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Should policy-makers allocate funding to vehicle electrification or end-use energy efficiency as a strategy for climate change mitigation and energy reductions? Rethinking electric utilities efficiency programs

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HIGHLIGHTS

- We compare subsidies for CO_2 cuts with electric efficiency and plug-in hybrid vehicles.
- Our model focuses PHEVs with a 20 km range and residential electric efficiency.
- The subsidy choice depends on technical, economic, and regulatory factors.
- These include grid emissions factor, size of subsidy, and efficiency program costs.
- PHEV grants of $800-1000/vehicle make sense in most U.S. states without decoupling.

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ABSTRACT

In order to reduce greenhouse gas emissions in the United States by an order of magnitude, a portfolio of mitigation strategies is needed. Currently, many utilities pursue energy efficiency programs. We study a case where utilities could choose whether to allocate their energy efficiency budget to either end-use efficiency or vehicle electrification as a means to reduce CO_2 emissions. We build a decision space that displays the conditions under which utilities should pursue either strategy. To build such decision space, assumptions are needed on how consumers respond to electric vehicle incentives, and what would be the baseline vehicle selected by consumers if no incentives were in place. Since these two aspects are highly uncertain, we treat them parametrically: if consumers are replacing a conventional vehicle with a PHEV, utility incentive programs to induce PHEV adoption appear to be cost-effective for a wide range of efficiency program costs and grid emissions factors.

1. Motivation

Should electric utilities in the United States (U.S.) use funding from energy efficiency programs to induce vehicle electrification adoption instead of using such funds towards end-use energy efficiency programs, namely as a way to reduce greenhouse gas emissions in a cost effective way? In order to reduce U.S. greenhouse gas emissions by an order of magnitude, a portfolio of mitigation strategies is needed. This, in turn, requires a large decarbonization of the U.S. electric grid, improving energy efficiency, and greater electrification of buildings and vehicles (Williams et al., 2012) in areas where the electric grid has low carbon emissions factors.

Residential electricity efficiency programs have been used to reduce energy and pollutant emissions in the electric power sector, in many cases at a lower cost than new power generation investments (National Academies, 2010). There is evidence that a large potential for cost-effective energy strategies, i.e., energy efficiency strategies that would reduce energy consumption while providing the same level of energy services (and while saving the consumer money over the lifetime of the efficiency investment), still exists (National Academies, 2010, Azevedo et al., 2013). In regions with low carbon intensity, alternative vehicles may also reduce emissions. The question we pose is whether it would make sense to have electric utilities choosing whether to invest resources in incentives for electrical end-use efficiency or through up-front capital cost incentives/subsidies to induce the adoption of alternative vehicles as a mean to reduce CO_2 emissions under a budget constraint. We assess the cost-effectiveness of reducing CO_2 emissions, and changes in electricity and gasoline consumption.

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Utilities provide up-front incentives for electricity efficiency for multiple goals: to reduce growth in demand – and thus reducing the investment costs in new power plants, to reduce pollutant emissions and their associated health and environmental impacts, and to reduce greenhouse gas (GHG) emissions that contribute to climate change.

Clean technology adoption subsidies may not be the most economically efficient policy towards the goal of reducing GHG emissions, namely when compared to a carbon price, or a carbon portfolio standard. Incentives may have limited influence on usage behavior and may lead to free-ridership (Stigler, 1974). However, federal and state tax incentives for emerging technologies such as wind, solar, and energy efficiency have proven to be politically feasible, since they provide benefits to small well-organized interest groups (i.e. manufacturers) while imposing costs (if any) on the broader, unorganized taxpayers (Victor, 2011). In the electric utility context, incentives for energy efficiency and distributed solar PV face strict cost-effectiveness tests aiming to limit costs imposed on electric rate-payers, including those who choose not to participate in these programs (National Action Plan for Energy Efficiency, 2008).

This paper focuses on decisions faced by utilities in a world where carbon reduction goals are to be met. Given a policy goal such as reducing CO_2 emissions, we explore two main reasons for utilities to consider being the providers of alternative vehicle incentives. First, it may be in the electric utilities interest to provide incentives for greater vehicle electrification because of the electric charging revenue they may accrue. Utility involvement in promoting electric end-uses is not without precedent. For example, during the 1950s, electric utilities funded information programs on the use of electric and natural gas appliances as part of the "modern home" through a network of saleswomen (Goldstein, 1997).

Second, utilities may justify incentives for vehicle electrification if they can be provided at similar cost-effectiveness to reducing CO_2 emissions as alternative approaches such as residential energy efficiency investments. In the NO_x regulatory context, scholars have demonstrated the significant differences in the cost-effectiveness of electricity versus transportation sector policies (where cost-effectiveness is defined as the marginal abatement cost for a pollutant, measured in costs per ton of pollutant avoided), calling for a cross-sectorial approach to emissions' mitigation (Fowlie et al., 2012).

In contrast, energy efficiency programs are typically evaluated on the basis of a number of benefit-cost ratio tests, with different scopes, perspectives, costs and benefits, to judge the cost-effectiveness of individual programs or portfolios (National Action Plan for Energy Efficiency, 2008), which is a feasible approach when benefits can be valued. Many of these cost-effectiveness tests exclude non-energy benefits of energy efficiency such as the reduction in air pollution or in greenhouse gases that contribute to climate change.

