Of Buses, Batteries and Breakdowns:

The Quest to Build a Reliable Electric Vehicle in the 1970s

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The 1970s were a window of opportunity to resurrect an old technology: the electric vehicle. A need for new business opportunities, saturated markets in countries where electricity was henceforth omnipresent, an emerging awareness of environmental issues, and two energy crises provided the environment to create renewed interest in electric road transport. In this chapter, I will discuss the activities of Électricité de France (EDF), the French state power company, and the German Gesellschaft für elektrischen Straßenverkehr (GES). The latter company was founded by the Rheinisch-Westfälisches Elektrizitätswerk (RWE AG), a major German electric utility, in order to develop electric vehicles on its behalf.[1] In both countries, the initiatives in the field came almost exclusively from the electricity industry – not from the car industry – and from these two companies.

In the first few sections I provide a short description of two electric vehicle test programmes carried out by EDF and GES, before discussing a series of problems discovered during these trials. I describe how the vehicles' batteries were identified by both companies in parallel as the most important and also problematic component of the vehicle. I then take a closer look at these problems, and argue that they were mostly related to maintenance, repair and reliability. These issues occupied the bulk of the engineers' attention, while also gener-

1 At EDF, the Research and Development Division (Études et Recherches) was in charge of the majority of the activities, but it often worked together with the Distribution Division (Direction de la Distribution), whose members were well placed to be test users for vehicles on the ground.

ating a series of connected problems related to the economic viability of the vehicles and the social context.

What I am describing here has traditionally been called a "reverse salient", "critical problem" or "technological imbalance".[2] Melvin Kranzberg defines this as "a situation in which an improvement in one machine" – for instance, modifying cars or buses so that they can drive on electricity – "upsets the previous balance and necessitates an effort to right the balance by means of a new innovation".[3] In this case, it meant improving the battery. Similarly, Thomas P. Hughes, who coined the term "reverse salient", describes a situation where an identifiable part of a technical system lags behind the rest of its components and holds back the further development and improvement of the whole, until the critical part itself is improved and allows the system to function correctly. This definition, as we shall see, neatly fits the problems with batteries in 1970s electric vehicles. They were a central critical issue within a larger technical system, with outsized importance for the functioning of its other parts.

However, I also intend to show that this theoretical framework is not sufficient to capture innovation processes in all their complexity. In the conclusion, therefore, I make some suggestions on how to integrate questions of use and maintenance into the empirical analysis of 1970s electric vehicles and their batteries.

The sources I am using in this chapter are mostly drawn from the EDF and RWE company archives. I remain close to the engineers' own perspective throughout the chapter. This is because I am not trying to determine whether the decisions they made were right or wrong, but rather to follow them through the innovation process in order to understand "what they knew and how they knew it".[4] However, I also present a battery maintenance process in more detail, in order to put the engineers' own claims into perspective.

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2 Hughes, Thomas P.: Networks of Power. Electrification in Western Society, 1880–1930, Baltimore: Johns Hopkins University Press 1983, p. 79–105; Kranzberg, Melvin: "Technology and History: 'Kranzberg's Laws'", in: Technology and Culture 27 (1986), p. 544–60, here p. 549. See also Lee Vinsel's comment on Kranzberg's second law from a maintenance-oriented perspective, "Kranzberg's First and Second Laws – Technology's Stories", https://www.technologystories.org/first-and-second-laws/ (accessed 04.07.2019).

3 Kranzberg, "Kranzberg's Laws", p. 549.

4 I am alluding to Vincenti, Walter G.: What Engineers Know and How They Know it: Analytical Studies from Aeronautical History, Baltimore: Johns Hopkins University Press 1997.

