Low-carbon European rail: solutions, opportunities, and challenges

Forsee Power – September 2022

a study by

In 2021, the European Union set a legal target to reduce GHG emissions by 55% (compared to 1990) and reach carbon neutrality by 2050. All sectors of the economy are contributing to this decarbonization effort, including the transportation sector. Since rail is already the most low-carbon mode of transport in Europe, its development for both passenger and freight is particularly critical to decarbonize the economy. However, some railway applications such as shunting locomotives, regional trains or freight trains still largely rely on diesel.

Several low-carbon technologies can replace diesel for these applications. In this paper, we assess and compare the potential of these solutions based on interviews with more than 20 players of the railway market in France, Germany, and the United Kingdom.

1. In the context of the EU's 2050 carbon neutrality target, rail transport is facing two challenges: increasing the offer to facilitate modal shift toward railway and phasing out diesel traction

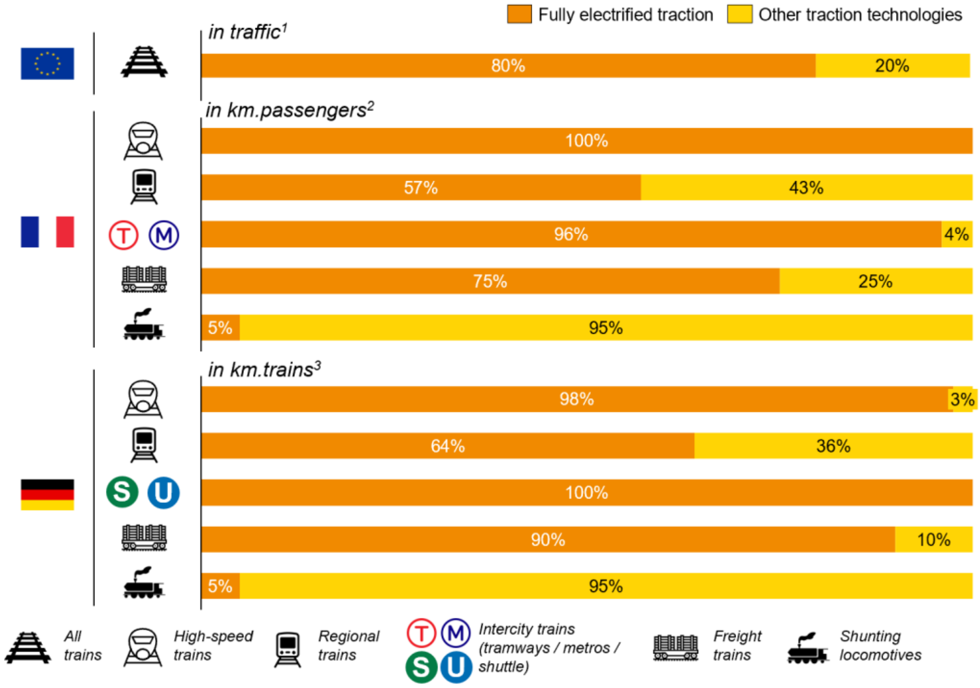
Train is the most decarbonized mode of transport: it accounts for only 0.5% of the CO_2 emissions of the transport sector in Europe (4.3 mt CO2e emitted in 2018). It is also the most CO_2-efficient mode of transport per passenger: between Paris and Toulouse, a passenger emits 60 times as much CO_2 when traveling by plane than by train. Because of this low environmental impact, the modal share of rail is expected to grow thanks to modal shifts from other modes.

European countries are strongly supporting this modal shift towards rail. This should increase passenger and freight train traffic in the next decade. In its Sustainable and Smart Mobility Strategy, the European Commission has decided to set a target of doubling high-speed rail traffic by 2030, tripling it by 2050, and doubling freight transport by 2050.

To be fully effective from an environmental point of view, this increase in rail traffic should be achieved without increasing CO_2 emissions from the railway sector. Yet, 50% of European locomotives still run on diesel today, and they account for 20% of total rail traffic. In the future, current and additional rail traffic will have to be powered by decarbonized technologies. As illustrated below, shunting locomotives, regional trains and freight trains are the least electrified railway applications:

The modal shift towards rail will partly rely on attracting new customers. As part of the France 2030 Plan, the French government plans to invest €75m (~40% of the Plan's total investment) into 5 innovative projects. Out of the 5 projects, 4 address light-rail vehicles prototypes designed to operate with less infrastructure and to lower rolling stock costs. In the medium run, these light-rail vehicles could enable the reopening of passenger train lines with limited traffic and offer an alternative to road transport in low-density areas.

