Electric trucks: economically and environmentally desirable but misunderstood

Auke Hoekstra

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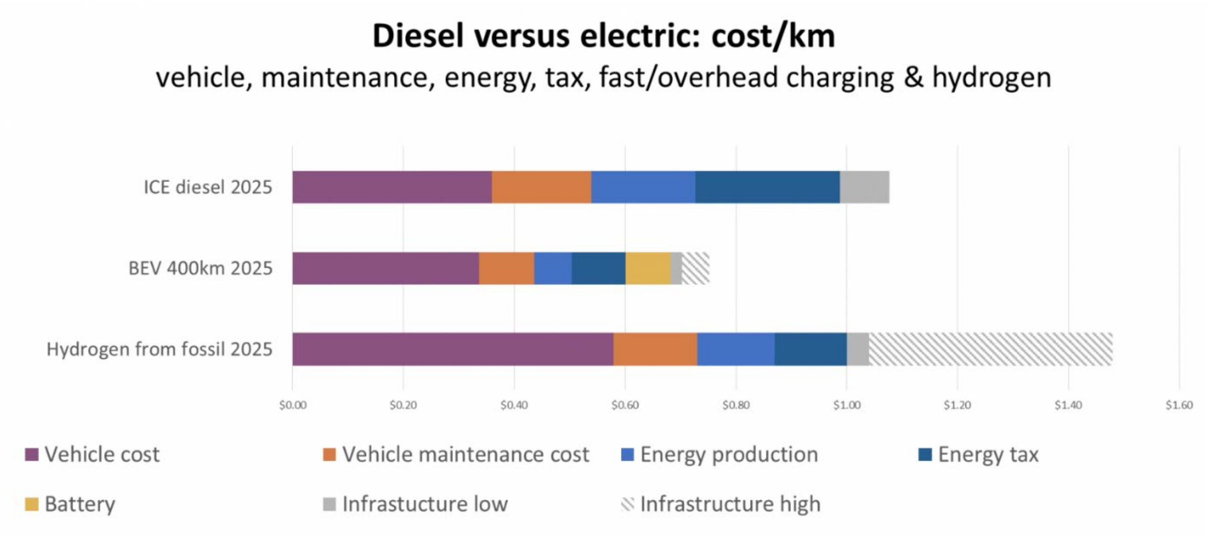
By Auke Hoekstra

In this blog series we will calculate the cost per kilometer of a heavy-duty long-haul battery electric truck. The real thing! We add this option to the comprehensive report "The Future of Trucks" that the International Energy Agency published this month. This report strangely omits this option from its comparison, even though we will see it is both the best way to combat global warming and to decrease costs. The end results are shown below and explained in detail in this blog series.



A counter narrative to the myth that heavy trucks cannot be electrified

When a distinguished but elderly scientist states that something is possible, he is almost certainly right.
When he states that something is impossible, he is very probably wrong.

Arthur C. Clarke's first law [1]

Allow me to start our short journey with a warning: you must be able to look past the *experts of the old* if you want to learn about disruptive innovations. The *experts of the old* are distinguished gentlemen and gentlewomen who speak with authority because they are part of a venerable tradition that has been studying a domain for many, many years. In the stable domains of energy and mobility their influence has become especially strong. They are connected to the largest companies and most prestigious institutions.

We should take them, and their facts, *very* seriously. However, they are only human. Just like everyone else they are prone to confirmation bias and groupthink [2], [3]. Individually they have trouble envisioning the disruption of the system they are the high priests of, and as a group they are immune to talk of disruptive solutions.

If I would have believed what *experts of the old* said about sustainable energy and electric road transport I would have hung my head in despair ten years ago. Fortunately I had already experienced similar opposition in my previous career as a consultant. I touted the potential of PCs, Internet, WWW, mobile phones and smartphones very early on and this invariably brought me into conflict with *experts of the old*. Often the old technology had to be wiped out before they started to come around. You could say this past experience inoculated me against the conservative bias they exude.

In 2007 I wrote that the fossil experts of oil companies and the international energy agency (IEA) kept failing to grasp or accept the rise of solar panels. Recently I've shown that this has been going on for more than fifteen years now. I'll admit that the attention this got was gratifying but for me this was a side issue. This article series focusses on my main research: the electrification of road transportation and its synergy with sustainable energy and the electricity grid.

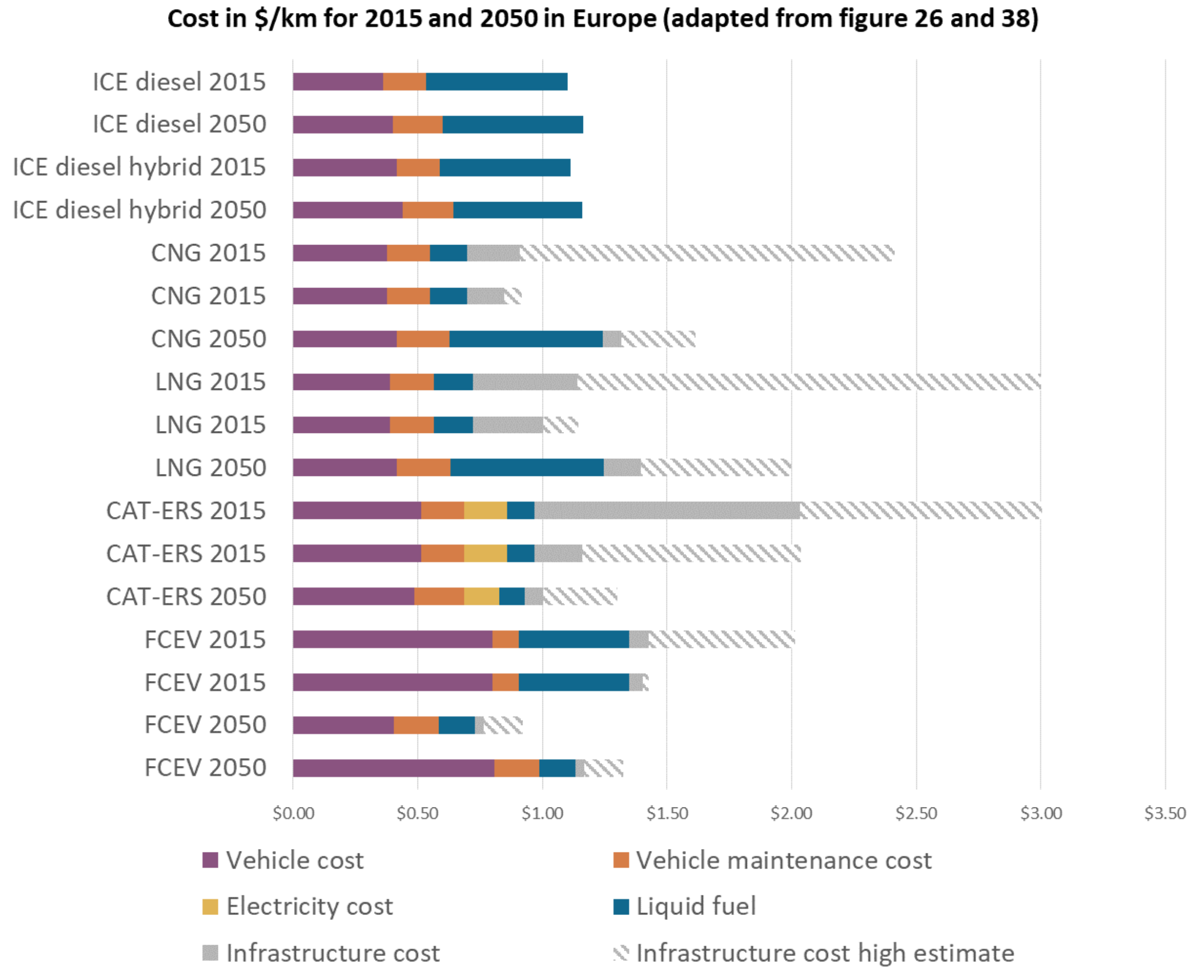
Since I started researching it for myself in 2005 there has been a remarkable shift in the attitudes towards electric personal transportation. My first book (2009) was mainly about convincing people that electric cars were possible at all. Now I'm asked to give lectures like debunking the myths hampering the electric car (in Dutch with English subtitles) and to talk about our future full of electric cars to Dutch members of parliament. By now most politicians and policy makers I talk to believe that we will make the switch to electric cars relatively quick.

But the discussion in road freight transport is like a journey back in time. *Experts of the old* are still perpetuating **the myth that heavy trucks cannot be electrified**. This keeps us from building the electric trucks and the charging infrastructure we need. I think that's bad because electric trucks are the only realistic way to radically reduce road transport CO2 emissions. This blog series is meant to put a can-do counter-narrative out there.

Adding a battery electric truck scenario to the new IEA report "The Future of Trucks"

I think the timing is right because this month the International Energy Agency (IEA) came out with a 167 page report called "The Future of Trucks". The IEA is the most influential organization in the field and the report deserves praise because it is chockfull of facts and perspectives. This makes it an invaluable starting point for any analysis of the future road freight system including mine. However, the report completely ignores battery electric trucks in its scenario analysis.

I've recreated all the scenarios the IEA has considered for Europe and the figure below shows the result. For me it summarizes the report and shows the conservative mindset that created it.



ICE diesel and ICE hybrid are basically same old same old. They are almost indistinguishable from each other. The IEA seems to think hybrids for long hauls are of questionable value (and says as much on e.g. page 75). Going forward modest increases in fuel efficiency are negated by modest increases in fuel cost.

CNG and LNG had a business case in 2015 because of cheap fuel. In the long run this advantage will disappear because diesel becomes cleaner and there are no CO2 advantages to CNG and LNG. That's what the IEA numbers say. Nothing to see here either.

CAT-ERS stands for Catenary Electrified Road System. Basically a diesel truck that can drive as a trolley on roads that have a power line overhead. But why would a truck that drives 80% of its kilometers using an overhead wire still use an internal combustion engine with its cost and maintenance? Why is the overhead line depreciated in just five years? I think conservative thinking managed to mess up this scenario and will revisit it in my last post.

FCEV stands for fuel cell electric vehicle: a hydrogen truck. You can see that some experts at the table were very optimistic about the price-performance improvements in 2050 while others didn't buy it. I can tell you already that electric trucks would be cheaper than hydrogen in almost all cases if the same amount of optimism was applied. Nevertheless there certainly is a place for hydrogen in a renewable energy system as we will see in my last post.

One sentence on page 105 is all the explanation we get for omitting electric trucks: “Battery-electric and plug?in hybrid vehicles are excluded from Figure 26 for simplicity, given the focus on long-haul mission profiles.” But looking at the unspectacular alternatives I think we should give it a try. I think that I can use the IEA’s own numbers and methodology to add a new scenario and to show that electric trucks are our best option. Not only environmentally but also economically.

I’ll make that case in four more posts (chapters) that correspond to the four most important components you can use to evaluate each option. See table below, with links to the single chapters.

