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Economic and environmental evaluation of compressed-air cars

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Abstract
Climate change and energy security require a reduction in travel demand, a modal shift, and technological innovation in the transport sector. Through a series of press releases and demonstrations, a car using energy stored in compressed air produced by a compressor has been suggested as an environmentally friendly vehicle of the future. We analyze the thermodynamic efficiency of a compressed-air car powered by a pneumatic engine and consider the merits of compressed air versus chemical storage of potential energy. Even under highly optimistic assumptions the compressed-air car is significantly less efficient than a battery electric vehicle and produces more greenhouse gas emissions than a conventional gas-powered car with a coal intensive power mix. However, a pneumatic–combustion hybrid is technologically feasible, inexpensive and could eventually compete with hybrid electric vehicles.

Keywords: compressed-air car, life-cycle analysis, greenhouse gas emissions, innovation, electric mobility

S Supplementary data are available from stacks.iop.org/ERL/4/044011/mmedia

1. Introduction

There is an urgent need for mobility technologies and infrastructures that are based on a technology other than oil and that have acceptable costs. Consumers are affected by high and fluctuating oil prices, and in 2008 total vehicle miles decreased for the first time in decades in the United States. Manufacturers must address plummeting car sales. The US government spends billions on national oil security while worldwide greenhouse gas emissions are still increasing at a rapid pace.

The compressed-air car has been promoted by companies such as *Motor Development International*, France, and *Energine*, Korea as an environmentally friendly car of the future. As a form of storage, compressed air is nothing new. Indeed, compressed-air engines were utilized in power mining locomotives in the United States and Europe at the beginning of the 20th century [1]. It is also reported that compressed-air engines have powered tramways in Bern, Switzerland and Nantes, France [2]. However, a tramcar kilometer needed more than 7 kg coal because the loading stations were run by steam engines. This corresponds to 13 kg CO_2 km^{-1}. To get a feeling for the magnitude: a fully occupied tram with 31 passengers has a worse carbon footprint per person km (410 g CO_2 pkm^{-1}) than a Porsche Cayenne (358 g CO_2 pkm^{-1}). Thus, a compressed-air tram had ten times more emissions than a modern electric tram per passenger km. In fact, tramways and locomotives were soon powered by more efficient electricity. This time, compressed air is proposed as a propellant for automobiles. Do high oil prices offer a second chance for the compressed-air engine?

Here we report on the thermodynamic limits, the overall efficiency, the environmental impact, the propellant volume

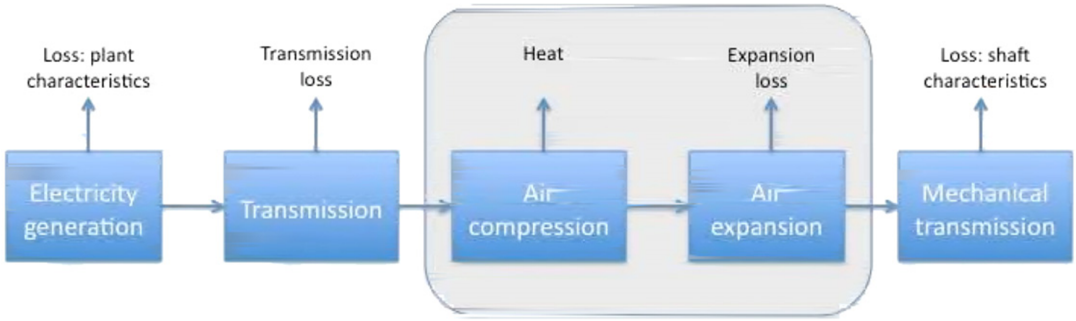

Figure 1. The different stages of efficiency loss for transportation with the compressed-air car. The two stages that are specific for compressed-air storage are marked in gray.

and the cost-benefit balance of the compressed-air car (CAC) and compare it with a battery electric vehicle (BEV). We discuss some of the advantages and disadvantages of this method of energy storage and propulsion mechanism while pointing out the range of uncertainty on real performance. We conclude that the main drawback is the thermodynamic efficiency loss and uncertainties about required technologies. Hence, in contrast to the BEV, the CAC is not likely to successfully compete against gasoline cars. The compressed-air technology, however, might be feasible in a hybrid configuration.

All calculations, graphs and consideration are also specified in a spreadsheet model. The model, compressed-air car analysis meta-model (CACAMM) can be downloaded at stacks.iop.org/ERL/4/044011/mmedia where users can verify the influence of different assumptions and variable values.

