BERYLLS STRATEGY ADVISORS

BATTERY LIFETIME VALUE: HOW ENERGY STORAGE WILL DETERMINE THE LIFE CYCLE OF ELECTRIC TRUCKS

AGENDA

The transformation of trucking in Europe towards zero-emission vehicles is accelerating and must be accomplished within two decades. Never since the switch from horse-drawn carriages to Diesel-powered trucks, has there been such fundamental change for the industry. Technologies are being replaced and value pools are being reallocated. But also, the daily use of trucks by their operators is changing: battery charging and range limitations heavily affect the usage and scheduling of electric vehicle fleets.

Batteries replace Diesel engines as being the most valuable single component of a truck. On a long-haul tractor with 600 kWh battery capacity, the energy storage accounts for 60% of the total product costs. Even though this share will gradually decrease because of improving economies of scale and evolving battery technology, batteries have a massive influence on the value of electric trucks throughout their life cycle. And here another difference to Diesel trucks comes into play: lifespans of vehicles and major components like the battery will increasingly be out of sync.

DIESEL TRUCKS – A SYNONYM FOR DURABILITY

Most first owners are using a 4x2 tractor over 5 years and half a million kilometers. Normally a second life use in Europe and often a third life use in an emerging market follow. The annual mileage typically decreases during the life of a truck, but 1.5 to 1.8 million kilometers in total are not uncommon before a heavy-duty truck is finally scrapped.

According to ACEA, the average age of the 7.3 million European medium- and heavy-duty trucks is 14.2 years. Some 57% of the total truck parc are older than 10 years! Especially in construction applications, where annual mileage is rather low and truck bodies are quite expensive, many customers use their vehicles far longer than a decade. And later, these trucks are being sold to the Middle East or Africa, to keep running until they fall apart.

Diesel engines are extremely durable and so widespread globally that maintaining trucks to last for many years has become normality. With the change to battery electric powertrains, this model will come to an end. Today there is little empirical information available, how long truck batteries will last. But it is very unlikely that their economic life exceeds 10 years.

This raises the question, what will happen to the used truck when the battery state of health (SoH) drops below the required 70-80%. And of course, it also must be defined what happens to the battery when the first life performance requirements are no longer met. To answer these questions, we must take a closer look at the respective residual values of the vehicle and the battery.

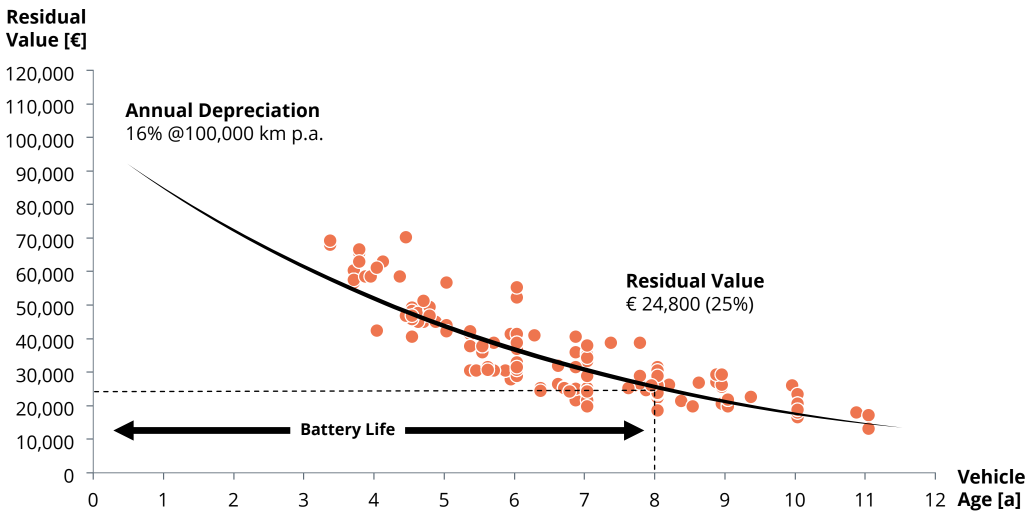
USED TRUCK PRICES AND RESIDUAL VALUES

Prices of used trucks are quite volatile and cyclical. When the transport sector accelerates, the need for additional capacity is partly covered by used trucks, which are quickly available. But when the economy slows down and the vehicles that were leased at the beginning of the cycle are being returned, the yards get crowded, and the prices drop. In recent years, restrictions in the supply chain of new trucks have caused significant backlogs – and thus boosted the vehicle prices on the used equipment market.

