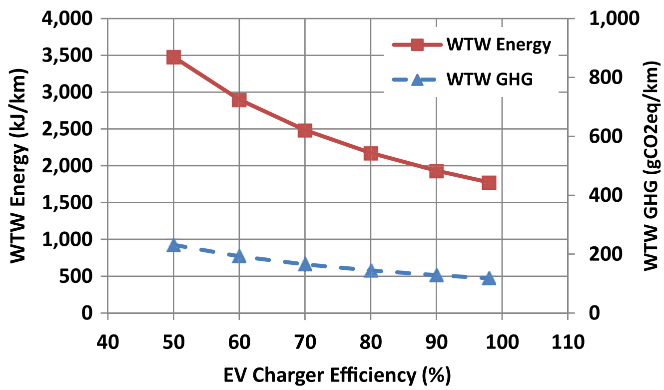

Fig. 7. EV charger efficiency impact on WTW energy and GHG emissions.

previous cases for T&D losses. A sweep of the EV charger efficiency effectively repeats the sweep of EV with charger fuel economy but clearly shows the sensitivity to EV charger efficiency. The results, shown in Fig. 7, indicate that when EV charger efficiency is reduced from 98% to 50%, the WTW energy use and GHG emissions double.

4.1.2. *Compressed natural gas vehicles*

To investigate the effect that CNGV fuel economy has on WTW energy and GHG emissions, the compressor efficiency was held constant at 95%. The results are shown in Fig. 8. Sweeping the CNGV fuel economy from 10 mpgge to 60 mpgge, demonstrates how sensitive WTW energy use and GHG emissions can be at the lower fuel economy values for a technology. The nonlinearity of the amount of fuel consumed with fuel economy at the lower fuel efficiencies results in a sharp upturn in WTW energy use and GHG emissions with the lowest CNGV fuel economies. Though these values are not representative of EPA label combined fuel economy, they are a good representation of low-speed, real-world driving. The WTP efficiency remained constant as expected at 81.1%.

The effect of CNG compressor efficiency economy on CNGV WTW energy use and GHG emissions was examined by holding the CNGV fuel economy at 30 mpgge, as shown in Fig. 9, for a range of compressor efficiencies from 75% to 98%. The WTP efficiency ranged from 52.3% with a compressor efficiency of 75% to a WTP efficiency of 86.7% at a compressor efficiency of 98%.

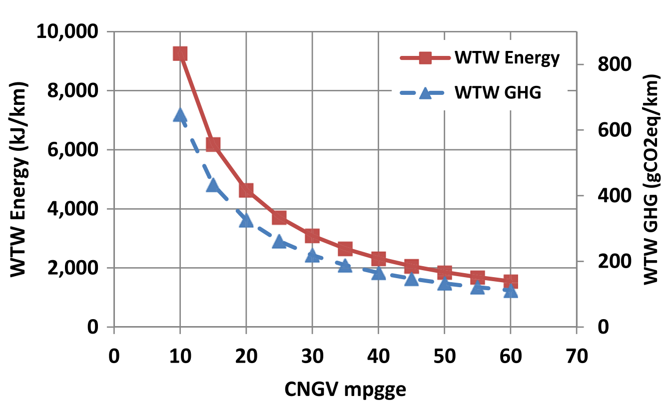

Fig. 8. CNGV fuel economy impact on WTW energy and GHG emissions.

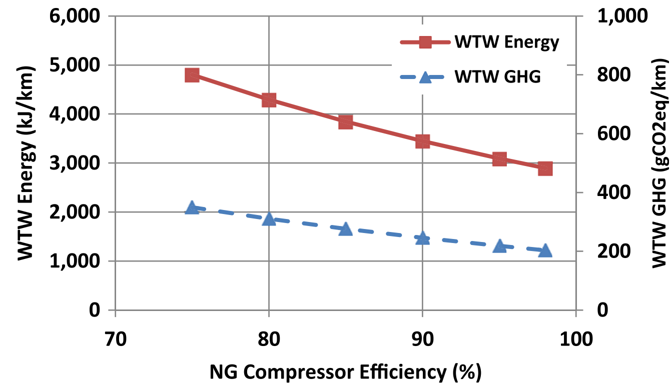

Fig. 9. NG (Natural gas) compressor efficiency impact on WTW energy and GHG emissions.