2. Thermodynamic efficiency

We first investigate the thermodynamic efficiency of compressed-air storage. The different stages of efficiency loss are depicted in figure 1. We focus on air compression and air expansion, two stages that are specific to the compressed-air car. Tank leakage loss is negligible compared to the loss of air compression and air expansion. A similar analysis was conducted by Bossel [3]. Our investigation differs from that study in assuming cooling at constant pressure [4, 5]. Furthermore, we specify that compression is polytropic and expansion adiabatic.

2.1. Compression

Our reference scenario corresponds to data published by Zero Pollution Motors, a subsidiary of MDI [6]. A volume $V_1 = 100\,000$ l is compressed from normal pressure $p_1 = 1.01325$ bar to $p_2 = 310$ bar (= 4500 psi), resulting in a final volume $V_2 = 327$ l. The technical work required for filling the tank under isothermal conditions is

$$W_{\mathrm{isoth}} = p_1 V_1 \ln \frac{p_2}{p_1} \sim 58 \text{ MJ}. \tag{1}$$

Isothermal conditions are not achievable in practice. Real processes deviate from the isothermal optimum. A lower bound is given by an adiabatic process, i.e. when there is no heat exchange and no rapid compression. The adiabatic coefficient is $n = 1.4$. The process is then characterized by

$$W_{\mathrm{com}} = \frac{p_1 V_1}{n-1}\left(\left(\frac{V_1}{V_2}\right)^{n-1} - 1\right) \sim 225 \text{ MJ}. \tag{2}$$

Then the overall efficiency of the process is the energy in the tank divided by the work done,

$$E_{\mathrm{com}} = \frac{W_{\mathrm{isoth}}}{W_{\mathrm{com}}} \sim 26\%. \tag{3}$$

There are two practical measures to increase efficiency: (A) multi-stage processing with inter-cooling at constant pressure and (B) slow compressing allowing for concurrent heat exchange [4, 5]. Compressors working in 4 stages are commercially available. MDI indicated that they use 2-stage compression. In this case, two subsequent compression processes have volume ratio ~17.5 instead of one compression with volume ratio ~310. Furthermore, using a 5.5 kWh compressor charging takes 4–5 h allowing for heat exchange, by this increasing energy efficiency. Taking this diabatic process into account, we assume $n = 1.2$. Hence, the overall work is calculated by repeatedly applying and updating equation (2), resulting in $W_{\mathrm{com}} \sim 61.9$ MJ and $E_{\mathrm{com}} \sim 93.6\%$.

2.2. Expansion

The expansion work can be retrieved similar to compression work by equation (2). In this case, we conservatively assume the process to be adiabatic, $n = 1.4$, as the expansion is instantaneous. If there is heat exchange, expansion would be more efficient. The pressure in the storage chamber can be kept constant by an adjusting valve. It is assumed that all expansion work is used to drive the car—with constant torque a normal driving cycle would be much more inefficient (see section 5). A single-stage expansion results in expansion work $W_{\mathrm{exp}} \sim 22.8$ MJ, i.e.,

$$E_{\mathrm{exp}} = \frac{W_{\mathrm{exp}}}{W_{\mathrm{isoth}}} \sim 39.3\%. \tag{4}$$

As for compression, a multistep expansion can increase efficiency, in this case $E_{\mathrm{exp}} = 49\%$ for 2 steps as used by MDI. The overall efficiency of the compressed-air storage only is $E_{\mathrm{air}} = E_{\mathrm{com}} E_{\mathrm{exp}} \sim 45.7\%$.

3. Model considerations

How does the compressed car perform compared to the conventional internal combustion engine and battery electric vehicle? In particular, we want to measure the overall energetic performance and the total fuel volume required to drive a reasonable distance. Furthermore, there are two major cost drivers for a switch in mobility technology: environmental externalities in terms of greenhouse gas emissions and increasing gasoline prices and price fluctuations. Hence, we compare different car technologies with respect to (A) required energy per km (B) greenhouse gas emissions per km (C) fuel volume and (D) cost per km. The real energy performance of CAC has not been verified in independent tests, and, like virtually all other vehicles, will depend on both technologies and behaviors, such as speeds and driving cycles.

As a reference vehicle with internal combustion engine (ICE), we rely on an established mini-car, the Smart fortwo [7, 8]. This car drives 5.2 l/100 km (45 mpg) in the European drive cycle, weighs (including driver) ca 900 kg and has a maximum speed of 145 km h^{-1}. This choice is appropriate as the same model will be available as an battery electric vehicle, the *Smart fortwo ed*. We compare the conventional internal combustion engine powered by gasoline with the compressed-air car (CAC) and the battery electric car (BEV), i.e. the Smart fortwo ed which drives 13.7 kWh/100 km (as measured from the grid), weighs 100 kg more than the Smart fortwo, has maximum speed 100 km h^{-1}, and a range of 115 km. Hence we limit our analysis to urban transportation. BEVs and CACs are commonly classified as electric cars as both types of car obtain their energy from the grid.

