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Commercializing light-duty plug-in/plug-out hydrogen-fuel-cell vehicles: "Mobile Electricity" technologies and opportunities

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Abstract

Starting from the premise that new consumer value must drive hydrogen-fuel-cell-vehicle (H_2FCV) commercialization, a group of opportunities collectively called "Mobile Electricity" is characterized. Mobile Electricity (Me-) redefines H_2FCVs as innovative products able to import and export electricity across the traditional vehicle boundary. Such vehicles could provide home recharging and mobile power, for example for tools, mobile activities, emergencies, and electric-grid-support services. This study integrates and extends previous analyses of H_2FCVs, plug-in hybrids, and vehicle-to-grid (V2G) power. Further, it uses a new electric-drive-vehicle and vehicular-distributed-generation model to estimate zero-emission-power versus zero-emission-driving tradeoffs, costs, and grid-support revenues for various electric-drive vehicle types and levels of infrastructure service. By framing market development in terms of new consumer value flowing from Me-, this study suggests a way to move beyond the battery versus fuel-cell zero-sum game and towards the development of integrated plug-in/plug-out hybrid platforms. As one possible extension of this Me- product platform, H_2FCVs might supply clean, high-power, and profitable Me- services as the technologies and markets mature.

Keywords: Hydrogen-fuel-cell vehicle; Plug-in hybrid; Plug-out hybrid; Mobile Electricity innovation; Vehicle-to-grid power; Vehicular distributed generation

1. Introduction

1.1. Problem: commercializing fuel-cell vehicles

Hydrogen-fuel-cell vehicles (H_2FCV) have been proposed as a potential solution to many transportation, energy, and environmental problems (e.g. [1–6]) and are receiving the attention of all of the world's major automotive and energy companies. Nevertheless, currently expensive, of limited driving range per refueling, and lacking a refueling infrastructure, H_2FCVs face similar challenges faced by past alternative-fuel vehicle (AFV) efforts, whose momentum typically could not be sustained over periods of low oil prices (e.g. [7,8]). How might H_2FCVs (or any AFV) succeed where past efforts have failed?

1.2. Approach: "Mobile Electricity" innovation

Even in the absence of vehicle performance limitations, robust private value propositions for H_2FCVs would be necessary to sustain their successful commercialization and to displace entrenched gasoline and diesel-powered cars and trucks. Because H_2FCVs thus far are not superior to today's vehicles on those dimensions conventionally valued by private consumers, product value must flow from other sources. The premise is that H_2FCVs will not sell simply as clean cars and trucks; they must be marketed as new products that provide innovative value to consumers. Given this premise, the question then becomes "What might help redefine H_2FCVs as new products?"

One group of opportunities for H_2FCV innovation stems from the ability of these vehicles to produce clean, quiet electrical power for purposes other than propulsion. These and related potential innovations, which we collectively call "Mobile Electricity" (Me-) opportunities, are illustrated in Fig. 1 and described in detail in Section 2.

Loosely defined, Mobile Energy (ME) is the interaction between vehicles and other energy systems. ME opportunities include both "Mobile Electricity" and non-forecourt refueling (e.g., home refueling for gaseous fuels). Mobile Electricity (Me-) includes both exporting electricity from the vehicle (e.g., to power gadgets/appliances/tools, provide emergency power, or to supply grid-stabilization services to utilities, such as voltage-regulation and spinning reserves [9–12]), as well as importing

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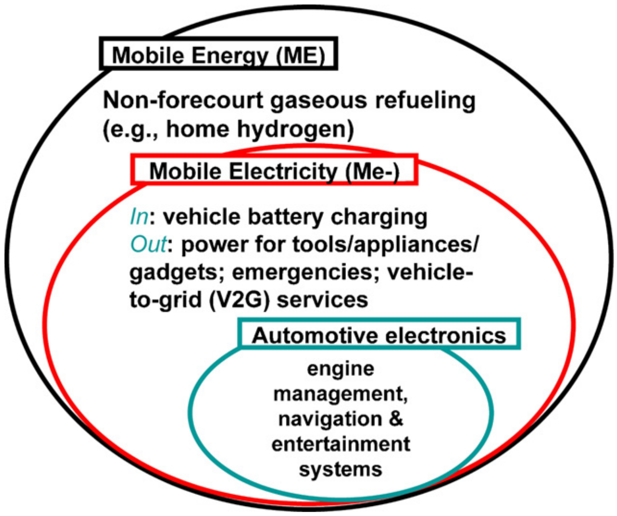

Fig. 1. Redefining H_2FCVs as new products: Mobile Energy innovation opportunities.

electricity to the vehicle (e.g., for vehicle battery charging of "plug-in" electric-drive vehicles [13]).

1.2.1. Focus: "Mobile Electricity" from light-duty vehicles in early households

The scope of this analysis is limited in two ways. First, H_2FCV value could arise from other sources, for example, the production and flexibility benefits of H_2FC integration into by-wire platforms or the development of niche-specific H_2FCV products such as forklifts. Those potential sources of value will not be considered here. Second, this research focuses on the first stages of relatively widespread commercialization of light-duty H_2FCVs in households. It does not focus on either the earliest customer placements, e.g., relatively controlled demonstration experiments in fleets, or widespread adoption by the mainstream, by which time commercialization would be foregone and the challenges become "sustaining" (e.g., sales and market share). There is some discussion of fleets as strategic niches and Me-aggregation opportunities (Section 2.3.4).

The authors believe ME innovations represent some of the most interesting, important, and desirable sets of opportunities, without which H_2FCV commercialization will be unlikely or problematic in the (relatively) near term.[1] Further, ME opportunities have additional appeal beyond the scope of H_2FCV commercialization, arguing for their robustness. First, they appear concordant with other societal and technological trends [14]. For example, as cell phones provide wireless communications, so might ME "untether" and otherwise reconfigure our energy systems and lifestyles. Additionally, ME is consistent with the convergence of transportation and other energy systems being ushered in by electric-drive vehicles (EDVs), whether battery-electric, gasoline-combustion-hybrid, or fuel-cell. The technological diversity that both supports and would be supported by ME innovation provides not only robustness to the failure of any given technology, but allows the construction of development pathways. For example, one can imagine first developing ME for combustion hybrids as a means to create market demand for services that might, in turn, support H_2FCV commercialization as those technologies mature [11].

1.3. Objectives

The objective of this study is to integrate and supplement related previous work (e.g., on plug-in hybrids, vehicle-to-grid power, and H_2FCVs) into a Mobile Electricity framework. Together with a previous investigation [15] that quantified and characterized the most promising early household market segment for light-duty H_2FCVs and plug-in hybrids in California and future work that will further explore the Me- framework as a driver for electric-drive-vehicle commercialization, this study is designed to inform public and private decision-makers about Me- opportunities and the early-market dynamics of commercializing H_2FCVs and other EDV technologies.

Although conducted for the purpose of exploring Mobile-Electricity-enabled H_2FCV commercialization, it should be noted that this study frequently uses techniques suitably general for, and derives results suitably applicable to, a wide variety of electric-drive vehicles (EDVs). Indeed, the potential innovations discussed are made more robust by their integration into a Mobile Energy framework that minimizes possible regrets by considering several potentially profitable pathways should insurmountable roadblocks bar the way to one or another specific aspects of the nominal end goal. For example, if FCVs "don't make it," vehicle-to-grid (V2G) power sales and home recharging for ICE hybrids might still be attractive. On the other hand, if regulatory considerations make V2G grid-support difficult, the ME framework can still help guide exploration of the commercialization-enabling benefits of, for example, home refueling for H_2FCVs. The conclusions drawn here should therefore have value for anybody interested in ME innovation, whether for fuel-cell, ICE-hybrid, or even battery-electric vehicles.

2. "Mobile Electricity" innovation: technologies and opportunities

2.1. Overview

This study integrates related analyses of H_2FCVs, plug-in hybrids (e.g. [13]) and, in some detail, vehicular distributed generation or vehicle-to-grid (V2G) power (e.g. [16]) into a Mobile Electricity (Me-) framework. This framework organizes the examination of seemingly disparate and competing technology developments into a coherent group of commercialization-enabling innovations by emphasizing the convergence of

[1] This may be considered a somewhat controversial and counterintuitive argument: that more "radical" distinguishing product features—which might reasonably be expected to evolve *after* more conventionally defined fuel-cell cars and trucks have been adopted—must be developed *first*. However, recall that this conclusion results from the innovation premises, i.e., H_2FCVs will not be competitive on conventional dimensions for the foreseeable future, and a private value proposition must drive their adoption. Thus, in this framework the "near-term" becomes a relative concept: new features must be developed in order to assure H_2FCV commercialization happens at all.

transportation and other energy systems. It describes the potential costs, benefits, performance, and current status of (1) "plug-in" opportunities (including battery charging and all-electric range) and (2) "plug-out" opportunities (including "untethered," emergency, and vehicle-to-grid power). This study also enhances and extends past analyses with a new spreadsheet model of: Mobile Electricity (Me-) vehicle power versus driving ranges, vehicle and building incremental costs, and illustrative vehicle-to-grid (V2G) net revenues under various assumptions.

Section 2.2 describes "plug-in" Me- opportunities. Significant and increasing activity is underway pertaining to the development of a conceptual subset of plug-in opportunities: plug-in hybrid electric/gasoline-combustion vehicles (PHEVs), which historically have emphasized configurations with big propulsion batteries. However, recent activities (some proprietary) and support has pushed a new generation of PHEVs into the public attention. Section 2.2 includes both a conceptual/analytical review of plug-ins as well as a brief discussion of "What is going on?" with known plug-in prototypes and advocacy activities.

In contrast to Section 2.2, Section 2.3's discussion of "plug-out" opportunities is about "What *could* be going on?" Relatively less developed, plug-out opportunities—such as power for tools/appliances/gadgets, for emergency power, or for grid-support services—are nevertheless increasingly pertinent and topical, and may provide the key to rounding out the product offerings of plug-in hybrids as they evolve conceptually into "Mobile Electricity platforms" (Section 2.3.5).

Sections 2.2 and 2.3 selectively present and integrate past work into the overall Me- framework, emphasizing and contextualizing the enhanced modeling. The modeling, in turn, is primarily used here to illustrate and extend the discussion of "plug-out" Me- opportunities, in particular vehicular distributed generation in Section 2.3.4 (which incorporates many of the important requirements of Me-).

