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A numerical investigation on the efficiency of range extending systems using Advanced Vehicle Simulator

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ABSTRACT

Series plug-in hybrid electric vehicles of varying engine configuration and battery capacity are modeled using Advanced Vehicle Simulator (ADVISOR). The performance of these vehicles is analyzed on the bases of energy consumption and greenhouse gas emissions on the tank-to-wheel and well-to-wheel paths. Both city and highway driving conditions are considered during the simulation. When simulated on the well-to-wheel path, it is shown that the range extender with a Wankel rotary engine consumes less energy and emits fewer greenhouse gases compared to the other systems with reciprocating engines during many driving cycles. The rotary engine has a higher power-to-weight ratio and lower noise, vibration and harshness compared to conventional reciprocating engines, although performs less efficiently. The benefits of a Wankel engine make it an attractive option for use as a range extender in a plug-in hybrid electric vehicle.

1. Introduction

1.1. Energy and transportation

Since the beginning of the twentieth century, combustion of fossil fuels has been a primary source of energy for the industrial world. Fossil fuels such as petroleum are a finite resource, and it is predicted that the release of greenhouse gases (GHG) from burning fossil fuels contributes to global warming [1] and can lead to health complications in afflicted communities. The U.S. Energy Administration estimates that almost 2/3 of total demand for petroleum is from the transportation sector [2]. Assuming that daily production holds steady at 63.5 million barrels, global oil reserves are conservatively predicted to last approximately fifty years [3]. There is great potential for the reduction of petroleum consumption by converting the current vehicle fleet from conventional vehicles powered by reciprocating gasoline or diesel engines, to battery electric vehicles which draw their energy from the electricity grid. Unfortunately, the limited range of battery electric vehicle [4] suggests that the needs of the average U.S. commuter will not be met without a supplementary energy source. One solution is to couple the strengths of the battery electric vehicle with the extended range of a petroleum fueled vehicle in a hybrid drive train. This alternative to the single fuel conventional vehicle is the plug-in hybrid electric vehicle (PHEV). These vehicles may be primarily powered by grid electricity, stored in an on-board battery system, with additional electricity generated by an on-board fuel converter. This vehicle configuration is termed the series PHEV, and the supplemental electricity generation system is termed the range extender.

With a transformation of the vehicle fleet on the horizon, it is important to intelligently select future vehicle technologies. This study demonstrates the use of virtual simulations to predict the effectiveness of different technologies for extending the range of battery electric vehicles. Performance characteristics in all-electric and range-extending modes are quantified on a well to wheel basis, comparing energy consumption and GHG emissions. Numerical simulation of energy consumption by various automotive range extending technologies can aid to focus and accelerate experimental research on energy storage and conversion for advanced vehicles.

We compare the performance of the reciprocating (spark ignition) engine to the Wankel (rotary) combustion engine when used as a range extender for a series PHEV. The Wankel engine has the advantage of a high power-to-weight ratio, more compact size and packaging, and reduced noise, vibration and harshness (NVH) compared to the reciprocating engine. These benefits come at the expense of lower fuel economy.

1.2. Hybrid system simulation

Hybrid vehicle development carries with it all the traditional challenges of automotive design, with added complexity from

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incorporation of hybridized drive train components. The research process for hybrid systems can be simplified by utilizing computer simulations to identify the most favorable vehicle configuration for given operating conditions. The literature has demonstrated different objectives and methods of approach for numerical analysis of hybrid vehicles. Automotive simulation models have been recently developed to yield vehicle performance, energy storage requirements and power conversion efficiency for given driving conditions. Brown et al. [5] developed and validated a "Light, Fast and Modifiable" platform for optimizing a hybrid power train with a forward-facing model that includes a driver component. Their approach resulted in a flexible simulation tool that is sufficiently reliable to predict the behavior of different hybrid power train configurations. While the work in [5] aimed to simulate and study the hybrid drive train as a whole, other researchers such as Gökdere et al. [6] have developed virtual prototypes with particular focus on the electronic aspects of power conversion. Still others have used basic modeling techniques to simplify the complex relationships between a hybrid vehicle energy storage system and the vehicle performance [7].

To date, the academic community does not have literature on numerical simulations of the Wankel engine for use in light-duty transportation. This study utilizes Advanced Vehicle Simulator (ADVISOR) for simulation of vehicle performance and energy consumption using the Wankel engine as compared to more traditional range extenders. The ADVISOR software package was developed by the National Renewable Energy Laboratory (NREL) to aid in the development of alternatively powered vehicles. It was intended to ease the numerical simulation process for vehicles under development. ADVISOR uses a combined backward-forward approach [8] that enables the software to accurately model advanced batteries and power train components while maintaining a relatively fast simulation speed. It has been demonstrated as a reliable tool for studying energy consumption and vehicle performance [9–11] and for testing energy-related control schemes [12]. Previous work by the authors has shown ADVISOR to be useful for optimization of hybrid power train configuration [13].

Well to tank energy use and greenhouse gas data are obtained through use of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) software package, produced by the U.S. Department of Energy. The GREET model simulates energy use and emissions associated with the production and distribution of transportation fuels.

1.3. Rotary engine

The Wankel (or "rotary") engine is lighter and more easily packaged as a range extending module in a hybrid electric vehicle compared to other candidates such as reciprocating engines and fuel cells [14]. The Wankel engine produces twice as many combustion events per revolution compared to a reciprocating 4-stroke engine, and thus has superior power density. The output shaft of the Wankel engine is centered relative to the rotor housing, and can be easily coupled with a generator to produce electricity. Due to strictly rotary (as compared to reciprocating) motion, and more frequent air intake/exhaust events, the Wankel has relatively low NVH, second only to the fuel cell. Reduced NVH is especially critical when extending the range of the electric vehicle, as the occupants of the vehicle will be accustomed to the smooth and silent operation of their electric traction system, and may dislike the NVH produced by a conventional power train unit with a reciprocating engine range extender.

The advantages of the Wankel engine come at the cost of reduced fuel economy. The combustion chamber of the Wankel engine is long and narrow, giving it a high surface area to volume ratio. This negatively affects the thermodynamic efficiency of combustion due to heat transfer with the chamber's walls. In addition, flame quenching can occur at the trailing edge of the combustion chamber, causing increased hydrocarbon emissions and reduced fuel efficiency. Both inefficiencies are thought to be improved by utilizing direct-injected stratified charge (DISC) combustion, which localizes the combustion event to a small pocket on the rotor face [15]. The data used for this paper is based on the projected performance of a DISC engine with a minimum brake specific fuel consumption (BSFC) of 270 g kWh^{-1} [16]. Even prior to the simulation study outlined in [16], DISC engines had been developed which could achieve a BSFC as low as 237.3 g kWh^{-1} on gasoline fuel [17]. In contrast, the reciprocating engines analyzed herein achieved 206.7 g kWh^{-1} BSFC at peak efficiency.

