The 10 big problems with simply replacing fossil cars with electric

December 6, 2021 by Schalk Cloete

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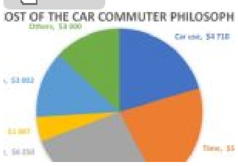
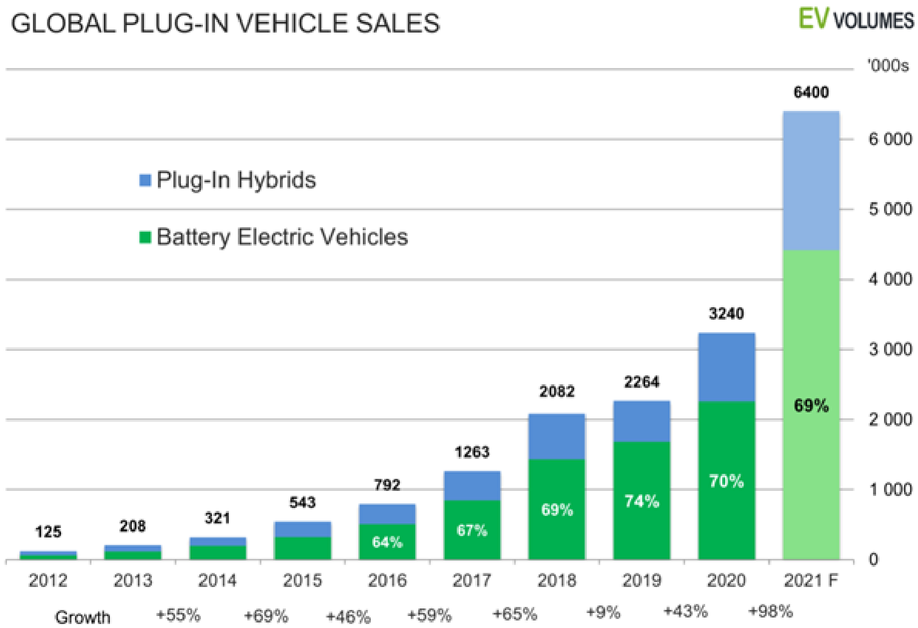


The planned rapid transition to electric vehicles has major challenges. ***Schalk Cloete*** *compiles them into a list of ten, including:* ***preserving our car-centric cities*** *preserves its inefficiencies and societal costs; it works against much of the* ***personal "behaviour change"*** *we need; though BEVs (battery electric vehicles) are better in cities,* ***when infrastructure costs are included they are less efficient than hybrids and modern ICEs for many driving needs*** *(i.e. there are cheaper ways for cars to cut emissions); BEVs require about six times more* ***critical minerals*** *than conventional cars, along with the mining ramp up challenges and consequences that entails; the optimal* ***charging patterns*** *BEVs require are badly matched with variable wind and solar; the* ***competition for investment*** *with proven wealth creation pathways that developing nations need. At its heart the argument is that* ***the CO_2 avoidance costs for BEVs will exceed \$100/ton****, both in the medium and long term. That means steering money away from the many other cheaper ways to cut emissions that could be exploited first. There are better ways to reduce transport emissions that blindly swapping fossil cars for BEVs, says Cloete.*

The world has a strange infatuation with cars. That is part of the reason why **the electric car has become the poster child for the fight against climate change**, despite its rather limited potential to avoid CO_2 emissions.

Behind the rapid growth in battery electric vehicle (BEV) sales lie a wide range of supporting policies. And behind these policies are governments that want to tap every last bit of marketing value from this highly visible climate action poster child. This is why **pure BEV companies are now worth as much as the entire legacy auto industry, even though these companies (mainly Tesla) sell only about 1% of global light-duty vehicles**.



The growth in global electric vehicle sales / IMAGE SOURCE

This article will cover ten fundamental problems with BEVs as a leading climate change mitigation option. The aim is not to discredit electric cars as a sustainable technology (they can certainly avoid CO_2 and reduce fossil fuel dependence). Instead, **this article aims to illustrate the huge disconnect between the ongoing BEV investment boom and the questionable societal benefit of the technology**.

Problem 1: a costly band-aid on our car problem

Enthusiasts like to equate the rise of the electric car with the rise of the car itself. A little over a century ago, mass-produced automobiles quickly displaced horses as the primary mode of transport. This is not surprising as the car is a superior transportation medium in almost every way.

This image of how rapidly cars displaced horses is often used to predict a similar displacement of the internal combustion engine with electric cars / IMAGE SOURCE

But applying this analogy to BEVs displacing internal combustion engine (ICE) cars is flawed. First off, as we'll see in the next three problems, **BEVs are nowhere near as superior to ICE cars as cars are to horses. More importantly, though: they're still cars**.

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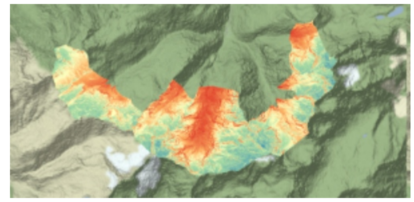

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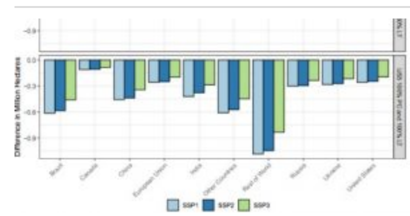

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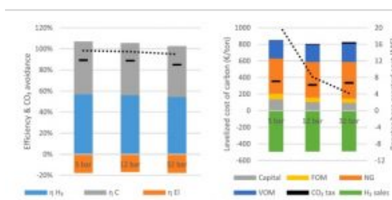

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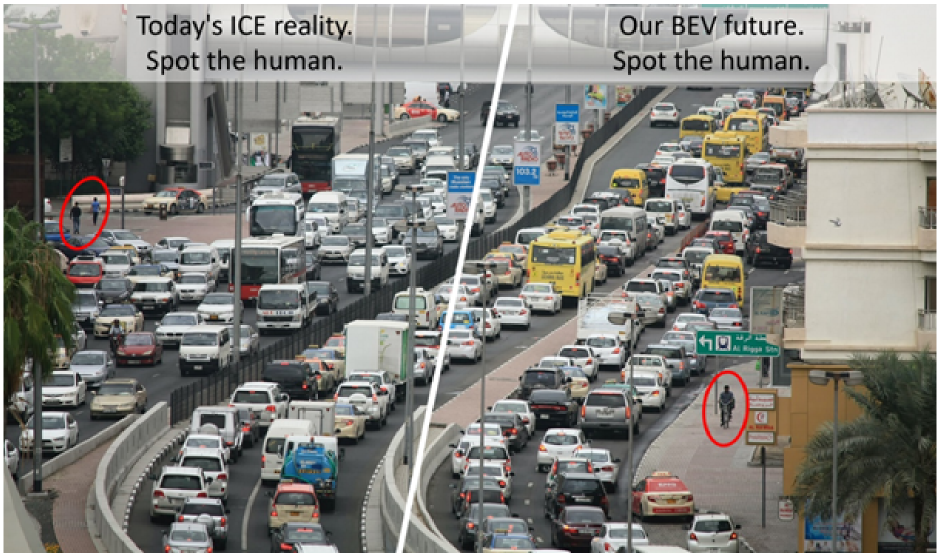
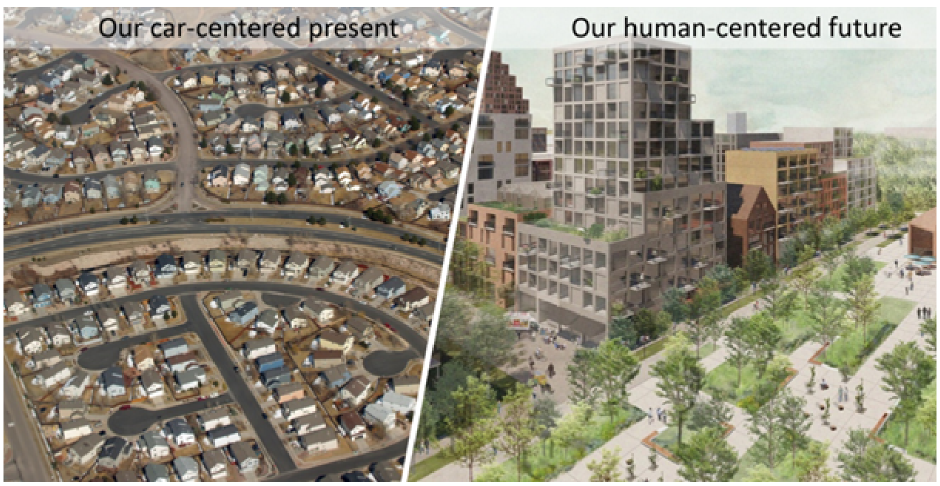