2.2. *"Plug-in" opportunities*

"Importing" electricity across the vehicle boundary could be used to charge vehicular energy storage systems (e.g., batteries, ultracapacitors, and/or, in principle, onboard electrolyzers) or to power onboard electrical devices without use of vehicular power systems (e.g., "hotel loads"). Existing examples of the latter service include powering parked RVs or docked boats using "shore lines" and the electrification of truck stops to avoid engine idling. These existing examples are not addressed in this report, which focuses on new opportunities for light-duty passenger vehicles (LDVs).[2]

Of particular interest for light- (and medium-) duty vehicles is the opportunity to take the performance of increasingly widespread hybrid-electric vehicles (HEVs) "to the next level" of Me- application by allowing—not requiring—HEV users to charge their vehicles' batteries from the electrical grid. The arguments in favor of a "plug-in" approach can now be built on the successes of current HEVs (with relatively small, power-assist batteries) and the hope that even deeply discharged PHEV energy batteries may not have to be replaced during 150,000-mile vehicle lifetimes. Bolstered by the belief that PHEVs thus offer a relatively near-term solution to various transportation and energy problems, a broadening base of utility, non-profit, local-government, and academic supporters are taking up the call for PHEVs[3] and seem to be gaining increasing traction with automakers, who nevertheless remain publicly cautious.[4] The rest of Section 2.2 describes many of these issues, including battery charging and supplementation, remaining uncertainties, and independent and automaker PHEV development activities.

2.2.1. *Battery charging*

In order to charge batteries onboard a hybrid- or battery-electric vehicle from an external source, additional hardware and software is required to create the connection, to control the rate of charging, and to prevent overcharging. Recognizing that the lack of a charging standard hampered battery-electric-vehicle (BEV) commercialization efforts in the 1990s,[5] the California Air Resources Board is now supporting conductive charging over inductive approaches. Conductive charging offers the possibility of using relatively standard wall sockets and power cords for PHEVs and hybridized H_2FCVs (Section 2.3) with smaller batteries than BEVs. Because of the potential convenience and familiarity of this incremental approach, conductive recharging is assumed here.

2.2.1.1. Costs and benefits. The Hybrid Electric Vehicle Working Group (HEVWG), led by the Electrical Power Research Institute (EPRI), estimated the price of an on-vehicle charging system at $690 (2003 dollars [13], p. A-7). Without overhead or OEM and dealer markups, the cost of the system supplied to the OEM is estimated at $460 ([13], p. C-4). For comparison, Delucchi et al. ([17] in [18]) acknowledge a large range about their mean estimate of $300 for an *off*-board charger, and Kempton and Tomic [16] estimate $200 to add wires and a plug to a FCV for grid connection.

Although the benefits from charging today's, circa-2006 hybrids would be relatively inconsequential, several categories of benefit are in principle enabled by the ability to connect to

2 One of the exciting aspects of ME innovation is its potential to evolve light-duty vehicles into a base for lifestyles activities previously reserved only for RVs, houses, and other large or stationary locales. As "activity" increasingly becomes decoupled from specific geographies, LDVs may, like PDAs, become the "locale" for "killer apps" previously executed in laptops (RVs?) or desktops (houses?).

3 The nomenclature for PHEVs is still growing and changing. They are referred to by various sources as "plug-in," "gasoline-optional," "grid-connected," "grid-able," or "e-" hybrids.

4 Further, automakers currently tout *not* plugging in as a virtue of their current HEVs, e.g, "you never have to plug it in." Thus, plug-in *opportunities* described in this paper may be confusing to consumers worried about plug-in *requirements*. Can the message "You get to plug in PHEVs" be successfully built upon "You never have to plug it in"? Possibly, particularly if the target market for PHEVs is the particularly motivated subset of knowledgeable existing or potential gasoline HEV buyers.

5 Failing to establish common standards is a common trap in high-tech commercialization (e.g., see Shapiro and Varain's "Art of the Standards Wars" in *California Management Review* 41(2), 8–32).

external electrical supply.[6] These benefits increase as the size of the onboard electrical storage and traction motor are increased (see next section), as well as if electrical power, flowing along the same bi-directional connection used for charging, could be exported for uses other than propulsion (see Section 2.3).

Among the potential benefits to emerge from enabling traction battery charging by giving hybrids electrical connections to other energy systems (i.e., by making them into Mobile Electricity (Me-) hybrids) might be:

- displacement of gasoline by electricity for vehicle power,
  - with the possibility of "all-electric range" (AER) that could offer more rapid acceleration[7] and potentially be cheaper, cleaner,[8] quieter, and smoother than driving the vehicle on gasoline,
  - which may allow vehicle operation in combustion- or noise-restricted areas,
  - or engine-free vehicle features (e.g., higher-power entertainment systems, (pre-) heat/cool, etc.);
- home recharging using off-peak grid electricity,
  - with the convenience of avoided trips to the petrol station[9] concordant to the amount of gasoline displaced and
  - a full battery each morning to maximize clean and silent operation in the residential neighborhood;
- reduced wear-and-tear on the vehicle's combustion system and certain mechanical systems,
  - with accordingly lower vehicle maintenance costs; and
- the ability to use the vehicle's electrical connection for exporting electrical power to a variety of other new and adapted innovations (see Section 2.3).

With electrical energy-storage and drive supplementation (e.g., bigger batteries and motors), consumers that are able to periodically charge their vehicles from the grid could gain significant engine-free driving range and might realize significant levels of the benefits described above. Battery augmentation and all-electric range are discussed next.

2.2.2. *Battery supplementation, all-electric range (AER), and plug-in hybrid-electric vehicles (PHEVs)*

Although new analysis is emerging, until mid-to-late 2006 a series of reports lead by EPRI for the HEVWG remained the definitive publicly available analyses of augmented-battery, grid-rechargeable, plug-in hybrid-electric vehicles (PHEVs). In their accumulative 2004 report [13], the HEVWG analyzed the costs and performance of hybrids with traction batteries and electric motors sized to provide all-electric range of 20 or 60 miles (PHEV20s and PHEV60s). Several vehicle types and configurations were analyzed, requiring the HEVWGs judgment on a variety of cost and design variables.

Assuming, as did the HEVWG, that NiMH batteries now can be reasonably assumed to have 10-year, 150,000-mile lifecycle characteristics sufficient for the frequent and relatively deep-discharge requirements of PHEV20s,[10] the report calculates the battery prices necessary for gasoline HEVs and PHEVs to achieve lifecycle cost parity with conventional vehicles. The estimated battery prices are higher than what the HEVWG report's authors believe can be achieved in high-volume manufacture. For example, the 2004 report argues a plug-in, full-sized SUV would need 9.3–11 kWh of battery at \$427–\$455 kWh^{-1}, but that, at volume production, such batteries might cost \$352 kWh^{-1} (p. A-7).

These and other calculations in the report are based on gasoline at \$1.75 gal^{-1}; sustained higher gasoline prices imply lower "lifecycle parity costs" for batteries. Further, the study notes but does not include in its pricing: tax breaks, additional Corporate-Average-Fuel-Economy (CAFE) credits, the common automaker practice of subsidizing across products lines (which could be used to lower the incremental price of early plug-ins), adopting a loss-leader strategy, or the possibility of leasing/renting vehicle batteries.

2.2.2.1. PHEV uncertainties: batteries and charging. Two important aspects of PHEV development and use that are likely to remain contentious for some time and deserve further comment are batteries and charging.

The 2004 HEVWG report is explicit about the challenges facing battery development while arguing that battery technologies might reasonably be expected to be able to meet some PHEV requirements in the near future. It focuses on NiMH batteries for their relative maturity, a conservatism if lithium technologies experience cost, life, and deep-discharge improvements. It uses performance and cycle-life data from battery suppliers, with increased confidence provided by real-world experience with similar technologies in fleet-operated RAV4EVs. It fur-

[6] Charging today's commercial hybrids would provide little benefit, because these vehicles' relatively small, power-assist traction batteries and control strategies are not meant to provide sustained energy for all-electric driving range, but rather are optimized to buffer the combustion engine from brief power transients, to capture bursts of power usually lost during braking, and to minimize idling by enabling engine shut-off and rapid restarting.

[7] Unlike combustion engines that need to rev up to high revolutions before offering full torque, electric motors offer full torque at zero speed (i.e., at launch); electric motors could therefore enhance a given vehicle's acceleration, depending on its size relative to the vehicle's total requirements and the amount of electrical energy available for a given acceleration.

[8] The extent of this depends, of course, on the source of electricity for charging. However, it should also be noted, whereas today's cars generally are dirtier in real use and grow more so with age, grid-mix electricity is expected to become cleaner with time, e.g., as old plants are retired and renewable portfolio standards are implemented.

[9] The opportunity to free oneself and family from gasoline refueling stations and oil-company profits via home recharging is often seen as attractive and has been the subject of consumer feedback given to GM, EPRI, UC Davis, and others. [13] EPRI, "Advanced Batteries for Electric-Drive Vehicles: a Technology and Cost-Effectiveness Assessment for Battery Electric Vehicles, Power Assist Hybrid Electric Vehicles, and Plug-In Hybrid Electric Vehicles," EPRI, Palo Alto 1009299, May 2004, [19] L. Burns, "Fuel Cell Vehicles and the Hydrogen Economy," presented at Asilomar IV: The Hydrogen Transition, Pacific Grove CA, 2003 [20]. K.S. Kurani, T. Turrentine, D. Sperling, Demand for electric vehicles in hybrid households: an exploratory analysis, *Transport Policy*, 1, 1994, 244–256.

[10] The 16 January 2006 edition of *Fleets and Fuels* newsletter notes that all 220 of utility SoCal Edison's Toyota RAV4-EV battery SUVs are still operating on their original NiMH batteries.

ther includes "car-company" battery cost estimates, scaled to appropriate energy levels, to validate its own.

Despite these efforts, automakers are likely to remain concerned about the availability and cost of batteries suitable for PHEVs. Achieving 10-year/150,000-mile life under repeated deep discharge conditions with the vehicle's original battery is of particular importance to the viability of PHEV20s when compared to vehicles with larger batteries. As the report acknowledges (pp. 2 and 3): ". . .confirmation of extensive deep cycling capabilities must still be sought through testing of batteries in modes representative of anticipated PHEV uses, and more confident cost predictions are needed for mass-produced PHEV-design batteries."

