CLIMATE FRIENDLY ROAD FREIGHT FACTSHEET

What’s the best strategy for **climate-friendly road freight transportation**?

In this report we will present an objective analyse and give a comprehensive deep dive on the topic trough seven articles. Let’s have a look at the facts!

SIEMENS

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1.Operational range

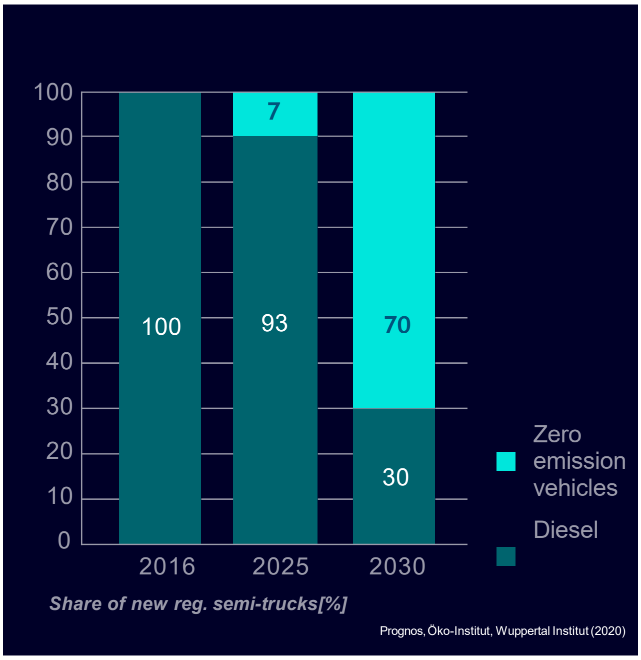
Sustainability isn't just the challenge of the 21st century but it will be a duty and responsibility forever. Hence it is only justified that sustainability should be at the top of all political agendas and an integral part of a company's strategy.

The European Union, for example, has set itself the goal to reduce CO_2 emissions by 55% by 2030 and to become carbon-neutral by 2050[1].Germany's goal is to cut emissions by 65% by 2030 and become carbon neutral by 2045 [2].However, the clock is ticking, and therefore a concerted effort by governments and industries is necessary in order to achieve these targets. Which role does transportation play in all this? Quite a big one as transportation causes 24% of global CO_2 emissions [3]. Most of these emissions are related to passenger transportation, but the share of road freight transportation is also considerable and it's growing [4].In Germany, for example, road freight transportation is responsible for one-third of the CO_2 emissions from transportation sector [5]. Even with ambitious scenarios to shift materials transportation to electrified rail, road freight is expected to grow in absolute terms and remain the largest source of CO_2 from all freight. Road freight therefore has a huge potential to help reduce CO_2.

But what is the right strategy for making road freight transportation climate-friendly?

For short journeys and for light commercial vehicles, there's a strong consensus in favor of battery-powered electric vehicles and low-power charging solutions. However, for heavy long-haul trucking, the picture is more complex. Currently, the 4 main concepts for climate friendly long-haul trucking are discussed:

1. Electric or hybrid trucks equipped with pantographs that connect to an overhead contact line (OCL)
2. Battery-electric trucks with stationary mega charging (BEVs)
3. Fuel-cell electric trucks using hydrogen from new fuel infrastructures (FCEVs)
4. Renewable fuels for conventional trucks and existing fuel infrastructures (RFs)



Siemens AG is active in all of these 4 technology fields across several industries. All the technologies have one thing in common: they all have the potential to eliminate CO_2 emissions. However, the key question is: are these concepts also suitable to reach the necessary CO_2 reductions in the required time?

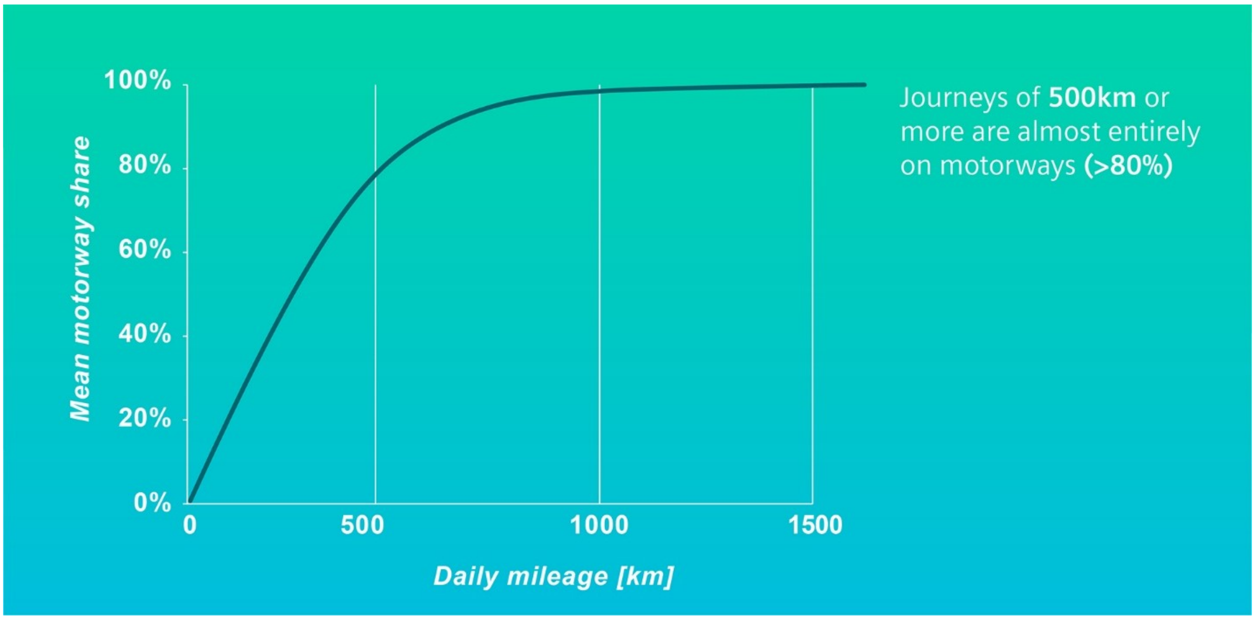
By 2030, CO_2 from heavy-duty vehicles in the EU must drop by -30% according to the 2019 legislation [6]. Given the agreement on April 21, 2021, to increase the EU's economy-wide ambition to 55%, it's plausible that road freight transportation sector will also see an increase in their 2030 goal. The analysis for Germany shows that achieving these ambitious goals will require 70% of new trucks sold in 2030 to be electrified [7]. The goal for 2030 is a crucial milestone on the path to becoming CO_2-free no later than 2050.

A strategy for achieving this has to begin by recognizing the workhorses of today's road freight system: semi trucks. They pull heavy trailers over long distances and face specific challenges, including restricted space on the vehicle and the need for high operational flexibility. Because they do most of the road transportation work (as measured in ton-km), they also emit most of the CO_2 [8].

Equally important to their operational needs is the economic element. This is important for a speedy transition in Europe, where trucking is a low-margin and highly fragmented business.

Finding the best solution requires looking at the 4 concepts, assessing their advantages and disadvantages, and exploring the potential for an intelligent combination of several concepts. In a series of articles, we will look at practical, economic, and ecological aspects and compare the 4 concepts using the following 7 criteria:

1. Operational range
2. Time to market
3. Scalability and resource efficiency
4. Energy efficiency
5. Total cost of ownership
6. Flexibility
7. CO_2 abatement cost



This first article is about operational range, which is a major concern for electric heavy-duty vehicles in particular.

First, let's consider that today's trucks have diesel tanks that provide a range of up to 2,300 km [9].That distance isn't driven in a single day, but it gives us an indication of how far trucks can go before needing to refuel. If we consider what range a truck used by one driver might travel in a day, then 750 km is a more realistic upper limit. Some trucks are used in shifts and will travel more, but most trucks on average will travel less, albeit occasionally they will come close to this maximum.

A second important observation about long-haul trucking is that 80 to 90% of it takes place on highways[10 and 11]. Furthermore, this activity is highly concentrated: more than two-thirds of the fuel burned in long-haul trucking on German highways happens on the busiest 4,000 km [12], which constitute just one-third of the highway network and about 2% of the national road network[14].
For purposes of discussing operational range, it is especially noteworthy that 89% of German truck trips that depart from the highways are only 50 km or less away from them[13].

Now let's turn to the 4 technologies.

Overhead Contact Line (OCL) enables unlimited operational range under the infrastructure. When the truck leaves the OCL, the range depends on its propulsion system.