	Chapter 1 Energy supply	Chapter 2 Motor	Chapter 3 Energy storage	Chapter 4 Energy delivery
Diesel	Fuel	<30% efficient	Gasoline tank	Gas stations
Electric	Electricity	>85% efficient	Battery	Chargers

In chapter one I'll talk about the most important factor: energy supply. I’ll show that we cannot rely on biofuels to replace oil and how this basically rules out the internal combustion engine from the get go.

In chapter two I’ll show how the electric truck pulls ahead because of the electric motors lower energy and maintenance cost.

In chapter three we will see that dramatic developments in batteries make electric trucks not only possible but even probable.

In chapter four we will look at all the ways you can charge these batteries, including fast charging, electrified road systems and hydrogen. I’ll show there is a charging solution for every business case.

My past experience with the *experts of the old* tells me that the IEA will probably not change its tune. But I dare you, dear reader, to tell me in the comments where my facts are wrong or my argumentation goes awry. I will also use your feedback to improve the scientific article I’m currently writing and I will credit you in the acknowledgements of the paper if I think you’ve come up with substantial facts and/or argumentation. I look forward to the discussion!

References

[1] A. C. Clarke, *Profiles of the Future*. New York: Warner Books Inc, 1985.

[2] R. Nickerson, “Confirmation bias: a ubiquitous phenomenon in many guises,” *Rev. Gen. Psychol.*, vol. 2, no. 2, pp. 175–220, 1998.

[3] T. Postmes, R. Spears, and S. Cihangir, “Quality of decision making and group norms.,” *J. Pers. Soc. Psychol.*, vol. 80, no. 6, pp. 918–930, 2001.

Electric trucks, chapter 1: Energy supply

[in the blog series: Electric trucks: economically and environmentally desirable but misunderstood]

By Auke Hoekstra

	Chapter 1 Energy supply	Chapter 2 Motor	Chapter 3 Energy storage	Chapter 4 Energy delivery
Diesel	Fuel	<30% efficient	Gasoline tank	Gas stations
Electric	Electricity	>85% efficient	Battery	Chargers

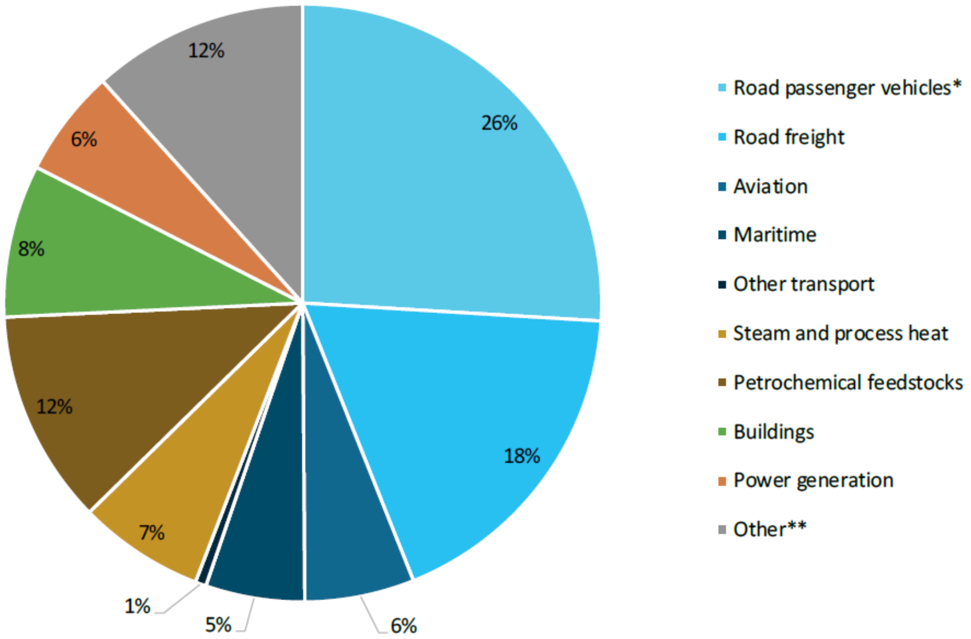
We are all passengers on "spaceship earth": a relatively small rock in an endless universe with thin sliver of life on its surface. But all is not well. We are unbalancing the wisp of air above us called the atmosphere by burning fossil fuels. Simultaneously we are exhausting the thin fertile carpet below us called topsoil. Biofuels are an attempt to save the atmosphere by exhausting the topsoil even faster: a recipe for disaster. Once you realize that we have to avoid *both* fossil fuels *and* biofuels you understand that electric transportation is the only way forward.

This chapter explains the point in more detail and illustrates how biofuels compete with nature and humans for scarce fertile topsoil and fresh water. It calculates that oil already provides *seven* times as much energy as *all humans eat* while a *single heavy truck* "eats" as much as *750 humans*.

Road freight is important

On page 17 the IEA provides a helpful chart (figure 1) that describes how we use our oil. As you can see 26% goes to passenger vehicles which is why many experts (me included) focused their energy on that first. But now that the option to electrify passenger vehicles is firmly established (see introduction) we must focus on the whopping 18% of oil that goes to road freight.

Figure 1 • Sectoral consumption of oil in 2015 (mb/d, primary energy)



* Passenger vehicles include buses and two- and three-wheelers.

** Includes agriculture, transformation and other non-energy use (mainly bitumen and lubricants).

Note: The percentages show the shares of oil consumption in 2015.

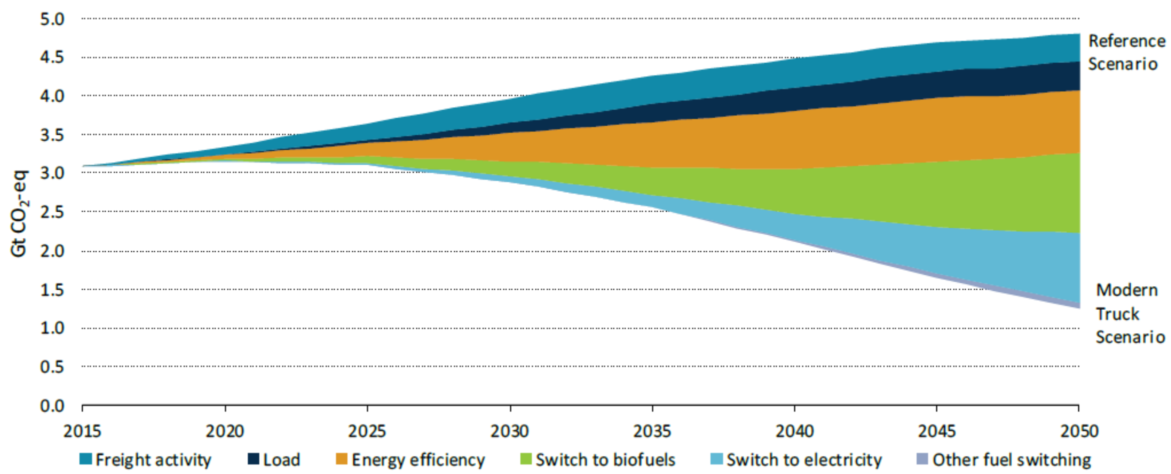
Source: IEA (2016a).

Conventional engines need fossil fuels or biofuels and both are bad

Right now road freight runs on fossil fuels. Almost all heavy trucks run on diesel because diesel engines can be made a bit more efficient and hence use less fuel than gasoline engines. Making a really good diesel engine that is also clean is expensive but since heavy-duty vehicles use so much energy this makes the needed investment worthwhile. The IEA report states (page 85-86) that CNG and LNG are interesting alternatives because they are better for the air quality in cities but that it is questionable if they reduce CO2 emissions at all.

So in order to achieve significant CO2 reductions the report turns to efficiency, electrification and – most of all – biofuels. Figure 39 shows that biofuels will provide the biggest CO2 reduction of all the measures the IEA proposes in its Modern Truck Scenario. This is both too little and too much. It is not enough if we want to stick to the Paris accord but simultaneously it is way too much if we want to keep spaceship earth a fun and livable place.

Figure 39 • Contribution to GHG emissions reductions by measure in the Modern Truck Scenario, relative to the Reference Scenario



I think people honestly advocating biofuels in order to mitigate climate change are unaware or in denial about how out of hand things have become since we have begun using fossil fuels. The following table breaks down the daily energy needs of a well fed human being, a car and a heavy truck.

Daily energy needs of a human, a car and a heavy truck (i)			
	kWh	liters of oil equivalent	factor
Human	4	0.4	1
Car	40	4	10
Heavy Truck	1500	150	375

Are we really thinking we can feed all our cars and trucks without having an impact on hunger or nature? **Already the oil we produce contains seven times more energy than what we eat worldwide (ii)**. If we want to provide all the ten billion people we expect in 2100 with the energy currently used by Americans we would need to feed our machines about a hundred times as much as we currently feed ourselves (**iii**). In what imaginary world is that even possible?

Rather we should try to put *less* pressure on our agricultural system. Depleting aquifers [2] are already causing food crises [3] and if we don't stop our abuse of topsoil our agricultural output will plummet (please read the links if you doubt that) [4]–[7]. Feeding humanity will be huge challenge, even without our growing appetite for meat. Adding biofuels to the mix is a recipe for disaster.

If the above argumentation and links have not convinced you yet, many scientific papers have already pointed out how commercially viable biofuels compete with food [8]–[10]

and nature [11]–[14] for globally scarce fertile topsoil and fresh water [16]. Palm oil is just one of the many examples [15]. The only way to "solve" this issue is by hypothesizing that somehow agriculture will become *much* more productive and that land use change can be avoided by globally enforced rules. This is theoretically possible but not very realistic. Literature that assesses land use change based on observed reality instead of hypothesized ideal situations concludes that commercially viable biofuels are actually worse for the planet than fossil fuels [17]–[19]. The UN rapporteur on food has even called it a crime against humanity [20].

So why are we still pretending biofuels are the solution? Well, biofuels fit neatly into the perspective of *experts of the old,* especially if they just look at the mobility system. The IEA report is a good example. On page 90 it states: "The long-term role for crop-based biofuels in decarbonizing heavy-duty transport in certain markets will depend on the extent to which the land-use change debate can be clarified." But after this cryptic warning it proceeds to ignoring the elephant in the room. Furthermore, biofuels are business as usual from a vehicle perspective and thus popular with car makers. Agricultural lobbyist push it as a new and potentially lucrative crop. Oil lobbyist push it because it's close to oil's current business model and can be processed by their refineries. That's three powerful lobbies supported by the *experts of the old*.

Now I know biofuels are also promoted by well meaning greenies and farmers that point to their lovingly cultivated patch of land and say: "I'm doing my part. I'm not hurting anybody. How can this be wrong?" So I feel like a party pooper but am obliged to tell it like it is: biofuels are a solution that predates the industrial revolution and in modern times it's broad application would result in even more problems than burning fossil fuels.

