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ANALYSIS

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Moving beyond alternative fuel hype to decarbonize transportation

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In the past three decades, government, industry and other stakeholders have repeatedly been swept up with the 'fuel du jour', claiming that a particular alternative fuel vehicle (AFV) technology can succeed in replacing conventional gasoline-powered vehicles. However, AFV technologies have experienced relatively little success, with fossil fuels still accounting for about 95% of global transport energy use. Here, using the US as a case study, we conduct a media analysis to show how society's attention has skipped among AFV types between 1980 and 2013, including methanol, natural gas, plug-in electric, hybrid electric, hydrogen and biofuels. Although our results provide no indication as to whether hype ultimately has a net positive or negative impact on AFV innovation, we offer several recommendations that governments can follow to move past hype to support significant AFV adoption and displace fossil fuel use in the transportation sector.

The transport sector accounts for roughly one quarter of global energy-related carbon dioxide emissions[1]. Although transport greenhouse gas emissions can be cut by improving the efficiency of conventional vehicles and reducing travel demand, deep decarbonization inevitably requires a substantial shift to alternative fuels such as electricity, hydrogen or biofuels. For example, the International Energy Agency suggests that to stabilize CO_2 concentrations at 450 ppm, 40% of new vehicle sales globally must be plug-in electric by 2040, with most remaining vehicles fuelled by biofuels[2]. Another study finds that 90% of California's vehicle travel must be powered by alternative fuels in 2050 to meet targets to cut greenhouse gas emissions by 80% (ref. 3).

To support objectives related to climate change mitigation, air pollution and energy security, numerous governments have set specific goals for the market adoption of AFV technologies. In the US, President G.H.W. Bush proposed regulations that would require 500,000 methanol vehicles by 1996 (ref. 4); President G. W. Bush set a goal of commercializing cellulosic ethanol production by 2012 (ref. 5); and President Obama set a goal of one million electric vehicles by 2015 (ref. 6). None of these goals were achieved. Fossil fuels still account for 95% of US transport energy use[7]. As of 2014, the only two AFV technologies to achieve substantive new market share in the US are hybrid electric vehicles (3%) and ethanol flex-fuel vehicles (12%; ref. 8). However, both of these AFV types rely on fossil fuels, and in the US flex-fuel vehicles most commonly fill up with conventional gasoline (biofuels account for only 5% of transport energy use, mostly as a 10% blend)[7]. Thus, despite numerous promises, targets and funding efforts, AFV technologies have experienced relatively little success. And when a particular AFV technology has failed to meet initially positive expectations, society has turned its attention to another AFV type and a new cycle of hype and disappointment has begun.

In this Analysis, we contribute to science and technology studies by using the US as a case study to explore the prevalence of hype and disappointment cycles for several AFV technologies. In describing these dynamics across the spectrum of AFV technologies, it is beyond our scope to richly discuss policy narratives and how they influence and are influenced by hype dynamics[9,10]. Instead, we take a more descriptive approach. We find that media coverage, a proxy for societal attention, has skipped among AFV technologies between 1980 and 2013, beginning in the US with methanol and natural gas in the 1980s, transitioning to plug-in electric vehicles in the 1990s, followed by hybrid electric, hydrogen and biofuels in the early 2000s. Most recently, attention has returned to plug-in electric vehicles. Similar, although not identical, sequences of 'fuels du jour'[11] prevailed in other countries, as revealed by global patent[12] and prototype[13] data, as well as European media[14,15]. Each wave of media attention is associated with rising and then falling expectations, or hype and disappointment. Our data sources enable us to present a relatively rich historical narrative, with the goals of increasing awareness about the history of hype cycle dynamics among AFV technologies and identifying recommendations for policymakers and other key stakeholders that genuinely want to achieve a transition to low-carbon transportation technology.

Expectations and the notion of hype

We draw on the sociology of expectations to describe and understand the repeated patterns of excitement, failure and disappointment for numerous AFV technologies observed over the past three decades. The sociology of expectations, which considers the significance of expectations in science and technology innovation, has identified hype and disappointment as an important dynamic across numerous fields, such as medical techniques and information and communications technologies[16]. Hype can be defined as a period of rising public attention and expectations about the potential of a new innovation[17]. This conceptualization differs from the colloquial definition of hype, which often implies the setting of implausible expectations[17,18], which is typically thought to be undesirable. In contrast, we are interested in identifying and describing patterns of shifting expectations, which may or may not have a net positive or negative effect on technological transformation.

Figure 1 presents one stylized representation of hype that builds on that presented by Fenn and Raskino[19]. The origins and dynamics of hype are complex, reflecting the development of collective expectations shaped by industry, government and other actors[20]. The beginnings or continuation of a hype may or may not involve technology breakthroughs (for example, the discovery of a new fuel cell manufacturing process) or policies (for example, an increase

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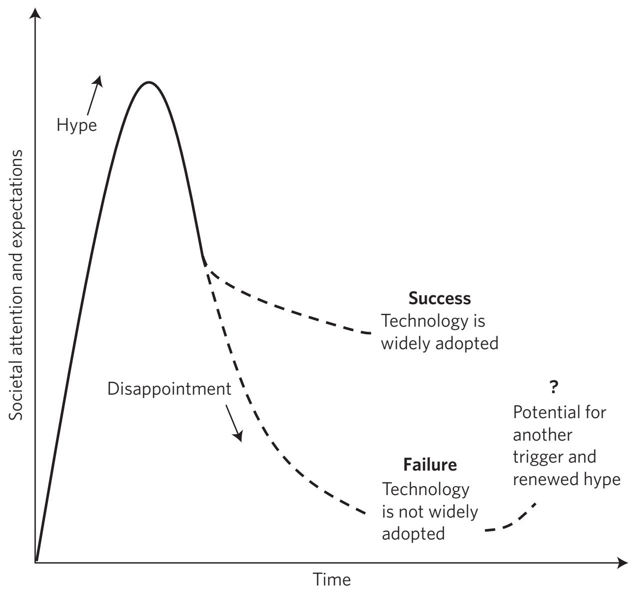

