What role can batteries play in a low-carbon transition?

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Several aspects of the "energy transition", in particular the development of the electricity sector and the electrification of transport, rely on energy storage and in particular batteries.

After describing the construction and operation of a lithium-ion battery, we analyse the expected progress and environmental impact of these batteries in the event of widespread deployment. Finally, we attempt to better identify the uses for which batteries are really relevant and those for which complementary solutions need to be found.

Composition and operation of a lithium-ion battery

A battery has two electrodes separated by an electrolyte, which is an ionic conductor but an electrical insulator. The first lithium batteries used metallic lithium at the negative electrode (the anode) and a metallic compound inserting lithium with good binding energy at the positive electrode (the cathode). But when the battery is recharged, the lithium that is redeposited in metallic form does so in a disordered manner (dendrites, foam) and, over the cycles, ends up creating short circuits between the two electrodes, reducing the battery's lifespan and threatening user safety.

Two solutions have been found. The first is to use a solid electrolyte, which blocks the formation of dendrites. The only batteries currently on the market based on this principle are those made by the company Blue Solutions, which were used in the Autolib vehicles. But their electrolyte has voltage limits (which reduce the energy density) and only works above 60° C, which means that cars have to be plugged in all the time, consuming around 25% of their energy every day to keep them at the right temperature. Research into new ceramic, glass or polymer electrolytes is proliferating, leading to the "all-solid" battery. These are often lauded for their energy density, power density, lifespan, safety and cost. In reality, none of these gains has yet been achieved, but the most important concerns safety, because thermal runaway of a battery, a dreaded event, involves the decomposition of its liquid electrolyte in the early stages.

The second solution is to eliminate the lithium metal from the negative electrode, by inserting it in another material whose binding energy is much lower than that of the positive electrode. This is generally graphite.

As lithium is then only in inserted or ionic form, but never metallic, these new batteries are called lithium-ion. Marketed since 1991, they have made continuous progress through improvements in active materials, but also through the optimisation of manufacturing processes, which have reduced the thickness of inactive materials (electrolyte, current collectors, etc.) and thereby optimising energy density. Today, the best-performing positive electrode materials are lamellar oxides of the NMC (nickel, manganese, cobalt) or NCA (nickel, cobalt, aluminium) type. Another material, which is less expensive and uses a more abundant metal, is LFP (iron phosphate $LiFePO_4$). It has a much lower energy density (160 Wh/kg_{cell} instead of 260 Wh/kg_{cell}), but a longer life and greater safety. Recent advances in LFP batteries have made it possible to reduce the gap in energy density with NMCs, particularly at 'pack' level (assembly of several cells connected together).

A battery pack is not just a stack of cells: to manage life and safety, it is necessary to provide electronic management (BMS, "Battery Mana-

