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Estimating the early household market for light-duty hydrogen-fuel-cell vehicles and other "Mobile Energy" innovations in California: A constraints analysis☆

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Abstract

Facing stiff competition from conventional and gasoline-hybrid vehicles, the commercialization prospects for hydrogen-fuel-cell vehicles (H_2FCVs) are uncertain. Starting from the premise that new consumer value must drive their adoption, early markets for H_2FCVs are explored in the context of a group of promising opportunities collectively called mobile energy (ME) innovation. An estimate of the initial market potential for ME-enabled vehicles is produced by applying various constraints that eliminate unlikely households from consideration for early adoption of H_2FCVs and other ME technologies (such as plug-in hybrids). Currently 5.2 million of 33.9 million Californians live in households pre-adapted to ME-enabled vehicles, 3.9 million if natural gas is required for home refueling. Several differences in demographic and other characteristics between the target market and the population as a whole are highlighted, and two issues related to the design of H_2FCVs and their supporting infrastructure are discussed: vehicle range and home hydrogen refueling. These findings argue for continued investigation of this and similar target segments—which represent more efficient research populations for subsequent study by product designers and other decision-makers wishing to understand the early market dynamics facing H_2FCVs and related ME innovations.

Keywords: Hydrogen-fuel-cell vehicle; Household market potential; Mobile energy innovation; Home refueling; Vehicle-to-grid power; Plug-in hybrid

1. Introduction

1.1. Problem: commercializing fuel-cell vehicles

Despite the potential benefits to society of commercializing alternative-fuel vehicles (AFVs), past efforts have largely been unsuccessful. Pervasive and mature automotive products and the petroleum-based energy system represent formidable performance and cost challenges to any alternative. Hydrogen-fuel-cell vehicles (H_2FCVs) face similar fundamental challenges for the foreseeable future, e.g., high cost, compromised driving range per refueling, and lack of a refueling infrastructure. Accordingly, H_2FCVs' commercialization prospects remain highly uncertain. How might H_2FCVs (or any AFV) succeed where past efforts have failed?

1.2. Approach: "Mobile Energy" 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 displacement of today's mature and high-performing 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 of this and related work at the University of California at Davis' Institute of Transportation Studies 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, thereby driving their commercialization?"

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1.3. Focus: "Mobile Energy" from light-duty vehicles in early households

One group of opportunities for H_2FCV innovation stems from the ability of these vehicles to produce clean electrical power for purposes other than propulsion. These and related potential innovations, collectively referred to here as Mobile Energy (ME) opportunities, are described in the next (Section 1.4). Of course, 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. To keep the scope of this work manageable, those issues will not be considered here. Further, this work focuses on neither the earliest customer placements, e.g., relatively controlled experiments in fleets, nor the widespread adoption by the mainstream by which time commercialization would be foregone and the challenges become "sustaining" (e.g., sales and market share). Rather, this research focuses on the first stages of relatively widespread commercialization of light-duty H_2FCVs in households.

Irrespective of scope considerations, 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 [1]. 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-ICE-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 evolutionary pathways. For example, one can imagine first developing ME for ICE hybrids as a means to create market demand for services that might, in turn, support H_2FCV commercialization as those technologies mature [2].

1.4. Mobile Energy

What then, is "Mobile Energy"? Loosely defined, 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 [2–4]), as well as importing electricity to the vehicle (e.g., for vehicle battery charging of "plug-in" EDVs [5]).

[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., (1) H_2FCVs will not be competitive on conventional dimensions for the foreseeable future and (2) 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.

1.5. Objective: early household market description

The specific objective of this study is to identify, quantify, and characterize a current estimate of the most promising early household market segment for light-duty H_2FCVs, under the premise that ME is a distinguishing new user value. Questions addressed include: "What is a reasonable maximum initial sales pool for H_2FCVs?"; "Who are the target consumers?"; "What conditions that limit the market potential today might change over time to expand the potential market?" Although conducted for H_2FCVs, it should be noted this study uses techniques suitably general for, and derives results suitably applicable to, a wide variety of EDVs. The conclusions drawn here should therefore have value for anybody interested in ME innovation, whether for fuel-cell or ICE-hybrid vehicles, whether for home refueling or Mobile Electricity.