To achieve ambitious climate change mitigation goals, not only must fuel economy must be improved but also total energy requirements (and travel demand) must be reduced. To elucidate the weight factor, we compare the Smart fortwo and its electric cousins with a hypothetical super-light car, or golf cart, that weighs 300 kg and is assumed to drive 1.7 l/100 km. The improved fuel economy is achieved mainly by weight reduction, as well as other feasible technological improvements, and reduced motor power. Such a vehicle is suited only for urban transport but not for highways and has a maximum velocity of around 60 km h^{-1}. As such it is more suitable for relatively dense European or Asian cities that have high accessibility and short distances.

3.1. Total energy requirement

First, the efficiencies of the three different storage technologies is calculated. The grid-to-wheel efficiency of BEVs is 77.5% [9–11]. Comparing energy content of fuels, an approximate fuel-to-wheel efficiency of 21.2% for gasoline can be inferred. Furthermore, one sixth of all carbon emissions of gasoline are upstream in the supply chain, resulting in a well-to-wheel efficiency of ca 17.7%. For CAC, we conservatively assume that additional to 45.7% storage efficiency, 10% are lost due to mechanical and flow losses. Furthermore, another 29% are lost due to shaft energy requirements [10, 12]. For the electric modes, an average grid transmission loss of 9.5% must be included [13]. If electricity is generated by thermal power plants, plant efficiency loss must be included, e.g. 0.4 for a relatively efficient coal power plant. The resulting efficiency values are summarized in table 1.

Table 1. Efficiencies for propellants. For the electric modes, specific power plant efficiencies must be added.

	Smart	CAC	Smart ed
Coal/well-to-wheel (%)	17.7	11.7	28.3
Wind/well-to-wheel (%)	17.7	29.2	70.8
Grid/pump-to-wheel (%)	21.2	26.7	77.5
Propellant-to-wheel (κ) (%)	21.2	34.6	90.0

Table 2. Fuel weight.

Car weight (kg)	Gasoline (kg)	CAC (kg)	BEV (kg)
900	4.8	53.0	140.3
300	1.6	17.7	46.8

4. Performance

4.1. Fuel storage weight and volume

The propellant weight is not significant as a fraction of total weight for conventional cars, but the weight of batteries can be considerable for BEVs. Here, we also compute the fuel weight for compressed-air cars. The weight of propellant needed is a function of the range required, the efficiency of conversion of stored energy to work at the wheels and the average storage capacity in MJ. The cruising range from here on is $r = 115$ km, as has been specified for the electric Smart. In a CAC or gasoline vehicle but not in a BEV, the weight of the fuel changes over time. To take this into account, average filling is $a = 0.6$ for gasoline and CAC, and $a = 1$ for BEV. The relationship between fuel weight and vehicle properties can be stated as follows.

$$w_f e_f = (w_v + a w_f) r E_{wr} \kappa^{-1} \tag{5}$$

where w_f is the propellant weight, e_f the energy per weight fuel (gasoline: 45 MJ kg^{-1}, CAC: 1.94 MJ kg^{-1}, BEV: 0.40 MJ kg^{-1}) and κ the fuel-to-wheel efficiency. Defining the range-specific energy required per weight as $E_{rs/w} \equiv r E_{wr} \kappa^{-1}$, the required propellant weight is

$$w_f = \frac{w_v E_{rs/w}}{e_f - a E_{rs/w}}. \tag{6}$$

The fuel weight for different storage technologies and car sizes is summarized in table 2. Compressed-air weighs ten times more than gasoline with similar energy content, but three times less than batteries with similar energy content.

One of the main objections against electric-only vehicles is their limited range. Above, we required that all vehicles have a 115 km range. This requires a significant amount of compressed air, adding more than 50 kg. However, the real issue is the low energy density: a large storage volume is required. For the 900 kg CAC, 780 l storage is required—more

