

The Electrification of the Automobile: From Conventional Hybrid, to Plug-in Hybrids, to Extended-Range Electric Vehicles

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ABSTRACT

A key element of General Motors' Advanced Propulsion Technology Strategy is the electrification of the automobile. The objectives of this strategy are reduced fuel consumption, reduced emissions and increased energy security/diversification. The introduction of hybrid vehicles was one of the first steps as a result of this strategy. To determine future opportunities and direction, an extensive study was completed to better understand the ability of Plug-in Hybrid Electric Vehicles (PHEV) and Extended-Range Electric Vehicles (E-REV) to address societal challenges. The study evaluated real world representative driving datasets to understand actual vehicle usage. Vehicle simulations were conducted to evaluate the merits of PHEV and E-REV configurations.

As derivatives of conventional full hybrids, PHEVs have the potential to deliver a significant reduction in petroleum usage. However, the fuel consumption benefits are limited by the underlying constraints of the base hybrid systems and vehicles. Even with incremental electric power and speed improvements, the PHEV's lack of full-performance, all-electric capability requires engine operation under everyday speed and/or load conditions, regardless of available battery energy. This creates emissions concerns and can severely limit the actual all-electric driving range in the real world.

The E-REV is principally an Electric Vehicle (EV) with full vehicle performance available as an EV. Significantly, it overcomes the historical EV re-charge time limitations by adding a fuel-powered electric generator to extend driving range. Actual all-electric driving can regularly be experienced throughout the working energy range of the vehicle's battery without fear of being stranded. The E-REV offers the opportunity for petroleum independence, and a dramatic reduction in emissions for many drivers.

An E-REV traction drive and battery system needs to be specifically designed for the task. The systems are significantly more capable and larger than those designed for PHEVs. An E-REV is typically also architected to accommodate packaging of these systems while retaining performance and utility. The compelling benefits of the E-REV drive GM to address these challenges.

The study results indicate that both the PHEVs and the E-REVs can play a role in addressing future needs. The study shows that in the real world the PHEV is quite likely to run with blended operation, but the E-REV is very likely to remain in EV mode for most drivers.

GM is currently developing both PHEV and E-REV vehicles. The Saturn VUE Green Line PHEV is being developed as a derivative of the conventional 2-Mode Hybrid. The Chevrolet Volt E-REV is also under development with full performance, all-electric capability, but without practical range limitations.

INTRODUCTION

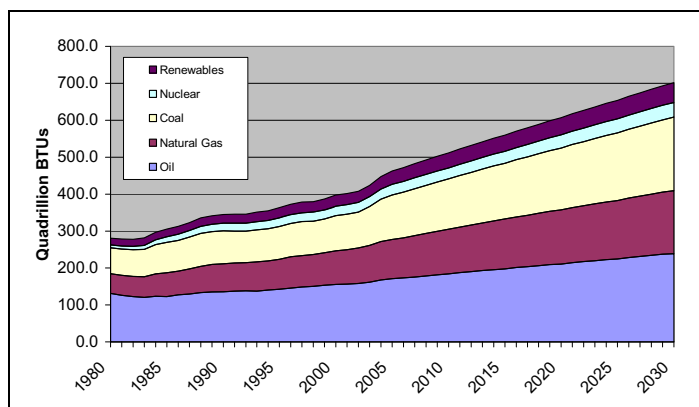


Figure 1 – Projected worldwide energy sources

ENERGY OUTLOOK - Worldwide energy production is projected to grow at an annual rate of over 2% providing



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for an expanding population and industrial development, despite increasing efficiencies in consumption. Figure 1 shows that fuels, primarily petroleum oil is projected to grow at a similar rate, even in scenarios where the fuel remains at relatively high historical costs. 2030 World oil consumption is accordingly projected at 210 quadrillion Btu (118 million barrels annually), an increase of over 30% compared to 2004. The portion of oil used for transportation is growing and is projected to use 68% of liquid fuel energy over the period 2004 - 2030. [1]

Significant concerns have been raised about the security of oil supply and initiatives have been outlined to diversify energy in transportation including initiatives proposed by the US Administration and the Department of Energy [2]. These initiatives include the development of a vehicle that plugs-in and derives a great deal of its utility using energy from the electric power grid. Recent enthusiasm in PHEVs and E-REVs, in part, stems from these concerns.