Similarly, it is likely that automakers as well as policy makers will also continue to be concerned about the extent of the charging infrastructure required and the willingness of consumers to use it on a regular basis. The HEVWG reports highlight these issues, yet tend to assume full daily charging in their analysis, a factor to which many of their conclusions are undoubtedly sensitive.

Additionally, the reports assume \$0.05 kWh^{-1} electricity for recharging. A rate this low implies time-of-use (TOU) metering and/or special recharging rates. Although available in many areas, the required additional or modified metering presents an investment and time hurdle that should be explicitly explored.

Further, the reports claim, "The great majority of prospective owners have access to the standard 120 V electric outlets. . ." (pp. 2 and 3). Yet it is unclear who "prospective owners" are and how many of them could cheaply and easily use such "existing infrastructure" for recharging PHEVs. For example, [15] found that only 5–10 million of 34 million Californians can be assured to currently live in households that appear to be able to easily adopt and benefit from home-recharged EDVs. That relatively small market *potential* identified represents something of a hypothetical—if temporary and mutable—maximum from which sales are likely to be drawn. Assuming a modest initial market share on the order of 1%, the 5-million Californian target market segment studied might be expected to initially buy only 50–60,000 plug-in vehicles per year, hardly the sweeping transformation that might be implied if electrical infrastructure requirements are over-simplified or dismissed. Further, even with relatively widespread access to 120 V outlets, Section 2.3.4 highlights the issue of additional, more expensive levels of infrastructure service.

2.2.2.2. What is going on? Plug-in hybrid status and activities.

2.2.2.2.1. PHEV prototypes. Several prototypes have demonstrated one or more aspects of plug-in hybrid platform potential. Table 1 illustrates the key features of five, including several Prius conversions in various stages of development and commercialization as of fall 2006.

As currently configured for sale, the Prius's power-assist batteries and relatively small[11] electric motor provide a couple miles or less all-electric driving range at speeds less than roughly 34 miles per hour without triggering the combustion engine to provide additional power and/or charge the batteries. Plug-in Prius conversions generally augment or replace the propulsion battery and thus increase the all-electric-range capability of the vehicle, but only within the limits of the original electric motor and overall control strategy. Claimed AER capabilities (at low speeds/power) for such vehicles are typically ∼30–35 miles (e.g. [21]). With the higher speed/power requirements of typical daily driving, Prius conversions blend grid electricity as available into their operation as combustion hybrids. From the time the converted vehicle is fully charged from the grid to when its depleted charge requires it to operate as a self-contained gasoline HEV (e.g., ∼40–60 PHEV-range miles)—the claimed fuel economy for Prius conversions is typically roughly double that of the original Prius per gasoline gallon, not including the required electricity (e.g. [22]).

2.2.2.2.2. Automaker PHEV activities. At least publicly, many automakers appear to still believe battery development has not progressed far enough to support PHEV commercialization. Nevertheless several automakers have revealed research activities. DaimlerChrysler is building plug-in prototype variants of its Dodge Sprinter Hybrid (see Table 1) to be tested in several U.S. cities. In 2005, the "PAPI Dream House" by Tron Architecture conceptually incorporated facilities for a Prius to both charge and provide emergency power. In April 2006, Toyota acknowledged a plug-in hybrid development program [23], but continues to highlight current battery limitations. Much speculation continues to surround any possible public release, including future generations of the Prius. The next-generation Prius may have a ∼9-mi AER (ibid). Meanwhile, GM, Ford and Nissan/Renault have announced various level of interest in, or at least scrutiny of, PHEVs.

Other notable activities (many of which are described in a chronology by calcars.org) include: a 2003–2004 demonstration of a plug-in diesel-electric HUMVEE by the Marine Corps, a Mitsubishi concept car, and prototyping and development by Southern California battery-EV developer AC Propulsion.

2.3. "Plug-out" opportunities: what could be going on?

We term the other side of the Mobile Electricity coin "plug-out" hybrids. Plug-out opportunities include exporting vehicle power under various conditions, such as "on the go," "in need," and "for profit."

2.3.1. Plug out "on the go": mobile power

The advent of electric-drive vehicles could facilitate the increasing use of mobile power for a wide variety of devices, gadgets, and appliances for work (whether blue-collar tools or white-collar office-on-wheels) or leisure. Much as roads allowed us to wander off the rails and wireless communications increasingly allow us to communicate off the wires, Me-could further facilitate a wide variety of "untethered" activities, thereby decoupling activities from specific geographical locations.

[11] This is relative to what might be used in a plug-in hybrid or battery vehicle; the Prius's electric motor provides a significantly larger proportion of total power than many other commercial "mild" hybrid models.

Table 1
Plug-in hybrid prototypes (circa Fall 2006)

	Dodge Sprinter plug-in prototype	EDrive Prius conversion	Prius+ NiMH conversion prototype	Hymotion L5 Prius conversion kit	Hybrids-Plus Prius conversion
Primary organizations	Daimler–Chrysler	EDrive (marketing) Energy CS (develop.) Clean-Tech (LA install)	CalCars, ElectroEnergy (EEEI)	Hymotion	Hybrids-Plus/Energy Sense
Status	3 prototypes in U.S. as of October 2006; 30+ to be tested worldwide (18 in U.S.)	Announced will do commercial conversion beginning 2006	Single prototype conversion	Claim: for authorized Government and fleet install; for consumer use in October 2006. Delivered 1st conversion to external customer HOURCAR September 2006	Doing conversion; delivered one September 2006; one conversion will be given V2G capability for study with NREL
Propulsion battery					
Type	Saft Li-ion	Valence Li-ion	EEEI Bipolar NiMH	Li-ion polymer	A123 Li-ion, same as DeWalt 36 V
Capacity (kWh)	14.4	9	7.3	5	~0.5 gal gasoline
Price	not available	$12 k installed (+Prius)	not available	$9500 target (+Prius) for orders >100	$32,500 (+Prius), $15 k by mid 2007

Relatively little activity outside of the recreational vehicle and cigarette-lighter-plug-in-inverter industries has emerged. However, 12 V outlets in cars are multiplying and increasing in power into 110 V home-style outlets in some vehicle makes and models.

More sophisticated examples of mobile power are also emerging. In February 2005, Toyota reported it would test a Prius capable of producing 3 kW at 120 V with a rural electrical cooperative in Oklahoma "to identify technical issues and determine if there is a commercial market" [24]. Further, as mentioned in Section 2.2.2, the "Toyota Dream House" by TRON Architecture was conceptually designed to be able to use the Prius for power in emergencies. In 2005, Toyota executive Shinichi Abe reportedly told the UKs Guardian newspaper that future Toyota hybrids will be able to operate as mobile generators [23].

2.3.1.1. Free your imagination. This study will not present a specific "killer app" of untethered mobile power. The wide variety of potential opportunities makes simply cataloguing them difficult. However, before moving on to "tethered" Me- innovation, for which more obvious applications have been identified, it is worth noting that untethered electricity applications may be accordant with recent coverage in the business press about the importance of harnessing "do-it-yourself" and "lead-user" innovation to corporate product and business development [25]. The question for the user-innovator then becomes, "What will you do when you can do anything, anywhere, anytime?" [14]

2.3.2. Plug out "in need": emergency power

Dissatisfaction with utilities perceived as large, remote, unreliable, and customer-unfriendly, events like the California electricity crisis, regional blackouts, and terrorist attacks fuel a desire for the independence and security of emergency power. An untethered example of emergency Me- is the publicized use of GM contractor hybrid pickups to run medical refrigerators in hurricane-damaged Florida. Taking this one step further, swarming multiple Me- EDVs to power an entire hospital or other facility is an example on the more "tethered" end of the emergency-power spectrum.

One of the most straightforward examples of plug-out opportunities to the consumer mind might be the use of a personal EDV to power an individual home in an emergency. Requiring relatively little coordination, using an EDV in this way might be the "simplest" plug-out opportunity. It would, nonetheless, presumably require onboard and off-board hardware. Onboard hardware will be discussed in more detail in Section 2.3.4. Off-board hardware—a "Mobile Electricity Interface" (Me-I) that, for example, determines which household loads are priority and safely routes and monitors Me- power—is not treated in detail here, but rather simply highlighted as a possible area of valuable intellectual property development.

2.3.3. Modeling untethered and emergency Me-

The next section describes vehicular distributed generation for a profit. Modeling so-called vehicle-to-grid (V2G) power includes a description of most of the requirements for all plug-out opportunities (the notable exception being the Me-I). However, it is worth introducing that modeling effort first in the somewhat simpler context of mobile power for untethered use and emergencies.

In order to illustrate plug-out Me- opportunities, a simple vehicle model was constructed for various EDVs using published vehicle energy-storage and fuel-economy and/or range ratings (EPA ratings were used where available for consistency). The model follows energy stored in the "tank" (i.e., compressed hydrogen vessel for H_2FCVs or traction battery for plug-ins and battery EVs) through various conversion losses to AC electricity potentially available for other uses, as a function of driving distance required. This allows the trade-offs between zero-tailpipe-emission[12] driving and zero-emission power to

[12] or "elsewhere-emission," henceforth simply "zero-emission".

