



SCUDERI ENGINE

**ELECTRIC CARS, HYBRIDS AND THE INTERNAL COMBUSTION ENGINE
CURRENT USES, FUTURE BENEFITS**



A DISCUSSION PAPER FROM SCUDERI GROUP

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Electric cars, hybrids and the internal combustion engine — current uses, future benefits

A barrel of crude contains approximately 42 gallons, which, refined, yields anywhere from 19 to 28 gallons of gasoline, depending on the crude used.³

Introduction

Governments worldwide are pushing electric car technology as a partial answer to climate change, pollution, dependence on foreign oil and the need to achieve fuel efficiency. However, many challenges face electric vehicles- lack of support infrastructure, vehicle cost (to produce, government subsidies, and cost to the consumer), effective range, weight, maintenance and the requirement for expensive, toxic batteries.

In fact, many technologies - some based on the venerable internal combustion engine - present environmentally effective alternatives to electric cars. Available today, these technologies represent a less-disruptive, more cost-effective path to energy independence and clean-air goals, without the significant risks inherent in most battery technology or the unintended consequences of pushing energy consumption from the gas pump to the coal-fired plant. And at least one of the alternate technologies takes advantage of car makers' existing investments in plant and tooling, offering a shorter, less risky path to success.

internal combustion engine that combines the advantages of efficient operation, reduced barriers to entry for carmakers, and a short design-to-production cycle. With the Scuderi Engine, which will have minimal retooling and adaptation costs, automakers and governments can meet the political and environmental challenges of reduced fuel consumption, higher efficiency, reduced weight and reduced pollution, supporting green and clean-power initiatives with minimal upfront investment.

Cars, trucks and buses

Few would argue that reducing dependence on fossil fuels is a good thing. With more than 120 million registered passenger cars, 110 million trucks and 1 million buses on US roads today¹ — most powered by internal combustion engines using fossil fuels — and the average consumer using upwards of 500 gallons of gasoline a year², reducing dependence on fossil fuels, and the internal combustion engines (ICE) that consume those fuels, appears to be a daunting task. (See Table 1 for a breakdown of energy resource use.)

In this discussion paper we will review the benefits and limitations of electric car technology, explore hybrid options, battery technologies and related issues, and introduce the Scuderi Engine, a split-cycle,

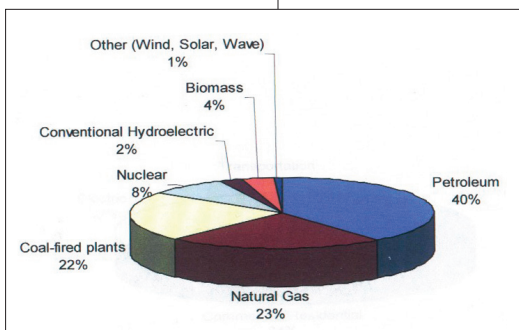


Table 1: Total Energy Resources Breakdown. Source: Institute for Energy Research

¹ <http://www.census.gov/compendia/statab/2010/tables/10s1060.pdf>

² http://wiki.answers.com/Q/How_much_gasoline_does_the_US_use_in_a_year

³ <http://www.newton.dep.anl.gov/askasci/eng99/eng99288.htm>

As governments struggle to find alternatives, they have turned to electric vehicles (EV) and battery-dependent electric hybrid vehicles (BEHV) as a potential savior, citing reduced operating and maintenance costs, reduced emissions and reduced dependence on foreign oil. These points, however, must be evaluated with care, because a range of factors - from a significant reliance on subsidies required to make EV and BEHV vehicles affordable, to the technology's impact on the country's electric generation infrastructure - must be considered to assess the true cost/benefit of electric and hybrid technologies.

Electric cars — the benefits and limitations

The first electric car, a motorized carriage, was built sometime in the 1830s by Richard Anderson in Scotland, followed in the 1840s by vehicles powered by non-rechargeable electric cells from a number of inventors. Gaston Plante, inventor of the lead acid battery (1859), improved the capacity for battery storage, paving the way for further advances in these easy-to-drive electric vehicles.