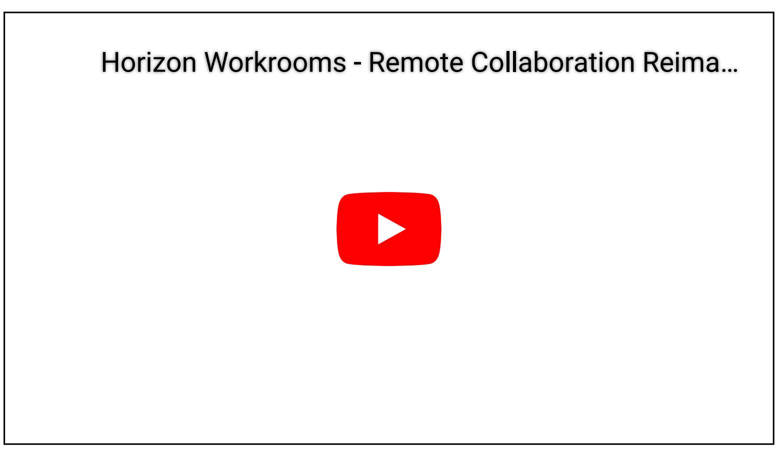
Cars remain cars, regardless of what's under the hood / IMAGE: adapted from Unsplash.

Back to our analogy, BEVs are just heavier and shinier horses that eat smaller quantities of a more expensive and (mostly) cleaner feed. **The real horse-banishing automobiles in this analogy are the twin forces of virtual mobility and human-oriented city design**.

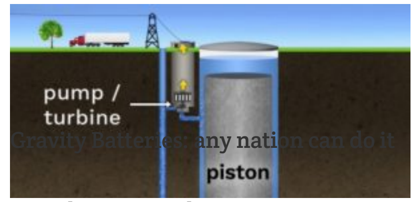


The real personal mobility revolution / IMAGE SOURCE: Wikipedia and Dutchreview

Indeed, as we'll see in the next section, **the urban car is one of the biggest inefficiencies in our economy**. Cities built for people that fully exploit emerging virtual mobility solutions (like Facebook's Horizon Workrooms) are the solution to this massive problem. Not BEVs.



[VIDEO: "Horizon Workrooms – Remote Collaboration Reimagined"]



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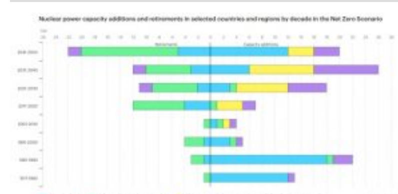

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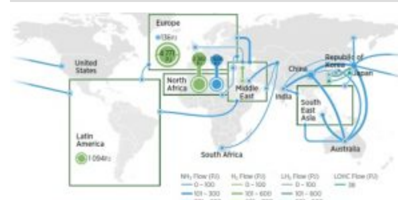

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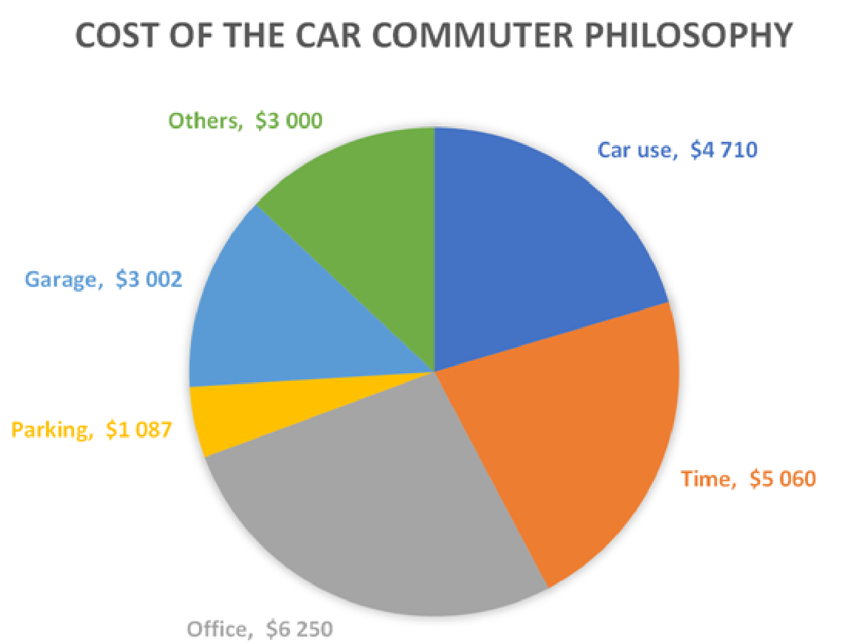
Just imagine living in a neighbourhood where the car-filled streets are replaced by peaceful walkways and cycle paths lined with greenery. **Every service your household needs is within easy walking/cycling distance**, and there are happy and friendly neighbours all around. Thus, even though you love working and playing virtually in the ever-expanding metaverse, your physical environment remains so attractive that you naturally spend lots of time outside in the sun, interacting with real humans.

Yes, transitioning from our current car-centred reality to such a high-tech human-oriented future has its challenges. But this does not justify our current trajectory of patching an expensive BEV band-aid over our massive car problem. Indeed, **a global transition to human-friendly cities will take care of all the problems BEVs aspire to solve as well as many much more severe problems they never can**.

Problem 2: promoting the worst car niches

BEV competitiveness spans a broad range. In some niches, BEVs offer an attractive solution. In others, they will never be competitive. And here's the problem: **the niches where BEVs make the most sense are those that bring out the worst of the car**.

The first of these niches is the **suburban commuter**, where a BEV with a relatively small battery pack is a compelling solution (especially for two-car families). I updated my earlier estimate of the **total societal costs of the car commuter philosophy and arrived at a whopping $23,100/year** (see below). This is about half the average wage of rich-world citizens. If we assume a worker creates about twice as much value as his salary, it means that about a quarter of the value created by the average commuter is cancelled by the costs of the (stressful and frustrating) model of getting to work.

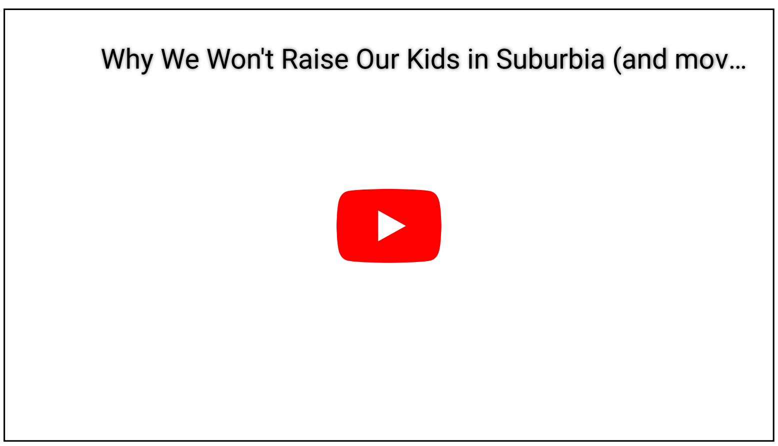


An estimate of the annual societal cost of the single-person-in-car daily commute. See Notes at end of article for more detail

Other forms of urban car transport are no better. Consider one of the most iconic symbols of a car-centred society: the supermall. **People haul their 2.5-ton SUVs many miles to this structure to go and pick up 0.05 tons of stuff** (much of it being wasteful impulse buys). Another highly ironic use-case for the **urban SUV is burning 15,000 kcal of fuel to go and burn 500 kcal of fat by running like a hamster on a treadmill in a distant gym**.

A typical mall and its gigantic parking lot / IMAGE SOURCE

Then, we have the stereotypical **"soccer mom" who spends her days as a children's chauffeur**. In an efficient society where kids can freely move around by foot or bicycle, our soccer mom could be doing so many more useful and fulfilling things with her life than stifling her children's independence. Unfortunately, this ultra-inefficient model is often the only option in car-centred societies as distances are so vast and walking/cycling is too dangerous (partly due to all the other soccer moms in oversized SUVs distracted by their frustrated kids fighting in the back.)



[VIDEO: "Why We Won't Raise Our Kids in Suburbia (and moved to the Netherlands instead)"]

The luxury car segment also deserves a special mention. BEVs work in this segment because the cost of a large battery pack is moderate relative to all the bells and whistles on a luxury car (the quiet performance of electric drive also fits the luxury image). But **while urban cars are a highly inefficient part of society, luxury urban cars ramp up the inefficiency by several additional notches**. They provide essentially the same service for a lot more money and don't even make their owners happier.