In this paper, we define cost-effectiveness as the ratio between utility program administrator costs (including the incentive payment and administration costs) for either a residential energy efficiency program or a novel program to spur alternative vehicles adoption and expected carbon reductions, measured in dollars per ton of CO_2e reduced. We note that investing in all options at the same level of cost-effectiveness in meeting a policy goal is a necessary but not sufficient condition for an economically efficient mitigation policy.

Incentivizing alternative vehicles may provide a way for utilities to meet environmental regulations to reduce CO_2 emissions, such as California's greenhouse gas cap and trade program (CA Assembly, 2006), while raising some electricity revenues, which can offset the cost of regulatory compliance.

The rest of this article is organized as follows. Section 2 provides an overview of the policy context for residential energy efficiency and alternative vehicle adoption at the federal and state level in the U.S. Section 3 provides an overview of the data and methods. Section 4 shows results and analysis, and Section 5 concludes with policy recommendations, and a discussion of the major sources of uncertainty to guide future research.

2. Policy context

In this section, we start by reviewing the policy context for energy efficiency in the residential sector. We then review the existing or recent policies for alternative vehicle adoption.

2.1. Residential electricity efficiency programs

Demand-side management (DSM) and energy efficiency (EE) programs in the electricity industry have been instituted in response to environmental concerns, a backlash over rate increases from power plant investment costs (Hirsh, 2002), and in recent years, as a cost-effective strategy to reduce greenhouse gas emissions.

Common technologies incentivized through residential EE programs include efficient lighting (CFLs), refrigerators, insulation, and air conditioners (see, for example, DSIRE[1] website for details on such programs). These programs can take the form of rebates, incentives or subsidies, or giving away products (for example in the case of efficient lighting). These programs range in cost-effectiveness depending on a number of factors including electricity prices, the age and scale of the program, effectiveness of program administration, degree of free-ridership, and the baseline efficiency of the residential sector prior to the program implementation (Allcott and Greenstone, 2012; Arimura et al., 2009; Auffhammer et al., 2008; Friedrich et al., 2009; Nadel and Langer, 2012; Parfomak and Lave, 1996). Technical resource manuals developed by the states outline various methodologies to estimate the energy savings and cost-effectiveness for these programs.

As of 2012, 23 states have implemented "decoupling" policies for utilities providing electricity, natural gas, or both (C2ES, 2012). Decoupling policies attempt to sever links between the utility's recovery of the fixed costs of service (a substantial part of revenues) and customers' consumption of electricity and natural gas.[2] This goal is accomplished through a regulatory process of setting a revenue cap for the utilities over a period of time and adjusting the rates to account for weather, number of customers, consumer behavior (i.e. conservation or price elasticity), inflation, productivity, and efficiency programs, that either increase or decrease sales from the forecasts used to develop the revenue cap (Lesh, 2009). Public utility commissions (PUCs) generally implement "non bypassable" surcharges to guarantee that utilities recover the investment costs. One design for such surcharges is to impose a "system benefit charge", generally on a per kWh basis, which may take the form of a small charge in ratepayers' electricity bills of a few "mills" per kWh, i.e., less than a cent per kWh. Another surcharge design used by PUCs is a flat monthly fee, rather than on a per kWh basis. While the specific decoupling policies differ across regions, they generally use the following framework: if actual sales are lower than forecasted, PUCs allow the electric and gas utilities to obtain a rate increase to recover

[1] http://www.dsireusa.org/.

[2] Variable costs of service such as fuel costs, emission charges, etc. are passed on to customers, whether or not their utility companies are subject to decoupling policies.

their fixed costs; if sales are higher than forecasted, a rate decrease is implemented. All such rate changes are typically constrained to be no more than 3% of the existing rate (Kushler et al., 2006) and are much less than the rate variation due to changes in commodity prices (Lesh, 2009).

The onset of electric sector restructuring in several states in the 1990s, in which utilities were separated into generation, transmission, and electric distribution or retailing companies, led to the trough in funding for traditional DSM programs, as utilities scrapped them in order to compete with new entrants without such programs (York et al., 2012). Since then, some states adopted Energy Efficiency Resource Standards (EERS) as an alternative policy that has increased energy efficiency spending from a low of $900 million in 1998 to over $4.6 billion in 2010 (all figures in current year dollars) (York et al., 2012). EERSs, similarly to Renewable Portfolio Standards or Clean Energy Standards, require that a certain percentage or absolute amount of electricity demand be met by a particular resource by a specific deadline, whether demand-side energy efficiency, renewable energy, or low-carbon electricity generation, respectively. Currently twenty states have some form of EERS and seven have voluntary goals (DSIRE, 2012). States vary in the starting date, stringency, and scope of their EERS policies, from 27% in cumulative savings by 2020 in Vermont to just under 3% in North Carolina (Sciortino et al., 2011). Unlike traditional DSM programs, which were founded to limit electric generation investment costs, EERS policies are sometimes explicitly linked to climate change mitigation goals, as in the case of California's state-level CO_2 cap and trade program and scoping plan.

There are many studies, with differing assumptions and methodologies, that have studied the cost-effectiveness of residential energy efficiency in demand-side management programs over time (Allcott and Greenstone, 2012; Arimura et al., 2009; Auffhammer et al., 2008; Friedrich et al., 2009; Nadel and Langer, 2012; Parfomak and Lave, 1996). Most studies have found that utility demand-side management programs can achieve energy efficiency savings at a cost[3] between 4 and 11 cents per kWh (Arimura et al., 2009). We consider the results of these studies as a proxy for the cost-effectiveness of utility-funded incentives for residential energy efficiency more broadly, whether through the prior DSM mechanism or through EERS policies.