For instance, hybrid trucks with a combustion engine would have the same range as conventional trucks. In any case, all OCL trucks have a battery that provides a certain electric range outside the infrastructure.

Battery-electric trucks (BEVs) with the typical daily mileage of long-haul trucks have to manage a trade-off between range, payload, and charging stops. The BEV 40-ton trucks currently on the market have a maximum range of 200 km[14], and models have been announced for the coming years with a maximum range of 400 to 500 km [15,16,17].

Fuel cell electric trucks using hydrogen from new fuel infrastructures (FCEVs) have the potential to offer sufficient range for long-haul trucking, especially if they use liquid-hydrogen storage, which is more compact and there's also less risk of affecting the volume of goods that can be transported.

Renewable fuels for conventional trucks and existing fuel infrastructures (RFs) have the same range as conventional trucks thanks to the similar energy density of their fuels[18], and they can even use existing refueling infrastructure.

This was our first assessment on operational range.
In the next articles we will cover the topics of "time to market", "scalability and resource efficiency", "energy efficiency", "total cost of ownership", "flexibility", as well as "CO_2 abatement costs" and our final conclusion.

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2.Time to market

In this article we want to talk about how quickly different solutions are ready to be on the market and able to generate impact.

This is of high importance, as we need to act fast to avoid exceeding the limited amount of greenhouse gases emissions we can emit before risking 2 degrees global warming. Recently Germany has tightened its CO_2 reduction target for 2030 to -65%, and studies find this means 70% of all new truck sales in 2030 need to be zero emission trucks (Overhead Contact Lines, Battery Electric Vehicles or Fuel-Cell Electric Vehicles). Reaching those goals requires putting in place the necessary supporting infrastructure.

So let’s look at how the 4 technologies compare in terms of how soon all pieces will be in place for the infrastructure, vehicles and renewable fuel/electricity production.

The Overhead Contact Line (OCL) solution is based on mature infrastructure technology of more than 100 years of experience. It enjoys established and deep supply chains and open standards. Its specific application to motorway trucking has been proven and tested since 2016. The OCL technology has shown itself easily integrable in tractor trucks and vehicle production is ready for industrialization and can be scaled up to match the roll out of OCL infrastructure. OCL thus has all the technical pieces in place to start scaling it up. Scalability is an issue in its own right and we are excited to present you more in the next article. The roll-out of the OCL infrastructure[1] can start now and a network large enough to contribute significantly to achieving the climate goals can be in operation by 2030.

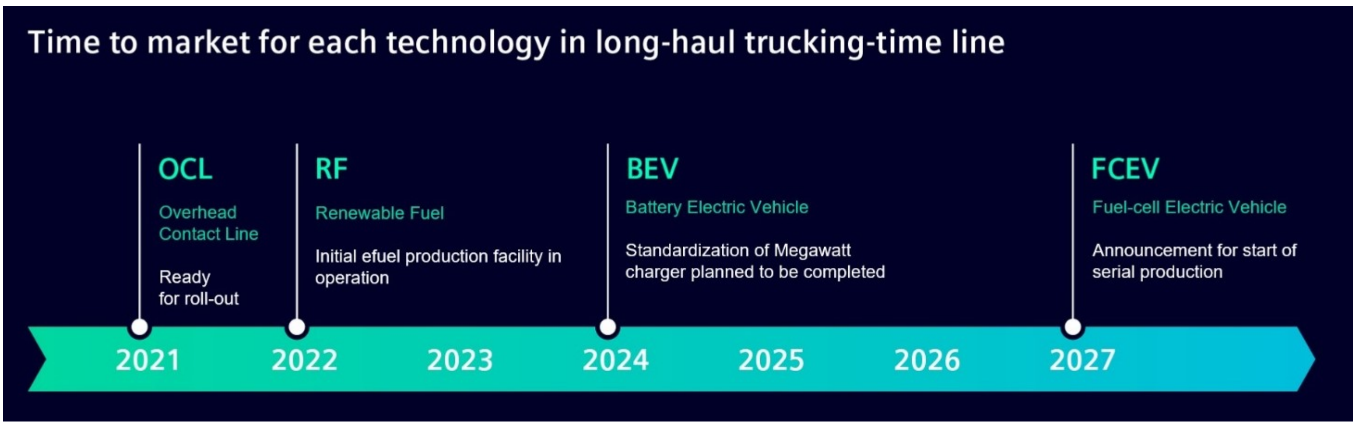
Battery electric Vehicles (BEVs) with increasing tonnage are already entering the market, but these are so far not able to charge very quickly (typically max 350kW) nor able to drive longer than 500 km (see article "operating range"). The most likely development to address this is by pushing for faster charging of trucks. For megawatt level charging the trucks need to be able to handle higher voltages (1.500 V) and currents. Such trucks can be expected to come but are likely contingent on a standard for such charging being agreed upon. Current expectations are that the standard for megawatt-charging infrastructure will be available in 2023. Such high power is only possible through either higher currents and/or voltages than currently used[2]. Robot-supported systems are likely to become necessary for handling these chargers[3]. Assuming existing technology can be used for this purpose, then the first long-range trucks with megawatt charging may be expected after 2023. BEVs with megawatt charging can then start to contribute as a piece of the puzzle of sustainable road freight in long haul.

For **Fuell Cell Electric Vehicles (FCEVs)** the technology for making green hydrogen exist, even if it is only a very small part of the global hydrogen production. The technology to transport it over oceans is currently tried with a vessel carrying 9,000 kg of hydrogen, whereas a much large vessel, capable of carrying 11.000 tons of hydrogen is planned for first operations in 2025. The pipeline technology for mass transport on land is available.

The infrastructure for refueling trucks only exists for 350 bar, which is not suitable for long-haul trucking. There is so far no agreement on a standard (liquid hydrogen or 700 bar gaseous) for this segment.
For liquid hydrogen, a recent report noted that the hydrogen industry has a lower sense of urgency to put such standards and regulations in place, than for gaseous hydrogen.
At the same time, one large truck manufacturer argues that gaseous hydrogen would not offer some of the crucial advantages hydrogen is supposed to offer (low impact on payload, fast refueling, high range). This explains why vehicles, especially for the crucial segment of long-haul trucking are currently not in commercial operation and only available as concepts[4] with announcements of serial production starting from 2027[5]. FCEV would thus appear to be missing several crucial technical proof points in long-haul trucking in order to be relevant for reaching the 2030 climate goals.

The making of **Renewable Fuels (RF)** using renewable electricity, so called e-fuels, is getting started, with the world's first integrated and commercial facility set to start producing 130.000 liters next year in Chile.
As RF would entail the use of existing fueling infrastructure and trucks with conventional drive trains, this is an option that is technically possible already very soon.
However, this is a very energy consuming process which will be further elaborated upon in the articles on energy efficiency and total cost of ownership.
From a pure technological perspective the above shows that today only Overhead Contact Lines, and arguably also Renewable Fuels are implementable for long-haul trucking. Battery Electric Vehicles should become available within a few years and Fuel Cell Electric Vehicles hopefully before the end of the decade.

This is an important consideration, but not the only one, when looking at each technology's ability to scale up and contribute to achieving the climate goals, including the crucial 2030 milestone.



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3.Scalability and resource efficiency

To achieve the necessary CO_2 reductions in time, it is not enough for a technology to be available now. It also needs to be possible to scale it up quickly so that intermediate goals can be met: for example, 70% of new semi-truck sales in 2030.

This challenge is one of "scalability", which depends on factors like the capabilities of the supply chains (including available expertise and staff) and the degree to which these capabilities can be quickly channeled into a rapid transformation of the road freight sector (for example by having open and common standards and fast approval processes).

Closely related to the issue of scaling is the availability of natural resources. Especially during a rapid growth in material demand, there's a risk of supply bottlenecks that could hinder a timely, large-scale implementation.[1]

In the case of **Overhead Contact Lines (OCL),** 2 factors that are sometimes mentioned as negatives – that it's an old, almost ancient, technology and that it's strongly associated with the railway sector – actually turn out to be strong positives. Thanks to more than a century of use across 6 continents and all climatic zones, there are plenty of relevant standards and regulations that can be utilized. And thanks to the roughly €10 billion annual market for rail electrification[2], there are strong supply chains that can be leveraged in road applications.

Installing OCL on roads has this advantage over today's railway applications: all OCL trucks have onboard batteries, which means the OCL doesn't need to cover the entire distance from A to B, which makes implementation faster. Studies already show how commercial OCL could work on shuttle routes of about 100 km in length.
As already demonstrated these initial routes can be used by both Battery-Electric Vehicles (BEVs) without large batteries and by hybrid trucks. Both and other truck configurations utilizing batteries can use the OCL for **dynamic charging**, which means only segments of a route would need to be equipped with OCL in order for the whole journey to be covered electrically.