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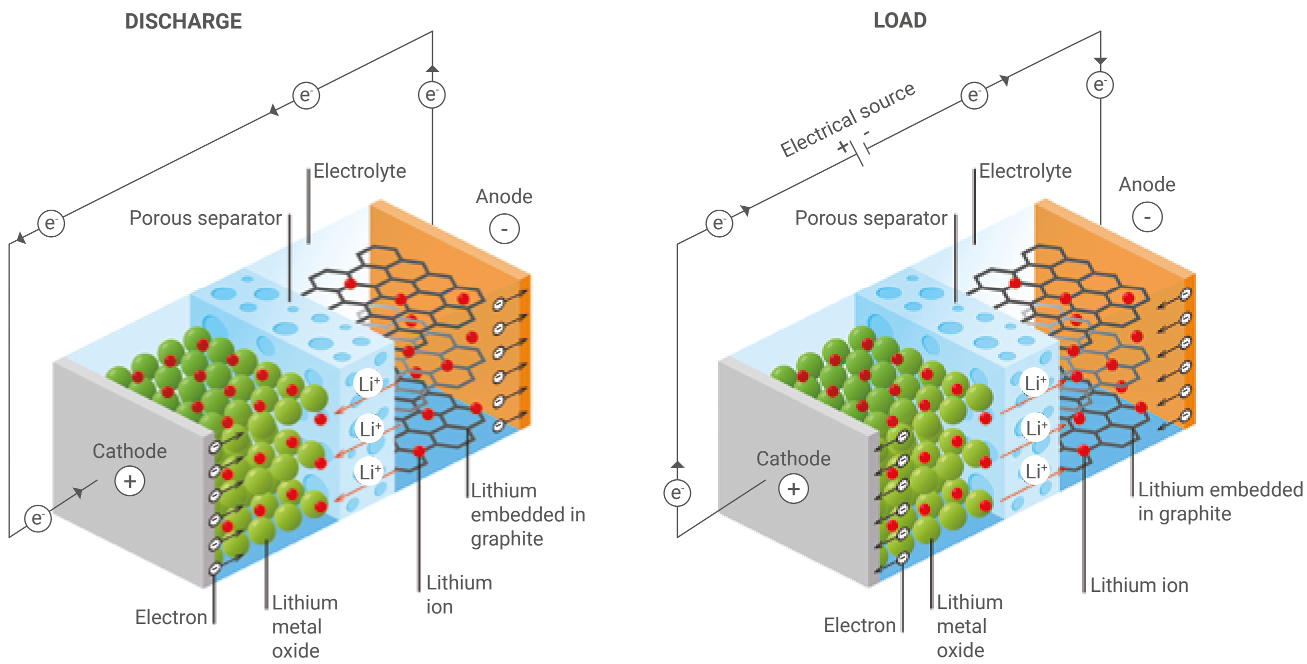

Schematic diagram of a lithium-ion battery. Left, discharge: Li+ lithium ions move from the negative anode to the positive cathode, through the electrolyte. Right, charging: an external electrical source applies a sufficiently high voltage to cause an electronic charging current to flow from the cathode to the anode; this forces the lithium ions to move from the positive cathode to the negative anode and intercalate in the graphite. (Figure adapted from an image by ser_igor on iStockphoto.)

gement System"), responsible for limiting voltages and currents, and balancing the cells. Thermal management is responsible for keeping the cells neither too hot, nor too cold, nor at temperatures too different from one another. Add to this mechanical protection, and the cells only represent around 60% of the pack's mass. Using safer, more robust cells therefore saves on the mass of the rest of the pack.

Progress in lithium-ion batteries

Lithium-ion batteries made great strides in energy density during the 2000s, reaching 250 Wh/kg_{cell} in 2012 (fig. 1).

However, eleven years on, the 300 Wh/kg_{cell} mark has still not been passed, at least not with proper cycling, despite repeated announcements of much higher figures (for the record, Californian designer Envia announced "400 Wh/kg is here" back in 2012). In fact, the progress

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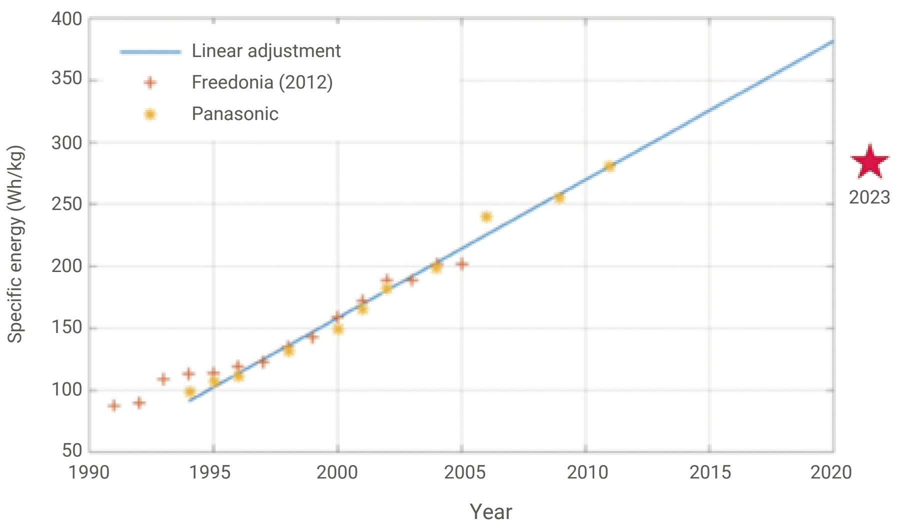
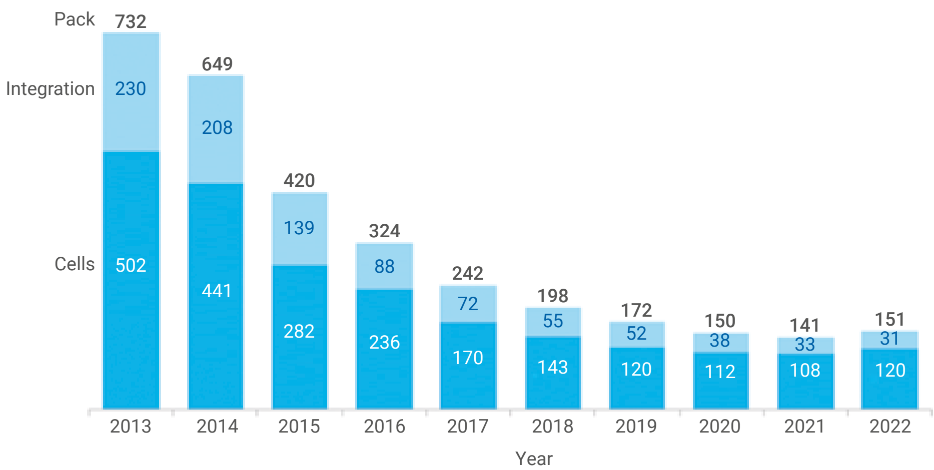