Figure 1 | Graphical representation of emerging technology hype. Our stylized representation of hype and disappointment is based on concepts presented in Fenn and Raskino[19], describing how a range of patterns is possible in which technologies may ultimately succeed or fail, and cycles of hype and disappointment can repeat over time. The core dynamic is that societal expectations actively create a new reality by guiding discourse and innovation activities. On the one hand, hype can play an important role in supporting successful innovation activities by legitimizing investments and encouraging innovators to coordinate efforts and generate knowledge. On the other hand, greatly raising expectations may create an impossible target for innovation and increase subsequent perceptions of disappointment. If this happens, renewed hype is always possible at a later date. Adapted from ref. 19, Harvard Business Press.

in funding for fuel cell research) that attract interest in that technology. Innovation stakeholders such as scientists, industry and governments inflate and communicate positive expectations or technological promises to attract attention and resources[21–24]. Collectively, the optimistic promises and expectations of industry, government agencies, political leaders and the media become part of the social discourse, creating an incentive for an even greater number of stakeholders to promote the technology and further contribute to the hype (raising expectations further still). Research suggests that there can be particularly strong incentives for stakeholders to raise expectations for technologies that require the build-up of new infrastructure, such as hydrogen fuel cell vehicles (that require the development of hydrogen production, storage, and refuelling stations)[25].

Hype can play an important role in supporting successful innovation activities, but over-inflated expectations may increase the chance of failure. Shared optimistic expectations can help to legitimize investments and encourage innovators to coordinate efforts and generate knowledge[20,25–27]. In some instances, hype may therefore help a technology become widely adopted, as shown by the top path in Fig. 1. On the other hand, greatly raising expectations may create an impossible target for innovation, harming the reputation of the technology and its developers, hampering sustained resource mobilization, and in some cases leading to abandonment of innovation activities[21,26,28]. Over-inflated expectations may therefore contribute to the likelihood of a technology not becoming adopted at all, as shown by the bottom path in Fig. 1. In such cases, renewed hype is always possible at a later date.

In addition to the automotive industry, governments and policymakers are thought to be at least partially responsible for 'inflaming successive cycles of hype and disappointment' (p225; ref. 26). For example, policymakers have at times set short-sighted and overly optimistic policies and sales targets for new alternative fuel vehicle technologies, with little or no acknowledgements of previous technological disappointments. Furthermore, relative to other actors, governments are typically in a unique position to address several of the major 'failures' described by Weber and Rohracher[29] that prevent major technological transitions or transformation. In addition to market failures such as negative environmental externalities and knowledge spillover (which both make pro-environmental innovations less likely to succeed), 'system' failures include directionality failure, the lack of shared expectations about the goals of technological development, and insufficient regulation, standards, or funding for research to guide this development. Also relevant is reflexivity failure, the lack of adaptiveness in policy design, and inability or unwillingness to deal with uncertainty, as is common with technological change[29]. To more effectively support a successful transition to AFV technology, governments can at least avoid contributing to excessive hype (although that is difficult to measure), and even more pro-actively could contribute to establishing a more long-term, stable, adaptive and plausible vision of transition[30,31].

Constructing a history of hype and disappointment

Our analysis summarizes mass media coverage, innovation activity[13] and US Department of Energy (DoE) funding[32] over the past three decades for several key AFV technologies: plug-in electric vehicles (PEVs), which include both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), biofuels (ethanol and biodiesel, produced by conventional means as well as advanced methods from non-food feedstock), hydrogen (combustion and fuel cell), hybrid electric vehicles (HEVs), methanol and natural gas. Although we collect data for all these technologies, we focus our review here on plug-in electric, hydrogen- and biofuel-powered vehicles, because they have the greatest potential to contribute meaningfully to deep decarbonization (that is, their source-to-wheel greenhouse gas emissions could approach zero). Furthermore, although we focus our analysis on the United States as a case study, we note that owing to the global nature of the automotive industry, many of the observed dynamics are likely to be relevant to other countries and regions[33].

We use a media analysis to explore articles in the *New York Times* and identify periods of AFV hype (see Methods for details). We define hype as a period with a rising number of media articles containing a growing share of positive evaluations about a particular technology, following Ruef and Markard[17] and van Lente, Spitters and Peine[18]. We developed a coding guide to help identify evaluative statements in each article, which were coded as positive or negative. The sum of positive minus negative statements (that is, net positive statements) provides an indication of societal expectations, or hype. The *New York Times* was chosen because of the paper's national coverage, high circulation and reputation; it has also been similarly used in other media analyses exploring hype cycles[34] and AFVs[35]. Before conducting the study, we compared trends in media coverage of each AFV technology in the *New York Times* with those from the Wall Street Journal and USA Today—two of the other top circulating newspapers in the US—finding a high degree of similarity.