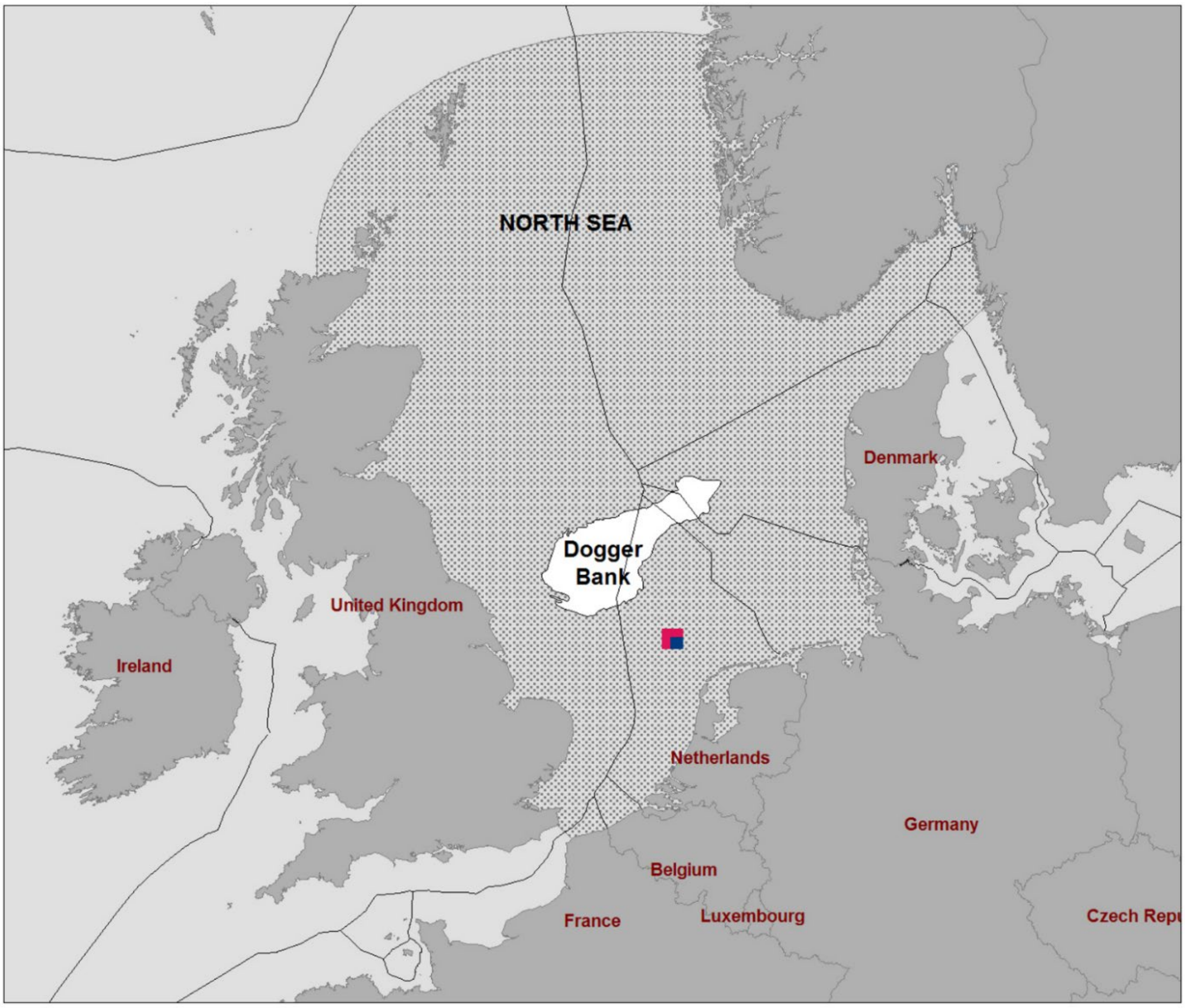
Finally a note about biofuels from waste or so called "advanced biofuels" because they are often used as "switch and bait" in biofuel discussions: in the business case discussion the traditional biofuels are presented and when the discussion shifts to land use change it's the biofuels from waste or the advanced biofuels that are presented.

There is nothing wrong with biofuels from waste. If you cannot turn waste into feedstock, biofuel is a great alternative. But compared to what our machines eat, the amount of waste we have is negligible and as we are moving closer to a circular economy we will hopefully get less waste. The IEA report acknowledges as much in several places. I would also say: save it for harder problems like airplanes.

Really advanced biofuels are basically fuels that are produced using photosynthesis – the way plants do – but that don't use scarce fertile topsoil and fresh water and thus don't compete with food and nature. An example is growing algae in glass tubes. These developments are not mentioned in the IEA report because they are too experimental and expensive. Furthermore, photosynthesis is inherently inefficient compared to solar panels and windmills so advanced biofuels will probably never be able to compete on price with synthetic "solar fuels" like hydrogen. They are still a great idea for high value added applications though! They are already a great source of high quality vegan feedstock that can be engineered to provide ample proteins and valuable and scarce nutrients like omega-3 fatty acids.

Electric trucks can drive using renewable electricity

As has been widely reported, we receive more energy from sunlight in an hour than we would need to power an affluent society for all of humanity an entire year. Solar panels can already harvest that energy with 20% efficiency so we need to dedicate less than 0.1% or surface to that. And instead of fertile land it can be desert, rooftops or ocean surface. Even wind energy (that uses this energy indirectly by harvesting the air currents generated by solar energy) can provide us many times the energy we need. Thus almost any country in the world could easily power itself this way.



The picture shows the ocean surface needed for both our current electricity need and the entire electrification of road transport. Red is wind area. Blue is floating solar panels. Combining them would decrease the surface needed.

More importantly the prices of solar and wind have been falling in a very predictable manner. E.g. in the case of solar every doubling of production has led to a 21% decrease in cost [21]–[23]. This has made solar cheaper by a factor of more than *one hundred* in the past fifty years while oil prices have doubled or tripled during that time. I was not the first to predict that solar panels would become the cheapest source of energy in the first place (I wrote about it in 2007) but by now it is becoming definitively mainstream. I now predict that airborne wind energy will become even cheaper if you factor in storage and I think we are in for a veritable renewable electricity tsunami.

So I hope that I've established that the electric drivetrain is the only real option forward if we want to save both the air above our heads and the soil beneath our feet. I hope I've also made the point that the renewable electricity to power it is abundant. But will electric trucks be expensive? Find out in the next chapter.

Footnotes

(i) The average person on this planet eats about 2940 kcal or 3.42 kWh but in industrialized countries it is 3440 or exactly 4 kWh per day [1]. So if we look at global energy intake we must multiply 7 billion inhabitants by 3.42 to get 2.39E10 kWh/day. The IEA reports we produce about 96 millions barrels of oil a day and an oil barrel contains about 1700 kWh of energy so that's 1.63E11 or 6.83 times as much.

(ii) An American uses about 80.000 kWh per year or 228 kWh per day so 10 billion of them would use 2.28E12. Divide that by the 2.39E10 we currently east (previous footnote) and you get a factor of 96. Now this is just to show how out of hand things have become. The same affluence can be achieved with much less energy by e.g. insulating your house, using heat pumps and switching to electric cars but that is precisely the point: we must find new solutions instead of falling back on biofuels, an idea that preceded the industrial revolution.

(iii) In the next footnote we establish the 4kWh/day for a well fed human. The average European car (more frugal than the US cars) uses about 8.7 liter gasoline / 100 km and travels around 15.000 km/year. If you assume 10kWh/liter and 25% added energy because of production you arrive at 40 kWh/day. The long haul track idem but it uses 40l/100km according to the IEA report and drives about 100.000km/year.

References

[1] "WHO | 3. Global and regional food consumption patterns and trends," *WHO*. [Online]. Available: http://www.who.int/nutrition/topics/3_foodconsumption/en/. [Accessed: 24-Jul-2017].

[2] D. Dimick, N. G. A. 21, and 2014, "If You Think the Water Crisis Can't Get Worse, Wait Until the Aquifers Are Drained," *National Geographic News*, 21-Aug-2014. [Online]. Available: http://news.nationalgeographic.com/news/2014/08/140819-groundwater-california-drought-aquifers-hidden-crisis/. [Accessed: 23-Jul-2017].

[3] "The Great Food Crisis of 2011," *Foreign Policy*. .

[4] "Only 60 Years of Farming Left If Soil Degradation Continues," *Scientific American*. [Online]. Available: https://www.scientificamerican.com/article/only-60-years-of-farming-left-if-soil-degradation-continues/. [Accessed: 23-Jul-2017].

[5] S. Yang, M. relations | M. 7, 2015July 9, and 2015, "Human security at risk as depletion of soil accelerates, scientists warn," *Berkeley News*, 30-Nov-2001. [Online]. Available: http://news.berkeley.edu/2015/05/07/soil-depletion-human-security/. [Accessed: 23-Jul-2017].

[6] W. E. Forum, "What If the World's Soil Runs Out?," *Time*.

[7] "Soil Erosion and Degradation | Threats | WWF," *World Wildlife Fund*. [Online]. Available: https://www.worldwildlife.org/threats/soil-erosion-and-degradation. [Accessed: 23-Jul-2017].

[8] B. G. Henning, "The Ethics of Food, Fuel & Feed," *Daedalus*, vol. 144, no. 4, pp. 90–98, Sep. 2015.

[9] "Biofuels and Agricultural Commodity Prices: A Review of the Evidence Base." [Online]. Available: https://ieep.eu/publications/biofuels-and-agricultural-commodity-prices-a-review-of-the-evidence-base. [Accessed: 15-Jul-2017].

[10] *The Economics of Biofuel Policies - Impacts on | Harry de Gorter | Palgrave Macmillan*. .

[11] E. F. Lambin and P. Meyfroidt, "Global land use change, economic globalization, and the looming land scarcity," *Proc. Natl. Acad. Sci.*, vol. 108, no. 9, pp. 3465–3472, Mar. 2011.

[12] D. M. Lapola *et al.*, "Indirect land-use changes can overcome carbon savings from biofuels in Brazil," *Proc. Natl. Acad. Sci.*, vol. 107, no. 8, pp. 3388–3393, Feb. 2010.

[13] F. Hellmann and P. H. Verburg, "Impact assessment of the European biofuel directive on land use and biodiversity," *J. Environ. Manage.*, vol. 91, no. 6, pp. 1389–1396, Jun. 2010.

[14] F. Danielsen *et al.*, "Biofuel Plantations on Forested Lands: Double Jeopardy for Biodiversity and Climate," *Conserv. Biol.*, vol. 23, no. 2, pp. 348–358, Apr. 2009.

[15] P. Meyfroidt, E. F. Lambin, K.-H. Erb, and T. W. Hertel, "Globalization of land use: distant drivers of land change and geographic displacement of land use," *Curr. Opin. Environ. Sustain.*, vol. 5, no. 5, pp. 438–444, Oct. 2013.

[16] E. B. Fitzherbert *et al.*, "How will oil palm expansion affect biodiversity?," *Trends Ecol. Evol.*, vol. 23, no. 10, pp. 538–545, Oct. 2008.

[17] K. Kleiner, "The backlash against biofuels," *Nat. Rep. Clim. Change*, vol. 2, pp. 9–11, 2008.

[18] J. R. Palmer, "Biofuels and the Politics of Land-Use Change: Tracing the Interactions of Discourse and Place in European Policy Making," *Environ. Plan. A*, vol. 46, no. 2, pp. 337–352, Feb. 2014.