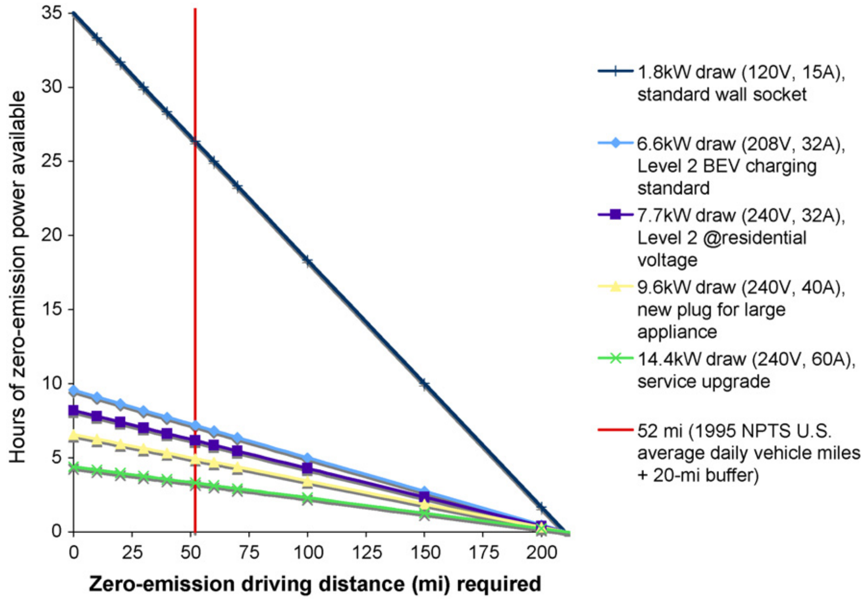

Fig. 2. Zero-emission Mobile Electricity vs. zero-emission driving: FCX 2006.

be explored. Figs. 2–4 explore such tradeoffs by introducing: the importance of infrastructure level-of-service (Fig. 2), the capabilities of various electric-drive-vehicle types (Fig. 3), and the abilities of these vehicles to provide residential emergency power (Figs. 3 and 4).

Fig. 2 illustrates zero-emission driving versus power tradeoffs for a vehicle based on the Honda FCX with 2006 refueling software upgrades. The *x*-intercept in the bottom right hand corner of Fig. 2 shows the FCX's EPA-rated range of 210 miles (expected to increase to 270 with the next generation). Were all of that fuel energy used for Me- rather than driving, a 1.8 kW load could be powered for roughly 35 h (the top left corner of Fig. 2). Higher-power loads would correspondingly reduce the amount of time a given level of fuel energy could sustain them.

The vertical red line in Fig. 2 represents a rough threshold for typical driving. As noted by Kempton and Tomic ([16], abbreviated K&T05a), the average daily vehicle miles in the U.S. was 32, according to the 1995 National Personal Transportation Survey. Similarly, the U.S. Department of Transportation Bureau of Transportation Statistics reports the average number of miles driven per day by people older than 15 in 2001 was 29.1 [26]. Adding a buffer of 20 miles for unexpected/unplanned trips [20] to the 32 average daily vehicle miles, 52 miles is used here to calculate the amount of driving energy one might want to reserve on a daily basis to assure use of Me- does not impede the primary

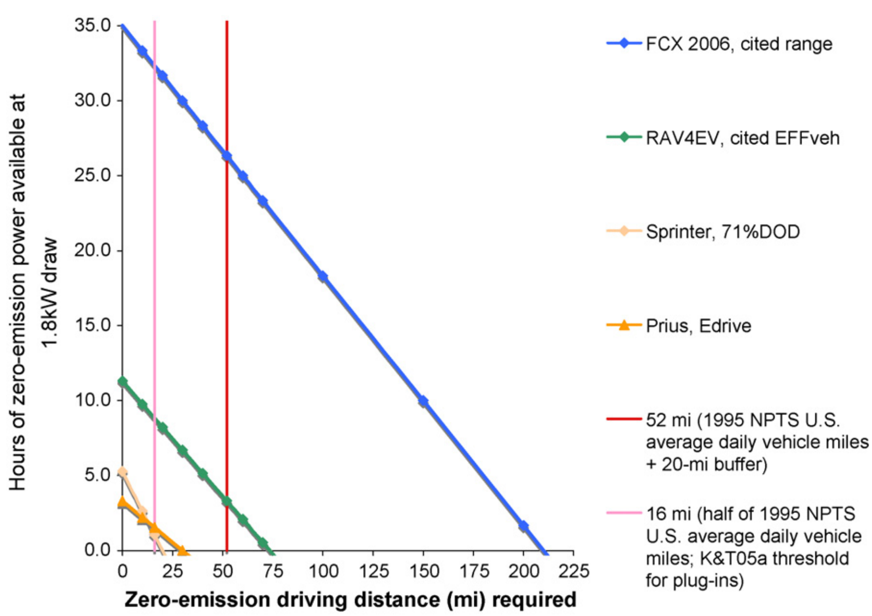

Fig. 3. Zero-emission Mobile Electricity vs. zero-emission driving: 1.8 kW load.

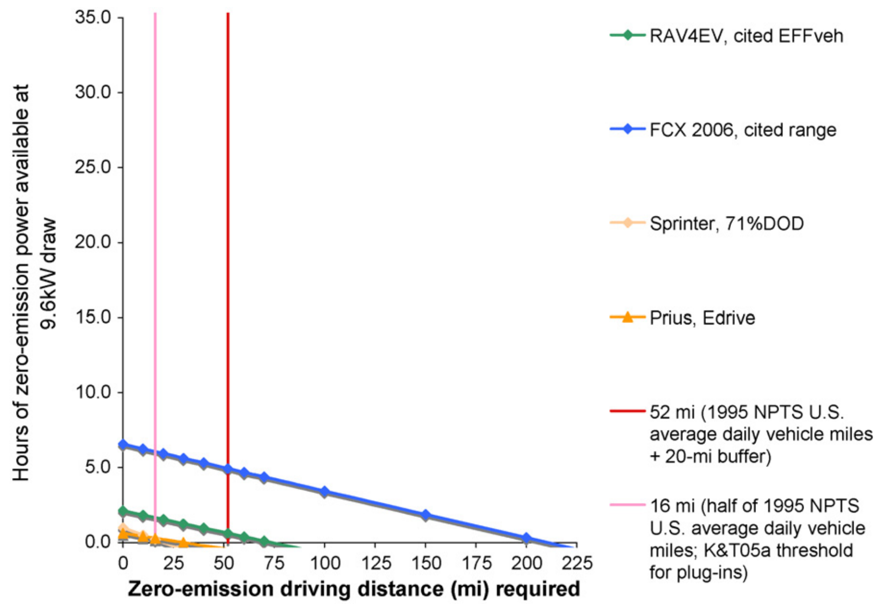

Fig. 4. Zero-emission Mobile Electricity vs. zero-emission driving: 9.6 kW load.

(transportation) use of the vehicle.[13] Thus, to reserve energy for average driving needs, only points on, or to the right of, the vertical red line in Fig. 2 and subsequent figures should be considered.

Rather than showing power versus driving distance for one vehicle at various loads, as in Fig. 2, Fig. 3 depicts power versus driving for several vehicles at one load (1.8 kW, representative of a standard wall socket and wiring). The FCX line extending from 210 miles to 35 h can be seen as in Fig. 2. In this and subsequent graphs, the FCVs are shown in blues. The model representation of the RAV4EV is shown in green, and two representations of plug-in hybrids are shown in oranges, one of the Sprinter PHEV and one representing the edrive Prius conversion. An additional, pink vertical line represents a driving threshold for plug-in combustion hybrids, which do not have to reserve battery charge for driving but which will probably not have fully charged batteries when called upon for Me-. In this case, following Kempton and Tomic,[14] it is assumed that half of average daily driving, or 16 miles, will have been completed in all-electric mode before providing Me-.

The 1.8 kW load level is a reasonable proxy for average U.S. household loads, making the results depicted in Fig. 3 an indication of how long each vehicle type could power a home in a blackout. Actually running an entire home would require matching transient loads higher than the average load, e.g., refrigerator/freezers and HVAC systems cycling off and on. Though these loads are not usually sustained for very long, as a bounding case Fig. 4 gives a rough indication of how long each vehicle type could power a home at loads closer to U.S.-average peak levels. Because an "average peak" is still not the maximum peak electrical load that a home might present, there is a need to prioritize electrical loads within the home in the event the vehicle is not capable of providing peak household power, either at all or for long periods.

2.3.4. Plug out "for profit": vehicular distributed generation

Passenger cars are most households' second-most expensive assets, after the home itself. By some measures, however, automobiles are extremely idle. Following a previous conceptual exercise [27], consider that we park our vehicles over 95% of the time, usually in habitual places. Further, even when employing the asset to move us from A to B, we typically use a small fraction of its peak power capacity. It takes roughly one-third of a typical car engine's peak power to cruise at highway speeds. This means households operate motor vehicles at an engine capacity factor of a few percent or less. From an electric utility perspective, this would be an abysmal generator utilization rate and a poor use of a valuable economic asset.[15]

Further, consider that the power-generating capability of the cars in the U.S. fleet is roughly 10^{12} hp, or several times the

[13] Note that Kempton and Tomic [16] use 36 miles (=$0.5 \times 32 + 20$) as their daily driving threshold for calculating V2G revenues. Only reserving half of average daily driving, however, has implications for infrastructure and behavior (e.g., it might imply both at-home and at-work charging/refueling) that (1) may not be accounted for in the assumed infrastructure costs, (2) may be a less appropriate paradigm for plug-in hybrids and FCVs than for BEVs, and (3) is not consistent with the 20-mile-range-buffer concept, which was meant as a safety net on top of a full day's driving. Further, it is noted that the NPTS data is cross-sectional and has a large standard error; longitudinal household data would be appropriate. Thus, using roughly 50 miles as a notional daily driving threshold is an improved, if imperfect, aid for the exploration of driving-distance vs. Me- power tradeoffs.

[14] Kempton and Tomic use a 36-mile threshold for BEVs and H_2FCVs, significantly lower than the 52 miles assumed here.

[15] Of course households are buying much more than a simple power plant. Part of what households buy when they buy an automobile is automobililty—self-directed mobility available when they want it. Even a parked car is generating value to the household in the form of potential mobility. In this way, plug-in and some plug-out applications of ME and Me- are ways to add to the value being generated by a parked vehicle.

installed generating capacity of the U.S. electrical grid. Were there some profitable way to bring the opportunity of idle car-engine capacity to bear on the chronic under-capacity and power-quality problems of the electric grid, we would have a situation similar to science fiction writer William Gibson's commonly quoted characterization of other opportunities: "The future is already here—it's just unevenly distributed." Indeed, "redistributing" opportunity into a profitable future—employing vehicle engines capable of producing surplus electricity when parked to provide various grid-support services—is no longer a fanciful idea. V2G power, it is the subject of a growing body of literature (e.g. [10,16,18,28]), initial proof-of-concept demonstrations [29], and continuing conversations between academics, technology providers, and government agencies.