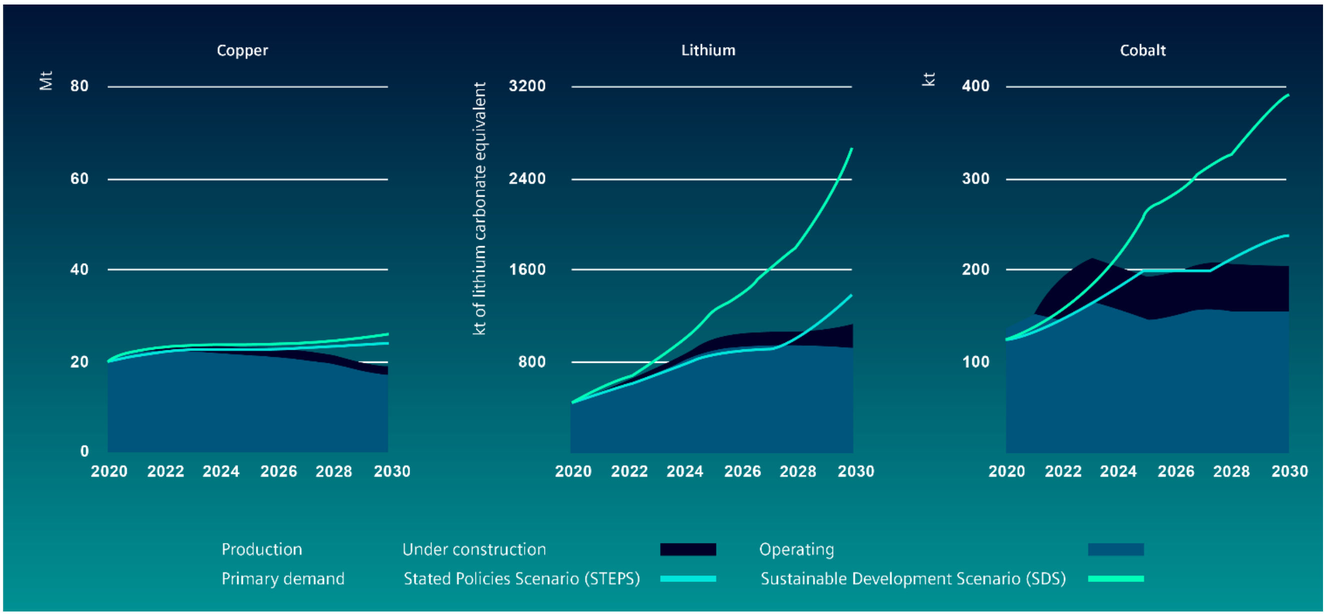
The latter vehicles will be able to operate across Europe right from the start: in other words, without having a comprehensive infrastructure network in place.

This helps OCL overcome the so-called "chicken and egg" problem.
From the early shuttle routes, the OCL infrastructure can be expanded stepwise and power levels increased as the number of users grow, into a national and continental network.[3]
The latter will be facilitated by recent work within CENELEC on Europe-wide standards for both OCL infrastructure and the interface between the OCL infrastructure and OCL trucks. Scaling up OCL vehicle production is mainly dependent on the speed of OCL infrastructure deployment.

It helps to know that in times past, Germany was able to electrify 5,000 km of railway in 10 years[4].

A large installation company estimates that in today's Germany it would be possible to electrify 500 km of highways (for example 500 km times two directions) per year.

One reason it would move quickly is that OCL can be built as an upgrade of existing motorways: It wouldn't require land to be claimed or changes to sensitive landscapes. One critical necessity for OCL is copper. If almost 4 tons of copper are needed per km of motorway, then 4,000 km of German roads would consume 16,000 tons. This is less than 0.1 % of the annual global production (around 20 million tons), and that's before considering that OCL infrastructure doesn't need to be replaced every year.[5]



Committed mine production and primary demand for selected minerals[7]

So even with interest in OCL increasing[6], there seems to be little reason to fear a shortage of copper.There's of course the risk that other developments will affect the price of copper, but the forecasted supply-demand mismatch up to 2030 is a relatively minor 25%.

Battery-Electric Vehicle (BEV) has the advantage of a strong ecosystem of actors working on producing batteries, chargers, and trucks. Of these 3 elements, the focus for scaling up is on battery production and the deployment of chargers. The BEV industrial ecosystem around is pushing for market consensus on industry standards (via the organization CharIN). A standard for megawatt charging systems (MCS) was expected by now, but it's been postponed until 2024. Even without a large European network of MCS, long-haul BEVs would be able to use slow-charge using less powerful chargers – however, a complete network of MCS is essential for making long-haul BEV operations run smoothly across Europe.

Finding space at truck parking areas is already a challenge today[8], and it won't get any easier if equipment is added that makes already tight side-by-side parking more difficult, or if only certain types of trucks can park in certain spaces. Taking new land and converting it into parking spaces will therefore be necessary in order to scale up BEV. The parking spaces will also need substantial grid connections. Because queuing at chargers means truckers losing valuable time, an international booking system is also required: without it, preventing queues would require the construction of so many MCS that their utilization – and therefore their economic return – would suffer. Ensuring that the booking system is robust against manipulation and enforceable against those who would abuse it will be crucial.

At the time of this writing, it is not known if this type of system is already being developed or on what legislative basis it would operate. In addition to the afore-mentioned issues for MCS, another possible bottleneck in scaling up involves the batteries. Battery cost and performance has improved dramatically in the past decade, and more economies of scale in their production as more factories come online is likely. However, this results in battery technology becoming cost-competitive with fossil fuels in segments like LCV and cars much earlier than with semi-trucks (which one BEV manufacturer thinks isn't possible before 2040)[9].

If the demand from other segments triggers a greater demand than can be supplied due to scarce raw materials, this will feedback into battery prices, which at large-scale production are primarily dictated by material costs.
IEA estimates that the mismatch between supply and demand by 2030 could be 1 to 2: for example, for every kg demanded, only 0.5 would be produced. Over the longer run, new production sites could be developed (recycling won't play a significant role this century [10]); but the issue is how the rapid ramping up of battery production and use could be navigated with minimal disruption in the coming one or two decades that are critical for climate protection.

To scale up **Fuel-Cell Electric Vehicle (FCEV)**, 3 components need to fall in place: vehicle production, fueling infrastructure and fuel supply. Ramping up vehicle production and their supply chains is of course possible, but the scale of ramping that is needed isn't well understood. Bringing down the cost of expensive vehicle components like fuel cells and hydrogen storage tanks will be highly dependent on the success of FCEV in the car market (Hyundai, IEA).
A recent Hydrogen Council report said that 900,000 units sold per year would help make fuel-cell vehicles cost-competitive. The current vehicle market is far from achieving that number, and realizing it will probably require substantial policy support.

When it comes to hydrogen refueling stations (HRS), scaling up is currently limited by a lack of standards, and the 3 different ways to store and refuel hydrogen (in liquid form or gaseous at 350 bar or 700 bar) are at very different levels of maturity (see "time to market" article).
Crucially the HRS network needs to be very large (at least Europe-wide) in order to serve long-haul trucking, because the trucks' batteries are too small to use stationary chargers for journeys beyond the HRS network. Nor are the trucks likely to be hybrids with an additional combustion engine.

Lastly, because Europe is viewed as unlikely to have enough renewable electricity to make all the green hydrogen it needs, most FCEV truck scenarios focus on importing green hydrogen. Scaling up imports requires both large-scale production abroad and a means to import it.

There are plenty of places with strong winds and lots of sunshine, which are needed for making renewable electricity. However, not all of those places are easy to do business or make large investments: for example, if they are too remote or are in ungovernable regions. Some locations do offer stable conditions (Australia): but even there, we need to ask if it wouldn't be better for the climate to decarbonize local energy consumption first before exporting green molecules. As to the international transportation of hydrogen, there is currently only one ship that can transport (liquid) hydrogen [11].