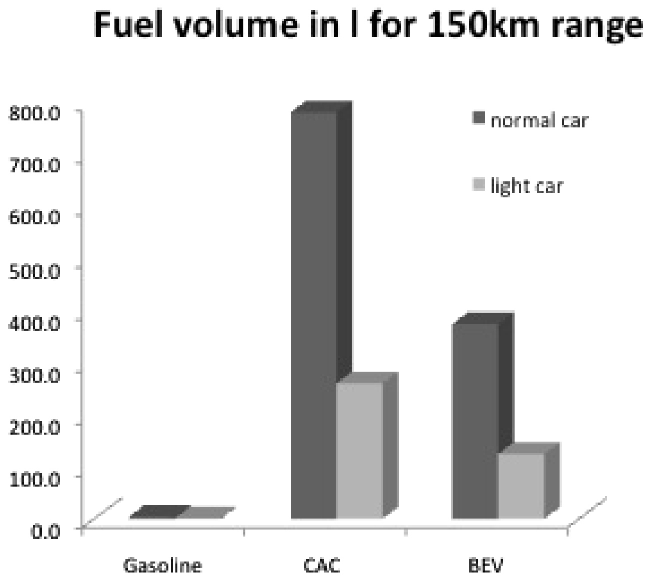

Figure 2. Compressed-air stores energy only at low density, and a combination of large tank volume, high pressure and low vehicle weight is required to provide an acceptable range. From here onwards *normal car* refers to the 900 kg model whereas *light car* refers to the 300 kg city car.

than double the trunk volume of the Smart—and hence posing a serious challenge for car design. In contrast, for gasoline less than 4 l is required. Li-ion batteries have values of 400 whr l^{-1} and 150 whr kg^{-1} [14]. This implies 0.375 kg l^{-1} density. In table 2 we specify 140.3 kg battery pack for the Smart, and 46.8 kg battery pack for the super-light car. Using the density above, this corresponds to 374 l for the normal car, a little above the trunk volume of the Smart, and 125 l for the small ca. Note that battery densities are defined in two different ways: either just the *active material*, or for the active material plus packaging. The numbers above refer to packaging, which is appropriate for this use since were looking at the volume of battery packs. Figure 2 summarizes the volume requirement for the different energy storage technologies. Whereas battery volume is already at the upper limits of what can be deployed for small cars, the volume of compressed-air cars poses a very serious hurdle for vehicles with suitable range.

4.2. Primary energy required

From the efficiency table 1, the primary energy per distance can be calculated, given the car plus fuel weight. The results are summarized in figure 3. The primary energy requirement is crucially dependent on the power plant. If electric cars are powered by renewable energies, less primary energy is required than for the gasoline car. If electric cars are powered by coal power plants, more primary energy is required for CACs but still less for BEVs. From the overall efficiency perspective battery cars are much more efficient.

4.3. Greenhouse gas emissions

Environmental performance as *zero local emissions* is one of the primary arguments for the compressed-air car. Indeed, noxious matter is not emitted locally when driving, thereby one of the main contributors to urban air pollution is eliminated. This benefit is shared by battery cars[7]. However, compressed-air tanks can be disposed of or recycled with less toxic waste pollution than batteries, depending on the precise recycling requirements. One important environmental concern relating to car use is the impact of cars on climate change. Greenhouse gas emissions themselves depend critically on the source of electricity used for charging batteries or running the CAC compressor. Whereas a compressed-air car or the BEV do not emit greenhouse gases (GHG) when operated, emissions are shifted to power plants. Emission levels then depend on the power plant characteristics.

In general there is a great deal of uncertainty associated with modeling the effect of electro-mobility on the grid. It is agreed that even huge penetration rate of electric cars can be serviced using the present power plant capacity if cars are mostly plugged-in at off-peak hours [15]. When advanced scenario-based simulations of overall grid growth, electricity dispatch and geographic generation distribution are performed, results are region specific. Usually emission reductions are larger than when assuming the current power mix [15].

Here, we calculate the emissions produced by electricity purchase from two different German utilities, RWE and EWS Schönau. Providers can be chosen in the German electricity market. Note that RWE produces the charging stations for the Smart ed in the Berlin trial. The power plant mix of RWE is dominated by coal plants, producing 887 g CO_2 kWh^{-1} [16], whereas EWS Schönau relies nearly exclusively on renewables and hydro-energy, producing 17.3 g kWh^{-1} [17]. The future power plant mix of RWE crucially depends on policy decision, such as permissions for new coal plants.

Results are summarized in figure 4. The choice of power plant mix has significant impact on greenhouse gas emissions. The compressed-air car indirectly emits more than twice the greenhouse gases than its conventional counterpart when powered by RWE. The poor environmental performance of the CAC is due to its thermodynamic inefficiencies, see section 4.2. Even the BEV performs only similar to the gasoline car. In contrast, the CAC and the BEV mitigate greenhouse gas emissions considerably when a renewable energy provider is chosen. PG&E, a major Californian energy provider, has medium GHG emission (238 g CO_2 kWh^{-1}). As a result, the deployment of both CAC and BEV produces some environmental benefits in California.

4.4. Consumer savings, break-even costs

One of the dominant concerns for consumers is high fuel prices. What fuel costs do consumers save when driving the compressed-air car? Two gasoline price scenarios and two regions are considered. The regions are California and Germany. California has a low gasoline price scenario with 2\$/gal and high gas price scenario with 4\$/gal. The price

[7] Modern superlow emission vehicles, comprising standard models such as the Toyota Prius, also emit substantially lower levels of hydrocarbons, carbon monoxide, nitrous oxides and particulate matter than conventional vehicles; hence, for addressing air pollution concerns neither a BEV or CAC is required.