Thus, BEVs not only promise to perpetuate the inherent inefficiency of car-centred cities; they also naturally promote the niches where cars cost society the most dearly.

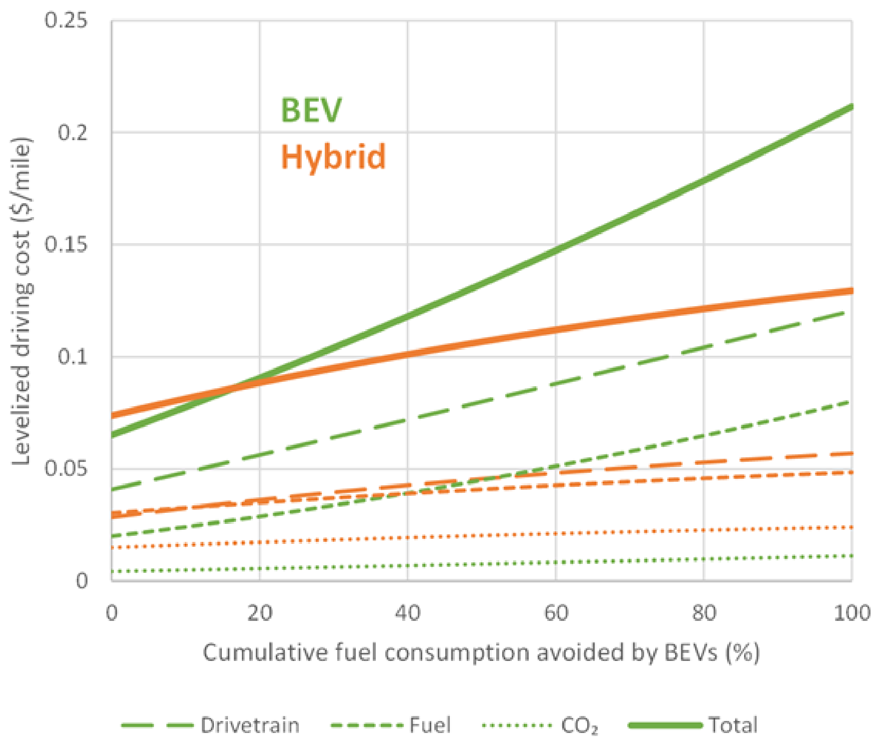
Problem 3: low competitiveness in many niches

For a long time, the magical battery cost point when electric cars were supposed to sweep aside the old ICE horses was $100/kWh. Now, it's apparently $60/kWh. But all this is just as silly as the notion of "grid parity" for wind and solar power. **Like wind and solar lose value with higher market shares, BEVs lose competitiveness as their market share grows into less favourable niches**.

On the positive end of the competitiveness spectrum is the suburban commuter car. These vehicles can get away with small battery packs, do all their driving in stop-and-go city traffic where electric drive excels, and operate exclusively on cheap slow charging at home.

On the other end, we have niches like **unstructured, long-distance journeys for holidays or business**. These vehicles need large battery packs, do most of their driving on highways where the ICE is at its best, and **rely more on public chargers (which can easily cost more than gasoline)**.

To illustrate, let's compare BEVs and hybrids in the medium and long-term future. As shown on the left of the graph below, BEVs are competitive in the niches where they make sense. However, **when we get to large, long-distance vehicles on the right, they quickly lose competitiveness**.

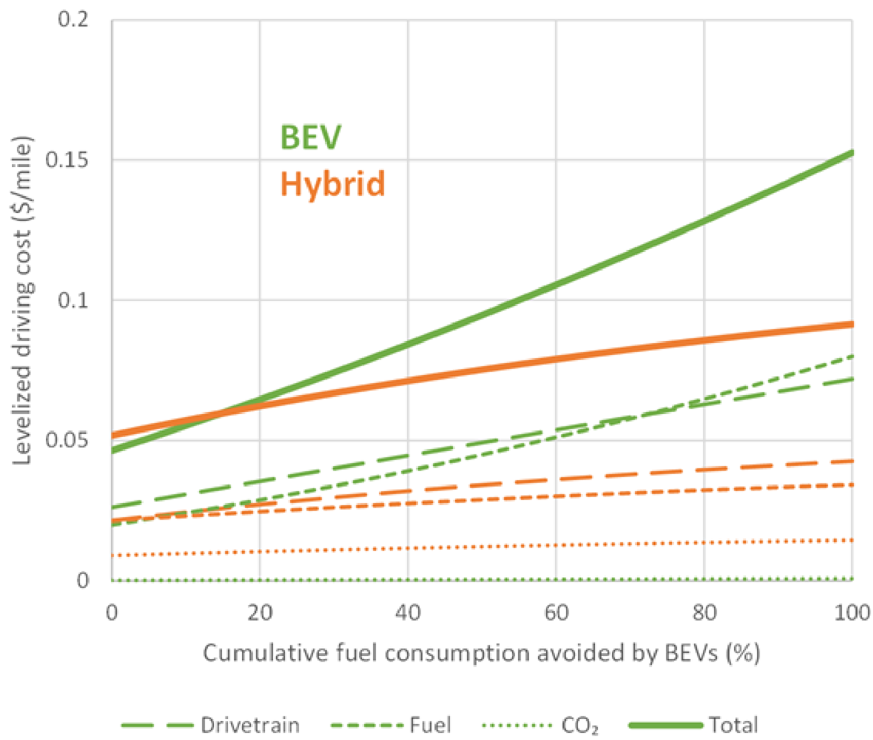


A levelised driving cost comparison for BEV and hybrid drivetrains, fuel, and CO_2 emissions ($100/ton) applicable to 2025. The left of the graph represents small commuter cars and the right represents large rural vehicles. See the Notes for detailed assumptions.

The main drivers of lost BEV competitiveness when moving from left to right in the graph are **the need for a larger battery pack**, the **increase in average electricity costs from more public charging**, and a **narrowing efficiency advantage on the highway**.

It is worth pointing out that BEV fuel costs exceed that of a hybrid over most of the investigated range. **The common assumption that electric cars always have much lower fuel costs is only true when we consider older inefficient ICE cars, almost no fast charging, and large gasoline taxes. Correct for those factors, and the BEV fuel-cost benefit disappears (and even reverses).** The CO_2 cost difference is also small (we'll return to this in Problem 5).

Another common misconception, illustrated by the graph below, is that BEV competitiveness will rapidly improve over the coming years. In fact, **the most dramatic battery cost declines are already behind us, and hybrid technology has plenty of headroom for further development** (see Notes).



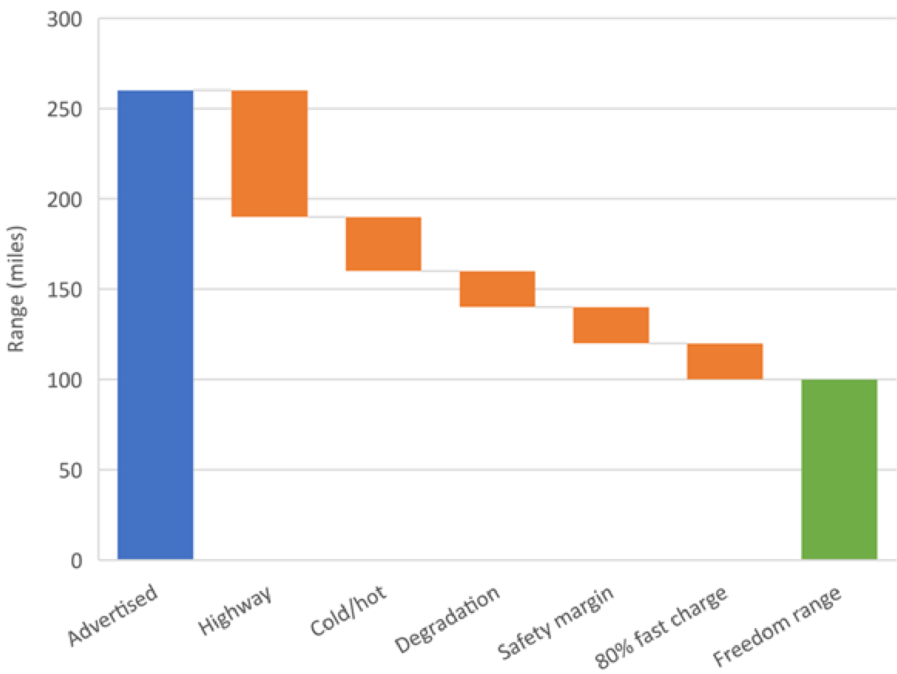
A levelised driving cost comparison for BEV and hybrid drivetrains, fuel, and CO2 emissions ($100/ton) at technological maturity. The left of the graph represents small commuter cars and the right represents large rural vehicles. See the Notes for detailed assumptions.