RAIL TRANSPORT ELECTRIFICATION RATE



Source: E-CUBE Strategy Consultants analysis based on data from SNCF (2019), BMDV (2019), UNIFE (2022) and interviews

2. A mix of solutions can replace diesel traction: railway electrification, battery[1], hydrogen, hybrid, bioNGV/e-fuels. Battery and hydrogen are expected to capture most of the demand for decarbonized on-board traction.

Electrifying railway infrastructure is the most mature and widely developed low-carbon rail solutions. Most countries have already electrified the high-traffic part of their railway network (see figure above). But further electrifying railways raises 3 issues:

1. Electrification costs of the remaining railway network are high: ~0.7 to 3 m€ per km
2. Fitting an entire railway line with power lines can take up to 10 years due to time-consuming permitting and authorization procedures
3. Public works for electrification disturb traffic

Although electrification remains the preferred decarbonization solution of many European governments[2], it is only suitable for lines with significant traffic: the break-even point could be around 4 trains per hour in France.

On-board decarbonized traction technologies such as full-battery trains, hydrogen trains, diesel-battery trains or biogas/ e-fuel trains have been developed to complement railway electrification. Hydrogen and full-battery trains are the most mature of these technologies and should capture most of the demand for on-board decarbonized traction in the coming years.

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[1] Battery train are defined as trains running only on batteries, although other solutions (hydrogen, hybrid) also integrate batteries for traction.

[2] Germany's *Federal 2030 Infrastructure Plan* targets 70% electrification of the German railway network by 2030 (from 61% today). In the UK, where 60% of railways are not electrified, the government's *Traction decarbonization network strategy* involves electrifying ~85% of these 60% for £18B-26B.

COMPARISON OF TECHNOLOGIES [2022]

	Incumbent technology	*New decarbonized on-board traction technologies*			
Criteria	**Electrical trains**	**H2 trains**	**Battery trains**	**Battery-diesel trains**	**Biofuel /e-fuel trains**
Technological maturity	●●● Mature	●●○ Industrializing	●●○ Industrializing	●○○ Prototype	●○○ Prototype
Robustness	●●● Known	●●○ In progress	●●○ In progress	●○○ Track record to be established	○○○ Unknown
Total cost (infrastructure + rolling stock)	€€€	€€	€€	€€	€€
Operational energy-related constraints	++ Very flexible technology	- Difficult H2 supply	+ Can be managed with partial electrification of tracks or fast-charging	+ + Very flexible technology	- Difficult biofuel supply
Range	●●● No range limit	●●● > 600 km	●○○ ~100 km	●●● ~1,000 km	●●● > 600 km

Technologies with highest expected captured market (H2 trains, Battery trains)

Source: E-CUBE Strategy Consultants analysis based on interviews and E-CUBE knowledge

Rail decarbonization will have to rely on a mix of traction technologies because no single technology can address all operational use cases. The most relevant low-carbon technology for each line depends on several criteria:

- **safety of the technology**: railway rolling stock certification is based on a zero-risk culture that is more demanding than for road rolling stock, especially regarding certain risks such as fire risks.
- **operational constraints and reliability**: railway networks are less flexible than road networks because each train can impact the entire local network. A train breakdown can delay other trains not only on the same line, but also on other nearby lines connected to the same rail nodes.
- **land topography and context**: each technology comes with constraints: range, fuel supply availability, etc. Therefore, the local context – length of the line, local topography, local fuel supply, etc. – is key when comparing low-carbon traction technologies.
- **energy delivered/weight ratio**: each train is designed to maximize usable volume and weight.

These criteria often trump economic criteria. Therefore, the choice of traction technology for a line is key and mobilizes multiple stakeholders (rolling stock owner, rail infrastructure operator, train operator) in order to take into account all technical and operational constraints specific to the line.