Ferdinand Porsche⁴ is credited with the creation of the first electric hybrid vehicle (c. 1900) followed by an electric-ICE hybrid developed by the Woods Motor Vehicle Company of Chicago, IL (c. 1911), which combined a four-cylinder internal combustion engine for high-speed travel (up to 35 mph) with electric power for lower speeds (up to 15 mph). These early hybrids were expensive (the Woods was \$2,700), slow and heavy, with limited range. By the 1920s improved roads, the discovery of cheap crude oil in Texas, and less-expensive mass-produced gasoline pow-

ered cars from Ford and other manufacturers contributed to a retreat from electric and electric hybrid technology.

In the 1960s and 1970s interest in electric and hybrid technologies reawakened, spurred by calls for reductions in emissions. Electric and hybrid vehicles, both commercial and consumer, were produced by a number of manufacturers but problems remained: battery technology; vehicle cost, weight, range and acceleration; lack of infrastructure to support all-electric vehicles and plentiful and cheap gasoline continued to be factors.

The U.S. 1990 Clean Air Act Amendment and the subsequent U.S. 1992 Energy Policy Act changed the game for automotive manufacturers, which began to look in earnest at electric and hybrid technologies. A variety of electric vehicles were produced by the “Big Three” US automakers in the 90s, but high prices, poor range, small vehicle size, weight, poor performance in extreme weather conditions and a lack of necessary infrastructure, e.g. electric fueling stations, kept buyers away.

⁴History of Hybrid Vehicles”. HybridCars.com. 2006-03-27. <http://www.hybridcars.com/history/history-of-hybrid-vehicles.html>.

Electric vehicle market barriers

A range of market barriers to the success of EVs and BEHVs still exists today.

Size, weight and power

The most efficient EVs tend to be small vehicles. Basic limits in physics and chemistry are the barriers: EVs must carry their fuel source, batteries, with them, and batteries are heavy, costly, typically made from rare earth minerals, and much less efficient as an energy storage medium than gasoline. One gallon of gasoline stores nearly 34 kilowatts of power at a weight of about 6.5 pounds. That same gallon of gasoline has 50 percent greater total energy capacity than the battery for the Nissan Leaf, which weighs 440 pounds yet stores only 24 kilowatts of power.⁵ A car carrying 20 gallons of gasoline, which weighs ~120 pounds, represents 2/3 of a megawatt of power. The EV's ability to transfer kilowatts into kinetic energy may be superior, but terrain, ambient temperatures, driving conditions and mass (weight) affect the vehicle's ultimate range.

Mileage range — a red herring

Most consumers think of range as average miles driven a day. With EVs, range is dependent on traffic conditions - for example, EVs consume more kilowatts in congested stop-and-go traffic, in hot and cold weather, and when travelling over hilly terrain. A more accurate measurement of range for EVs is kilowatts consumed. Take the BMW Mini-Cooper E, advertised to have a range of 156 miles per charge; in real driving, however, reports indicate the

actual range is 100 to 110 miles⁶. The Mini-E sports a 35 kilowatt battery pack; the Nissan Leaf, projected to go 100 miles between charges, has a 24 kilowatt battery pack.

Modern electric hybrids — benefits and limitations

The Toyota Prius achieved its formal debut in the US in 2001. The first four-passenger mass-produced electric hybrid vehicle to achieve commercial success (the earlier Honda Insight seats two) is powered by two motors - a 1.5 liter four cylinder gasoline engine and an AC electric motor, with two control systems and a large nickel-metal hydride battery.

The Prius, like many of its predecessor all-electric cars, is a small, streamlined vehicle, reflecting the reality that mass affects range, acceleration, battery life and performance. After 10 years on the market, the Prius has captured only 2.5 percent of total US vehicle sales⁷, reflecting continued consumer interest in larger, more comfortable cars

(see table below for top vehicle sales numbers from February 2010.)