Furthermore, if we have any sense, the demand for urban driving toward the left of the graph will greatly diminish over the coming decades, whereas demand for free-spirited highway driving toward the right may actually increase. Let's discuss the right of the graph in more detail now.

Problem 4: practical challenges in the best car niches

The car is about freedom—a machine that can comfortably, practically, and affordably transport you anywhere you want to go. And while BEVs excel in the highly inefficient car niches covered in Problem 2 (where the car has tragically devolved into a destroyer of freedom), they will always hamper the experience in the most socially beneficial car niches.

The three main problems are practical "freedom range," recharge times, and recharge availability. First off, **the range that a BEV can guarantee under all circumstances—here called the "freedom range"—is much lower than the advertised range**. I previously presented the following list of range-limiting factors applicable to the new Volkswagen ID4:



The vast difference between the advertised range and the "freedom range" of the Volkswagen ID4. More details are provided in the Notes.

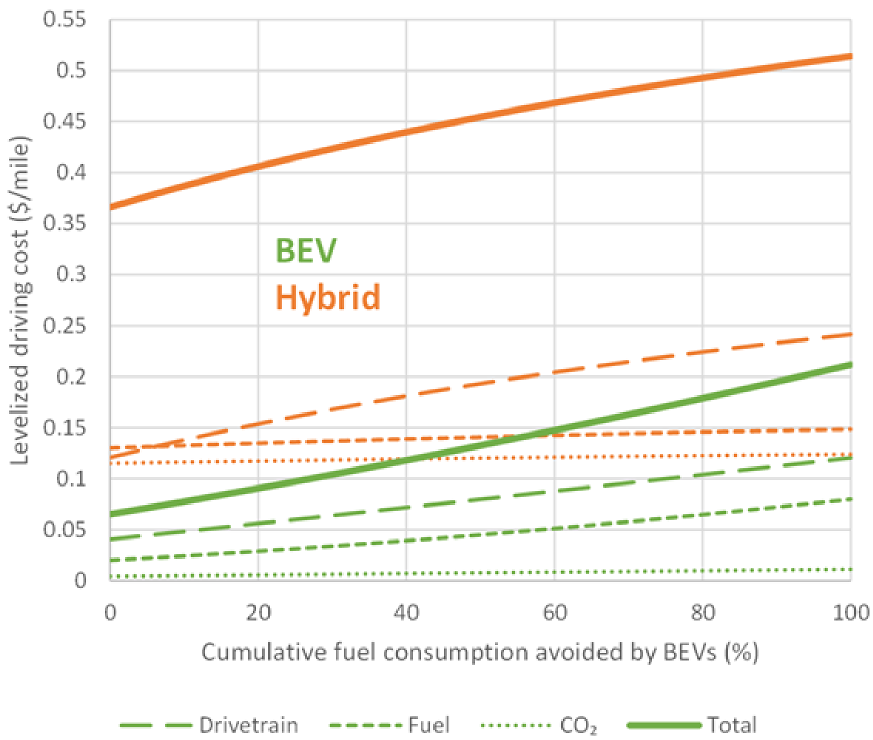
So, after all these considerations, the freedom range of a BEV would be well below half the advertised range.

Charge times and charge point availability are the next issues. DC fast-charging infrastructure has come a long way, but even modern fast chargers at 350 kW are sluggish relative to 20,000 kW from a standard gas pump (10 gallons per minute).

More importantly, **the ubiquitous availability of very fast chargers at a reasonable cost will remain problematic**. The issue is not so much the cost of the charging infrastructure itself, but rather the cost of the grid connection required for very high charging speeds.

A single 350 kW charger needs a grid connection equal to about 70 homes. Even in the city, a connection to the distribution network costs about $75/kW/year, which translates into a levelised cost of $86/MWh at a 10% utilisation factor. When looking at a remote location, this cost would be several times higher because of the need for large upgrades to long transmission and distribution lines. Utilisation factors may also be considerably lower, adding another cost multiplier.

Due to these factors, **ICE cars will retain a sizable "freedom premium" over BEVs in the niches where the car offers the most value to society**. Norway, where incentives are so massive that anyone with any sense would buy a BEV, presents a good example. BEVs account for only about two-thirds of sales despite our graph from Problem 3 looking like this:



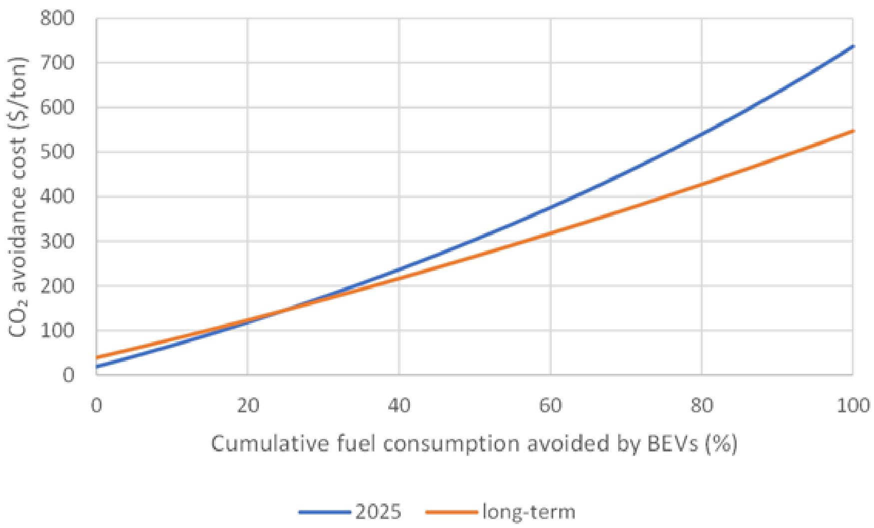
The effect of Norway's enormous ICE taxes on the comparison presented in Problem 3. Additions to hybrid costs include a $23,000 upfront tax and fuel taxes, tolls, and other fees amounting to $0.2/mile. See this previous article for details.

This is the ICE freedom premium in action.

Problem 5: limited CO_2 avoidance at extreme costs

There is no question that BEVs can avoid CO_2 relative to hybrids if the electricity grid is relatively clean. But the potential for CO_2 avoidance is low. **First off, passenger transport accounts for only about 10% of global CO_2 emissions** (see Notes), and this is at a woeful fleetwide fuel efficiency of about 8 litres per 100 km (derived from new car fuel economy trends). **Today's hybrids can already halve this number**.

Second, **almost all the CO_2 avoidance of BEVs will cost more than $100/ton, both in the medium and long term**. **There are many other ways to avoid CO_2 emissions at costs below this price point that should be exploited first**. When adding the freedom premium from the previous section, this cost magnifies further, which is why **Norway currently pays $2,400/ton of CO_2 avoided to push beyond a two-thirds BEV market share**.

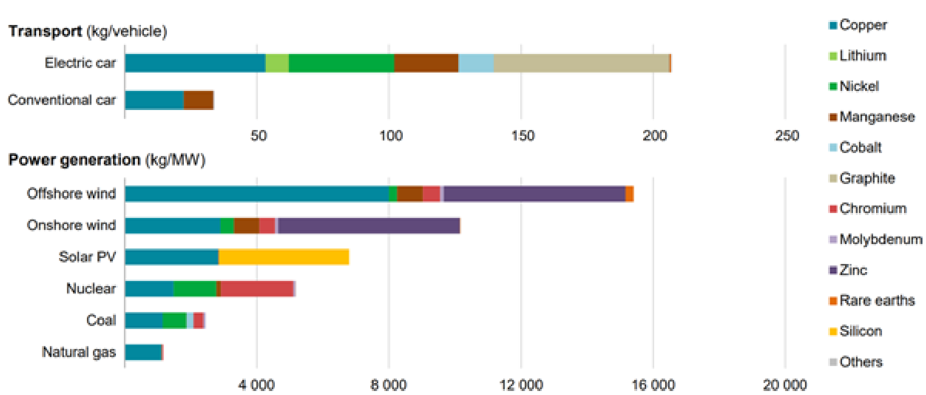


CO2 avoidance costs of BEVs as derived from the cost comparisons presented in Problem 3.

Furthermore, by avoiding social costs of the order of $20,000 per year (see Problem 2), **human-centred city design with a central role for virtual mobility can avoid CO_2 for a massive $14,000/ton less than BEVs**. As mentioned in Problem 3, these savings apply to urban driving on the left of the graph where BEVs work best, making today's massive BEV investment look rather pointless.