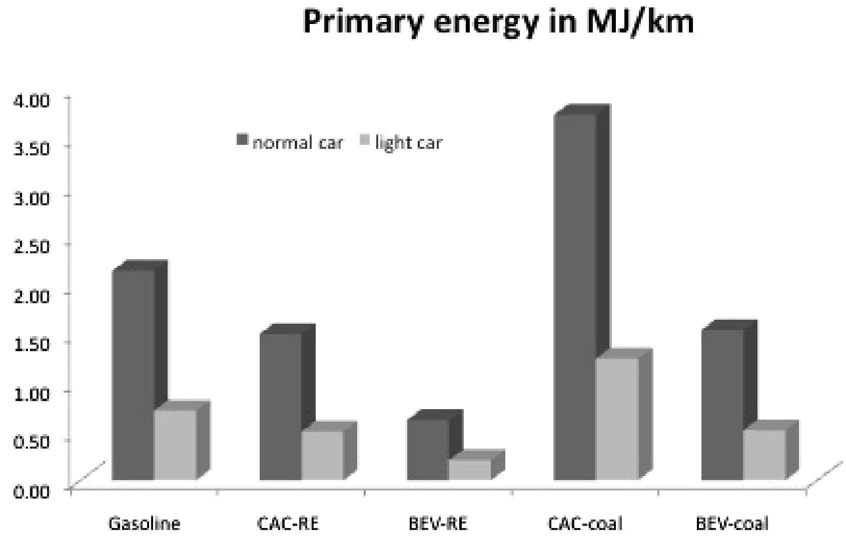

Figure 3. Primary energy required. When powered by renewable energies, the compressed air needs less energy per km than the gasoline car but significantly more than the battery car. The CAC needs 75% more primary energy than the gasoline car when the CAC is powered by a conventional coal plant.

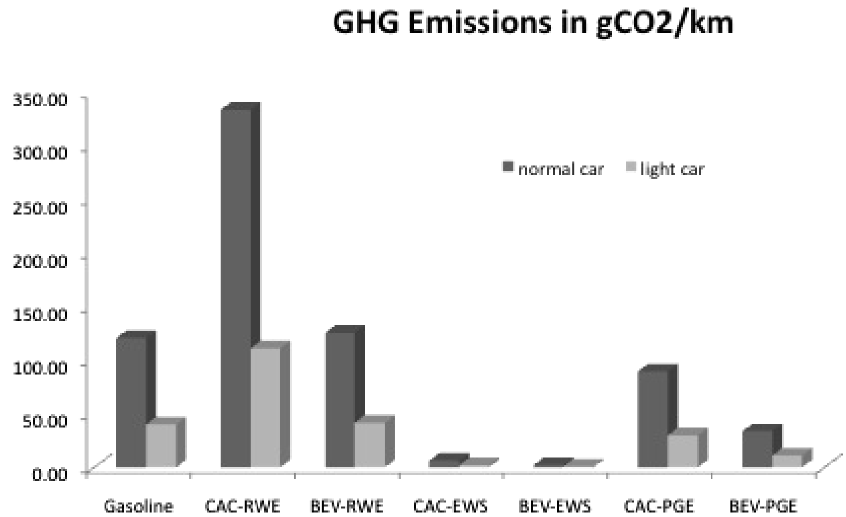

Figure 4. Greenhouse gas emissions per km of the compressed-air car are even higher than those of the conventional gasoline car. Total emissions are crucially dependent on the choice of provider in Germany. The BEV has lower emissions for typical Californian conditions.

for electricity is taken as 0.128$ kWh^{-1}, the Californian average retail price in 2007 [18]. Road maintenance costs are usually recovered via fuel taxes, e.g. $0.37/gal in California, corresponding to roughly[8] to 0.0065$ km^{-1} which must be added to the marginal cost of using cars that are run by electricity. Assuming that this charge is levied as tax on electricity for cars, the price would increase by another $0.046 kWh^{-1} for the average 900 kg electric vehicle and $0.017 kWh^{-1} for the more inefficient compressed-air car (taxes are proportional to km kWh^{-1}). Results as marginal costs per km driven are presented in table 3.

For Germany, the low gasoline price scenario is €1.2 l^{-1} ($6.4/gal), the high price scenario €1.6 l^{-1} ($8.4/gal). The higher gasoline prices favor electric cars. However, both electricity prices and fuel taxes are significantly higher in Germany than in California, €0.19 kWh^{-1} and €0.66 l^{-1} respectively [19]. This translates into very high electricity charges for electric cars, with road taxation amounting to more of 50% of the total price of 0.57$ kWh^{-1}. Results are displayed in table 4.