2. Methodology

2.1. Capability-constraints analysis

"There are two sorts of people, those who divide people into two sorts, and the others."—statistical maxim.

In order to identify early markets for vehicles fueled at home and/or connected to energy grids other than gasoline, a capability constraints approach is used here. This approach segments the population into two groups on the basis of physical and behavioral constraints deemed desirable, if not necessary, for early ownership of ME-enabled H_2FCVs. The target market segment identified is thus a group of households or individuals "pre-adapted" to use and benefit from ME innovation.

2.1.1. Pre-adapted

Several aspects of this approach are worth highlighting. First, the identification of the "pre-adapted" target segment for early adoption of H_2FCVs is based solely on measures thought to indicate a consumer's *ability* to benefit from ME innovations. Thus it does not take into account *beliefs, tastes*, or other important determinants or aspects of *purchase behavior*. It identifies a more narrowly defined research population for subsequent study of these factors.

2.1.2. Initial market potential

Further, the target segment identified in this study gives an indication of *market potential*, the pool from which initial H_2FCV sales are likely to be drawn. Thus, vehicle *sales*, a given automaker's or product's *market share*, and the *buy-down base* over which the incremental costs of the technology can be spread are necessarily (much) smaller numbers. In this sense, the market potential identified here represents a sort of theoretical maximum initial sales pool.

This maximum, however, is not immutable. It is more like a "snapshot," formed on the basis of historical relationships embodied in the data and a set of assumptions about how consumers might, or might not, be able to benefit from ME as it is now conceived. Not only are the constraints identified in the literature less precise than might be hoped (unnecessarily eliminating certain consumers from consideration while keeping many unlikely to adopt ME), the filtering criteria are also, not surprisingly, blunt proxies for these theoretical constraints. Additionally, the market potential identified is the *initial* potential. Given time, the consumers eliminated from consideration by this study will overcome one or more of the constraints currently thought to preclude their easy adoption of the technology (an issue at least partially addressed by a sensitivity analysis of the assumptions employed—see Section 3.1). However, to the extent that the filtering criteria used here *are* precise enough to be thought useful, the constraints they represent are not expected to be overcome without cost (i.e., requiring an additional investment of time, effort, and/or money on the part of the consumer that would reduce the likelihood of adoption), making the analysis sufficiently robust to usefully define the limits of the market potential for ME in the near-to-mid term.

2.2. Data: U.S. Census microdata sample

The data used in this study came from the 1% Public Use Microdata Sample (PUMS) of the 2000 U.S. Census. This data set consisted of some 274 variables describing 339 thousand individual cases representing 34 million Californians (choice of California described in Section 2.3). This data set includes the most detailed Census demographic and household characteristics available to the public, suitably aggregated and otherwise treated so as to not reveal individually identifiable confidential information.

2.3. Theory: constraints/filtering criteria

The filtering criteria employed were derived from demographic, behavioral, and other characteristics gathered in various bodies of the alternative-fuel-vehicle (AFV) literature as indicating the ease with which a household or individual could adopt AFV technology. These characteristics largely speak to the household's/individual's ability to incorporate an AFV into their "household vehicle fleet" and to connect vehicles to other energy systems, such as refueling, at home. They have been boiled down to a handful of relatively simple, commonsense criteria.

2.3.1. Spatially segmented AFV commercialization strategy

Geographically limited deployment could aid AFV commercialization by: concentrating demand; focusing marketing, distribution, and sales efforts; increasing utilization of infrastructure [6] and other complimentary assets; creating business clusters; simplifying regulatory compliance and the establishment of supportive standards; and consolidating a political-support base. This scope of this study is limited to the state of California for these and other reasons. California is an obvious choice for its long regulatory support of AFV technologies and high consumer demand for green technologies. Less obvious might be its relatively self-contained and somewhat geographically distinct large economy and history of uniquely stringent fuel and conventional vehicle standards [7].

2.3.2. Home connection hardware

In order to enable most ME innovations—in particular home refueling and/or recharging or emergency, back-up, or vehicle-to-grid power provision—some sort of hardware connection between the vehicle and the home will be necessary. The argument here is that consumers will be more likely to go to the effort and/or expense of required installations or modifications if they: own their residence, have parking access close to their homes, and live in a structure otherwise supportive of such a connection. Proxies for these considerations using variables available in the Census data were constructed, for example by limiting residence type to exclude vans, boats, and RVs on the one hand, and residences of five or more connected units on the other.