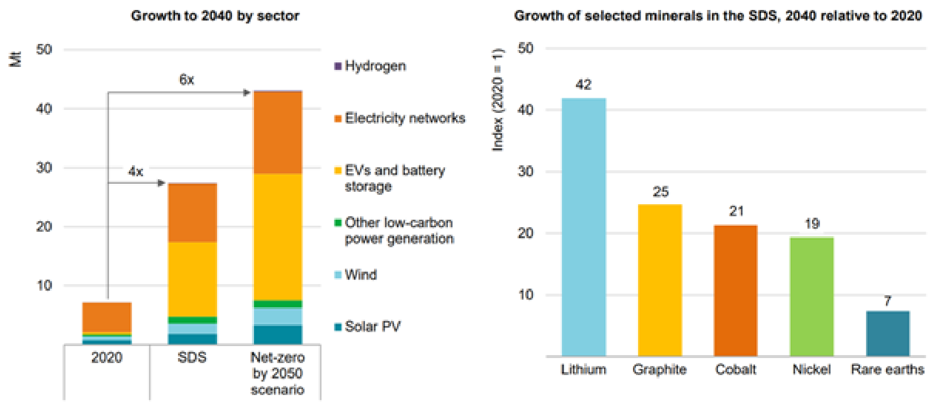
Problem 6: material intensity and waste

Similar to wind and solar power covered in an earlier article, BEVs are much more material-intensive than their ICE counterparts. As shown below, **BEVs require about 6x more critical minerals than conventional cars**.



A comparison of the mineral intensity of new and conventional energy technologies / IMAGE SOURCE

This material intensity will require an **incredible scale-up of mining operations**. Here are the numbers:



Required growth in selected critical minerals / IMAGE SOURCE

There are **many risks associated with such a tremendous mining expansion**. Five of them are highlighted by the IEA:

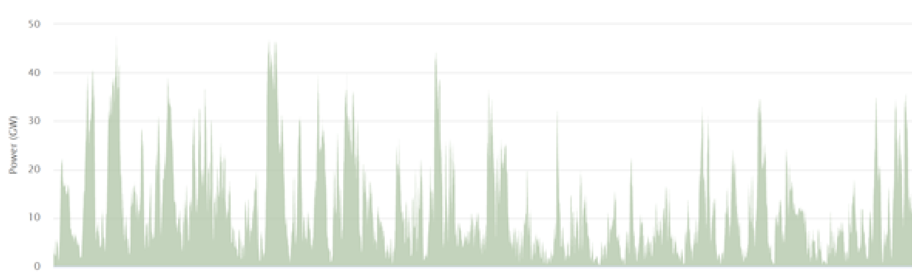
1. Mineral resources are more geographically concentrated than oil and gas, causing considerable geopolitical risks.
2. Mining projects have very long lead times of around 16 years, creating challenges for rapid expansion.
3. Resource quality will decline considerably with increased scale, driving up costs and environmental impacts.
4. Production and processing of these minerals involve a broad range of environmental and social issues that require careful management.
5. Ironically, climate change poses an additional risk, especially regarding water-intensive copper and lithium mining operations concentrated in water-stressed regions.

This high material intensity also brings end-of-life concerns. **If BEVs are to be sustainable, a highly efficient recycling industry will need to boom** while the mining industry busts around mid-century to prevent serious environmental impacts from battery waste. This will be challenging. There are good reasons why **only about 5% of Li-ion batteries are recycled despite their high content of valuable materials like cobalt**. As battery chemistries move away from expensive materials (especially cobalt), profitable recycling will only become more challenging.

Problem 7: low compatibility with Wind and Solar

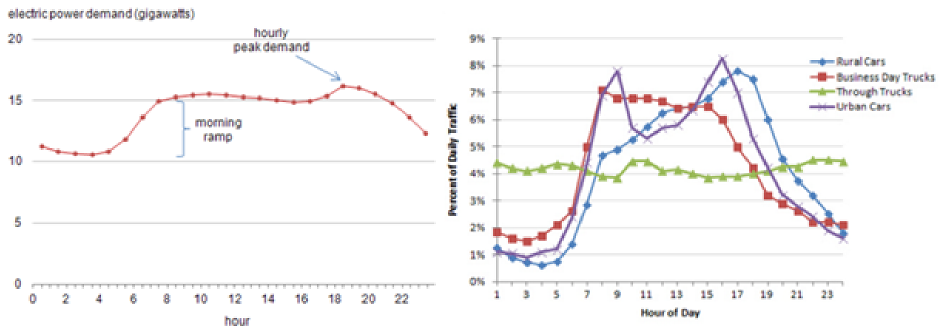
BEVs are often portrayed as good complements to variable and non-dispatchable wind and solar generators. After all, **if the BEV can charge during times of excess wind and sun, it could access cheaper electricity and help integrate more renewables**. It could even discharge when there is little wind and sun to generate some revenue.

Unfortunately, there are **several problems with this idea**. First, implementing such weather-dependent charging and discharging at no inconvenience to the car owner will be very difficult. The only practical option I see is to oversize the battery to reserve a certain excess capacity for such grid services. But this means that people need to buy cars with larger batteries than they need, creating a substantial cost.



German wind power thus far in 2021 (source). Irregular variations over long timescales mean big challenges with integrating BEV charging.

Next, **wind and solar each present their own challenges**. Wind simply varies too irregularly over too long timescales to be a practical option for smart charging. Exploiting such wide-ranging variations effectively will also require unnecessarily large battery packs. Solar, on the other hand, is inherently misaligned with prime charging time: the middle of the night.

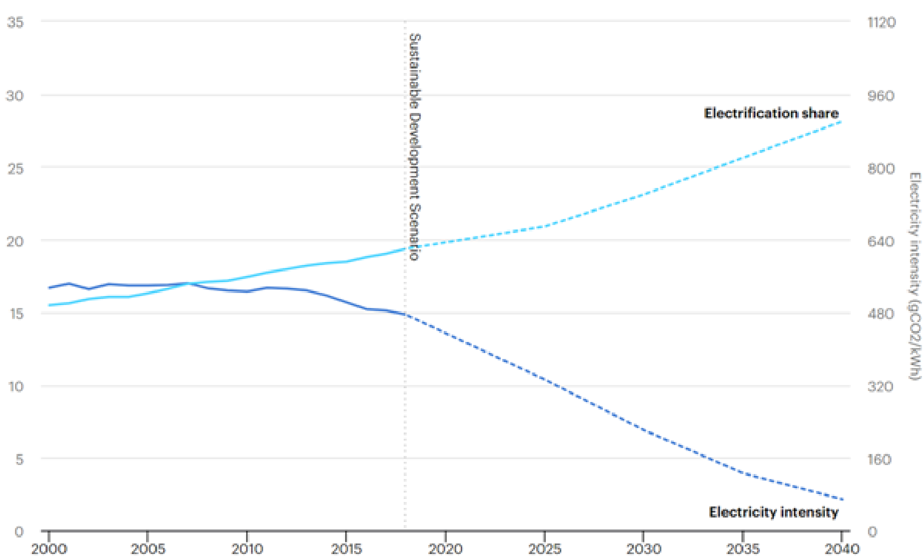


Most cars stand idle at night, conveniently at the same time as electricity demand is lowest. Solar generates electricity at precisely the wrong time to exploit this attractive synergy / IMAGE SOURCES for electricity demand and traffic

The synergy illustrated above makes BEVs (and plug-in hybrids) ideal for integration into a baseload (e.g., nuclear) electricity system. Everyone can conveniently charge their cars at night when demand and prices are low, thus allowing the power plants to operate at a higher capacity factor to lower electricity costs. In addition, charging only during off-peak hours avoids the need for costly grid expansions.

Indeed, **grid expansion is another big challenge for BEV grid integration**. Since BEVs will charge from the low-voltage distribution network, their power needs to flow through hundreds of miles of transmission and distribution lines (and several substations). If they increase the peak system load (as would certainly be the case for solar charging), **the required grid upgrades will quickly erode any economic benefits**.

All told, **nuclear advocates can certainly claim good synergy with BEVs, but wind and solar advocates cannot**. This challenges the notion that electric vehicles can be a leading driver of electrification in a renewables-dominated future where electricity grows far beyond its relatively small share of the current energy mix.