[19] S. Tokgoz and D. Laborde, "Indirect Land Use Change Debate: What Did We Learn?," *Curr. Sustain. Energy Rep.*, vol. 1, no. 3, pp. 104–110, Sep. 2014.

[20] J. Ziegler, "Burning food crops to produce biofuels is a crime against humanity," *The Guardian*, 26-Nov-2013.

[21] "International Technology Roadmap for Photovoltaic (ITRPV)," ITRPV, Mar. 2017.

[22] Seth Miller, "Experts have massively underestimated solar. Why? (Solar: Part 1)," *perspicacity.xyz*, 14-Feb-2017. [Online]. Available: https://perspicacity.xyz/2017/02/13/experts-have-massively-underestimated-solar-why-solar-part-1/. [Accessed: 23-Jul-2017].

[23] "What is the Learning Curve—and What Does it Mean for Solar Power and for Electric Vehicles?," *Union of Concerned Scientists*, 29-Sep-2016. [Online]. Available: http://blog.ucsusa.org/peter-oconnor/what-is-the-learning-curve. [Accessed: 23-Jul-2017].

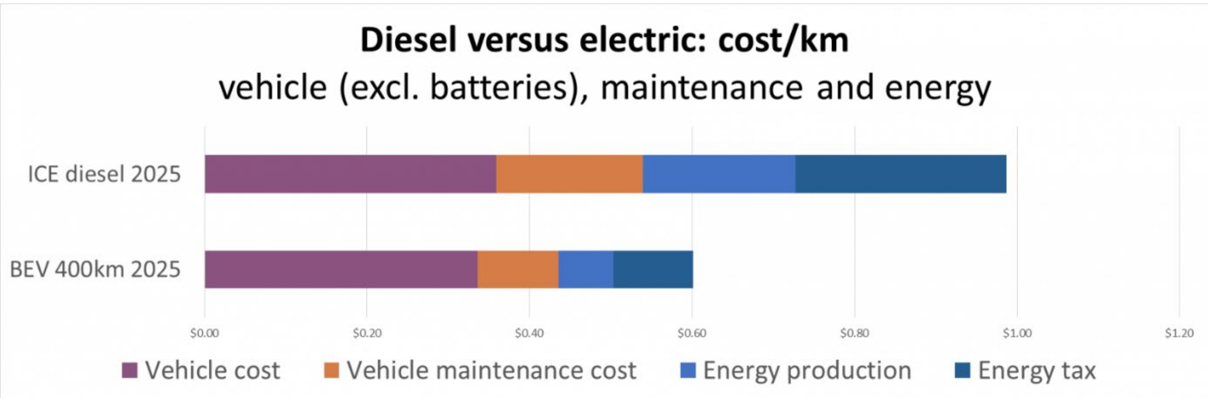
Electric trucks, chapter 2: Motor

[in the blog series: Electric trucks: economically and environmentally desirable but misunderstood]

By Auke Hoekstra

	Chapter 1 Energy supply	Chapter 2 Motor	Chapter 3 Energy storage	Chapter 4 Energy delivery
Diesel	Fuel	<30% efficient	Gasoline tank	Gas stations
Electric	Electricity	>85% efficient	Battery	Chargers

In the previous chapter we saw that the electric motor is our only realistic sustainable option. Fortunately it can also be cheaper. In this chapter we find out how the advantage in vehicle cost, maintenance cost and energy cost puts the electric truck at a strong advantage. The graph visualizes the result. In the next chapters we will calculate what part of this advantage is lost by having to buy expensive batteries and because the charging infrastructure needs to be build and maintained.



Electric engines are cheaper, lighter, stronger and easier to maintain

Electric engines are compact and will make an engine compartment unnecessary. Per the IEA report: "Furthermore, electric motors can be mounted either in the drivetrain before the transmission to provide energy to the driveshaft and then to the axles, or they can be installed directly in the wheelers of a truck or trailer. This can further improve the efficiency of translating energy to work at the wheels, although trucks operating at highway speeds generally need a transmission."

Also important: electric drivetrains are about 3x lighter and 2x cheaper than conventional drivetrains [1]. Finally efficiency hardly suffers when the motor is larger. So just like a Tesla Model S, a truck can have great acceleration and great efficiency at the same time. Tesla's CEO Elon Musk even made the bold claim that the Tesla's heavy truck prototype (using a cheap Model 3 motor in multiple axles) "drives like a sports car".

The IEA report assumes that in the long run an electric motor can have a USD 30,000 lower sticker price **(i)**. Let's assume that in 2025 about USD 20,000 of that promise is realized. That brings down the vehicle cost per kilometer from USD 0.36 to USD 0.34 **(ii)**.

Maintenance can also be lower. From proprietary Dutch research passenger cars we know that maintenance of full electric vehicles is already about one third. Basically the drivetrain needs zero maintenance and the brakes need hardly any maintenance. Most of the remaining maintenance is tires.

For diesel trucks the IEA assumes USD 0.18/km in maintenance **(iii)**. From other sources we know tires and rethreading for a heavy truck costs about USD 0.04/km [2]. If we assume the remaining USD 0.14 can be halved (a very conservative assumption knowing that the motor needs no maintenance) we arrive at USD 0.11 for electric motor maintenance.

The efficiency of electric motors lowers the energy cost

The most important advantage of the electric motor is that it's about three times more efficient. Let me quote the IEA report: "When driving on an uncongested highway, a modern truck can achieve efficiencies from the engine to the wheel of no higher than 30%, while electric trucks can reach powertrain-to-wheel efficiencies of as high as 85% or more." To which I'd like to add that electric trucks keep that efficiency when driving through the city or on congested highways while the efficiency of combustion engines drops to even lower levels. The end result is that a truck uses 4 kWh/km while an electric truck uses 1,5 kWh/km **(iv)**.

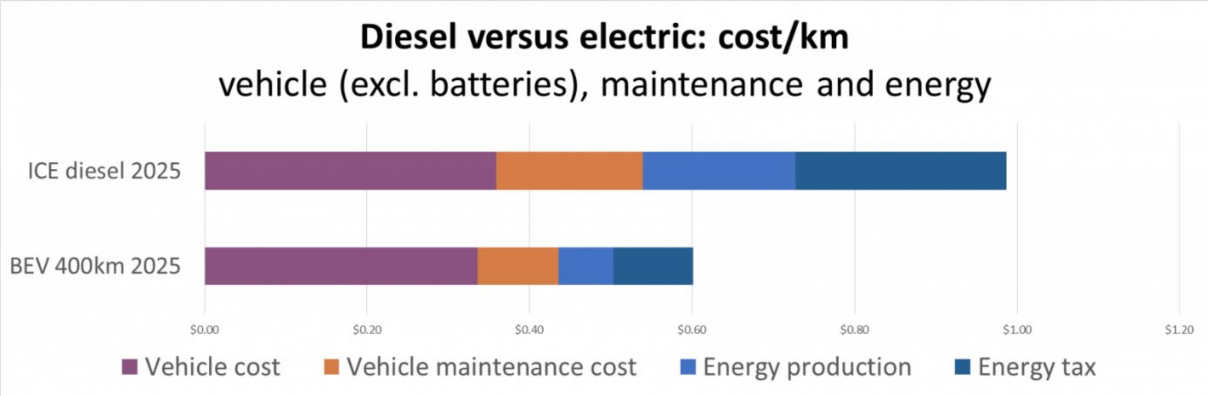
The price for electricity in the IEA report is less clear because the numbers don't add up **(v)**. Also I want to do the calculation in a bit more detail. So let's start from scratch and do it right. The table shows the most important price components of diesel and electricity in the EU.

Price/kWh	Production	Distribution	Taxation	Total
Diesel	USD 0.047 **(vi)**	USD 0.02	USD 0.065 **(vii)**	USD 0.135
Electricity	USD 0.045 **(viii)**	USD 0.02-USD 0.09	USD 0.001- USD 0.12 **(ix)**	USD 0.07-USD 0.26

Tax is a thorny issue because it varies so wildly and because it is only partly related to CO2 emissions (of which Diesel emits around 3,23 kg per liter **(x)** or 323 gram per kwh). But because electric vehicles use so little energy it actually doesn't matter very much. So

I propose we give electricity a tax of USD 0.065: the same as diesel, even though this energy is much cleaner.

I've chosen the base year of 2025 for the rest of our analysis. That gives us the graph we already saw at the start of this chapter:



So the fully electric truck is significantly cheaper when you just look at motor, maintenance and most of all energy. But will it be possible to store all the energy needed in a battery? Let's find out in the next chapter.

Footnotes

[i] The report states that the added cost of an heavy electric truck with 400 km range will fall from USD 250,000 with batteries costing USD 350/kWh to USD 40.000 with batteries costing USD 100/kWh. Since the cost of the motor is dwarfed in the first scenario this teaches us that a 400km range truck needs 715 kWh in the IEA scenario. Even if efficiency increases reduce that to 700 kWh it would still cost USD 70,000 with USD 100/kWh batteries. Hence there is also a USD 30,000 somewhere and that can only be the drivetrain. It doesn't seem like a crazy number to me by the way.

[ii] The IEA tells us it depreciates the vehicle with 58% in five years. Question what is assumed for personnel cost. If you add USD 110,000 to the above depreciation you get exactly the right value for all the scenarios regarding vehicle cost. So that is how I calculate vehicle cost: USD 110,000/500,000km + 0.58*vehicle_cost/500,000km.

[iii] Actually it's USD 0.17 in 2015 and USD 0.20 in 2050. The maintenance increases because more efficient trucks have more bells and whistles. We are interested in 2025 so I stay closer to the 2015 number.

[iv] The report states: a truck is at most 30% efficient and an electric vehicle is at least 85% efficient. That is 0.85/0.3=2.83 times better. Energy use of a diesel truck is around 40l/100km or 4kWh/km and 4/2.83=1.4kWh/km. Because I think that is slightly optimistic I round it up to 1.5 kWh/km.

[v] The report says it assumes "an electricity price of USD 0.17 in all regions and all cases". You would assume that's a price/kWh but the CAT-ERS truck uses USD 0.17/km. However it cannot be USD 0.17/km exactly because the CAT-ERS also runs 1/5 of its km on diesel so the price per full electric km is USD 0.21. Based on efficiency calculations in the report the truck should use about 1.4 kWh/km. The report states: a truck is at most

30% efficient and an electric vehicle is at least 85% efficient. That is 0.85/0.3=2.83 times better. Energy use of a diesel truck is around 40l/100km or 4kWh/km and 4/2.83=1.4kWh/km. But USD 0.21/km with an energy use of 1.4kWh/km would imply an energy cost of USD 0.15/kWh. And the drones flying around in the report (page 72) use electricity at USD 0.1/kWh.

[vi] If you take the slightly different energy density in the US and EU into account the base price of diesel and gasoline is almost exactly the same on both sides of the Atlantic: USD 0.047/kWh for diesel and USD 0.058/kWh for gasoline and [2].

[vii] Taxes are highly different in the US and EU. In the US the tax is almost the same for diesel and gasoline and averages about USD 0.013/kWh. In the EU the average tax is USD 0.05 for diesel and USD 0.08 for gasoline and the expectation after dieselgate is that diesel will soon be taxed comparable to gasoline [3].