General Motors' Advanced Propulsion Technology Strategy is to remove automobiles from the environmental dialogue. The strategy calls for reduced consumption, reduced emissions, and diversification of energy sources. Continued improvements in base vehicle and powertrain efficiencies figure prominently in GM's plans, as does an aggressive rollout of ethanol-blended fuels.

Another key element of the strategy is to allow automobiles to shift significant portions of their required energy from petroleum to other sources. Figure 2 shows a network of the various energy sources, energy pathways, and possible on-vehicle energy storage media. Higher power motors, higher energy on-board electrical storage, and systems that allow for driving without a combustion engine enable vehicles that can use non-petroleum energy sources for transportation. We call the increase in electrical content and magnitude onto the vehicle "electrification".

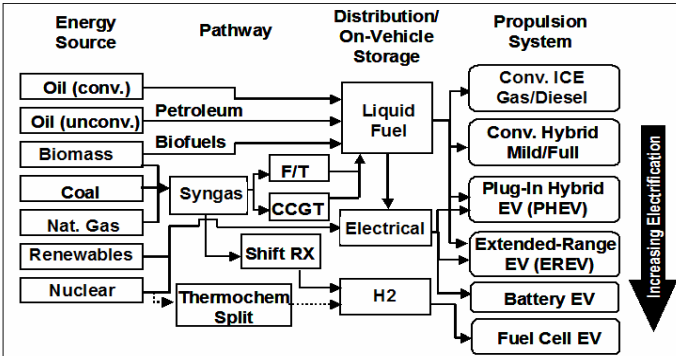


Figure 2 – Energy sources, paths, on-vehicle storage and vehicle propulsion systems

Diverse energy sources figure into the future of the worlds total energy bill. Yet today, automobiles rely

almost exclusively on liquid fuels as the on-vehicle storage medium. Note that most other sources can be, and are already, used as part of the electric grid as shown Figure 3.

Electric grid power is a natural candidate for transportation energy distribution with on-vehicle storage. Worldwide grid electricity is expected to approximately double in the next two decades, outstripping the growth in total energy consumption. Improved generating efficiency from new plants means that electrical generation will continue to use approximately 40% of the world energy sources [1].

If electric energy can be effectively stored and integrated to propel automobiles, the full range of energy sources could be tapped for future automotive needs. Furthermore, future improvements in the efficiency and environmental impact of electric power generation will be directly realized by the PHEVs and E-REVs on the road at that time.

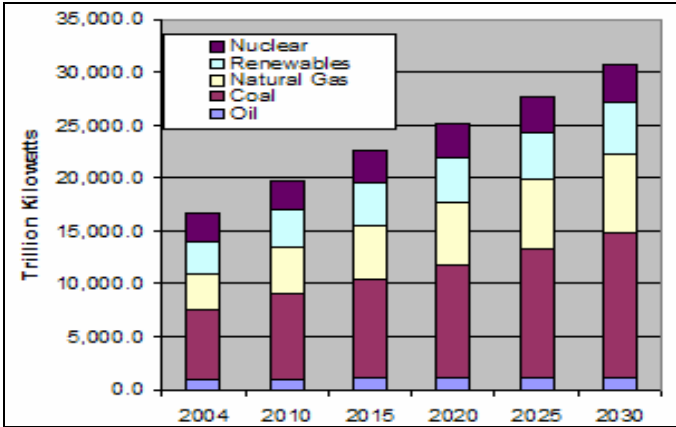


Figure 3 – Projected worldwide electric power capacity

ELECTRIFICATION - Several technical and commercial challenges are associated with charging, storing and making use of electric energy to propel automobiles. The term "electrification" means development and integration of systems and components that enable electric energy to be used for transportation. Challenges of electrification include providing automotive levels of reliability and durability, package density, acceptable noise, vibration and harshness, and automotive levels of cost in a set of new components and control algorithms.

Electrification has its roots in modern times with introduction of the first modern electric vehicle, the 1996 GM EV1. The EV1 was a full performance Battery Electric Vehicle (BEV) with a complete set of vehicle electrification technologies [3]. They included the first modern:

- Vehicle charging interface

- Off-board charging system
- Battery pack and charge control system
- Electric isolation system
- Electric drive and traction system
- Electric accessory power system
- Electric steering system
- Electric air conditioning system
- Electrically actuated brakes
- Regenerative braking systems

The EV1 also included an efficient vehicle package and structure designed at the outset to accommodate a battery pack with sufficient energy and power for full performance as an electric vehicle.