Further, many ME innovations might require an electrical connection that exceeds the capabilities of some standard wall sockets. Nesbitt et al. [8] highlight the importance of compliance with 1974 electrical codes in the context of a similar capability-constraints assessment of the market potential for battery-cars requiring at-home recharging. Although the electrical requirements for other ME technologies, such as H_2FCVs and plug-in ICE hybrids, are likely to be significantly different than those for battery-car recharging, the availability of adequate electrical wiring continues to be pertinent. Even if H_2FCV propulsion batteries are not charged at home, other supporting or related equipment—communications, monitoring, refueling, or emergency-power—may have significant electrical loads. The Census data does not provide an easy way to accommodate this concern. However, building age was explored as a proxy for likely compliance with 1974 electrical codes.

2.3.3. Lifestyle accommodation

Kurani et al. [9] explore in some detail with trials, interviews, and surveys the behavioral aspects of private use of range- and infrastructure-compromised vehicles (emphasizing, in that study, neighborhood-electric vehicles). Kurani et al. found considerable opportunity for adaptive accommodation of AFVs in individual or household lifestyles. Two important constructs related to AFV purchase and use highlighted in that and related work are those of the "household vehicle fleet" and "household activity space."

The household vehicle fleet construct led to the characterization of "hybrid households" that can easily accommodate an AFV into a household fleet consisting of both alternatively and conventionally fueled vehicles through trip planning, vehicle swapping, and other adaptive behaviors. This construct is captured in this study by targeting individuals living in households with more than one vehicle, allowing the possibility that one could be replaced by an AFV while retaining household access to a conventional vehicle.

Because H_2FCV driving range capabilities are still unknown, household activity space is not used in the data filtering process, but reserved for subsequent discussion.

2.3.4. Initial price premium

Initially, ME innovations will carry with them significant price premiums, not the least of which will apply for home-fueled H_2FCVs. However, projected vehicle and related costs (not to mention pricing) both vary widely and are the subject of significant continuing debate. To avoid contentious pricing predictions and allow the reader to explore these issues from a greater variety of perspectives, target consumer income distribution will be presented and discussed rather than overly prescribed. Nevertheless, two loose criteria were applied: target consumers were not allowed from completely unemployed households or households with no income whatsoever. This seemed appropriate to reflect a bare-minimum ability to pay for the expensive new technologies under consideration and to increase the validity of the target market identified.

2.4. Analysis: overview

The analysis consists of two major parts. First, the reductive effect on market potential of various sets of assumptions was assessed. This was carried out by applying over 25 filtering criteria singly and in combination to the PUMS Census data. A multivariate approach and the microdata sample allowed customized assumption combinations to be *simultaneously* applied to the data, providing capabilities beyond the simple, univariate Census data tabulations.

Second, once the target market was identified and the sensitivity of the reductive effect to each of the criteria used assessed, the target segment was then characterized using relevant residential, personal, and household variables in the Census data.

3. Results

3.1. How many? Initial market potential

Simultaneously applying the constraints described in Section 2.3 produced an initial target segment for ME H_2FCVs consisting of 5.2 million Californians, an 85% reduction from the 33.9 million population-as-a-whole.

3.1.1. Sensitivity analysis

Fig. 1 illustrates the sensitivity of the initial market potential to various assumptions. The farthest left, red bar in Fig. 1 shows all 33.9 million Californians represented by the 1% PUMS of the 2000 U.S. Census. The next, green bar is the initial estimated target segment of 5.2 million. The next eight bars illustrate the market potential resulting from relaxing, one at a time, each of the constraints used to derive the target segment.