2.2. *Incentives to induce alternative vehicles adoption*

There have been several incentives to induce alternative vehicles' adoption, provided by federal and state governments, which use both monetary (tax credit, subsidy) and non-monetary (high occupancy vehicle, or "HOV", lane access, priority parking spots) incentives (Plug In America, 2012). These incentives have been justified using a number of reasons, including creating jobs and supporting economic development in automobile manufacturing states, promoting technological innovation and learning, and reducing CO_2 emissions that contribute to climate change. In Jenn et al. (2013) we provide an overview of the historical incentives for alternative vehicles. For example, the first federal incentive for alternative vehicles came from HR 1308, Section 319 of the Working Families Tax Relief Act of 2004 (Law no: 108-311), where a $2000 taxable income deduction was provided with the purchase of an AEV. In 2005, the Energy Policy Act (Law no: 109-58) included a direct tax credit to consumers for the purchase of a hybrid electric vehicle, a policy that ended at the end of 2010. Another recent effort was the 2-month policy in 2009: the Car Allowance Rebate System, or *Cash For Clunkers*, which provided a tax credit of either $3500 or $4500 for the trade-in of low fuel efficiency vehicles.

2.3. *Interaction between electricity decoupling for utilities and alternative vehicles*

Analysts have called for a reform of decoupling policies in states where vehicle electrification could result in lowering GHG emissions (Swisher et al., 2008). Proposed reforms include submetering for electric vehicles and other environmentally beneficial electric loads, such as more efficient heat pumps, as a way to separate revenues from these loads from other electric loads subject to decoupling rate adjustments (Swisher et al., 2008).

3. Methods, data, and key assumptions

We develop a decision space for a wide range of grid emissions factors and cost-effectiveness for energy efficiency programs – wider than the current range of these parameters across U.S. states – to illustrate how clean the grid must be and how expensive >residential electricity efficiency must become in order for vehicle subsidies to make sense for electric utilities. For the transportation option, we consider two different baseline vehicles being substituted (internal combustion engines powered vehicle, CV, or hybrid electric vehicles, HEVs). The alternative vehicle considered is a plug-in hybrid electric vehicle (PHEV). A PHEV possesses an extended range electric battery as well as a conventional internal combustion engine. The vehicle is propelled by electric power for a limited range, at which point it functions as a hybrid-electric vehicle (HEV), fueled by a blend of gasoline and battery power (Plotkin and Singh, 2009). The use of electric propulsion and an electric drivetrain allows for greater energy efficiency from a tank to wheels perspective, which reduces gasoline use and, depending on the electricity grid mix, can reduce CO_2 emissions.

We consider a range of PHEV subsidies. We illustrate these decision-spaces by first ignoring electricity revenues obtained from PHEV charging and then, in a separate scenario, by including these revenues as a means to defray the electric utility's cost of meeting a CO_2e regulation.

In summary, we provide a decision-space based on the cost-effectiveness of end-use energy efficiency and vehicle electrification for two scenarios of utility structures (*with* and *without* decoupling) and for two baseline vehicles being substituted by a PHEV (either conventional internal combustion engine vehicles, CVs, or hybrid-electric vehicles, HEVs).

3.1. *Base-case*

We develop a decision space for subsidies for PHEV compared to residential electricity efficiency investments, as a function of the cost per kWh conserved and grid emissions factors. In these decision plots, the central decision-maker would choose the option with the lower cost per ton CO_2e avoided. We assume that cost-effectiveness of electricity efficiency from utility-administered demand-side management programs could range from 2 to 11 cents per kWh, which is consistent with the values reported in Arimura et al. (2009) and Friedrich et al. (2009). PHEVs can have different all-electric battery ranges (AER), and previous studies have shown that PHEVs with 10 to 20 km for the AER (also known as PHEV10s or PHEV20s) require smaller battery packs at a lower weight than vehicles with a higher AER (Michalek et al., 2011). Thus, PHEVs10 or PHEVs20 would results in lower social costs, when including oil displacement and environmental costs, than PHEVs with higher all-electric battery ranges (Michalek et al., 2011). In our analysis, we use a PHEV20 as an

[3] In Arimura et al. (2009), utility DSM program costs were determined using the program administrator costs, which includes program overhead costs, utility/program incentive costs, and utility/program installation costs, if any.

example of the vehicle the utility could incentivize. We assume that the PHEV20 is replacing either a conventional (internal combustion engine) vehicle (CV) or a hybrid electric vehicle (HEV). We assume that the adoption of the PHEV20 would not have occurred otherwise as a result of natural adoption, other policies or regulation such as Corporate Average Fuel Economy (CAFE) standards. For the gasoline and electricity consumption for vehicles, we draw on Michalek et al. (2011) study of the energy consumption of 2015 models of CVs, HEVs, and PHEV20s, using the "Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation" (GREET) model, version 1.8d for 2015 vehicles, and based on analysis of household driving patterns and simulated fuel mode from the National Highway Transportation Survey (NHTS).

There is no clear single minimum value that one can assume would induce consumer adoption of PHEVs. Given that, we assume a set of parametric values for the level of incentive that would induce consumers to adopt the PHEV instead of a CV:

1. \$800/vehicle, which corresponds roughly to the discounted electricity revenues from PHEV charging, for a real discount rate of 5% and a vehicle lifetime of 12 years;
2. \$900/vehicle, which is about the same as the incremental levelized cost of ownership of a PHEV20 compared to a CV;
3. \$2500/vehicle, which is similar to the level of the current federal incentive available for a PHEV20, with a battery pack capacity of 4.0 kWh;
4. \$3800/vehicle, which represents the incremental upfront capital cost of the PHEV battery and the cost of charging infrastructure.