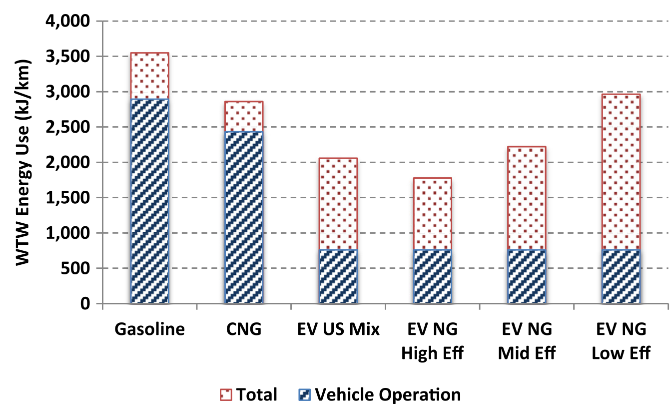

Fig. 10. WTW energy use.

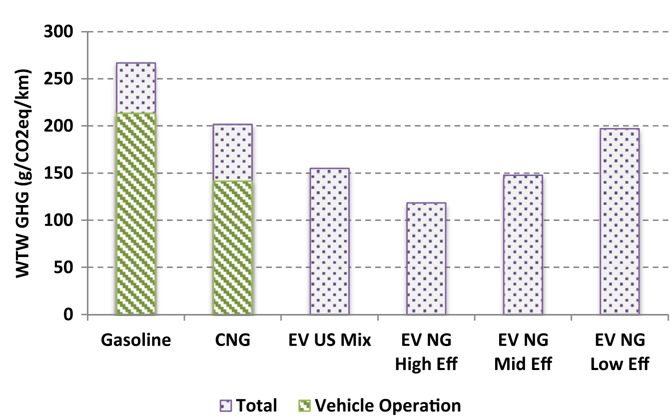

Fig. 11. WTW GHG emissions.

Table 3
Fuel economy assumptions for future vehicle technologies.

Vehicle type	WTP efficiency (%)	Fuel economy (mpgge)
SI ICE	81.6	26.0
SI E85—Corn	48.2	26.0
SI E85—Switchgrass	53.7	26.0
SI M90	64.2	26.0
SI CNG	85.1	30.9
CIDI - ULSD	83.3	31.2
CIDI—DME	63.8	31.2
SI HEV	81.6	36.4
CNG HEV	85.1	36.4
PHEV 10—US mix	76.5	49.0
PHEV 40—US mix	65.0	86.2
PHEV 10—NG	75.8	49.0
PHEV 40—NG	63.1	86.2
CNG PHEV 10—US mix	79.3	49.5
CNG PHEV 40—US mix	66.6	87.2
CNG PHEV 10—NG	78.6	49.5
CNG PHEV 40—NG	64.6	87.2
CNG fuel cell	85.1	38.5
Fuel Cell—H_2 NG	55.0	38.5
EV w/charger—US mix	41.2	99
EV w/charger—CNG	38.5	99
EV w/charger—Coal	31.6	99

4.2. WTW energy use and GHG emissions summary for available technologies

WTW comparisons were completed for the available vehicle technologies using a gasoline ICE vehicle as a baseline. (Table 2 gives the fuel economy for these vehicles under various driving conditions.) These vehicles are compared to an EV charging on the US mix and on electricity generated from natural gas with a low turbine efficiency of 30%, a mid turbine efficiency of 40%, and a high turbine efficiency of 50%. Fig. 10 shows a breakdown of the WTW energy use for these cases for total and vehicle-operation-only energy use on an energy-use-per-mile basis. Fig. 11 shows the same breakdown in terms of GHG emissions. For the EV cases, the fuel economy does not change with electrical generating efficiency; instead, the total WTW energy use and the total WTW GHG emissions are what are affected.

4.3. Estimations for proposed vehicle technologies

The previous section compared the results of direct and indirect use of natural gas in current vehicle technologies. WTW energy and GHG emissions performance can be considered for future CNGVs and EV w/Ch (EVs with charger), including possible CNG hybrid electric and fuel cell vehicles in GREET. A number of different transportation scenarios can be evaluated since GREET has built-in pathways for CNG, liquefied natural gas, liquefied petroleum gas, methanol, dimethyl ether, FT diesel, FT naptha, and hydrogen.