Apart from these cyclical effects, the residual value of a used truck basically depends on its age, mileage, and overall condition. To quantify residual values, Berylls Strategy Advisors has done extensive research on online used truck offerings. We assumed that the residual values correlate with the price offers and the average dealer margin is 10%. There is a multitude of standard 4x2 long-haul tractors available on the respective online sales platforms, while more specialized trucks are less common. We tested different ways of modelling the residual value as a function of vehicle age and mileage and found that a degressive approach with a fixed annual rate has the best fit to the actual price offers.

For the selected "bread & butter" long-haul truck model, a 4x2 tractor with 430 hp, we found nearly 200 offers on five different platforms. The vehicles were on average 6.5 years old and had 624,000 km on the odometer, which equals an annual mileage of approx. 100,000 km. The price offers ranged from 13,100 € for an 11-year-old tractor with 1.3 million km up to 70,000 € for a well-preserved truck that had run only 100,000 km in 4.5 years.

We found that vehicle age has a stronger correlation with residual values than mileage. In fact, a combined model with an annual rate of 16% worked best and achieved a mean square deviation of R^2 = 0.0147. The graph below shows the residual value curve for the tractor with an annual mileage of 100,000 km.



Residual Value of 4x2 Long-Haul Tractors (430 hp) in Europe
Data Sources: TruckStore, TruckScout24, BasWorld, Europa-LKW, Kleyn Trucks

BATTERY END-OF-LIFE SCENARIOS

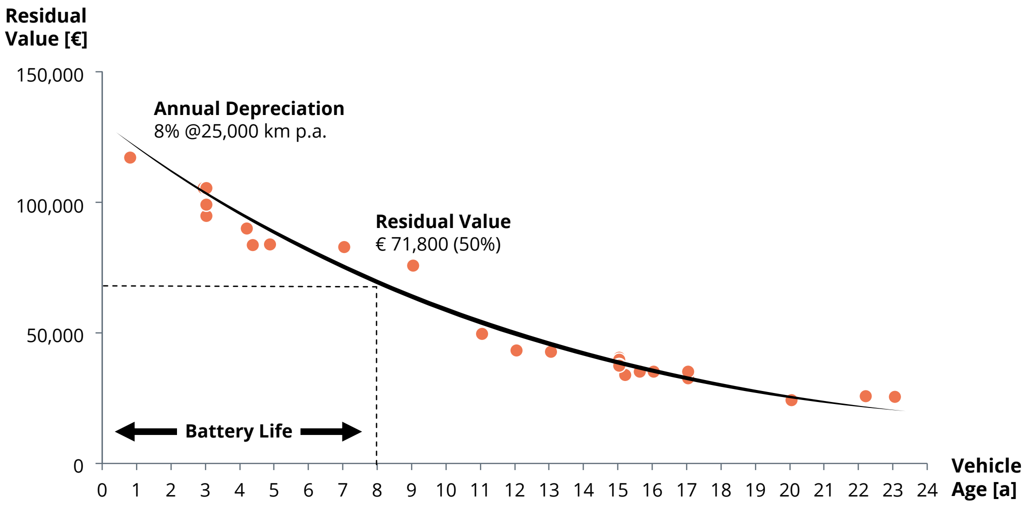
After 8 years, the residual value of such a vehicle is 25% of the new price. If the truck was battery electric and the battery reached its end of life after 8 years, the owner would have two options: (1) Replace the battery or (2) scrap the vehicle.

Replacing the battery would mean to fit a new component worth 40,000 € into a used asset worth 20,000 € – considering the gradual decrease of battery prices as mentioned above. It would boost the value of an 8-year-old truck to 50% of a comparable new one. Scrapping the vehicle would mean to write off an asset worth 20,000 € to its mere material value. Consequently, annual depreciation would rise considerably with negative effects on the total cost of ownership (TCO). Moreover: How sustainable is a zero-emission transport sector, that puts properly working machines into the scrap press? There seems to be a real dilemma!

LONG-LIFE TRUCK APPLICATIONS

Tractors are only one application of heavy-duty trucks. To broaden the perspective, we have analyzed another one – the other extreme, so to say. While 4x2 tractors are standardized and include no bodywork, 8x4 concrete mixers are rather complex and costly regarding axle configuration, power take-off and drum equipment.