For those consumers who would have purchased an HEV before PHEVs were available in the market, we assume a similar set of parametric values for the level of incentive that would induce these consumers to adopt the PHEV20:

1. \$800/vehicle, which corresponds roughly to the discounted electricity revenues from PHEV charging, for a real discount rate of 5% and a vehicle lifetime of 12 years;
2. \$1000/vehicle, which is about the same as the incremental levelized cost of ownership of a PHEV20 compared to a hybrid electric vehicle;
3. \$1700/vehicle, equal to the difference in upfront capital cost of the PHEV battery versus the HEV battery, and the cost of charging infrastructure;
4. \$3500/vehicle, for illustrative purposes only.

3.2. *Accounting for consumer behavior*

We expand on the decision space described above, now accounting for consumer behavior, namely for *rebound effects*. Rebound effects are defined as changes in consumer behavior in response to the changing price of energy services with an investment in an efficient technology. We focus on the rebound effect in CO_2e emissions, simply calculated from the difference between expected or potential emissions savings (PES), and actual emissions savings (AES) after accounting for behavior change, expressed as a percentage, i.e., rebound $= 1 - \text{AES/PES}$.

The two rebound effects we include in our analysis are the *direct rebound*, R_D, or more use of the same energy service in which an efficiency investment was made, and the *indirect rebound*, R_I, or re-spending energy cost savings from efficiency on other goods and services which require energy and release emissions during their production and use.

We draw on Thomas and Azevedo (2013) to estimate the indirect rebound effect, given a direct rebound parameter, for residential electricity efficiency and for PHEV20s, under a "proportional spending" assumption. This means that energy savings from an energy efficiency investment will be proportionally re-spent in the same good and in other goods and services, following the same spending allocation that the household did prior to the energy efficiency investment. In Thomas and Azevedo (2013) we analyzed a number of alternative methods of simulating the pattern of re-spending, and found that proportional spending patterns tend to overestimate the indirect rebound effect from driving (PHEVs) and underestimate the indirect rebound effect from electricity compared to approaches to estimate the marginal pattern of spending. However, we also found that the differences in the results across different re-spending pattern assumptions are small. In this analysis, we assume a direct rebound effect, R_D, of 10%, which means that a 100% increase in lighting efficacy, which results in a 50% reduction in electricity costs without behavior change, also results in a $(50\% \times 10\%) = 5\%$ increase in lumen-hours of lighting service demanded due a lower cost of lighting service. We assume the same direct rebound effects (of 10%) in both electric end-uses and transportation in line with past empirical studies (Davis, 2008; Dubin et al., 1986; Gillingham, 2011; Small and Van Dender, 2007). The indirect rebound is computed as (for the full derivation please refer to Thomas and Azevedo, 2013)

$$R_I = \frac{Z_O \times (1 - R_D)}{Z_E \times (1 - w_s)} \tag{1}$$

where Z_O is the emissions intensity of re-spending energy cost savings on other goods [kg CO_2e/\$], Z_E is the emissions intensity of the energy end-use under study, either in electricity or transportation [kg CO_2e/\$], and w_s is the average household's budget share for electricity [fraction]. R_D is the direct rebound effect and R_I is the indirect rebound effect. For the case of electric end-uses targeted through a traditional utility-funded DSM or EE program, Z_E is equal to the ratio of the electric grid CO_2e emissions factor, GEF [kg CO_2e/kWh] to the electricity price, P_E [\$/kWh]. For the case of an incentive program targeted to reduce gasoline consumption in conventional or hybrid electric vehicles through the adoption of PHEVs, Z_E [kg CO_2e/\$] is equal to the ratio of the carbon content per gallon of gasoline (kg CO_2e/gal) of 8.92 kg CO_2e/gal to the price of gasoline, P_G [\$/gal], assumed to be \$2.75/gal. Although other analysis argue that emissions for the marginal generator (i.e. marginal emissions factors) are important for assessing the emissions effects of electric vehicles (Zivin et al., 2012) and of end-use energy efficiency (Siler-Evans et al., 2012), we focus our analysis on average grid emissions factors, which are within 30% of marginal grid emissions factors for the case of CO_2e emissions in the U.S. electric grid.

The cost-effectiveness of CO_2e reductions after accounting for direct and indirect rebound effects (in \$/ton CO_2e avoided) for either end-use electric efficiency or improved vehicle efficiency is provided by:

$$CE_{rebound} = CE/(1 - R_D - R_I) \tag{2}$$

where $CE_{rebound}$ is the cost-effectiveness of either energy efficiency for end-uses or for PHEV when accounting for rebound (in \$/tonCO_2e avoided) and CE is the cost-effectiveness of either energy efficiency for electric end-uses or for PHEV without accounting for rebound.

The rebound effect estimates are from Thomas and Azevedo (2013), which simulates rebound effects using spending patterns from the 2004 Consumer Expenditure Survey (CES) and emissions factors from the Economic Input–Output Life-cycle Assessment (EIO-LCA) model of the U.S. economy for the year 2002 developed by Carnegie Mellon's Green Design Institute, which can be found at www.eiolca.net.