1. Progress in the energy density of 18650 lithium-ion cells (cylinders 18 mm in diameter and 65 mm long, voltage: 3.7 V). Between 1995 and 2010, specific energy increased by 11.2 Wh/kg/year. (Courtesy: Prof. Maarten Steinbuch, Director Graduate Program Automotive Systems, Eindhoven University of Technology). on the right, the 2023 point has been added.



2. Change in the cost of lithium-ion battery packs and cells from 2013 to 2022, according to research firm BloombergNEF [1] (values in US $ 2022 per kWh).

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made since 1990 has been due less to chemistry than to improved processes and a reduction in the amount of inactive material. Most of the potential gains of this type have already been made: for example, the thicknesses of separators and collectors can no longer be reduced without losing integrity. Without a major technological breakthrough, we cannot envisage achieving much more than 300 $\text{Wh/kg}_{\text{cell}}$.

To go beyond this, the anode needs to be radically modified, with a high proportion of silicon (which is currently incompatible with cycling life), or even better, by finally mastering lithium metal. This prospect is uncertain as to when it will happen, let alone when it will, after thirty years of research. In any case, a doubling at best of the cell's energy density can be expected, to around 500 $\text{Wh/kg}_{\text{cell}}$.

However, the really useful energy density is at pack level, where there is a little more margin. In the next few years, we can hope to exceed 200 $\text{Wh/kg}_{\text{pack}}$, compared with 160 today, by reducing the mass of elements other than the cell.

But above all, very significant progress is being made on less visible but fundamental parameters, such as cycle life (which has increased rapidly from 500 cycles to 2,000 cycles), safety, resistance to cold and heat, and so on. This progress has been made possible by continuous improvements in electrode and electrolyte composition.

Battery costs

Battery costs have fallen very rapidly over the last decade, as shown in Figure 2, dropping by 89% between 2010 and 2020.

Most of the cost is accounted for by the cells. The main factors driving down costs are increased energy density on the one hand, and process optimisation on the other. The former reduces the quantity of material to be processed and all the associated costs, while the latter makes industrial investment more profitable and reduces energy costs.