2.3.4.1. The electrical grid. Recent major regional power outages in the U.S. and California's power crises demonstrate the complexity of assuring adequate production and delivery of electricity. Investment planning for generation capacity sufficient to meet uncertain future demands for electricity is a balancing act between the financial risks of over-construction and the benefits of economies of physical scale. Grid operation is complicated by daily and seasonal demand peaks and the need to precisely maintain power quality in the face of variable loads. Several markets have been created to help grid operators meet these and other challenges, a few of which have been targeted in the literature as promising opportunities for V2G power.

2.3.4.1.1. Problem: "Keeping the lights on". "Keeping the lights on" is a complex and difficult mission. The electrical grid is seemingly easily disrupted by such commonplace occurrences as falling trees—let alone hurricanes or terrorist attacks—and its operation is perhaps poorly appreciated by household consumers expecting electricity with flip-of-the-switch convenience. Businesses, whose profits often critically depend on reliable power at predictable prices, equally depend on the successful operation of the grid. The challenge of successfully matching supply with demand for electrical services is pertinent to this investigation in several ways.

Investment in generation is lumpy. Conventional power plants require large investments based on uncertain forecasts of electrical demand a decade or so into the future. Further, the consequences of underestimating demand (and therefore having inadequate supply) are too great, requiring a construction schedule that assures an electrical surplus. The bigger the plant size used in a practice of over-construction, the lower the overall capacity factor, the more idle capital, and the greater the susceptibility to unexpected softening of demand.

One potential response is the deployment of smaller and flexible units of generation, abandoning the economies of scale of traditional power plants for an improved risk profile. There is evidence that the many, primarily financial, benefits of a more "distributed" power-generation approach have already begun to outweigh the physical economies-of-scale benefits that have historically led to ever-increasing power-plant size [30].

Electricity demand is peaky. Daily and seasonal peaks in electrical demand must be met, diminishing the capacity factor and hurting the economics of plants that are not used during off-peak hours. Further, some of the largest generation units are the least flexible in this regard—it would not make sense to fire up a spare nuclear plant or two for a couple hours per day or year—and are therefore dispatched with the highest priority to ensure demand for their maximum, constant output. On the other hand, some of the plants used to cover the peaking requirement, e.g., single-cycle combustion turbines, operate at relatively low efficiency and produce relatively high emissions. This difference between the average and the marginal, e.g., peaking, efficiency and emissions resulting from powering the electrical grid is an important feature of discussions of vehicular distributed generation.

The current response to meet the highly variable electric demand is the establishment of several "behind-the-scenes" markets for peak power and power quality, to be described next.

There's more to it than generating electricity. In addition to electricity generation, several issues relating to transmission and distribution are pertinent. Two important types of grid operators are: (1) local utilities, who manage "the wires" and (2) regional system operators (e.g., the California Independent System Operator or Cal ISO). The former faces complex investment decisions about maintaining and upgrading congested power systems. Distributed power, typically small enough and clean enough to be located close to sources of demand, can be utilized in these local distribution decisions as a tool to avoid or defer costly upgrades.

The regional operators, on the other hand, are charged with the larger-scale balance of supply and demand to maintain the quality of the electricity being bought by consumers. In order to precisely control the voltage and frequency of power on the grid, additional "behind-the-scenes" markets have been created for power-quality services, such as "voltage-regulation" and "spinning-reserves." These markets involve paying a certain amount of reserve generation capacity to run in synchrony with the grid (or to otherwise be prepared to quickly supply grid-synchronized power) in the event that it is needed to maintain power quality, e.g., voltages within a narrow target range. Importantly, capacity employed in this manner gets paid for contracted availability whether or not energy is actually produced and used. In California, both of these markets are formed on the basis of day-ahead and hour-ahead contracts, generally using a bidding process in which the regional system operator procures capacity until a sufficient amount of power is contracted, thereby setting the price [9].

As should already be clear by even the cursory discussion of the electrical grid presented here, several opportunities exist for suitably rapid-response, available, and/or distributed electrical-power and -service provision. Supplying these services with vehicular generation capacity is described next.

2.3.4.2. Kempton and Tomic V2G articles. Kempton and Tomic [16,18] have clearly articulated the technical and business fundamentals of using vehicles to supply grid-support services. Their work argues that doing so could:

- earn owners of electric-drive vehicles from zero to thousands of dollars in annual net revenues,
- reduce demand charges for commercial electrical consumers,

Table 2
Characteristics of electricity markets appropriate for V2G power[a]

	Response time	Revenue payments	Dispatch call frequency	Generation duration per call	Generation time ($h\ year^{-1}$)
Peak power	>10 min, e.g., day ahead or long-term	For *energy* generated [$0.50 kWh^{-1}]	~40–60 calls per year (back calculated from rule of thumb)	3–5 h [4 h]	Industry rule of thumb for central CA: [200 $h\ year^{-1}$]
Spinning reserves	10 min	For *energy* [$0.03 kWh^{-1}] and *capacity* per kilowatt available for contract period [$0.007 kWh^{-1}]	[20 calls per year]	10 min to 2 h [1 h]	[20 $h\ year^{-1}$]
Regulation (reg. up = supply electricity to grid; reg. down = draw from grid)	<1 min; direct control of independent system operator (ISO)	For *energy* [$0.10 kWh^{-1}] and *capacit y* [reg. up and down: $0.04 kWh^{-1}; reg. up only: $0.02 kWh^{-1}]	Many short calls per day	A few minutes [reg. up and down: 20 min; reg. up only: 1.4 h]	[1/10th of time plugged in = 657 $h\ year^{-1}$]

[a] Kempton and Tomic model values are included in brackets for convenience and subsequent comparison.

- increase the stability and reliability of the grid,
- lower electrical system costs, and, eventually
- act as inexpensive storage for intermittent renewable electricity.

The latter point has caught the attention of the National Renewable Energy Laboratory (NREL), which has analyzed the potential use of PHEVs to buffer intermittent wind power, thereby increasing wind capacity and generation share [31].

2.3.4.2.1. Electric markets. Table 2 summarizes some of the key features of the three markets considered as amenable to V2G power provision. Markets for peak power, spinning reserves, and voltage regulation require increasingly rapid response. Peak-power markets only pay participants for the energy actually supplied. In contrast, ancillary-service (spinning-reserve and voltage-regulation) markets also pay generation for being on-call and available, based on the power capacity promised over a given contract period. Actual generation is typically rarely called upon each year in these markets, and even when it is, it is generally required for very short periods of time. Taken together, these features mean that these markets are relatively difficult to serve with large, expensive, power plants, and might be better served by small, agile, mobile generators scurrying about the electrical landscape.

2.3.4.2.2. V2G profits. Peak power revenues (and therefore profits) are sensitive to the usual variety of electricity-generation factors, such as “fuel”/input prices. However, because actual energy-production levels tend to be small in voltage-regulation and spinning-reserves markets, their revenues tend not to be very sensitive to the cost of fuel inputs or engine/energy-converter degradation. The profits for these markets are sensitive, however, to the prices offered to generation capacity for being on call and to the capital costs of the various generation technologies.

2.3.4.3. The Mobile Electricity model, including vehicular distributed generation. Starting from Kempton and Tomic’s conceptual description of V2G power [16], this section incorporates the new vehicle model described in Section 2.3.3 into a plug-out Mobile Electricity model, including onboard and off-board costs and V2G net revenues.

Whereas Figs. 3 and 4 presented the plug-out capabilities of various EDVs at 1.8 and 9.6 kW loads, respectively, Fig. 5 shows the power capacity those EDVs could sell into V2G markets for a 1-h contract, as a function of how much energy they need to reserve for driving. Notice the familiar red and pink vertical lines representing the typical driving thresholds discussed in Section 2.3.3.

The intersection of the red and blue lines in Fig. 5 indicates that the FCX as represented in the model could drive 52 miles and then sell up to 47 kW for 1 h before depleting its fuel. This “red-line” or “fuel-limited” scenario will be used in subsequent discussion. Similarly, the intersection of the pink and orange-yellow lines shows the edrive Prius as modeled could sell 2.8 kilowatts of capacity for 1 h (2.8 kWh) and 2.8 killowatt-hours (2.8 kWh) of zero-emission energy after driving 16 miles—i.e., half the average daily vehicle miles—in all-electric mode.

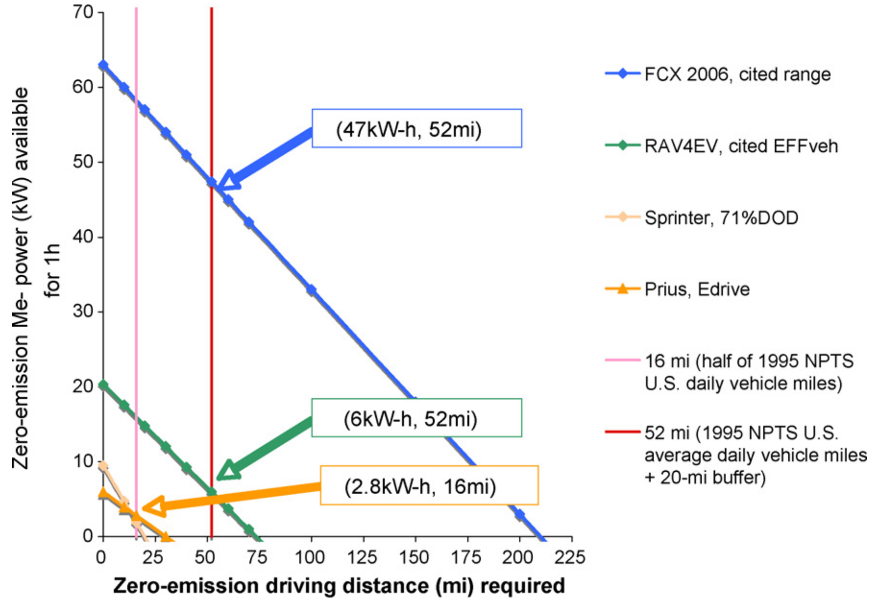

Fig. 5. One-hour zero-emission power capacity vs. zero-emission driving distance.

Fig. 6 presents a similar picture, this time focusing exclusively on FCVs: the P2000 in the Mobile Electricity model using specifications characterized by Kempton and Tomic, the 2006 FCX (demonstrating a significantly improved capability relative to previous V2G analysis), and the FCX-V concept car. The latter has an uncertified range of roughly 350 miles and a correspondingly large Me- production possibilities frontier.