[viii] Wholesale day ahead prices often hover around USD 0.035/kWh. New fossil power and renewable power is currently around USD 0.05. I expect prices for renewable energy to keep falling so I consider USD 0.045 actually a kind of worst case scenario, even if we have to include some storage. The fact that hydrogen in the IEA report will be produced using USD 0.01/kWh electricity that is available during the cheapest 50% of the time shows that hydrogen is calculating with lower average prices still.

[ix] If you have a large factory you almost no tax for electricity in most European countries. If you are an end user the tax can be up to USD 0.14 in the Netherlands (regardless of the electricity source).

[x] In Dutch the leading source gives 3.230 kg/liter[4]. An international source would be the EIA that estimates 22.4 pounds of CO2/gallon or 2.68kg/l [5]. If you include life cycle emissions (mostly refining) which averages around 20% you would arrive at that same number.

References

[1] S. Fuchs, J. Laubmann, and M. Lienkamp, “Parametric Modelling of Cost arising from the Production, the Operation and the Recycling of Vehicles,” *Conf. Future Automot. Technol. Focus Energy Storage*.

[2] Iain Staffell, “Energy and Fuel data sheet,” 2011.

[3] “Europe’s tax deals for diesel,” Transport & Environment, Oct. 2015.

[4] “Lijst emissiefactoren,” *CO2 emissiefactoren*. .

[5] “How much carbon dioxide is produced from burning gasoline and diesel fuel?,” *US Energy Information Administration*. [Online]. Available: https://www.eia.gov/tools/faqs/faq.php?id=307&t=11. [Accessed: 23-Jul-2017].

Electric trucks, chapter 3: Energy storage

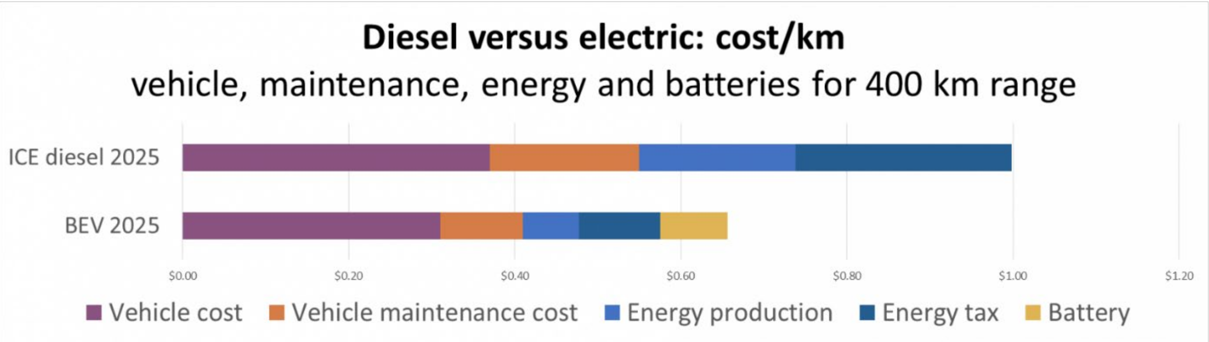
[in the blog series: Electric trucks: economically and environmentally desirable but misunderstood]

By Auke Hoekstra

	Chapter 1 Energy supply	Chapter 2 Motor	Chapter 3 Energy storage	Chapter 4 Energy delivery
Diesel	Fuel	<30% efficient	Gasoline tank	Gas stations
Electric	Electricity	>85% efficient	Battery	Chargers

Only twenty years ago, batteries where so heavy and expensive that giving any vehicle a 400 km highway range was practically impossible. But thanks to the advent of laptops and mobile phones the battery was reinvented. And while diesel only became more expensive, batteries quickly became lighter and cheaper. In the last 20 years the price of batteries has come down by a factor of 20! That's definitively a disruptive innovation and all of a sudden the heavy electric truck is not only possible but highly probable.

The graph shows the resulting cost per km of diesel versus electric for a heavy truck. I hope this helps to put an end to the myth (also propagated by the IEA) that heavy trucks cannot be electrified, even though this chapter also describes some caveats.



Plummeting battery weight

3,5 ton should be enough to propel a 40 ton truck for 400 km

If I was to write a report on the future of trucks, the battery would get more attention than vehicle efficiency. Batteries have by far the most disruptive potential of all the options the IEA report examines. The IEA talks a bit about volumetric density but if you ran the numbers you would know that the size of the battery is not a problem: there is a lot of room under a (semi-)truck and batteries can be given any shape you like. I think the IEA should have been talking about gravimetric density because weight is a serious issue. Fortunately it is becoming less so because in the last 20 years we went from lead acid batteries weighing 30kg/kWh to lithium batteries weighing 3 kg/kWh excluding pack to 5 kg/kWh including pack **(i)**. So the 700 kWh that IEA posits is needed for a heavy 40 ton truck with 400 km of range would have weighed 20 ton 20 years ago. Now we have 3,5 ton left and the weight is still coming down.

Plummeting battery prices: times 20 in 20 years

The figure shows a famous graph depicting the fall in battery prices, augmented with a line (2016-2030) that was added based on the research of master student Vedant Sundrani and myself in collaboration with some battery experts at the Eindhoven Technical University.

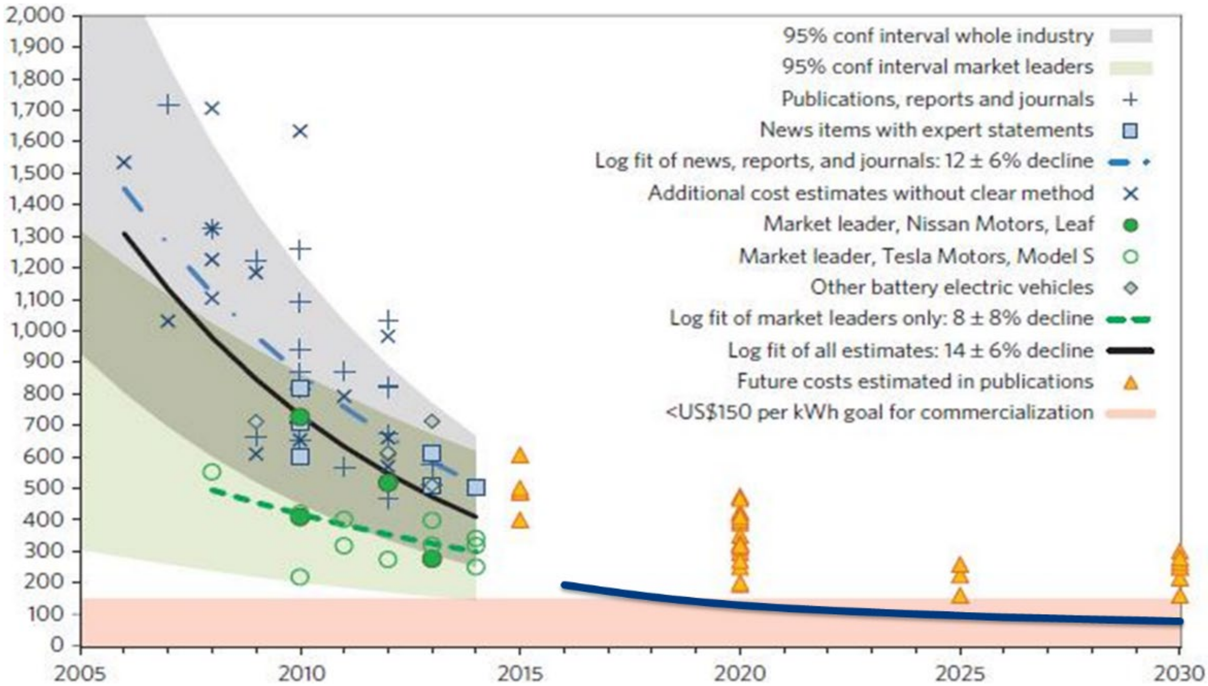


Figure 1 Rapidly falling battery prices. Source [1] and original research by Vedant Sundrani and the author.

Because this is so important let me show another curve to corroborate this. This one is from the Bloomberg New Energy Finance report that came out in July 2017. It's significantly more optimistic than their prediction from 2016: things are moving fast.

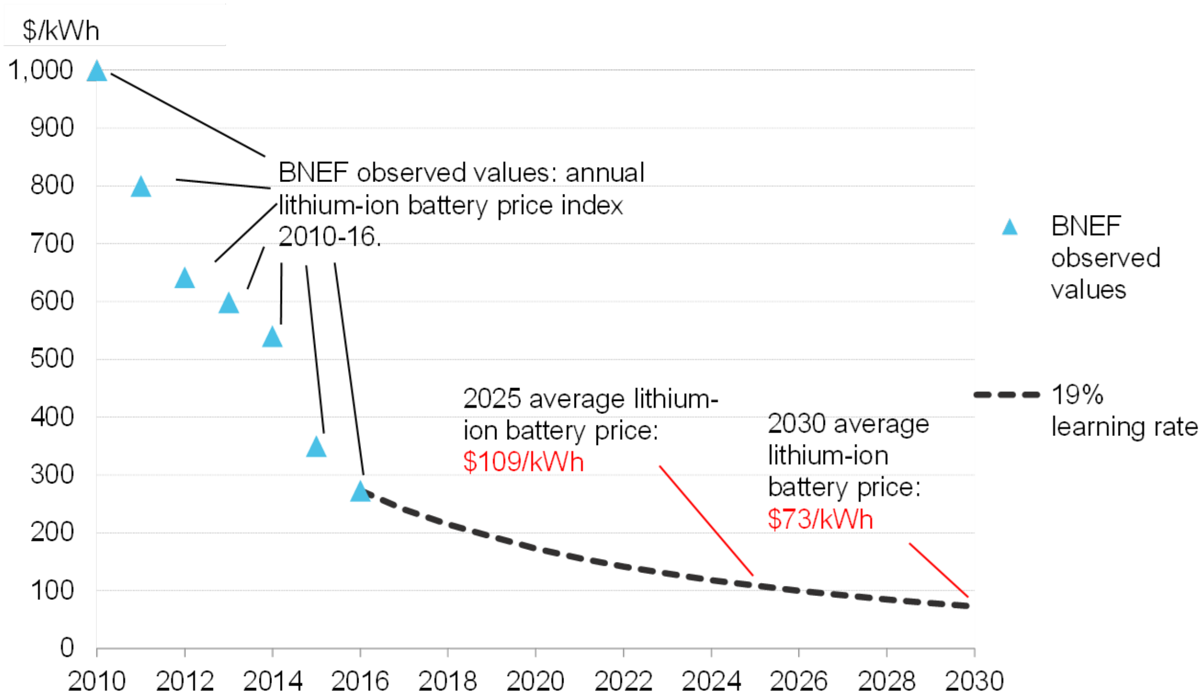


Figure 2 We see a price drop by more than a factor of 10 over the 2005-2025 time frame.