We specified a usual 32 t vehicle setup with 400 hp and found approximately 40 offers on the online used truck platforms in scope. The vehicles were much older than the tractors above – 11.8 years on average – and had only 264,000 km on the odometer, which equals an annual mileage of 25,000 km. The price offers ranged from 26,800 € for a 20-year-old (!) mixer with 523,000 km up to 130,000 € for a nearly new vehicle with 14,000 km after 9 months.



Residual Value of 8x4 Concrete Mixers (400 hp) in Europe
Data Sources: TruckStore, TruckScout24, BasWorld, Europa-LKW, Kleyn Trucks

Parameterization of our residual value model led to an annual depreciation of 8%, which is only half as high as for long-haul tractors. The influence of mileage on used concrete mixer prices is close to zero. The mean square deviation of R^2 = 0.0087 is excellent. Our graph shows the derived residual value curve for the concrete mixer with an annual mileage of 25,000 km.

NEED FOR REPLACEMENT BATTERIES

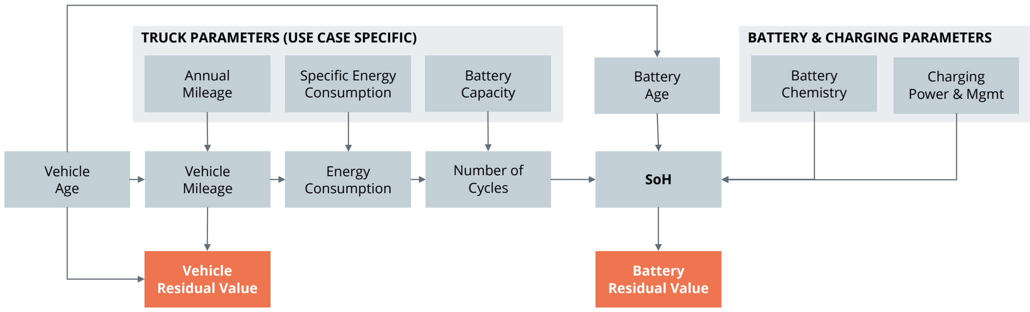
Let's apply the two different battery end-of-life scenarios described above to our concrete mixer example: Replacing the battery would mean to fit a new component worth 30,000 € into a used asset worth 70,000 € (which equals 50% of its new price). That doesn't sound too unreasonable! On the other hand, scrapping the vehicle would mean to write off 70,000 € and thus double the annual depreciation. This is no longer a question of TCO, this is just unthinkable.

The mixer example illustrates that there will be a need for replacement batteries after the original energy storage has reached end of life. An asset of such high and stable value as an 8x4 concrete mixer must be operated for at least two battery life cycles. Compared to long-haul tractors, the battery size and share of total product costs are smaller, and the depreciation of components other than the battery is significantly lower.

Conclusion: For an economically viable and sustainable zero-emission truck business, the residual value and life cycle management of the battery is essential.

BATTERY STATE OF HEALTH & END OF LIFE

We have assumed that the lifespan of a vehicle battery is 8 years. This is what most OEMs currently predict or even guarantee. In fact, the end of life of the battery is often defined as the point in time when the state of health (SoH) drops below 80%. The end of life depends on the battery chemistry, the battery's age, the number of charging cycles as well as some basic parameters of charging power and management.



Vehicle & Battery Residual Value Model for Trucks
Source: Berylls Strategy Advisors

Battery ageing models differentiate between two major drivers: Calendaric capacity loss and cyclic capacity loss. So basically, the degradation of the battery is driven by similar parameters as the depreciation of the truck. Battery age is equivalent to vehicle age, and the number of charging cycles is proportional to the mileage. However, some additional charging parameters must be considered, which make the residual value model for the battery more complex than the one for the truck.

Calendaric Capacity Loss

- **» Battery Age [a]**
- **» Average State of Charge (SoC) in %**
- **» Average Temperature [°C]**

Cyclic Capacity Loss

- **» Average C-Rate [h^{-1}]**
- **» Average Depth of Discharge (DoD) in %**
- **» Full Equivalent Cycles**

We have applied a proven battery ageing model based on a study by TU Munich, that tested 1,000 batteries over more than 3.5 years in controlled environments. By integration of battery ageing into our residual value model, the combined residual value of vehicle and battery can be determined. Moreover, the synchronicity between both can be analyzed and a life cycle strategy can be derived.