3.3. Estimating the appropriate level of PHEV incentive

Finally, we also estimate the subsidy, X, that utilities should be willing to provide to customers, so that the cost-effectiveness of a PHEV program would be equivalent to the range of reported cost-per kWh conserved estimates for end-use energy efficiency programs, which is given by

$$X = \Delta E(1 - R_D - R_I)CE_{EE} \tag{3}$$

where ΔE is the difference in CO_2 emissions from the PHEV and the baseline vehicle (either and ICE or a HEV), R_D and R_I are the direct and indirect rebound effects, and CE_{EE} is the cost-effectiveness for the end-use energy efficiency program.

4. Results and analysis

4.1. Base-case results

Fig. 1 shows a decision space on whether electric utilities should subsidize PHEVs or energy efficiency programs for electricity end-uses for all cases studied. Fig. 1a and b represent states with decoupling programs, i.e., we assume utilities obtain no net revenue from PHEV charging. Fig. 1c and d represent states without decoupling programs.

The horizontal axis shows the assumption about the emissions intensity of electricity generation in a state, while the vertical axis provides the range of values assessed for the cost-effectiveness of end-use electricity energy efficiency programs. Note that this decision plot does not take into account the scale of CO_2e emissions reductions possible with each type of subsidy.

The interpretation of the figures is as follows: areas labeled as "*always choose EE subsidy*" means the most cost-effective strategy for utilities is to promote end-use energy efficiency programs. An area labeled as "$3500" means that even if it takes a $3500 incentive to induce consumer to adopt a PHEV20 instead of a baseline vehicle (either CV or HEV depending on the scenario), that is a more cost-effective use of incentives than investing in end-use energy efficiency programs. In these decision plots, the "$3500" subsidy includes both the incentive payment to a vehicle owner and the program administration costs incurred by the utility. The scenario with HEVs as the baseline technology is indicative of the cost-effectiveness of PHEV subsidies once CAFE standards are binding and the average U.S. vehicle must reach a fuel economy of 54.5 miles/gallon (which is the 2025 goal). In all cases, we are assuming that the alternative fuel vehicle would not have been sold without the incentive. For example, in Fig 1a, we find that in states with decoupling policies, if we assume modest subsidies (and associated program administration costs) of $800 to $900 per vehicle are sufficient to encourage CV owners to substitute to PHEV20s, such strategy would make sense in states where the cost-effectiveness of energy efficiency programs is above $0.04/kWh, and where grid emissions factors are about 0.65 kg CO_2e/kWh.

Subsidies for PHEVs may be a feasible option for more electric utilities over time, if residential electricity efficiency becomes more costly and the grid becomes less carbon-intensive. As the Energy Independence and Security Act of 2007 comes into force, it may remove low-cost efficiency opportunities in the market, such as the ban on incandescent lamps in many common residential fixtures, which leaves more efficient halogen, CFL or LED lamps as the baseline technology. In addition, utilities with extensive residential energy efficiency programs may experience diminishing returns to efficiency investment that lead to higher costs in the short-term, although there is a large debate in the literature on whether such diminishing returns are observed, as efficient technologies themselves may become more efficient and cheaper, thereby increasing the supply of energy efficiency over time (Swisher and Orans, 1995).

Fig. 1c and d show similar decision plots for electric utilities operating in states without decoupling policies. In these states, utilities may generate additional revenues from PHEV electric

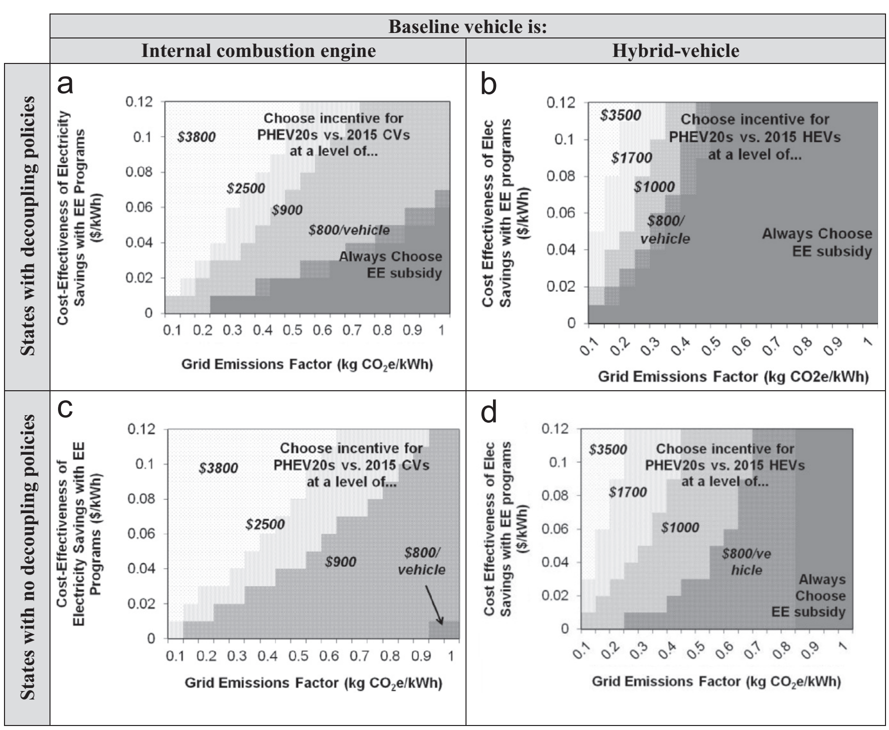

Fig. 1. Decision space on whether electric utilities should subsidize PHEVs in states (a) with decoupling programs and assuming CV vehicles as a baseline; (b) with decoupling programs and assuming HEV as a baseline; (c) without decoupling programs and assuming CV vehicles as a baseline; and (d) without decoupling programs and assuming HEV vehicles as a baseline.