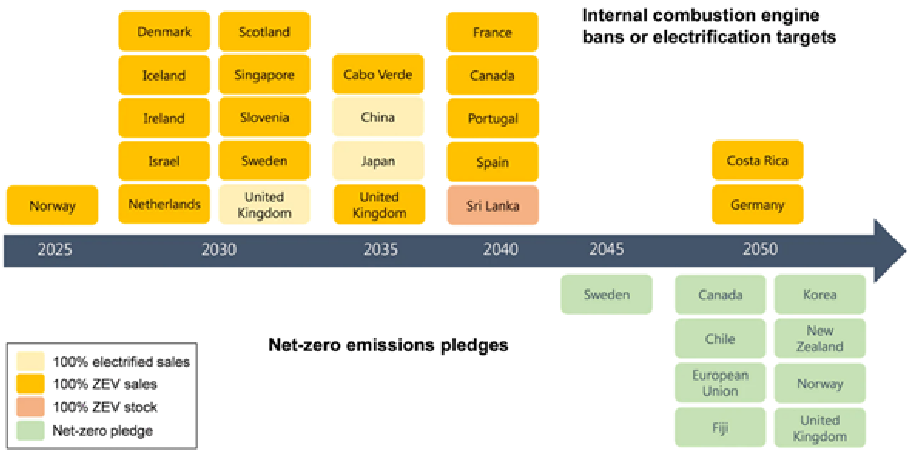


The evolution of electrification in the IEA Sustainable Development Scenario (the left axis shows the percentage share of electricity in the final energy mix) / IMAGE SOURCE

Problem 8: stifling innovation in other clean transportation solutions

The BEV sector is **attracting tremendous amounts of capital**, largely based on a 2-part investment thesis: **1) almost all cars must be zero-emission by 2050**, and **2) cars will remain the dominant mode of personal transportation**.

Several countries have announced imminent bans on ICE vehicle sales to comply with this narrative (and to exploit the climate action poster child mentioned in the introduction). Since BEVs are the most mature non-ICE technology option, such strict timelines make them the only viable option in such a scenario. Hence, the BEV investment boom.

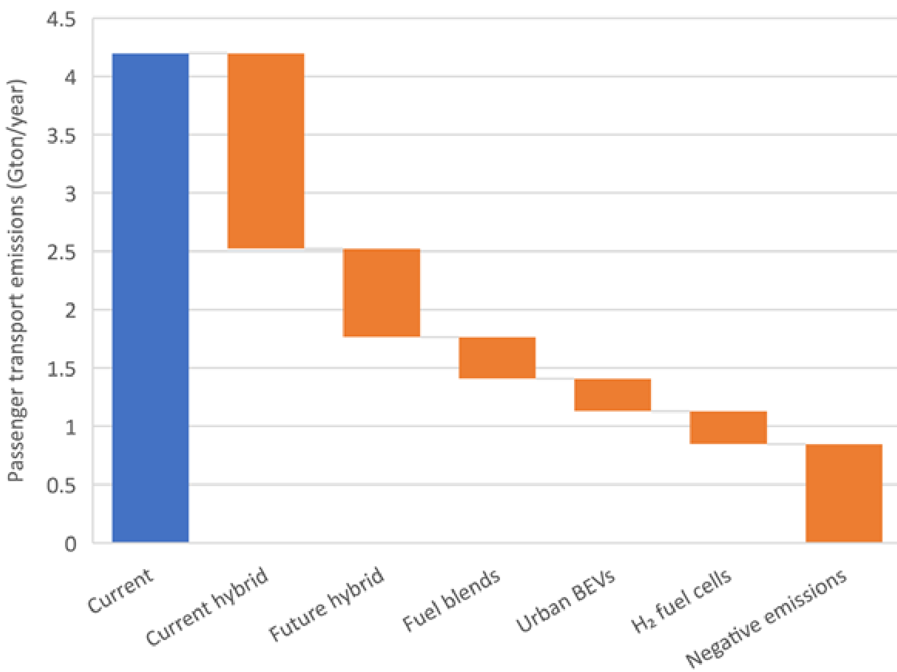


Policy mandates for electric cars / IMAGE SOURCE

But **there is a much more attractive alternative 2-part investment philosophy at our disposal**: 1) a **technology-neutral climate change mitigation framework** incentivises an economy optimised for \$100–200/ton CO_2 prices by 2050 that 2) includes a **reimagined personal mobility sector with a much smaller role for the urban car**.

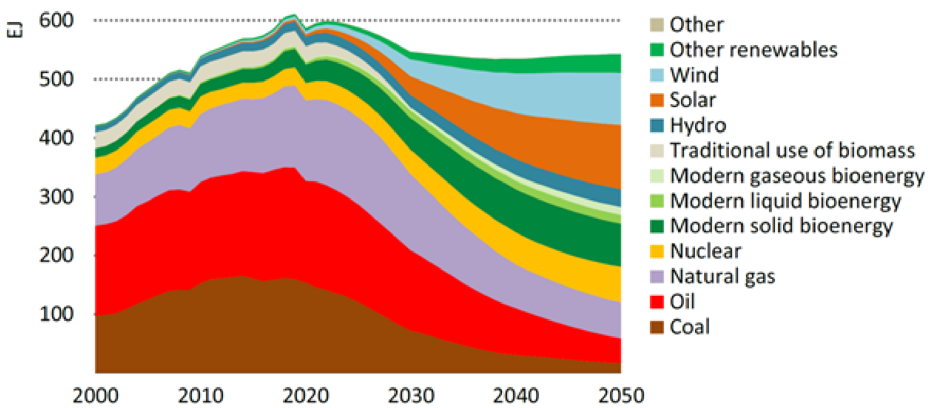
In such a scenario, **the old ICE still has a lot to give, halving fuel consumption**. If urban driving is largely displaced by human-oriented city design and virtual mobility (see Problem 1), fuel savings can be even greater as driving happens mostly on the highway where the ICE is at its best.

As illustrated below, **hybridised ICE drivetrains can cut global passenger transportation CO_2 emissions by more than half. BEVs applied in their best niches, gasoline blends with lower-carbon fuels, and fuel cell vehicles could halve emissions again, reducing the global total below 1 Gton/year**.



An illustrative breakdown of passenger transport emissions reductions in a technology-neutral policy framework. See the Notes for more details.

Yes, that magical zero-emission goal is not achievable with such a strategy, but it really is quite silly to aim for zero in each individual economic sector. The **negative-emission potential of biomass with CO_2 capture in the power and industrial sectors is about 10 Gton/year** (see below). And this is just one of many ways to achieve negative emissions.



Sustainable bioenergy can expand to 100 EJ/year. At 0.1 tons of CO_2 per GJ, this equates to a negative CO_2 emission potential of 10 Gton/year / IMAGE SOURCE

Given the attractiveness of a future with minimal urban cars and maximum freedom delivered by rural cars, it would be a **real shame if BEV technology-forcing policies keep directing investment flows away from better ICE hybrid drivetrains, cleaner fuels, and fuel cell drivetrains**.

Problem 9: low compatibility with Autonomous Driving Technology

The future of autonomous driving technology is still uncertain. The massive hype from a few years ago has died down somewhat as the industry comes to terms with an intimidating list of technical and political challenges.

Nonetheless, **autonomous cars will almost certainly become a reality at some point in the future, changing car design priorities**. The three main change drivers include the following:

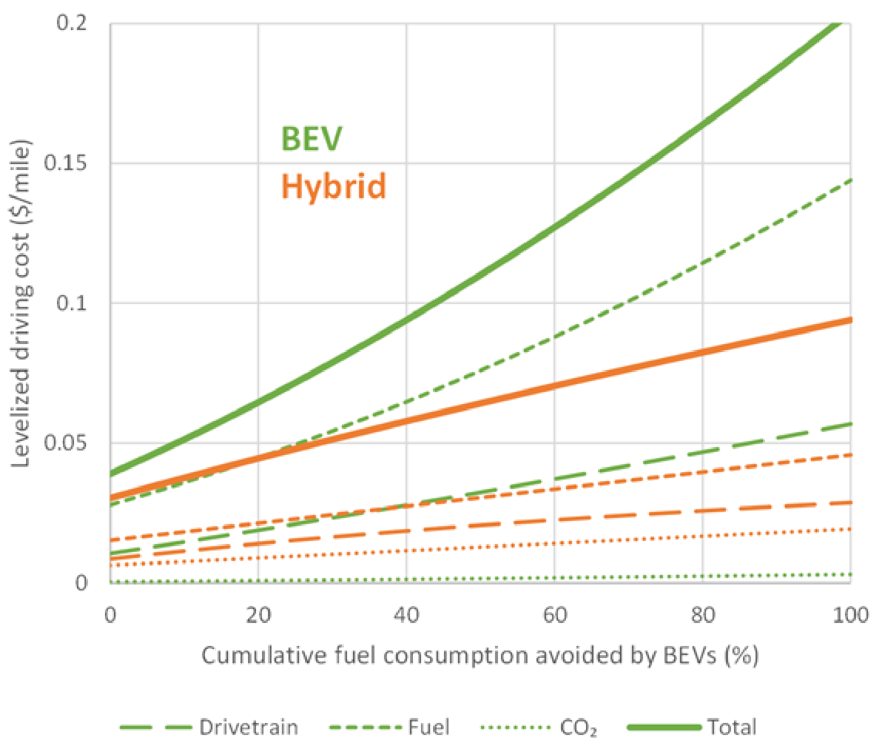
1. Higher utilisation rates
2. Smoother driving patterns
3. Higher highway speeds

The first factor will have both positive and negative consequences for BEVs, but the remaining two play right into the hands of the ICE.