The current vehicle WTW results shown in Figs. 10 and 11 were compared to a number of advanced vehicle architectures. These include both a grid-independent HEV without plug-in capabilities and a PHEV (plug-in HEV) with a 20 mile (PHEV 20) and 40 mile (PHEV 40) all-electric range, an SI ICE, and a CNG engine. For the PHEV cases, both charging from the US mix and charging from a natural gas turbine with a 45% electrical generating

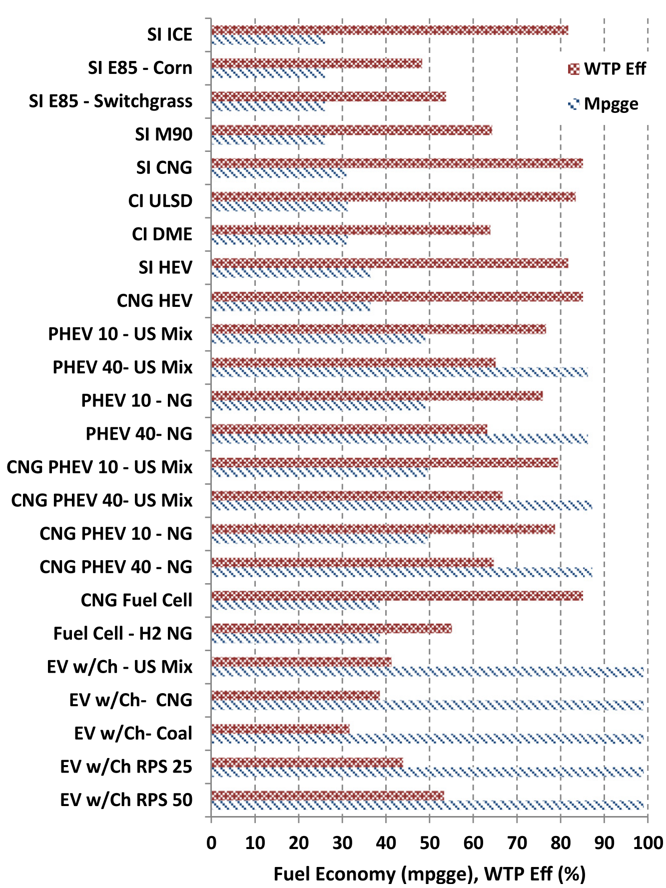

Fig. 12. Fuel economy and WTP Eff (efficiency) assumptions for future vehicle technologies.

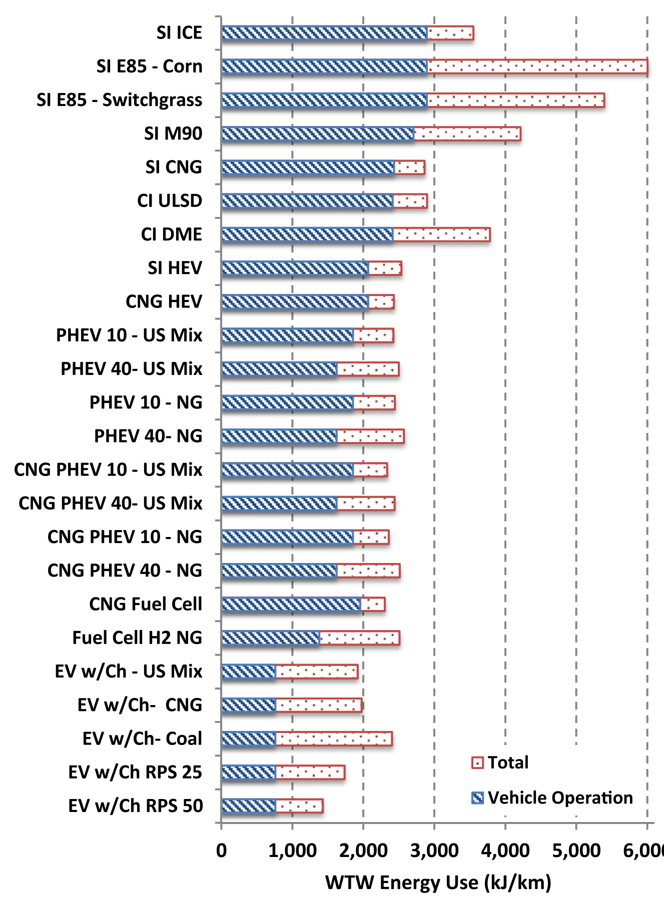

Fig. 13. Estimated WTW energy use for future vehicle technologies.