For each AFV hype, we review the relevant articles to identify key policy and technology events, including the implementation of or changes to policies that directly influence AFV development in the US, as well as industry announcements regarding the release of AFV models. We subjectively select the events that we perceive to be widely accepted (among AFV researchers and policy analysts) as potentially influencing or being influenced by the observed hypes, disappointments or transitions. Identification of these events is meant to assist with interpretation of each hype pattern; owing to

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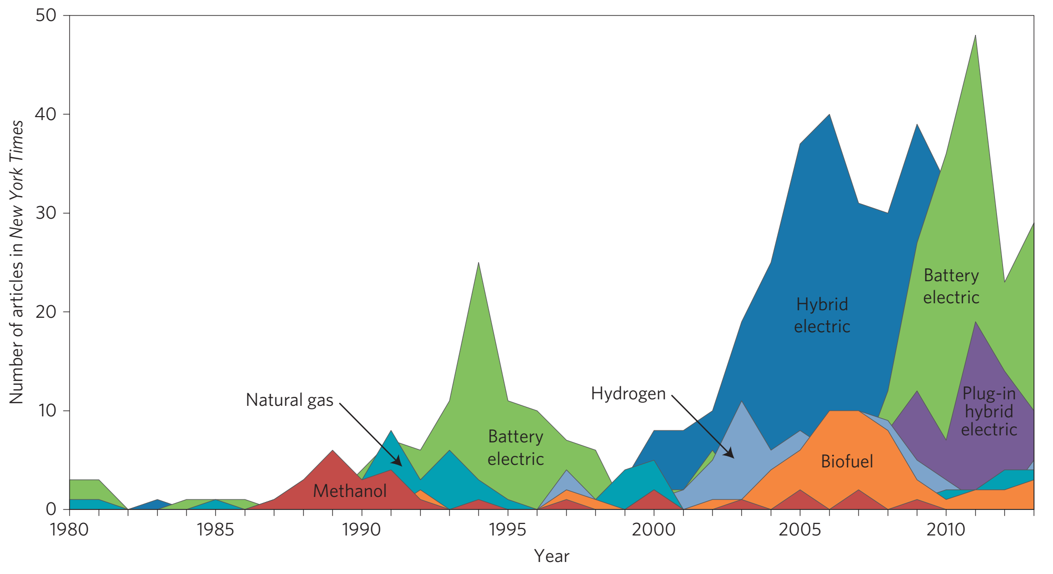

Figure 2 | Media attention for all alternative fuel vehicle technologies for 1980–2013. Media attention skipped among numerous AFV technologies between 1980 and 2013. These waves of attention are indicative of sequential and repeated shifts in society's focus from one emerging technology to another over time.

the complex nature of these histories we cannot comment on the relative importance of each event, and we may omit events that other scholars or stakeholders believe to be important. We also depict the amount of funding provided by the US Department of Energy for each AFV type as further indication of government action during these cycles. Finally, to provide further context we depict the number of AFV prototypes developed by the world's 15 largest auto manufacturers, as identified by Sierzchula and colleagues[13]. Prototype development provides a gauge of industry participation in hype cycle dynamics, whether it is in terms of actual innovation or symbolic action[25]. We define prototypes as vehicles that are not intended for commercial production, but rather to demonstrate and sometimes bring attention to new technologies and designs. By contrast, a production model is manufactured in quantity and sold or leased to consumers. We make no a priori hypotheses for what the relationship between these three measures might be, or in what order their respective dynamics might occur—although we presume that all three are generally more likely to increase as societal expectations (hype) increase.

A brief history of AFV hype in the US

Societal attention skipped from one AFV technology to the next in successive waves between 1980 and 2013 (see Fig. 2). The total number of articles written about all AFV technologies rose from an average of two annually between 1980 and 1985, to 80 annually between 2008 and 2013. Furthermore, the share of all *New York Times* articles about AFVs rose from 0.02 to 0.4%, suggesting that AFV technology in general has increased in importance in societal discourse. The first substantial waves of media attention became apparent in the late 1980s and early 1990s, related to methanol, natural gas and then PEVs. Later hypes related to HEVs, hydrogen, biofuels, and most recently PEVs once again. Below, we discuss the hypes observed for PEVs, hydrogen and biofuels, which are also summarized in Fig. 3 and Table 1. Additional information describing the media analysis results are presented in Fig. 4 and Fig. 5.

The first electric car hype. In 1990, General Motors unveiled its prototype electric car, the Impact. That same year, California announced its Zero Emission Vehicle (ZEV) mandate, requiring that zero-emission vehicles (as measured at the tailpipe) account for 2% of sales by each automotive firm operating in the State by 1998. At the time only PEVs were thought viable for compliance.

Following these events, media coverage grew from an average of one article per year in the 1980s to 25 in 1994 (Fig. 4), greatly exceeding preceding coverage of methanol and natural gas. Media coverage also became increasingly positive during this time (Fig. 5), including optimistic quotes such as the New York Times' declaration that 'the electric-car future is not far off'[36]. Aligning with hype in the media, the number of PEV prototypes rose, with 14 models presented to the public between 1990 and 1995 (Fig. 3). Over this same period, US DoE funding for PEV technology increased from US$17 million to US$102 million per year. However, these trends lasted only a few years. In 1996, a group of auto manufacturers successfully lobbied the California government to relax and delay the ZEV mandate. Although General Motors released the EV-1 (the production version of the Impact prototype) in that same year, barely 1,000 of these vehicles were produced, most of which were later recalled and scrapped[37]. The release of PEV prototypes by major auto manufacturers wound down and ceased in 1999. US DoE funding fell by half between 1995 and 2003.

The hydrogen hype. When it became clear that the ZEV mandate could not easily be met by electric batteries, auto manufacturers and government began investing in hydrogen and fuel cell technology. In 1999, DaimlerChrysler, Ford and General Motors announced that each would have hydrogen-powered vehicles for sale by 2004 (ref. 38). In 2001, Toyota and Honda made similar announcements. Two years later, California amended its ZEV mandate to include a new fuel cell vehicle 'alternative compliance path', and President George W. Bush proposed US$1.3 billion in research funding for hydrogen vehicles, stating that '...the first car driven by a child born today could be powered by hydrogen, and pollution-free'[39].