TESTING ELECTRIC UTILITY VANS AND BUSES: THE SETUP

The sourcing and construction of the vehicles and parts in question, as well as the relationships of EDF and GES with the automotive industry, deserve a discussion of their own. The vehicles discussed below, the Renault 4 delivery van and the MAN SL-E bus, were based on internal-combustion engine (ICE) series models converted to electric drive.[5] Despite the fact that purpose-design vehicles existed and were built and tested by both companies, such conversion designs were the norm, especially in the early years. Although Renault and MAN built the vehicles and delivered them to the electric utilities, they did so in close cooperation with GES and EDF and according to their specifications, and in both cases the vehicles were the result of a cooperative effort between a number of companies that was coordinated by electric utilities. This included the vehicle industry as suppliers of the chassis, body and conventional vehicle parts, battery manufacturers such as VARTA AG and Fulmen, as well as suppliers of electrical components and motors (BOSCH AG). Indeed, both GES and EDF were aware that they would have neither the ability nor the interest to produce vehicles themselves in the short or long term. In an early phase, however, they accepted the need to support efforts to develop electric vehicles with specialised know-how and resources.[6]

5 For reasons of space and precision, in this chapter I concentrate on these two particular vehicle types. It must be noted, however, that both utilities developed and tested delivery vans and buses and also ventured into the realm of private vehicles, in particular GES towards the end of the decade. As far as the timeframe goes, most of the activities in this area began as early as the mid-1960s and declined from the mid-1980s onwards, without ever coming to a complete halt. Despite the deliberate limitation in this paper, the selection of vehicles is therefore representative of both utilities' electric vehicle programmes.

6 For introductions to the EV projects, see Döring, Peter/Thomas, Hans-Georg: "Vom 'Pfennigspaß' zum Milliardengrab? RWE und die Entwicklung eines Elektroautos in den Jahren von 1964 bis 1986", in: Horstmann, Theo/Döring, Peter (eds.): Zeiten der Elektromobilität. Beiträge zur Geschichte des elektrischen Automobils: Beiträge der Tagung des VDE-Ausschusses "Geschichte der Elektrotechnik" in Kooperation mit dem VDE Rhein-Ruhr e.V. vom 7. und 8. Oktober 2010 in Dortmund, Berlin: VDE 2018, p. 123–180; Griset, Pascal/Larroque, Dominique: L'odyssée du transport électrique, Paris: Cliomedia 2006; Nicolon, Alexandre: Le véhicule électrique: mythe ou réalité, Paris: Éditions de la Maison des Sciences de l'Homme 1984; Callon, Michel: "L'État face à l'innovation technique: le cas du véhicule électrique", in: Revue fran-

EDF's testing programme began in 1973 and initially concerned 36 Renault 4 (R4) vehicles, a fleet that increased to 90 vehicles two years later.[7] Testing consisted of two stages: in stage one, cars were delivered to EDF's own distribution centres in the Greater Paris region, where employees would use them to complete their daily work schedules – performing regular maintenance on the distribution infrastructure – and report back to EDF. After six months of this preliminary test, EDF extended its trial for another six months to private and public partner companies in the Paris region who would drive the R4s, on the condition that they could provide fixed routes in advance that corresponded to the range of the vehicles.[8] The partners included aircraft engine manufacturer Snecma in Melun, local post offices, waterworks and the Melun prefecture. In both cases vehicles were driven under everyday conditions and on public roads, although EDF tried to make sure that there were clearly defined boundaries: the vans were used for mail distribution, client visits or simply to run errands during the day or drive to the canteen. The cars used in these tests managed average ranges of between 20 and 30 km per day, or between 250 and 500 km per month, depending on the location and specific use. By 1974, the EDF vehicles had been driven for about 120,000 km in these two tests.[9] In parallel, EDF continued testing a number of R4s and a variety of other types of vehicles at its research centre in Les Renardières close to Paris, and did so for several years after the on-road tests. By 1979, those vehicles had been driven for more than a million kilometres in total.[10]

GES's bus testing programme began in autumn 1974, after a preliminary phase during which two prototypes had already been put into service for a few months in Koblenz and other German cities.[11] When the on-road trials began in

çaise de science politique 29 (1979), p. 426–47; Callon, Michel: "The Sociology of an Actor-Network: The Case of the Electric Vehicle", in: Callon, Michel/Law, John/Rip, Arie (eds.): Mapping the Dynamics of Science and Technology, London: Palgrave Macmillan 1986, p. 19–34.