charging, which offsets the cost of meeting CO_2e regulations through PHEV subsidies. In states without decoupling policies, if we assume that the PHEV is displacing a CV (Fig. 1c.), PHEV20 incentives between \$800 to \$3800/vehicle are as cost-effective as residential energy efficiency programs, for a very wide range of grid emissions factors. If we assume that the PHEV is displacing a HEV vehicle (Fig. 1d.), a modest PHEV subsidy of somewhere between \$800 and \$1000 per vehicle would reduce CO_2e emissions at a lower cost than residential energy efficiency in states with GEFs less than 0.8 kg CO_2e/kWh. These carbon emissions factors of 0.8 kg CO_2e/kWh or less include most central U.S. states except Colorado and Kansas (as of 2009), although both of these states have Renewable Portfolio Standards which may have reduced grid emission factors even further in recent years. Larger subsidies for PHEVs could be justified as the U.S. electric grid becomes less carbon intensive and as residential energy efficiency programs become more expensive to implement.

4.2. Accounting for rebound effects in consumer behavior

Results for the same scenarios as the ones provided in Fig. 1, but incorporating rebound effects, are shown in Fig. 2. Fig. 2 illustrates that rebound effects are small relative to other important parameters in determining the cost-effectiveness of CO_2e reductions with PHEV20 subsidies, such as the baseline vehicle (CVs vs. HEVs) and the grid emissions factor (GEF) of the location in which the PHEV is charged. For residential electricity efficiency, the most important parameter for net emissions reductions is the grid emissions factor (GEF) at the household's location. For PHEV20s, the most important factor for net emissions reduction is determining which vehicle the PHEV20 replaced, whether a CV or HEV.

In all cases, the direct rebound effect is set to be 10%. The indirect rebound effect for residential electricity efficiency varies by grid emissions factor and fuel saved with efficiency, from as low as 6% for an region with a grid emission factor of 0.8 kg CO_2e/kWh (e.g. Colorado in 2009) to as high as 15% in a region with a grid emission factor of 0.3 kg CO_2e/kWh (e.g. California in 2009) (Environmental Protection Agency, 2012). We calculate indirect rebound effect for gasoline/driving efficiency to be 9%, and dependent mostly on gasoline prices, which we do not vary in this analysis. Since we are ignoring marginal spending patterns and electricity and gasoline price differences across states, these results underestimate the extent of indirect rebound effect from residential electricity efficiency compared with prior studies.

Fig. 3 shows that the cost-effectiveness of CO_2e reductions with residential electricity efficiency or PHEV20s is most influenced by rebound effects in regions with low grid emissions factors. Assuming that a PHEV20 subsidy is set to achieve an equivalent \$/tonCO_2e saved without accounting for rebound effects, we then compute how direct and indirect rebound effects alter this metric. Using a different starting point for the cost per kWh saved with efficiency would alter the absolute cost per ton CO_2e saved for residential electricity efficiency and PHEVs but would not alter the relative (i.e. percent) differences in \$/ton CO_2e between the two interventions in regions with high and low grid emission factors.