Higher utilisation rates mean that the cost of a large battery pack can be recovered faster. However, it also implies a **higher fraction of costly fast charging to ensure that the car is always available for use**.

Smoother driving patterns are ideal for the ICE. If the engine can continuously operate in its optimal band, efficiency and lifetime increase, whereas emissions and maintenance costs reduce. Steady operating patterns also simplify the implementation of advanced engines and enable substantial engine downsizing.

Higher highway speeds considerably increase range requirements and reduce fuel efficiency. These effects will make the BEV battery pack more expensive while increasing the BEV fuel cost disadvantage.

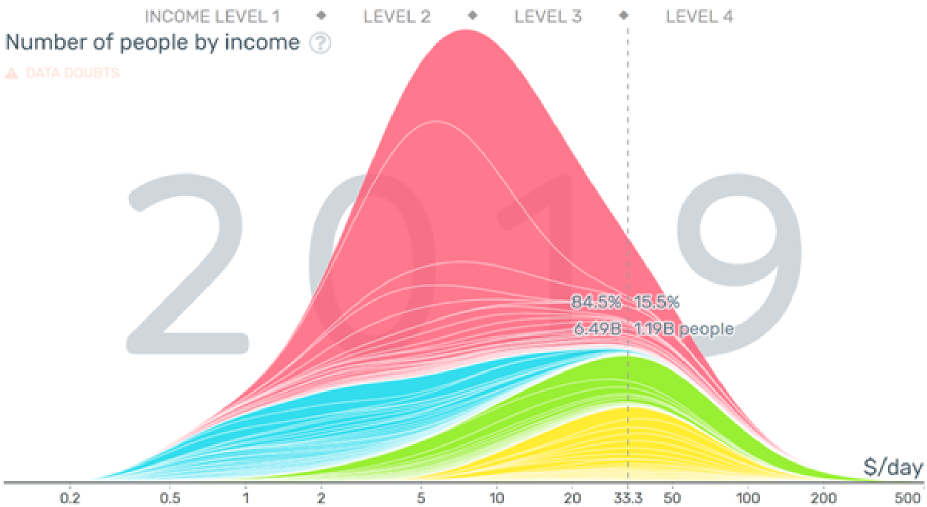


Long-term drivetrain, fuel, and CO2 costs for a BEV and a hybrid using autonomous driving technology. Compared to the long-term costs shown in Problem 2, the changes include: 1) 4x greater annual mileage and half the total lifetime, 2) a 10% reduction in hybrid fuel consumption with highway efficiency across the range, 3) 20% more fast charging, 4) 200 miles more range and 200 Wh/mile higher energy consumption at the top end (high highway speeds).

When all these factors are considered, **the CO_2 avoidance costs of BEVs relative to hybrids increase from $39–547/ton (calculated in Problem 5) to $224–779/ton**. Whereas non-autonomous BEVs can at least avoid around 20% of overall fleet emissions below a reasonable future CO_2 price of $150/ton, even these niches are likely to become uneconomical with autonomous cars.

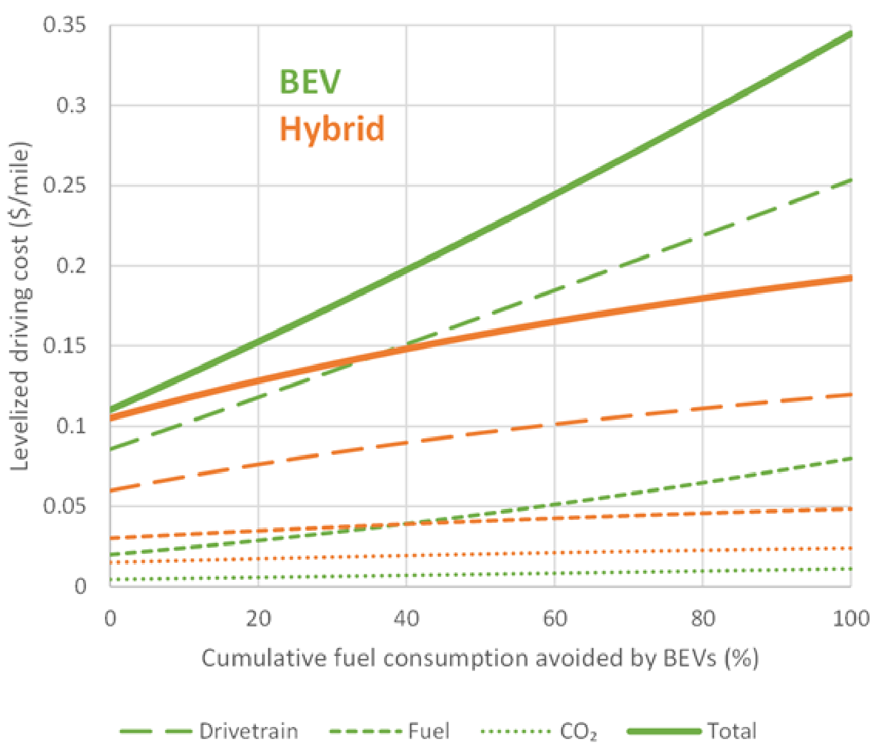
Problem 10: competition with economic upliftment

As outlined in a previous article on wind and solar power, a big challenge with clean energy is its capital-intensive nature. If the world was already properly developed, this would not be much of a problem. Unfortunately, **about 80% of the world remains underdeveloped, requiring massive capital expenses to uplift people to decent living standards**.



The global income distribution from Gapminder. The vertical line shows $1,000/month ($33/day).

Capital-intensive technologies like BEVs with large battery packs compete with all the infrastructure needed for economic upliftment (housing, schools, hospitals, etc.). To accurately reflect this competition in an environment of rapid decarbonisation, a discount rate of 12–16% needs to be applied, significantly increasing the levelised capital cost of all technologies.



BEV and Hybrid drivetrain, fuel, and CO2 costs in 2025 with the discount rate increased from the value of 5% used in Problem 3 to 16%, which is representative of rapid decarbonisation in a developing nation.

When a welfare-optimal 16% discount rate is applied in the figure above, **the CO_2 avoidance cost of BEVs in 2025 increases from $19–737/ton to $146–1279/ton due to the higher capital cost of BEVs**.

And it's not just the BEV drivetrains themselves that are capital-intensive. The BEV-dominated future envisioned by advocates will require **massive additional investments in mines, material processing, battery manufacturing, charging infrastructure, electricity grids, and recycling capacity**. If all these investments are correctly discounted at 12–16%, it will show that **the welfare-optimal cost of batteries and charging in a rapid BEV transition is much higher than commonly assumed**.

It should also be noted that most of the capital costs of a car are unrelated to the drivetrain. Any personal mobility philosophy that can reduce these non-drivetrain costs can benefit the energy transition. Higher capital utilisation via autonomous driving technology could play an important role here, although it remains to be seen whether fully autonomous cars can become a reality in time.

However, the biggest potential gain comes from the virtual mobility solutions mentioned in Problem 1. **Avoiding most urban car travel entirely will free a large amount of capital for more useful purposes** (aside from avoiding lots of cars, it can also avoid roads, parking spaces, and office buildings). **Hopefully, this holistic personal mobility solution prevails over the short-sighted paradigm of perpetuating car-dominated cities using BEVs**.

Conclusions

This article is basically one long contrast between **two opposing visions for the future of personal mobility**:

1. **Technology-forcing of BEVs** to approach zero emissions in a passenger transportation system that remains completely dependent on cars.
2. **A technology-neutral system that fully internalises all the societal costs of urban car transportation**. Such a system will correctly incentivise people-oriented cities with a central role for virtual mobility and avoid forcing BEVs into niches with excessive CO_2 avoidance costs.

Even though Option 2 is far more desirable, our existing car-centred paradigm means that the current policy landscape and investment momentum are with Option 1. Powerful forces support this trend. For example, **electric cars are an important source of the consumption growth and climate virtue-signalling** prized by governments around the world, and **powerful auto lobbies** will support any policy that helps automakers sell more cars. These twisted incentives will hamper our ongoing efforts to balance true economic upliftment and environmental protection in the 21st century.

I should also emphasise that BEVs have a role to play in Option 2 (see the graph in Problem 8). Despite the serious inefficiencies, **the BEV-friendly niches covered in Problem 2 will remain a necessity for many people**. Here, BEVs can help, but we should be very careful to treat them as an interim solution in a transforming urban environment and not as an excuse to perpetuate car-centred city design.