2.3.4.3.1. Vehicles modelled. Table 3 lists the various vehicle and infrastructure combinations modeled in the present analysis. Whereas [16] examines vehicles at illustrative power levels (e.g., 15 kW), this analysis explores each vehicle type at a variety of levels of infrastructure investment. The vehicles in black font and white (no) shading represent scenarios limited by infrastructure investment. The red and pink vehicles represent the "red-line" or "fuel-limited" design points discussed previously. The vehicles shaded in yellow with "max" labels represent bounding cases that use all of their fuel for Me- power, reserving none for driving.

2.3.4.3.2. Incremental costs. *Cost inputs*. Table 4 summarizes the major cost assumptions for both the model presented here and by Kempton and Tomic ([16], hereafter "K&T05a").

In both the K&T05a case and this analysis, capital is annualized over 10 years at a discount rate of 10%, resulting in a capital recovery factor of 0.163 (with a minor variation of 0.16 used for the K&T05a RAV4EV case). In this analysis FCVs are charged an additional 33% of their initial engine costs over a 5000-h life for use as Me-/V2G generators. At \$100 kW^{-1},

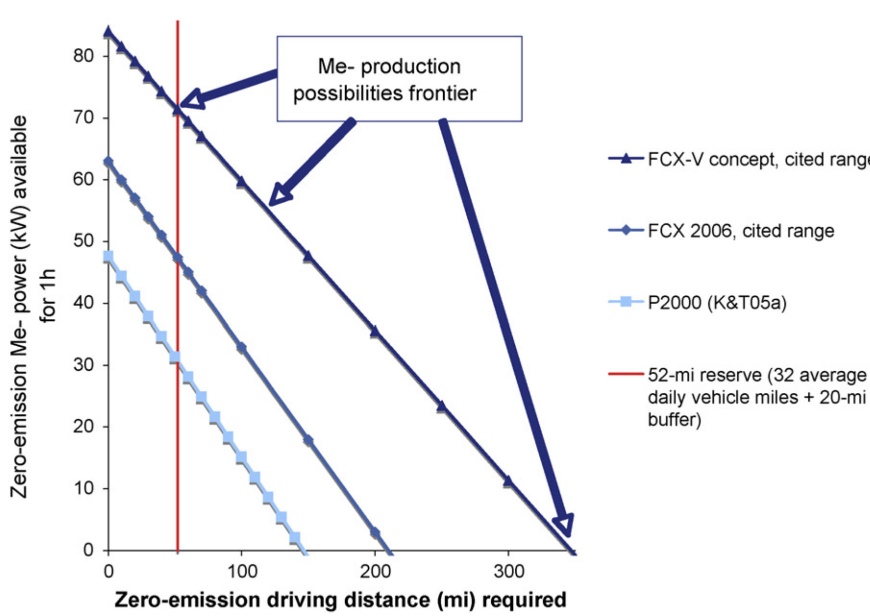

Fig. 6. One-hour power capacity vs. driving distance for various FCVs.

Table 3
Vehicle and infrastructure combinations modeled

	Pspin (kW)	Preg (kW)	Ppeak (kW)
RAV4EV (K&T05a)	15	15	
RAV4EV	1.8	1.8	
RAV4EVfuellimit	6.0	17.9	1.5
RAV4EV	9.6	9.6	
RAV4EV	14.4	14.4	
RAV4EVmaxkW	20.4	50	
edrive Prius	1.8	1.8	
edrive Priusfuellimit	2.8	8.3	0.7
edrive PriusmaxkW	6.0	17.9	
P2000 (K&T05a) high	15		15
P2000 (K&T05a) low	15		15
FCX	1.8	1.8	
FCX	9.6	9.6	9.6
FCX	24.0		
FCXfuellimit	47.4	33.9	11.9
FCXmaxkW	63.0	45.0	15.8
FCX-Vfuellimit	71.5	51.0	17.9
PFCX	1.8	1.8	
PFCX	9.6	9.6	
PFCX	14.4	14.4	
PFCX	24.0		
PFCXfuellimit	47.4	8.3	11.9
PFCXmaxkW	63.0	17.9	

this amounts to ~1¢ kWh^{-1} Me- produced, a rate four times greater than assumed in K&T05a and roughly equal to the "high-cost" scenario[16] described in Lipman et al. [10]. In this analysis, \$4 kg^{-1} hydrogen is converted to AC electricity at ~50% average efficiency. The \$4 kg^{-1} hydrogen roughly represents an efficiency-adjusted gasoline-cost-competitive level. It is between the K&T05a high (\$5.50) and low (\$1.70) cases, which are included for additional perspective.

Cost per unit energy (\$ kWh^{-1}). Based on the cost inputs just described, Table 5 presents the cost per kWh produced by various vehicles in the model. FCVs produce energy at roughly \$0.25 kWh^{-1} (again, between the K&T05a high and low cases). Plug-in hybrids do worse because of high-assumed battery degradation costs due to relatively deep discharging. Indeed, the \$0.29 kWh^{-1} for PHEVs may be optimistically low, and could be as high as \$0.42 kWh^{-1} assuming shorter battery life. The model calculates that battery EVs will produce energy less expensively than either FCVs or PHEVs (~\$0.23 kWh^{-1} calculated here) because of shallow discharges and overall higher vehicle efficiencies.

Time energy produced. Table 6 shows the assumed time per year vehicles will be asked to generate energy (i.e., call time or dispatch time) for each of the three markets being considered (spinning reserves, regulation, and peak power). An important determinant of both costs and revenues is the number of hours it is assumed vehicles will be plugged in and on call each day (tPLUG in Table 6). K&T05a assumes 18 h day^{-1} (365 day $year^{-1}$). This may seem high, but vehicles tend to be parked for even longer periods, but perhaps not at a single location. To explore results more reflective of a single vehicle-to-grid infrastructure investment per vehicle—e.g., either at home or work, but not both—this analysis assumes vehicles are parked and available to the grid for 12 h day^{-1} (and 11 months $year^{-1}$).

Infrastructure capital costs. Building upon K&T05a, Table 7 shows the assumed investment required for residential V2G at various levels of power capacity. It is assumed that electrical service upgrades will be required at higher power levels, increasing costs and decreasing market potential (e.g., from 10 to 5 million Californians)—an issue of concern explored in the market analysis described previously [15].

Vehicle incremental capital costs. Table 8 shows assumed incremental vehicle capital costs for V2G (i.e., on top of what you pay for to drive the vehicle from A to B). See Section 2.2.1.1 for comparison to charging-only costs.

Cost summary: red-line vehicles. Table 9 summarizes the costs for each of the vehicle types providing V2G at the "red-line" or fuel-limited design point and are characterized as such in red and pink in the table (not to be confused with the accounting convention of using red).

Costs range from a couple hundred dollars per year for providing low-power spinning reserves (using batteries, the green box) to several thousand dollars per year providing high-power regulation (using FCVs, the blue box). It is also worth noting that peak-power costs are similar in nature and magnitude to those for spinning reserves (the brown boxes).

2.3.4.3.3. V2G net revenues. Table 10 summarizes revenue inputs and red-line-vehicle net revenue results. Spinning-reserves and regulation revenues are very much a function of the capacity prices offered (the black box), as well as, to a lesser extent, the energy prices offered (the grey box).

Using batteries to provide spinning reserves or peak power appears to be of limited interest from a net revenue perspective (the green boxes in the NETrevSPIN and NETrevPeak columns). Net revenues for the edrive Prius and RAV4EV in these markets are negative or small in each case. The best financial play is for battery EVs to sell regulation (the other green box). This is in part because batteries allow the vehicle to sell both regulation-up (capacity to produce power) and regulation-down (capacity to consume power, which can be used to charge the battery).

The next most promising V2G opportunity is to use a FCV to sell spinning reserves (left blue box), due to its high power capabilities even in fuel-limited conditions. Additionally, it appears a FCV selling peak power might also do well (right blue box). Indeed, it might be profitable to design plug-in FCVs capable of selling regulation (teal box), although that depends on the life of small (and therefore more deeply discharged) batteries and the details of how regulation from a PFCV would be provided and managed.

The model indicates it is not worth (from a net revenue perspective) selling regulation-up only using a FCV, unless the vehicle is so high-power capable, like the FCX-V concept, that it can cover the high costs of high-power regulation (center blue box).

Table 11 shows net-revenue results for the full array of vehicle/infrastructure combinations modeled. Two additional sets of observations are worth noting from the net-revenues perspective.

First, because infrastructure capital costs are lumpy and uncertain but assumed high at high power levels (due primar-

[16] The three scenarios described are: 25% over 4 kh, 33% over 10 kh, and 50% over 40 kh.

Table 4
Cost inputs

	RAVEVs	K&T05a RAV4EV	PHEVs	FCVs	K&T05a FCV
Capital recovery factor (CRF)	0.163	0.160	0.163	0.163	0.163
(kWhAC/kWhFUELavail)	0.74	0.73	0.74	0.50	0.41
Cost of degrdation ($ kWh^{-1})	$0.0752	$0.0752	$0.1350	$0.0100	$0.0025
$/unit fuel (kWh or kgH2)	$0.1143	$0.10	$0.1143	US$4	US$1.7–$5.6

Table 5
Vehicle generation costs per unit energy ($ kWh^{-1})

	cgen (/kWh)
RAV4EV (K&T05a)	$0.21
RAV4EV	$0.23
RAV4EVfuellimit	$0.23
RAV4EV	$0.23
RAV4EV	$0.23
RAV4EVmaxkW	$0.23
edrive Prius	$0.29*
edrive Priusfuellimit	$0.29*
edrive PriusmaxkW	$0.29*
P2000 (K&T05a) high	$0.42
P2000 (K&T05a) low	$0.13
FCX	$0.25
FCX	$0.25
FCX	$0.25
FCXfuellimit	$0.25
FCXmaxkW	$0.25
FCX-Vfuellimit	$0.25
PFCX	$0.25/$0.29*
PFCX	$0.25/$0.29*
PFCX	$0.25/$0.29*
PFCX	$0.25/n.a.
PFCXfuellimit	$0.25/$0.29*
PFCXmaxkW	$0.25/$0.29*

*May be as high as $0.42 kWh^{-1} with shorter battery life assumptions.