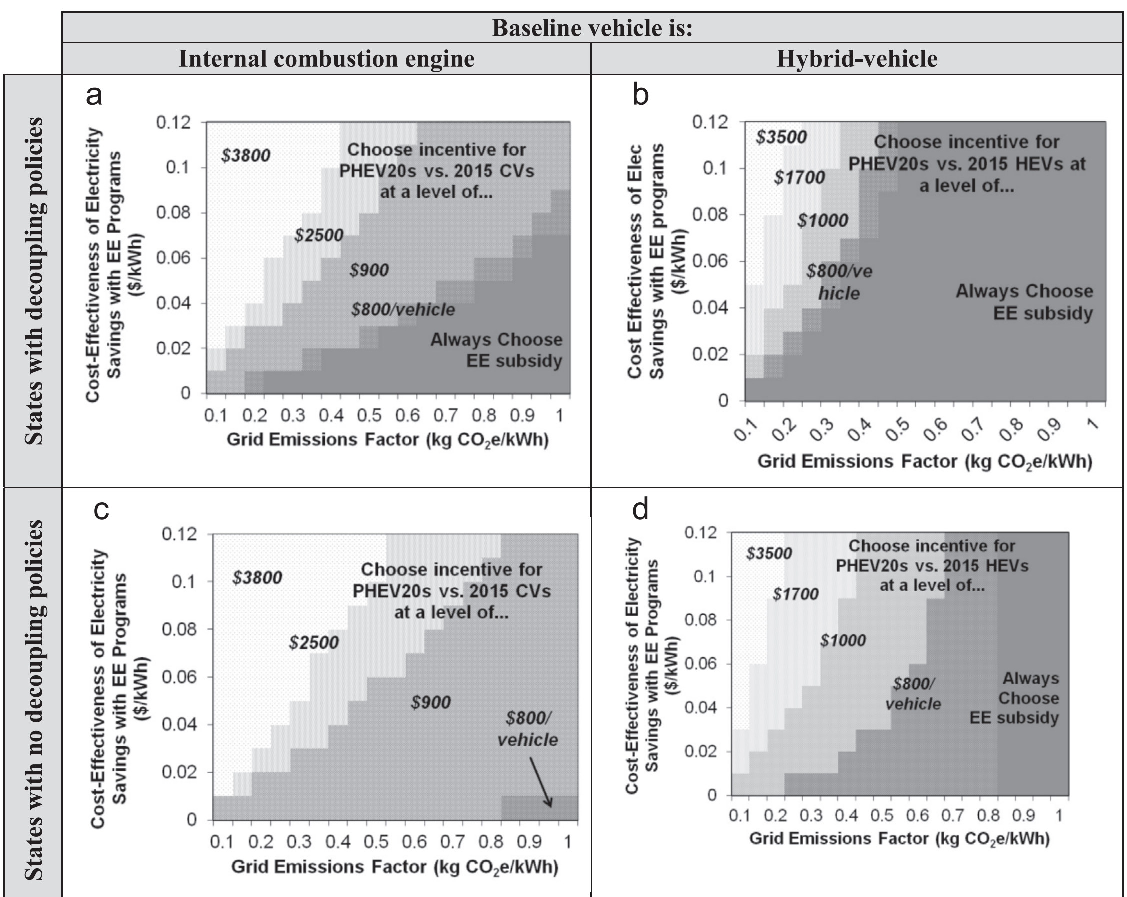

Fig. 2. Decision space on whether electric utilities should subsidize PHEVs when accounting for rebound effects and for states (a) with decoupling programs and assuming ICE vehicles as a baseline; (b) with decoupling programs and assuming HEV as a baseline; (c) without decoupling programs and assuming ICE vehicles as a baseline; and (d) without decoupling programs and assuming HEV vehicles as a baseline.

4.3. PHEV subsidies

We estimate the level of PHEV20 subsidy that would reduce CO_2e emissions at an equivalent cost as current residential electricity efficiency programs, assuming either an ICE baseline vehicle (Fig. 4a) or a HEV baseline (Fig. 4b). We show results for a smaller range of cost-effectiveness for residential efficiency programs from $0.02 to 0.06/kWh, including rebound effects for both transportation and end-use energy efficiency programs. Assuming a conventional vehicle as the baseline, larger subsidies for PHEV20s on the order of $1000 to $2000 per vehicle are only as cost-effective as residential electricity efficiency programs in regions with grid emissions factors under 0.45 kg CO_2e/kWh, i.e., the Northeast, Pacific Northwest, New York, and California. Virginia, North Carolina, Mississippi, Alabama, and parts of Louisiana have grid emissions factors just over 0.45 kg CO_2e/kWh in 2009, but these states do not have Renewable Portfolio Standards enforcing further emissions reductions. If one uses a HEV baseline, a subsidy of $1000/vehicle would only be as cost-effective as residential efficiency in regions with grid emissions factors lower than 0.3 kg CO_2e/kWh, which is cleaner than any state in the U.S – for reference, California was about 0.3 kg CO_2e/kWh in 2009.

5. Conclusions

5.1. Policy assessment

In this analysis, we have shown that if modest subsidies of $800 to $1000 per vehicle for PHEV20s paid for by electric utilities were enough to induce adoption *m* then these may be as cost-effective as residential energy efficiency programs at reducing CO_2e emissions. Of course, the level of incentive needed to induce adoption is a critical question – but one that is outside the scope of this paper.

This level of subsidy is far lower than the initial subsidies provided by various states, at a level of $2500/vehicle in California, $1000–$3500 in Pennsylvania, and income tax exemptions of up to $4000 in Illinois (Plug In America, 2012), although states may also have been trying to promote technological innovation and in-state manufacturing or charging station investments through tax credits or other incentives. Michalek et al. (2011) argue that subsidizing many small PHEVs or HEVs will do more to move battery technology down the learning curve than subsidizing a few large PHEVs or BEVs. Note that we assume that the adoption of these alternative fuel vehicle would not have happen otherwise due to other existing and competing policies.

The case for electric utilities to provide subsidies between $800 and $1000 per PHEV is justified in states with grid emissions factors lower than 0.4 kg CO_2e/kWh with decoupling policies, and lower than 0.8 kg CO2e/kWh without decoupling policies since these electric utilities would gain revenue from PHEV charging that could be used to defray the cost of regulatory compliance. The group of states that might benefit from PHEV subsidies provided by electric utilities includes most states, including Florida, Pennsylvania, Texas, California, the Pacific Northwest, New York, and New England. States that would not benefit would due to their decoupling policies and grid emissions factors over 0.4 kg CO_2e/kWh include Arizona, and the Midwest states, including Ohio, Illinois, Michigan, and Minnesota. These states should consider waiting until more progress is made in lowering grid emissions factors (i.e. through the Renewable Portfolio Standards already in place in these most of these states) before embarking on vehicle electrification incentives.

The decision space analysis illustrated in this paper would also be applicable in the international context, where decoupling policies are not common. However, the framework described in this paper assumes an existing utility-funded program to incentivize energy efficiency, which may not be applicable in other regions. With higher gasoline prices and lower-carbon electricity, Europe and Japan may find PHEV subsidies to be a cost-effective approach for reducing carbon emissions. However, until China, India, and other countries with coal-heavy electric grids transition to lower-carbon resources, PHEV incentives would not be an effective carbon mitigation strategy (Wilson, 2013).

5.2. Uncertainties, limitations, and future work

This analysis has highlighted a number of uncertainties for future research and policy-making for a holistic treatment of CO_2e mitigation in both the electric and transportation sectors, including the PHEV adoption process and interactions between PHEV subsidies and Corporate Average Fuel Economy (CAFE) standards.