The goal of this study is to determine whether the positive aspects of the Wankel engine can offset its poorer fuel economy when used as a range extender for a PHEV. The simulations described in this study are used to analyze vehicle energy consumption under different range-extender configurations to determine the most optimal application of the Wankel engine.

Nomenclature

ADVISOR	Advanced Vehicle Simulator
AER	all-electric range
BSFC	brake-specific fuel consumption
CVT	continuously variable transmission
DISC	direct injected stratified charge
GHG	greenhouse gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
kWh	kilowatt-hour
mph	miles per hour
mpg	miles per gallon
NASA	National Aeronautics and Space Administration
NVH	noise, vibration and harshness
PHEV	plug-in hybrid electric vehicle
VMT	vehicle-miles travelled

2. Vehicle design

Advanced Vehicle Simulator (ADVISOR) is a software package that is designed to simulate the performance of hybrid electric vehicles when driven over user-defined driving cycles. For this study, ADVISOR was used to estimate the efficiency of vehicles with different all-electric ranges (AERs) powered with different range extending engines. Sizing of the reciprocating engine is discussed in Section 3.

2.1. Rotary engine model

A Wankel engine was modeled in ADVISOR in order to enable vehicle simulation for this study. ADVISOR uses a matrix of BSFC referenced horizontally by engine speed and vertically by engine torque to determine the efficiency regions of an engine. These values are used during simulation to optimize the fuel efficiency of the vehicle. Detailed engine characterization data was required to construct such a matrix. In 1990, the National Aeronautics and Space Administration (NASA) simulated the performance of a DISC Wankel engine using MIT engine simulation code [16]. Results for a 75 kW class Wankel engine are shown in Fig. 1.

The data published by NASA was simulated utilizing a model based on a Wankel engine designed by Outboard Marine Corporation (Freedom Motors Rotopower product line). Research is being carried out at the University of California, Davis to improve the

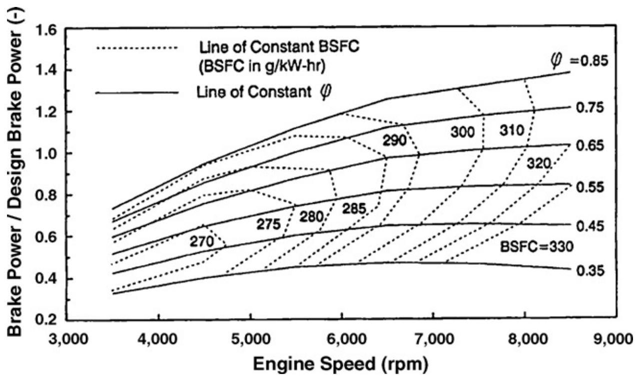

Fig. 1. NASA simulation results for DISC Wankel engine at 12.5 psi boost pressure [16].

Table 1
Freedom Motors 530 Series Specifications [18].

# of rotors	1	2
Displacement	530 cc	1060 cc
Max power	37 kW	74 kW
Max speed	6500 RPM	6500 RPM
Rated power	26 kW	52 kW
Rated speed	4500 RPM	4500 RPM
BSFC	243–304 g kWh^{-1}	243–304 g kWh^{-1}
Weight[a]	27.2 kg	40.8 kg
Dimensions (*L*, *W*, *H*)	10 in. × 13 in. × 11 in.	16 in. × 11 in. × 11 in.

[a] Incl. starter, alternator, lubrication, fuel and ignition.

efficiency of the engine to the values published in the NASA study. Table 1 shows the specifications of single and double rotor port-injected versions of the engine.

Preliminary simulations were conducted in ADVISOR to determine the feasibility of using the single and dual rotor Wankel engines for this study. A simple model of a small car with a Wankel engine was created, and the maximum power of the engine was modified against performance criteria. The vehicle was required to maintain a maximum speed of at least 80 mph (128.7 km h^{-1}), and was also required to meet the speed trace of the Urban Dynamometer Driving Schedule (UDDS) as defined by the U.S. Environmental Protection Agency. Using these criteria, it was determined that the single rotor engine was not sufficient to sustain extended range vehicle travel. The vehicle with the dual rotor engine did meet the criteria mentioned above. The BSFC matrix for a Wankel engine was therefore populated using the engine performance data shown in Fig. 1 and the rated power output of the dual rotor Rotapower engine. The torque-speed-efficiency plot shown in Fig. 2 was generated when this matrix was input into ADVISOR.

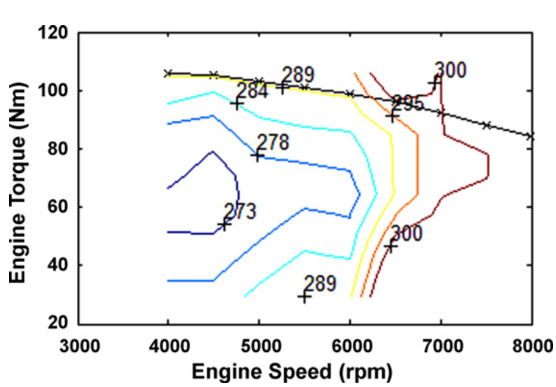

Fig. 2. Dual rotor Wankel engine: torque–speed–fuel consumption plot.

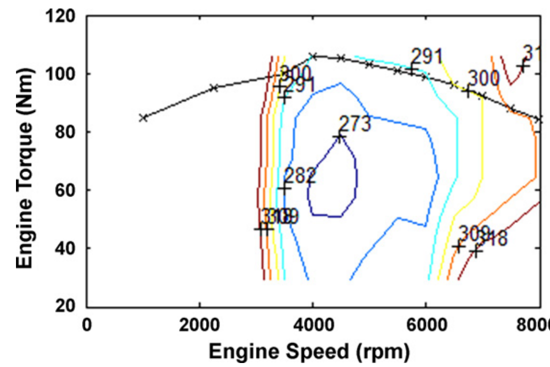

Fig. 3. Dual rotor Wankel engine: torque–speed–fuel consumption plot with modified low speed region.

Data for engine efficiency is most robust above speeds of 4000 RPM, but ADVISOR simulations operate the engine at speeds below 4000 RPM in some situations. To gain some control over the low speed region of the model, data was constructed to severely penalize the use of the engine below the calibrated region. The updated ADVISOR engine model is presented in Fig. 3. This engine model is only suitable for vehicle configurations which allow ADVISOR to operate the engine within its high efficiency regions. The series hybrid vehicle configuration is most promising in this regard because the engine can be sized such that it is operated consistently near its peak efficiency.