Model	February 2010	% Change from 2009
Ford F - Series PU	32,895	39.30%
Honda Accord	20,024	25.30%
Chevrolet Silverado PU	19,822	0.20%
Toyota Corolla/Matrix	16,996	-6.10%
Toyota Camry/Solara	16,552	-19.80%
Honda Civic	16,471	5.00%
Ford Fusion	16,459	116.50%
Nissan Altima	16,198	1.20%
Ford Escape	15,156	50.20%
Chevrolet Malibu	15,150	31.60%
Chevrolet Cobalt	14,101	69.50%
Ford Focus	13,708	38.40%
Honda CR-V	11,828	-4.40%

Table 2: Top Vehicle Sales, February 2010

⁵ <http://green.autoblog.com/2010/05/27/details-on-nissan-leaf-battery-pack-including-how-recharging-sp/>

⁶ <http://online.wsj.com/article/SB10001424052748703561604575282491734663452.html>

⁷ "2009 U.S. Vehicle Sales," October 1, 2009 http://online.wsj.com/mdc/public/page/2_3022-autosales.html

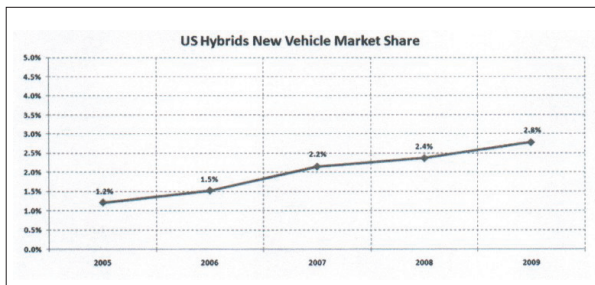


Table 3: US Hybrid Market Share, 2005-2009.

Even at the peak of the gasoline crisis in July 2008 hybrid sales were anemic and trending down from

a peak of 39,898 units in April 2008 to a year-end rate of 17,698 units in December 2008 (See Table 3 for hybrid vehicle market share data.).

Lack of affordable battery technology

Current modern battery technology costs about \$600 per kilowatt⁸. For EVs and BEHVs to be competitive with traditional ICE-powered cars, this figure must shrink to \$150-200 per kilowatt, a figure not feasible with existing battery technologies. Raw material costs of most batteries in use in EVs and BEHVs today are \$240, or 40 percent of the \$660 kilowatt estimate; this cost will not go down if demand increases due to the scarcity of material. Additionally, the typical EV may require 75 pounds or more of lithium carbonate, whose price has tripled in recent years⁹; additionally, the world supply of lithium is concentrated in South America, a region not politically aligned with the United States. In addition to lithium, many rare earth minerals required for the manufacture of EVs and BEHVs are not available in the United States, and shift US dependence on scarce natural resources from the Middle East to countries such as China, which accounts for 96.7 percent of the total production of rare earth materials. (See Table 4, Rare Earth Mineral Production by Country.)

Reliance on subsidies

Selling price has a huge affect on the marketability of a vehicle. With

Country	2009 Production (tons)	% Total	Reserves (tons)	% Total
United States	0	0.00%	13,000,000	13.13%
Australia	0	0.00%	5,400,000	5.45%
Brazil	650	0.52%	48,000	0.05%
China	120,000	96.77%	36,000,000	36.36%
Commonwealth of Independent States	N/A	0.00%	19,000,000	19.19%
India	2,700	2.18%	3,100,000	3.13%
Malaysia	380	0.31%	30,000	0.03%
Other Countries	N/A	0.00%	22,000,000	22.22%
Total	124,000	100.00%	99,000,000	100.00%

Table 4: Rare earth mineral production by country

current battery technologies, an EV with a 24 kilowatt battery (assuming \$600 per kilowatt) carries a price premium of approximately \$14,000 per vehicle. Government subsidies of up to half the price premium (~\$7,500) are the only way to bring these vehicles within reach of the average consumer. Such subsidies - assuming a 10 percent market share and annual sales of 11 million vehicles - would top \$8.25 billion per year. The federal government, however, in its ten-year projected budget for plug-in EV subsidies, has allocated a mere \$2.8 billion.¹⁰ These subsidies diminish with higher OEM volume; in addition, consumers affected by the alternative minimum tax may lose the benefits of such tax credits.