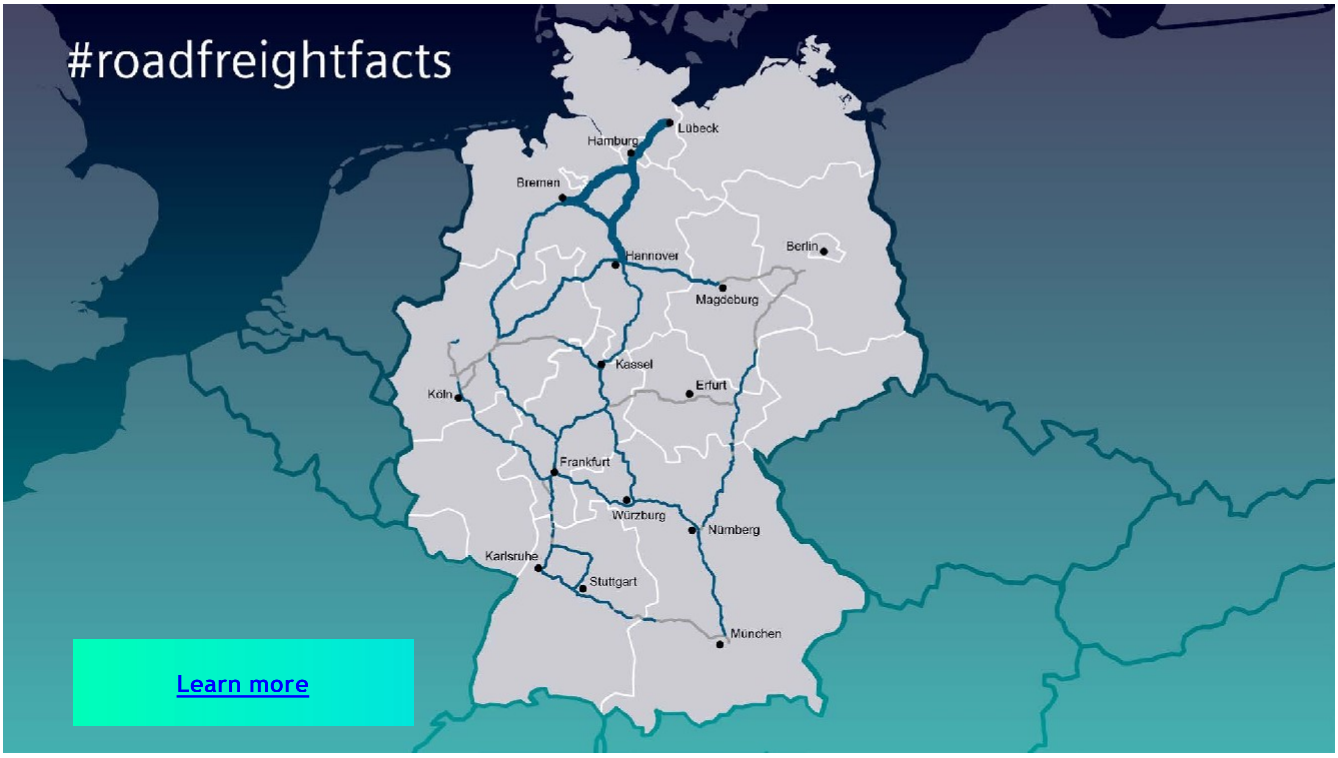
Although a bigger one has been announced for 2025, there are few indications that much transportation capacity will be available in this decade or even the next.

Only from experience with the first trials will we know if many shipyards will be able to add to the production capacity of such vessels.

Renewable Fuel (RF) "only" require the scaling up of fuel availability, which nevertheless remains a major challenge to solve. Synthetic fuels are hydrogen-based and would – due to the additional energy losses in their production – require even larger investments in renewable energy production and additional processing facilities than for the FCEV case.

Biofuels are restricted from scaling up because of indirect land use changes, and many studies advocate deploying them only where no other alternative is feasible.

Illustration of a possible national eHighway network and how it could be gradually expanded[12]



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4. Energy efficiency

The International Energy Agency (IEA) has alerted the industry that the materials needed for renewable electricity generation are also at risk of bottlenecks – so there's a direct link between resource efficiency and energy efficiency.

Energy efficiency isn't just at the core of the transformation of transportation; it is the key to the entire economy. All sectors need to transition, and the less energy that is needed, the easier it will be to meet the demand for renewable energy.

The IEA therefore sees energy efficiency as the "first fuel": in other words, the lowest-hanging fruit [1].

Overhead contact lines (OCLs) and **battery electric vehicles** (BEVs) are both solutions that use electrical energy directly and so they have the highest energy efficiency, with well-to-wheel efficiency of about 73%, factoring in the losses in the energy transmission and distribution system and the vehicle. This puts them in a different league than alternative fuels that have to be made synthetically using electricity. OCL trucks have additional advantages: they use fewer batteries, whose production is energy intensive, and the overall vehicle weight is lower, which reduces energy consumption even more. OCL trucks have slightly higher wind-resistance when the pantograph is raised; but on the other hand, OCL trucks provide energy directly to the electrical engine, which prevents the losses that occur when energy is passed into the battery and then pulled back out.

Another difference is that OCLs enable **dynamic charging**, which helps prevent the peak loads (in time and space) that strain the grid. To lower the cost of reinforcing the grid, BEVs are likely to have on-site energy storage for buffering, and this requires even more battery materials (see previous article on "Scalability and resource efficiency"); and this means that the electricity used in BEV trucks has passed through two separate sets of batteries before reaching the wheels.

With **fuel-cell electric vehicles** (FCEVs), the energy losses in the production, transportation, storage, and distribution of hydrogen mean that more than twice as much energy is required to power the same truck movement compared with using electricity directly.

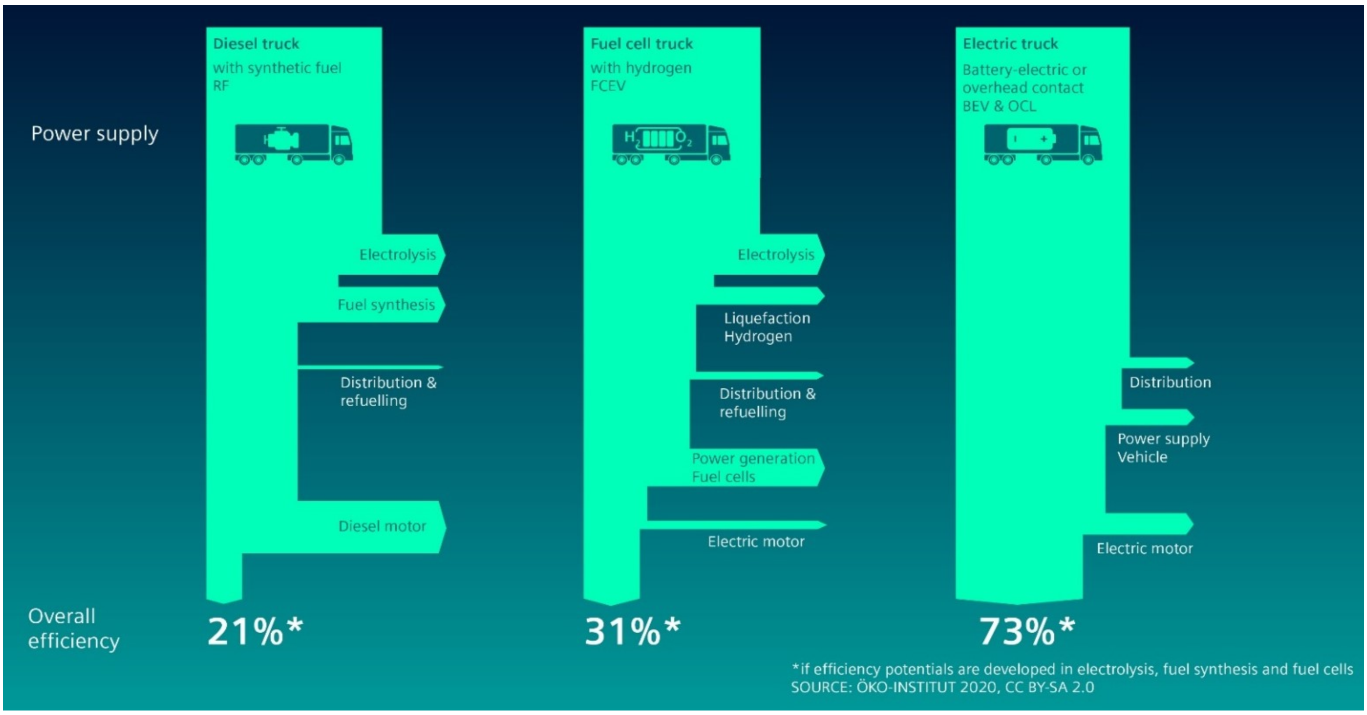
For **renewable fuels** (RFs) like e-fuels, the energy required is more than three times higher than the direct use of electricity.It is sometimes argued that energy efficiency isn't so important because surplus renewable energy is sometimes available in Europe for free. However, just because electricity can be free doesn't mean that the fuels can be made for free, or that the fuels will be available in sufficient quantities. Production requires a capital investment, and if that investment is to be supported by the very small amount of energy that can be produced using free electricity, the customer price will be higher than if the same investment was used for production during most of the year paying close to the average electricity price[2].