ADVISOR includes a calculation for the mass of an engine based on scaling factors and the maximum power output, as shown in Eq. (1):

$$\text{ADVISOR fuel converter mass}: \ m_{\text{total}} = \text{Power}_{\max} \times (C_{\text{bass}} + C_{\text{acces}} + C_{\text{fuel sys}}) \quad (1)$$

where C_{base}, C_{acces} and $C_{\text{fuel sys}}$ are scaling factors for the base weight, weight of accessories and the fuel system weight, and are equal to 1.8, 0.8, and 0.6, respectively, for the default 1.0-L reciprocating engine. This scaling resulted in a calculated engine mass of 227 kg at 71 kW maximum power. The scaling factors C_{base}, C_{access} and $C_{\text{fuel sys}}$ were reduced by 550% to 0.324, 0.144 and 0.108, respectively, for the Wankel model in order to obtain the manufacturer-specified engine mass of 41 kg [18]. This dramatic reduction in engine mass is one of the strengths of the Wankel engine compared to the 4-stroke reciprocating engine.

2.2. Series hybrid vehicles

A typical series hybrid drive train is shown in Fig. 4. In a series hybrid vehicle, the wheels are powered directly by an electric motor. The motor draws energy from a battery pack and drives in all-electric mode while battery capacity is available. Once the batteries have been mostly depleted, the motor draws power from the internal combustion engine/generator range extending module, in conjunction with the battery pack. Series hybrid vehicles are designed with a predetermined all-electric range (AER). The AER represents the distance the vehicle can travel using only the energy stored in its battery pack, without using the engine and generator. Vehicles with a higher AER must have larger, heavier and more expensive battery systems. The series hybrid configuration is the most attractive application of the Wankel engine because of its inherent simplicity and ability to operate the engine near its highest efficiency. This study therefore focuses on series PHEVs.

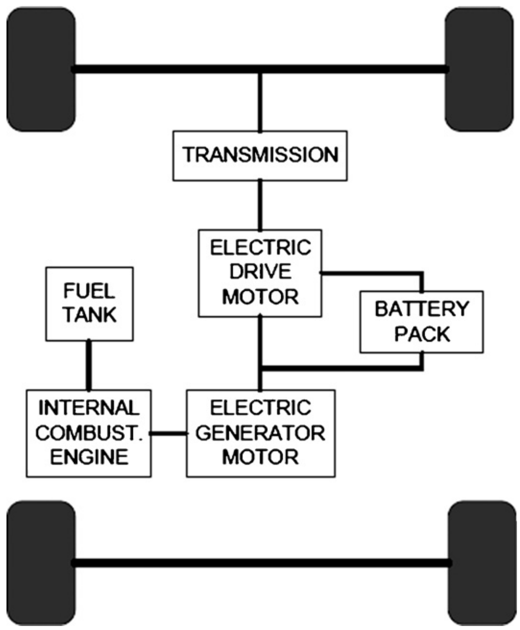

Fig. 4. Series PHEV block diagram.

3. ADVISOR simulation

3.1. Vehicle design

Series PHEVs were modeled in ADVISOR beginning with the default "small car" parameters. The following three vehicle models were included in our comparison:

- Series hybrid, low-power engine/generator
- Series hybrid, high-power engine/generator
- Series hybrid, rotary engine/generator

3.1.1. Electric motor/engine selection

The vehicle body, wheels, and accessories were kept constant at default values. The electric motor of the series vehicle was increased in size until the vehicle achieved a constant speed of 80 mph and met the required speed trace of the UDDS driving cycle. The smallest electric motor that could satisfy these requirements had a peak power of 83 kW. This motor size was used for all vehicles studied.

Reciprocating engines and generators were selected with two different peak power levels for comparison to the rotary engine. The low-power engine and generator system was sized based on the rated power of the dual rotor Rotapower engine (52 kW). The higher-power system was sized based on the peak power of that same engine (71 kW). The high-power engine and generator added 80 kg of mass to the vehicle compared to the low-power system.

3.1.2. Transmission selection

For the series vehicles, power was transmitted directly from the electric motor to the wheels. The electric motor selected was able to perform efficiently over a broad range of speeds, and no gear box was required. Power from the internal combustion engines was directly transmitted to their respective generators. ADVISOR simulations were designed with a single-speed transmission having 100% efficiency to achieve this effect.

3.1.3. Battery selection

As discussed earlier, hybrid vehicles are designed with a certain AER according to battery capacity. We chose to simulate the performance of series hybrid vehicles with three different AER values: 20, 40 and 60 miles (32.2, 64.4 and 96.6 km). These values represent a reasonable range based on existing and proposed vehicle designs and the cost and energy density of modern batteries. We based our values of battery capacity on the specifications of the Chevrolet Volt. The Volt is a series PHEV with an AER of 40 miles (64.4 km) and a battery capacity of 16 kWh [19]. The battery capacities of the vehicles in our simulations are shown in Table 2.

Table 2
Battery capacity and weight.

AER (miles)	AER (km)	ess_cap_scale multiplier	Capacity (kWh)	Weight (kg)
20	32.2	5	8	142
40	64.4	10	16	284
60	96.6	15	24	426

Lithium ion batteries were used for all simulations. Lithium ion batteries have a greater energy-to-weight ratio than other chemistries that have been used in electric vehicles (such as nickel metal hydride or lead-acid). The default lithium ion battery pack in ADVISOR is constructed of 25 modules, each of which has a capacity of 6 Ah. The nominal voltage of the battery pack is 267 V. Capacity in terms of kilowatt-hours can be calculated with the following relationship:

$$\text{kWh} = \text{Ah} \times \text{V}$$

This relationship shows that the default lithium ion battery model in ADVISOR has a capacity of approximately 1.6 kWh. We therefore modified the energy storage capacity input variable ("ess_cap_scale") by 5, 10, and 15 to arrive at the desired AERs of 20, 40 and 60 miles, respectively.

3.2. Driving cycles

The objective of vehicle simulation using ADVISOR was to accurately model the driving habits of American drivers. Therefore, all vehicles were analyzed on both city and highway driving conditions.

We chose to use the Urban Dynamometer Driving Schedule (UDDS) to simulate city driving, and the US06-Highway Supplemental Federal Test Procedure (US06-HWY) to represent highway driving. Velocity profiles for these driving cycles are shown in Figs. 5 and 6, respectively.

The UDDS cycle involves frequent acceleration and braking that one would encounter in a city or suburban setting. In contrast, the US06-HWY cycle has higher speeds and less braking, which simulates driving on the highway. A typical vehicle will be subjected to a mix of these two conditions.