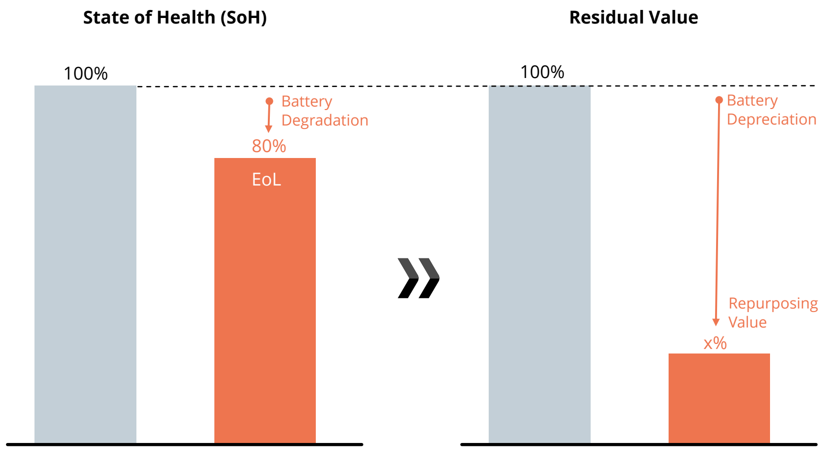
EXEMPLARY USE CASES

Based on our use case examples, an application of the battery ageing model shows that a battery lifespan of 8 years is a pretty good rule of thumb! For the 4x2 long-haul tractor with 100,000 km per annum, lithium iron phosphate (LFP) battery with 600 kWh capacity and 50% megawatt charging share, the model predicts a state of health (SoH) of 80.6% after 8 years. Two thirds of the capacity loss are driven by the calendaric component, one third by the cyclic component. If the same total mileage is completed in 5 years – with 160,000 km annually – the SoH will be 83.1%. In fact, two more years of operation with the same mileage would be possible before the threshold of 80% SoH is reached. In other words: LFP batteries can do more than a million kilometers. They don't suffer much from usage; they simply suffer from ageing.

In the 8x4 concrete mixer use case with 25,000 km annually, 400 kWh LFP battery capacity and 100% overnight charging, the state of health (SoH) will be 82.3% after 8 years. Due to the relatively low mileage, the calendaric component accounts for more than 75% of the capacity loss. Two more years of operation would be possible before the 80%-threshold is reached. Alternatively, the annual mileage could be doubled to 50,000 km to cause the same effect. That's good news for the operator! However, even after 10 years the residual value of vehicle and body excluding the battery is close to 60,000 € – so the truck will outlive the original battery in any case.

DEGRADATION VS. DEPRECIATION

Once the battery has reached its end of life, it is literally "useless" for the truck. That means that degradation from 100% to 80% SoH corresponds with depreciation from 100% to zero residual value – at least in theory. Some operators might keep going even with a low performing battery, taking the risk of fast degradation. But from an economic perspective, it makes sense to take degraded batteries out of service and look for an alternative purpose.



Battery State of Health (SoH) vs. Residual Value
Source: Berylls Strategy Advisors

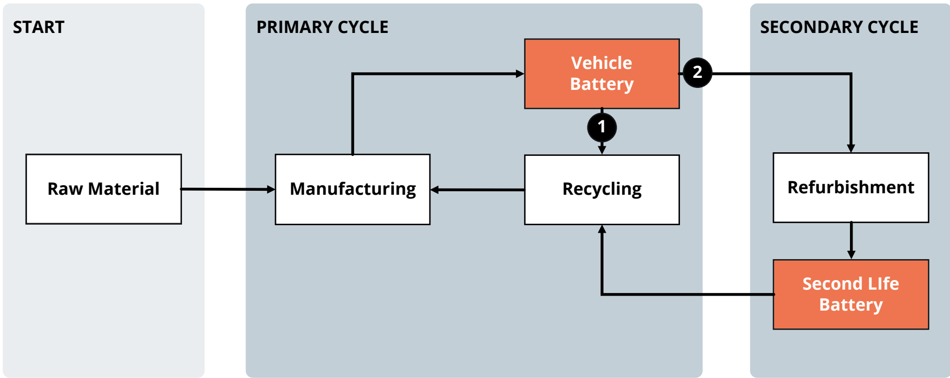
Repurposing helps maximizing the lifetime value of the battery. And it helps minimizing the total cost of ownership (TCO) of the truck, as it lifts the residual value of the battery above zero. Planned repurposing requires battery life cycle management.