Table 7
Infrastructure capital costs

Residential plugs and wires			
Voltage (V)	Amperage (A)	Pline (kW)	Cost
120	15	1.8	
			$50
240	40	9.6	
			$655
240	60	14.4	
		24.0	
			$1,500
240	80	19.2	
			$1,800
240	400	96.0	
			$5,000

ily to electrical service upgrades which include significant labor costs), the benefits in high-power V2G scenarios tend to be dampened. This disproportionately hurts FCVs. Further, comparing net revenues from the same vehicle but at different levels of infrastructure shows that "bigger isn't always better," especially on a per kW basis. Note how the FCX loses money on regulation at 33.9 kW, but nets a profit selling regulation at 9.6 kW. Thus red-line power scenarios are not always, as one might initially expect, the optimal revenue point, particularly when they lie at a power level just high enough to require a major infrastructure upgrade to connect the vehicle to the grid.

A second observation from Table 11 is that the most infrastructure-limited vehicles have difficulty making profits (the green, orange, and small blue boxes). Thus the "no new infrastructure" claim for charging PHEVs may not hold for plug-out opportunities, especially for V2G power, and in particular for the sale of spinning reserves.

Table 6
Dispatch time (time energy produced in h year^{-1})[a]

	Here	K&T05a
tspin (h/y)	3.3	20
tPLUG (h/y)	4020	6570
disptch/contrct	0.1	0.1
treg (h/y)	402	657
tpeak (h/y)	200	200

[a] Throughout, yellow font indicates uncertain value (caution).

Table 8
Vehicle incremental capital costs for V2G

Plugged-in vehicles (BEVs and PHEVS, incl. PFCVs)	
$400	AC Propulsion purpose-built V2G power electronics with "extensive control and safety to ensure no back feeding of power onto the grid during an outage..." (Letendre & Kempton 2002, p. 18)
Fuel-cell vehicles (FCVs)	
$450	power electronics to synch to 60Hz and provide protection
$200	wires and plug for grid connection
$650	

Table 9
Cost summary: "red-line" (fuel-limited) vehicles

	Pspin (kW)	Preg (kW)	cSPIN	cREG	Ppeak (kW)	cPEAK
RAV4EVfuellimit	6.0	17.9	$176	$2,004	1.5	$141
edrive Priusfuellimit	2.8	8.3	$174	$1,138*	0.7	$113
FCXfuellimit	47.4	33.9	$959	$4,298	11.9	$801
FCX-Vfuellimit	71.5	51.0	$979	$6,009	17.9	$1,236
PFCXfuellimit	47.4	8.3	$918	$1,138*	11.9	$760

*Shorter battery life may increase by ~$450

Table 10
Revenue inputs [16] and the bottom line: V2G net revenues, red-line vehicles

pcapSPIN (/kW-h)=	$0.007	pcapREGup&down (/kW-h)=	$0.04	pelSPIN (/kWh)=	$0.03	pelREG (/kWh)=	$0.1143

	Pspin (kW)	Preg (kW)	NETrevSPIN	NETrevREG	Ppeak (kW)	NETrevPeak
RAV4EVfuellimit	6.0	17.9	-$8	$1,696	1.5	$8
edrive Priusfuellimit	2.8	8.3	-$96	$584*	0.7	-$44
FCXfuellimit	47.4	33.9	$381	-$17	11.9	$385
FCX-Vfuellimit	71.5	51.0	$1,039	$440	17.9	$550
PFCXfuellimit	47.4	8.3	$421	$584*	11.9	$426

*May be as low as $133 with shorter battery life.

Table 11
Net revenues: the whole gang

	NETrevSPIN	NETrevREG	NETrevPeak
RAV4EV (K&T05a)	$331	$2,532	
RAV4EV	-$24	$133	
RAV4EVfuellimit	-$8	$1,696	$8
RAV4EV	$92	$930	
RAV4EV	$86	$1,343	
RAV4EVmaxkW	$201	$4,859	
edrive Prius	-$24	$90*	
edrive Priusfuellimit	-$96	$584*	-$44
edrive PriusmaxkW	-$9	$1,262*	
P2000 (K&T05a) high	$175		-$145
P2000 (K&T05a) low	$261		$717
FCX	-$65	-$66	
FCX	$51	9.6kW: $43	$271
FCX	$308		
FCXfuellimit	$381	33.9kW: -$17	$385
FCXmaxkW	$809	$280	$444
FCX-Vfuellimit	$1,039	$440	$550
PFCX	-$24	$90*	
PFCX	$91	$699*	
PFCX	$86	$997*	
PFCX	$349		
PFCXfuellimit	$421	$584*	$426
PFCXmaxkW	$849	$1,262*	

*Regulation net revenues for plug-in hybrids (edrive Prius and PFCX) decrease considerably with shorter battery life.

2.3.4.3.4. Further observations. Sensitivities. The results are sensitive to variation in the number of hours per day the vehicles are plugged-in (tethered) and on-call.[17] This may largely explain why the “maxed out” RAV4EV (reserving *no* fuel for driving) calculated here as a bounding case did not perform as well as the K&T05a RAV4EV illustrative example. The results are not sensitive to even a four-fold increase in FC degradation costs. Nor are they sensitive to a four-fold increase in the price received for spinning reserves energy. (However, spinning-reserves energy price of course becomes more important as the dispatch time per year increases.)

So is V2G an attractive opportunity? At first glance, some of the annual net revenues offered by selling grid-support services appear modest. Do they provide enough motivation to all the players that need to be involved, either in terms of shared margins or embodied in properly accounted for costs? On the other hand, netting even a few hundred dollars per year with a previously idle asset with system-wide benefits for the electrical grid and commercialization benefits for EDVs may seem a “no-brainer” to some. Or, from a more academic point of view, if the assumptions in this analysis are reasonable, with sufficient conservatisms to help balance the effect of simplifications and uncounted or unforeseen additional costs, one might argue that the overall promise of vehicular distributed generation is at least good enough to continue its study. However, assuming for the moment that the generally more conservative set of assumptions[18] used in this study relative to previous work squeezes the margins of V2G profitability somewhat uncomfortably, the question of how to frame the potential benefits becomes more important. One might ask, “What might make the margins look better?” One possible approach is aggregation.

Aggregation. The residential case is perhaps a relatively simple case in that it would involve individual households having the freedom to make individual decisions about how to use their vehicles and what costs to bear for what level of plug-out services they desire. In most other regards, however, it is likely to be the most difficult to implement and the longest-term of the Me- opportunities. For example, it requires each vehicle to bear the costs of relatively high-power V2G infrastructure and requires tremendous coordination between the grid, the independent system operators, and every household selling V2G services. Although previous research has argued that this may be possible and profitable, this modeling effort views the residential case as a high-cost launching point for these markets, vehicles, and services.

The residential case requires sophisticated aggregation of *transactions*, much as cell-phone and other companies manage for large numbers of customers, sometimes at quite narrow margins. Initially for vehicular distributed generation, however,

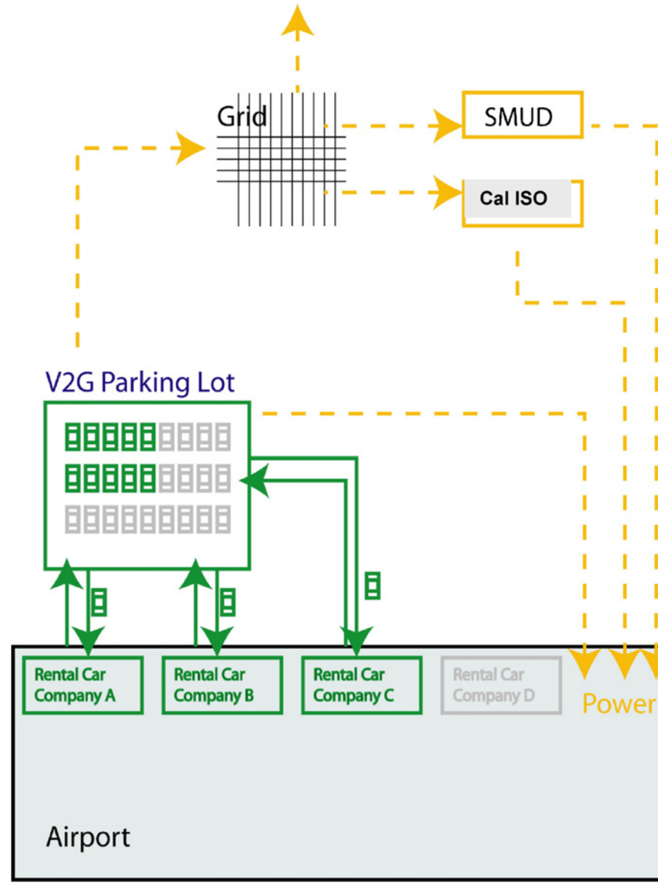

Fig. 7. V2G aggregation: airport rental example.

spatial aggregation might be attractive. Whether initially for fleet-owned or privately owned vehicles, spatial aggregation into “parking-lot power plants” would offer various benefits. These include the ability to spread infrastructure costs, simplify coordination, limit bi-directional power flow centers and the need for time-sensitive price signals, aggregate capacity and energy supply into utility-friendly and distributed-generation-hardware-friendly units (e.g., megawatts), and aggregate V2G benefits. It could also open up additional, related opportunities, such as supplemental refueling, green branding and other product differentiation, reduced commercial demand charges, and strategic load shedding (especially off congested distribution trunks).

A conceptual example of a parking-lot power plant using idle hybrid airport-rental cars to provide local and system-wide electricity services is shown in Fig. 7 [11]. This configuration might smooth the car-rental industry’s seasonal and weekly rental-revenue variability and relax inventory constraints while increasing the public’s exposure to EDVs at reduced rental costs.

The airport-rental-car parking-lot power plant is one example to stimulate thinking about V2G aggregation opportunities and early (pre-household-market) business development. To conclude this discussion of vehicular generation and plug-out opportunities, let us return to the net-revenue results and some comments about technology development. Both are the subjects of future work.