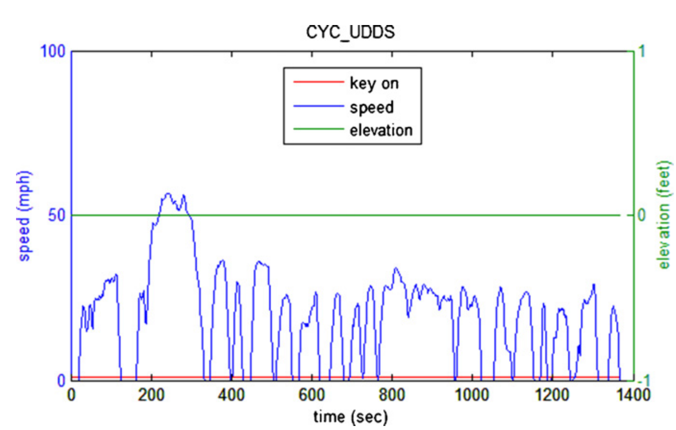

Fig. 5. Urban dynanometer driving schedule.

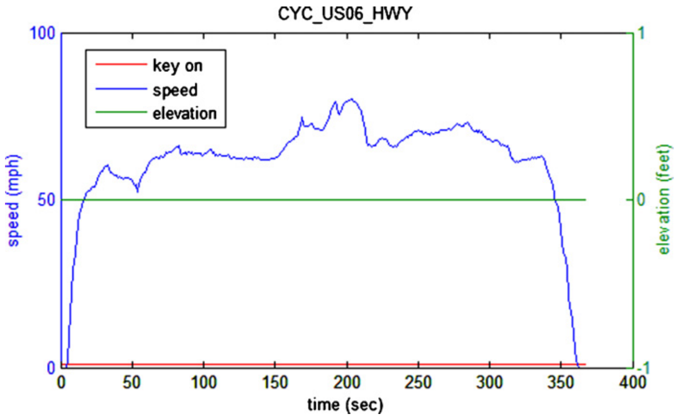

Fig. 6. US06-Highway Driving Cycle.

3.3. *All-electric/charge-sustaining*

Once the driving cycles were identified, the next step was to determine the energy required for each vehicle to drive a given distance under city and highway conditions. The vehicles were simulated using two different control strategies for each of these conditions: all-electric or charge sustaining. An all-electric simulation assumes a full initial battery charge and allows the vehicle to be propelled using only the energy stored in the battery pack. Charge-sustaining operation forces the final battery state of charge to be equal to the initial state of charge, requiring use of the gasoline-powered range extender.

It was assumed that all PHEVs were fully charged before embarking on a trip, including return commute trips from work (discussed further in Section 5). While operated within their AER, the vehicle performance was approximated by the all-electric control strategy. If the requested trip required the vehicle to operate beyond its AER, the charge sustaining control strategy was used to simulate vehicle operation with a depleted battery pack.

4. Simulation results

4.1. *Energy consumption: tank to wheel*

The individual driving cycles used in simulation were shorter than the AER of the vehicles, so both city and highway driving could be simulated with the all-electric strategy by running one single driving cycle. Ten consecutive driving cycles were simulated for charge-sustaining situations with an initial battery state-of-charge of zero in order to approximate a vehicle with an exhausted energy storage system.

This simulation yielded energy consumption values for each vehicle when powered by electricity (all-electric) or gasoline (charge-sustaining). These outputs represent the energy use between the fuel tank/battery pack and the vehicle drive train. This path is therefore described as "tank-to-wheel." Tank-to-wheel electricity and gasoline consumption is detailed in Table 3 for each vehicle in our comparison.

4.2. *Energy consumption: well to wheel*

The energy-related outputs from ADVISOR are limited to the tank-to-wheel path. To fully understand the energy consumption of the transportation sector, one must consider the complete well-to-wheel path, which includes the energy required to produce the fuel before it reaches the vehicle.

The U.S. Department of Energy "Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation" software model

Table 3
Tank-to-wheel energy consumption.

AER (mile)	Low power (52 kW) Reciprocating engine				High power (71 kW) Reciprocating engine				Dual rotor (71 kW peak) Wankel engine			
	City (UDDS)		Highway (US06-HWY)		City (UDDS)		Highway (US06-HWY)		City (UDDS)		Highway (US06-HWY)	
	Elect (kWh mile^{-1})	Gas* (gal mile^{-1})	Elect (kWh mile^{-1})	Gas (gal mile^{-1})	Elect (kWh mile^{-1})	Gas (gal mile^{-1})	Elect (kWh mile^{-1})	Gas (gal mile^{-1})	Elect (kWh mile^{-1})	Gas (gal mile^{-1})	Elect (kWh mile^{-1})	Gas (gal mile^{-1})
20	0.252	0.0241	0.304	0.0277	0.261	0.0256	0.311	0.0282	0.242	0.0253	0.296	0.0293
40	0.266	0.0252	0.309	0.0285	0.274	0.0264	0.316	0.0290	0.256	0.0264	0.302	0.0302
60	0.280	0.0265	0.319	0.0294	0.289	0.0272	0.325	0.0300	0.271	0.0274	0.311	0.0313

* *Note*: 1 gal = 3.79 L.

Table 4
Well-to-wheel energy consumption.

AER (mile)	Low power (52 kW)	Reciprocating engine			High power (71 kW)	Reciprocating engine			Dual rotor (71 kW peak)	Wankel engine		
	City (UDDS)		Highway (US06-HWY)		City (UDDS)		Highway (US06-HWY)		City (UDDS)		Highway (US06-HWY)	
	Elect (kWh mile^{-1})	Gas (kWh mile^{-1})	Elect (kWh mile^{-1})	Gas (kWh mile^{-1})	Elect (kWh mile^{-1})	Gas (kWh mile^{-1})	Elect (kWh mile^{-1})	Gas (kWh mile^{-1})	Elect (kWh mile^{-1})	Gas (kWh mile^{-1})	Elect (kWh mile^{-1})	Gas (kWh mile^{-1})
20	0.647	1.014	0.779	1.166	0.669	1.079	0.797	1.189	0.620	1.063	0.760	1.234
40	0.681	1.060	0.792	1.199	0.703							
60	0.719	1.114	0.817	1.124	0.742	1.147	0.833	1.264	0.694	1.153	0.798	1.315

Table 5
Well-to-wheel GHG emissions.