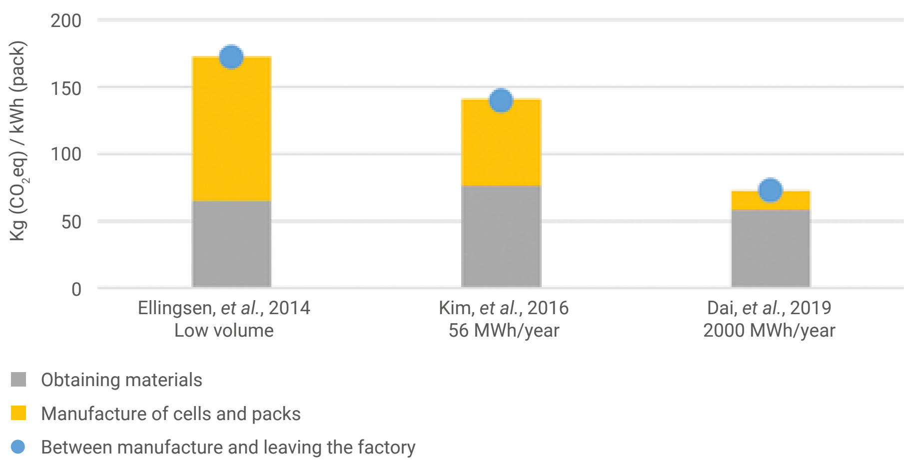
However, both of these factors are currently slowing down: firstly, we have seen that energy density has reached a plateau waiting for any technological breakthrough; and secondly, process costs have become less important than material costs. For the first time in 2022, jolts in the cost of materials (especially lithium, in this case) have pushed up the cost of batteries. Costs are likely to continue falling until around €100/kWh_{pack}, but the two reasons mentioned above should limit this in the longer term.

Environmental impact of batteries

The environmental impact of battery manufacture and their content of critical materials are two points to watch before considering their mass deployment.

The greenhouse gas emissions associated with battery manufacture are still subject to a number of uncertainties, particularly with regard to the supply of materials, but Figure 3 provides an initial overview based on three publications using high-quality primary industrial data.

It appears that over time, and in the same way as for costs, the increase in production volume has led to a significant reduction in greenhouse gas emissions during manufacture, thanks to the reduced contribution of manufacturing



3. Results of life cycle analyses of batteries, taken from the literature, showing a sharp drop in greenhouse gas emissions as production volume increases.

> **"While batteries are an effective solution for decarbonising mobility, they still generate significant CO_2 emissions during manufacture and immobilise a large quantity of critical materials"**

processes (drying of electrodes, anhydrous rooms, etc.) On the scale of a "gigafactory" (giant factory), emissions will probably be less than 100 kg CO_2eq/kWh$_{pack}$.

Emissions linked to the manufacture of the cell are the most significant, particularly those linked to the production of its constituent materials. Of these, the active material in the NMC cathodes (nickel, manganese, cobalt) is the main contributor.

The impact of the energy used at various stages is crucial. Certain key stages can be relocated in France to take advantage of our low-carbon electricity: cell manufacture, synthesis of active materials, manufacture of aluminium from ore. A saving of around 40% can then be expected compared with cells manufactured in Asia.

Recycling still has an uncertain impact on emissions: it is itself a source of emissions because it consumes energy, but it avoids the extraction of new materials. The balance is fairly favourable, but depends very much on the processes involved. The main benefit of recycling is to reuse critical materials rather than to reduce emissions.

The value of 100 kg CO_2/kWh$_{pack}$ is high: this means that if a 1 kWh battery is cycled 100 times, it will have stored and discharged 100 kWh. Each kWh it stores will therefore have an impact of 1 kg CO_2. If the battery is cycled 1000 times, each stored kWh will have an impact of 100 g CO_2. Compared with the content of electricity produced in France (~ 60 g CO_2/kWh), it is clear that a battery would have to be used intensively to make its manufacture profitable.

This does not mean, however, that the electric vehicle is a nonsense, because it must be compared with the internal combustion vehicle. This is shown in Figure 4.

The figure shows the emissions associated with the manufacture and operation of a combustion-powered vehicle, a battery-powered vehicle (the battery is produced in China) and a hydrogen-powered vehicle (hydrogen is assumed to be produced by electrolysis). In a country like France, where electricity production is highly decarbonised, both battery-powered and hydrogen-powered vehicles show significant life-cycle gains, of the order of a factor of three compared with internal combustion vehicles. When the CO_2 content of the electricity used for driving increases, the hydrogen vehicle rapidly loses its appeal, whereas the battery vehicle retains its appeal in most countries. This effect is due to the efficiency of the energy chains: to cover the same number of kilometres, almost three times more electricity is needed using electrolysis and hydrogen than using batteries.