Producing green hydrogen and e-fuels outside the EU has therefore been suggested as the solution. However, the import of green hydrogen is still in its infancy, with just one ship able to transport 9 tons of liquid H_2.[3]

Because hydrogen is so light, it's not very energy-efficient to move it around – which explains why 85% of the world's current hydrogen production is consumed on site[4].

It is possible to make ammonia, which is easier to transport, and then transform it back to H_2; but in that case, between 81% and 89% of the renewable energy is lost in the process[5].Using electricity directly is up to 6 times more efficient.

Therefore, the energy efficiency picture is very clear, and it will have an impact on the total cost of ownership, as the next article shows.



Climate-neutral, renewable, efficient: electric trucks ahead | Comparison of the efficiencies of various truck propulsion systems[6]

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5. Total costs of ownership

Despite the important role of road freight in our economy – it transports roughly 70% of all goods – this has not translated into high profitability.

The road freight sector is known to operate on thin margins, which means that buyers of clean-energy trucks will look closely to see if the new technologies will offer a good business case.

Closely behind cost of the driver, which we can assume to be the same in all 4 technologies, fuel costs today make up about one-third of the total cost of ownership for trucking companies.

So even if there are large differences in fuel efficiency and associated costs (see previous article), we need to consider the other factors as well, including vehicle acquisition cost and maintenance.

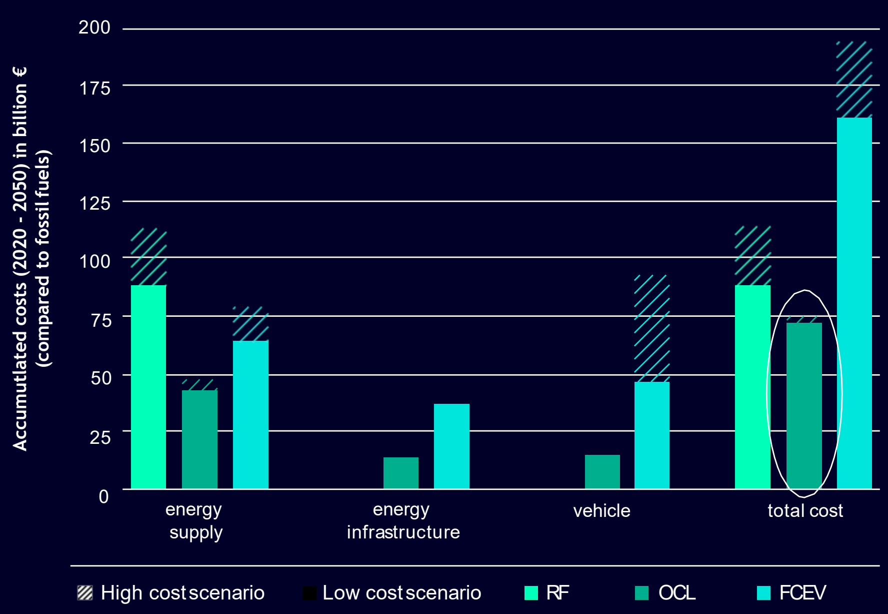
Another important factor will be the infrastructure cost per user, which depends on its investment and operational cost, as well as its lifetime and how much it will be utilized.

When it comes to overhead contact lines (OCL), the vehicle can be cheaper than either a battery electric vehicle (BEV) or a fuel-cell electric vehicle (FCEV). For the motorway network where most of the freight transportation (ton-km) takes place, the user's cost of infrastructure will be low enough to make it the cheapest solution.[1,2,3] For OCL, the expected utilization would be similar to that of the traffic flow already on the motorway – a fairly smooth curve throughout the day – with no behavioral changes necessary.

BEVs are the most economical for use cases where the daily mileage is short, predictable and ideally there can be a long period of standing still to charge, because this helps keep the cost of energy low. With improved battery technology the cost is coming down and ranges are going up, leading some to suggest that long-haul shuttles, in cases where the use of the infrastructure is predictable, can also be economical. A system of stationary chargers will need to rely on a reservation system in order to manage general long-haul trucking. As a rule, operators face the challenge of ensuring high availability for users vs. achieving high utilization of the charging points so they can earn a positive return.

Case study: Decarbonisation of German long-haul freight transport

Overall costs of carbon neutral road freight transport until 2050: energy costs of particular importance

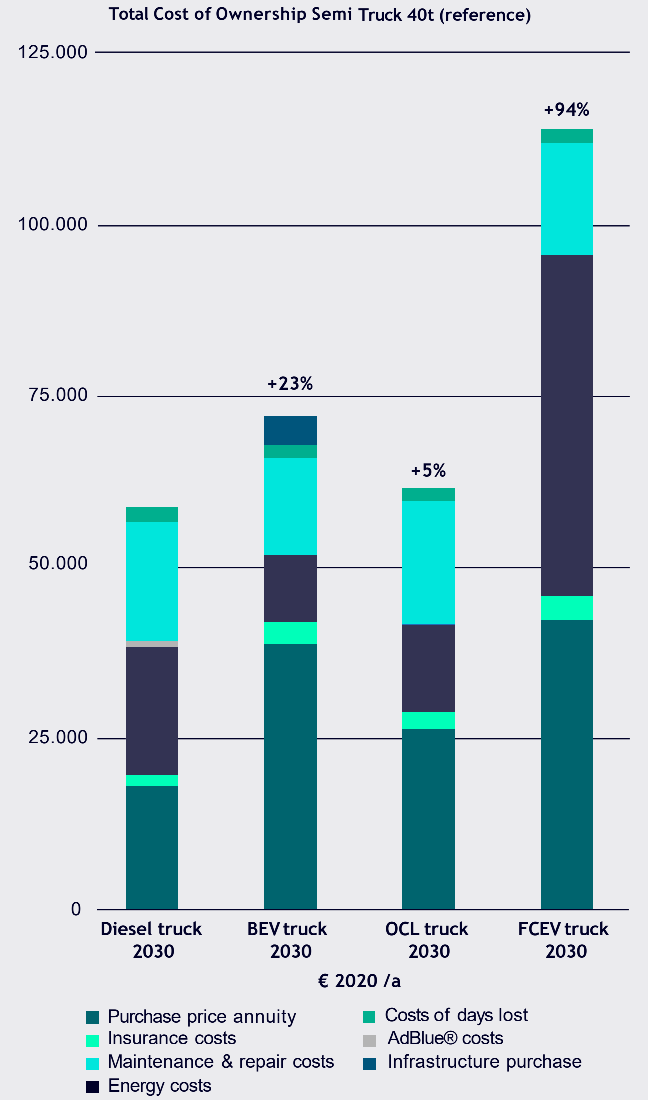


FCEVs would come with both the highest vehicle cost and high energy costs, even in 2030 – meaning that their role is likely to be limited to applications that require zero tail-pipe emissions and where daily mileage is high but traffic flow is too low to justify the investment in an electrical infrastructure.

For renewable fuels (RF), there is no change required in the refueling infrastructure or the vehicles themselves, so the only thing that matters is that the fuel can be made as cheap or cheaper than conventional fuels (primarily diesel). So far, studies show that the energy losses are too high to make this a realistic prospect in the near term.

In addition to the total cost of ownership (TCO), it is worthwhile to add 2 nuances. Some small operators are constrained from making large initial investments. This implies a premium for solutions that keep the vehicles as cheap as possible, because this is the only upfront cost when the energy is paid by use and is delivered via public infrastructure.

Second, TCO is important in helping us understand how trucking companies will be affected; however, it is also important to look at the income side. In other words, if the technology limits operations in terms of payload or distance to be driven, then revenues may be lost, and that will not compensate the cost savings. That is why our next chapter will look at operational flexibility.



Source: own calculations TUHH-VPL and M-Five with input from NPM members)

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6.Flexibility

Flexibility is important for both trucking operators and policy makers.
The operators are keen to ensure that alternative technologies can perform at least the same missions as existing technology.That way the operators can sustain their businesses.
This requirement also influences the re-sale price of alternative trucks, which feeds back to the total cost of ownership (TCO) calculations discussed in the previous article. Policy makers also prize flexibility.
Even though infrastructure for zero-emission heavy-duty trucks needs to be deployed at scale within this decade, requiring fast and substantial action, policy makers still value having the flexibility to tailor the roll-out of infrastructure over time, so that the right capacity and set-up for each roll-out phase can be ensured. Another motivation is that flexibility allows infrastructure to accommodate future technology developments, e.g., highly automated trucking on corridors.