AER (mile)	Low power (52 kW)	Reciprocating engine			High power (71 kW)	Reciprocating engine			Dual rotor (71 kW peak)	Wankel engine		
	City (UDDS)		Highway (US06-HWY)		City (UDDS)		Highway (US06-HWY)		City (UDDS)		Highway (US06-HWY)	
	Elect (kWh mile^{-1})	Gas (kWh mile^{-1})	Elect (kWh mile^{-1})	Gas (kWh mile^{-1})	Elect (kWh mile^{-1})	Gas (kWh mile^{-1})	Elect (kWh mile^{-1})	Gas (kWh mile^{-1})	Elect (kWh mile^{-1})	Gas (kWh mile^{-1})	Elect (kWh mile^{-1})	Gas (kWh mile^{-1})
20	0.488	0.485	0.587	0.557	0.505	0.516	0.601	0.568	0.468	0.508	0.573	0.590
40	0.513	0.507	0.598	0.573	0.530	0.531	0.611	0.583	0.495	0.531	0.584	0.608
60	0.542	0.532	0.616	0.592	0.560	0.548	0.629	0.604	0.523	0.551	0.602	0.629

(GREET) was used for well-to-wheel energy analysis. The GREET model simulates energy use and emissions associated with the production and distribution of transportation fuels. The mix of electricity generation methods was set to the 2010 U.S. average: 50.4% coal, 20% nuclear, 18.3% natural gas, 9.5% other, 1.1% residual oil, and 0.7% biomass [20].

This analysis yielded two important results. First, the average efficiency of electricity generation in the United States in 2010 was shown to be 39.0%. This value was used to adjust the electricity consumption values listed in Table 3 in order to estimate well-to-wheel energy consumption of vehicles driving on grid electricity.

Secondly, GREET analysis determined the well-to-wheel energy use for gasoline fuel. The GREET software assumes a constant fuel economy of 23.4 mpg when calculating vehicle fuel consumption. Based on this value, a vehicle using gasoline consumes 1.799 kWh of energy per mile (1.118 kWh per km). The hybrid vehicles in our simulation achieved better fuel economy than the 23.4 mpg (10.1 L 100 km^{-1}) constant used in the GREET model. Gasoline well-to-wheel energy use for our simulated vehicles can be estimated using the following relationship:

Well-to-wheel energy consumption per mile for gasoline :

$$\left(\frac{\text{kWh}}{\text{mile}}\right)_{\text{gas}} = \frac{1.799(\text{kWh/mile}) \times 23.4\,\text{mpg}}{\text{FE}_{\text{ADV}}} \quad (2)$$

where FE_{ADV} refers to the fuel economy calculated using ADVISOR for each vehicle. Well-to-wheel electricity and gasoline consumption data are presented in Table 4 for each vehicle in our comparison.

4.3. Greenhouse gas emissions: well to wheel

The same GREET simulation used to study energy consumption also generated information about GHG emissions for the well-to-wheel path. The GREET model enables analysis of the emissions of GHGs such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The GREET software predicted that the current U.S. electricity generation mix produces 0.754 kg of GHG equivalent per kWh energy production [20]. This value can be directly applied to the energy consumption data in Table 4 to determine GHG emissions for the vehicles in our simulation.

Greenhouse gas emissions data for gasoline must be adjusted according to the fuel economy values of the vehicles in our simulation. According to the GREET model, vehicles powered by gasoline produce 0.478 kg of GHG emissions per mile based on a default fuel economy of 23.4 mpg. Similar to Eq. (2), the GHG emissions from gasoline can be calculated using the following relationship:

GHG emissions per mile for gasoline : $\left(\frac{\text{GHG}}{\text{mile}}\right)_{\text{gas}}$

$$= \frac{0.478(\text{kg/mile}) \times 23.4\,\text{mpg}}{\text{FE}_{\text{ADV}}} \quad (3)$$

Greenhouse gas emissions data are included in Table 5 for each vehicle in our comparison.

5. Analysis

5.1. Driving trips

The simulation outputs from ADVISOR summarize the total energy consumption and GHG emissions per mile in either city or highway driving conditions. This data was then utilized to calculate the energy use and GHG emissions for specific driving trips. The following four trips were used to simulate typical driving behavior:

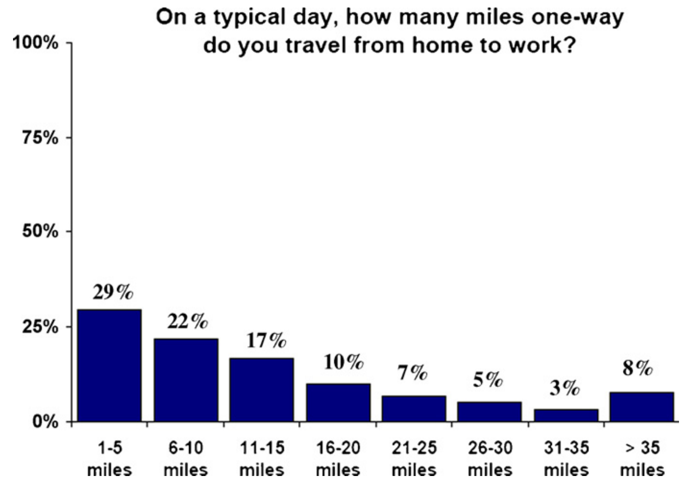

Fig. 7. One-way commute distance distribution [21].

- Average commute (city—15 miles [24.1 km])
- Long commute (city—30 miles [48.3 km])
- Weekend drive (highway—150 miles [241.4 km])
- Vacation (highway—400 miles [643.7 km])

Fig. 7 displays a distribution of commuting distances for American drivers. According to the Bureau of Transportation Statistics, 68% of Americans commute up to 15 miles (one-way), and another 22% have a longer commute of up to 30 miles [21]. As these two driving distances account for 90% of U.S. commuters, we elected to partition the analysis to study these two distinct commuting distances.

We applied the city (UDDS) driving cycle to commuting trips. Weekend and vacation trips were simulated using the highway (US06-HWY) cycle, and were chosen based on illustrative destinations from the California Bay Area. For example, a San Francisco resident may be interested in knowing the energy consumption and GHG emissions of his PHEV on a weekend drive to Lake Tahoe (150 miles) or a vacation to Los Angeles (400 miles).

The distance driven on electricity and on gasoline was calculated for each trip based on the AER of the vehicle. Using the data presented in Tables 4 and 5, energy use and GHG emissions of each vehicle were calculated for the four driving trips of interest. These results are presented in Figs. 8 and 9.

Fig. 8 shows that the Wankel engine is the most effective range extender for both average and extended commute trips. The average reduction in energy consumption for the different AER vehicles over the 15 mile commute distance was 3.72% compared to the low-power and 6.78% compared to the high-power reciprocating engine-equipped vehicles. A lesser reduction of 2.41% and 5.91%, respectively, was recorded for the 30 mile commute distance. The low-power and high-power reciprocating engine equipped vehicles weighed an additional 186 kg and 226 kg, respectively, compared to the Wankel equipped vehicle. The series hybrid vehicles in this simulation were powered with energy stored in their battery systems and did not require supplemental power from their range extending systems for daily commute trips. The higher weight of the reciprocating engines resulted in poorer energy efficiency of those vehicles compared to the vehicle equipped with a Wankel engine.