efficiency were considered. Hydrogen fuel cells using hydrogen derived from natural gas and CNG fuel cell vehicles, where the CH_4 to H_2 conversion takes place onboard, were considered. Though currently there are no production vehicles for sale in the United States that are dedicated for the use of 90% methanol, the results for methanol from natural gas in an SI ICE are also presented. A CIDI (compression ignition direct ignition) vehicle running on ULSD (ultralow sulfur diesel) fuel is also shown. For comparison purposes and to illustrate the benefits of renewable fuels on upstream GHG emissions, vehicles compatible with up to 85% ethanol (E85) are presented for conventional corn-based ethanol and for cellulosic ethanol from switchgrass. In addition, it is assumed that as future regulations on RPS (renewable portfolio standards) are enacted, the GHG emissions factor associated with the US mix will change [42, 43]. For this analysis, it is assumed that the RPS mandate would be met with an upstream carbon neutral source, in this case, wind power, and the ratio of the other components of the US mix would remain fixed. Scenarios for 25% (RPS-25) and 50% (RPS-50) renewable portfolio standards are presented for EV use along with the current US mix, natural gas, and coal. The assumed fuel economies of all vehicle architectures considered are shown in Table 3 and Fig. 12. All other assumptions are standard GREET assumptions as illustrated earlier.

The estimated WTW GHG emissions for future vehicle technologies are compared in terms of WTW energy use in Fig. 13, which indicates the contributions from vehicle operation alone as compared to the WTW energy use. Fig. 14 shows the estimated WTW GHG emissions, and Fig. 15 shows estimated WTW petroleum use, including future vehicle technologies. It is clear from these figures that even though the fuel economy of EVs is very high on a TTW basis, the upstream efficiencies from generating electricity can significantly degrade the WTP efficiency and therefore the total GHG emissions and energy use. The high-efficiency CNG hybrid case illustrates the importance to fuel economy of ICE engines of keeping the WTW energy use and emissions low, regardless of WTP efficiencies. The RPS cases illustrate the effectiveness of renewable power generation on the EV. Similarly, severe WTW GHG reductions would also be expected for both CNG and EV scenarios that used bio-methane or landfill gas.

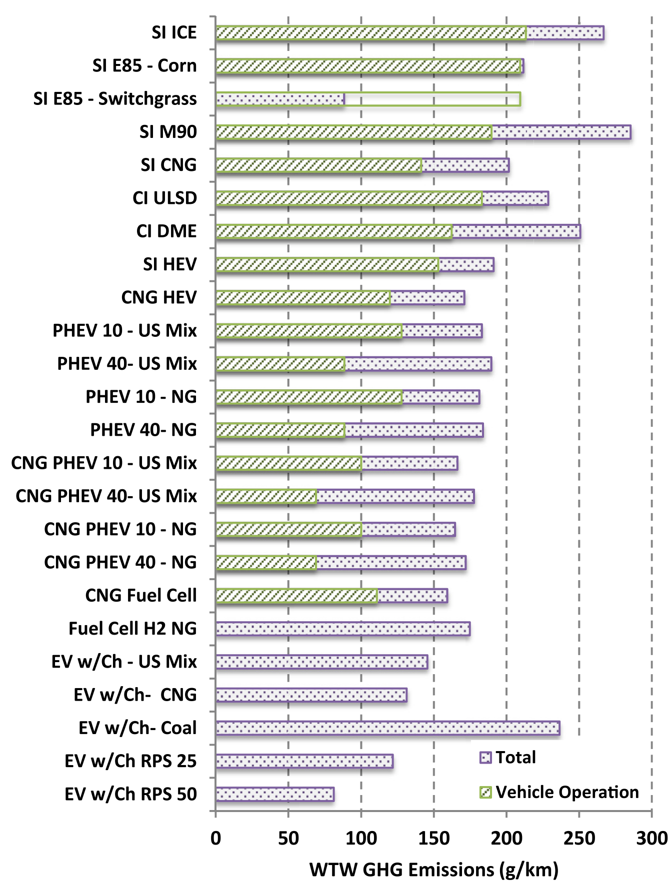

Fig. 14. Estimated WTW GHG emissions for future vehicle technologies.