Critical materials and mass deployment

For each kWh, a lithium-ion battery contains around 1 kg of metals in the cathode (nickel, manganese, cobalt, lithium) and 1 kg of graphite in the anode. It also contains, in varying quantities, copper (from 400 to 700 g) and aluminium (from 600 g to 2.7 kg).

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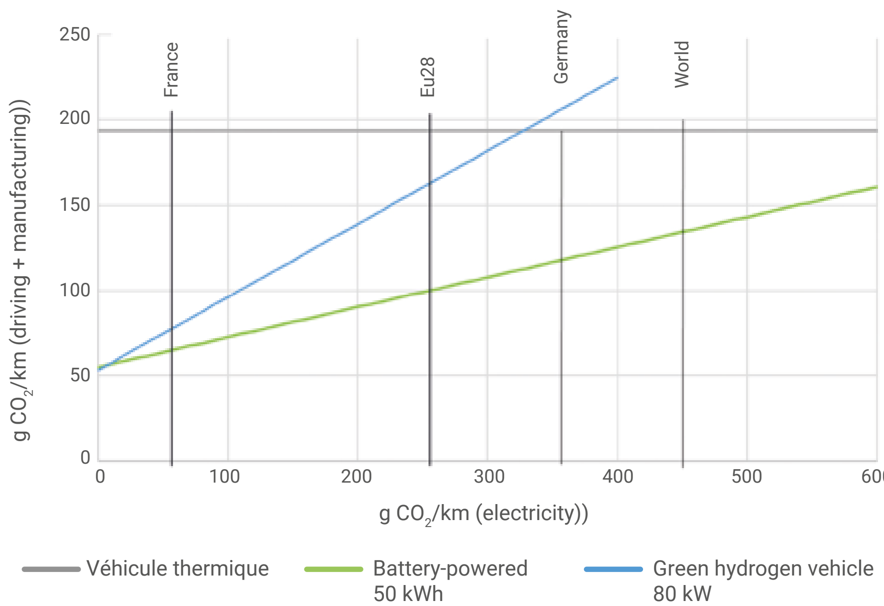

4. lifecycle emissions for three types of vehicle, based on the carbon content of the electricity used to run them.

- Internal combustion vehicle: 160 g CO_2/km on the road (including upstream fuel emissions).
- Battery vehicle: 100 kg CO_2/kWh, with an electrical/electrical efficiency of 85%. Fuel cell: 30 kg CO_2/kW, electrolysis: 50 kWh/kg CO_2.
- Hydrogen vehicle: hydrogen tank made up of 65 kg of carbon fibre, consumption 35kg CO_2/kgfibre; chassis: 6t CO_2, consumption: 15 kWh/100 km, or 0.9kg$_{H_2}$/100 km.

Service life: 200,000 km.

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Tensions over copper supply are likely, but batteries are only a small fraction of this market, and copper is more easily substituted for aluminium in other applications. Natural graphite is seen as a critical material, but vehicle batteries are more likely to use synthetic graphite, which offers better performance. The real limits to battery materials concern cobalt, nickel and lithium. They may be linked to available reserves (cobalt), the medium-term production capacity of mines (nickel), operating conditions, etc.