Interestingly, increases in hydrogen prototypes preceded peaks in media coverage and positive evaluations, with an average of 15 prototype vehicles presented to the public annually between 1999 and 2003 (Fig. 3). Media coverage increased from an average of less than one article per year during the 1990s to a peak of 11 by 2003, with continued high coverage through to 2008 (Fig. 4). The number of net positive statements particularly increased in the latter portion of this hype, from 2004 to 2007 (Fig. 3). US DoE funding for hydrogen and fuel cells strongly aligns with these

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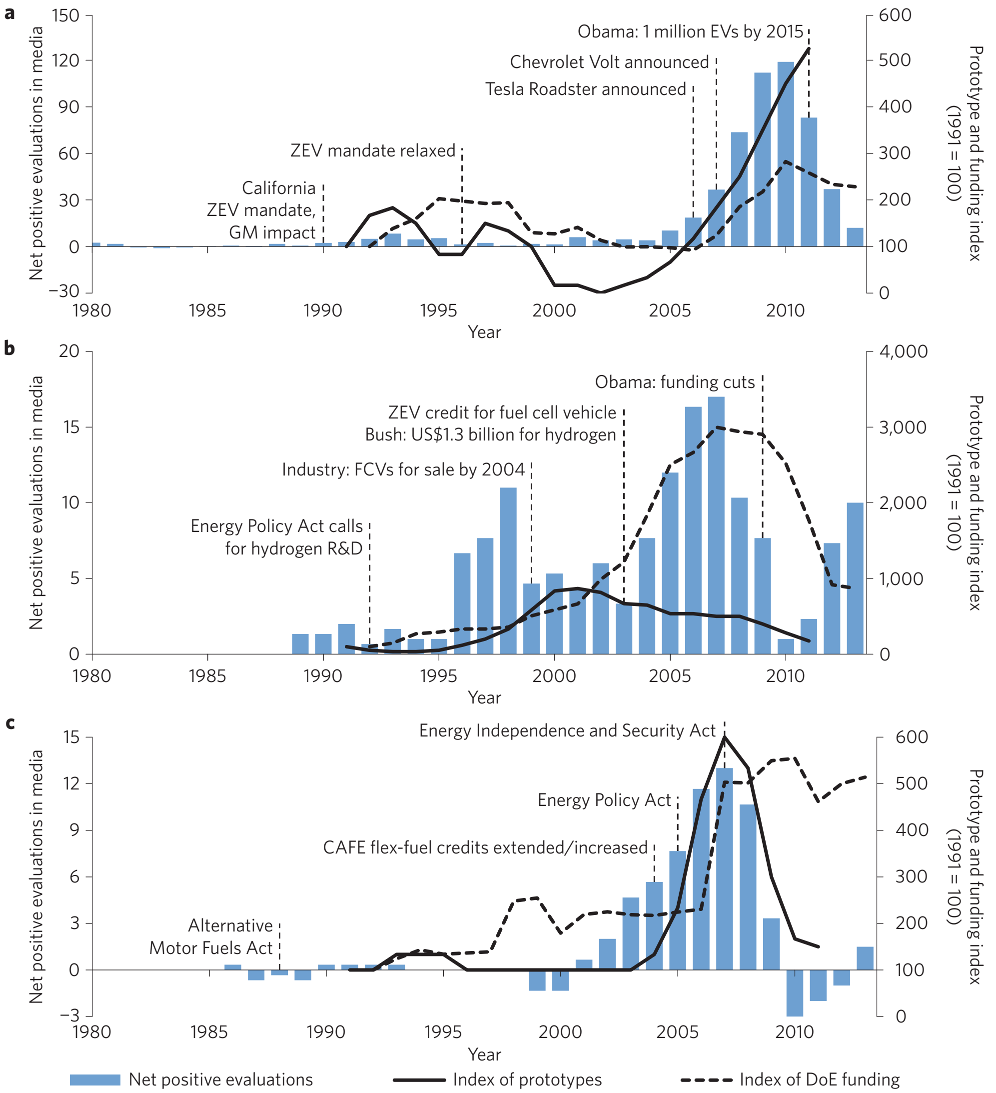

Figure 3 | Hype and disappointment cycles for select AFV technologies. Trends in societal expectations and innovation are indicative of at least one period of hype for each technology for which we have data, including plug-in electric vehicles (**a**), hydrogen (**b**) and biofuels (**c**). Societal expectations are measured based on the number of positive minus negative evaluations observed in the media (left axis). Vehicle prototypes are used as a proxy for innovation, which is shown on the right axis as well as research and development funding provided by the US Department of Energy. Key events are also included.

media trends, increasing fivefold between 2000 and 2007, from US$65 million to US$330 million annually (Fig. 3). However, hype as observed in media coverage dropped after 2007, coinciding with the second wave of renewed PEV hype. In 2009 the US Secretary of Energy, Steven Chu, told Congress that hydrogen cars were unlikely to be deployed on a mass market scale within the next 20 years[40]. The number of new prototype announcements gradually decreased to only 2 in 2011, and by 2013 US DoE funding fell to less than one-third of 2007 levels. Up to 2013, the hydrogen hype had resulted in virtually no hydrogen light-duty vehicles reaching the market. Possibly signalling a renewal of hydrogen hype, in 2013 seven major automotive firms promised fuel cell cars within the next few years (including Hyundai, Toyota and Ford)[41]. As of 2015, Hyundai and Toyota had begun leasing a limited number of hydrogen vehicles in the US[42].

The biofuels hype. The biofuel hype lasted from 2004 to 2008, as shown in Fig. 3. In 2004, the US Department of Transportation extended and increased the credits available for flex-fuel vehicles (those that can be powered by gasoline or a blend with up to 85% ethanol) under the Corporate Average Fuel Economy (CAFE) regulations. In 2005 the US Energy Policy Act eliminated an incentive for gasoline refiners to use methyl tertiary butyl ether (MTBE, which improves combustion and reduces air pollution) because of concerns that when leaked it contaminated groundwater[43]. Instead, the Act required 7.5 billion gallons per year of renewable fuel to be blended into gasoline by 2012, which in practice meant mostly ethanol from corn.