The Wankel engine was the least effective range extender for longer driving distances. For the 150 mile trip, the Wankel vehicle consumed an average of 6.7% more energy than the low-power and 2.4% more energy than the high-power recipocating vehicle (averaged across the 20-, 40- and 60-mile AER simulations). For the 400 mile trip, the energy consumption of the Wankel engine

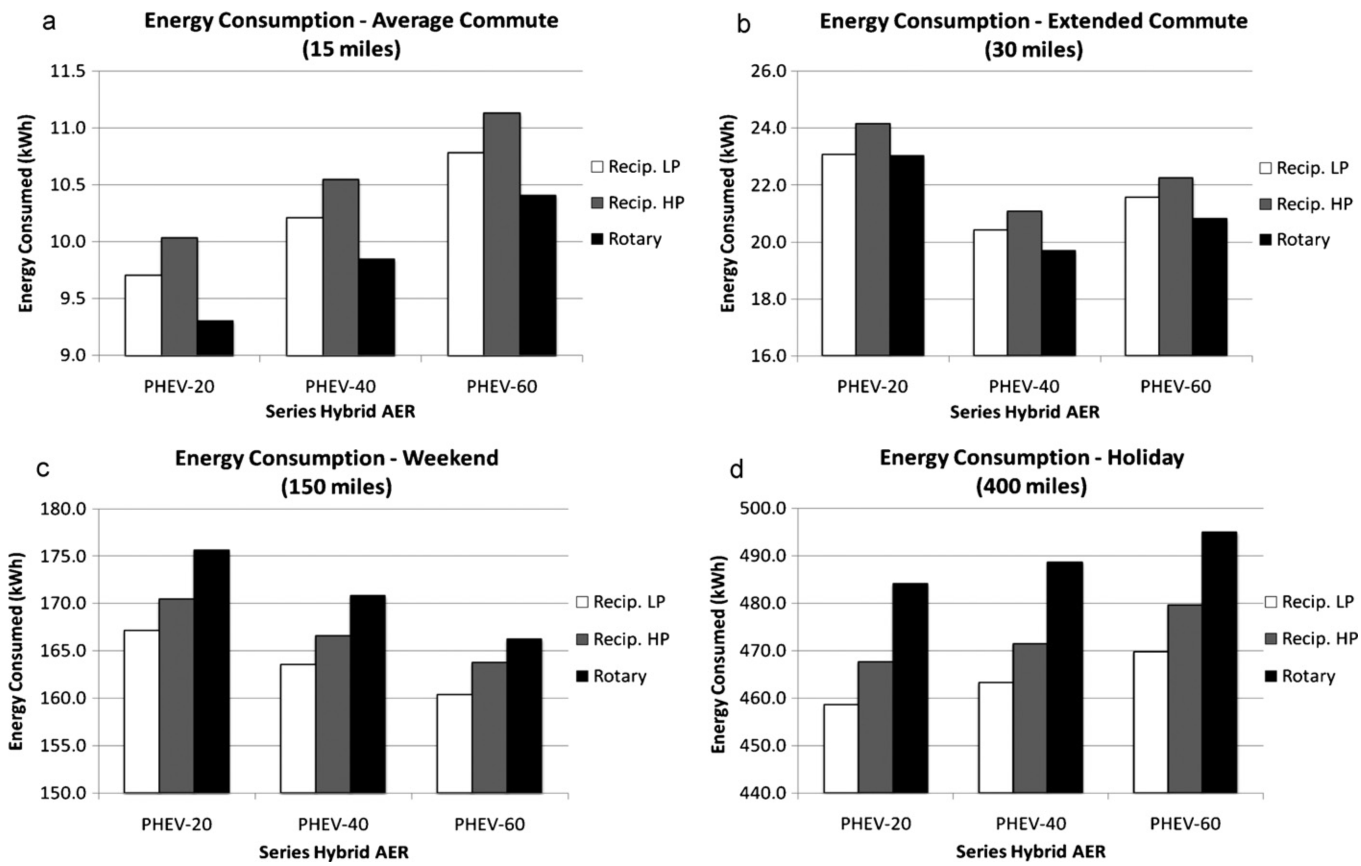

Fig. 8. Energy consumption per driving trip, (a) 15-mile (city) commute; (b) 30-mile (city) commute; (c) 150-mile weekend (highway) trip; (d) 400-mile vacation (highway) trip.

was 8.6% greater than the low-power reciprocating engine and 3.5% greater than the high-power engine. The series hybrid vehicles exhausted their AER on these extended trips and were forced to rely on the range extending module for supplemental energy. The poorer fuel efficiency of the Wankel engine overshadowed the advantage of weight reduction in these scenarios, and the vehicles with Wankel engines consumed more energy during operation than those with reciprocating engines.

The GHG emissions for the four different trips discussed in this paper, shown in Fig. 9, generally mimic the trends in energy consumption shown in Fig. 8 and discussed above. Vehicle emissions generally exhibit a strong relationship to energy consumption. A discrepancy is discussed in Section 5.3.2.

5.2. Annual driving

The annual average vehicle-miles travelled (VMT) per capita in the United States is approximately 10,100 miles (16,254 km) [22]. This total distance was divided among the trips discussed in Section 5.1 based on a commuting distance of 15 miles. Drivers were assumed to make the same non-commute trips (weekend and holiday) independent of commuting distance. Table 6 displays the annual trips chosen to simulate drivers in the partitioned commuting groups.

5.3. Annual vehicle performance

Based on the well-to-wheel energy consumption of each vehicle in the study, and the annual driving trips summarized in Table 6, the following sections discuss the annual energy consumption and GHG emissions of series PHEVs with varying AER and engine type.

5.3.1. Average (15-mile) commute performance

Figs. 10 and 11 display the annual energy consumption and GHG emissions for a driver with a 15-mile commute. The plots compare the total energy consumed against varying battery capacities and engine configurations.

The rotary engine is the most efficient range extender for a series hybrid vehicle when driven on a 15-mile daily commute. This is true regardless of AER, as all vehicles in the simulation were able to complete commute trips (74% of annual mileage) without requiring use of their range extending modules. The reduced vehicle weight of the Wankel engine equipped vehicle for the majority of miles travelled produced the most energy efficient vehicle, regardless of the poorer operating efficiency of the Wankel engine.

Because of this improved efficiency, the rotary engine equipped series PHEV has lower GHG emissions when compared to the vehi-

Table 6
Total mileage per year, U.S. drivers.