Impact of EVs on the US electric power grid

Most discussions of the ecological, social and cost benefits of EV vehicles focus on the benefits to consumers and ignore two basic issues: a profit motive for the power industry, and dependence on the nation's power generation infrastructure for refueling (49+ percent of the grid relies on coal-fired plants¹¹.) EVs depend on the power grid, and it turns out that when vehicles are recharged could have an enormous impact on the nation's power system

⁸ <http://news.google.com/newspapers?id=IG8qAAAAIBAJ&sjid=nVQEAAAIBAJ&pg=7137.6613653&dq=lithium+sulfur+history&hl=en>

⁹ Koerner, Brendan I., "The Saudi Arabia of Lithium," *Forbes Magazine*, November 24, 2008.

¹⁰ Vijayenthiran, Viknesh, "Obama's Stimulus Package Expands Plug-in Hybrid Incentives, But Diesel Fans Unhappy," *Motor Authority*, March 4, 2009.

¹¹ Energy Information Administration, 2009 "Fans Unhappy," *Motor Authority*, March 4, 2009.

In a very simplified overview, to make EVs an attractive proposition to power companies, recharging must take place during off-peak hours when power companies have excess capacity that is difficult to store. Additionally, EVs must be concentrated within a power company's operating footprint, preferably in one of the top 10 markets (Los Angeles, San Francisco, New York, Washington D.C., Seattle, Chicago, Boston, Philadelphia, Sacramento and Phoenix.)

Shifting charging to peak hours puts EVs in competition with businesses using power, would require the construction of new generating plants (more than 50 permits are required before a plant can be constructed) and introduces the additional complication that charging stations would have to be built by cities and municipalities to accommodate peak demand. Today, some 160,000 gasoline refueling stations exist in the US, about 50 percent of which have diesel capacity; by comparison, there are only 538 electric charging stations nationwide, which can recharge only three vehicles per hour (an average gas pump can handle up to 10 times as many vehicles per hour).

Finally, as with telecommunications, the last mile problem exists. Even if consumers constrain themselves to off-peak charging, power companies would have to upgrade transformers and metering equipment to homes to support EVs. An added wrinkle: while most new homes have 100-amp electrical service, older homes may have 60 amp service. Today's Level 2 vehicle chargers draw up to 80 amps, meaning many homes simply are not capable of recharging EVs.

Traditional ICE technology — it's not going away any time soon

Traditional gasoline-powered internal combustion engine technology remains attractive to consumers for a variety of reasons:

- **Power density:** Gasoline is a more effective power source than batteries - a gallon of gasoline costs about \$3.00, weighs just 6.5 pounds and has a significant energy density advantage over batteries
- **Refueling range:** Gasoline-powered cars have a refueling range of about 400 miles. Fuel cell vehicles have about 12 percent less range; battery-gasoline hybrid vehicles have a best-estimate refueling range of approximately 240 miles, while pure electric vehicles have refueling ranges as low as 40 miles before requiring a recharge (or a tow).
- **Cost:** A driver clocking 15,000 miles a year in a 22.5 mpg gasoline-powered vehicle paying ~\$3.00 a gallon can expect to pay ~\$2000 per year for fuel; the cost of a battery lease, (should the cost of the battery be separated from the cost of the vehicle e.g., the Better Place¹² model), is estimated at \$2,057 per year.
- **Safety:** larger vehicles are safer in an accident. Yes, small hybrids have federally-mandated 5 mph bumpers and other modern safety equipment, but a small car is no match for an SUV, pickup truck or full-size automobile in a highway accident.
- **Comfort:** Americans are bigger and heavier than ever before. Bigger vehicles are more comfortable.
- **Standards:** Amazingly the only standard item on an EV is the plug (SAE J1772). No standards are in place for battery quick-charge stations or battery location – OEMs view battery technology as a competitive differentiator.

¹² <http://www.betterplace.com/>

A solution — The Scuderi Split Cycle Engine paired with hybrid technology

An alternative path exists: pairing a more-efficient internal combustion engine with a battery hybrid vehicle. One ICE engine stands apart from the rest as an immediate solution: the Scuderi Split-Cycle Engine.

The Scuderi Split-Cycle Engine is a novel internal combustion engine that combines operating principles from four-stroke and two stroke engine designs into an efficient and low-polluting powerplant.