During the biofuel hype, media coverage increased from one article in 2003 to 20 in 2006 and 2007 (Fig. 4), and the number of net positive evaluation statements increased in every year from 2002 to 2007 (Fig. 5). In 2006 President George W. Bush touted ethanol as a means to reduce reliance on oil imports from the Middle East, declaring a goal of making advanced ethanol production (for example, cellulosic ethanol) competitive within six years[5]. US DoE funding for biomass and biorefinery systems more than doubled from US$90 million in 2006 to US$196 million in 2007. The number of flex-fuel prototypes increased from one in 2005 to seven in 2007, and by 2011 these vehicles made up 12% of new light-duty vehicle sales[8]. Although these sales were the highest ever for any AFV technology

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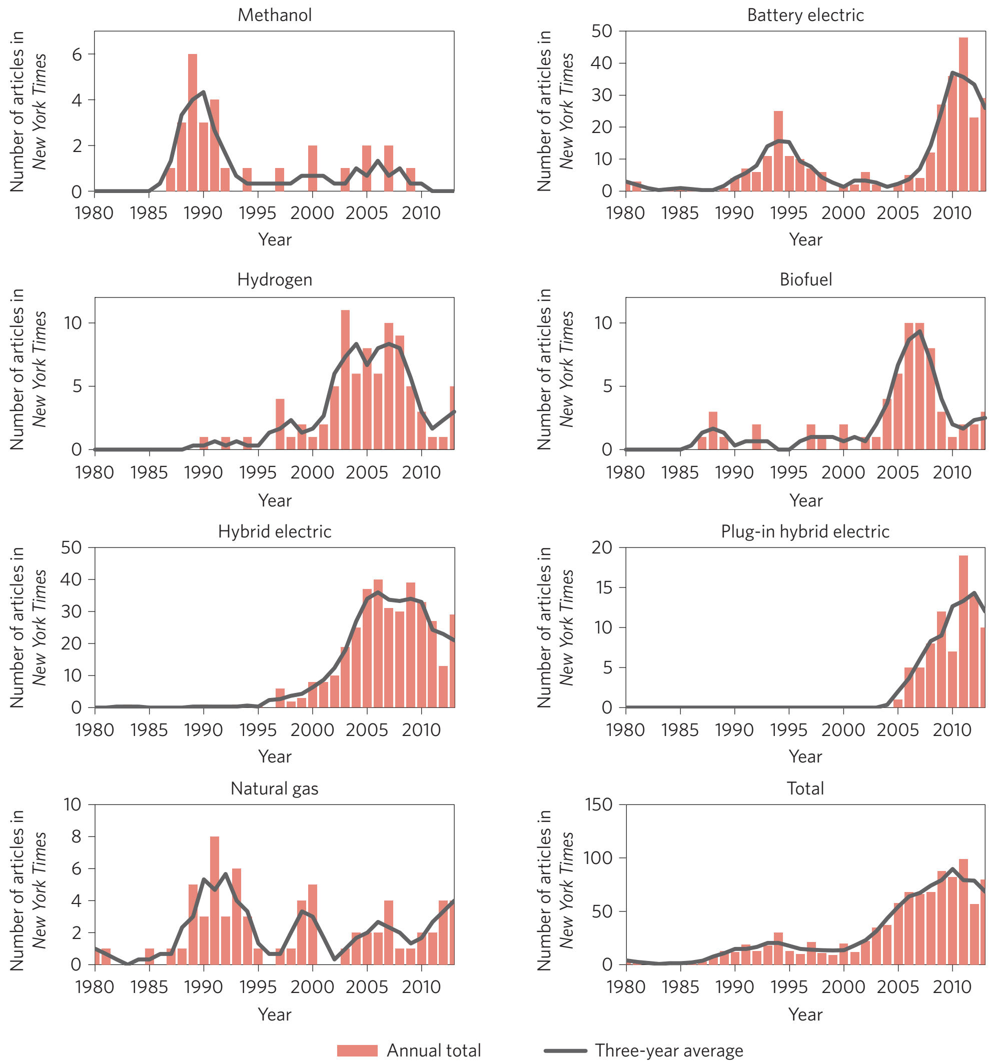

Figure 4 | Media attention for each alternative fuel vehicle technology for 1980–2013. The annual total and three-year average of media articles is shown for each AFV technology.

in the US, in practice the vast majority of them are fuelled with conventional gasoline, with biofuels accounting for only 5% of total US transport fuel use in 2014, and almost all of this is as 10% blends in gasoline[7]. Furthermore, advanced biofuels such as the cellulosic ethanol targeted by President George W. Bush in 2006, which could be more helpful for achieving deep decarbonization, accounted for only a fraction of a percent of motor gasoline sales in 2014 (ref. 44). After 2008, media attention and prototype development dropped significantly, although US DoE funding for biorefinery systems remained stable at around US$200 million annually.

The second electric car hype. After a lull in media attention lasting about a decade, a second PEV hype emerged after 2005. The beginning of this hype aligned with announcements by several automotive firms of forthcoming releases of PEV production models, including the Tesla Roadster (announced in 2006) and Chevrolet Volt (2007). Soon after, California amended its ZEV mandate to provide increased credits for plug-in hybrid electric vehicles starting in 2012 (ref. 45).