Overhead contact line (OCL) infrastructure can be understood as an upgrade of existing motorways and can be installed with practically no impact on regular traffic operations. The vehicles using the system have on-board energy storage which allows for some gaps in the OCL infrastructure while still enabling fully electrical operation. This makes it possible to build the infrastructure in a cost- and time-efficient way, as potentially complex sections of the route, like motorway junctions, can be skipped. OCL infrastructure can also be phased in, so as to meet growing energy demand step by step, i.e., by gradually adding more substations, more km of OCL infrastructure, or both.

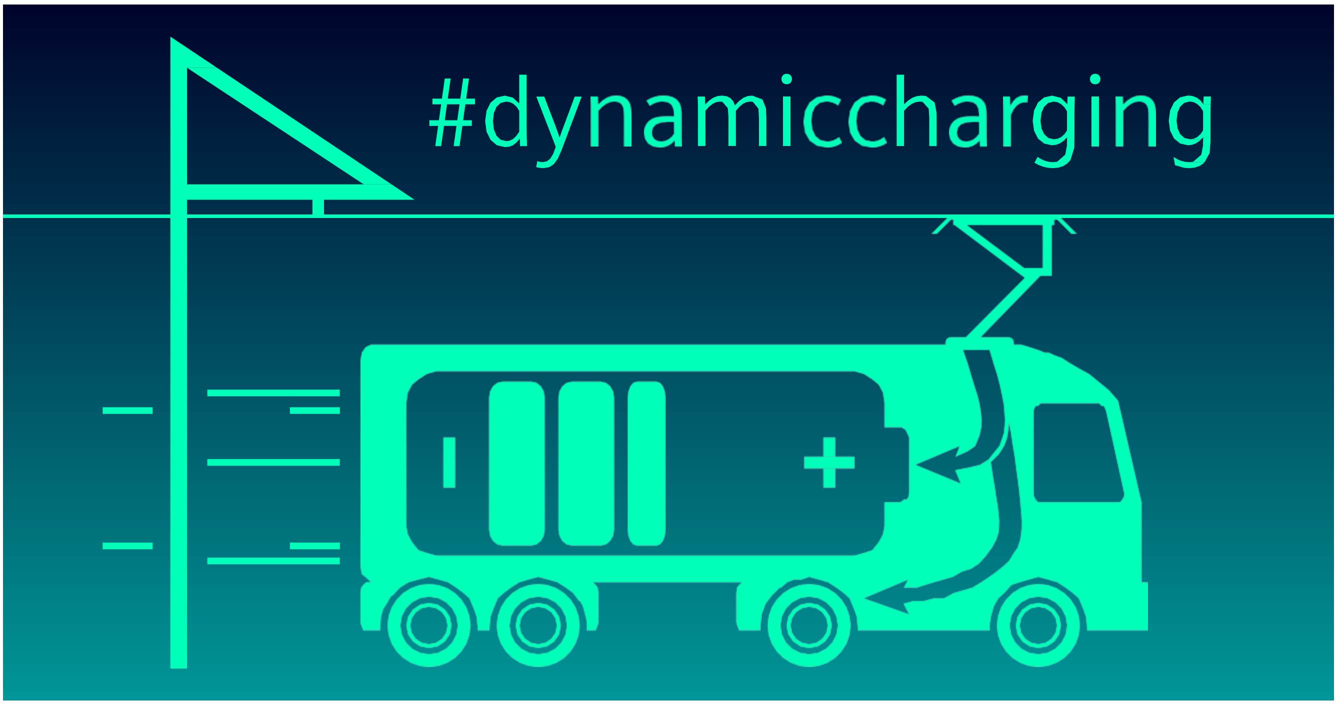
No down-time due to dynamic charging

Trucks can use the OCL flexibly because it requires no charging downtime. Instead, the technology is built for **dynamic charging**, i.e., charging while driving. This is possible due to the trucks' ability to connect to and disconnect from the OCL even at highway speeds. The ability of the trucks to drive electrically outside of the OCL, combined with the robust overhead contact line and its segmented installation, means truckers can rely on the fact that the OCL is making power available for the truck's mission. Furthermore, because such trucks do not need large batteries, the OCL gives trucking operators the same flexibility with payloads as conventional trucks.

OCL technology is compatible with and complements other fuels and drive trains. This includes hybrid vehicles, which may have a role to play in the transition phase, when the only consistent refueling infrastructure available across Europe is the network of current service stations. The OCL also complements and combines with other possibly significant trucking technologies in the coming decade. To give just 2 examples: High-capacity vehicles (HCV), or even just efforts to maximize the loading of the trucks, increase energy consumption per truck and thus give an advantage to highly energy-efficient technologies. Second, automated highway trucking (e.g., "Hub-2-Hub"), which Germany aims to deploy nationwide as early as 2022, increases the value of time. OCL's **dynamic charging** capacities give it the best flexibility to make use of this parallel technology development. For these reasons implementing OCL is a no-regret decision.

OCL technology is compatible with and complements other fuels and drive trains

When considering the flexibility of battery electric vehicles (BEVs), balancing the desired range, payload, battery size, and cost requires choosing a specific vehicle configuration that in one way or another limits flexibility. For instance, small batteries make vehicle cheaper, but will rely more heavily on megawatt charging in the operational stage, with correspondingly higher costs in delivered electricity, to overcome the range limit imposed by small batteries. If an operator instead wants to rely on overnight charging to reduce electricity costs, this requires larger batteries, which lead to a higher vehicle cost (and possibly a reduction in payload). The megawatt infrastructure is flexible in that it can be thinly deployed over a geographically spread-out area [1]. If the targeted locations are equipped with enough space and strong grid connections, it is also possible to gradually add individual charging points to meet rising demand. Although long-haul operations in Europe today need to respect the requirement of 45 minutes of rest time for every 4 hours' driving time, there are already operations where drivers are swapped, thus making it important to have short refueling times. As mentioned above, with the prospect of highly automated trucking, this aspect can become increasingly important to ensure the operational flexibility desired by trucking operators. One important advantage for BEVs is that there is a more wide-spread deployment of less powerful chargers, providing a safety net for Europe-wide operations, albeit with longer charging times.