Furthermore battery degradation has at least halved during that time. Regular lead-acid batteries can be recharged only hundreds of times while lithium EV batteries can increasingly be charged thousands of times. Most Tesla Model S cars will probably have more than 80% of their capacity left after driving 500,000 km.

So in the time that regular cars have basically stayed the same, the battery has become 20 times cheaper. That is so radical that it changes *everything*. It is no wonder that conventional experts have trouble wrapping their heads around the implication: what do you do when “your” technology that has been dominant for over a century but hardly improves anymore suddenly gets competition from some new brat that improved by a factor of 20 over the last 20 years?

The answer seems to be a (probably unconscious) combination of ignoring implications and massaging numbers. In 2015 the report can take a relatively safe USD 350/kWh (although the report acknowledges that some companies are already claiming USD 180/kWh). But the price that changes everything (USD 100-150) is supposed to wait until 2050. That is not supported by the findings of e.g. the author or Bloomberg. There is even reason to believe big factories will reach USD 100 in 2020: 30 years faster.

If we analyze the price in 2025 the most up to date number is somewhere around USD 100 per kWh and this is the number and timeframe we will use in the rest of this analysis.

The generic business case for electric trucks

Contrary to popular belief, the business case for electric vehicles is best for the heaviest trucks and for trucks with the highest annual mileages.

Unfortunately the IEA adds some unfounded confusion regarding trucks:

"While the technical principles for the electrification of trucks are similar to those available for cars, the greater size and weight of trucks, and their more rugged operations, substantially increase the barriers to batteries serving as a substitute for diesel." So the IEA claims that scaling up the electric motor and making it rugged poses a barrier. That is backwards. The electric motor has one moving part and is maintenance free. You can hardly be more rugged than that.

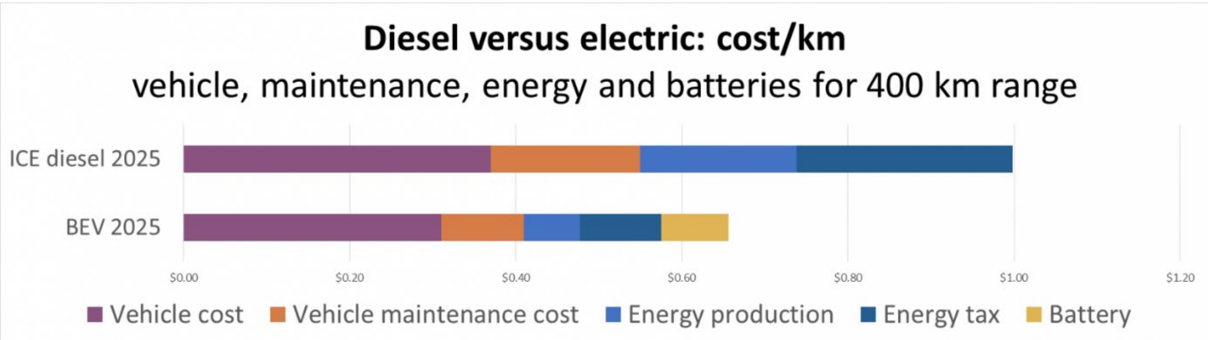
The IEA also states: *"The hurdles to electrification are lower for trucks with lower GVW [gross vehicle weight] and shorter annual mileages."* Once again this is backwards. Yes you need bigger batteries for larger trucks but the weight of the batteries *per ton of cargo* actually *decreases* when trucks get larger (as the IEA explains on page 59). Let me repeat that: the cost and weight of batteries per ton of cargo *decrease* when the truck becomes bigger.

Furthermore shorter annual mileages are killing. *You want a truck with a* ***high*** *annual mileage*. Why? Because **in essence the business case for the electric truck is simple**:

1. When you buy the vehicle you pay more because of the expensive battery. The size of the battery depends on the maximum distance between charging sessions (not the mileage).
2. When you drive the vehicle you pay less because the electric motor requires about 1/3 of the energy and does not need maintenance. *So the more km you drive, the more you save.*

Adding a battery to our heavy duty truck

If we assume the battery size the IEA proposes for a heavy duty truck with 400 km of range and we assume a battery price of USD 100/kWh this is the result. You can see that relative to production cost and tax on energy this is small fry.



Now it's time to look at how we will charge our heavy-duty truck. And for that some out of box thinking produces the best results, in our next and last chapter.

(i) The energy density of the new first gen Tesla cells was 250Wh/kg. The new 2170 cell is said by Tesla to have a 13% more dense chemistry (bringing it to 280Wh/kg) and more efficient packaging due to the larger size. Some enthusiast calculations put it at 322Wh/kg. That equals 3.1 kg/kWh. The question is of course how much the packaging will add to the weight and how much capacity needs to be left unused in order to prevent rapid degradation. My estimate would be that large blocky battery packs you will find in ladderframe trucks can be more efficiently packaged hence the usual 30% (bringing us to 4kg/kWh) can be reduced. On the other hand you want a battery that can last 1 million km and for a 700 kWh battery that means about 2000 lifecycles. Current Tesla batteries last about 500.000 km for a 85kWh battery before they degrade to 80% so that's about 1200 cycles. I could imagine an NCM chemistry that lasts longer is a bit heavier, thus 5 kg/kWh. By the way: China already set an official minimum goal for batteries of 200 Wh/kg so 5kg/kWh is quickly becoming the new normal.

Electric trucks, chapter 4: Energy delivery

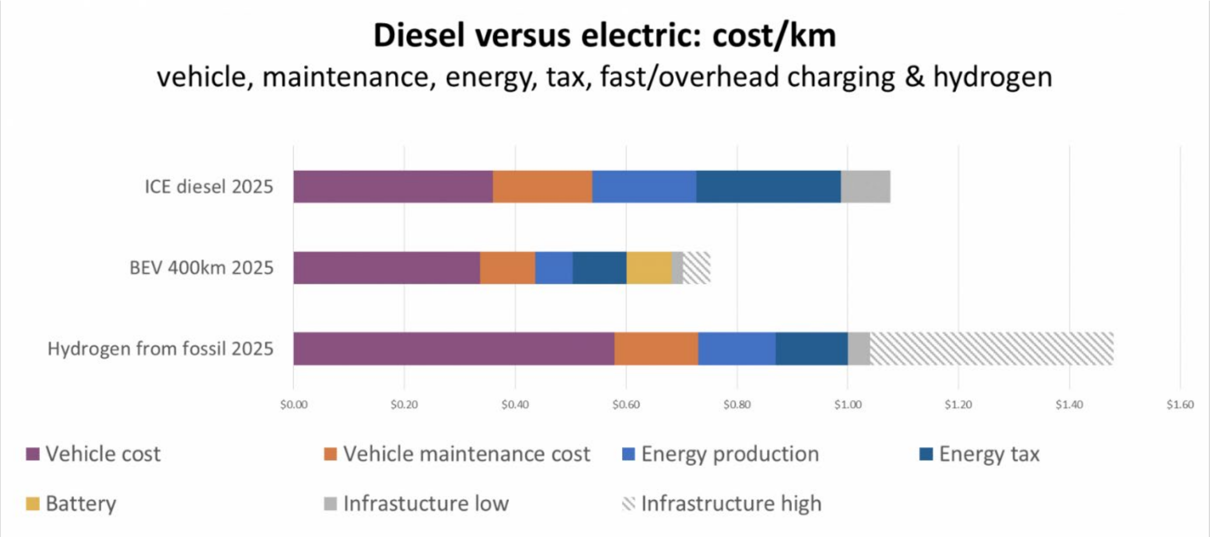
[in the blog series: Electric trucks: economically and environmentally desirable but misunderstood]

By Auke Hoekstra

	Chapter 1 Energy supply	Chapter 2 Motor	Chapter 3 Energy storage	Chapter 4 Energy delivery
Diesel	Fuel	<30% efficient	Gasoline tank	Gas stations
Electric	Electricity	>85% efficient	Battery	Chargers

The Netherlands has a long history with gasoline cars. At the start of the 20th century we were one of the first to standardize the oil for cars so you could drive from apothecary to apothecary and everyone would sell you some bottles of oil that where compatible with your engine. Now we are the proud world leader in charging infrastructure for passenger cars. But charging infrastructure for heavy trucks is a different ballgame altogether as we will see in this final chapter.

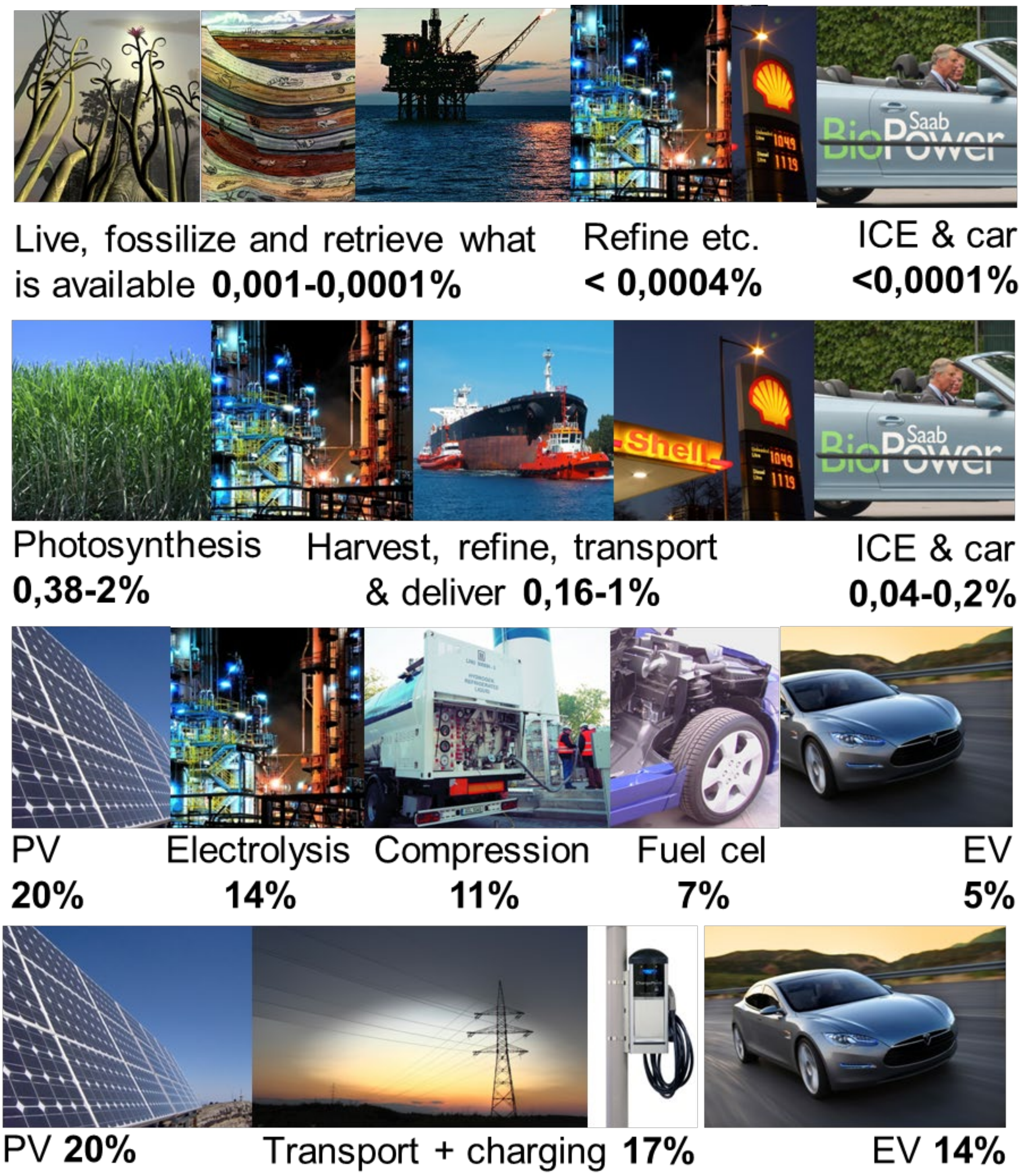
Our final result is shown in the chart: electric trucks will be our cheapest option in 2025. And whether you charge them with a network of fast chargers or overhead lines, the infrastructure cost are relatively low. So let's find the political will to extend our increasingly clean electricity grid to cover road freight as well.