This second PEV wave yielded the largest US hype cycle observed in the 1980–2013 study period. Media coverage grew from an average of three PEV-related articles per year in 2000–2005 to a peak of 67 in 2011 (Fig. 4), while the number of net positive evaluation statements steadily increased until 2010 (Fig. 5). US DoE funding tripled between 2006 and 2010, reaching US$142 million annually. In 2009, President Obama announced US$2.4 billion in stimulus funds for electric vehicles and battery development, and two years later he declared that the US could 'become the first country to have a million electric vehicles on the road by 2015' (ref. 6). The number of PEV prototypes released increased from three between 2000 and 2005 to 27 between 2006 and 2010, and more than 20 production models were released by more than a dozen automakers from 2010 to 2013.

Although societal attention to PEVs remained high through 2013, it is too early to consider PEVs a 'success'. In 2013, President Obama and the DoE backed off the goal of putting one million vehicles on the road by 2015 (ref. 46). As of 2014, PEVs accounted for only 0.7% of new light-duty vehicle sales in the US, with higher market share in some US regions (for example, 3.0% in California) and in a few other countries (for example, close to 18% in Norway)[47]. In the media coverage, we observe an increasing number of negative evaluations of PEVs after 2010, relating to high vehicle cost, low sales and specific incidents of post-impact fires involving PEVs. Thus, the outcome of the second PEV hype is not yet clear.

Moving beyond hype to decarbonization transportation

Applied to this US case study, our analysis reveals numerous and repeated cycles of hype and disappointment since the late 1980s

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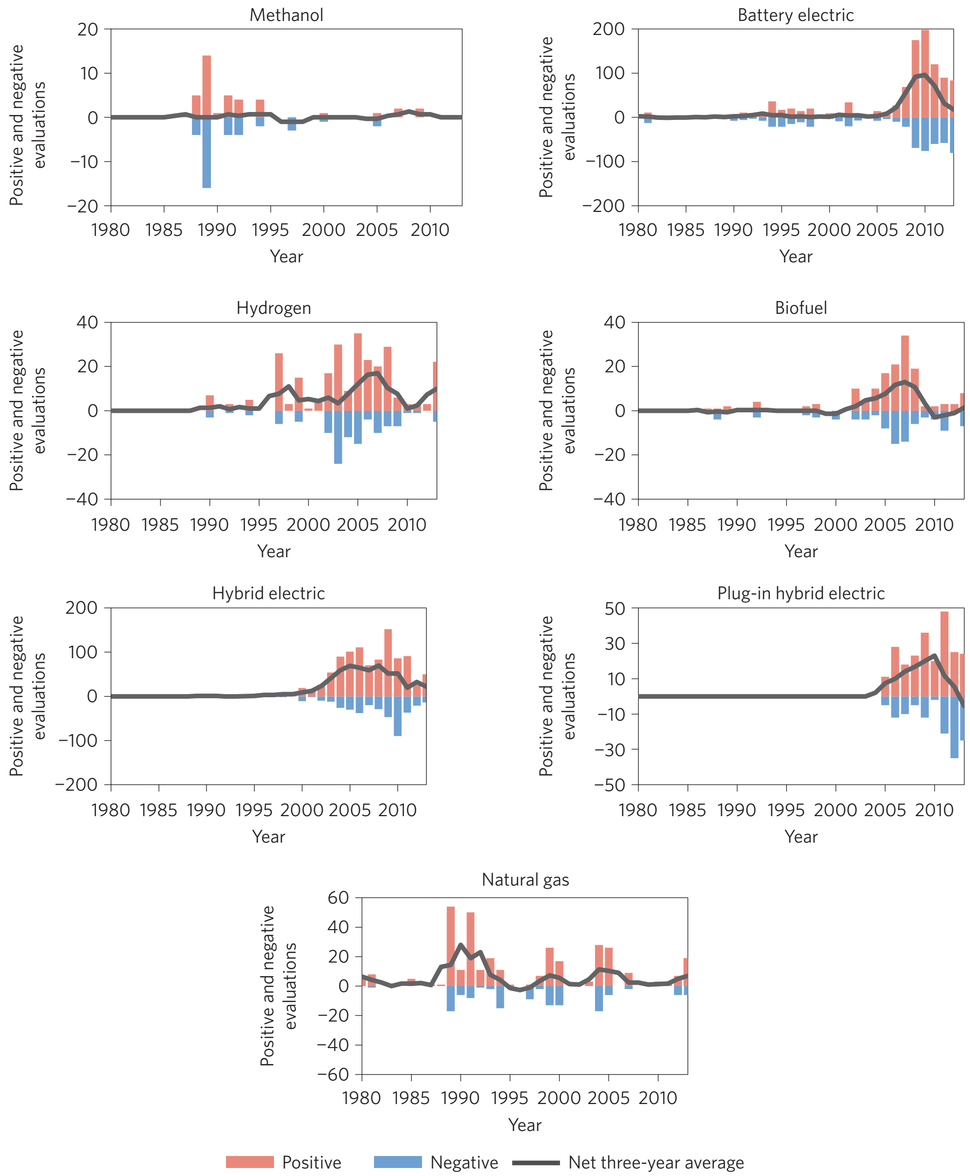

Figure 5 | Positive and negative evaluations for each alternative fuel vehicle technology. Trends in positive (red) and negative (blue) evaluations reveal shifts in societal expectations about AFV technologies over time. The solid grey line represents a rolling three-year average of net positive evaluations, which is an indicator of the overall positivity of evaluations.

(summarized in Fig. 3 and Table 1), with no AFV technology having seriously threatened the dominance of fossil fuels. Each hype is characterized by rising media attention and more positive expectations about the potential of a given technology, and is associated with an increase in prototype development (a proxy for innovation activity). Each AFV hype also aligns with the enactment of or changes to energy or environmental policy. Furthermore, levels of government funding (as measured by US DoE funding) tend to align with trends in media coverage and innovation activity. Thus, it seems clear that governments participate in and contribute to hype and disappointment cycles through policy and funding and by making high-level political announcements, including the setting of AFV sales goals.