[8] For the Californian value, the US Environmental Protection Agency rating of 36 mpg is assumed for the Smart fortwo.

Table 3. California: marginal price (c km^{-1}) with $4/gal ($2/gal).

	Gasoline	CAC	BEV
Normal fuel	5.5 (2.7)	—	—
Light fuel	1.8 (0.9)	—	—
Normal grid	—	5.2	2.3
Light grid	—	1.7	0.8
Break-even normal $		300 (−2700)	3500 (400)
Break-even light $		100 (−900)	1200 (100)

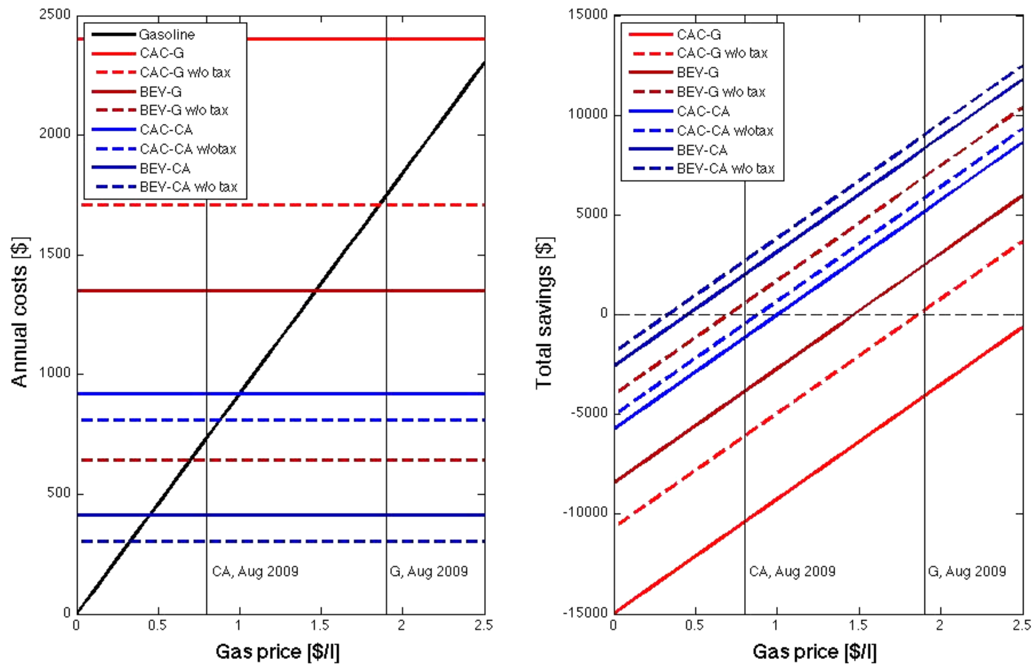

Figure 5. Costs and savings of different propellants as a function of the gas price. (a) Annual costs of each propellant for driving 17.700 km. (b) Total savings for CAC and BEV. Total savings are considerably higher for BEV drivers. The CAC does not provide saving for gas prices below \$4/gal. Note that we included a road charge in the electricity price, equivalent to today's gasoline tax. Without the road charge, both modes are more profitable.

Table 4. Germany: marginal price (c km^{-1}) with \$8.4/gal (\$6.4/gal).

	Gasoline	CAC	BEV
Normal fuel	11.5 (8.8)	—	—
Light fuel	3.8 (2.9)	—	—
Normal grid	—	13.6	7.6
Light grid	—	4.5	2.5
Break-even normal \$		−2400 (−5400)	4300 (1300)
Break-even light \$		−800 (−1800)	1400 (400)

In the following, we focus on the high fuel costs scenarios which are more optimistic for the compressed-air cars. Consumer have—for a variety of reasons [20]—a high discount rate of ca 16% [21]. Taking the respective gasoline car (Smart fortwo) as a benchmark, in California the CAC has total usage savings of only \$300 whereas the Smart ed accumulates savings of \$3500 over its lifetime. In this calculation, a user fee or road charge for electric vehicles substitutes for fuel taxes. If there are no road charges, and electric vehicles are subsidized, the CAC saves \$1000, and the BEV \$4200. In Germany, the CAC produces additional usage costs of \$2400 whereas the Smart ed accumulates savings of \$4300 over its lifetime. This is due to comparatively high fuel taxes (or equivalently road charges) in Germany. If there are no road charges, the CAC saves \$2000, and the BEV \$8700.