	Distance (miles)	Occurrence (trips per year)	Total (miles per year)
Average commute			
Commute	15	500	7500
Weekend	150	12	1800
Holiday	400	2	800
		VMT	10,100
Extended commute			
Commute	30	500	15,000
Weekend	150	12	1800
Holiday	400	2	800
		VMT	17,600

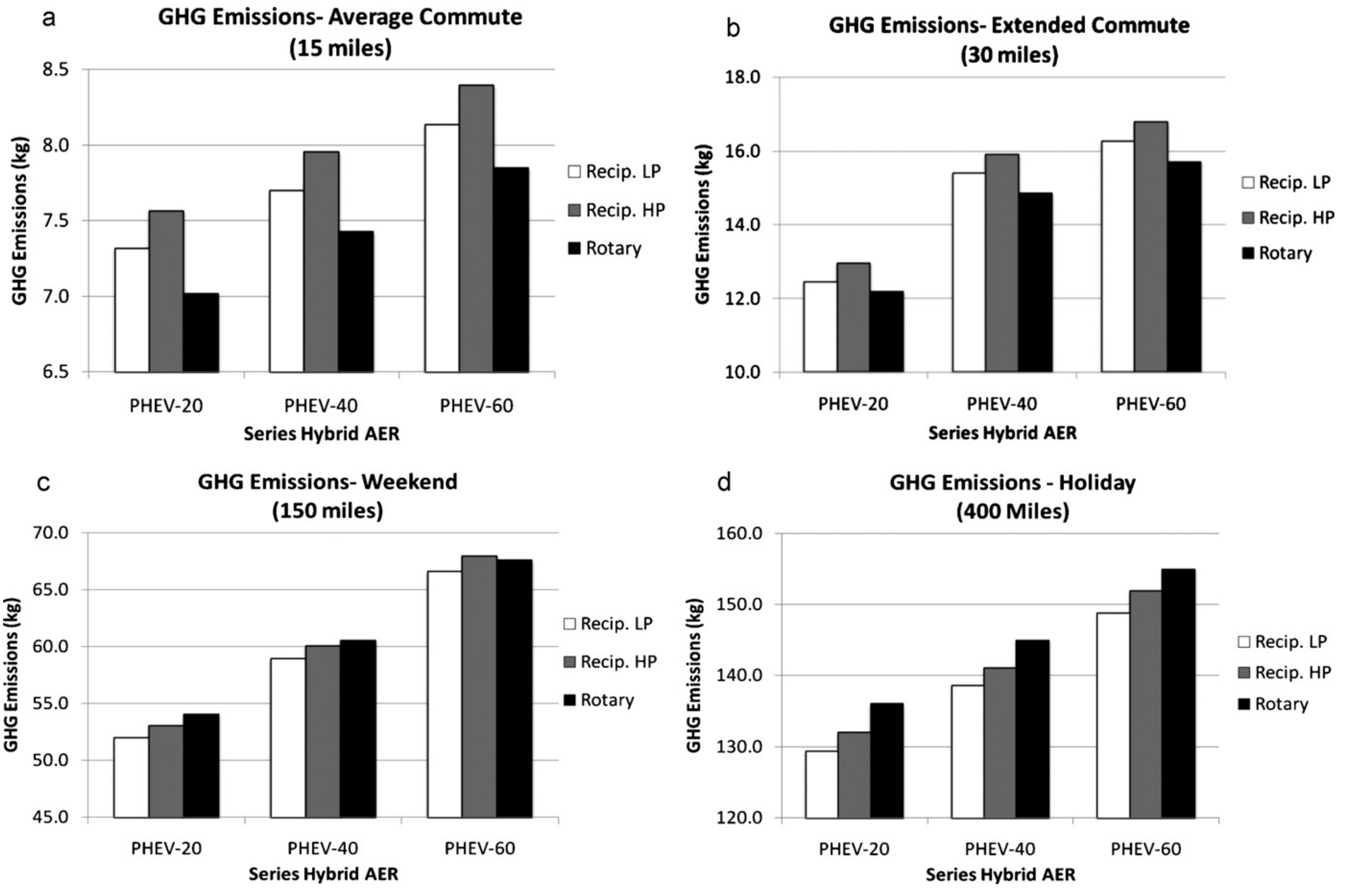

Fig. 9. Greenhouse gas emissions per driving trip, (a) 15-mile (city) commute; (b) 30-mile (city) commute; (c) 150-mile weekend (highway) trip; (d) 400-mile vacation (highway) trip.

cles with reciprocating engine range extenders. Overall, the most energy-efficient vehicle with the lowest GHG emissions for the average commuter was the series PHEV-20 (20 mile AER) with a Wankel engine range extender. Based on this simulation, a single PHEV-20 equipped with a Wankel range extender would save 46 kWh of energy and 112 kg of GHG emissions annually compared to a vehicle powered by a low-power reciprocating range extender. These savings increase to 269 kWh of energy and 254 kg of GHG emissions compared to a high-power reciprocating range extender.

The annual cost of driving a PHEV on average commuting distances corresponds with energy use. Table 7 displays the annual energy cost for all vehicles with a 20-mile AER. Cost data are based on an estimated gasoline price of $3.00 per gallon and the national average electricity price of $0.10 per kWh [23]. The series hybrid with a rotary engine yields the lowest energy cost.

5.3.2. Extended (30-mile) commute performance

Figs. 12 and 13 display the annual energy consumption and GHG emissions for a driver with a 30-mile commute. In this case, PHEV-20 vehicles are required to operate the gasoline-powered range extender for 10 miles (16.1 km) during each individual commute trip, which is equivalent to 21% of the annual miles travelled by the extended commuter. This daily reliance on gasoline adversely affects the overall energy efficiency of vehicles with a 20 mile AER. The lower fuel efficiency of the rotary engine resulted in the greatest energy consumption of vehicles with a 20 mile AER.

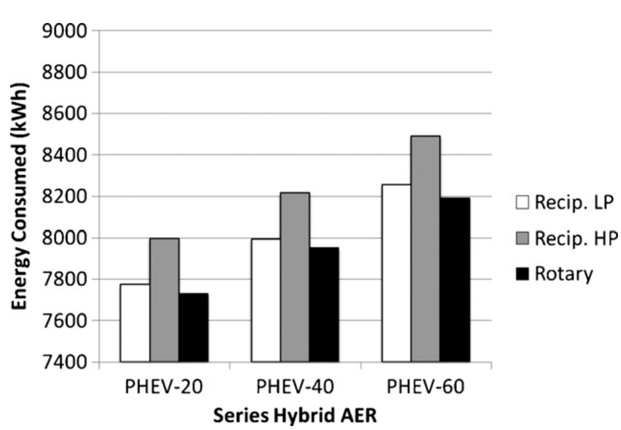

Fig. 10. Annual energy consumption, 15-mile commute.