Although the observed AFV hype cycles have not yet led to widespread AFV adoption, we cannot conclude that hype has ultimately had a net positive or negative impact on innovation. Researchers suggest that hype can be positive or perhaps necessary in helping to stimulate interest and investment in new technologies, although excessively positive expectations that turn out to be impossible can contribute to more extreme disappointment[20,21,25,27,29]. Regarding the latter effect, we observe some actions by US National and State governments that may have contributed to establishing excessive expectations and thus negatively affecting innovation, namely by publicly announcing what proved to be unattainable sales targets, followed by changes in policy and removal of funding support. Furthermore, governments have continually shifted their attention and policy focus among different AFV technologies across the three decades of our study period, a pattern that can contribute to the delay or reversal in technological learning (that is, negative learning[48]). In effect, governments seem to be contributing to at least two major system failures that can hinder technological transformation: directionality failure (lack of consistent vision, policy and funding) and reflexivity failure (an inability to deal with uncertainty)[29]. We thus reason that governments can take steps to improve their role in AFV development and commercialization, including the manner in which they contribute to hype.

Our primary recommendation is for policymakers to improve their institutional capacity to conduct balanced, science-based

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Table 1 | Observed roles of industry and government in alternative fuel vehicle hype.

	Methanol	**Natural gas**	**Plug-in electric**	**Hydrogen**
Duration	1988–1989	1989–1993	1993–1995	1999–2008
Government				
Hype*	High	Low	Low	High
Example discourse fragment	*"[Methanol has] the potential to reduce emissions by an amazing 50% and improve efficiency."* —Ronald Reagan, 1988 (ref. 4)	*"Natural gas is an excellent clean fuel for transportation."* —EPA, 1989 (ref. 58)	*"We are excited and enthusiastic about [the EV-1]."* —California Air Resources Board, 1996 (ref. 59)	*"...the first car driven by a child born today could be powered by hydrogen, and pollution-free."* —George W. Bush, 2003 (ref. 39)
Industry				
Hype*	Low	Low	Low	High
Example discourse fragment	*We can build methanol vehicles if required to do so.* —Ford, GM, Chrysler, 1989 (ref. 60)	*Announce plans to build natural gas vehicles.* —Ford, GM, Chrysler, 1991 (ref. 61)	*"People are concerned about [range], but they're also very much impressed by the fact that the Impact produces zero emissions."* —GM, 1990 (ref. 62)	*FCVs will be for sale by 2004.* —Ford, GM, DaimlerChrysler, 1999 (ref. 38)
Commercialization to date				
Success or failure?	Failure	Failure	Failure	Failure
Share of new light-duty vehicles sales in the US, 2013 unless otherwise noted[8,46]	0.0%	0.5%	0.5%	0.0%
	Hybrid	**Biofuel**	**Plug-in electric (2nd wave)**	**Hydrogen (2nd wave)?**
Duration	2003–2010	2004–2008	2008–?	2013–?
Government				
Hype*	Low	High	High	Low
Example discourse fragment	–	*"Our goal is to make [cellulosic] ethanol practical and competitive within six years."* —George W. Bush, 2006 (ref. 5)	*We can "become the first country to have a million electric vehicles on the road by 2015."* —Barak Obama, 2011 (ref. 6)	*"...automakers are saying, 'Look, hydrogen could be a long shot. But we're going to put a little bet on it, and we'll see.' "* —Steven Chu, 2013 (ref. 41)
Industry				
Hype*	Low	High	High	High
Example discourse fragment	*Hybrids are "the solution for today."* —Toyota, 2003 (ref. 63)	*Will double production of flex-fuel vehicles by 2010.* —Automakers, 2006 (ref. 64)	*"The electrification of the automobile is inevitable."* —GM vice chairman Bob Lutz, 2007 (ref. 65)	*"The fuel-cell car is going to be a big part of our future."* —Toyota, 2013 (ref. 41)
Commercialization to date				
Success or failure?	Growing	Mixed†	Limited	Failure
Share of new light-duty vehicles sales in the US, 2013 unless otherwise noted[8,46]	2.9%	12.2%	0.7% (2014)	0.0%

*Our characterization of the level of hype is a subjective assessment based on observed government and industry claims in the mass media. †Data represent market share for flex-fuel vehicles, which are regularly fuelled with conventional gasoline. In 2013, biofuels accounted for 4.7% of transportation sector energy use[7].

technology assessments, an analytic practice that contributes to the formation of public and political opinion regarding societal aspects of science and technology[49]. If such assessments are designed to be cross-disciplinary, participatory, ongoing (that is, regularly updated), and ultimately grounded in scientific evidence, they can contribute to the creation of reasonable shared expectations, effective coordination among key stakeholders, and the design of adaptive (reflexive) policy[26,29,30]. Although such a process cannot eliminate uncertainty, efforts to draw on the best possible knowledge in the present can help to develop more plausible expectations about the future[31]. One example is the California Air Resources Board's efforts to conduct periodic reviews of AFV technology with independent expert panels. The 2007 panel assessed the status of electric battery and hydrogen fuel cell technologies and possible time frames for deployment, in effect providing a useful anchor for discussions about AFV feasibility and policy design in California[50]. However, these expert panels are not perfect examples of institutional practice, and in some cases may contribute to the hype and disappointment patterns described above—say if the expert panel is too narrowly technology-focused or short-sighted in their assessment. At present, the US federal government seems to have limited technology assessment

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capacity. Congress established a technology assessment function within the Government Accountability Office in 2008, but it has produced a small number of studies and none related to AFV technologies. We therefore echo others who have called for a source of science and technology policy advice for the US federal government, a function formerly provided by the Office of Technology Assessment[51,52].