The Scuderi Engine employs a new and proven thermodynamic process known as the Scuderi Cycle, a significant advancement in internal combustion engine technology over the Otto Cycle, developed over 130 years ago and the basis for most engines in use today. The Scuderi Engine's design separates the four strokes of a conventional engine over two paired cylinders. One cylinder does intake/compression while the other cylinder does power/exhaust. Using a unique combustion process known as "firing after top-dead center," the Scuderi Engine has more power, higher efficiency and lower emissions than a conventional gasoline engine, delivering the weight and torque advantages of a two-stroke design with the performance, reliability and cleaner operation of a four-stroke engine. Studies indicate that the naturally aspirated Scuderi Engine's efficiency has the potential to be up to five percent better than a standard gasoline ICE, with a reduction in

NOx of up to 80 percent. Thus the Scuderi Engine not only saves energy and reduces CO2 and NOx emissions — it also offers increased power density in a smaller footprint. When turbocharged, studies show it has the potential to be up to 15 percent more efficient than a conventional gasoline engine.

The Scuderi Split-Cycle Engine, in its current configuration, is also an ideal ICE platform upon which to build an efficient, low-polluting battery-hybrid vehicle.

The next breakthrough — the Scuderi Air-Hybrid Engine

Split-cycle engines are essentially air compressors on one side of the engine with a combustion chamber on the other side of the engine. Because the Scuderi Split-Cycle Engine is a dedicated compressor on one side and an engine on the other, it requires only the addition of an air storage tank and related controls to convert it into a system that has the ability to capture and store energy - in the form of compressed air - that is normally lost during operation of the engine.

This breakthrough is the next step in the development of the Scuderi Split-Cycle Engine: the Scuderi Air-Hybrid Engine. The Scuderi Air-Hybrid Engine is the first engine that has the ability to recapture and use wasted energy in the form of compressed air. By feeding the compressed air into the combustion process of the Scuderi Engine, the stored energy is used much more efficiently. Early computer simula

tion studies show the Air-Hybrid — based on the new and proven Scuderi Cycle thermodynamic process — achieves up to 50 percent greater fuel efficiency than conventional engines while emitting up to 80 percent less NOx than any conventional engine on the road today.

The cost and weight of the Scuderi Air-Hybrid Engine also is a significant advantage compared to battery hybrids. Battery hybrids require two separate systems. One is the internal combustion engine; the other consists of batteries, electric motors and their controls. This separate drive/control system adds significant weight and cost to the vehicle, on the order of 400 to 500 pounds and \$3000 to \$4000 per vehicle. The Scuderi Air-Hybrid requires only the addition of an inexpensive air tank and simple controls. The weight is about one-tenth that of an electric system.

In addition, because the Scuderi Air-Hybrid takes one-third of the time to store energy than it does to use that energy, it could potentially be the most efficient hybrid system to date — at a fraction of the cost of an electric battery hybrid system.

Conclusion

Electric vehicles and battery-hybrid vehicles currently on the market offer clear benefits to consumers, yet the benefits come at the cost of moving dependence on foreign resources from one region of the world - the Mideast - to other, arguably less accommodating regions - the Far East (rare earth minerals) and South America (oil and lithium carbonate). In addition, adop-

tion of pure, plug-in electric vehicles will require significant upgrades to infrastructure, including new power generation plants and construction of local refueling stations - not to mention solving the last-mile problem of extending infrastructure upgrades to homes, where most refueling will take place.

For the short term (~30 years), battery hybrid vehicles offer the most flexibility, utility and value for consumers and automotive OEMs. The challenge lies in selecting the most efficient, least-polluting internal combustion engine to pair with the battery. The Scuderi Split Cycle Engine offers an immediate solution to OEMs seeking to improve BEHV offerings, requiring minimal changes in plant and tooling to manufacture. And the Scuderi Air-Hybrid Engine offers a solution to reducing or eliminating the need for toxic, expensive batteries with the addition of a simple air tank.

The Scuderi Engine combines the advantages of efficient operation, reduced barriers to entry for carmakers, and a short design-to-production cycle. With the Scuderi Engine, automakers and governments can meet the political and environmental challenges of reduced fuel consumption, higher efficiency, reduced weight and reduced pollution, supporting green and clean-power initiatives with minimal upfront investment.