3. In the next few years, decarbonization efforts are likely to focus on regional trains and shunting locomotives, whereas the decarbonization of freight trains should take place mostly after 2025

Of these tree applications, regional trains are being decarbonized first thanks to strong political support, a large base of diesel trains to decarbonize, and the availability of adequate technical solutions:

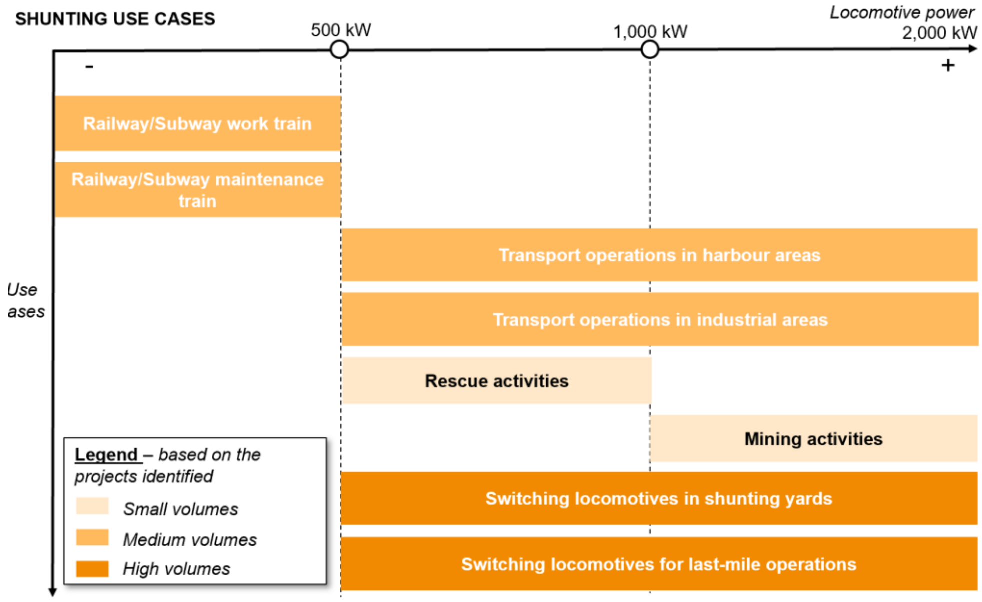
- Regional and local public authorities are the main decision makers when it comes to purchasing and operating regional trains. Since they transport passengers, regional trains also enjoy higher political visibility compared to other segments, e.g. freight. Several European governments have set targets to decarbonize regional trains: in France, the *Contrat Stratégique de Filière* targets the low-carbon conversion of 1/3 of the 326 diesel-electric *AGC* trains. Other countries introduced subsidy schemes to support the transformation of rolling stock: for instance, the German government offers a grant for 40% of the extra cost of alternative-technology rolling stock.
- In France, Germany, and the United Kingdom, 200 to 400 diesel trains are expected to be renewed (UK, Germany) or retrofitted (France) every year as low-carbon trains, as they are respectively at their end-of-life or mid-life.
- Alternative on-board traction technologies are adequate for regional trains thanks to their limited size (100-160 seats) and speed (~140-160 km/h). Furthermore, distances between stops are often short and lines are regular, which makes alternative on-board traction technologies such as batteries easier to implement and to deploy: in Germany, 50% of the lines are shorter than 58 km.

The second major market to decarbonize should be shunting locomotives: about 10,000 locomotives are operating in Europe, of which 95% run on diesel. Moreover, they are around 40 years old on average. However, the time-to-market is expected to be longer for this application because solutions are technically more complex, the market is more fragmented and political support is less strong.

Most shunting locomotives are heavily customized and produced in small series, which hinders industrialization and product standardization. These locomotives also enjoy less political attention since they run little and mostly away from the public eye. Nonetheless, if diesel were banned from the railway sector, the need for decarbonized on-board solutions for this application could grow more rapidly than expected. There are two main operational differences between shunting locomotives and regional trains:

- Catenary electrification is often not an option for shunting locomotives since they partly operate in places where line electrification is technically impossible, not allowed or not functional (e.g. during maintenance works on the railway lines).
- Shunting locomotives are used for many different tasks, which tends to make this market more fragmented than others. For instance, they can be used to build or maintain railways, or move train sets over short distances on shunting yards or industrial sites as part of “last-mile” operations. As the figure below shows, the size and power of a locomotive depend on the way it is used. Consequently, no single technical solution can address all shunting use cases.

For now, diesel-battery is the most ordered alternative traction technology because of the high starting power requested for most uses of shunting locomotives.