The target market potential is most sensitive to the constraint that only residences built after 1969 can easily be ME-enabled. This constraint is a blunt proxy for likely compliance with 1974

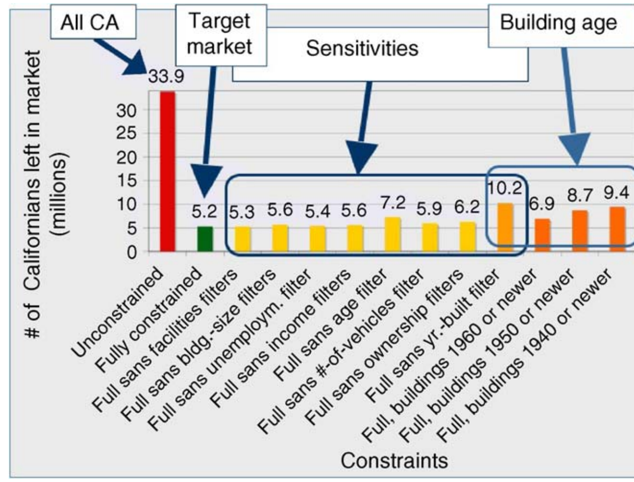

Fig. 1. Target segment and sensitivities.

electric codes, and thus ability to accommodate ME innovation electrical loads as described in Section 2.3. Relaxing this constraint—in essence assuming that all Californians who otherwise would be in the initial target segment lived in residences that have sufficient electrical service to support the physical connection between a ME-enabled vehicle and their home—nearly doubles the estimated initial market potential to 10.2 million Californians. Because this effect was large, the sensitivity of the market potential to building age is subdivided by decade in the four bars furthest to the right in Fig. 1.

3.2. Who are they? Characterizing the target segment

The target market cannot be directly compared to the California population as whole on a strict apples-to-apples basis. However, when interpreted cautiously, differences between the groups can be illustrative. Selected differences are presented next.

3.2.1. Mean value comparisons

Mean values for the initial target market were statistically different than the mean values for the population as a whole for all variables examined, although most target-market mean values were within one standard deviation of the population mean. For example, relative to the population as a whole, target households on average tend to: have longer commutes, be married couples, have more vehicles, have larger families, have more workers, have higher incomes, be older, have higher educational attainment, and pay more for all utilities and their mortgages. Target residences on average are: newer, worth more, cost more, occupied longer, larger, and heated in more cases by utility gas. Note though that the number of household vehicles, personal age, and residence age are directly influenced by application of filtering criteria.

3.2.2. Distribution comparisons

Mean values are not always the most meaningful results, and for some variables are essentially meaningless. Therefore, distributions were explored for several variables.

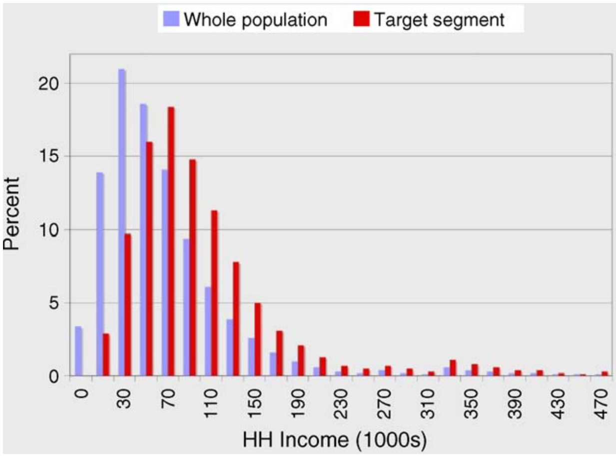

Fig. 2. Household income distribution (percentages).

3.2.2.1. Household income. Figs. 2 and 3 show the household income distribution of the target segment and whole population. Household income has been grouped into $ 10,000 bins with midpoints plotted on a percentage basis (Fig. 2) and on an absolute frequency (i.e., number of individuals) basis (Fig. 3).

Fig. 2 shows that the household income distribution of the target group is shifted toward higher incomes relative to the State population as a whole. Additionally, Fig. 2 shows that the highest income households are disproportionately represented in the target segment. Fig. 3 illustrates the overall reductive effect of the constraints employed in the study.

3.2.2.2. Number of vehicles per household. Keeping in mind that the number of vehicles per household is a filtering criterion, Fig. 4 gives a sense of the vehicles available to the target segment relative to the whole population. It also illustrates that households with a large number of vehicles are disproportionately represented in the target segment. While the target group is only about 15% of the total population, the target group makes up about one-third of all households that own four or more light-duty motor vehicles.