7 Anon.: "Véhicules électriques. Expérimentation et proposition de programme 1975", 060134, D0000252716, Archives EDF.

8 Heurtin, J.: "Expérimentation dans les Villes Nouvelles : Examen des réponses au questionnaire 'véhicule électrique'", 9 May 1974, 823334, Archives EDF.

9 EDF, Direction des Études et Recherches, département Applications de l'Électricité: Leaflet "Véhicule électrique", 1974, 823349, 29105, Archives EDF.

10 Pasquini, P.: "Bilan 1979 de l'expérimentation des véhicules électriques aux Renardières", 24 Mar. 1980, B0000428243, D0000259426, Archives EDF.

11 "'Elektro-Bus', Referat H. Dir. Scheffel (KEVAG) am 27.1.1971 anläßlich der Vorstellung in Koblenz", 6153, Historisches Konzernarchiv RWE.

earnest, twenty MAN buses, also a conversion design from a regular series model, were put into service in two cities in North Rhine-Westphalia: seven buses on one line in the city of Mönchengladbach, followed a few months later by thirteen buses on two lines in Düsseldorf. The Mönchengladbach test ran until 1981, when public funding came to an end, while the Düsseldorf trial continued until 1987. Each bus covered around 300 km per day when in service. Taking the two cities together, this added up to 225,000 km per month, and over 5 million km by 1981. The distance covered was therefore by several magnitudes greater than in the EDF trials – but also concerned an entirely different class of vehicle.

The enormous difference in daily range compared to EDF's vehicles was made possible by a system of battery-changing stations developed by GES that allowed buses to replace a depleted battery with a charged one in a matter of minutes. Unlike EDF's delivery vans, which had permanently installed batteries, the GES buses would change theirs 5 to 9 times per day. In heavier traffic, more changes were needed to reach the daily range of about 300 km.[12] To make the changing process easier, the batteries were not integrated into the vehicle body but rather housed in a trailer attached to the bus. To change the battery, a bus driver would drive the bus in front of the station, which resembled a container and had an opening through which batteries could slide in and out. Either the driver or a specialised mechanic would then swap the batteries using a fully automated process that could be controlled from a remote control panel located outside the station. In the station, batteries were stored on a rack with threaded rods, which allowed them to be moved upwards and downwards depending on whether they were ready to be exchanged or had to be stored. Towards the end of the testing phase, in 1981, GES abandoned this system in order to replace it with one that allowed the buses to be recharged at each stop. It should be noted that no such system, of either kind, was ever used by EDF.

MAINTENANCE, REPAIR AND RELIABILITY: PROBLEM AREAS

The result of the tests was twofold: on the face of it, the vehicles of both EDF and GES were proven to be functional. It was demonstrated that they could, in principle, meet the conditions that had been set for the trials. Engineers and

12 Döring/Thomas, "Vom Pfennigspaß zum Milliardengrab", p. 144; Moneuse, M.: "Mission en Allemagne Fédérale des 3 et 4 Novembre 1975. Visite d'installations de la GES à Essen et Düsseldorf", B0000428238, D0000259410, Archives EDF.

managers from both companies repeatedly pointed this out in various reports on the tests. They did realise, however, that the range, speed and weight of the vehicles were grossly inferior to conventional vehicles. For instance, a survey among EDF's test users revealed that most of them considered the range of the vehicles to be "insufficient" or "totally insufficient", but none complained that this had prevented them from using the vehicles as planned during the trial. The head of GES acknowledged after several years of testing that electric vehicles had the "uncontested drawback of a limited operating range".[13] When French carmaker Renault decided to reduce its efforts to develop electric vehicles in 1976, the company based its decision on such performance criteria. For Renault, an electric car's properties could be converted into an equivalent internal-combustion engine car with a maximum speed of just 70 km/h, a tank with a capacity of 5 litres that needed 8 hours to be refilled, and a vehicle that was constantly at its maximum weight and able to carry only half the load.[14] Similarly, a manager of the German car manufacturer Daimler pointed out that the battery block of an electric vehicle was 120 to 170 times heavier than the equivalent in petrol, while coming at a higher cost.[15]