Source: E-CUBE Strategy Consultants analysis with data from press review and E-CUBE Knowledge

MARKET MATURITY BY RAIL SEGMENT
2022

volumes from

	Regional trains	Shunting locomotive	Freight locomotive	National/ International trains	Intercity trains
Need for further decarbonization	YES			NO	
Volume (in # of trains to renew / year)	200-400	200-300	60-100 *Post 2025*	OUT OF SCOPE National / international and intercity trains are already decarbonized	
Maturity of alternative solutions	> 200 trains sold	> 100 trains sold	Prototype stage		
Time-to-market	Short run	Medium run	Long run		
Political support	✓	~	~		
MARKET MATURITY	DEVELOPING	EMERGING	NOT MATURE		

Source: E-CUBE Strategy Consultants analysis based on data from SNCF, UK government, German government

Freight trains are expected to be decarbonized later because currently available decarbonized traction technologies do not provide enough power to replace diesel: freight trains are about 5-10 times as heavy as passenger trains (2,000 tons vs 300 tons for a regional train). New traction technologies need improvement to pull such weight, so projects for this application are at R&D stage. Further R&D effort and government subsidies are needed to create alternative-power solutions for freight trains.

Batteries can also be used for emergency traction in specific use cases to mitigate the impact of operational issues. For instance, Alstom fitted the new TGV M (TGV 2020) with 2 battery packs that enable it to travel 40 km without catenary power. This solution is specifically designed to bring passengers safely to the next train station in case of emergency, for instance in case a power outage occurs in a tunnel. For the same reason, the London subway decided to add emergency batteries to their systems so that subway trains can travel to the next station in case of catenary breakdown, thereby increasing passenger comfort and safety.

4. As batteries are used in most main alternative traction technologies (H2, hybrid, full battery), the market for batteries could account for €100-200m/ year in the next 10 years on the 3 most mature European markets (Germany, France, and the United Kingdom).

Hydrogen, hybrid, and full battery traction technologies include batteries, making them a key component to decarbonize railway transport. The most train OEMs have developed one or several alternative-traction trains using batteries. They work with many battery suppliers that have historically either provided auxiliary train batteries or batteries for other modes of transport.

BENCHMARK OF ALTERNATIVE TRACTION TECHNOLOGIES FOR REGIONAL TRAINS
2022

	Diesel-Battery		H2-Battery			Full Battery				
OEMs	ALSTOM	HITACHI	ALSTOM	SIEMENS	STADLER	SIEMENS	STADLER	CAF	[redacted]	ALSTOM
Train model	Regiolis Hybride	Battery Hybrid Train	Coradia i-Lint / Regiolis H2	Mireo Plus H	Flirt H2	Mireo Plus B	Flirt Akku	Civity	AGC bi-mode / Talent 3	Coradia Stream & Continental
Retrofit/ New	Retrofit	Retrofit/ New	Retrofit/ New	New	New	New	New	New	Retrofit/ New	New
Technology	**LTO**	**NMC**	**NMC / LTO**	**LTO**	N/A	**LTO**	**LTO**	N/A	**NMC** (retrofit) **NMC/ LTO** (new)	N//A
Geography										

Source: E-CUBE Strategy Consultants analysis based on Railway Gazette and International Railway Journal articles

Although batteries are key to decarbonizing rail transport, the current offer of batteries is not yet fully mature due to the technical constraints of rolling stock and the lack of return on experience. Many OEMs consider that there will need to be more battery suppliers: as of today, most OEMs have selected a single battery supplier but they consider that they will need more to develop best-in class products. But because the battery demand from train OEMs is expected to grow in the coming years, they would prefer to work with at least two battery suppliers to ensure access to suitable products and avoid supply disruptions.

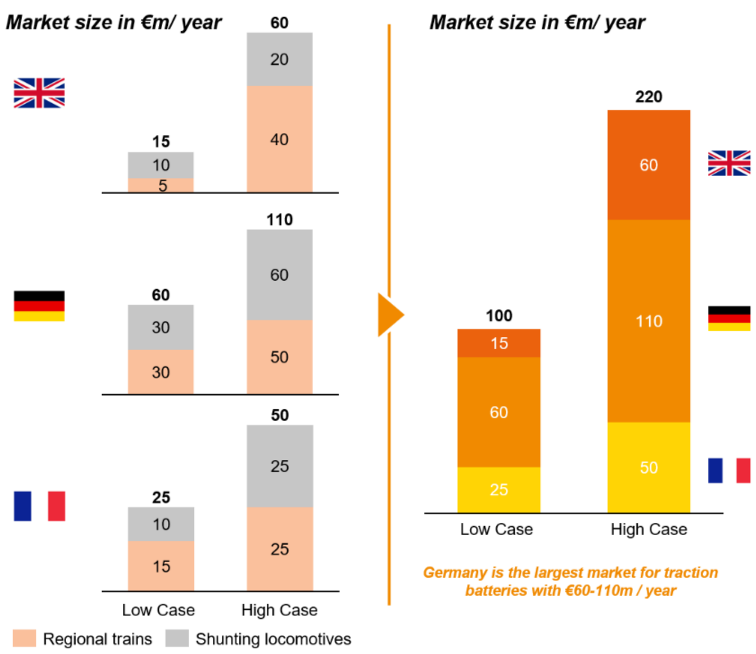
Furthermore, since each line has a specific topography, it is difficult to develop a single product that fits every line. Each supplier needs several battery chemical modules (LTO, NMC or LFP technologies) in portfolio to address the market. In Germany, the LTO technology has been favored for regional trains because it offers a relatively high power to energy ratio. On the contrary, in France, regional trains travel longer distances without electrified railways, and with fewer stops, so they would need more autonomy. In this case, NMC or LFP technology batteries with higher energy density could be more suitable to the demand.