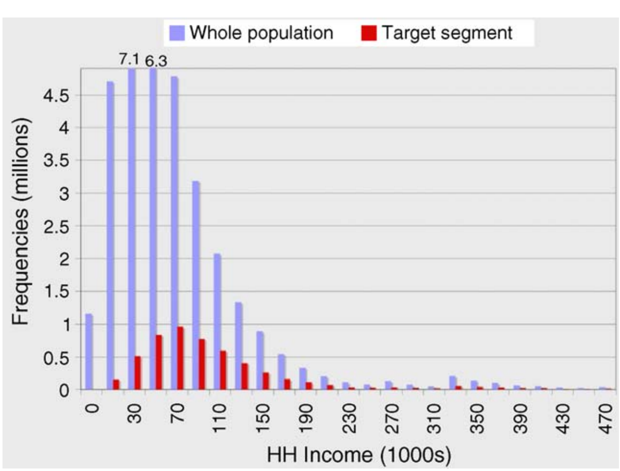

Fig. 3. Household income distribution (frequencies).

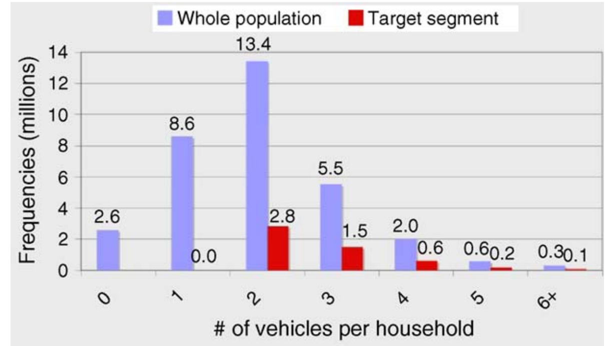

Fig. 4. Number of vehicles per household (frequencies).

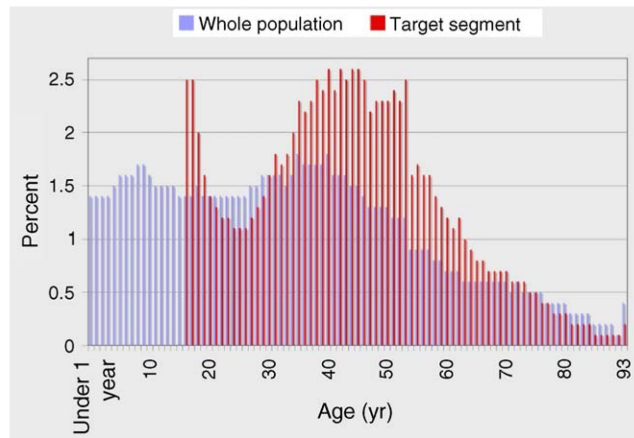

Fig. 5. Age distribution (percentages).

3.2.2.3. Personal age. The experimental design makes precise direct age comparisons between the target group and the total population difficult. However, Fig. 5, which plots the age distributions on a percentage basis, indicates the following trends: 20-somethings appear to be underrepresented in the target segment, as are those over 75 years of age. The target group's age distribution appears to be shifted toward the 35–55-year range.

3.2.2.4. Educational attainment. The target group has a higher average level of educational attainment (some college) than the population as a whole (not completed high school, a result biased by the presence of more youth in the whole population). This trend can be seen in Fig. 6.

3.2.2.5. Travel time to work. Table 1 shows the travel time to work for the target group and total population on a cumulative percentage basis. For a given cumulative percentage, the target group appears to have a roughly 15 min longer commute than

Table 1
Travel time to work

Travel time to work (min)	Whole CA population (%)	Target market (%)
≤30	90	82
≤45	95	91
≤60	98	96
≤75	98	97

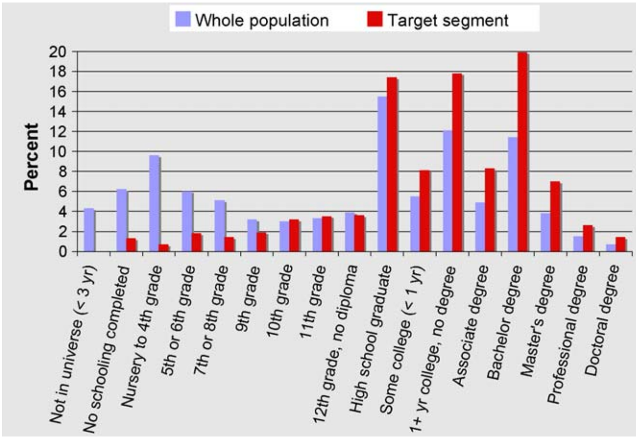

Fig. 6. Educational attainment (percentages).

the population as a whole. For example, 90% of Californians commute for a half-hour or less, whereas a 45 min commute is required to include 90% of the target group.