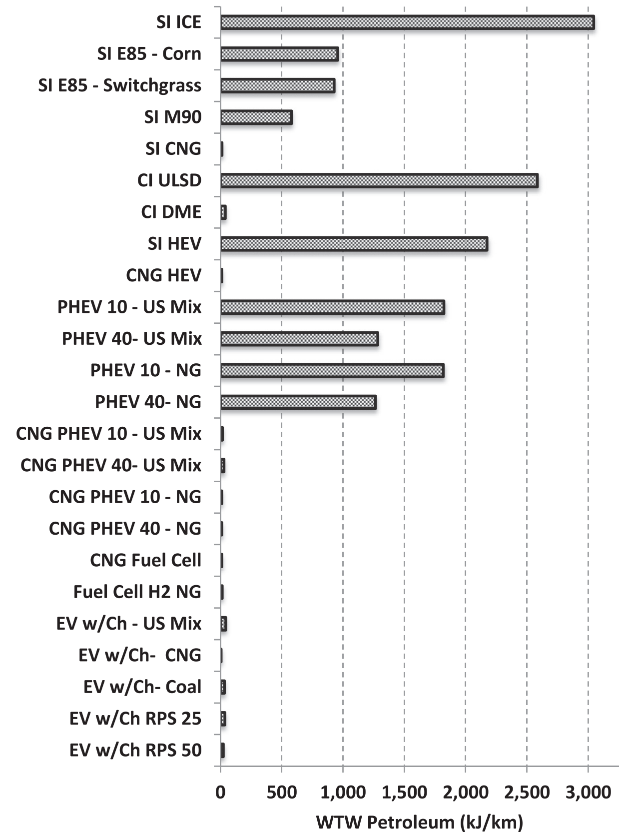

Fig. 15. Estimated WTW petroleum use for future vehicle technologies.

5. Conclusions

Natural gas for transportation has advantages, but the mobile nature of transportation means that the lower heating value and low density present a significant challenge. Using a WTW analysis to investigate optimal use of natural gas in transportation, it was determined that the high PTW (pump-to-wheels) efficiency and potential for high electrical generation efficiency with NGCC turbines make using natural gas in a stationary power application for charging EVs the optimum with current technologies. However, the high PTW efficiencies and moderate fuel economies of today's CNGVs make them a viable option as well. If CNG were to be eventually used in HEVs, the electric advantage shrinks. This can be generalized to say that the most effective use of natural gas in transportation ultimately depends on the efficiency of the combustion prime mover, whether on vehicle or in a stationary power plant. The difference in WTW energy use and emissions between CNGVs and EVs depends on the method of producing electricity from natural gas. The results presented here for the high-efficiency

CNG hybrid case also illustrate the potential benefits of increasing the engine efficiency for CNGVs, which could be realized by optimizing engine operation around the high octane of CNG. In terms of petroleum energy reductions, all of the options that use solely natural gas offer nearly complete displacement of petroleum.

The efficiency of both the prime mover and the fuel pathway processes is critical for keeping WTW energy use and GHG emissions low for the both the EV and CNGV scenarios. In each case there are multiple processes to convert natural gas to motive power, all of which have losses. With an EV, the primary energy use is in converting fuel into electricity for grid charging, while for a CNGV, the primary energy use is in converting fuel into vehicle motion. With current US fuel prices of $2.12/gge for CNG and $3.71/gge for electricity, the cost to drive 25 miles with the currently available vehicles is $1.65 for CNGVs and $1.02 for EVs [6]. Price fluctuations in CNG prices or regional differences in electricity prices can markedly affect these example values.

This analysis focused solely on the fuel-motive power cycle and disregarded the vehicle cycle, which would include the associated energy and emissions for the battery, PE, and auxiliary systems found only on battery EVs and for the CNG tank and auxiliary systems only found on natural gas vehicles. This analysis did not address the vehicle cycle cradle-to-grave energy use for batteries and CNG tanks. Cost considerations on the total infrastructure or cost of ownership were also outside the scope of this work but are nevertheless important.

Disclaimer

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