Despite these obvious shortcomings of electric vans and buses in terms of raw performance, which became obvious in the trials, EDF and GES remained optimistic that electric vehicles could find their niche on the market if they could at least be made more reliable, easier to repair and low maintenance.[16] If this was possible, then maybe they could be used in ways similar to the trials: in a context where delivery vans were needed for predictable, clearly-defined and short trips, or in cities that might be willing to invest in electric buses in order to resolve problems with noise and reduce air pollution. When they presented their insights from the tests at the 1976 Electric Vehicle Symposium, an international conference on the matter, engineers from EDF and from GES independently concluded

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13 Müller, Hans-Georg: "Energiewirtschaftliche Überlegungen zum elektrischen Strassenfahrzeug", in: ZEV-Glasers Annalen 103, May 1979, p. 233–236, Historisches Konzernarchiv RWE; Heurtin, Expérimentation dans les Villes Nouvelles.

14 TREGIE: Véhicules électriques. Position Renault, March 1976, 823338, 29094, Archives EDF.

15 Breitschwerdt, Werner: "Letter to Helmut Meysenburg", 8 Jul. 1980, 6155, Historisches Konzernarchiv RWE.

16 Hagen, H./Zelinka, J.: "The MAN Electrobus. Experience Gained in Large-Scale Tests", 1976, AVERE Archives; Heurtin, J./Moneuse, M.: "Expérimentation de véhicules électriques légers et lourds à EDF. Exposé des problèmes qui se posent", 1976, AVERE Archives.

that, instead of performance, it was reliability that should become front and centre in their further work on electric vehicles.

Indeed, in addition to the mediocre speed, range and weight, both companies' vehicles were equally unfavourable in terms of reliability when compared with conventional vehicles. The problems began with vehicle parts that had not been modified from the conventional versions of the vehicles. They suddenly failed or needed to be modified when used in an electric vehicle. An example of this is tyre wear: due to the higher weight of the GES buses, the service life of tyres on the drive axle was reduced to 20,000 km instead of a standard 80,000 km.[17] Added to this were overheating and jamming pressured-air systems in buses; unusually high axle wear due to the higher weight of the vehicles; blown fuses; or buses starting to move unexpectedly because of faulty ignitions.[18] Such problems were irritating, constant reminders to engineers that developing electric vehicles did not mean just replacing vehicles' engines but that they were dealing with complex systems that had to be adjusted to real-world operating conditions in various ways. While the problems with conventional vehicle parts could eventually be brought under control, they were overshadowed by vastly more important issues with batteries, the central component of the new vehicles.

BATTERIES: THE KEY COMPONENT

It had been expected from the outset that batteries would be a delicate issue, and tests confirmed that they were indeed the most crucial and problematic component of the vehicles. Engineers at both companies framed the problem above all in terms of battery lifetime. In the case of EDF, the reason for this was that the first-generation batteries used in 1973 lasted only 50 cycles on average, and because of this limitation were quickly understood to be unpractical for any real-life use.[19] A second generation of batteries with lower energy density but higher weight, subsequently installed in the vehicles, was reported to have reached 200

17 GES: "Ergänzung zum Besprechungsvermerk vom 30.3.1976 über den Einsatz der Elektrobusse bei den Stadtwerken Mönchengladbach", 6 Apr. 1976, 11142, Historisches Konzernarchiv RWE; see also Döring/Thomas, "Vom Pfennigspaß zum Milliardengrab", p. 145.

18 GES: "Zwischenbericht vom 31.12.74", 11131, Historisches Konzernarchiv RWE.

19 A "cycle" refers to a charge-discharge operation. MIT Electric Vehicle Team, "A Guide to Understanding Battery Specifications", Dec. 2008, p. 3.

cycles in at least one instance; and a third generation of batteries used from 1976 onwards doubled this value again to 400 cycles. EDF's engineers therefore concluded from the first tests that lifetime was the "essential problem" to be resolved before turning to performance again.[20]