3.2.2.6. Heating fuel. Fig. 7 shows the distribution of residential heating fuel type. On a percentage basis, the target group is more likely to heat its residences with natural gas and propane than the total population.

4. Discussion

4.1. Overall impressions

A "first-order approximation" of the comparison between the target market and the total population can probably be achieved by considering the target market group for ME-enabled H_2FCVs to be "home owners." One might be tempted to speculate that 20-somethings are underrepresented in the target segment because they have not yet settled into their own homes, whereas home ownership necessarily requires higher income, and so forth. However, even if this were the case, this is clearly not the whole story. In particular, the reductive impact of the constraints considered here go far beyond home ownership: there are roughly 20 million individuals in California living in residences owned by the household, but the initial market potential of the target segment is only 5 million individuals. (This 85% reduction is greater than the 72% reduction found by a 1992 study [8] for battery cars using a similar approach but using different constraints and data.)

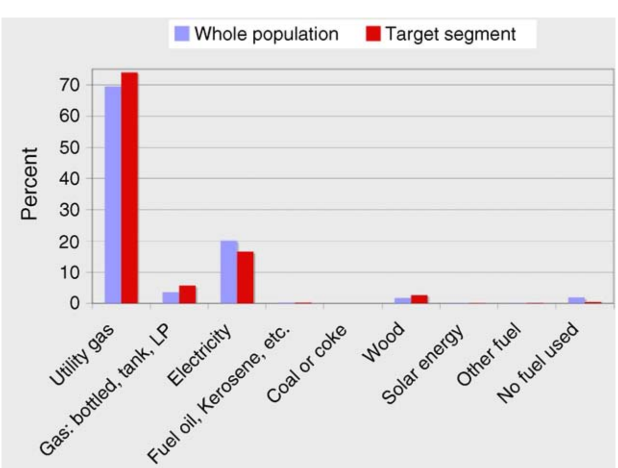

Fig. 7. Household heating fuel (percentages).

This analysis, therefore, prompts several questions that a consideration of home ownership alone would not. For example, is the fraction of a 5-million-Californian initial market *potential* that can be captured as market share by an individual company, or even the buy-down base for the incremental costs of the entire new technology supply industry, *sufficient*? On the one hand even 50,000 vehicles (1% of 5 million) would appear to be sufficient to maintain interest in ME technologies, particularly given the mutable nature of the *initial* market potential and the possibility of locating additional, similarly appropriate market segments to broaden the buy-down base at small marginal cost.

On the other hand, a 5-million-individual *potential* sales pool—or a 10- or 25-million one for that matter—may provide little comfort in the face of the anticipated costs and difficulties of the system-wide innovations implied by a transition to H_2FCVs. This may be of particularly little comfort to an automotive industry used to thinking in high volumes and might argue for the need to find not only other household market segments, but more fundamentally different niches in which to nurture the new technologies and spread buy-down costs.

So the magnitude of reduction in market potential and its implications are effects not entirely captured by the "home owner" simplification. And there are many other, if sometimes subtle, differences between the target group and the whole population, some of which were presented in Section 3. Marketing managers, H_2FCV product designers, and ME innovators would do well to note these differences, and to seek others by asking relevant research questions of target groups such as the one identified and characterized here.

In that spirit, this analysis can also contribute to the creation of a dialogue that will be increasingly important as H_2FCVs are brought from vision to commercialization. This dialogue highlights the differences between solutions created by modeling an abstract technical optimum and those acknowledging the need to successfully market products that meet real or anticipated consumer demands. This tension between technical and marketing optima for vehicle and infrastructure design motivates the following brief contributions to ongoing discussions about vehicle range and home refueling.