[17] The results are not particularly sensitive to variation in the number of days the vehicles are available per year, perhaps simply because the variation thought reasonable to explore here (12–11 months) is much smaller on a percentage basis when compared to the number of hours per day (18–12 h).

[18] The major exception is of course the overall improved capabilities of FCVs resulting from the vehicle specifications and model used here relative to previous representations.

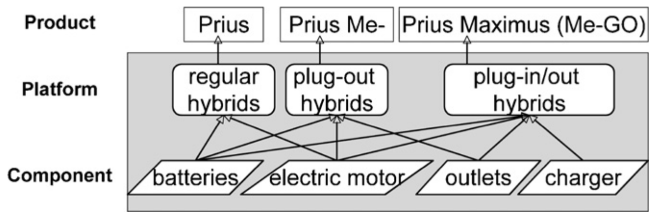

Fig. 8. Me- hybrid platform development.

2.3.5. Plug-in/-out hydrogen-fuel-cell vehicles

Given (1) that even the best FCX/infrastructure combination modeled here earns modest spinning-reserves net revenues, (2) that even a relatively small plug-in battery doing regulation appears profitable (assuming ongoing improvements in battery life), and (3) the Me- framework presented here, there is a case to be made for commercializing H_2FCVs as plug-in/-out H_2FCVs, i.e., Me-FCVs.

The opportunity to develop Me-FCVs opens up new infrastructure questions. Might Me-FCVs be recharged at home (for daily needs) and hydrogen refueled abroad (for longer trips)? Or vice versa? Although the latter option seems less likely due to the costs of stand-alone small-scale hydrogen production, the home energy station being developed by Honda to supply hydrogen to cars and electricity and heat to homes might be even more valuable if it sends the family car with a full tank each day out into a fuel-neutral Me- world to earn some revenues.

Either way, it is time to move beyond framing batteries and fuel cells in a zero-sum game, and starting thinking of them as complimentary. A “Unified Theory of Mobile Energy” of sorts might argue for the following.

2.3.5.1. Strategic recommendation: unifying Mobile Electricity and hydrogen. Starting with the here and now, Fig. 8 illustrates the possible development of today’s gasoline hybrids into plug-in/-out hybrids based on a Me- platform (GO refers to gasoline-optional operation).

Vehicles based on the Me- hybrid platform would begin creating markets for Me- services, thereby transforming FCVs from radical and disruptive into sustaining products that emerge as one possible extension of this progression, when hydrogen and FCs mature. To illustrate such a progression, Fig. 9 incorporates hydrogen and fuel cells into a roadmap that incorporates various aspects of the Me- framework discussed in this study, and points the way towards future work exploring business and marketing strategies for commercializing Me- technologies (as described briefly in the next section).

Developing H_2FCVs in this way—as one possible manifestation or extension of a Me- platform (creating a Mobile Energy (ME) platform)—repositions H_2FCVs as a potentially cleaner, higher power, and more profitable contender in established and valuable ME markets.

3. Overall summary and conclusions

This and related research lay a foundation for subsequent research into how to successfully commercialize H_2FCVs, other EDVs, and other Mobile Energy technologies. Such research bridges several disciplines and activities to inform effective demonstration projects, scenario formulations, and other technology assessments and marketing studies. Additionally, use of Mobile Electricity (Me-) innovation as the example of an innovative driver of commercialization highlights the important relationship between H_2FCVs, plug-in hybrids, and broader energy systems, such as the electrical grid.

This study, a “Mobile Electricity assessment,” integrates previously disparate technology analyses and activities into a Me- framework. It describes both “plug-in” and “plug-out” opportu-

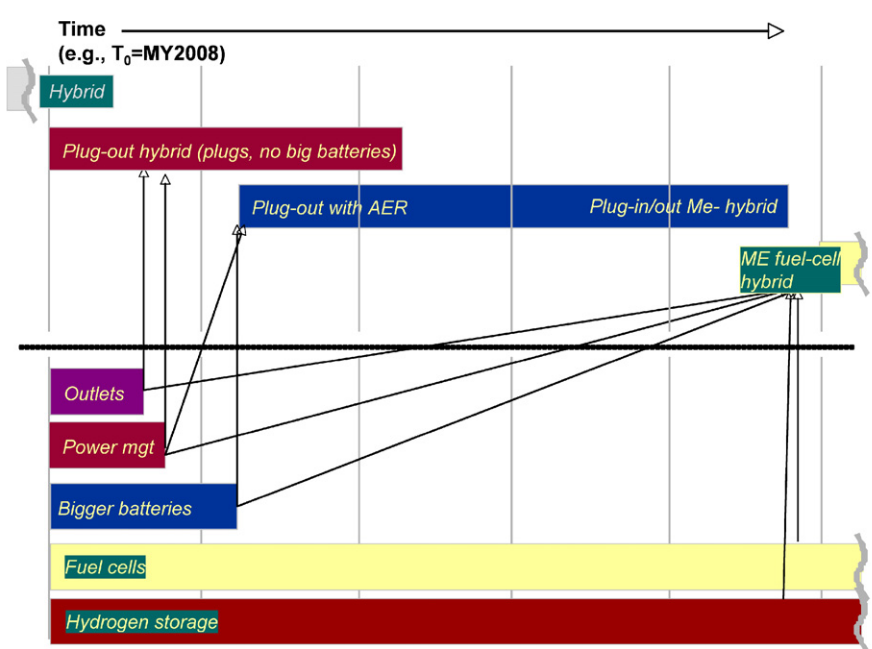

Fig. 9. Mobile Electricity hydrogen-fuel-cell vehicle development.

nities. The plug-in discussion presents an overview of analysis and activities and discusses critical issues related to the Me- framework as a whole (e.g., batteries and charging). The discussion of plug-out opportunities is more a discussion of what *could* be going on in Me- development. To describe exporting electricity off-board the vehicle for non-motive purposes, "on the go," "in need," and "for a profit," it illustrates costs and benefits, power versus range trade-offs, vehicle and building incremental capital costs, and vehicular distributed generation net revenues under various sets of assumptions for various EDVs. The discussion of vehicular-distributed-generation (the "endgame" of plug-out opportunities?) builds upon, and is indebted to, previous vehicle-to-grid (V2G) power studies, particularly Kempton and Tomic [16].

Compared to past work, the electric-drive-vehicle and net-revenue models developed for this Me- study have been adapted to better accommodate H_2FCVs and other "fueled" vehicles and to explore Me-power vs. driving-range tradeoffs, infrastructure level-of-service, and other aspects of the Me- framework. Additionally, the modeling discussed here uses somewhat more conservative input assumptions (e.g., more energy reserved for daily driving and less vehicle availability for vehicular distributed generation) but up-to-date H_2FCV specifications. The results are largely concordant with previous studies, but highlight the importance of: vehicle recharging infrastructure limitations and uncertain capital costs; battery life; daily plugged-in availability; and aggregation of vehicular distributed generation.

This analysis indicates that Mobile Electricity opportunities appear to be an initially expensive yet promising driver of the commercialization of green vehicle technologies. If their costs appear prohibitive when considered as add-ons to conventional vehicles, they must be weighed against consumer willingness-to-pay for "green cars" and, perhaps more importantly, new products and services. This raises interesting questions about what constitutes optimal vehicle, refueling, and electric infrastructure design and how the benefits of green vehicle technologies can be successfully realized. The next step is to pursue the strategic recommendation to explore plug-in/-out H_2FCVs (Me-FCVs) by bringing together battery and fuel-cell development activities into a unified view of Mobile Energy platform development. Doing so would create new consumer-behavior and infrastructure opportunities (e.g., recharge at home, refuel abroad) and reposition H_2FCVs, when they are ready, as one possible gold standard for providing clean, high-power, and potentially higher profit ME services into markets created by early Me- market pioneers. Indeed, as Fig. 5 illustrates, the Me- production possibilities frontier (i.e., the capability of H_2FCVs to provide zero-emission driving and Me- power) appears to be large and expanding at a relatively rapid rate. Concordant with a desire to present results for existing, not speculative, vehicles, this study did not explore the capabilities on the relatively near horizon of vehicles such as the FCX-V prototype. However, the improvements embodied in such combustion-free vehicles offer even greater potential Me- benefits, such as V2G profitability (although at diminishing returns in cases where vehicle capability outstrip infrastructure capability/investment). Thus, over time the prospects for Me- from various sources will undoubtedly shift, and might be even brighter overall than those presented here.

A past investigation quantified and characterized a promising early market segment for plug-in hybrids, H_2FCVs, and other Mobile Energy technologies [15]. Future work amalgamating that analysis with the present one will allow a subtler, less averaged exploration of who is Me- capable and how they might benefit. Target market demographics can be used to increase Me- modeling sophistication by helping to determine and characterize important model inputs such as vehicle availability (hours per day and daily driving, which varies significantly by, e.g., employment status, gender, and age), vehicle type (energy storage and conversion), and housing characteristics (likely required infrastructure investments and emergency power needs). Research questions specific to market/case-study selection will also help drive the development, as needed, of other model enhancements (e.g., battery cycle life, fuel-cell power production efficiencies, and engine degradation as a function of scenario-specific load and use) as well as further, context-specific sensitivity analyses.

Other related future work will apply innovation, business-development, technology-management, and strategic-marketing lenses to the problem of commercializing H_2FCVs, other EDVs, and other Mobile Energy technologies. One of the goals of this planned work is to take one possible future state (e.g., widespread commercialization of the Me-FCVs characterized in Section 2.3.5) and assemble a technology-evolution and market-development roadmap for ME innovations that emphasizes the particular challenges of "getting started."

The "roadmap" ultimately developed may not point comprehensively nor directly to a V2G H_2FCV future. Many unanticipated and unknowable factors will doubtlessly impact progress and change the destination, let alone the signposts along the way. Rather, the roadmap discussion will try to encourage the discourse about electric-drive commercialization to focus on the relatively specific details of product design—which is critically important to consumer adoption and the successful formation of a supportive industrial community [32]—and present a plausible development pathway that highlights important considerations and indicates how to proceed, or not, at various decision points along the way.

Collectively, these discrete-but-linked studies explore how decision-makers might support ME development and legitimize the technology with private-vehicle consumers—ideally illustrating how H_2FCVs, other EDVs, and other ME technologies might succeed where previous AFV efforts failed in this regard.

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