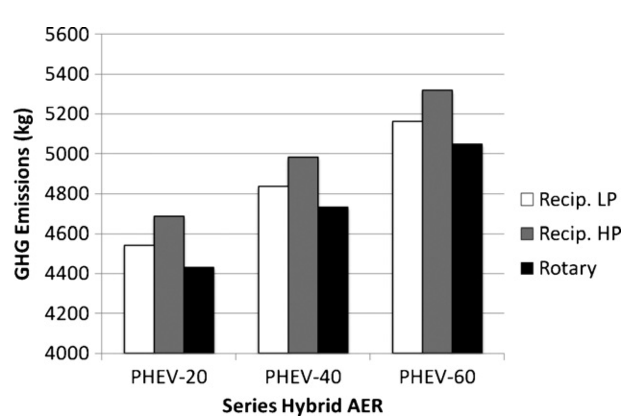

Fig. 11. Annual GHG emissions, 15-mile commute.

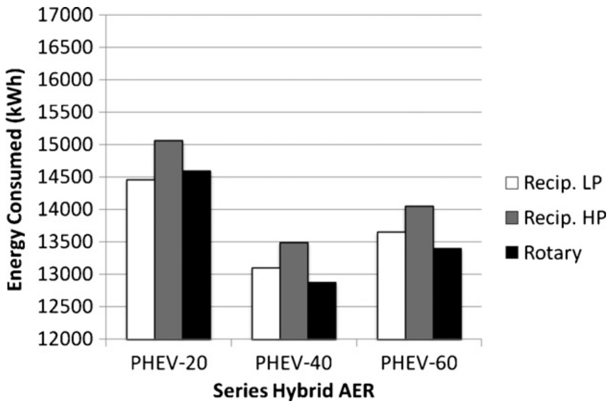

Fig. 12. Annual energy consumption, 30-mile commute.

The PHEV-40 and -60 vehicles are able to complete the 30-mile commute using all-electric mode. Such vehicles with rotary engines exhibited lower energy consumption and GHG emissions compared to their reciprocating-engine counterparts due to reduced vehicle weight.

Overall, the most efficient vehicle for the extended commuter is the series PHEV-40 powered by a rotary engine. This vehicle saved 223 kWh of energy per year compared to the low-power reciprocating engine and 613 kWh per year compared to the high-power PHEV-40.

Interestingly, the vehicles with the lowest energy use did not exhibit the lowest GHG emissions. The discrepancy between energy consumption and GHG emissions is due to the heavy reliance on coal in the U.S. electricity generation mix. Coal is heavy in carbon, and emits high amounts of GHGs compared to other fuel sources. Combustion of coal is used for just over 50% of all electricity generation, but is responsible for 83% of primary carbon dioxide emissions [24]. The PHEV-40 and -60 vehicles are powered exclusively by electricity on the long commute, producing a significant amount of GHG emissions when considered on a well-to-wheel basis. In contrast, the PHEV-20 vehicle uses supplemental energy from its gasoline range extender, reducing the amount of coal which must be combusted to power the vehicle. The lighter Wankel powered vehicles emitted the least GHG emissions due to their more efficient all electric operation. Compared to the low- and high-power reciprocating engine PHEV-40s, the Wankel equipped PHEV-40 reduced GHG emissions by 240 kg and 513 kg per year, respectively.

Table 8 displays the annual energy cost for vehicles with 40-mile AER. The PHEV with a rotary engine range extender yields the lowest energy cost in this situation.

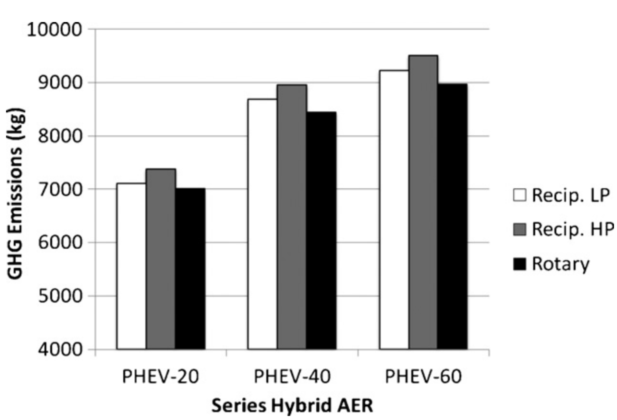

Fig. 13. Annual GHG emissions, 30-mile commute.

Table 7
Annual energy cost, 15-mile daily commute, 20-mile AER.

Range extender	Annual energy cost
Recip. LP	$696.34
Recip. HP	$716.97
Rotary	$687.32

Table 8
Annual energy cost, 30-mile daily commute, 40-mile AER.

Range extender	Annual energy cost
Recip. LP	$1232.33
Recip. HP	$1269.91
Rotary	$1206.09

5.3.3. Renewable energy considerations

Improving the U.S. energy mix by supplementing fossil fuel power with renewable, low-carbon sources such as wind and solar energy will greatly reduce the GHG emissions of electricity generation. This reduction would be directly realized by the PHEV fleet. Using renewable energy sources for power generation will also help to avoid the problem of depleting another finite natural resource.

Wind and solar power can potentially help to build energy independence into the transportation sector, but are currently cost inhibitive. Vehicles equipped with the rotary engine as a range extender utilized electricity most efficiently due to reduced vehicle weight. These vehicles could operate on a reduced amount, and thus reduced cost, of renewable energy. The rotary engine as a range extender could therefore ease the transition towards renewable electricity generation.

6. Conclusions

The Wankel (rotary) engine has the advantage of lower weight, more compact size and packaging, and reduced NVH compared to the reciprocating engine. These benefits come at the expense of lower fuel economy. The properties of the Wankel engine make it an attractive option for use as a range extender in series PHEVs. PHEVs with varying battery capacities were modeled using the ADVISOR software package. Well-to-wheel fuel economy and greenhouse gas emissions data were obtained using the GREET software model. Series hybrid vehicles with DISC rotary engines are proven to be more efficient in all-electric mode, in terms of energy consumption and GHG emissions, than vehicles with reciprocating engines. Vehicles with rotary engines are generally less efficient when powered by gasoline.

Average U.S. driving habits were used to predict the annual energy consumption and GHG emissions of PHEVs. The optimal vehicle configuration, in terms of energy consumption, GHG emissions, and energy cost, is shown to be a series PHEV with a rotary engine as a range extender. The ideal battery capacity depends on the driver's daily commuting distance. It is concluded that the benefits of the rotary engine do indeed counteract the detriment of lower fuel economy. Application of the DISC rotary engine as a range extender for PHEVs would have positive effects on the transportation sector and would ease the transition to renewable power generation.

7. Future work

The UC Davis Green Transportation Laboratory is currently conducting engine experiments to map the performance of a 35 hp single-rotor Wankel engine. The resulting data will be used to construct a detailed Wankel engine model in ADVISOR, including engine performance and tailpipe emissions for a variety of alternative fuels.

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