4.2. Vehicle design: range requirements

It is anticipated that further focus on and exploration of target market niches and segments like the one analyzed here will yield important guidance for *design*—the specific details of products with which consumers interact, and which ultimately determine the success or failure of the technologies embodied in them in one specific way [10]. An important attribute of H_2FCV design is driving range per refueling. This attribute is subject to high levels of uncertainty because of the challenges facing hydrogen storage technologies, refueling infrastructure, and fuel-cell and system efficiencies. What can this analysis say about H_2FCV range requirements?

One first-cut indication is provided by the commute time results presented in Table 1 (Section 3.2). If over 95% of the target segment has a commute time of an hour or less, even a high (and thus conservative) assumed commute speed of 55 mph (the national average speed for commute trips made in privately-occupied vehicles in 2001 was 32.2 mph [11]) translates into a 110-mile daily roundtrip commute requirement. Adding, as discussed in some reports [12], a reserve buffer of 20 miles for unanticipated trips, this supports the weak assertion that the daily range requirements of most Californians who commute by automobile are already more than met by the nearly 200-mile range capabilities of current H_2FCV prototypes.[2] It can be argued, therefore, that technological "breakthroughs" are not *required* to meet the typical daily driving requirements, as defined, of many members of the target group.[3]

However, that argument is only credible with several caveats. First, such a conclusion assumes that consumers could refuel regularly, as often as daily depending on the closeness of the fit between their daily travel requirements and vehicle range capabilities. In the absence of an existing pervasive hydrogen refueling network, a ME opportunity would be to give consumers the capability to at least partially refuel at home (see Section 4.3). Second, range *requirements* are often quite different than *perceived* range requirements, or most importantly, range *wants*. Third, whether truly pertinent or not to consumer behavior, "compromise" is generally detrimental if perceived by the consumer. And fourth, the *increased* range performance of some gasoline-combustion hybrids as compared to today's conventional gasoline vehicles may make that compromise more readily apparent. This is one of the arguments for the need of further H_2FCV differentiation along different product dimensions discussed in Section 1.

Acknowledging the desirability of minimizing real and perceived driving range limits, it is nevertheless valid to question the importance of driving range per se. Just as consumers really care about good lighting in their buildings, but, in a lumens-undifferentiated world, have developed the unfortunate habit of judging their bulb purchase options on the basis of wattage—which ironically is a measure of cost not benefit—it is valid to ask whether or not driving range is a pertinent attribute from the consumer perspective. Were driving range limits not explicitly raised to the attention of the consumer, would they be (de)valued per se? Are there thresholds above which marginal range improvements become relatively less important? Is *sufficient, equivalent*, or *optimal* range the most relevant? More importantly, is refueling convenience the more operative concept? Research by UC Davis, GM, and EPRI [5] indicate that avoided trips to the gasoline station are an important source of value to consumers. Just as driving range *requirements* are only one aspect of a complicated picture for the consumer, driving range itself is just one piece in a complicated vehicle purchase decision process.

Returning to the challenges of product design, the uncertainties surrounding hydrogen storage, fuel-cell-system efficiency, and infrastructure availability are made more complicated by these questions relating to vehicle range. And this complicated relationship between range, energy storage, and conventional infrastructure availability is further complicated by ME, which brings with it the prospect of increased use of on-board energy for purposes other than propulsion on the one hand, and the prospect of non-conventional refueling regimes on the other.

4.3. Infrastructure design: home reformation or electrolysis?

Home hydrogen is another example of the potential tension between technical and marketing optima. Although less inherently scale-sensitive than some other fuel production methods, hydrogen production experiences economies of scale, as do hydrogen separation/cleaning, storage, and dispensing. Current indications are that home hydrogen might be an expensive proposition in general, with the heat-management requirements of natural-gas-to-hydrogen reformation making that option possibly less down-scaleable than water-splitting electrolysis at the one-car level. The latter option, in turn, tends to suffer on electricity-input operating costs (and environmental consequences if that electricity is coal based). However, it is important to ask, "Expensive relative to what?" Relative to initial H_2FCV purchase/lease prices, into whose financing a home hydrogen appliance might be rolled? Relative to a sustainable-community home mortgage? Relative to the budget of a motivated early adopter with a reasonable income? In short, price, financing, and willingness-to-pay are marketing concepts often neglected by, or difficult to incorporate into, techno-economic cost estimates.