Decoupling energy demand and supply using fuels versus efficiency

Fossil fuels give us access to sunlight that was collected and stored hundreds of millions of years ago. Putting this condensed ancient sunlight in diesel trucks allows the truck to travel 1,500 kilometers without recharging. This present from mother earth has made it possible for us to decouple energy supply (sunlight) and energy use.

But this decoupling comes at a price in terms of efficiency. We are depleting many fossil resources almost a million times as fast as they where created. This means the efficiency of turning sunlight into fossil fuel and then burning it is millions of times less efficient than using solar panels and charging an electric car directly. The picture illustrates the dominant conversion routes.



Although inefficient in the grand scheme of things, the fossil route decoupled sunshine from driving very effectively. It even made it possible to drive all over Europe and give very little thought to where you could recharge.

Unfortunately that is different with electric vehicles, but let's see if it is really an insurmountable problem.

Destination charging: a good first step

The IEA assumes 100,000 km/year for long haul trucks. If the truck is used on working days that's about 380 km a day. That actually means that a 400 km range would suffice on most days if overnight charging is available. Maybe this is another case of overblown range anxiety.

A straightforward solution for many cases could be to have extra battery packs in your fleet of trucks to you can occasionally boost the range to say 500 or 600 km when the required distance is long and the cargo is not near the maximum judicial limit.

Another option is that the places you visit have a charger. E.g. delivery locations like supermarkets or cargo hubs could charge the truck while it was being loaded or offloaded. In many cases such locations already have a powerful grid connection and if charging the trucks would be outside of peak hours it might already be able to handle the extra load.

Pricing this solution is hard because it heavily depends on the situation. Whether it is a sufficient solution depends on the driving pattern. I'll throw in the towel for now and focus on the next two alternative charging solutions.

Fast charging: long distance, no problem

To many people this is the most straightforward solution: simply replace gas stations with fast chargers. In the EU, truck drivers must take a 45 minute break every time they have driven 4.5 hours. So they could use the fast chargers while they rest. An easy way to do that would be with a pantograph or with an inductive pad to a charge below ground, using systems currently used for electric busses.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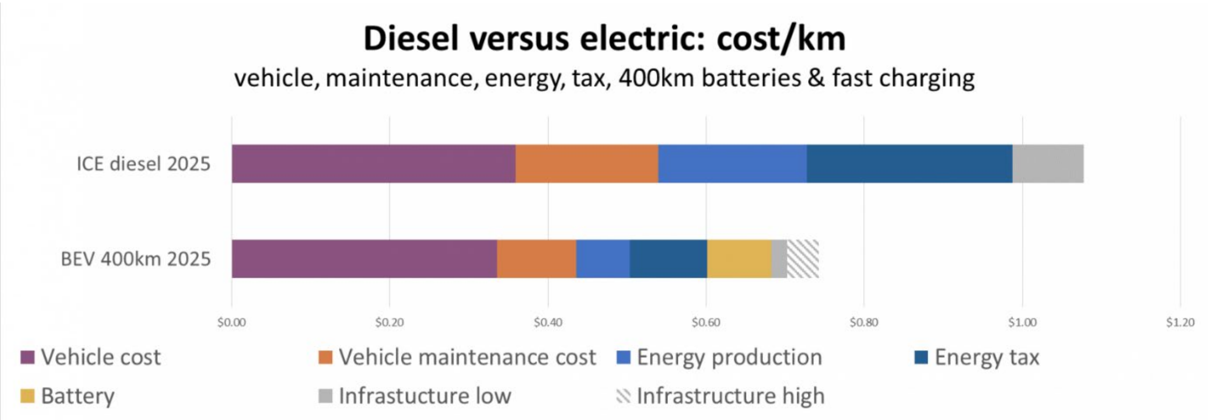
The required power is nothing to sneeze at. To recharge a range of 400 km on a truck that uses 1.5 kWh/km requires 600 kWh of energy. If you want to recharge in 30 minutes you need a 1.2 MW fast charger (and possible a row of them). For comparison: the average household has a peak power of 10kW. So every fast charging slot would need a connection comparable to a hundred households. Still that is far from impossible: power lines that can service thousands or even hundreds of thousands of households have become common in developed countries. Someone in the smart charging business pointed out to me that most sessions would be less than 450 kW and would last 45 minutes. Using smart load balancing, 600 kW per docking location would be enough. That would make the business even better.

Would there be a business case for that? Sources in the know tell be that fast chargers cost around USD 350 per kW now and will cost around USD 290/kW in 2025. That's around USD 300,000 for a 1.2 MW charger. If we include the pantograph etc. it could be USD 350,000.

Let's assume that the slot lasts 15 years. That's USD 23,000 per year or about USD 65 per day. Add a grid connection and some maintenance and capital cost and make it USD 100 per day.

How many 30 minute visits would such a slot get per day? The maximum is 48 (2 x 24) but let's a assume a fast charging slot would be occupied 20% of the time. That's about 10 visits a day. That would mean USD 10 per charging session. Since a charging session was 600 kWh that would be USD 0.017/kWh for the infrastructure. Assuming 1.5 kWh/km that becomes USD 0.025/km. Let's take a somewhat safe margin of between USD 0.02 and USD 0.05 per km.

Let's compare against the diesel again. We have to add the USD 0.09 that we subtracted as an estimate of infrastructure earlier to make it a fair comparison **(i)**. After doing that we get:



So adding fast charging actually increases the advantage of the fully electric truck.

Electrified road systems: the ultimate solution?

What if there as a way to charge while driving? Actually it's not so hard to imagine because we have been doing this for a long time. This is how trains, trams and trolley busses get around. And nowadays there is even talk of doing this using wireless charging through the road (so without unsightly overhead lines).

It is so conventional that it is even in the IEA report. They have one mostly electric scenario (CAT-ERS) and it uses this technology. But there are a range of problems with the assumptions the IEA makes regarding this scenario:

1. The truck will drive electric 80% of the time and on diesel 20% of the time.

But why would you want to incur all the extra production, maintenance and energy costs if you can already drive electric 80% of the time. Why not give the car a battery that let it travel independently while not charging electrically? In our scenario we keep the battery costs of the 400 km extra range. We will just replace the infrastructure costs of fast charging with the infrastructure costs of the electrified road system (ERS).

2. The infrastructure is depreciated in 5 or 6 years **(ii)**.

This seems like an oversight or hard to explain bias. Common depreciation periods for these types of infrastructures range from 30 to 60 years. We will put the depreciation period at 20 years as a compromise. With a cost of USD 1 million per km (the *higher* cost in the IEA report) the cost per kilometer per year would be USD 50,000.

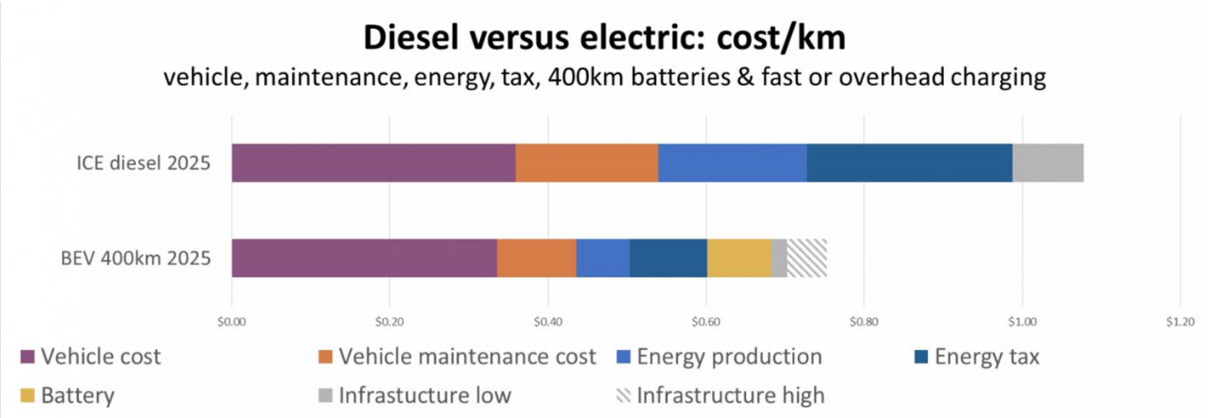
3. The amount of vehicles is estimated at 0-30 trucks per hour in 2015 and 30-160 trucks in 2050.

That actually seems pretty conservative because the estimates the IEA uses actually come from a study that dimensions the lanes for 250 trucks/hour (page 97) and many lanes on EU roads have a much higher average usage. Still, let's keep that. That means a km of overhead wire will dispense an astonishing 0.4 to 2 *million* kWh per year. I foresee a scenario where the truck is serviced by destination chargers, fast chargers *and* ERS and where ERS will be used for the busiest highways on out of sight trajectories.

4. The truck cannot charge faster than it uses energy.

This is probably a lack of imagination. Most studies I have reviewed assume that you would use overhead lines on 50% or even 25% of the distance. An example: assume a trip from Rotterdam to Hamburg of 500 km. The first 50 km to leave Rotterdam would be without overhead wire (using destination charging or charge left from when the truck arrived). Then 50 km of overhead wires to top the truck up. Then 150 km without overhead wires (but no problem for the 400 km batteries), then 50 km to top the battery up again. Et cetera. Let's assume this way the investments would be much lower and difficult pieces of highway (complex intersections, crowded areas) could be avoided. If we assume a coverage of 1/3 it increases the number of kWh per to kilometer to between 1.2 and 6 million.

If we make those adjustments, ERS is actually astonishingly cheap. It could even be cheaper than our already cheap fast chargers. But let's keep it simple and stay safe.



Of course this assumes some economies of scale so it would be helpful if government would step in to create a scenario that assures enough supply and demand, analogous to how roads, railways, electricity grids and other infrastructure was created. So let's do a little thought experiment.

There is about 75,000 km of highway in the EU (and also in the US by the way). If we electrify *all the highways in Europe* (covering one third of the highway, see point 4 above) it would only cost us 1.25 billion dollar per year. That is 0.01% of EU GDP. Furthermore the project would need no subsidies, just political will to get it done. If there is one thing I would hope this blog instigates, it is a serious study into electrifying EU roads.