Hopefully, the ten problems outlined in this article did their little bit to strengthen the case for a shift to the holistic solution offered by Option 2. It promises a highly attractive future with far fewer cars, much more liveable cities, and an overall richer and happier society.

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Notes

Car commuter cost (Problem 2)

The average car ownership cost is $0.64/mile and the inflation-adjusted value of time is $22/hour. For an average daily commute of 32 miles in 1 hour, 230 days of work would cost $4710/year in driving and $5060/year in time.

A standard office space costs about $50/ft with 125 ft2/person being the recommended space allocation. This results in costs of $6350/year.

Parking costs about $15,000 to construct. Assuming a 50-year lifetime with a 7% discount rate amounts to an annual levelized cost of $1089.

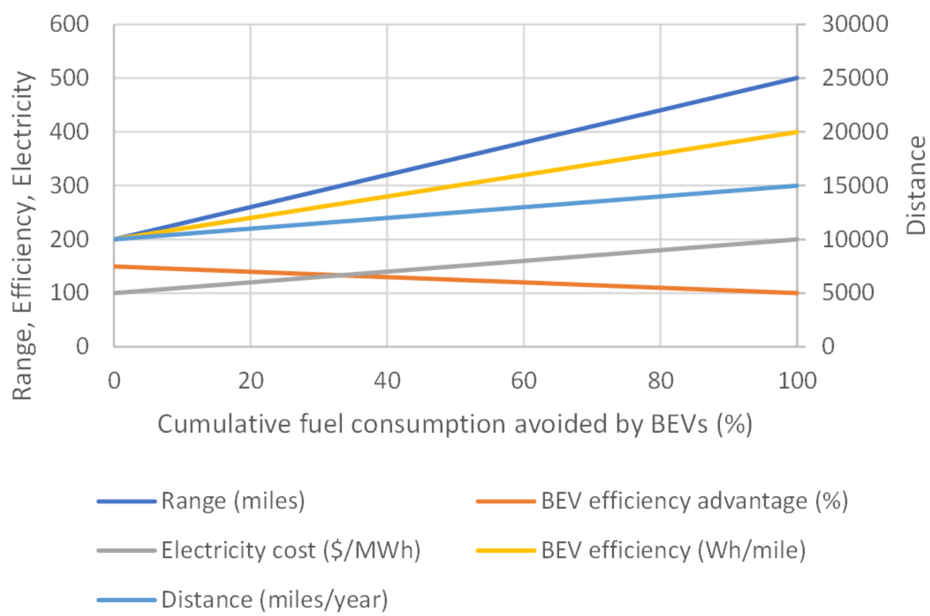
An average 264 ft2 garage at the average cost of $123/ft2 would add $32,500 to the price of a home. With 2% annual maintenance, this amounts to $3000/year for a 50-year lifetime discounted at 7%.

There are many other societal benefits to removing many commuting cars from the road. The city would become more liveable and safer, healthy levels of physical activity would be much more natural, people who still have to drive would save plenty of time and stress, and road construction and maintenance costs would decline. It is hard to estimate these benefits, so although I think they would total well over $10,000/year, we'll take $3000/year as a conservative estimate.

BEV/Hybrid cost comparison (Problem 3)

The comparison is a simple way of looking at the drivetrain, fuel, and CO_2 costs of a BEV and a hybrid car across market niches. A key assumption is that all other costs are similar between BEVs and hybrids. For example, BEVs may have slightly lower maintenance costs, but higher insurance costs generally cancel out these minor savings (e.g., Leaf vs. Prius).

Here is a graph of key assumptions:



Key assumptions employed in the simplified cost assessment presented in Problem 3. The left of the graph represents small commuter cars and the right represents large rural vehicles.

The minimum BEV range requirement is taken as 200 miles, rising to 500 miles at the top end (which may be conservatively low given the limited "freedom range" discussed in Problem 4).

Electricity costs are assumed to be $100/MWh for home charging (below average US rates to account for night charging) and $300/MWh for public fast charging (similar to Tesla superchargers), with 100% home charging on the left and 50% home charging on the right of the graph.

Larger rural vehicles are assumed to cover 50% more annual miles than small urban vehicles.

For city driving on the left of the graph, BEVs are assumed to be 150% more efficient than hybrids, while this advantage drops to 100% on the right (based on BEV and hybrid models from Kia and Hyundai).

BEV fuel efficiencies are taken from studying the rated efficiencies of various models representing small city cars on the left and full-size SUVs or pickups on the right.

Other important assumptions include the following:

- Drivetrain costs of $2800 for the BEV and $7100 for the hybrid (source). The drivetrain costs are applied to the middle of the range and scaled linearly with the BEV efficiency, assuming that larger vehicles will have larger drivetrains. The extra cost of a home charging station is neglected.
- Battery costs of $100/kWh by 2025 and 50/kWh in the long term.
- A 25% long-term reduction in hybrid drivetrain cost and fuel consumption. Fuel reductions are based on Mazda's long-term efficiency target and Nissan already cracking 50%. Cost reductions are expected from cheaper batteries enabling large ICE downsizing.
- Annualization of drivetrain and battery costs over a 20-year lifetime with a 5% discount rate.
- Oil prices of $55/barrel in 2025 and $50/barrel in the long term (based on IEA scenarios). Additional refinement and distribution costs of $0.75/gallon are added.
- A 20% hybrid CO_2 emission reduction in the long-term via blending with biofuels and other synfuels.
- BEV battery CO_2 emissions of 100 kg/kWh by 2025 and 25 kg/kWh in the long term.
- Highly decarbonized electricity that emits 128 kg of CO_2 per MWh by 2025 (based on the IEA Sustainable Development Scenario for the US by 2030) and 0 kg in the long term. It is assumed that this decarbonization will not raise electricity costs (a highly optimistic assumption).

BEV freedom range (Problem 4)

The practical range that the Volkswagen ID4 would be able to deliver under any conditions on a road trip is much lower than the advertised range:

- It is rated at 250–260 miles of range in mixed driving. City-oriented use should yield an even greater range.
- For highway driving, however, the range may fall to 190 miles.
- If it's around freezing point, you're looking at 160 miles. Very cold (or very hot) days can be even worse.
- After some years with battery degradation, perhaps this goes down to about 140 miles.
- On a road trip, it's too risky to go all the way to the limit, so you might want to drive only about 120 miles on a cold or hot day before recharging.
- When recharging, you can reach 80% in a reasonable time, but getting a full charge could take too long, cutting the practical range to 100 miles.
- If advanced driver-assistance tech one day safely increases highway speed limits, these restrictions will become even more severe.

Share of passenger transport in global CO_2 (Problem 5)

The passenger transport sector (cars, buses, and two-wheelers) consumes about 27 million barrels of oil per day, and each barrel emits about 0.43 tons of CO_2 for about 4.2 Gton of CO_2 per year. Global CO_2 emissions from human activities (mainly fossil fuel combustion, cement production, and land-use change) amounted to 43 Gton in 2019 (with a temporary reduction to 40 Gton in 2020). Thus, passenger transport has a 10% share of CO_2 emissions.

Technology-neutral CO_2 emissions reductions (Problem 8)

The first assumption in this assessment is that people-oriented cities (e.g., public transport, walking, cycling, electric 2-wheelers, and mobility scooters) and virtual mobility (e.g., VR-based telecommuting and online retail) cancel out future growth in car travel demand. These highly attractive mobility options could actually reduce car travel demand, but we will make a conservative assumption that demand stays constant.

Current hybrids can reduce fuel consumption by at least 40% relative to the current global fleet (see comparisons to models from a decade ago). Future hybrid efficiency improvements can drop fuel consumption by another 30% by reaching thermal efficiencies in the mid-50% range and using smart energy management strategies enabled by a larger battery capacity.

Fuel blending can substantially reduce ICE CO_2 emissions, especially if total fuel consumption drops considerably as described above. However, electricity, hydrogen, and heat production with CO_2 capture for negative emissions will probably be the best use of biomass in the future. Thus, CO_2 emission reductions of only 20% are assumed, similar to what can be achieved with current total biofuel production (if it is done sustainably).

BEVs are assumed to displace 20% of efficient future hybrids based on the CO_2 avoidance costs in Problem 5. This will be lower if human-oriented cities greatly reduce the demand for urban car transport.

Fuel cells involve greater uncertainty. Their best niche is structured transport solutions with high utilization rates (e.g., buses or taxis). Such options can use a small number of large H_2 refuelling stations at a high utilization rate, greatly reducing H_2 fuel costs. In this event, I estimate that fuel cell vehicles can displace about 20% of future hybrid drivetrains.

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