Further, how one defines "the problem" of course has important implications for what solutions are attractive: sluggish or non-existent vehicle sales may doom or prevent H_2FCV commercialization until sufficient conventional infrastructure is somehow justified and put into operation. A home refueling strategy might help technology developers do an end run around the chicken-and-egg problem. That prospect may be motivating a major automaker, which is experimenting with the third generation of its home energy station (HES) research unit for hydrogen refueling [13]. (It has also partnered with an alternative-fuel technology developer, which is offering a garage-mountable natural-gas refueling device to compressed-natural-gas-vehicle consumers.) The HES concept further "redefines the problem" by integrating into one device electricity and heat production for the home as well as hydrogen refueling, allowing costs to be spread over multiple value streams.

[2] The natural temptation is to refine this range "calculation" with precise inputs and/or model the phenomena more accurately. This should of course be done, but is not necessary to support the contention here. Further, as described next, daily *requirements* are just one of several design issues relating to ME vehicle range.

[3] Indeed, battery-car analyses have argued for the sufficiency of far lower range performance. For example, Kurani et al. [12] found evidence of comfort-thresholds for 100 miles or less in many households, assuming daily home recharging.

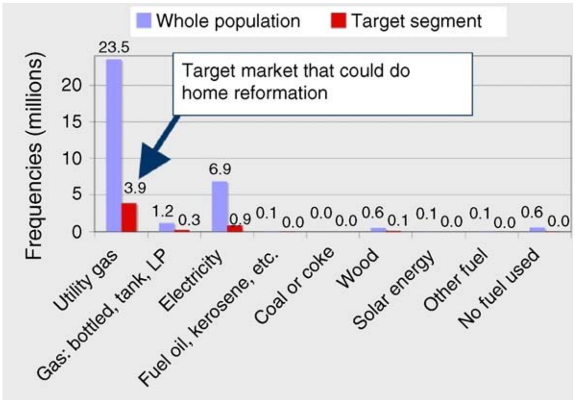

Fig. 8. Household heating fuel (frequencies).

What can this analysis of an early market potential contribute to the question of home refueling? Two contributions are readily apparent. The first is that the target market segment pays more for all household utilities on average, implying that they might be receptive to investing in the home energy strategy. The second contribution begins to address the question of "electrolysis or reformation?" Not everybody has access to utility gas, or even propane, eliminating them from the *initial* market for home reformation. How does the target segment compare in this regard? As illustrated by Fig. 7, on a percentage basis, the target market has greater access to utility gas. Nevertheless, the percentage is not 100%. Fig. 8 depicts heating fuel on an absolute frequency basis, and indicates the 5.2 million individuals in the target segment have been further reduced to 3.9 million by the utility-gas requirement.

5. Conclusions

H_2FCVs cannot be sold simply as clean cars and trucks; innovative value must drive their adoption. From this launching point, the early markets for H_2FCVs were explored in the context of a group of promising opportunities collectively called Mobile Energy (ME) innovations. By applying various common-sense constraints that eliminated unlikely households from consideration for early adoption of H_2FCVs and other ME technologies (such as plug-in hybrids), a dramatic reduction in the "initial market potential" for these technologies was found. Only 5 million out of 34 million Californians remain in the target segment identified. Only 4 million remain if the additional requirement of natural gas use at home is included. This target market represents those individuals that would currently appear *able* to easily adopt, and therefore more readily derive added benefits from, ME-enabled H_2FCVs. It does not take into account tastes or purchase behavior. The magnitude of the target segment thus represents a maximum, though not immutable, *initial market potential*, from which sales will be drawn, forming the buy-down base for the incremental costs of the required innovations. Several differences between the target market and the population as a whole were found and highlighted, and two issues related to the design of H_2FCVs and their supporting infrastructure were discussed: vehicle range and home refueling options.

The target segment identified, and its differences with the population as a whole, are neither trivially small nor overwhelmingly large. These findings would appear to justify both continued investigation of this or similar target segments—which represent more efficient research populations for subsequent study by marketing managers, product designers, and other decision-makers wishing to understand the early market dynamics facing H_2FCVs—as well as investigation into other market niches that can further nurture and support product development and Mobile Energy innovation.

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