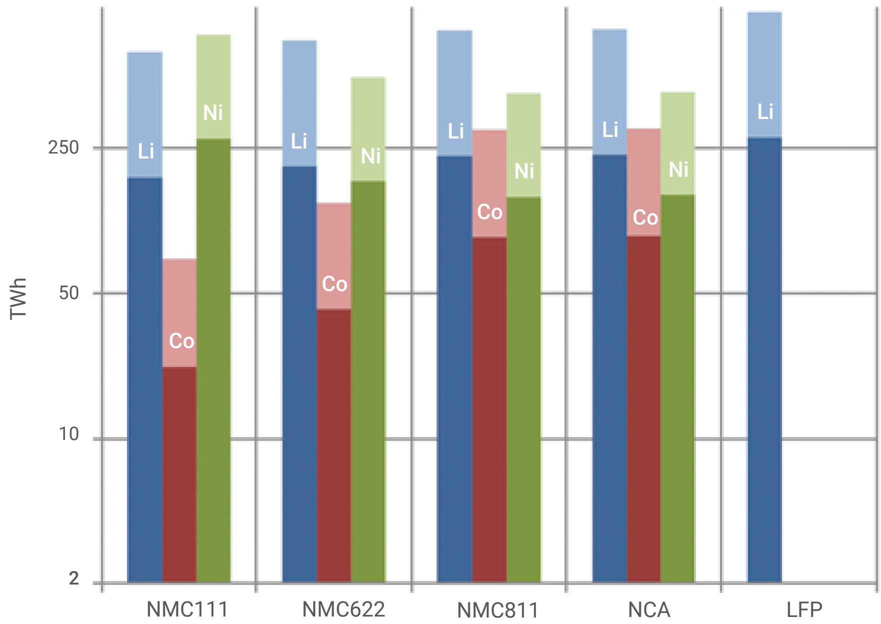
Developments such as the all-solid state battery are unlikely to change this picture (or could even make it worse), while the use of iron phosphate reduces the lithium problem (~ 80 g_{Li}/kWh).

To get a better idea of the situation, let's take a look at what would happen if lithium-ion batteries were deployed on a massive scale. Since the majority of the market will be for mobility, let's consider converting one billion combustion engine vehicles into Renault Zoe electric vehicles. This implies 50 TWh of batteries, or an annual production of 5 TWh/year if the fleet is built up in ten years. This is not excessive, as the IEA's Sustainable Development Scenario already forecasts 3 TWh/year by 2030. These 50 TWh correspond to 115 years of Li-ion battery production (2021 figure), and their production would require 140 gigafactories. The battery market is growing by more than 25% a year. We can imagine that the consumption of raw materials will be very high.

Figure 5 shows the quantity of batteries that can be produced with the reserves and resources of the various critical materials, as assessed today. It can be seen that the 50 TWh target is achievable, but that the margins are small, suggesting that there will be supply tensions.

In order to reduce these tensions, current work is aimed at gradually replacing cobalt with nickel, which is relatively more abundant. But two recent studies by Roskill [2] and Rystad Energy [3] predict a nickel sulphate deficit from 2027 and 2024 respectively. So manufacturers are planning to replace nickel itself, or even lithium. LFP iron phosphate batteries already represent a nickel- and cobalt-free alternative, at the cost of lower energy density. Following recent rises in the price of materials and the expiry of basic patents, LFP chemistry has regained market share, particularly in China.

All these considerations show that, while batteries are an effective solution for decarboning mobility, they also generate significant CO_2 emissions during manufacture, and immobilise a large quantity of critical materials. **It is therefore necessary to minimise their size and optimise their use.**



5. Quantity of batteries that can be produced using all the reserves (or resources) of each element lithium, nickel, cobalt. Reserves are shown in dark colours, and resources in light colours (USGS 2022 data). The vertical axis is logarithmic. The abscissa indicates different chemical compositions of the cathode. NMC = $Li(Ni,Mn,Co)O_2$, where the numbers indicate the relative ratios of nickel, cobalt and manganese. NCA = $Li(Ni,Co,Al)O_2$, with ratios close to those of NMC 811. LFP =$LiFePO_4$ or iron phosphate.

Mobility applications

Transport, the vast majority of which is road transport, accounts for 30% of France's greenhouse gas emissions. A good half of these emissions come from private cars, with the remainder divided between light commercial vehicles and heavy goods vehicles [4].

While the most effective lever is certainly to reduce the number of vehicles and the number of kilometres travelled, we are focusing here on technological solutions.

So let's focus on private vehicles. Their use is far from uniform: the vast majority of journeys are less than 50 km, accounting for around 70% of annual mileage, while long journeys are the exception. However, it is these rare long journeys that are driving investment in ever-larger batteries. In just a few years, the typical size of a battery has risen from 24 kWh to 50 kWh, with a number of models offering between 90 and 110 kWh, and Chinese manufacturer Nio even announcing 150 kWh and 1000 km of range. Clearly, this race for the biggest battery makes no environmental sense, especially as a 10 kWh battery already meets 70% of the need.