BATTERY LIFE CYCLE MANAGEMENT

Active management of the battery lifetime value includes finding the right point in time for replacement as well as finding the best possible use after its end of life (EoL) in the truck application. Essentially, there are two different options as illustrated below: (1) Recycling to keep the material in the primary cycle, (2) refurbishment to upfit the material for a secondary cycle.

Which option is better, depends on the corresponding residual value of the battery. For the primary cycle, the residual value equals the material value minus the recycling and logistics costs. Battery material that is returned into the manufacturing process of new truck batteries will dampen the raw material prices. As the latter are volatile and hard to predict, the battery business will be quite cyclical and require flexible options for EoL usage.

This is where the secondary cycle comes into play. Here the residual value depends on the respective use case and the economics of the second life application. The higher the profit potential, the higher the willingness to pay for a used truck battery.



Battery Life Cycle Options
Source: Berylls Strategy Advisors

We assume that the residual value of the battery in the primary cycle defines the lower limit for any secondary cycle option. To maximize the battery lifetime value, you can either bet on high raw material prices and cut the costs of the recycling process or develop profitable ways of using partially degraded batteries for as long as possible.

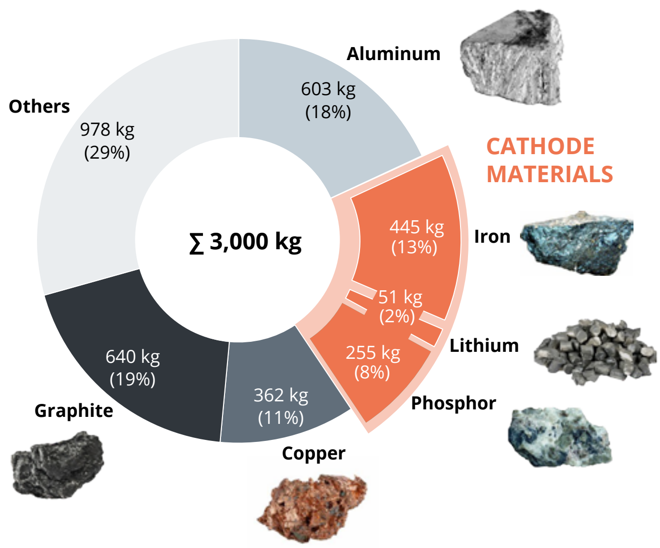
Conclusion: The residual value of the battery will depend on the demand and supply situation in second life application markets.

RECYCLING OPTION

We consider battery material recycling as indispensable for a sustainable adoption of zero emission vehicles. Moreover, in many regions it is a legal requirement already today. The so-called "urban mining" addresses the long-term supply constraints on resources and reduces the dependence on mined metals. Used battery modules that do not meet the requirements for second life applications have to be recycled. Others might be as well, if the repurposing value of recycling is higher than that of alternative uses.

Regarding recycling economics, LFP batteries are much less attractive than their NMC (Nickel-Manganese-Cobalt) counterparts, because they contain none of those valuable metals. Thus, the incentive for recycling of LFP batteries is largely dependent on the lithium price, which accounts for up to 50% of the total recycling revenue – although lithium has a share of only 2% of the LFP battery weight. Other metals that represent a significant material value are aluminum and copper with weight shares of 18% and 11% respectively.

As raw material prices are volatile, battery life cycle management partly has the character of a commodity future. In total, the materials that can be recycled from a 600 kWh LFP battery weighing 3,000 kg were valued at 4,800 to 9,800 € in the period between 2017 and 2021. With recycling costs (including logistics) of 1.00 € to 1.50 € per kg, the repurposing value of that battery would range from 300 to 6,800 € – quite a spread and related business risk!