All results are summarized in figure 5. Figure 5(a) displays the annual usage costs for the 2 different storage technologies in California and Germany with and without user fees and compares them with varying gasoline prices. In figure 5(b), the total savings for each scenario are displayed as a function of the gasoline price. Only the usage of battery electric vehicles allows significant savings in each region. Furthermore, the political choices of how and when to introduce user fees for electric vehicles has a significant influence on the costs and benefits of electric cars.

These numbers can be interpreted as break-even costs, i.e. the total costs that the storage technology can costs, including for the BEV battery costs, battery maintenance, battery substitution, and for the CAC compressed-air tanks plus compressor. Only if the storage technology produces fewer additional costs than total usage savings, can the respective technology becomes economically reasonable.

Hence, if costs for batteries fall below \$290 kWh^{-1} in California or below \$360 in Germany, it becomes economical to drive the BEV, assuming all other costs remain the same. The CAC produces lifetime savings only in California. It becomes only economical to drive the CAC, if the engine construction saves costs compared to the combustion engine.

4.5. Capital costs

It is instructive to compare the break-even costs with known capital costs for the storage technology. Note that the storage technology costs are not necessarily equivalent to the additional full vehicle costs. The front-up cost for the CAC are mostly (a) the on-board compressor and (b) the carbon-fiber tank. A commercially available 4700 PSI compressor costs ca \$3000 [22]. Carbon-fiber tanks with ca 300 l total volume cost \$3500 [23]. However, wholesale prices should already be much lower. Nonetheless, the low savings achieved by driving the CAC (see table 4) do not allow for costs above \$300 for the

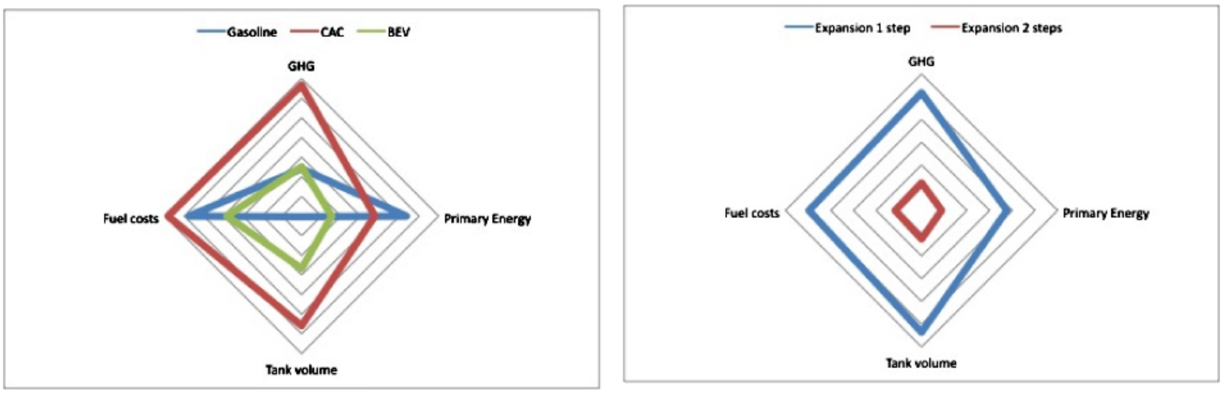

Figure 6. Performance summary (Germany, electric cars powered by RWE power mix). Left: overview on the performance of the CAC, BEV and gasoline car. GHG emissions, primary energy requirement, storage volume and marginal costs are plotted against each other. Performance is better for points further inwards. With the exemption of primary energy requirement, the CAC performs worse than the other vehicles. Right: comparison of two CAC scenarios. The scenario with two expansion steps corresponds to the scenario used on the left side. The 1-step expansion scenario is most likely used in existing air cars.

storage technology; the CAC technology is not competitive. The break-even costs for batteries above corresponds to a battery price of ca \$290–360 kWh^{-1}. Current prices are in excess of \$1000 kWh^{-1} [24], and there are additional costs for ancillary cooling and electronics. That is, total costs for batteries must come down by a factor of at least 4.

4.6. Summary of performance comparison

From the analysis above, it is clear that the CAC is outperformed by the BEV and even the gasoline car in most dimensions. The only exception is primary energy required—the gasoline car has higher total energy needs. The results are summarized in a radar plot (figure 6, left).

5. Discussion of assumptions and costs

There is reason to believe that currently projected CAC costs are optimistic because current models have much lower real performance.

We specified two expansion steps. Commercially available air motors work with one expansion step. There is no physical reason why both expansion steps cannot be used, although this may be technologically very challenging. To circumvent this challenge, one could use the second expansion step alone to power the vehicle. For example, assuming zero technological innovation and using a commercial air motor that is driven by input pressure of 9 bar for the second expansion step only, would reduce expansion efficiency from 68% to maximal 16% and total efficiency from 34% to not more than 8%. In this scenario, we still assume storage at 300 bar and the first expansion step is only used to bring down the pressure to the appropriate input pressure for the commercial air motor. Of course, such low efficiency translates into poor performance of the compressed-air car, e.g. more than four times higher GHG emissions than a conventional gasoline-powered car. A comparison of this modification in comparison to the default model is drawn in figure 6, right panel.