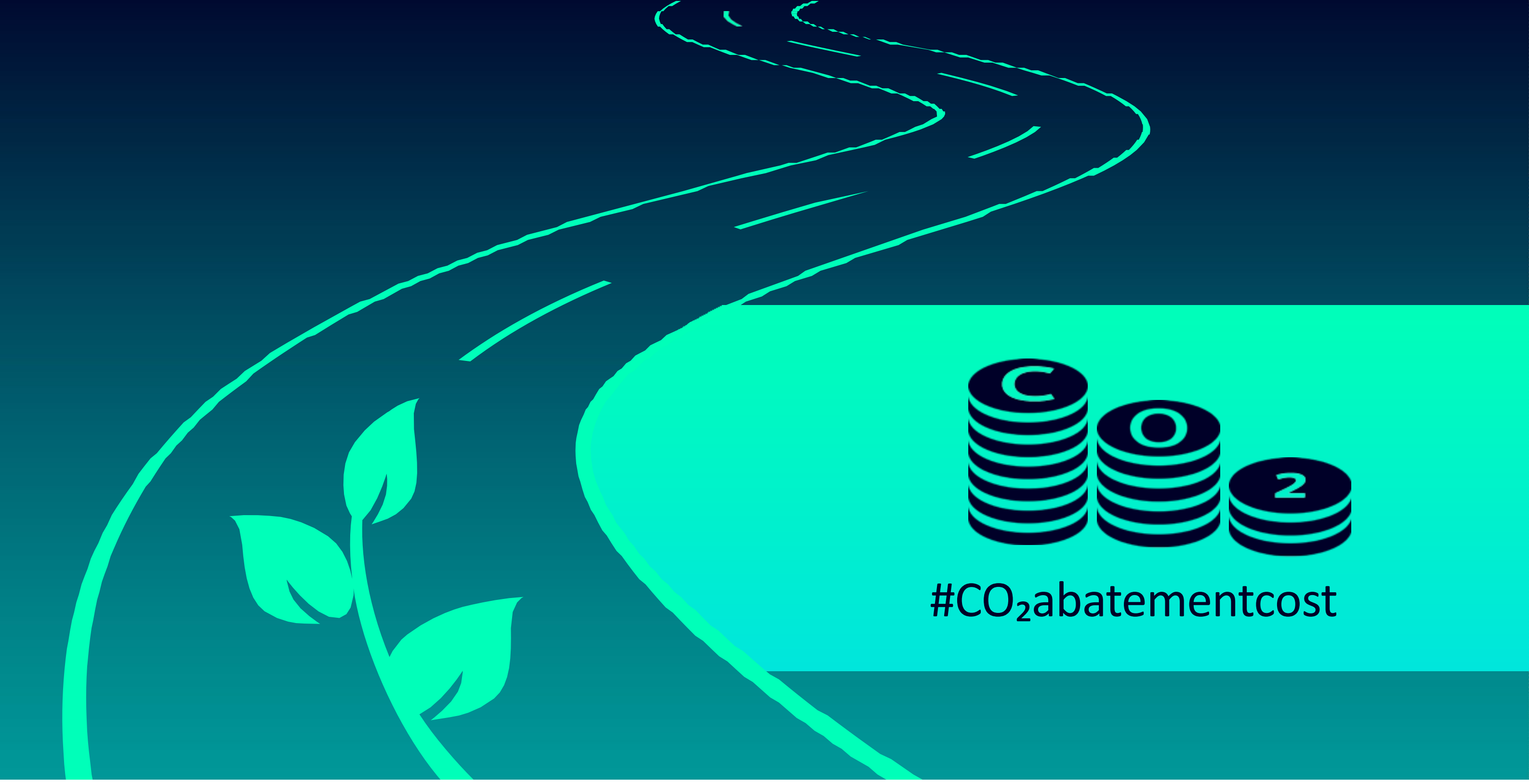


A commonly touted advantage of fuel cell electric vehicles (FCEV) is that their high refueling speeds and energy density (energy per kg) are superior to BEV technology for providing the range that flexible long-haul operations require. However, FCEVs' energy density per m^3 is much less favorable, because H2 itself is very voluminous and because the tanks add to the size of the whole system. Space is just as much of a concern as weight when trying to pack as much cargo as possible in a shipment. Moreover, the two benefits stated above — refueling speed and energy density per kg — depend on how H2 is stored on board, with the highest benefits achieved only when using liquid H2 [2]. Compared with BEVs [2], there are also more concerns about the use of FECV trucks in confined spaces like tunnels or garages, due to the increased fire risk[3] . This too could pose a challenge for flexibility of operations.

Although some hydrogen stations are already deployed (e.g. almost a hundred in Germany[4], for 507 registered cars, in 2020[5]), these currently cannot supply trucks with liquid hydrogen without substantial modifications. The available refueling infrastructure is thus likely to be a hard constraint on the flexible operations of FCEV — especially until consistent standards for such refueling have been set (see previous article on time to market). Regarding the fuel itself, FCEVs require very pure hydrogen to avoid shortening the lifetime of the fuel cells. Although the climate goals demand that all hydrogen be made by electrolysis using renewable electricity ("green hydrogen"), FCEVs are flexible in the sense that they can use hydrogen regardless of its origin, which today in 99,3 % of cases means relying indirectly on fossil fuels. These are used to make the ca. 120 m tons of H2 annually that the world currently consumes (of which less than 0.01 % is used in transport). Hydrogen production thus emits ca. 830 m tons CO_2 per year[6].

For renewable fuels (RF), as noted in a previous article, the infrastructure would remain the same and the operation and service of the trucks would stay the same. However, this theoretical promise of maintaining today's flexibility can only be realized if enough renewable fuels can be affordably supplied. As another article noted, that too is an unlikely prospect any time soon.

This article and the previous one dealt with the primary concerns of trucking operators (TCO and flexibility). The next and final article will look at the CO_2 abatement costs, since policy makers are primarily concerned with reaching climate goals as cost-effectively as possible. That article will also provide a conclusion, synthesizing the different perspectives offered in this series.



FACTS ABOUT CLIMATE-FRIENDLY ROAD FREIGHT TRANSPORTATION

7. CO_2 abatement cost

If total cost of ownership (TCO) is the key metric for commercial haulage operations considering new technical solutions, then the cost involved in order to abate (i.e., decrease) emissions is what guides public policy.

The CO_2 abatement cost differs from TCO in important ways. While the latter looks solely at the aspects which are relevant to the owner of a heavy-duty vehicle (HDV), the abatement cost also adjusts for those aspects of TCO which are essentially transfers between the road freight sector and other parts of society. Examples of these are: how road usage is paid for, taxes/subsidies on vehicle purchases, or the level at which fuel prices are taxed. Adjusting such aspects can greatly influence TCO (and thereby affect how quickly a new technology is adopted), although the total cost to society will be the same.

By comparing the total societal costs of different technologies with the level of CO_2 reduction which can be achieved for each, **the abatement cost shows how cost effective each technology is at reducing CO_2.This metric is therefore the key factor in helping policy makers put limited public resources to best use for achieving their climate protection objectives.**

Furthermore, by effectively filtering out many local aspects, such as fuel taxes, the abatement cost figure is more likely to be globally relevant than an individual TCO calculation. CO_2 abatement cost is not just therefore useful for guiding national decisions, rather also for understanding which solutions have the best global potential. It is therefore not surprising that, when a review of the scientific literature was implemented on alternative fuels and drives for heavy duty vehicles (HDVs), it found that 15 studies took this into consideration, and just 2 did not.[1]

Overhead catenary line (OCL)

That same study found that there was a great diversity in which technologies were considered in the various studies. It is however noteworthy that of the 1/3 of studies which included the OCL option, essentially all [2] of them concluded that OCL would be the most effective decarbonisation technology for heavy duty vehicules (HDVs).This is also what a major study by the Federation of German Industries found.[3] Just last year, Germany´s National Platform Future of Mobility (NPM)[4] estimated the expected CO_2 abatement cost in 2030 for HDVs heavier than 20 tons and it also found OCL to come out with the lowest cost [5].

Battery electric vehicles (BEV)

The NPM estimate for the abatement cost of battery electric vehicles (BEV) was slightly higher than for OCL used by hybrid HDVs. That finding left open the possibility that a combination of BEV and OCL would therefore result in an even lower abatement cost: low-cost vehicles which are able to travel fully electrically along the core corridors, without losing time to charge, while also able to travel significant distances under electric power away from the core corridors. This would yield the maximum CO_2 savings and do so while being economical with savings in energy, resources and time.

Fuel cell electric vehicles (FCEV)

The NPM calculation also looked at the third technology-option for zero emission heavy road freight: fuel cell electric vehicles. According to the NPM report, FCEV provides a CO_2 reduction at nearly three times the cost of the alternatives using electricity directly (e.g., OCL).

The significance of this difference is well illustrated with an example calculation provided by the German federal ministry of environment: At a targeted reduction of 10m tons of CO_2 per year in Germany, this difference in CO_2 abatement cost amounts to an annual cost difference of 7bn EUR.[6]

Renewable fuels (RF)

Renewable fuels are sometimes excluded from CO_2-abatement reports, since it would not be a zero-emission solution. However, as it is a technology option which can decarbonise the existing vehicle fleet (and in 2030 and even 2050, it is still very likely that there will be HDVs in operation with combustion engines), this should not be excluded. A more serious aspect is the large amounts of energy needed to produce renewable e-fuels (refer to the earlier article on energy efficiency). Primarily for this reason, the BDI study mentioned above found RF to be one of the five most expensive measure for reducing CO_2 in the transport sector.

This was despite the Federation of German Industries assuming that the RF would mostly be made outside Europe using low-cost electricity. Scenarios where RF is made abroad are frequently preferred, arguing that a wind turbine in some places can generate much more energy than in others.
The logic being that even with higher energy losses (both in generating e-fuels and by using it in combustion engines), the same wind turbine could generate similar amounts of usable energy for a HDV, as would be the case when the wind turbine is generating electricity used directly by a nearby HDV in a region without strong winds.
A key variable in order to evaluate such claims is the discount rate. It has been reported that the cost of capital for a wind farm project in Indonesia is twice that of a similar project in Germany.[7] So even though some places have better weather conditions for generating renewable electricity, that still does not automatically mean that electricity will be much cheaper than in places where the business environment makes a lower cost of capital possible.

However, that should not be the last word on RF. Because they are still likely to be expensive, it makes a lot of sense to focus on the use of RF to hybrids. Especially hybrids which drive a very large share of the mileage in electric mode, as would be the case with hybrid HDVs using OCL infrastructure. Conversely, when the OCL hybrids are not in electric mode, using RF helps ensure that CO_2 is eliminated from all the HDV's operations.
Some reports find that this combination, given a sufficiently large OCL network, would be the most cost-effective solution to decarbonise the road freight sector [8].Although one should note that the OCL-BEV combination was not included in that study.