Material Composition of a 600 kWh LFP Battery
Source: PEM Motion, Berylls Strategy Advisors

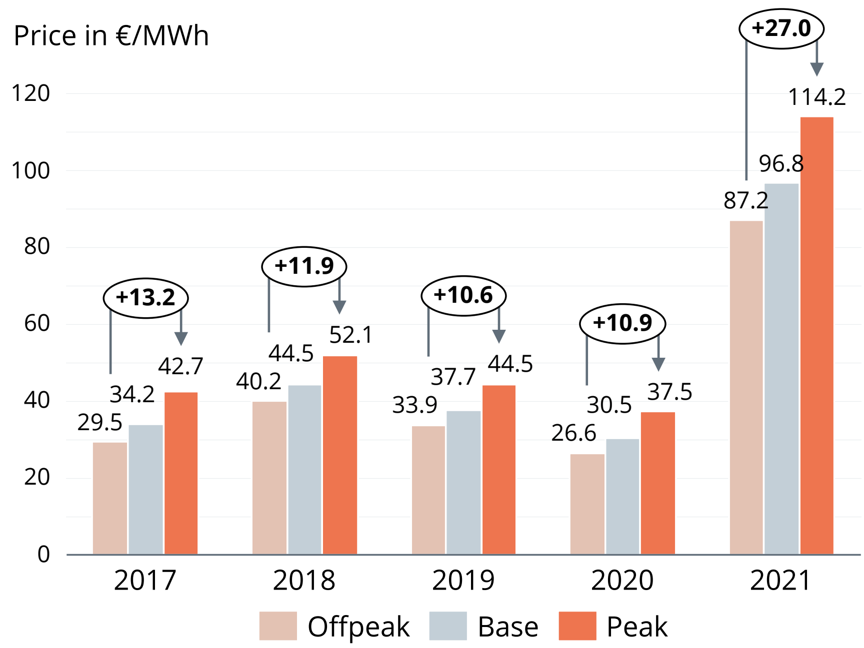
The lithium market is currently cooling down from the 2022 peak price levels. But we expect a structural supply deficit from 2025 as battery electric vehicle penetration rates will increase considerably for cars, vans, trucks, and buses. Which share of batteries ends up in recycling or second life use cases remains to be seen and will change from time to time and region to region.

SECOND LIFE BATTERIES FOR ENERGY ARBITRAGE

Since the energy systems change to renewable production in most European countries, the supply side will be much more volatile than today. Thus, the ability to adjust the supply to the demand at any time will require new flexibility options. Energy storage in batteries is a viable possibility of balancing supply and demand. Second life batteries are technically capable and economically beneficial for the use case of energy arbitrage, as they are cheaper than new batteries.

Energy spot markets include the day-ahead market, the intraday auction, and the continuous intraday trading. Other arbitrage options with more specific load profiles are peak shaving for energy consumers with volatile demand or self-sufficiency maximization for prosumers with volatile supply, for example photovoltaic systems. In the best case, the economic benefit of energy arbitrage equals the difference between the price for (avoided) electricity purchase and the sales price for self-generated electricity per kWh. But this is rather a special use case for smaller batteries (5 – 10 kWh) like home storage solutions.

For an energy trader, however, the margin potential of a second life battery depends on the difference between peak and off-peak prices. Our graph below shows this for five consecutive years until 2021. On average, the price delta on the German day-ahead-market was 15 €/MWh or 1.5 ct/kWh.



Price Development on the German Day-Ahead-Market
Source: FfE.de

If we assume that the 600 kWh battery of our 4x2 tractor example above is applied in a second life use case for 10 years – degrading from 80% to 60% SoH with 420 kWh useable capacity on average – the accumulated energy of the daily cycles amounts to 1.500 MWh. Given the price of 1.5 cents per kWh, this results in a gross margin of 22,500 Euros over the (second) lifetime of the battery.

How does that translate into repurposing value of the battery at the end of its first life? We must subtract OPEX (5%) and profit margin (25%) from the amount above to get the allowable CAPEX in a positive business case. Discounted to the net present value (NPV) we end up with 12,000 Euros which equals 20 €/kWh of original battery capacity. It is obvious that this value does not leave much room for refurbishing measures. Since battery disassembly is too costly, we believe second life preparation will mainly consist of testing and reconnecting the retired LFP battery modules.

The above figures illustrate that the business case of second life batteries in large scale energy arbitrage use cases is only viable if the achievable price per kWh is sufficient. In 2022 the gap between peak and off-peak prices increased to 49.6 €/MWh, due to the market disruption caused by the Ukraine war. In such a scenario, the net present value (NPV) of our 600 kWh battery would be around 40,000 € or 67 €/kWh. According to the U.S. National Renewable Energy Laboratory (NREL), refurbishing will cost around $27 per kWh (or 25 €/kWh) on batteries of that size. This would lead to a residual value of 25,400 € at the end of the battery's first life.