We reason that if governments improve their ability to conduct ongoing, systematic technology assessment, they are likely to set more reasonable and credible goals for AFV market penetration, at least relative to the goals observed in the AFV cases we summarize (including four failed AFV goals of several US presidents). Our analysis reveals that such goals are often announced without a plan for their achievement, and with apparently little consideration for factors such as supply constraints, rate of innovation adoption and consumer acceptance. It is possible that such implausible goal setting has contributed to ensuing disappointment and the discrediting of AFV technology, reducing the credibility of government[24], which in turn provides less clarity for industry and other stakeholders regarding how to channel their innovation efforts[34]. Instead, governments could utilize rigorous technology assessment to revive the credibility of their stated goals and expectations, and to establish a relatively stable and consistent framework to support AFV investment and development in the long term[30].

We further speculate that enhanced technology assessment and goal setting should help government to identify the policies needed to achieve substantial AFV market penetration, including how to design, implement, monitor and update them. Policy options vary widely (including taxes on carbon, fuel or vehicles, R&D funding, regulations on fuels and vehicles, consumer incentives, and deployment of refuelling infrastructure), and the ideal portfolio of policies will probably vary by technology, region and socio-political context. A particular challenge is that assuming a large carbon tax is politically unacceptable[53], at least some of these policies will need to be technology-specific[54]. Effective use of technology assessment could help policymakers to identify policy strategies that are adaptive to technological development and societal learning, while at the same time providing a consistent and stable signal for stakeholders and innovation activities[29]. Policymakers may also make use of technology assessment and knowledge about hype cycles to identify 'techno-economic windows' and 'policy windows', opportunities that might allow for the politically acceptable implementation of policies of the stringency that are likely to be required to induce a substantial AFV transition[30].

To conclude, we can make no claims about the likelihood of future success for any of the AFV technologies reviewed here. Our analysis demonstrates, however, that efforts to deploy various AFV technologies over the past three decades are characterized by repeated periods of hype, disappointment and ultimate failure to achieve the level of AFV market adoption needed to substantially cut carbon emissions from transportation. Policy makers that genuinely want to decarbonize their transportation sector should therefore have an interest in moving beyond hype, which will inevitably require improvements in their capacity to assess technologies and thus to implement effective policy. Although technology development will always remain uncertain, effective technology assessment practices should only improve governments' ability to set adaptive, long-term goals and policies that can effectively guide stakeholders and innovation activities towards a low-carbon transportation system.

Methods

Article search. The following search terms were used to identify articles related to seven AFV technologies: battery electric ('electric'), hybrid electric ('hybrid'), plug-in hybrid electric ('plug-in' AND 'hybrid'), biofuels ('ethanol' OR 'biofuel' OR 'biodiesel'), hydrogen ('hydrogen' OR 'fuel cell'), methanol ('methanol') and natural gas ('natural gas'). Because our focus is road transportation, each article also had to contain the word 'car,' 'vehicle' or 'truck.' The initial search, conducted through the Factiva database, returned 9,310 articles published in the *New York Times* between 1 January 1980 and 31 December 2013. To increase article relevance and achieve a more tractable number of articles for content analysis, articles were screened out if they were less than 300 words in length or if the search term did not appear within the first 200 words. The remaining 1,549 articles were reviewed and any irrelevant articles excluded manually. The final selection of 963 articles was imported to NVivo 10 media analysis software for detailed content analysis.

Table 2 | Intercoder agreement results based on reliability test with 50 articles.

Coder	Simple agreement (%)	Weighted-average Kappa of positive and negative evaluative statements	Number of articles coded
1	86.8	0.49	144
2	87.2	0.49	379
3	88.4	0.57	195
4	86.0	0.43	93
5	91.8	0.35	152

Article evaluation. For each article, evaluative statements were identified that described benefits or drawbacks related to the AFV in question. Each evaluative statement was coded as either positive or negative (neutral statements were ignored). These evaluative statements formed the basis for characterizing collective expectations. We take periods of rapidly rising media attention and expectations as indicative of hype, with the reverse indicative of disappointment[17,29]. To facilitate future analysis of the data, we also coded each statement based on topic (for example, financial, environment, and so on), actor (for example, government, industry, and so on) and level (similar to those used by van Lente, Spitters and Peine[18]). These additional details are beyond the scope of the current paper, which aims to bring awareness to a broad set of AFV hype cycles in the US case study, highlighting the particular role of, and implications for, government.

Coding guide. To structure the collection of qualitative data, we prepared a detailed coding guide for the five coders (the authors did not conduct the coding). The authors developed the guide in an iterative, participatory fashion with the coders to help clarify research objectives, adapt the coding guide and strengthen intercoder reliability[55]. Coders were encouraged to voice questions and concerns, and group discussions were held to resolve issues and to develop common approaches to challenging situations. Agreement was first assessed informally during coder training (via group discussion), and then agreement was formally assessed with a test of fifty randomly chosen articles that were coded by all five coders (5% of the population, corresponding with guidelines developed by Lacy and Riffe[56]). The level of agreement was calculated for each coder relative to the rest of the group, as shown in Table 2. The level of simple agreement ranges from 86.0% to 91.8%. A more conservative measure, Cohen's Kappa, takes into account the level of agreement expected by chance. This coefficient measures agreement on a scale of negative one to positive one, where positive one indicates perfect agreement, zero is exactly what would be expected by chance, and negative values indicate agreement less than chance (that is, potential systematic disagreement between coders). Our scores using Cohen's Kappa suggest fair to moderate agreement according to the criteria suggested by Landis and Koch[57].

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Author contributions

D.S. provided initial inspiration for this project. J.A. and N.M. developed the study design, and N.M. analysed the data. All authors contributed to writing the paper.

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Competing interests

The authors declare no competing financial interests.

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