Unfortunately, the market experience with the EV1 indicated that additional improvements in BEVs were needed. Some EV1 drivers gave the term “range anxiety” to their continual concern and fear of becoming stranded with a discharged battery in a limited range vehicle. Improvements in on-board energy storage and charging time were necessary for more widespread deployment of BEVs. Most EV-enabling electric components and systems have found utility in the meanwhile when used in mild and full Hybrids Electric Vehicles (HEVs).

TRANSITIONAL ELECTRIC VEHICLES - Electrification has continued in the industry with the development of conventional HEVs. These vehicles do not provide full performance on electric power alone, and therefore the power and energy level required for the systems is reduced when compared with full performance BEVs. In addition, while conventional hybrids (both mild and full) improve vehicle efficiency and directly reduce petroleum consumption and CO₂ emissions, all the energy they consume is from an on-board liquid medium. In HEVs, electric storage and power on board are only used to better utilize the liquid fuel. Therefore, HEVs offer no additional energy pathways for diverse sources, including CO₂ neutral renewables.

However, hybrids are being produced at volumes now sufficient to develop and improve the reliability and cost effectiveness of electrification subsystems. Considering a long-term goal of greater energy diversification, hybrids can be considered the first of transitional electric vehicles. Figure 4 is a table illustrating the features of transitional electric vehicle types, including HEVs, Plug-In Hybrid Electric Vehicles (PHEVs) and Extended-Range Electric Vehicles (E-REVs). Each is progressively more electrified and we expect plays a progressively larger role toward shifting a portion of the transportation energy burden toward other sources and away from petroleum.

Vehicle Type	Electric Power	Onboard Electric Storage	Grid Conn.	Electric Driving
Mild HEV	low	low	no	no
Full HEV	med	low	no	very limited
PHEV	med	med	yes	limited
E-REV	high	high	yes	Full

Figure 4 - Features of Transitional Electric Vehicles

MAIN SECTION

DEFINITIONS – Before beginning a detailed discussion on the benefits of varying degrees of electrification it is necessary to define the key systems.

Hybrid - A hybrid is defined by SAE [4] as: “A vehicle with two or more energy storage systems both of which must provide propulsion power – either together or independently.” In practice, hybrid vehicles typically require both sources to provide full vehicle capability. The engine is also typically the larger of the two propulsion sources, being sized to provide most of the power during high power vehicle events. The motor is typically the smaller of the two propulsion sources, being sized to maximize the amount of energy that can be captured during braking and for limited low speed EV operation.

Plug-in Hybrid (PHEV) - A PHEV has been defined by SAE [4] as: “A hybrid vehicle with the ability to store and use off-board electrical energy in the RESS (rechargeable energy storage system).” These systems are in effect an incremental improvement over the Hybrid with the addition of a large battery with greater energy storage capability, a charger, and modified controls for battery energy management and utilization.

There are two types of PHEVs operating strategies. These operating strategies require the definition of a schedule for discussion. The EPA urban, referred to as the urban, schedule is a common reference for PHEVs and will be used for this discussion.

The first type has an operating strategy which is very similar to the conventional hybrid. The engine use is required for most accelerations and speeds. The characteristics of this mode of operation are shown in Figure 5. Here you can see that the engine starts almost from the start and engine power is used throughout driving to supplement battery power usage. For PHEVs that use conventional hybrids as the starting point, this mode of operation is typical due to the operational speed and electrical power capabilities of the underlying hybrid systems. We call such a hybrid a conversion PHEV.

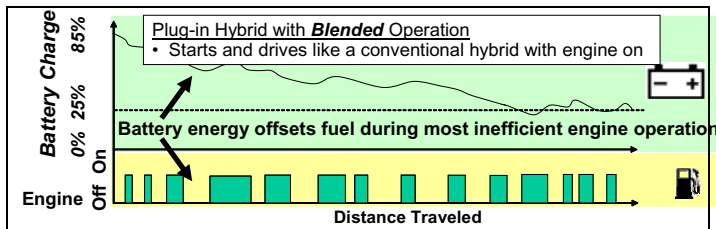


Figure 5 – A Conversion PHEV using a blended operating strategy

The second type of PHEV operation strategy is referred to as *Initial EV*. This type of system requires that the battery, motors, thermal systems, power electronics and system configuration be set to allow electric-only operation over the complete power and speed range of a cycle, in this case the urban schedule. The characteristics of this mode of operation are shown in Figure 6. In this figure you see that while the battery is depleting the stored energy the vehicle operates electric-only, without any engine operation. Once the battery is depleted, the vehicle operates like a conventional hybrid.