SECOND LIFE BATTERIES FOR HIGH POWER CHARGING

The cost of charging stations for electric trucks heavily depends on the need for investment into the grid connection. While 50 kW overnight chargers normally can be installed without grid upgrade, high power charging stations often require separate transformers and a costly medium voltage line to the next substation.

Second life batteries can be used as a buffer in such high-power charging stations. They allow charging the vehicle at 350 kW to maximize its availability and then recharging the buffer battery at 50 kW (e.g., during night or off-peak hours) without investing into a grid upgrade. For a transport operator who uses overnight charging on his own premises this creates a business opportunity: he can offer semi-public charging to third parties visiting his depot during the day.

Let's assume our transport operator uses the 600 kWh battery from our example above as a second life buffer. The useable capacity will be sufficient to charge a new truck battery of the same size from 20% to 80% SoC at 350 kW in approximately one hour, even at the end of the second life after ten years with 60% SoH. Recharging the buffer battery at 50 kW will take seven hours; so up to two charging cycles are possible per workday, leaving enough time to use the station for a ten-hour overnight charging cycle as well.

Even if the average utilization of the high-power opportunity charging is only 50%, there will be a positive business case! Given that our transport operator buys electricity at 25 ct/kWh and is able to sell it at 35 ct/kWh, his daily gross margin will be 36 Euros. This sums up to 90,000 € over the 10-year life cycle! With 5% OPEX and 25% profit margin the CAPEX has a net present value (NPV) of 48,000 € or 80 €/kWh. Subtracting the refurbishing cost leads to a residual value of 33,000 € at the end of the first life of the battery, which is higher than in the energy arbitrage use case and far higher than in the recycling option.

CONCLUSIONS

The energy storage is the most valuable single component of a battery electric truck. But not only the value of the new truck, even more so the residual value of the used truck is very much determined by the battery. Unlike Diesel-powered trucks, there is no synchronicity of degradation between the vehicle and its most valuable component. While the battery reaches its end of life after 8 years or 10 years at the latest, the truck itself still has a residual value between 25% and 50% after that period, depending on the application and specification.

Moreover, there is no proportionality between the degradation and the depreciation of the truck battery. Even though its state of health is still 80% after 8 years, its first life ends as it doesn't fulfill its purpose any longer. However, a used truck battery is everything but worthless: Second life options provide various opportunities to turn potential lifetime value into additional life cycle profit. And ultimately, recycling the battery allows using its material value, if raw material prices are high enough to amortize the logistics and recycling effort.

It is obvious that managing the lifetime value of the battery is an essential success factor in the age of zero-emission vehicles. Truck manufacturers must make sure to control the return of used batteries at the so-called end of life, because they are by far too valuable to just let them go. We cannot foresee which life cycle options will be the best in the future, as this trade-off depends on different, non-predictable variables. But we do recommend thinking about the future options now and set up the required business models, value propositions and processes in time.

MEET BERYLLS.

Zero-emission vehicles will change the way transport operators schedule and use their fleets. And it will also change the way how used equipment is treated as residual values of vehicle and battery have to be considered separately. Managing the battery lifetime value is a must in the future.

We have identified the following need for action:

- » Development of methodologies to measure and control **battery lifetime value** depending on truck & battery use case, battery chemistry and charging parameters
- » Implementation of **remote monitoring** and **battery analytics** to create transparency on the state of health throughout its life cycle
- » Development and rollout of innovative business models like **Battery-as-a-Service** and/or **Truck-as-a-Service** to keep control of these assets beyond their end of life
- » Development of **fleet management services** for battery electric vehicles including predictive maintenance
- » Elaboration of a comprehensive strategy regarding **replacement batteries** for used trucks, especially for trucks with high residual value, e.g., concrete mixers
- » Development and implementation of **recycling** and **refurbishing** capabilities at competitive cost to capture the raw material or repurposing value of truck batteries
- » Elaboration of **partnering strategies** to be able to include second life applications into battery life cycle management