So electrified roads and fast chargers are both good options and I expect they could complement each other. Also nice: you could add both capabilities as after-market functionality to an electric truck that's already sold.

Hydrogen: storage for the sustainable energy system

First let's get one thing out of the way: hydrogen is not a competitor for the electric drivetrain. Basically a hydrogen truck is an electric truck to which we have to added two components. First we add hydrogen tanks that allow us to carry energy in the form of hydrogen. Finally we add fuel cells that transform the hydrogen into electricity for the electric motor or the battery.

There are three possible reasons to do this:

1. Hydrogen is relatively light (the tanks weighs more than the hydrogen itself) so you can take a lot of energy and give a heavy truck a range that is comparable with a diesel truck.
2. Hydrogen can be tanked almost as fast as diesel (faster than charging a battery).
3. Hydrogen can be produced using sustainable electricity that is available at moments it is not needed and would otherwise be thrown away.

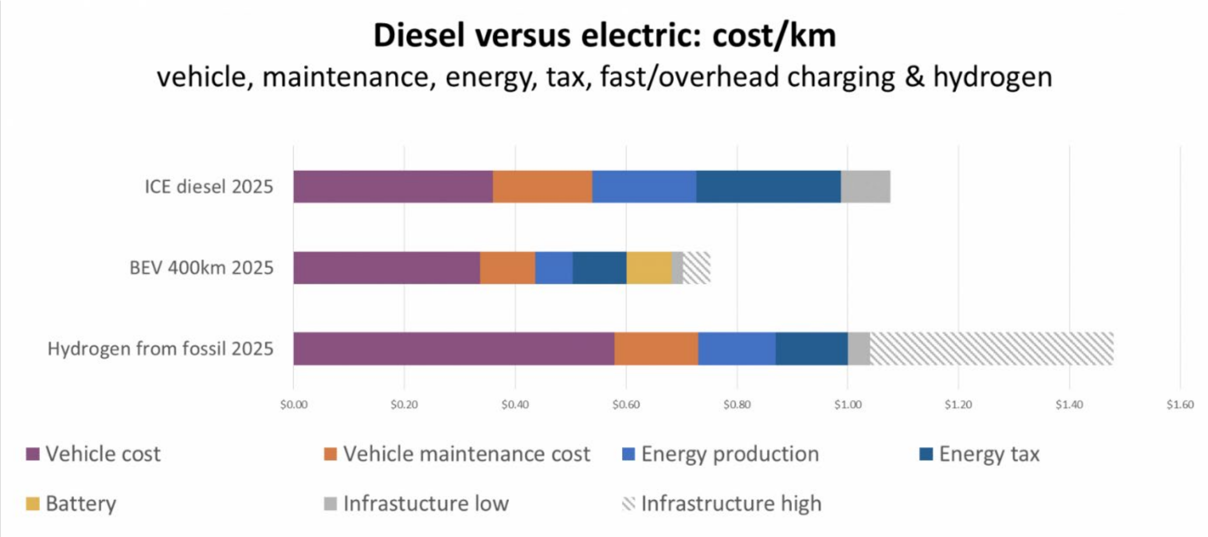
However there are also some drawbacks (congruent with the IEA report unless otherwise noted):

1. Currently more than 90% of hydrogen is made from fossil fuels [1] and does not lead to CO2 reduction. The reason is that electrolysis is still very expensive and not very efficient **(iii)**.
2. You have to compress and distribute the hydrogen which costs energy and according to the IEA report costs a *lot* of money, even though the infrastructure seems depreciated in more than 60 years (against 6 years for the electric overhead wires) **(iv)**.
3. The hydrogen the truck carries is compressed to 700x normal air pressure! For comparison your tire is just 3x normal air pressure. These formidable tanks will cost about USD 50.000 now and USD 25.000 in the long run **(v)**.
4. Fuel cells are falling rapidly in price and could cost between USD 13.000 and USD 52.000 per truck in 2050. But for now they cost a whopping USD 286.000 per truck **(vi)**.
5. You lose 40% or more when converting the hydrogen to electricity in the vehicle. So a fuel cell is clearly more efficient than a internal combustion engine but you still lose a lot of energy.

What could be the price in 2025 so we can add hydrogen to our estimate?

Let's assume that we are talking about continuous learning curves between 2015 and 2050, similar to what we have assumed for batteries. That leads to a relatively quick decrease in absolute prices in the early years but the cost would still be considerable:

1. Fuel cells would still cost USD 150,000 **(vii)** and hydrogen tanks USD 40,000 **(viii)**. This increases the price of the truck from USD 120,000 to USD 310,000. That's USD 0.58/km **(ix)**. Ouch.
2. Maintenance costs was probably mixed up and will be USD 0.15/km **(x)**.
3. Hydrogen USD 0.07/kWh and USD 0.14/km. This would have been USD 0.32 if hydrogen from renewables was used. So in 2025 there is not yet CO2 reduction from hydrogen trucks **(xi)**.
4. Tax USD 0.065/kWh (just like diesel and clean electricity) gives USD 0.13/km.
5. Infrastructure USD 0.04-0.44/km **(xii)**.



Now this might look kind of bad for the hydrogen truck (especially since it is still using "dirty" hydrogen) but remember: prices of both the truck and clean hydrogen *will* come down. I also think that you could scale down the number of fuel cells for the time being and combine them with the battery electric vehicle to get a great range at an interesting price point. For a range of 600-800 km such a combination will probably be your cheapest option.

In the long run our move to renewable electricity will require some form of storage. That could be hydrogen or some other fuel made with hydrogen. A broader term is P2G for power to gas denoting a gas made with electricity. Germany is especially strong in researching this field. You could even turn hydrogen into a liquid by adding some carbon. This way you can e.g. create formic acid or ammonia. This is even easier to transport than hydrogen and could in the future be used in fuel cells to produce electricity.

Professor Ad van Wijk from the Delft University of Technology sees great potential in the hydrogen economy (and rightfully so I think) and wants to produce it from renewable energy that is produced either remote locations (e.g. solar panels in the Australian desert) or inconvenient times (e.g. solar panels in mid summer). This hydrogen could potentially become very cheap. The fact that hydrogen trucks won't be the cheapest option in 2025 should not deter us from this path.

To summarize: in my opinion hydrogen is a great and potentially clean range extender that nicely complements the battery electric long-haul truck and I see a great future for hydrogen and other solar fuels.

Conclusion

The heavy-duty battery electric long-haul truck should have been included as a scenario in the IEA report "The Future of Trucks" and this series of blogs could be used as an addendum that does just that.

The first chapter described how only the electric drivetrain can provide a real solution because they can be propelled using abundantly available renewable energy from solar and wind. All internal combustion engines rely on either fossil fuel (bad) or biofuels (worse) and acknowledging that makes clear we must focus on the electric drivetrain. An expressive number was that a heavy truck needs to "eat" as much as 375 people.

The second chapter showed how the lower purchase price, maintenance cost and the three times lower energy use gives the electric motor a huge economic advantage.

The third chapter focused on battery prices and how the price-performance has improved by a factor twenty in the last twenty years. This is basically the disruptive innovation that changes everything. The IEA acknowledges this but still disqualifies the battery electric vehicle. After this is remedied and the latest battery predictions are included a heavy truck with a 400 km range shows an appreciably lower price per km in 2025 than a diesel truck.

This fourth and last chapter looked at charging options for the electric truck, including hydrogen. The IEA assumptions that electrified roadways must be depreciated in six years and will still be used by diesel trucks are challenged. Straightforward calculations show that both heavy duty fast chargers and electrified roadways have a very low cost per kWh and km.

If you have made it this far: thank you! I hope you've learned something from this set of blogs. If you have learned that I have made a mistake I implore you to tell it in the comments or send me a mail at a.e.hoekstra at tue.nl.

Footnotes

[i] A variety of sites pegs the margin on gasoline (before tax) at around 14% resulting in a price per liter of around USD 0.22 at current average European diesel prices. The IEA tells us a truck uses about 0.4 liter per km bringing us to a little above USD 0.08. What's more important: the IEA gives us a total price/km for diesel in Europe of USD 0.53 in 2015 and USD 0.57 so for 2025 we should get to about USD 0.54. So far we calculated with USD 0.45 so we subtracted USD 0.09 that we will now add again.

[ii] My reverse engineering calculation come out at a range of 5.7 to 6.2 years.

[iii] Electrolysis is currently only 60-80% inefficient although (although 90% has been reached in the laboratory).

[iv] The IEA estimates USD 0.05-0.66 per km now and USD 0.04-0.19 in 2050. But based on the information for refueling stations mentioned in the text this infrastructure must have been depreciated in more than 60 years. So either other information was used for the calculations than is in the report or the infrastructure is much more expensive than the graphs make us believe.

[v] Not as much as batteries but still -60/kWh in 2015 and -30/kWh in 2050. So for a 700 km range that's USD 50,000-100,000 per truck extra now and USD 15,000-45,000 in 2017.

[vi] Currently fuel cells would make a truck with a 260kW motor at least 6.000 more expensive according to the IEA report. In 2050 it could become between USD 13,000 to USD 52,000 (there seem to be two camps of experts attributing to the IEA report that cannot agree on this).

[vii] The IEA estimates the price for a 260kW truck was 6.000 in 2015 and will be .500 in 2050 (the average of the .000 low estimate and .000 high estimate). A price reduction of 6% per year will produce a learning curve hitting both numbers. The result in 2020 would be fuel cells costing ~0.000.

[viii] A starting point of USD 63,000 in 2015 and end point of USD 17,000 in 2050 (from average to lowest estimate so a bit positive) gives 3.7% a year or USD 43,000 in 2025. We'll round it down to USD 40,000.

[ix] A depreciation of 62% over five years like everywhere else yields USD 192,000. Divided by 5 years time 100,000 km that yields USD 0.38.

[x] A strange incongruence that I cannot explain is that maintenance cost would rise from USD 0.10 now to USD 0.17 in 2050. Since all maintenance cost in 2015 are USD 0.17 I'm going to go out on a limb and assume that they were switched and that FCEV maintenance will decrease with 1.5% per year to USD 0.15 in 2025.

[xi] The IEA report uses USD 0.44/km in 2015 and this equates to USD 0.22/kWh. At the same time it states that "dirty" hydrogen from fossil fuel that is currently used in >90% of cases is USD 0.07/kWh. In 2050 it takes USD 0.07/kwh although it notices in the text that it will probably will never be cheaper than USD 0.10/kWh (page 103). What to do with so many mixed signals? If I had chosen to keep it consequent and base myself on the 2015 and 2050 graphs and interpolate using a learning curve with a fixed percentage per year the price per km would yield USD 0.32. Instead I've decided to use mostly dirty hydrogen, thus helping the innovation along. But it is strange because the whole point was CO2 reduction and that is not realized this way.

[xii] For infrastructure the low price would drop to USD 0.04 and the high price to USD 0.44 per km using the same learning curve approach.

References

[1] "Hydrogen production," *Wikipedia*. 07-Jul-2017.