In real world operation, anytime during operation that the driver requests more power or speed than the motor and battery can provide, the engine is required to start and the controls will default to a *Blended* mode of operation to maintain emissions capability. In order to delay engine start in an Initial EV PHEV, a full hybrid system may have to be additionally modified to raise the traction power capability, and to extend the speed at which the vehicle operates electrically. We will examine the benefits of such modifications sufficient to drive the urban driving schedule, and call it an “urban-capable PHEV”.

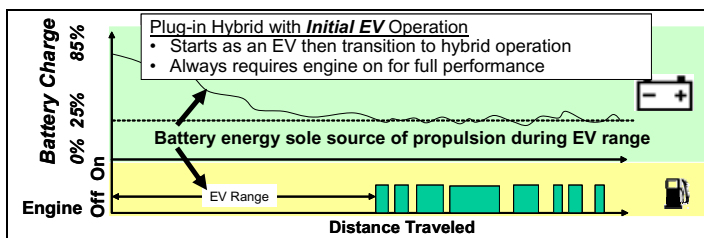


Figure 6 – A Urban-Capable PHEV using an Initial EV operating strategy

Extended-Range Electric Vehicle (E-REV) - SAE has not established a definition for an E-REV. The authors propose the following definition: “A vehicle that functions as a full-performance battery electric vehicle when energy is available from an onboard RESS and having an auxiliary energy supply that is only engaged when the RESS energy is not available.” This is very similar to a vehicle envisioned in the 2007 ARB Expert panel report [5], when they described,

“ This type of vehicle can operate as a full performance ZEV, during the time the ICE is not operating, and can avoid the cold start emission

problem discussed above and it requires a relatively large energy battery and a large full performance, electric drive propulsions system, similar to FPBEV or FCEV....”

The E-REV is unique from a PHEV in that the vehicle, battery and propulsion system are sized such that the engine never is required for operation of the vehicle when energy is available from the battery. The definition of this type of vehicle does not require the specification of a operating cycle (urban schedule in the PHEV discussion). As a full-performance battery electric vehicle, the battery, motor, and power electronics must be sized for the full capability of the vehicle. The vehicle must also be architected to allow packaging of the large E-REV battery which has a greater size due to the full EV requirement. The characteristics an E-REV are shown Figure 7. The operation of an E-REV looks similar to that of an Initial EV PHEV; however an E-REV must maintain this mode of operation on all operating schedules when energy is available from the battery. An E-REV does not need to start the engine for speed or power demands from the driver and therefore does not need to transition to a *Blended* operation strategy when battery energy is available, unlike the *Initial EV* PHEV.

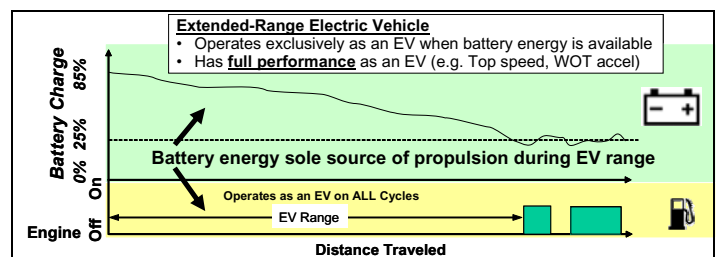


Figure 7–Characteristics of E-REV operation

A better understanding of the different systems is gained by examining Figures 8. This figure shows that as greater electric-only operation is required, there is a need to increase motor size and overall electric propulsion capability. Hybrid and PHEVs are able to blend electric and engine power to propel the vehicle and therefore require less total onboard power than the E-REV. The E-REV requires full electric propulsion capability and as such, the additional power capability of the total onboard power exceeds what is required to propel the vehicle. The E-REV does allow significant engine downsizing in that the engine power is not required to meet peak vehicle power demands and can be sized to meet only continuous power demand.