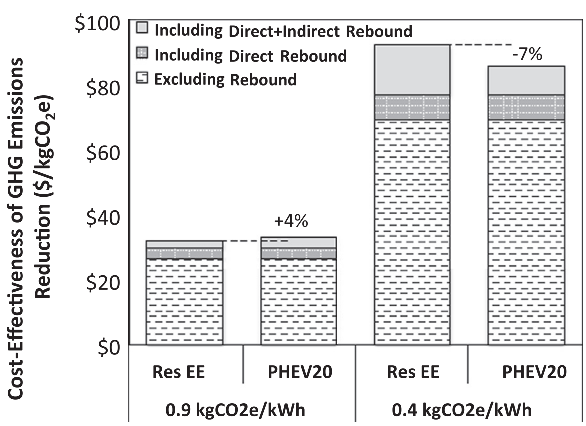

Fig. 3. Effect of direct and indirect rebound on the cost-effectiveness of CO_2e reductions with residential electricity efficiency (Res EE) and plug-in hybrid electric vehicles with a 20 km range (PHEV20s) replacing conventional vehicles (CVs). Figure assumes a 0.025 $/kWh from residential electricity efficiency programs cost effectiveness.

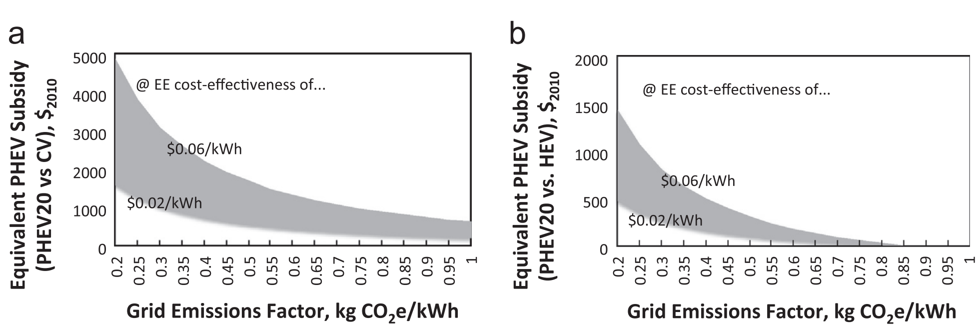

Fig. 4. PHEV subsidies equivalent to residential electricity efficiency costs per kWh conserved, with a baseline of a conventional vehicle (CV) (a), and HEV (4).

While modest subsidies for PHEVs may be justified, it is unclear that they would help to spur significant PHEV adoption. Current federal tax credits for PHEVs are $7500 per vehicle and several states provide rebates for PHEV and BEV purchases of $750–$4000 per vehicle (Plug In America, 2012). With these incentives, 2012 sales of PHEVs across the country have reached 13,000 across all makes and models (Hirsh, 2012). The historical experience with hybrid electric vehicles (HEVs) shows that it took 12 years to reach cumulative sales of 2.2 million HEVs and annual sales of 300,000 HEVs out of the 14–15 million new vehicles sold each year in the U. S. (Department of Energy, 2012). This level of hybrid vehicle adoption occurred under federal tax credits of $450–$3400 per vehicle depending on the make and model (Berman, 2011). However, the results in this study indicate that PHEV subsidies may be a complementary addition to utility energy efficiency programs in states with low grid emissions factors, without decoupling programs, and experiencing high costs per kg CO_2e saved with residential energy efficiency, to meet a policy goal of economically reducing CO_2e emissions.

Another major source of uncertainty is whether or not subsidies for PHEVs will actually lead to any additional CO_2e emissions reductions in the near future. The Congressional Budget Office (2012) argues that the CAFE standard will be a binding constraint on automobile manufacturers before 2025, due to the high cost of compliance. Since PHEVs exceed the fuel economy standard imposed by CAFE, additional PHEV sales spurred on by an incentive program would allow automobile manufacturers to sell more trucks and other low-fuel economy vehicles that provide higher profit margins while still meeting the CAFE standard on their overall sales. Whether or not CAFE standards are binding in practice is an empirical question; automobile manufacturers did not significantly exceed CAFE standards during the 1980 to 2000 time period. Empirical study of manufacturers' response to CAFE standards in an era with higher oil prices, greater awareness of climate change, and greater technological diversity would illustrate the role of PHEV subsidies in spurring technological innovation and the policy process for setting of the CAFE standard.

Utilities may still be interested in incentivizing PHEVs to a limited extent if vehicle-to-grid technology further develops so that utilities can rely upon the ancillary services provided by the PHEV battery to stabilize the grid. Alternative options for utility incentives for PHEVs that are currently under exploration include battery leases by the utility to the vehicle owner to reduce the upfront cost of a PHEV vehicle. These schemes are still under development, and require charging infrastructure for PHEVs to connect to the grid during parked times to provide these ancillary services, supporting technologies, and forecasting battery availability. However, battery leasing represents a significant departure from the traditional electric utility business model, more so than providing incentives for end-uses, whether in electric end-uses or for PHEVs, as explored in this analysis.

The current independent approaches to promoting energy efficiency in the residential (and commercial) electricity sector and the transportation sectors may require rethinking with further market penetration of PHEVs. PHEVs offer one of the largest sources of new electric load growth in the twenty-first century. Managing this load growth in an environmentally sustainable manner will be essential to addressing climate change goals. Assessing incentive programs across sectors offer a first step towards an integrated view of the energy sector.

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Appendix A. Supplementary materials

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2013.11.015.

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