So the real question is how to make the few long journeys possible

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without oversizing the battery. The simplest solution is to use a combustion engine as a range extender or rechargeable hybrid. Long journeys do consume fuel, but they are in the minority. Range extension can also be provided by a fuel cell (which adds a costly system to the vehicle), by a standard battery swap such as the one offered by the standard battery exchange as proposed by Nio in China or Ample in the United States, or by renting trailers (a system proposed in France by EP Tender [5], for example).

A final solution involves supplying electricity directly to the vehicle along major roads. There are three types of ERS (Electric Road System): ground power, induction and catenary, the latter technology (fig. 6) being reserved for lorries. These electric road solutions are being studied in Sweden and Germany, as well as in France [6], where they are the subject of a call for projects by the public investment bank Bpifrance.

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6. The A5 motorway equipped with catenaries (eHighway) over 5 km, near Gräfenhausen (Baden-Wurtemberg, Germany), to be built in 2019 by Siemens. The aim is to use lorries equipped with articulated devices (pantographs) to capture the current.

These electric road technologies offer a solution to a second thorny problem: that of road haulage. Heavy goods vehicles regularly make long journeys, and electrifying them would require very large batteries. electrifying 9,000 km of motorway would reduce the range required on batteries to 250 km, three times less than without ERS. In terms of both environmental and economic criteria, the gain obtained by reducing the size of the batteries outweighs the investment in infrastructure.

Electric roads are therefore an effective lever for accelerating the electrification and decarbonisation of road transport, with very good efficiency and no inflation in battery size. However, their deployment requires a major decision to invest in this new infrastructure, necessarily on a European scale.

Stationary application

Providing flexibility to the electricity grid is another major application for batteries. To understand this, we need to quantify the amount of storage that needs to be used if we want to smooth out residual demand, defined as electricity demand minus non-dispatchable production (wind and solar).

It turns out that this need for flexibility increases sharply with the time scale over which we want to smooth, even more than with the penetration rate of renewables (fig. 7). Thus, in the event of a change in the electricity mix, the new flexibility requirements will be more a consequence of the loss of the dispatchable capacity that currently provides this flexibility than of the addition of new intermittent capacity.

What's more, the fewer the number of cycles performed by a storage system, the lower the associated investment needs to be in order not to penalise the price of the stored electricity too much. If we don't want to add more than €0.05/kWh to the electricity stored, and with a storage lifetime of twenty years, then daily storage can cost up to €350/kWh (350/20/365 ~ 0.05). If it only cycles once a year, then for the same result it can cost no more than €1/kWh.

This simple consideration limits the field of application of batteries to daily storage, or at most up to a few days. Longer time scales need to be managed by much more massive and very inexpensive storage systems. Only hydrogen storage in cavities comes close to the necessary costs, but with very low efficiency (25%). In addition, heating consumption can be controlled by massive thermal storage in water or in the ground, which is more expensive than hydrogen but has a seasonal efficiency of 60% [8].

Returning to daily storage, Figure 7 shows that the order of magnitude of the requirement is 10^5 MWh for a limited penetration of renewables. This figure should be understood as the size of storage needed to smooth out residual demand on any given day. This does not mean that the energy surplus or deficit is zero, but that it is smoothed out over the day. RTE provides a visual explanation of this breakdown [9]. Assuming it is managed entirely by batteries, this represents the equivalent of just two million Zoe electric vehicles. In reality, the need to be met by batteries will be lower than this value, because the management of hot water tanks *via* the peak/off-peak signal already provides significant flexibility on this timescale.