Battery lifetime was also a concern for the GES buses. Although GES originally claimed in 1971 that battery lifetime was approaching 100,000 km,[21] the results of the first bus tests were sobering: first-generation batteries began to fail "prematurely" in 1976 and unexpectedly reduced the availability of the buses.[22] Nevertheless, the bus batteries were able to reach a lifetime of about 1,000 cycles.[23] In kilometres served, the first generation of batteries only lasted for about 47,000 km, whereas the subsequent generation managed up to 65,000 km – still far short of the initially hoped-for 100,000 km.[24] Nevertheless, when GES engineers reported on the bus trials, they did not point first and foremost toward to the life cycle of the batteries. Changing stations eliminated the risk that a dead battery would immobilise a bus for too long. Yet batteries "dying" was by no means the only possible problem: "increased consumption of water at high operating temperature, more pronounced pollution in road traffic, more frequent checking caused by five cycles per day, extremely high proportion of peripheral apparatus, [and] requirements higher than usual for the insulation value of the batteries" were problems only discovered during the first on-road tests.[25] Many of these were rather unexpected and would only appear once the vehicles were driven in real-world conditions. Better insulation of the batteries was needed for instance because in winter, on icy roads, thawing salt got into the battery blocks and compromised insulation values.

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20 Heurtin/Moneuse, Expérimentation de véhicules électriques légers et lourds.

21 GES: "Gedanken von RWE, GES und SELAK zum elektrischen Straßenverkehr", 6153, Historisches Konzernarchiv RWE.

22 GES: "Zwischenbericht vom 11.9.1976", Zwischenberichte an das Ministerium für Arbeit, Gesundheit und Soziales, 11132, Historisches Konzernarchiv RWE.

23 Indeed, there is a considerable difference between this figure and the life cycle of the batteries that EDF used. This can be explained by two factors: first, the bus batteries were being charged in a controlled environment in the charging stations, which certainly contributed to their longer overall lifetime. Sources are also unclear as to whether the same standards were used on both sides to determine whether a battery was "dead".

24 GES: "Zwischenbericht vom 6.10.1980", Zwischenberichte an das Ministerium für Arbeit, Gesundheit und Soziales, 11133, Historisches Konzernarchiv RWE.

25 Hagen/Zelinka, The MAN Electrobus.

As a consequence, GES noted between 13 and 18 such incidents with batteries per 10,000 km, or in other words, a problem with a battery about every 500 km during the first year of operation of the MAN electric buses in Düsseldorf and Mönchengladbach. When one adds other issues with conventional vehicle parts and changing stations, this meant that buses were taken out of service by some kind of incident about every other day on average. That was a rate nine times higher than that of conventional buses.[26] During the initial period, the buses were available only 38% of the time, and had to be replaced by conventional buses for the rest.[27] Therefore, even though the life cycle of individual batteries was less of a concern due to the changing system, reliability, maintenance and troubleshooting were still pressing concerns for GES as well.

ECONOMICS: THE COST OF MAINTENANCE

One of the major concerns for EDF and GES was to make the economic case for electric vehicles and compare them favourably to conventional vehicles in terms of costs. This led to the first "well-to-wheel" calculations, which compared the overall energy efficiency and costs of conventional and electric vehicles. In other words, such analyses did not just take into account fuel and electricity costs needed to drive the vehicles, but also the efficiency of their motors and how much primary energy they consumed overall.[28] The patchy reliability record of both EDF's and GES's vehicles also had important implications in this respect, however. Maintenance requirements were so high that they played a major part in making the vehicles more expensive and less economically viable.

For EDF, the limited lifetime of the batteries it tested was above all a problem in economic terms. EDF engineers duly noted that batteries were already the most expensive part of the vehicle, and therefore would have to be changed as rarely as possible. The *technical* operation of changing batteries was not out of the ordinary in terms of difficulty, and could even be sped up and automated, as

26 Döring/Thomas, "Vom Pfennigspaß zum Milliardengrab", p. 145.

27 GES: "Niveau de développement des bus électriques desservant une ligne fixe et exploitation de ces bus à Mönchengladbach et Düsseldorf-Benrath (situation au 30 juin 1977)", 1977, B0000428237, D0000259406, