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Decarbonising the Road Transport Sector: Breakeven Point and Consequent Potential Consumers’ Behaviour for the US case

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Key words

Low carbon transport, present value of costs, breakeven analysis, electric vehicles, bio-fuels, lifecycle analysis, external costs of road transport, alternative fuels, alternative fuel vehicles.

Abstract

A breakeven analysis of low carbon vehicle/fuel systems is conducted for the US for the year 2020, taking into consideration both private and external costs. All comparisons are made with respect to the conventional gasoline car as the baseline. Interestingly, the social cost of carbon prevailing in the literature is not high enough to justify the prioritization of low carbon vehicle/fuel technologies and the only way forward if such a track were to be chosen would be a political decision not necessarily grounded on economic principles. Nonetheless potential policies for the most financially viable alternative vehicle/fuel systems are considered.

1. Introduction

Transport currently accounts for 14% of total global greenhouse gas (GHG) emissions, to which road transport alone contributes 45% (HM Treasury, 2007a, p.10). In most OECD countries, transport even makes up more than 25% of all GHG emissions and the relative share is estimated to increase further in the future (Albrecht, 2001). Under the scenario of business-as-usual, road transport emissions will be doubled by 2050 (HM Treasury, 2007a, p. 3). Global temperature could raise 2-3^{o}C by 2050 (Intergovernmental Panel on Climate Change, 2001, p.398), which in turn, would very probably result in various negative environmental effects, such as extreme weather events, sea level rise, floods, droughts, population displacement, ecosystem destruction and malnutrition (Lee, 2007).

A number of policies and policy packages with the aim of reducing CO_2 emissions from road transport have been suggested both in the academic literature and in the real world. These range from economic instruments such as vehicle ownership and usage taxes and cap-and-trade systems, to changes in public transport provision, land use and urban design, cycling and walking facilities and new technologies which rely on low-carbon fuels.[1]

Although there are already a number of low emission vehicle technologies and

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[1] Santos et al. (2010a,b) provide an overview of such policies both in theory and practice, with a summary of the experience to date and some failures and successes. Cambridge Systematics, Inc. (2009) assesses the potential effectiveness of individual and combined strategies to reduce GHG emissions in the US. The US Department of Transportation (2010) also estimates the impact of a number of policies, individually and combined. Similarly, Akkermans et al. (2010) assess the GHG emissions reduction potential and feasibility of a number transport policies in Europe and aim, under the project GHG-transpord, to develop an integrated European strategy. At the time of revising the present paper, the integrated European strategy had not been published yet.

alternative fuels, most of them with some shortcoming to one extent or other, some likely to be solved in the short-term whilst others only likely to be solved in a much more distant future (three or more decades), none have yet penetrated the market massively.[2] In any case, they are all substantially more expensive to produce than the standard fossil-fuel car and therefore even if they were ready for mass use, their production costs and market prices would be very high. Except for motorists who cared so much about their personal CO_2 emissions that were prepared to incur in such higher costs, the majority would probably remain unconvinced and would need some persuasion in order to change their behaviour.[3] Caulfield et al. (2010), for example, conduct a survey of car buyers in Ireland and find that respondents do not rate GHG emissions as an important point to take into account when buying a car. Turrentine and Kurani (2007) interview 57 households in California and find that although some appear to have ‘longer-term commitments to environmental and social issues’ the most important attributes for at least one household vehicle are its size (should accommodate children, pets, holiday luggage and shopping), four-wheel or all-wheel drive for access to difficult terrains, and, for those with young children, safety (p.1218).

This paper aims to compare various vehicle/fuel systems in terms of their private and CO_2e costs for the US case in 2020. It also aims to assess whether there is an

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[2] Inderwildi et al. (2010), Schäfer et al. (2011) and Andress et al. (2012) provide an excellent review of current road vehicle technology and the potential for a number of alternative vehicle/fuel technologies.

[3] If the utility a consumer derived from using alternative fuels (and caring for the environment) were high enough to make marginal benefit equal to marginal cost she would be prepared to pay a higher price for alternative fuels and vehicle technologies, subject to her budget constraint. In that sense, there may be scope for advertising and information campaigns aimed at changing consumers’ preferences. Budget constraints, however, are likely to cap the potential market to only high income segments.

economic case for favouring some vehicle/fuel types and regardless of whether there is one or not, how this can be achieved by the government. Even when there is not an economic case for favouring cleaner technologies there may be a political case.

For the CO_2e costs we conduct a full life cycle emissions analysis for both vehicles and fuels. We then use break-even analysis to compare the full costs of each vehicle/fuel system and complement it with the calculation of the Present Value of costs (PVC), which summarizes in just one number, the present costs of each vehicle/fuel system.

Interestingly, we find that the social cost of carbon prevailing in the literature, even at its highest end, is not high enough to justify the prioritization of low carbon vehicle/fuel technologies and the only way forward if such a track were to be chosen would be a political decision not necessarily grounded on economic principles.

This is, to our knowledge, the first study that pulls together private and external costs for such a large number of alternative vehicle/fuel systems, estimates breakeven points with conventional gasoline cars, calculates present values of costs and entertains possible financial incentives that could change relative private costs, looking at a short-term horizon like 2020. The literature is vast but previous studies differ from the current one in that they focus on fewer vehicle/fuel systems (Schäfer and Jacoby, 2006; de Haan et al., 2007; McKinsey & Company, 2009, 2010; van Vliet et al., 2010; Lee and Lovellette, 2011), do not discuss policies that could change consumers' choices (Schäfer and Jacoby, 2006; Lee and Lovellette, 2011), do not conduct a full vehicle and fuel lifecycle analysis (Morrow et al., 2010), focus on Europe instead of the US (Akkermans et al., 2010; McKinsey & Company, 2010; van Vliet et al., 2010; Schäfer et al., 2011; Pasaoglu et al., 2012) or focus on a longer time horizon where much more technological progress can be reasonably expected (McCollum and Yang, 2009; Andress et al., 2011). Some even only focus on one alternative vehicle/fuel technology (Bradley and Frank, 2009) or completely oppose to favouring one or more vehicle/fuel technologies and argue for a technology-neutral policy package (Bandivadekar et al., 2008).

2. Technologies

There are a number of promising vehicle/fuel systems which are either already in the US market, at least to some extent, or will probably be in the market in the near future and the not so near future. All comparisons in this paper are made against the spark ignition internal combustion engine (ICE) conventional vehicles on gasoline (SICEG). This is taken as the baseline as gasoline cars with ICEs are by far the dominating vehicle/fuel system in the US. We use the average US passenger car as the benchmark and improvements are assumed in this benchmark technology (and in other technologies) between 2010 and 2020. For instance, the fuel economy of the benchmark vehicle is improved from 22.4 miles per gallon (mpg) in 2010 to 23.2 mpg in 2020.[4]

The technologies we consider are the spark ignition direct injection vehicles on gasoline (SIDIG), compression ignition ICE vehicles on diesel (CICED), which have already penetrated many markets worldwide,[5] are more fuel efficient and produce less carbon emissions, compression ignition ICE vehicles on biodiesel (20% biodiesel and 80% diesel blend) (CICEBD), spark ignition flexible fuel ICE vehicles on E85 (15% gasoline and 85% ethanol blend) (SFFICEV), spark ignition dedicated ethanol ICE vehicles E90 (10% gasoline and 90% ethanol blend) (SDEICEV), spark ignition ICE on compressed natural gas (SICECNG), fuel cell vehicles (FCV) on hydrogen (FCVH) and on methane (FCVM), and hybrid and pure electric vehicles. The electricity used by pure electric vehicles always comes from the grid but the electricity used by hybrid electric vehicles can either be sourced from the grid (grid

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[4] Only passenger cars are modelled.

[5] Although almost half of the European car fleet runs on diesel, diesel vehicles represent less than 1% of vehicle sales in the US (Canis, 2012, p. 1).

connected) or independently (grid-independent). Thus, we have grid-connected hybrid electric vehicles (GCHEV), grid-independent hybrid electric vehicles (GIHEV),[6] and pure electric vehicles (EV). These three technologies are slowly penetrating the US market. GIHEVs have been on the market for a while and due to their compatibility with current refuelling stations, they have been gradually accepted by the motoring public. In fact they represented 3% of all new car sales in the US in the period January-July 2012, whereas GCHEVs and EVs only represented 0.18% and 0.06%, respectively, during that same period (Electric Drive Transportation Association, 2012; HybridCars.com, 2012).

The main reason for including biomass-based fuel vehicles in this analysis is that biomass-based fuels are renewable resources which have the potential of alleviating energy dependence on fossil fuels. According to the US Department of Energy (US DOE), corn has and will continue to have the largest share of bio-ethanol feedstock in the US by 2050 (Ward, 2008). This, however, is a fairly strong assumption, especially given the recent debate on net lifecycle CO_2 emissions savings of corn-based ethanol over conventional gasoline, with some arguing that instead of producing savings, it would double GHG emissions (Searchinger et al., 2008). In addition to that, biodiesel and ethanol would compete with food and livestock for agricultural and farming land (Ou et al., 2010; Timilsina and Shrestha, 2011).

Both grid-independent and grid-connected HEVs are expected to achieve significant CO_2 emission reductions owing to their improved fuel economy, expressed as miles per gallon (MPG).[7]

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[6] In the US the GCHEV is also known as Plug-in HEV (PHEV) and the GIHEV is also known as HEV.

[7] In this paper, gallon refers to a US gallon, which is different from a UK gallon (1 US gallon = 0.833 UK gallon = 3.7854 litres).

Because of the technological challenges and high costs involved, the massive penetration of both pure EVs and FCVs can only be seen as long-term options. However, this study still includes them. Due to the fact that lifecycle CO_2 emissions of EVs and FCVs are concentrated during their well-to-pump process, the emissions can be relatively straightforward to collect by methods such as carbon capture and storage (CCS) and the potential for CO_2 emission reduction is large.

Table 1 summarizes the vehicle/fuel systems considered in this study.

TABLE 1 ABOUT HERE

3. The GREET Model

To fully evaluate energy and emission impacts of alternative vehicle technologies and fuels, the whole fuel cycle from well to wheel (WTW) and the whole vehicle cycle need to be considered.

In this study, CO_2 emissions are estimated for each vehicle/fuel system using the ‘Greenhouse Gas, Regulated Emissions and Energy Use in Transport’ (GREET) Model, which is funded by the US DOE and developed and updated by the Argonne National Laboratory (ANL).

For the fuel emissions lifecycle assessment we use GREET 1.8b, that covers the fuel lifecycle emissions from feedstock recovery and transport; fuel production, distribution and final consumption in vehicle engines. We estimate energy consumption and emissions from passenger cars in the US for different vehicle/fuel systems. We assume that all gasoline (for ICE or blended in bio-fuels) is ‘standard US conventional reformulated gasoline’.

The **fuel lifecycle emissions** assessment in GREET contains two parts: the well-to-pump (WTP) process and the pump-to-wheel (PTW) process.

The WTP process is further subdivided into feedstock recovery from wells or fields, transport to refineries and storage for use; fuel production, transport to storage terminals and distribution to refuelling stations. For the feedstock recovery and fuel production, GREET applies the “process fuel” method, which estimates emissions based on the process fuel consumption.[8] Essentially, since during the very recovery process there is fuel consumption and energy loss, the fuel feedstock that needs to be recovered in the first place is more than the fuel that will be ultimately produced.

The obtained process fuels are integrated by GREET with emission factors (provided by the US DOE and embedded in the default parameters that GREET uses) to estimate CO_2 emissions. The WTP processes of all alternative vehicle fuels are estimated in the same way. The energy efficiency data plays a significant role in the lifecycle assessment. GREET 1.8b uses estimates of fuel efficiency produced by the ANL, in the context of the US energy industry. Since this study uses GREET 1.8b, it automatically adopts the ANL estimates as well.

For the PTW process, GREET simply adopts the vehicle operation simulation results from the MOBILE6 model[9] for benchmark ICE gasoline vehicles and the US Environmental Protection Agency’s (EPA) fuel economy predictions for alternative vehicle/fuel systems. In other words, GREET does not produce any new numbers for PTW but rather, takes the results from MOBILE6 and EPA (entered into the database

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[8] Details of how GREET does this are provided in Appendix 1.

[9] The MOBILE6, produced by the EPA National Vehicle and Fuel Emissions Laboratory, is an emission factor model for predicting grams per mile emissions of hydrocarbons, carbon monoxide, nitrogen oxides, carbon dioxide, particulate matter, and toxics from cars, trucks, and motorcycles under various conditions and taking into account any predicted changes in vehicle, engine and emission control system technologies (US EPA, 2003).

of GREET) and combines these with WTP emissions in order to estimate fuel lifecycle emissions.

For **vehicle lifecycle emissions** from production, maintenance and disposal we use the database from GREET 2, a newer version of the GREET model, because GREET 1.8b does not have that information.

4. Lifecycle CO_2e Emissions Assessment for US 2020

4.1 Fuel Lifecycle Assessment

All GREET 1.8b outputs are expressed in grams of CO_2e emitted per mile for a typical passenger car within each of the categories listed in Table 1.

The results are described below.

4.1.1 WTP Emissions

Figure 1 shows the WTP results.

FIGURE 1 ABOUT HERE

From Figure 1, it can be observed that EV has the highest WTP CO_2e emissions among all vehicle/fuel systems. This is mainly due to the electricity generation pathways simulated by the GREET model, which assumes that 48.6% and 24.3% of electricity for transport use are generated from coal-fired power plants and natural gas-fired power plants, respectively. Both types of power plants burn a large amount of fossil fuel while generating electricity. Low carbon technologies, such as nuclear, water and wind, have a combined share of only 25.1% of electricity generation used for transport. On the other hand, the feedstock recovery and fuel refinery of fossil fuels only involves the combustion of a small amount of process fuels. The combustion of fossil fuel products, which produces considerable emissions, only occurs during vehicle operation.

CO_2e emissions from land use change by corn farming are assumed to be 195 grams/bushel but because GREET 1.8b accounts for carbon absorption during biomass growing, the WTP net carbon emissions from bio-fuels are very low and for corn-ethanol and biodiesel, they are actually negative. Thus, WTP CO_2e emissions for SFFICEV, SDEICEV and CICEBD are all negative on Figure 1.

For GCHEVs, the WTP carbon emissions are highly dependent on the share of electricity and gasoline. In order to simplify the assessment, GREET 1.8b assumes a 2:1 ICE mode and electric mode for GCHEVs in terms of the vehicle travelled mileage. An interesting finding is that the WTP emissions of GCHEVs are significantly higher than those from conventional gasoline, owing to the high WTP emissions from electricity generation. For GIHEVs, the WTP carbon emissions are about 25% lower than those for baseline SICEGs. This is not surprising given that the electricity in GIHEVs is generated in the vehicle itself[10] and the demand for gasoline by these vehicles is much lower than the demand for gasoline by SICEGs.

The WTP CO_2e emissions from SICECNG are around 30% lower than those from the baseline SICEG. Also, as it can be seen from Figure 1, WTP CO_2e emissions from SIDIG and CICED are only marginally lower than those from baseline SICEG.

Finally, WTP CO_2e emissions from fuel cell vehicles vary. Those from FCVH are relatively high, and only lower than those from EV. The reason for this is that the production of hydrogen entails high CO_2e emissions, under the assumption of a 100%

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[10] There are a number of technologies to achieve this, including regenerative braking, which converts the vehicle’s kinetic energy into battery-replenishing electric energy, and motor electricity generation, which consists in the internal combustion engine generating electricity by spinning an electrical generator.

natural gas feedstock share for hydrogen production, which involves a steam methane reforming process. This steam methane reforming process causes extra emissions.

WTP CO_2e emissions from FCVM are around 30% lower than those from baseline SICEG and 71% lower than those from FCVH. This is because the fuel production of methane involves a significant lower volume of process energy consumption than the production of hydrogen.

4.1.2 PTW Emissions

For the PTW assessment, GREET 1.8b relies on the modelling results of benchmarking SICEG's emissions through EPA's vehicle emission modelling software, MOBILE6, and their "emission changing ratio" for various alternative fuel vehicles. The emission changing ratio is the ratio of the CO_2e emissions of alternative fuel vehicles to those of the baseline SICEG.

It should be highlighted that the GREET model assumes a changing fleet of cars to more efficient cars. For example, for the year 2010 the fuel efficiency of a standard ICE vehicle on gasoline (SICEG) is 22.4 miles per gallon, that of a GIHEV is 30.8 miles per gallon and an EV is assumed to use 82.5 mile per gallon equivalent. For the year 2020 the numbers change to 23.2 miles per gallon for SICEG, 32.5 miles per gallon for a GIHEV and 92.8 mile per gallon equivalent for an EV. All the vehicle technologies modelled by GREET have an annual efficiency improvement.

Figure 2 shows the PTW CO_2e emissions for the US 2020 for the different fuel/vehicle technologies listed on Table 1.

FIGURE 2 ABOUT HERE

Figure 2 shows that the PTW CO_2e emissions from various vehicle/fuel systems almost follow an inverse profile to that of the WTP process. Obviously, EVs and FCVHs produce zero CO_2e emissions during vehicle operation. Just like in the WTP process, SICECNG can also effectively reduce CO_2e emissions in the PTW process. Bio-fuel vehicles have a comparable CO_2e emission level to that of fossil fuel vehicles. In particular, SFFICEV (which run on E85 produced from corn), cause PTW CO_2e emissions close to those from baseline SICEG. Both GCHEV and GIHEV cause significantly lower emissions than those from fossil fuel vehicles, mainly due to the improved MPG and electric driving.

FCVM produces significant CO_2e emissions during vehicle operation. In contrast with hydrogen, fuel cell vehicles running on other fuels need an additional fuel process, which converts the fuels chemically to hydrogen, and this involves intensive CO_2e emissions. Then the cleaned up hydrogen is transmitted to a fuel cell stack which converts hydrogen electrochemically to electric power as hydrogen. Therefore, although the hydrogen reaction in a fuel cell stack only generates electric power and water, the fuel processing prior to the hydrogen reaction produces a considerable amount of CO_2e emissions, which are generally somewhere in between the emission levels of GIHEVs and GCHEVs.

4.1.3 WTW Emissions

After obtaining emission estimates from WTP and PTW processes, the total net CO_2e emissions of the various vehicle/fuel systems can be compared in terms of their full WTW cycle. It should be noted that the WTP emissions for a vehicle/fuel system also depend on MPG. GREET 1.8b firstly converts the WTP emissions to the unit of grams per km based on vehicle MPG and then combines the WTP and PTW results to produce the final output. Figure 3 shows the final output for each vehicle/fuel system.

FIGURE 3 ABOUT HERE

Throughout the whole WTW cycle, the conventional SICEG produces the greatest amount of CO_2e emissions. SIDIG, CICED and SICECNG achieve modest but welcome emission reductions, and since they are already in the market they could be considered feasible short term alternatives to SICEG.

Although biomass-based fuels produce the greatest levels of CO_2e emissions in the refinery and vehicle operation process, their carbon absorption during photosynthesis when they are being grown largely reduces their overall emission level. Thus, CO_2e emissions from SFFICEV, SDEICEV and CICEBD are approximately equal to those from GCHEV.

GCHEVs, GIHEVs, EVs, FCVMs, and FCVHs yield very low CO_2e emissions in the LCA. HEVs are already penetrating the market and EVs are a realistic option in the short and medium term. FCVHs, on the other hand, still face challenges related to the storage and transport of hydrogen in the vehicle.

FCVMs yield relatively low CO_2e emissions but they also pose problems. FCVMs rely on biomass, and there is simply not enough capacity on the planet at the moment for mass production of methane in that way.

The main (and expected) result of conventional SICEG causing the highest CO_2e emissions is in line with previous LCA estimates, like for example those by Weiss et al. (2000), van Vliet et al. (2010), Thiel et al. (2010) and Safarianova et al. (2011). The actual precise estimates for WTW emissions for different vehicle/fuel systems, however, are different. van Vliet et al. (2010), Thiel et al. (2010) and Safarianova et al. (2011) focus on Europe, where the electricity mix in 2020 is assumed to be different to that in the US, and the distances and modes of transport from transporting conventional and alternative fuels are also different. Safarianova et al. (2011) assume that ethanol is produced from wheat and wood, not from corn as is the case in the US. Weiss et al. (2000) focus on the US but the study is over 12 years old, and a number of assumptions have been superseded. On top of all that, the specific characteristics of each vehicle/fuel system vary across studies. To cite just one example, GCHEVs in our study are assumed to have a battery range of 32 km in 2020, whereas Safarianova et al. (2011) assume 40 km. Even WTW emissions from SICEG differ amongst studies. However, it is important to highlight that emissions from alternative fuel vehicles relative to SICEG in those studies are similar to ours, which only validates our results.

4.2 Vehicle Lifecycle Assessment

This paper uses the vehicle lifecycle emission assessment from GREET 2 database, released in 2012. We include the energy required and consequent emissions for vehicle component production, battery production and disposal, fluid production and use, and vehicle assembly, disposal, and recycling.

For vehicle lifecycle emission analysis, the different vehicle types presented in Table 1 can be grouped in five different classes, as shown on the last two columns in Table 1.

Figure 4 shows vehicle lifecycle CO_2e emissions, as estimated by GREET2 for the vehicle groups from Table 1.

FIGURE 4 ABOUT HERE

Assembly, disposal and recycling are identical for all vehicle types. Unsurprisingly, batteries from EVs cause relatively high CO_2e emissions, followed by those from GCHEVs.

FCVs and EVs cause the lowest fluid production and use CO_2e emissions from all vehicle groups because of two reasons: (a) they are transitioning to a fluid-less electric power assist steering system, which requires fewer parts, no maintenance and weighs less (Bohn, 2005; Sullivan et al., 1998), and (b) transmission fluid is used significantly less in FCVs and EVs compared with ICE vehicles because of differences in the gearboxes in the vehicles compared with the automatic transmission in conventional vehicles (Bohn, 2005; Royal Purple, 2006).

All in all, FCV have significantly higher CO_2e lifecycle emissions. As it can be seen on Figure 4 the production of vehicle materials represents the most carbon-intensive activity in the vehicle cycle. The CO_2e emissions from vehicle materials production is lowest for the spark ignition and compression ignition vehicles (SCEV) group, and highest for the fuel cell vehicles (FCV) group. This difference is attributable to the energy-intensive materials in the fuel cell stack and auxiliaries, such as graphite composite for the bipolar plates, aluminium for the current collector, and carbon paper for the electrode's gas diffusion layers (Burnham, A., Wang, M. and Y. Wu, 2006 , p. 75).

With the estimated fuel WTW cycle and vehicle lifecycle emissions, the integrated emission evaluation for the various vehicle/fuel systems can be made. Figure 5 shows this integrated result.

FIGURE 5 ABOUT HERE

The intercept in Figure 5 is the vehicle lifecycle CO_2e emissions, which range between 7.63 and 10.05 tonnes of CO_2e/vehicle. Fuel cycle CO_2e emissions are significantly greater than vehicle cycle CO_2e emissions for all vehicle/fuel systems. In all cases 10,000 km of travelled distance generates more CO_2e emissions than vehicle component production, battery production, fluid production and use, and vehicle assembly, disposal, and recycling.

5. Break-Even Analysis

Having ranked all vehicle/fuel technologies according to their lifecycle CO_2e emissions, it is interesting to ask why the low carbon ones are not yet widely being chosen by producers and consumers.

It is reasonable to argue that the answer is two-fold. First, not all alternative vehicle/fuel systems can provide performance, range, maximum speed, engine size, and other characteristics to comparable levels to those of conventional gasoline vehicles. Second, the costs of alternative fuel/vehicle systems may be high relative to those of conventional gasoline vehicles.

The first potential reason should not be underestimated. The range and reliability of EVs and GCHEVs are perceived as lower than those of conventional gasoline vehicles (Lee and Lovellette, 2011, p. 19). In general, consumers expect driving range and performance similar to the conventional gasoline car before they are prepared to consider switching to an alternative vehicle/fuel system (Dagsvik et al., 2002; Backhaus et al., 2010; Caulfield et al., 2010). The only answer to this problem lies in technological advances, which are not the focus of the present study. We therefore devote the rest of the paper to the second reason why consumers may not be choosing alternative vehicle/fuel systems: relative costs.

Two further points then need to be considered. First, is there a breakeven point where consumers are indifferent between choosing cleaner cars with higher initial costs but lower operating costs and less environmentally friendly cars with lower initial costs but higher operating costs? Second, would relative costs change if the environmental damage caused by the different vehicle/fuel technologies (often not fully paid for by consumers) were taken into account? We conduct a break-even point analysis in order to determine the number of kilometres (or years, if we assume an average annual distance driven) at which consumers would be indifferent in terms of costs between paying a higher vehicle price but lower operating costs and paying a lower vehicle price but higher operating costs.

We conduct the analysis taking into account private costs only and also private plus external costs.

5.1 External Costs

An external cost exists when the following two conditions prevail: (a) an activity by one agent causes a loss of welfare to another agent and (b) the loss of welfare is uncompensated (Pearce and Turner, 1990, p.61).

In order to estimate the external costs of the different vehicle/fuel systems, two pieces of information are needed. First, the total carbon emissions resulting from each vehicle/fuel system, including both the vehicle and fuel life cycle, which were presented in Section 4 above, and second, the social cost of carbon (SCC).

The SCC measures the full global cost today of emitting an additional tonne of carbon now and sums the full global cost of the damage it imposes over the whole of its time in the atmosphere (UK Department of the Environment, Food and Rural Affairs, DEFRA, 2007, p.1). Importantly, ‘the SCC varies depending on which emissions and concentration trajectory the world is on’ (DEFRA, 2007, p.1).

In recent years there have been a number of studies attempting to estimate the SCC (Nordhaus, 1991, 1994; Cline, 1992; Fankhauser, 1994; Tol, 1999; Tol and Downing, 2000) as well as a number of reviews (Clarkson and Deyes, 2002, Tol, 2005, 2008), including a couple of reviews by the UK government (UK Department of Energy and Climate Change, DECC, 2011) and by the US government (US Interagency Working Group on Social Cost of Carbon, IAWG, 2010). Estimates differ greatly: Tol (2005, 2008) finds that estimates of the SCC are driven to a large extent by the choice of the discount rate (the lower the discount rate the higher the SCC estimated) and equity weights (when a higher weight is assigned to developing countries the final aggregate impacts tend to be higher because developing countries are expected to suffer the worst impacts). He also finds that the more pessimistic estimates, which correspond to pessimistic scenarios, have not been subject to peer review.

Since this is a study for the US 2020 we use the SCC figures from IAWG (2010) for a social discount rate of 3%. This is \$22.09/tCO_2 for the year 2010 and \$27.17/tCO_2 the year 2020, expressed, like all monetary values in this study, in 2009 prices.

As we show further down, the results are not sensitive to the SCC chosen, unless we use numbers out of the range of values suggested in the literature.

Non-CO_2 emissions, such as CO, CH_4 and NO_x, are converted by GREET 1.8b to CO_2 equivalent (CO_2e) under a 100-year scale according to the Intergovernmental Panel on Climate Change (IPCC) suggested rates (IPCC, 2007). Once converted to CO_2e we use the same SCC to value their damage, although this ignores other externalities, such as air pollution and health effects.

5.2 Private costs

Private costs are simply the costs actually faced by consumers. They include the purchase cost, maintenance cost and operating costs of the vehicle. Federal and state taxes are excluded at the initial comparison stage because they only distort relative prices[11] and are precisely the subject of discussion in the policy recommendations section.

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[11] For example, if the pre-tax price of good *x* is \$5 and the pre-tax price of good *y* is \$10, the ratio of the prices is 0.5. That ratio changes to 0.6 if the government introduces a tax of 20% on good *x* but not on good *y*.

The different vehicle post-tax prices as well as bio-diesel and hydrogen post-tax prices for the US 2020 were taken from the VISION model[12] database spreadsheets. Since not all the vehicles considered in this study were included in the VISION spreadsheets, the data was complemented with data from Weiss et al. (2000). Petrol, diesel, natural gas, LPG, E85 and electricity prices (both for commercial and residential purposes) were taken from the US Energy Information Administration (EIA), which provides official energy statistics.[13] For example, the gasoline price, excluding taxes, is $2.05 per litre and $2.74 per litre in 2010 and 2020, respectively, expressed in 2009 prices. The data on fuel taxes and subsidies (which had to be subtracted from the figures we had) was taken from the US Internal Revenue Service (IRS) Form 720.[14] We also subject the model to a sensitivity test for gasoline and diesel prices.

Commercial and residential electricity prices are different. Charging points at work or shopping centres do and will continue to pay a commercial tariff, whereas those charging at home would pay domestic tariffs. We think that 2/3 to 1/3 domestic to commercial might make most sense as a rule of thumb for EV in the US 2020.[15]

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[12] The VISION model was developed by the Argonne National Laboratory to ‘provide estimates of the potential energy use, oil use and carbon emission impacts of advanced light and heavy- duty vehicle technologies and alternative fuels through the year 2050’, later extended to 2100 (ANL, 2011).

[13] www.eia.gov/oiaf/aeo/tablebrowser/#release=AEO2011&subject=3-AEO2011&table=3-AEO2011&region=1-0&cases=ref2011-d120810c

[14] www.irs.gov/pub/irs-pdf/f720.pdf

[15] Electricity for EV charging is a fairly new market and there is no much previous experience on how the charging rate should be formulated. We assumed that EV charging would be classified as household usage. However, there is also the possibility that an ‘operator’ could charge batteries for consumers to swap them quickly, and in that case the rate would be commercial.

5.3 Payback periods

The most controversial issue when estimating payback periods is the discount rate assumed. There is evidence that suggests that consumers do not even analyse their fuel costs in a systematic way in their vehicle or fuel purchases (Turrentine and Kurani, 2007). Even if they did, not much is known about how consumers estimate the value of improved fuel economy and factor it in the purchasing decisions (Greene et al., 2005, p.758; Greene, 2010, p. vi). Allcott and Wozny (2010), for example, find that consumers are willing to pay only $0.61 up front to reduce discounted gasoline costs by $1.

Hausman (1979) analyses the trade-off between capital costs and operating costs of more energy efficient air conditioners for 46 households and finds that they trade off capital costs and expected operating costs with an implicit discount rate of about 20%, although this discount rate can vary widely with income (from 5% for high income groups to 89% for low income groups). It should be highlighted that these results, as Hausman himself warns, may not apply to other appliances, let alone cars.

Gallagher and Muehlegger (2011) compare consumer response to purchase tax credits and estimated future fuel savings and estimate an implicit discount rate of 14.6% on future fuel savings. Greene et al. (2005, p.758) cite a number of studies with conclusions and assumptions that include payback periods of 2.8 years, 3 years, 4 years and annual discount rates of 10% and 30%. Furthermore, and to make the range wider, Greene (2010, p. xi) reviews 27 studies and reports implicit annual discount rates of 0.2%, 37% and 60%. More importantly, he highlights the fact that the ‘consistency with which the literature has yielded widely varying, inconsistent estimates over a period of more than three decades suggests that there is either a fundamental empirical problem in estimating the value consumers place on fuel economy, or that the presumed theory of consumer behaviour is incorrect, or both’ (p. vii).

With this inconsistency problem in mind, we aim at estimating payback periods using the spark ignition ICE conventional vehicle running on gasoline (SICEG) as the baseline and assuming discount rates of 0%, 6%, 30% and 60% including and excluding external costs, and including and excluding current fuel and vehicle taxes and subsidies in the US. We assume an average annual distance driven of 20,000 km[16] and annual vehicle maintenance cost of 3% of the purchase cost, increasing 5% per year (although we do sensitivity analysis of this assumption in Section 6.1).

We conduct this exercise for all the vehicle/fuel systems included in Table 1. When no taxes or subsidies are considered and costs and prices are free from any corrective or distortive instruments, the spark ignition ICE conventional vehicle running on gasoline (SICEG) constitutes the undisputedly cheapest vehicle/fuel technology, for all discount rates and all years. With a 6% discount rate, the only vehicle/fuel technology that breaks even with SICEG is compression ignition ICE vehicles running on diesel (CICED), and it only does so after nine years (if environmental damage is included) or ten years (if only private costs are included in the calculations). With a 0% discount rate, which would imply that consumers put as much weight to future operating costs as to year 0 initial vehicle purchase costs, CICED breaks even with SICEG after six years (if environmental damage is included) or seven years (if only private costs are included in the calculations). With a 0% discount rate, spark ignition direct injection (SIDIG) vehicles and grid independent hybrid electric vehicles (GIHEV) break even with SICEG after nine years if environmental costs are included in the calculations.

For the higher discount rates used none of the alternative fuel/vehicle technologies breaks even with SICEG.

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[16] This is roughly the average distance driven by passenger cars in the USA. In 2009 the annual vehicle distance travelled was 16,608 km (US Department of Transportation, 2009). In 2020 this distance can reasonably be assumed to be 20,000 km.

If the average annual distance driven were assumed to be higher, the payback period would be shorter. For example, if average annual distance were 40,000 km, the cost line for CICED would intersect the one for SICEG in the fifth year, regardless of whether environmental costs were included in the calculations or not.[17]

Also, if consumers put more weight on operating costs than on capital costs (in other words, if they put more weight on future than present costs) the discount rate would be negative. With a high enough absolute value for the negative rate all alternative vehicle/fuel systems eventually break even with SICEG, except for the spark ignition flexible fuel ICE vehicle running on 85% ethanol and 15% gasoline (SFFICEV), the spark ignition dedicated ethanol ICE vehicle running on 90% ethanol and 10% gasoline (SDEICEV), the compression ignition ICE vehicle running on 20% biodiesel and 80% diesel blend (CICEBD) and the fuel cell vehicles (FCVH and FCVM). When no taxes or subsidies are included in the calculations all these vehicles have higher operating costs in the first year and from then onwards their cost trajectories only diverge from that for SICEG. Also, fuel cell vehicles have an initial (capital) cost which is almost two and a half times that of a conventional SICEG. For this reason it would be virtually impossible for these vehicles to be commercially viable, at least until a breakthrough to reduce costs is made. This finding is in line with van Vliet et al. (2010), who argue that the fuel cell car remains uncompetitive even if production costs of fuel cells come down by 90%.

Figures 6 and 7 illustrate cost trajectories for a 6% discount rate, excluding fuel cell vehicles, whose costs are much higher and would make visual interpretation of the figure difficult. Figure 6 includes both private and external costs, while Figure 7 includes private costs only. As it can be seen, the figures are very similar, i.e. external

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[17] This is because the environmental cost is very small in relative terms. If it is included the breakeven point occurs slightly earlier but still within the fifth year.

costs are small relative to vehicle and operating costs.[18]

The points of intersection between lines show breakeven points. As already advanced above, the only vehicle/fuel system that breaks even with SICEG is CICED. The other points of intersection are breakeven points between alternative vehicle/fuel systems, which are not our baseline. For example, the cost line for CICEBD intersects the one for GIHEV around 2012 and the one for GCHEV, around 2018. In other words, whilst compression ignition ICE vehicles that run on 20% biodiesel and 80% diesel blend may be cheaper than hybrid electric vehicles to start with, within two years, the lower operating costs of grid independent hybrid electric vehicles make up for the initial vehicle price difference and within eight years, grid connected hybrid electric vehicles do the same.

The two questions we asked at the beginning of this section can now be answered. First, in most cases there is no reasonable payback period and consumers are unlikely to tilt towards other vehicle/fuel systems on the basis of costs. Second, the picture does not change much when the environmental costs of carbon emissions are included in the calculations.

The immediate conclusion from these calculations is that without tax or subsidy incentives it will be fairly difficult to persuade consumers to switch from SICEG to other more environmentally friendly vehicle/fuel technologies.[19] Another important

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[18] For example, the social cost of carbon emissions for a spark ignition ICE conventional vehicle running on gasoline is $126 in the first year, whereas fuel costs are $1,036 and maintenance costs are $665.

[19] In economics it is standard to assume that a consumer maximises her utility function subject to a budget constraint. If one of the arguments of her utility function were ‘concern for the environment’, a consumer would probably choose a more expensive vehicle/fuel system, even one that never paid back, only because doing so would increase her marginal utility.

conclusion is that a tax or subsidy computed on the basis of environmental costs will not be enough to change consumers' choices. Taxes or subsidies favouring cleaner vehicle/fuel systems will need to be political and will have no economic grounding.

FIGURE 6 ABOUT HERE

FIGURE 7 ABOUT HERE

6. Present Value of costs and discussion

The Present Value of costs (PVC), calculated in this section, summarizes in just one number, the present value of all the costs, private and external, for each vehicle/fuel system over ten years, for discount rates of 0%, 6%, 30% and 60%.[20] Like in the Breakeven Analysis, costs include vehicle purchase, vehicle operating costs, annual depreciation and maintenance costs, and damage from CO_2e emissions. Table 2 shows the results of these calculations. The different vehicle/fuel systems are ranked by ascending private cost, the factor most likely to influence consumers' choice in the first instance. This is done for each of the four discount rates assumed.

TABLE 2 ABOUT HERE

The signs and trends of the results on Table 2 are in line with those from Schäfer and Jacoby (2006, Table 4, p.980) and Lee and Lovellette (2011, p.16). The magnitudes are different because a number of assumptions are different.

The lower the discount rate used the higher the potential savings from diesel vehicles (CICED), which can be computed as the difference between the PVC of CICED and the PVC of SICEG. Also, the lower the discount rate the lower the difference in PVC of alternative vehicle/fuel technologies and SICEG, except for the spark ignition flexible

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[20] The equation used is shown in Appendix 2.

fuel ICE vehicle running on 85% ethanol and 15% gasoline (SFFICEV), the spark ignition dedicated ethanol ICE vehicle running on 90% ethanol and 10% gasoline (SDEICEV), the compression ignition ICE vehicle running on 20% biodiesel and 80% diesel blend (CICEBD) and the fuel cell vehicles (FCVH and FCVM). For these alternative fuel vehicles, the lower the discount rate used, the higher the difference in PVC relative to the PVC of SICEG. As already explained in Section 5.3, all these vehicle/fuel technologies have higher operating costs than SICEG in the first year and they continue to diverge from then onwards. If these higher operating costs are given almost the same or even the same weight as the initial vehicle purchase cost, the difference in PVC becomes bigger.

It should be noted that if gasoline and diesel taxes in the US are included in the calculations, SDEICEV and CICEBD have lower operating costs than SICEG in the first year, although they do not manage to break even before year 10. For this, additional taxes and subsidies would be needed, as we discuss in Section 7. Also, as we discuss in Section 6.1, SFFICEV breaks even with SICEG if gasoline prices, inclusive of taxes, are assumed to be twice as high.

The present value of the cost of environmental damage produced by the carbon emissions from the different vehicle/fuel systems, depicted on the column entitled ‘External costs’ is lowest (in line with Figure 5 in Section 4) for fuel cell vehicles (FCVM and FCVH), spark ignition dedicated ethanol ICE vehicles E90 (SDEICEV) and electric vehicles (EV), obviously under all interest rates. Apart from fuel cell vehicles having higher operating costs in the first year and only diverging indefinitely from those of SICEG, they are not available for mass production yet, and they have a very high initial price, so consumers would be unlikely to choose them. It would be virtually impossible for the US government to introduce tax or subsidies to match the PVC of fuel cell vehicles with those of SICEG.

SDEICEV, on the other hand, would be more plausible. With enough financial incentives, there might be room for making this vehicle/fuel system an attractive technology for consumers. The problem with SDEICEV for mass penetration is that the production of ethanol poses important challenges.[21]

Over a ten-year period the external cost savings from EVs are 37% and 28%, with discount rates of 0% and 60%, respectively. The private PVC is 1.2 and 1.5 times that of SICEG, for a 0% and a 60% discount rate respectively, which makes this a relatively expensive, although not completely impossible, option for the government to subsidize.

Other vehicle/fuel systems that would achieve savings in environmental costs of between 29% and 32% (for a 0% discount rate) or 24% and 27% (for a 60% discount rate) include grid-connected and grid-independent hybrid electric vehicles (GCHEV and GIHEV), compression ignition ICE vehicles running on biodiesel (CICEBD), and spark ignition flexible fuel ICE vehicles (SFFICEV). SFFICEV, however, never breaks even with SICEG, because the operating costs in the first year are higher and continue to diverge from then onwards, as already highlighted in Section 5.3. In contrast with SDEICEV and CICEBD this cannot be reverted with policies, unless some politically unacceptable increase in gasoline prices or taxes is assumed, as we discuss in Section 6.1.

GCHEV, GIHEV and CICEBD have PVC which are higher than the PVC for SICEG but not impossible to match with fiscal incentives. CICEBD, however, could face problems for large scale market penetration, as it relies on biodiesel.[22]

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[21] An important barrier would be the competition for livestock feed (Ou et al., 2010, p. 3952), since ethanol is produced mainly from grain and sugar crops on agricultural land (Inderwildi et al., 2010, p.18).

[22] Biodiesel faces the problem of food versus fuel competition (Timilsina and Shrestha, 2011, p.2067) and the issue of agricultural land remains, just like in the case of SDEICEV.

Leaving to one side the political (and perhaps ethical) problems of ethanol and biodiesel production for road transport use, the five alternative vehicle/fuel systems that stand out from this analysis as potential ways forward due to their relatively low environmental costs and private PVC, are SDEICEV, CICEBD, EV, GCHEV and GIHEV.

As stated in Section 2, the shares of EV, GCHEV and GIHEV in total new car sales in the US in the period January-July 2012 were 0.06%, 0.18% and 3%. GIHEV is a fairly mature technology which achieved this 3% share without any car purchase subsidy or tax break.

In Section 7 we discuss some financial incentives that could potentially help change consumers’ choices in favour of SDEICEV, CICEBD, EV, GCHEV and GIHEV.

6.1 Sensitivity analysis

We test sensitivity of our results to three assumptions: fuel prices, maintenance costs and the SCC.

If gasoline and diesel prices (including taxes) are assumed to be twice as high and all remaining current policies remain in place then all alternative vehicle/fuel systems break even with SICEG, often well before year 10, under 0% and 6% discount rates, except for fuel cell vehicles. Under 30% and 60% discount rates, only SFFICEV and SDEICEV break even with SICEG, from year 1 onwards, and EV, in year 10, under a 30% discount rate. Given that we are assuming that gasoline and diesel become relatively more expensive than other types of fuel, this is not a surprising result.

Although it is common and reasonable to assume annual maintenance costs of 3% of the purchase cost, increasing 5% per year, this has an unusual high weight on fuel cells, given their high initial cost. However, even if we assume zero maintenance costs for fuel cells, these do not break even, under any discount rate.

As for the SCC, if we assume SCC ten times higher than those assumed for the period 2010-2020, then:

(a) Under a 0% discount rate SIDIG, CICED, SFFICEV, SDEICEV, GIHEV and GCHEV all break even with SICEG by years five, five, seven, two, five and nine, respectively.

(b) Under a 6% discount rate SIDIG, CICED, SFFICEV, SDEICEV and GIHEV all break even with SICEG by years six, six, eight, two, and six respectively.

(c) Under discount rates of 30% and 60% only SDEICEV breaks even with SICEG by years 3 and 4 respectively.

A SCC ten times higher would in general not be acceptable in the academic community or in policy circles. This sensitivity analysis with respect to the SCC only confirms our previous conclusion that alternative fuel/vehicle systems are not viable on economic grounds, but rather on environmental or political grounds.

7. Financial incentives

A number of policy options could be implemented to encourage adoption of low carbon fuels, including fuel standards, market incentives, such as pricing and tax policies, and additional funding for research and development (US Department of Transportation, 2010, p.3-7). In this section, we present some examples of fiscal policies that might help change consumers' decisions. We do not assess the effects that these measures would have on the US Budget or the US economy as a whole, nor on its social welfare. That analysis exceeds the scope of this paper. Also, all pending or proposed legislation, regulations and standards in the US, not yet currently in place, are ignored.

Since we have already concluded that there is no economic justification for favouring lower carbon vehicle/fuel systems, these measures would not be ‘corrective’. They would only be intended to change payback periods (i.e. breakeven distances) and PVC.

Before we venture into proposing any policy, we present on Figure 8 the breakeven points of the different vehicle/fuel technologies, including current taxes and tax credits in the US as of 2011. These reflect all the taxes and tax credits in place in the US, which are summarized on Table 3. We assume a discount rate of 6% so that the curves can be compared with those in Figures 6 and 7.

TABLE 3 ABOUT HERE

FIGURE 8 ABOUT HERE

The feature that stands out of Figure 8 is that the cost trajectories for GCHEV and EV have changed their relative positions when compared to Figures 6 and 7. This is thanks to the federal tax credit of up to $2,500 and $7,500 that GCHEVs and EVs receive, respectively. A number of intersection points have also moved forward and backward, according to the different taxes and subsidies.

The cost trajectory for GCHEV now intersects that for SICEG vehicles, although it does so at a very late stage, towards the end of the ten-year period in question. The cost trajectory for GIHEV still does not intersect that of SICEG. Also, before any policy the cost trajectory for GCHEV was always above and never intersected that of GIHEV, whereas now they do break even in 2018.

The policies currently in place in the US do not yield payback periods that encourage motorists to purchase and use SDEICEV, CICEBD, EV, GCHEV or GIHEV. If anything, it is surprising that GIHEV achieved a 3% share of all new car sales in January-July 2012. In order to boost the sale of any of these vehicle/fuel technologies the options can be many. The idea is essentially to change payback periods and relative PVCs over the lifetime of the vehicle.

Table 4 summarizes some combinations of taxes and subsidies that make the PVC of these vehicle/fuel technologies equal to that of SICEG. We only present the numbers for two of our discount rates: 60% and 6%, to show a range of possible values. The first three columns show the vehicle taxes and subsidies needed in order to equate PVC after 10, 6 and 2 years. The second three columns show the vehicle taxes and subsidies needed in order to equate PVC after 10, 6 and 2 years when combined with an increase in gasoline and diesel taxes to bring both to the 1$/gallon mark.[23] All other current taxes and tax credits, summarized in Table 3, stay the same. We do not include external costs in the calculations for two reasons: first, consumers do not include them and most importantly, we have already showed that these are negligible in any case.

With an increase in fuel taxes, the subsidies needed are obviously lower. Also, the shorter the payback period, the higher the subsidy needed. It should be noted that SDEICEV can actually be taxed when combined with an increase in fuel taxes in all cases except when the required payback period is 2 years under a 60% discount rate. It can also be taxed under a 6% discount rate if the payback period is 6 or 10 years. This makes SDEICEV an attractive option from a fiscal point of view. Sadly, as highlighted above, the problem with this vehicle/fuel technology is that the mass production of ethanol for fuel is controversial.

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[23] Although this is an arbitrary choice it may be just about politically acceptable and is also close to the efficient tax. Parry and Small (2005) suggest that the efficient gasoline tax for the US for the year 2000 was just over $1/gallon.

It should also be noted that, given that GIHEVs rely on gasoline and CICEBDs rely on diesel, the impact of the tax increase is greater on these vehicles and for a payback period of 10 years they can actually be taxed.

Although it would be politically difficult to implement such an increase in gasoline and diesel taxes in the US, it could potentially help fund the vehicle purchase tax credits, which in any case, would be smaller, if not negative, depending on the required payback period. CICEBD, however, faces the same constraints as SDEICEV, regarding the competition for land for fuel vs. food production.

These are examples of plausible policies. Many other combinations can be thought of and before any decision was taken, a thorough general equilibrium analysis would need to be carried out.

More importantly, further research is needed on payback periods, discount rates and consumers' purchasing decisions. Greene (2010, p.vii) suggests investigating the reasons behind such a great variation in estimates from the literature and also investigating the very applicability of *Homo Economicus* assumptions to this type of problem.

8. Conclusions

This paper has conducted a breakeven analysis of low carbon vehicle/fuel technologies for the US for the year 2020, taking into consideration both private and external costs as well as calculated the present value of the costs of the different options.

Not even the highest estimates of the social cost of carbon prevailing in the literature justify the mass introduction of low or zero carbon vehicle/fuel technologies. If this were to be done, it would be a political decision rather than one based on economic principles.

Potential fiscal measures are entertained with a view to changing consumers' choices to favour green technologies. We shortlist SDEICEV, CICEBD, EV, GCHEV and GIHEV as potential candidates, although SDEICEV and CICEBD are controversial because of the fuel vs. food competition for agricultural land.

All five vehicle/fuel systems are initially more expensive than spark ignition internal combustion engine (ICE) conventional vehicles on gasoline (SICEG). Their running costs, however, are much lower. In order to persuade consumers to buy any of these vehicles, a number of subsidies could be implemented and potentially combined with an increase in gasoline and diesel taxes. The magnitude of these financial incentives depends on the discount rate and acceptable payback period assumed as well as on whether the subsidy is implemented on its own or accompanied with an increase in taxes. In any case, a general equilibrium analysis of the implications of alternative policy packages would be in order before deciding on a particular one.

Although we do not find an economic justification for favouring cleaner fuel/vehicle systems, we do not discard the possibility that these could be justified if the social cost of carbon were revised upwards by the academic community or more importantly, if other externalities were also taken into account, including non-GHG emissions and oil dependence. The inclusion of these in our breakeven analysis falls outside the remit of the present paper but are postulated here as future lines of research.

Finally, consumers' acceptable payback periods, implicit discount rates and car purchasing decisions do not seem to be well understood, a fact that questions the very assumption of the *Homo Economicus* model. This area needs further research, which could benefit from behavioural economics and psychology.

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Any errors and shortcomings are the authors' own.

Appendix 1

Wang (1999, pp.19-20) summarizes GREET’s “process fuel” calculation procedure as follows. To obtain 10^6 BTU fuel feedstock out of well, the total required process fuel is given by Equation (1):

$$\text{Process fuels} = \left[\frac{1}{\text{efficiency}_{\text{crude recovery}}} - 1 \right] \text{x}\, 10^6\,\text{BTU} \qquad (1)$$

where efficiency$_{\text{crude recovery}}$ = energy output/energy input. For instance, according to estimates produced by the Wang et al. (2007), recovering 10^6 BTU fuel feedstock requires 20,400 BTU process fuels, which comprise 204 BTU crude oil, 204 BTU residual oil, 3,057 BTU diesel, 408 BTU gasoline, 12,635 BTU natural gas and 3,872 BTU electricity. As 20,400 BTU fuel are consumed during the recovery process, the fuel feedstock that needs to be recovered in the first place is much more, coming to a total of 1,020,400 BTU. This is to cover the process fuel consumption and energy loss during the whole pathway. However, to recover 1,020,400 BTU feedstock, additional process fuel $\left(20{,}400\,\text{BTU}\ \text{x}\ \frac{20{,}400}{10^6} \right)$ is required again. GREET in this case applies a circular calculation until the difference between successive results is less than 0.001 BTU.

Appendix 2

The PVC is calculated using the following equation:

$$PVC = \sum_{t=0}^{n=10} \frac{C_t}{(1+r)^t} = C_0 + \frac{C_1}{(1+r)} + \frac{C_2}{(1+r)^2} + \ldots + \frac{C_{10}}{(1+r)^{10}}$$

where *C* is cost and includes the costs described in Section 6, *t* indicates the year and varies from year 0 (2010) to year 10 (2020) and *r* is the discount rate, for which we assume four different values (0%, 6%, 30% and 60%).

References

Akkermans L., Vanherle, K., Moizo A., Raganato P., Schade B., Leduc G., Wiesenthal T., Shepherd S., Tight, M., Guehnemann, A., Krail M., and W. Schade (2010), *Ranking of measures to reduce GHG emissions of transport: reduction potentials and qualification of feasibility*, Deliverable D2.1 of GHG-TransPoRD: Project co-funded by European Commission 7th RTD Programme. Transport & Mobility Leuven, Belgium. http://www.ghg-transpord.eu/ghg-transpord/downloads/GHG_TransPoRD_D2_1_GHG_reduction_potentials.pdf

Albrecht, J., (2001), 'Tradable CO2 permits for cars and trucks', *Journal of Cleaner Production* , 9(2), pp. 179-189.

Allcott, H. and N. Wozny (2010), 'Gasoline Prices, Fuel Economy, and the Energy Paradox', Working Paper 10-003, Center for Energy and Environmental Policy Research, ftp://wuecon195.wustl.edu/opt/ReDIF/RePEc/mee/wpaper/2010-003.pdf

Andress, D., Nguyen, T.D. and S. Das (2011), 'Reducing GHG emissions in the United States' transportation sector', *Energy for Sustainable Development*, 15(2), pp. 117-136.

Andress, D., Das, S., Joseck, F. and T.D. Nguyen (2012), 'Status of advanced light-duty transportation technologies in the US', *Energy Policy,* 41(February), pp. 348-364.

Argonne National Laboratory (2011), *The Vision Model,* Argonne National Laboratory, U.S. Department of Energy, October. www.transportation.anl.gov/modeling_simulation/VISION/

Backhaus, J., Bunzeck, I.G., Mourik, R. (2010), *First come, first served: Profiling the potential early users of H2 cars - Analysis of current car purchasing, driving and refuelling behaviour in the Netherlands*, Report ECN-E--10-081, Energy Research Centre of the Netherlands. http://www.ecn.nl/docs/library/report/2010/e10081.pdf

Bandivadekar, A., Cheah, L., Evans, C., Groode, T., Heywood, J., Kasseris, E., Kromer, M., and M. Weiss (2008), 'Reducing the fuel use and greenhouse gas emissions of the US vehicle fleet', *Energy Policy,* 36(7), pp. 2754-2760.

Bohn, T. (2005), Argonne National Laboratory, personal communication with Andrew Burnham, Argonne National Laboratory, Argonne, Illinois, July and August, cited in Burnham, A., Wang, M. and Y. Wu (2006, pp.28-29).

Bradley, T.H. and A. A. Frank (2009), 'Design, demonstrations and sustainability impact assessments for plug-in hybrid electric vehicles', *Renewable and Sustainable Energy Reviews*, 13(1), pp. 115-128.

Burnham, A., Wang, M. and Y. Wu (2006), *Development and Applications of GREET 2.7 - The Transportation Vehicle-Cycle Model*, ANL/ESD/06-5, Energy Systems Division, Argonne National Laboratory, November. http://www.transportation.anl.gov/pdfs/TA/378.PDF

Canis, B. (2012), 'Why Some Fuel-Efficient Vehicles Are Not Sold Domestically', Congressional Research Service Report for Congress, 12 August. http://www.fas.org/sgp/crs/misc/R42666.pdf

Cambridge Systematics, Inc. (2009), *Moving Cooler: An Analysis of Transportation Strategies for Reducing Greenhouse Gas Emissions*, Washington, D.C.: Urban Land Institute, July.

http://www.fta.dot.gov/documents/MovingCoolerExecSummaryULI.pdf

Caulfield, B., Farrell, S. and B. McMahon (2010), ‘Examining individuals preferences for hybrid electric and alternatively fuelled vehicles’, *Transport Policy*, 17(6), pp. 381-387.

Clarkson, R. and K. Deyes (2002), *Estimating the Social Cost of Carbon*, Government Economic Service Working Paper 140, HM Treasury, London; available at www.hm-treasury.gov.uk/mediastore/otherfiles/SCC.pdf

Cline W. (1992), *The Economics of Global Warming*, Institute for International Economics: Washington, DC.

Dagsvik, J.K., Wennemo, T., Wetterwald, D.G. and R. Aaberge (2002), ‘Potential demand for alternative fuel vehicles’, *Transportation Research Part B: Methodological*, 36(4), pp. 361-384.

de Haan, P., Peters, A. and R. W. Scholz (2007), ‘Reducing energy consumption in road transport through hybrid vehicles: investigation of rebound effects, and possible effects of tax rebates’, *Journal of Cleaner Production* 15(11-12), pp. 1076-1084.

Electric Drive Transportation Association (2012), *Electric drive vehicle sales figures (U.S. Market)*. http://electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952

Fankhauser, S. (1994), ‘The Social Cost of greenhouse gas emissions: An Expected Value Approach’, *Energy Journal*, 15(2), pp. 157-184.

Gallagher, K.S. and E. Muehlegger (2011), ‘Giving green to get green? Incentives and consumer adoption of hybrid vehicle technology’, *Journal of Environmental*

Economics and Management, 61(1), pp. 1-15.

Greene, D.L. (2010), How Consumers Value Fuel Economy: A Literature Review', EPA-420-R-10-008, Assessment and Standards Division, Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Washington D.C., March. http://www.epa.gov/oms/climate/regulations/420r10008.pdf

Greene, D.L., Patterson, P.D., Singh, M. and Jia Li (2005), 'Feebates, rebates and gas-guzzler taxes: a study of incentives for increased fuel economy', *Energy Policy*, 33(6), pp. 757-775.

Hausman, J.A. (1979), 'Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables', *The Bell Journal of Economics*, 10(1), pp. 33-54.

HM Treasury (2007), *The King Review of low-carbon cars Part I: the potential of* CO_2 *reduction*, www.hm-treasury.gov.uk/king

HybridCars.com (2012), *July 2012 Dashboard*. http://www.hybridcars.com/news/july-2012-dashboard-49476.html

Inderwildi, O., Carey, C., Santos, G., Yan, X., Behrendt, H., Holdway, A., Maconi, L., Owen, N., Shirvani, T. and A. Teytelboym (2010), *Future of Mobility Roadmap: Ways to Reduce Emissions While Keeping Mobile*, Final Report of the Future of Mobility horizon-scanning project, conducted at the Smith School of Enterprise and the Environment, University of Oxford. www.smithschool.ox.ac.uk/wp-content/uploads/2010/02/Future_of_Mobility.pdf

Intergovernmental Panel on Climate Change (2001), *Climate Change 2001: Synthesis Report.* Cambridge University Press, Cambridge. www.ipcc.ch/pdf/climate-changes-2001/synthesis-syr/english/front.pdf

Intergovernmental Panel on Climate Change (2007), *Climate Change 2007: Working Group I: The Physical Science Basis*. [2.10 Global Warming Potentials and other Metrics for comparing different Emissions] http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10.html

Lee. C. (2007), ‘Transport and climate change: a review’, *Journal of Transport Geography*, 15(5), pp. 354-367.

Lee, H. and G. Lovellette (2011), ‘Will Electric Cars Transform the U.S. Market?’, *Faculty Research Working Paper Series*, RWP11-032, August. http://ssrn.com/abstract=1927351

McCollum, D. and C. Yang (2009), ‘Achieving deep reductions in US transport greenhouse gas emissions: Scenario analysis and policy implications’, *Energy Policy*, 37(12), pp. 5580-5596.

McKinsey & Company (2009), Roads toward a low-carbon future: Reducing CO_2 emissions from passenger vehicles in the global road transportation system, New York, March. http://www.mckinsey.it/storage/first/uploadfile/attach/141271/file/roads_toward_a_low_carbon_future.pdf

McKinsey & Company (2010), A portfolio of power-trains for Europe: a fact-based analysis - The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles. http://www.europeanclimate.org/documents/Power_trains_for_Europe.pdf

Morrow, W.R., Gallagher, K.S., Collantes, G. and H. Lee (2010), ‘Analysis of policies to reduce oil consumption and greenhouse-gas emissions from the US transportation sector’, *Energy Policy*, 38(3), pp. 1305-1320.

Nordhaus W. (1991), ‘To slow or not to slow: The economics of the greenhouse effect’, *Economic Journal*, 101(407), pp. 920-937.

Nordhaus W. (1994), *Managing the Global Commons: the Economics of Climate Change,* MIT Press: Cambridge, Mass.

Ou, X., Zhang, X. and S. Chang (2010), ‘Scenario analysis on alternative fuel/vehicle for China’s future road transport: Life-cycle energy demand and GHG emissions’, *Energy Policy*, 38(8), pp. 3943-3956.

Parry, I. and K. Small (2005), ‘Does Britain or the United States Have the Right Gasoline Tax?’, *American Economic Review,* 95(4), pp. 1276-1289.

Pasaoglu, G., Honselaar, M. and C. Thiel (2012), ‘Potential vehicle fleet CO_2 reductions and cost implications for various vehicle technology deployment scenarios in Europe’, *Energy Policy*, 40(1), pp. 404-421.

Pearce, D. and K. Turner (1990), *Economics of natural resources and the environment,* Harvester Wheatsheaf, London.

Royal Purple (2006), ‘Synthetic Transmission Fluid’. http://www.royalpurple.com/prodsa/matfa.html, cited in Burnham, A., Wang, M. and Y. Wu (2006, p.29).

Safarianova, S., Noembrini, F., Boulouchos, K. and P. Dietrich (2011), ‘Techno-Economic Analysis of Low-GHG Emission Passenger Cars’, Deliverable D1 (WP1 report), TOSCA Project (Technology Opportunities and Strategies towards Climate friendly trAnsport), FP7-TPT-2008-RTD-1 , ETH Zurich Institut f. Energietechnik, Zürich. http://www.toscaproject.org/documents.html

Santos, G., Behrendt, H., Maconi, L., Shirvani, T. and A. Teytelboym (2010), ‘Externalities and Economic Policies in Road Transport’, *Research in Transportation Economics*, 28(1), pp. 2-45.

Santos, G., Behrendt, H. and A. Teytelboym (2010), ‘Policy Instruments for Sustainable Road Transport’, *Research in Transportation Economics*, 28(1), pp. 46-91.

Schäfer, A. and H. D. Jacoby (2006), ‘Vehicle technology under CO_2 constraint: a general equilibrium analysis’, *Energy Policy*, 34(9), pp. 975-985.

Schäfer, A. Dray, L., Andersson, E. Ben-Akiva, M.E., Berg, M., Boulouchos, K., Dietrich, P., Fröidh, O., Graham, W., Kok, R., Majer, S., Nelldal, B., Noembrini, F., Odoni, A., Pagoni, I., Perimenis, A., Psaraki, V., Rahman, A., Safarinova, S. and M. Vera-Morales (2011), TOSCA Project Final Report: Description of the Main S&T Results/Foregrounds. www.toscaproject.org/FinalReports/TOSCA_FinalReport.pdf.

Searchinger, T., R. Heimlich, R. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T. Yu (2008), ‘Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change’, *Science*, 319(5867), pp. 1238-1240.

Sullivan, J.L., Williams, R. L. ,Yester, S., Cobas-Flores, E., Chubbs, S.T., Hentges, S.G. and S.D. Pomper (1998), *Life Cycle Inventory of a Generic U.S. Family Sedan: Overview of Results USCAR AMP Project*, SAE 982160, Society of Automotive Engineers, Warrendale, Penn, cited in Burnham, A., Wang, M. and Y. Wu (2006, p.28).

Thiel, C., Perujo, A. and A. Mercier (2010), ‘Cost and CO_2 aspects of future vehicle options in Europe under new energy policy scenarios', *Energy Policy,* 38(11), pp. 7142-7151.

Timilsina, G.R. and A. Shrestha (2011), 'How much hope should we have for biofuels?', *Energy*, 36(4), pp. 2055-2069.

Tol, R. (1999), 'The Marginal Costs of Greenhouse Gas Emissions', *Energy Journal,* 20(1), pp. 61-81.

Tol, R. (2005), 'The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties', *Energy Policy,* 33(16), pp. 2064-2074.

Tol, R. (2008), 'The Social Cost of Carbon: Trends, Outliers and Catastrophes', *Economics: The Open-Access, Open-Assessment E-Journal,* 2(25), 12 August. www.economics-ejournal.org/economics/journalarticles/2008-25/

Tol, R. and T. Downing (2000), *The Marginal Costs of Climate Changing Emissions*, Institute for Environmental Studies, Vrije Universiteit, Amsterdam. http://dare.ubvu.vu.nl/bitstream/1871/1749/2/ivmvu0748.pdf

Turrentine, T. S. and K. S. Kurani (2007), 'Car buyers and fuel economy?', *Energy Policy,* 35 (2) pp. 1213-1223.

UK Department of Energy and Climate Change (2011), *Valuation of energy use and greenhouse gas emissions for appraisal and evaluation,* October. www.decc.gov.uk/assets/decc/statistics/analysis_group/122-valuationenergyuseggemissions.pdf

UK Department of the Environment, Food and Rural Affairs (2007), *The Social Cost of Carbon and n the Shadow Price of Carbon: What they are, and how to use them in Economic Appraisal in the UK*, Economics Group, DEFRA. www.defra.gov.uk/environment/climatechange/research/carboncost/pdf/background.pdf

US Department of Transportation (2009), *Highway Statistics 2009*: Annual Vehicle Distance Traveled in Miles and Related Data - 2009 1/ By Highway Category and Vehicle Type, Federal Highway Administration. www.fhwa.dot.gov/policyinformation/statistics/2009/vm1.cfm

US Department of Transportation (2010), *Transportation's Role in Reducing US Greenhouse Gas Emissions, Volume 1: Synthesis Report*, Report to Congress, Washington DC, April. http://ntl.bts.gov/lib/32000/32700/32779/DOT_Climate_Change_Report_-_April_2010_-_Volume_1_and_2.pdf

US Environmental Protection Agency (2003), *User's Guide to MOBILE6.1 and MOBILE6.2: Mobile Source Emission Factor Model*, EPA420-R-03-010, Assessment and Standards Division, Office of Transportation and Air Quality, US Environmental Protection Agency, August. http://www.epa.gov/oms/models/mobile6/420r03010.pdf

Interagency Working Group on Social Cost of Carbon, United States Government (2010), *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*, February. http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf

US Internal Revenue Service Form 720. http://www.irs.gov/pub/irs-pdf/f720.pdf van Vliet, O.P.R., Kruithof, T., Turkenburg, W.C and A.P.C. Faaij (2010), 'Techno-economic comparison of series hybrid, plug-in hybrid, fuel cell and regular cars', *Journal of Power Sources*, 195(19), pp. 6570-6585.

Wang, M. (1999), *GREET 1.5 – Transportation Fuel-Cycle Model, Volume 1: Methodology, Development, Use, and Results,* ANL/ESD-39, Vol. 1, Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, U.S. Department of Energy. http://greet.es.anl.gov/files/20z8ihl0

Wang, M., Wu, Y. and A. Elgowainy (2007), *Operating Manual for GREET: Version 1.7,* Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, U.S. Department of Energy. www.transportation.anl.gov/pdfs/TA/353.pdf

Ward, J. (2008), *VISION 2008 User Guide,* Argonne National Laboratory, U.S. Department of Energy. www.transportation.anl.gov/pdfs/TA/534.pdf

Weiss, M., Heywood, J., Drake, E., Schafer, A. and F. AuYeung (2000), *On the Road in 2020: A life-cycle analysis of new automobile technologies,* Energy Laboratory Report #MIT EL 00-003, Energy Laboratory, Massachusetts Institute of Technology, October. http://web.mit.edu/energylab/www/pubs/el00-003.pdf

Table 1: Vehicle/fuel systems considered in this study

Vehicle	**Energy**	**Acronym**	**Vehicle group for vehicle lifecycle emissions**	**Acronym for vehicle lifecycle emissions**
Spark ignition ICE conventional vehicle	Gasoline	SICEG	Spark ignition and compression ignition vehicles	SCEV
Spark ignition direct injection vehicle	Gasoline	SIDIG		
Compression ignition ICE vehicle	Diesel	CICED		
Spark ignition ICE on compressed natural gas	Compressed natural gas	SICECNG		
Spark ignition flexible fuel ICE vehicle	E85 (85% ethanol and 15% gasoline)	SFFICEV		
Spark ignition dedicated ethanol ICE vehicles	E90 (10% gasoline and 90% ethanol blend)	SDEICEV		
Compression ignition ICE vehicle	Biodiesel (20% biodiesel and 80% diesel blend)	CICEBD		
Grid independent hybrid electric vehicle	Gasoline and electricity	GIHEV	Grid independent hybrid electric vehicle	GIHEV
Grid connected hybrid electric vehicle	Gasoline and electricity	GCHEV	Grid connected hybrid electric vehicle	GCHEV
Pure electric vehicle	Electricity	EV	Pure electric vehicle	EV
Fuel cell vehicle	Hydrogen	FCVH	Fuel cell vehicles	FCV
Fuel cell vehicle	Methane	FCVM		

Note: Both GIHEVs and GCHEVs in this study are assumed to run on a combination of electricity and gasoline.

Table 2: PVC of Alternative Vehicle/Fuel Systems in the US 2020

	Private costs	External costs	Private and external costs
0%			
CICED	42,626	1,213	43,839
SICEG	43,462	1,425	44,888
GIHEV	43,560	966	44,526
SIDIG	43,602	1,247	44,849
SDEICEV	45,185	831	46,016
GCHEV	46,216	1,011	47,227
SFFICEV	47,269	985	48,254
CICEBD	49,421	1,001	50,422
SICECNG	50,106	1,053	51,159
EV	53,877	905	54,782
FCVM	79,181	868	80,049
FCVH	104,943	720	105,662
6%			
CICED	37,520	894	38,414
SICEG	37,565	1,049	38,614
SIDIG	38,029	919	38,947
GIHEV	38,481	715	39,195
SDEICEV	39,012	616	39,627
SFFICEV	40,532	728	41,260
GCHEV	41,374	748	42,121
CICEBD	42,462	739	43,202
SICECNG	44,702	777	45,479
EV	48,802	673	49,475
FCVM	72,158	645	72,803
FCVH	91,254	538	91,792
30%			
SICEG	28,279	449	28,728
SDEICEV	29,243	273	29,516
SIDIG	29,259	396	29,655
CICED	29,490	386	29,876
SFFICEV	29,865	318	30,183
GIHEV	30,498	314	30,813
CICEBD	31,477	323	31,799
GCHEV	33,774	329	34,103
SICECNG	36,148	338	36,487
EV	40,803	303	41,107
FCVM	61,126	292	61,418
FCVH	69,322	248	69,569

60%			
SICEG	25,308	253	25,561
SDEICEV	26,077	160	26,237
SFFICEV	26,403	184	26,587
SIDIG	26,456	225	26,681
CICED	26,918	220	27,138
CICEBD	27,941	187	28,127
GIHEV	27,953	183	28,136
GCHEV	31,358	191	31,549
SICECNG	33,379	195	33,573
EV	38,234	182	38,416
FCVM	57,607	176	57,783
FCVH	62,047	153	62,200

Note: All figures are in 2009 US dollars and 2010 values. The fuel cell options are presented in a lighter colour font because they are substantially more expensive, and therefore, do not seem to be financially viable in the short and medium run.

Table 3: Summary of taxes and tax credits in road transport in the US as of 2011

Energy and Vehicle	Tax, tax rebate and/or subsidy
Petrol	The average tax, which includes the federal and state taxes, is \$0.47 per gallon.
Diesel	The average tax, which includes the federal and state taxes, is \$0.51 per gallon.
Compressed natural gas	The average tax, which includes the federal and state taxes, is \$0.42 per Gasoline Gallon Equivalent (GGE). There is also a tax credit of \$0.5 per GGE.
E85 (15% gasoline and 85% ethanol blend)	The average tax, which includes the federal and state taxes, is \$0.42 per GGE. There is also a tax credit of \$0.45 per GGE.
E90 (10% gasoline and 90% ethanol blend)	The average tax, which includes the federal and state taxes, is \$0.42 per GGE. There is also a tax credit of \$0.45 per GGE.
Biodiesel (20% biodiesel and 80% diesel blend)	The average tax, which includes the federal and state taxes, is \$0.51 per GGE. There is also a tax credit of \$1 per GGE.
Electricity	Electricity is subject to a (state) sales tax, which is, on average, 6% of the pre-tax price.
Hydrogen	The average tax, which includes the federal and state taxes, is \$0.42 per GGE. There is also a tax credit of \$0.50 per GGE.
GCHEVs and EVs	Consumers receive federal vehicle purchase tax credits ranging from \$2,500 to \$7,500 (\$417 per kWh) according to the battery size (from 6kWh onwards). We assume GCHEVs receive a purchase tax credit of \$2,500 and EVs receive a purchase tax credit of \$7,500.

Source: US Department of Energy, Federal and State Incentives and Laws (http://www.afdc.energy.gov/afdc/laws/matrix/incentive) and IRS 720 form (http://www.irs.gov/pub/irs-pdf/f720.pdf)

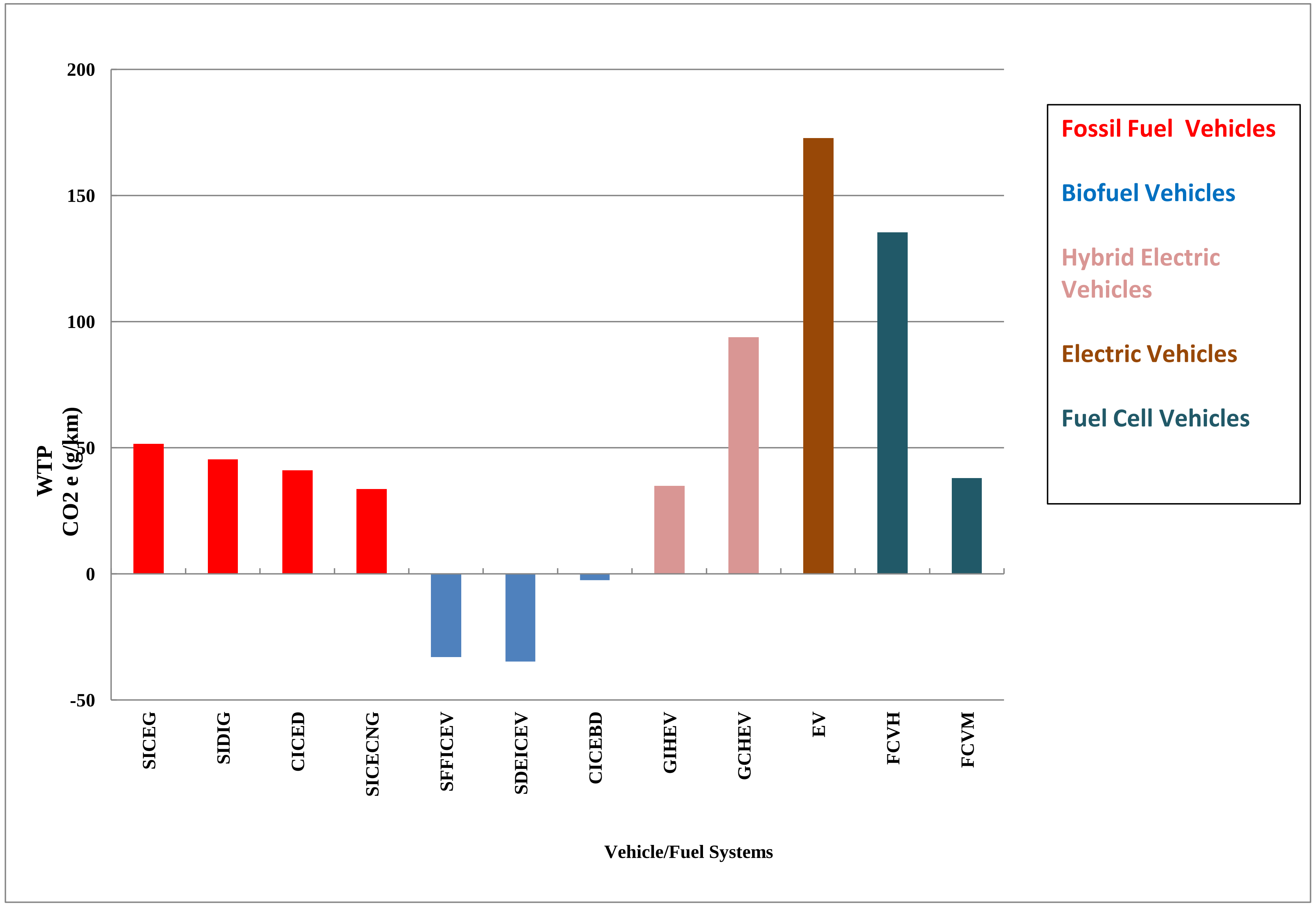
Note: Gasoline Gallon Equivalent is essentially the amount of compressed natural gas, E85, E90 or any alternative fuel it takes to have the energy content of one gallon of gasoline.

Table 4: Possible policies under a 6% and 60% discount rates

	No tax change			Gasoline and diesel tax increases to $1		
	PVC breaks even in			PVC breaks even in		
	10 years	6 years	2 years	10 years	6 years	2 years
60%						
GIHEV	2,569	2,609	2,853	2,425	2,472	2,763
GCHEV	5,945	6,006	6,381	5,724	5,796	6,242
EV	12,719	12,803	13,289	12,274	12,380	13,009
CICEBD	1,884	1,894.5	1,970	1,439	1471	1,691
SDEICEV	343	358	449	-102	-65	169
6%						
GIHEV	435	1,296	2,515	-96.5	909	2,356
GCHEV	2,672	3,993	5,863	1,856	3,398.5	5,618
EV	8,355	10,195.5	12,650	6,712	4,9760	12,157
CICEBD	1,258	1,482	1,858	-385	285	1,365
SDEICEV	-362.5	-30	432.5	-2,005.5	-1,227	-60

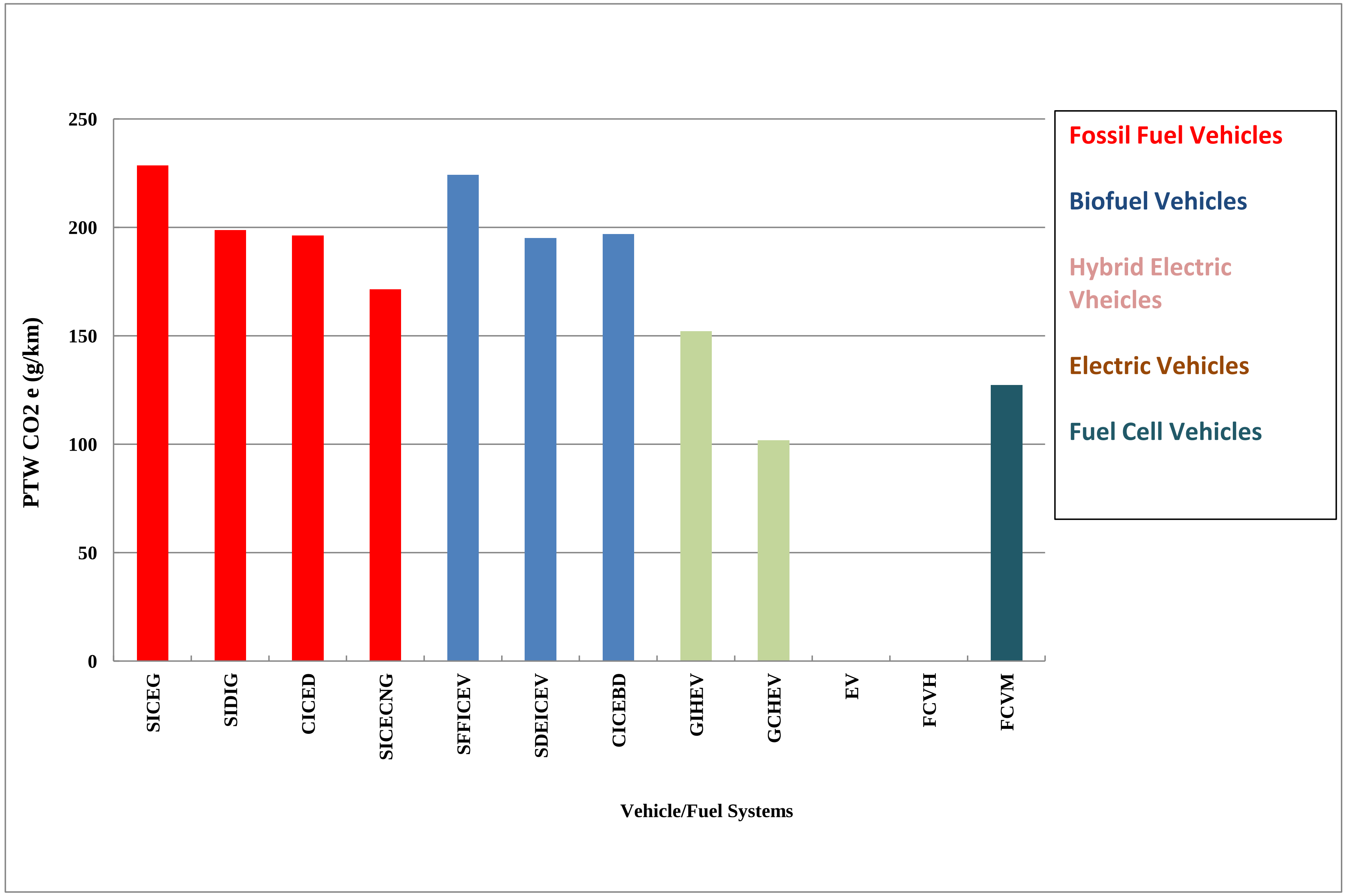
Note: Positive numbers are subsidies. Negative numbers are taxes. All current taxes and tax credits, summarised in Table 4, stay the same except for the vehicle subsidies proposed here and the gasoline and diesel taxes, which are increased to 1$/gallon. We do not include external costs in the calculations for two reasons: first, consumers do not include them and most importantly, we have already showed that these are negligible in any case.

Figure 1: Well-to-Pump CO2e emissions in the US for 2020



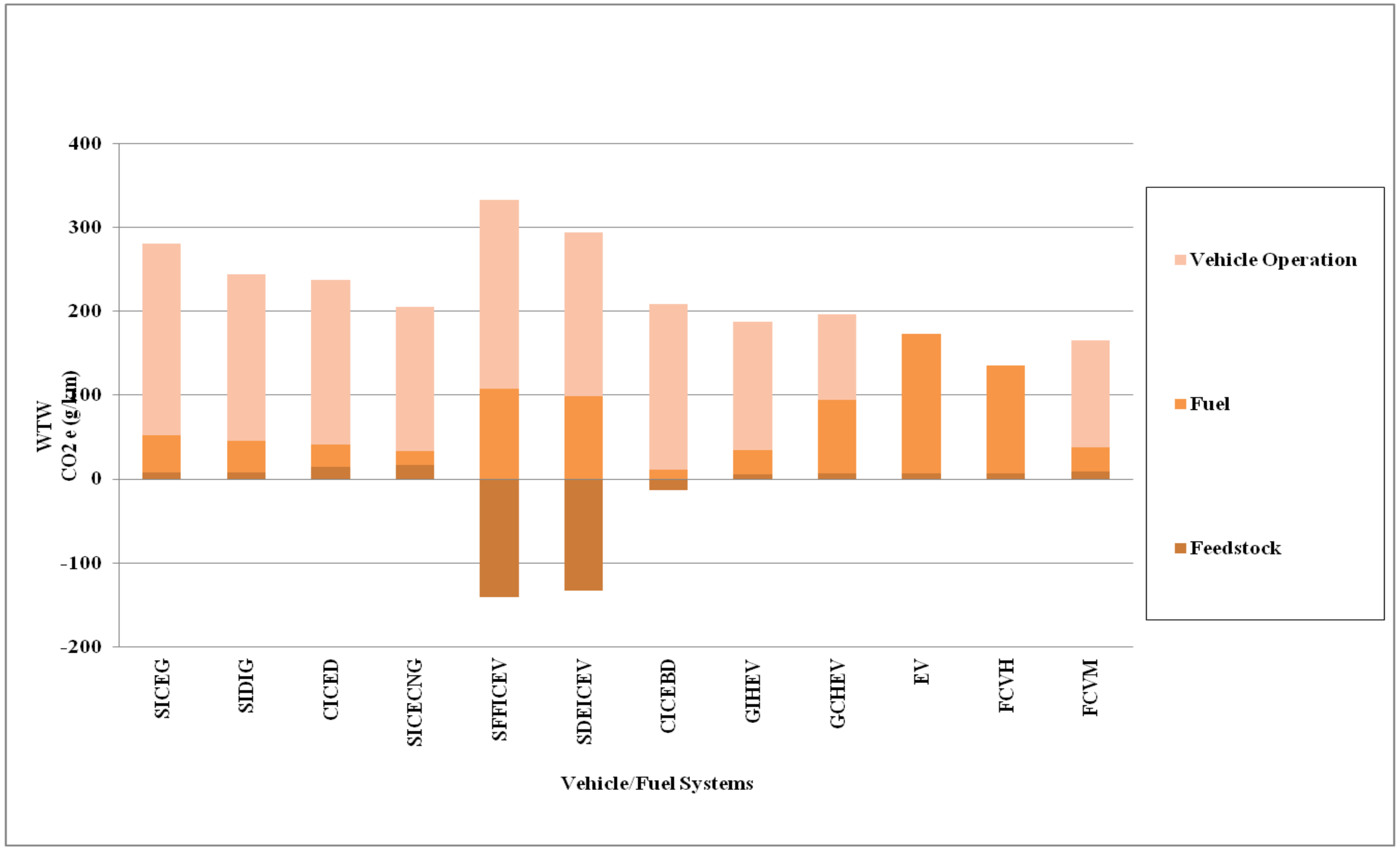
Source: estimates produced by GREET 1.8b

Figure 2: Pump-to-Wheel CO2e emissions in the US for 2020



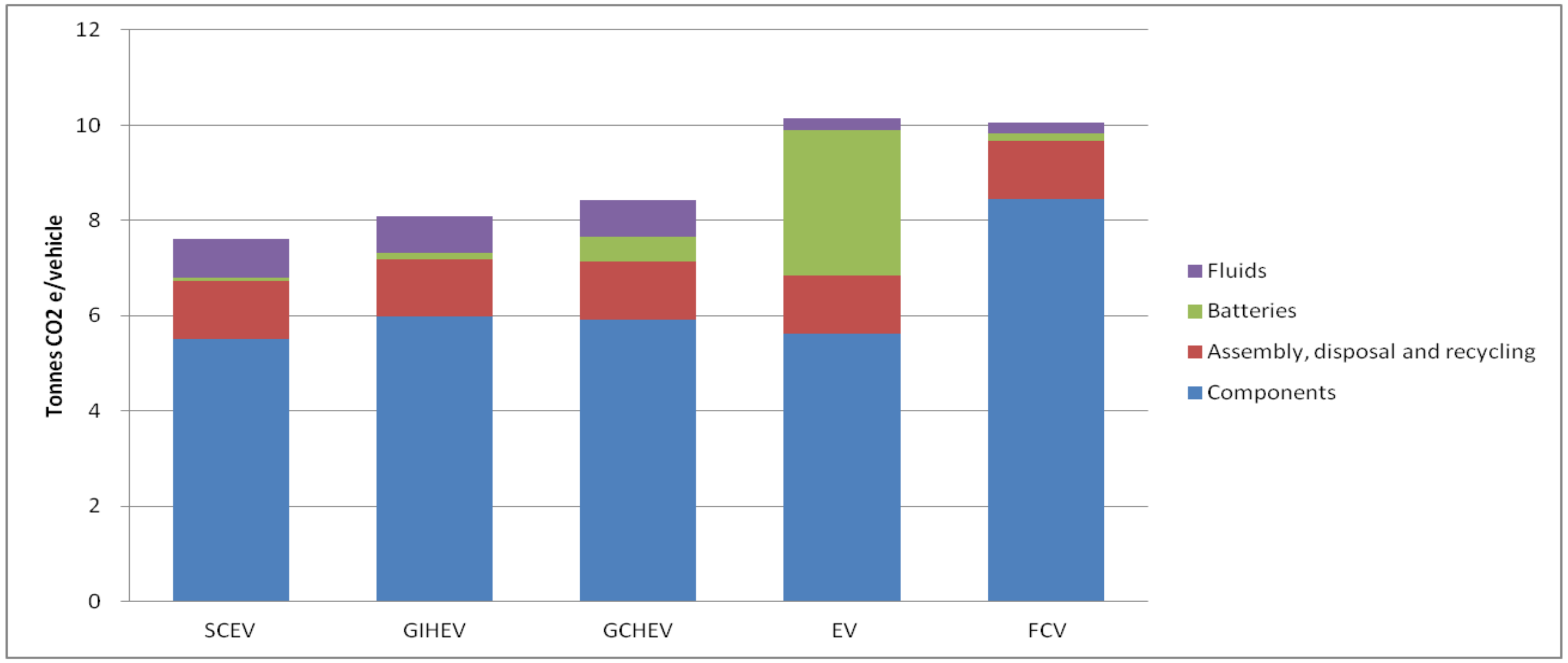
Source: estimates produced by GREET 1.8b

Figure 3 Well-to-Wheel CO2e emissions in the US for 2020



Source: estimates produced by GREET 1.8b

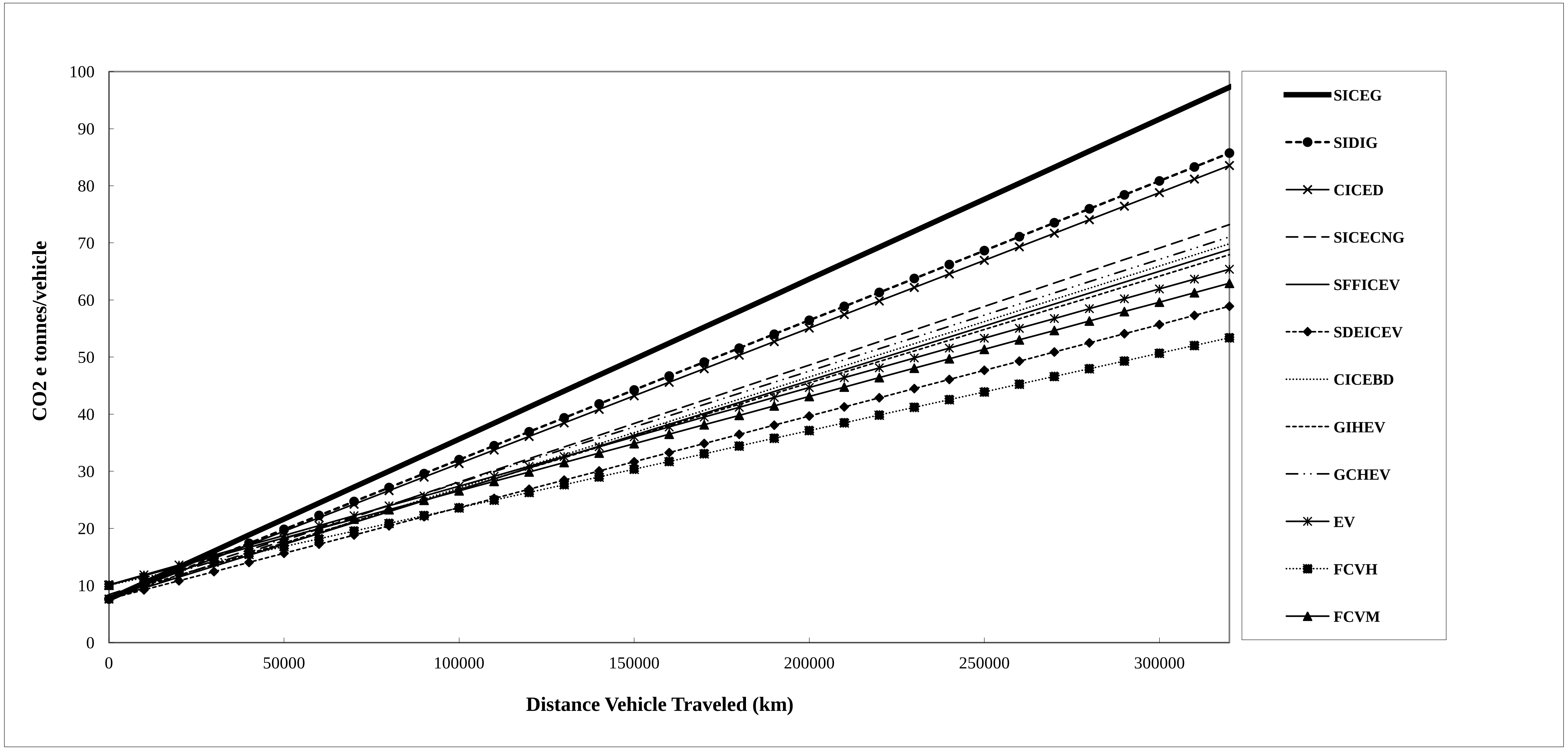
Figure 4: Vehicle lifecycle CO2e emissions in the US for 2020



Source: Values taken from GREET 2 database

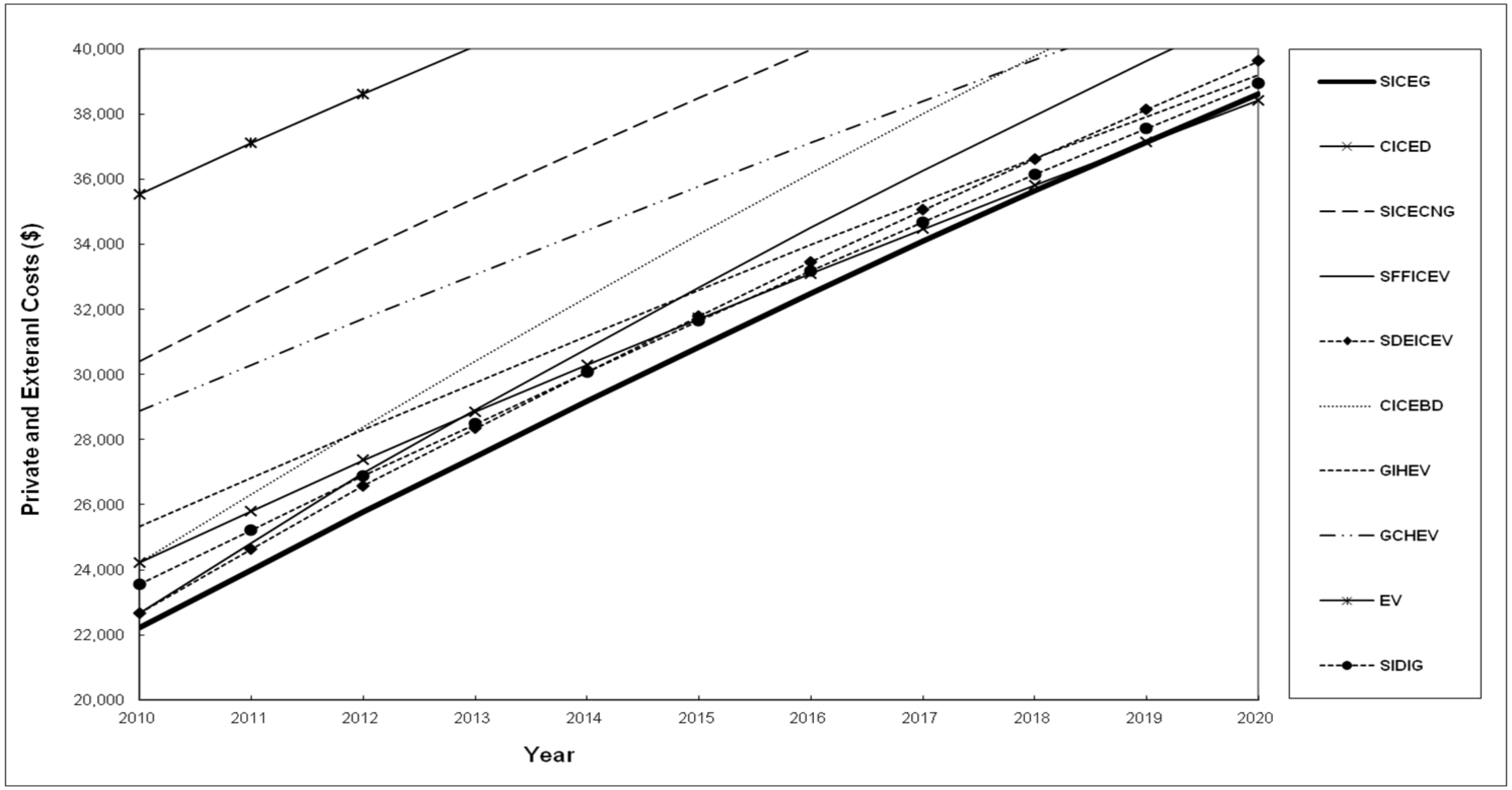
Source: see text

Figure 5: Integrated CO2e emissions from different vehicle/fuel systems in the US for 2020 (including both vehicle and fuel lifecycles)



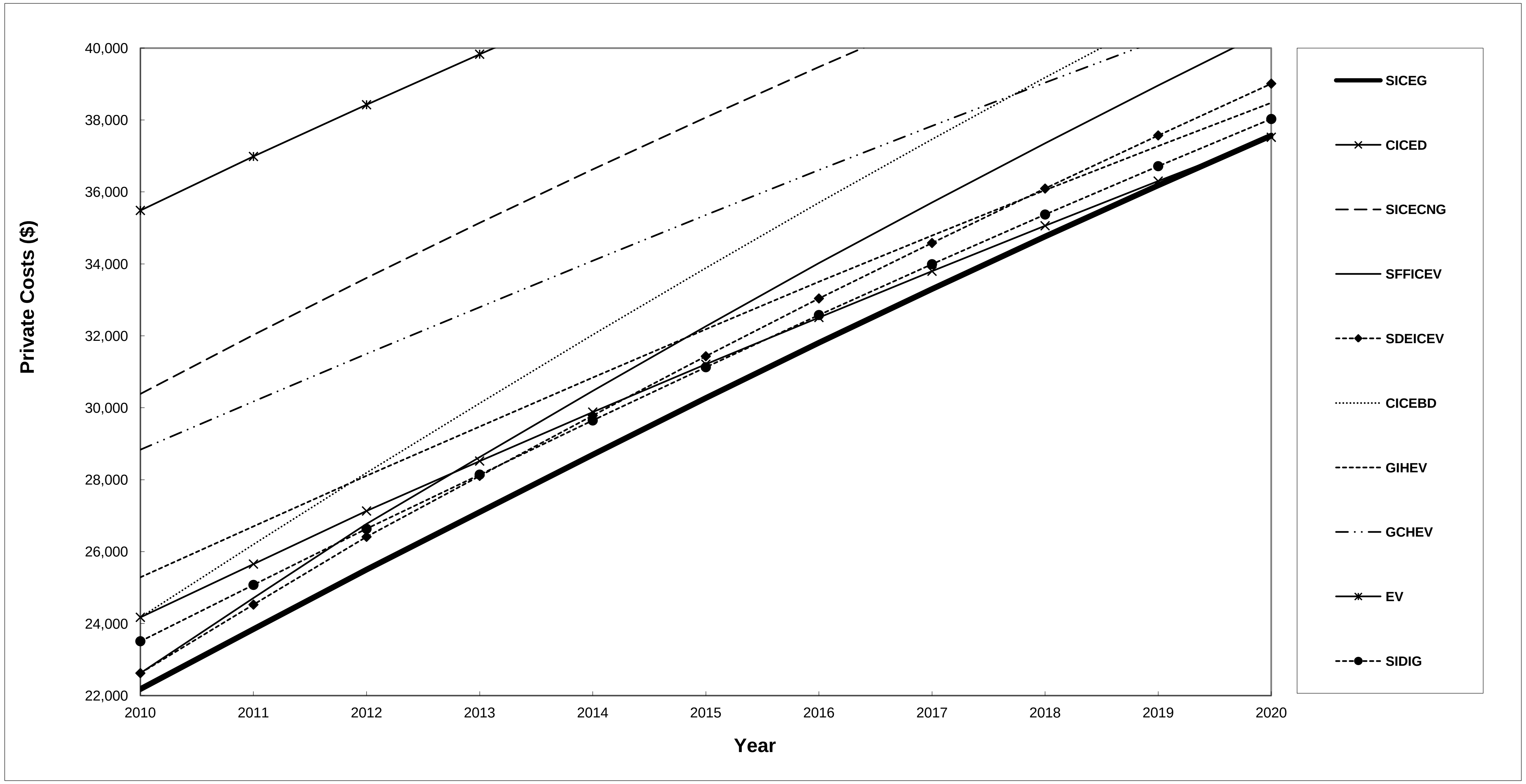
Source: Figures 3 and 4 of the present paper

Figure 6: Breakeven points including private and environmental costs (excluding all taxes and subsidies)



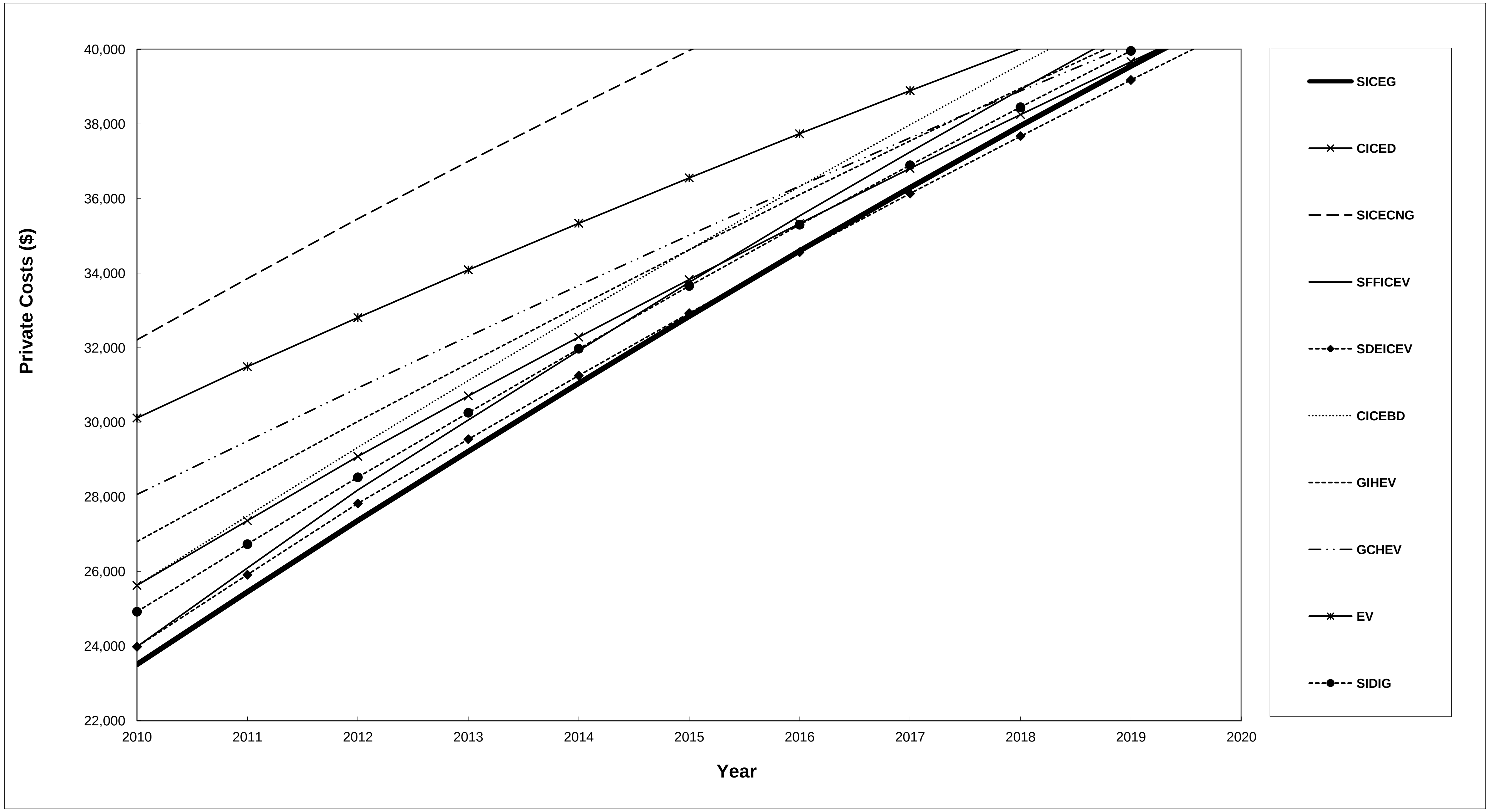
Source: see text

Figure 7: Breakeven points including private costs only (excluding all taxes and subsidies)



Source: see text

Figure 8: Breakeven points including private costs only (and including taxes and subsidies from Table 3)



Source: see text