As a limitation, we did not carry out a drive-cycle analysis here. Instead, we assumed that the air motor can operate at equal efficiency across different output power regimes. However, at least with conventional commercially available air motors, such as piston air motors, this is not true. More specifically, the air flow rate translates into rotational speed and torque of the air motor and from their into output power. Hence, the optimal efficiency regime is a property of the air motor [25]. A complete drive-cycle analysis would certainly lead to inferior results.

6. Hybrid solutions

Internal combustion engines are usually driven usually at low load and hence, in a low efficiency regime. Also their thermodynamic cycle cannot be reversed and in braking situations kinetic energy dissipates as heat. A hybrid powertrain is one solution to these problems, requiring a battery as the storage system. The downside of this solution is the additional weight and costs of the battery, electric motor and generator. The obvious question is whether hybrid pneumatic–combustion engines offer better performance.

Two different hybrid approaches have been proposed, one based on the combustion engine, the other on the air engine. We explore both approaches conceptually.

6.1. The pneumatic–combustion hybrid

This approach takes the conventional internal combustion engine and adds an additional valve that connects the combustion chamber to an air tank. The tank is charged by the combustion engine when performing below peak efficiency and adds power to the engine in supercharged mode, i.e. when additional power is required. Additionally, the tank can be charged when the engine operation is reversed upon regenerative braking. One theoretical study found that optimizing a hybrid air tank to 16 kPa and 80 l with combined engine downsizing can improve fuel efficiency by 31% [26]. Fuel economy improvements of 64% in the city and of 12% on the highway have been reported in another model [27]. Experimental work demonstrated the feasibility of this concept, recovering up to half of the energy content of the compressed air; the expansion efficiency is >48% [28].

In contrast to the battery hybrid, the pneumatic hybrid approach does not require a second propulsion system nor does it increase the car's weight considerably. The main costs of pneumatic hybrid arise from the variable valve actuation system. As no batteries are required, costs are considered to be lower than in the hybrid electric vehicles. A switch from a two-stroke to a four-stroke pneumatic engine would further reduce costs for actuated valves [29].

6.2. Air engine hybrid

The other hybrid concept is focused on the air engine. Here, a combustion engine would be used to recharge the air tank. Here the internal combustion engine can constantly work in the maximum efficiency regime. Energy is lost in the compression and expansion stages, comparably to section 4.2. However, waste heat of the combustion engine can be used to heat up the expanded air and, hence, increase expansion efficiency. Modeling studies claim that such an air engine hybrid can reach total vehicle efficiency >33% [30, 31], compared to vehicle efficiency of 20% of the conventional car in our study. These results have to be independently verified.

7. Conclusion

The compressed-air car should be regarded as a car similar to the common BEV, powered by electricity from the grid but different in storage technology. In principle, compressed-air cars could compete with BEVs in substituting for gasoline cars. The life-cycle analysis of the compressed-air car, however, showed that the CAC fared worse than the BEV in primary energy required, GHG emissions, and life-cycle costs, even under our very optimistic assumptions about performance. Compressed-air energy storage is a relatively inefficient technology at the scale of individual cars and would add additional greenhouse gas emissions with the current electricity mix. In fact, the BEV outperforms the compressed-air car in every category. Uncertainty in technology specifications is considerably higher for CACs than for BEVs, adding a risk premium. We provide a transparent spreadsheet model that can be used to replicate results or experiment with other values.

A hybrid concept, where the air tank is recharged with an internal combustion engine, is more efficient but has yet not been experimentally verified. However, a pneumatic–combustion hybrid is similar to the hybrid electric vehicle in concept and efficiency gain, offers potential cost and weight advantages and is closest to implementation.

Overall, the CAC does not appear to offer any advantage over purely electrical means of storing energy on board a vehicle. Batteries are common and improving almost daily, while the compressed-air cycle has no present role in any popular automobile platform. Since there are great pressures on battery performance from other applications such as cell phones, it is hard to imagine that CAC will gain an advantage over BEV in the foreseeable future. Automobiles must become lighter and more efficient if even the best batteries are to provide longer autonomous ranges. At the same time, combustion technology itself is evolving rapidly in the face of concerns about oil and climate change. As long as there are no substantial innovations in compressed-air technology and its deployment, the real progress in this sector may be the emphasis on light materials and small car design, for which the competition between batteries and fuel will just intensify.

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