Since each train OEM uses specific designs (e.g. batteries over or under the train – differences between tramway, regional train etc), battery products will need to be more flexible and suitable to most projects without customizing the battery for every customer and project.

In order to address all these technical and market constraints, battery suppliers will have to develop more rail-certified, modular and proven products. To make sure that they develop products that match demand, battery suppliers have to test, co-develop and certify batteries with several OEMs.

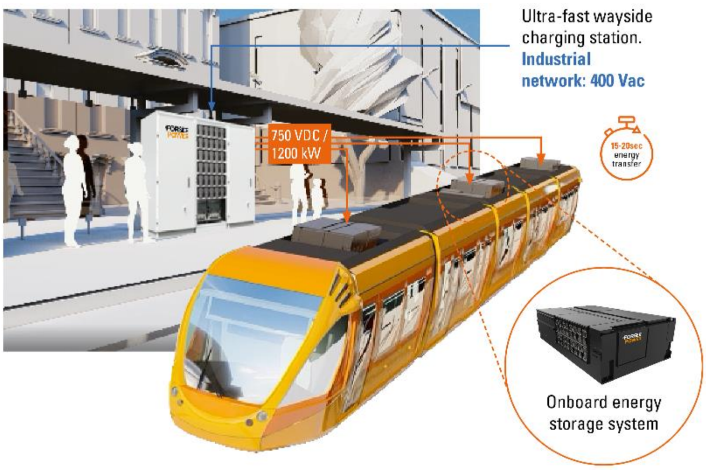
Forsee Power has developed with Alstom the Pulse Rail product to power hybrid (diesel-battery), retrofitted regional trains. SNCF should run the first prototype in 2023. The Pulse Rail is based on the LTO technology that enables fast charging and higher power.

However, the development potential is significant: the market for traction batteries in trains could account for €100-200m / year over the next 10 years on the 3 most mature European markets (Germany, France, United Kingdom). This market is equally split between regional trains and shunting locomotives.



Source: E-CUBE Strategy Consultants analysis

This situation is making batteries a keystone to decarbonize the railway market. However, developing batteries for rail transport comes with specific challenges: safety standards are much higher than in other transport applications and the certification time is quite long. In addition, batteries must be customized to fit each train model and even each train line, which requires battery suppliers to develop modular products since no single product will match every use case. Suppliers that have pioneered the supply of batteries to other modes of transport, such as Forsee Power, will be key players to address this need for customization and support the transition of rail transport to battery traction systems. These suppliers will have to develop flexible and compatible products to overcome rail-specific challenges (certification, standardization, modularity). The development and certification of best-in class, modular products will also require collaboration between battery suppliers and train OEMs.



Batteries for tramways is also an emerging market: the market for batteries for tramway operations could reach €1-10M/ year over France, Germany, and the United Kingdom because the use of catenaries in historical city centers, in narrow streets and around hospitals is increasingly problematic. In 2018, Forsee Power and Alstom developed a catenary-less tramway in Nice using Forsee Power's SPIKE rail product.

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- **30 interviews with various players:**
  - Train OEMs
  - Operators
  - Engineering companies
  - Public authorities
  - Network manager
  - Rolling stock procurement stakeholders

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Forsee Power is a French industrial group specializing in smart battery systems for sustainable electric transport (light vehicles, off-highway vehicles, buses, trains, and ships). A major player in Europe, Asia and North America, the Group designs, assembles, and supplies energy management systems based on cells that are among the most robust in the market and provides installation, commissioning, and maintenance on site and remotely. More than 1,200 buses and 100,000 LEV have been equipped with Forsee Power's batteries. The Group also offers financing solutions (battery leasing) and second-life solutions for transport batteries. Forsee Power recorded revenue from sales of EUR 72.4 million in 2021 and has more than 600 employees. For more information: www.forseepower.com | @ForseePower

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