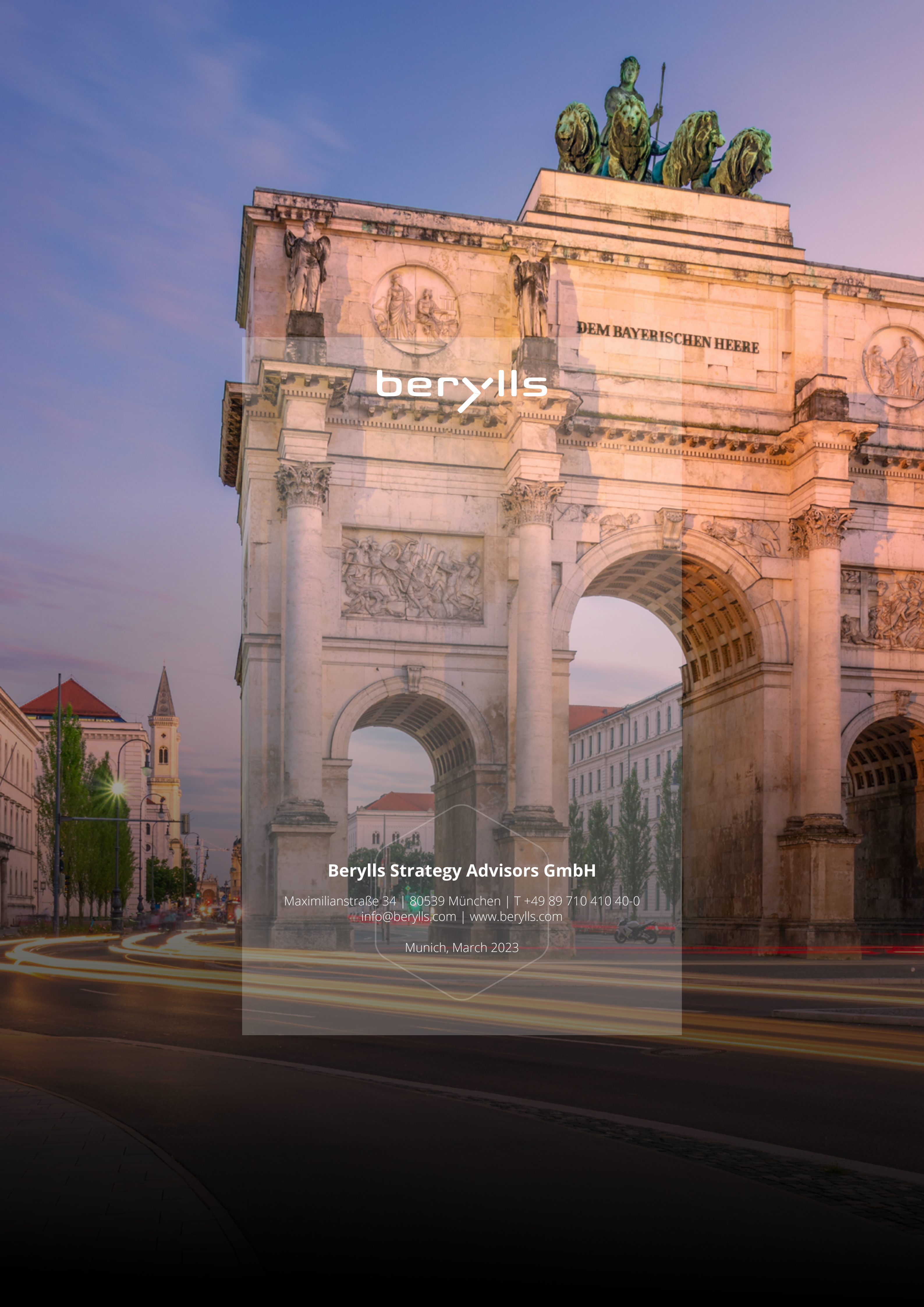
Berylls Strategy Advisors is well prepared to support you in dealing with these challenges. We have a deep understanding of the commercial vehicle industry and an impressive track record of strategy & implementation projects in e-mobility and battery management.The future of zero-emission trucks will be – but different, as are we.

YOUR CONTACT PERSONS

Steffen Stumpp
Associate Partner
steffen.stumpp@berylls.com

Florian Müller
Consultant
florian.mueller@berylls.com

Lukas Auchter
Consultant
lukas.auchter@berylls.com



berylls

Berylls Strategy Advisors GmbH

Maximilianstraße 34 | 80539 München | T +49 89 710 410 40-0
info@berylls.com | www.berylls.com

Munich, March 2023