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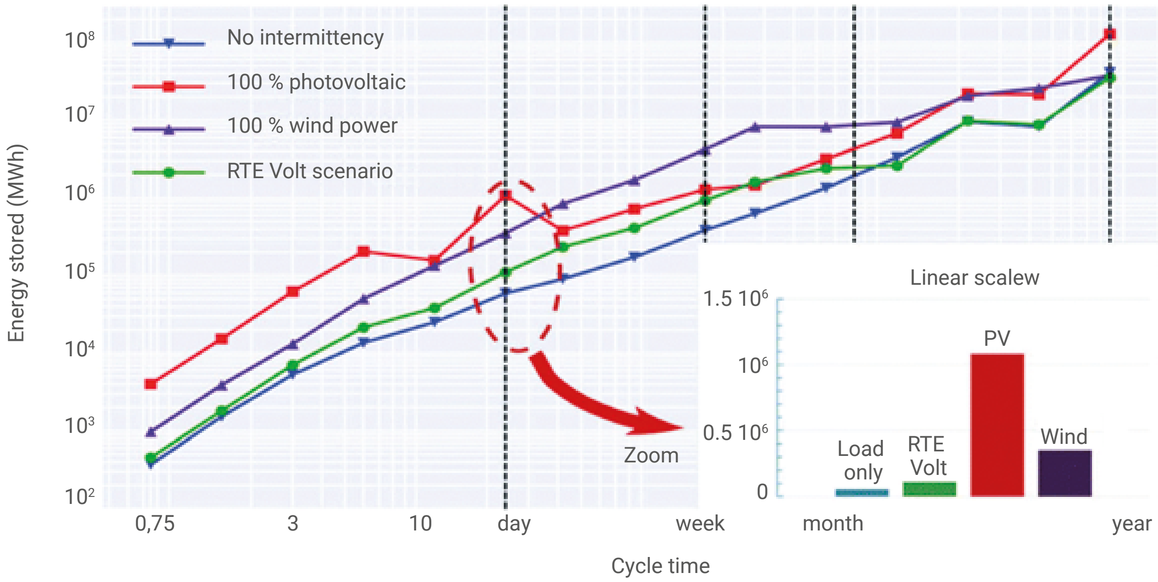

7. Size of storage required (in MWh) to smooth residual demand in France according to time scale (x-axis), and for various renewable penetration rates [7]. The extreme scenarios represent generation without any intermittence ("Load only") or with 100% PV or 100% wind penetration. The RTE Volt scenario represents a limited penetration of renewables, with 10% PV and 26.5% wind. Photovoltaics are highly intermittent on a daily basis (inset), but even more so on an annual basis. Wind power is highly intermittent over a period of several weeks.

> **"In stationary applications, (to bring flexibility to the power grid), batteries are only relevant on a daily scale"**

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Yet the electrification of the mobile vehicle fleet is proceeding apace, and RTE, for example, predicts that there will be fifteen million electrified vehicles in France by 2035. This means that the flexibility needs of the electricity grid could be met by a small fraction of the capacity of the on-board batteries in vehicles. The technologies needed for this have already been mastered: controlled recharging or, better still, bi-directional recharging (Vehicle-to-Home, Vehicle-to-Grid).

As a result, except in special cases such as non-interconnected areas, it does not seem necessary to develop or install batteries specifically for stationary storage, as vehicle batteries will be sufficient to provide this service.

Conclusion

Based on the characteristics of batteries and their foreseeable development, we have outlined the uses for which they are relevant. They are highly efficient, but have a significant impact on manufacturing and require critical materials.

In terms of mobility, batteries are a very effective way of decarbonising road transport, but we need to avoid over-dimensioning them and therefore find a complement for long journeys and heavy vehicles. Electric roads could play this role, provided they are widely deployed.

Stationary batteries are only relevant on a daily scale, and on this scale the use of vehicle batteries by controlled or bi-directional recharging will be sufficient. In the event of a significant reduction in dispatchable nuclear generation capacity, higher time scales can only be managed by massive thermal storage or hydrogen in cavities, at the cost of much lower efficiency. ■

1• https://cutt.ly/Lithium-ion-Battery

2• Roskill for JRC, 'Study on future demand and supply security of nickel for electric vehicle batteries' (2021).

3• https://cutt.ly/globalmining-rystad-energy-2024

4• Chiffres clés du Climat, 2021, Ministère de la transition écologique

5• eptender.com

6• www.ecologie.gouv.fr/lautoroute-electrique

7• A. Clerjon et F. Perdu, "Matching intermittency and electricity storage characteristics through time scale analysis: an energy return on investment comparison", *Energy and environmental science*, **12** (2019) 693-705.

8•https://cutt.ly/gouv_stock_electricite_pdf, p. 15.

9• https://cutt.ly/concertation_2020_pdf, p. 44.