Conclusion

As the facts for each subject in this series have shown, there are strengths and weaknesses with each individual technology.
Given that these do not overlap, there should be especially high synergies in combinations of the different technologies.This, plus the urgency of the moment necessitating a multipronged approach, points to a future with a mix of the four technologies.
However, this does not imply agnosticism about their relative impact. It is unlikely that there will be an equal split between the technologies, as economic and practical concerns will lead to a greater role played by certain technologies.**The key for the future of road freight lies in understanding which combinations of technologies can achieve the greatest synergies.**

From this series' review of the public facts, it is clear that **electrification is very well placed to be at the core of the future road freight system. Due to its higher energy efficiency and associated lower abatement cost, it should be the preferred choice wherever it is practically possible. Furthermore, electrification is also the option available already now**.This applies both to vehicles (BEV) and infrastructure (OCL as well as high-power chargers, HPCs). Based on the existing ecosystems of standards and suppliers, these can most easily be scaled up in the limited time which is left to achieve the climate goals.

Overhead contact line (OCL) is the most economically beneficial solution on the core motorways, where the volume of heavy goods vehicles justifies the installation of the infrastructure. It is compatible with all the other technologies and helps overcome their main obstacles for wider adoption e.g., lessens the need for large batteries, provides dynamic charging, and helps spread out the load on the grid, reduction of use of costly fuels as would be the case for FCEV and RF.

OCL is also technically feasible. Catenary is a technology which is already in global use, showing that no environmental barriers exist against its scaling up and explains why interest from around the world is strong. Due to the past five years of demonstration projects and field trials involving HDVs in commercial operations using OCL on public motorways, it has been possible to work with standardisation bodies such as CENELEC.

By setting standards for the OCL infrastructure as well as the interface between the vehicles and the OCL, the conditions have been created which will enable the broad electrification industry (with an annual global turnover of around 10 bn EUR) [9] to mobilise and support the rapid implementation of OCL.

OCL is also politically possible. As politicians are looking for solutions for achieving climate targets, including those for 2030, OCL provides an option which is available today and without needing any further technical breakthroughs. It does require the active cooperation of the owners and/or regulators of the motorways. In many cases around the world, these would be the same politicians who are looking for the cheapest and fastest way to decarbonise the road freight sector.

Battery electric HDVs are being launched by all major producers and they are well placed to become the dominant vehicle architecture. Initially these will be focused on urban areas and short distances, but with growing availability of charging infrastructure, operating ranges will be greatly extended. On less intensely used corridors, this is likely to be the exclusive domain of stationary chargers.
For the corridors, where lots of heavy-duty HDVs drive the main part of their journeys, a strong case can be made for why BEVs should want to make use of OCL infrastructure.[10]

Hydrogen is already a much-needed resource in different sectors today. Green hydrogen plays a negligible role so far. Substituting green hydrogen for the existing hydrogen which is produced (approx. 120m tons) will take a long time and require significant investments in renewable energy.
Even advocates for green hydrogen say it is at least 10-15 years away.[11] So as with any hydrogen solution, the case for fuel cell-powered electric vehicles, make the most sense „where other alternatives might not be feasible or have higher costs".[12] In the case of road freight, this means the missions where electrification is not economical (e.g., long range on roads with low traffic density in areas with poor grids – think of a HDV collecting timber deep in the forest) and where zero emission operations are needed. Furthermore, the infrastructure for green hydrogen production, hydrogen distribution and refueling is not available. The standard for refueling is still to be defined and has a direct impact on operational range, refueling speed, and time to market (35 MPa / 70 MPa / liquid).

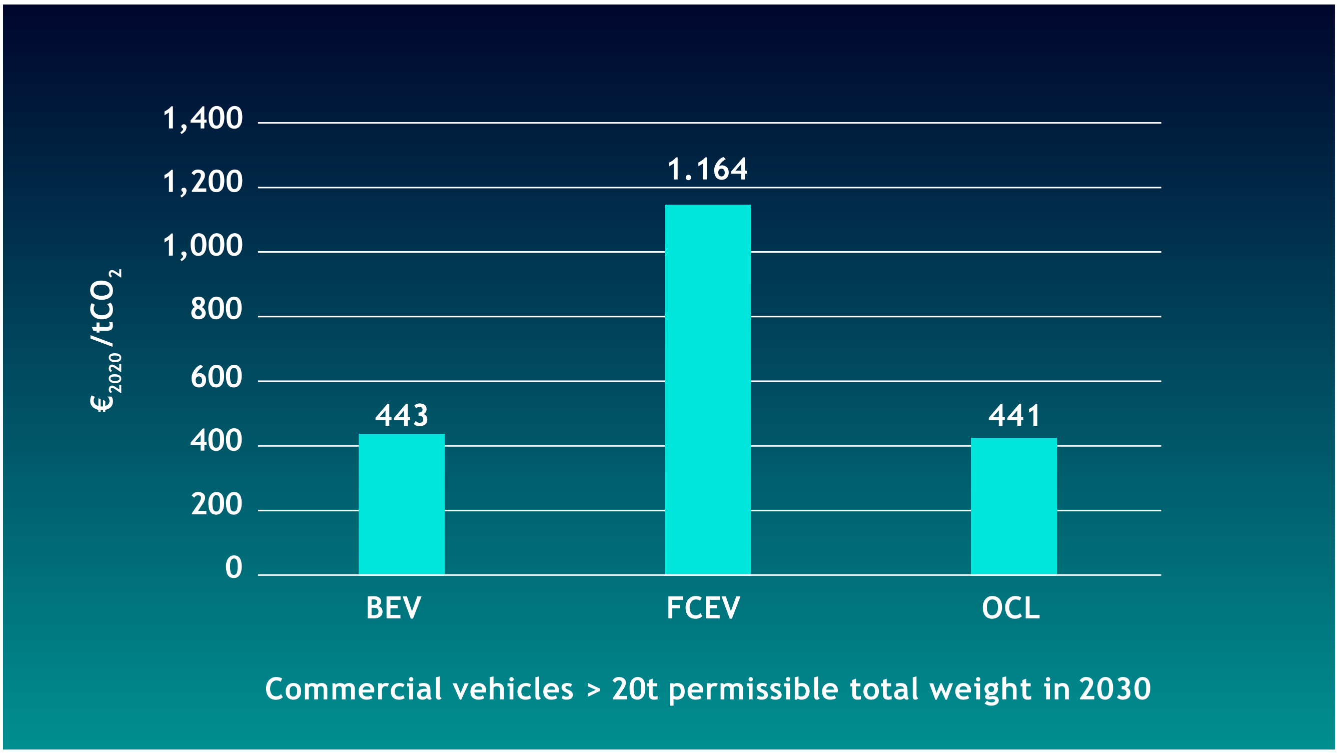
In order to overcome these challenges, it would be essential for FCEV to be easily compatible with other technologies. Although FCEVs come with sizable batteries, their primary purpose is to buffer the energy from the fuel cells so that extra power can be achieved when accelerating or driving uphill. The batteries are not meant to be the main source of onboard energy storage. Nor would FCEVs be able to make use of RF. However, if one wanted to scale FCEV today, relying on the only standardised solution for HDVs (35 MPa gaseous hydrogen), one could make a solid case for combining FCEV-OCL. 35 MPa is usually not considered suitable for long distance operation because of the highly voluminous tanks. However, when combined with OCL, much smaller tanks are necessary, as most miles and especially most long-distance miles, can be powered via the OCL. As green hydrogen is likely to remain a more expensive fuel, OCL also helps ensure that it is only used where electrification isn't possible.

The future for e-fuels greatly depends on the prospect of achieving nearly limitless and super cheap electricity. As such, it represents a very optimistic view of the future.

As a precaution, in case this future does not materialize so easily, it makes sense to focus on the more energy efficient solutions, while developing RF as an addition to achieve decarbonisation of the combustion engine vehicles which may still be part of the future vehicle fleet. In this case too, it is worth mentioning that the use of RF in hybrids seems to make a lot of sense, especially in hybrids which can use the OCL to achieve most of their mileage in electric mode.

Just by looking at the ability of various technologies to be combined with the others, it is clear that the strongest synergies come from OCL. It therefore represents the lowest risk investment of all the aforementioned technologies, as it can most easily adapt and support whichever other technology makes the most progress in the coming years. Furthermore, due to its high efficiency in energy, resources and time savings, it is also the best suited technology to be combined with other technology trends in the road freight sector.

National Platform Future of Mobility - Total cost of ownership graph[13]



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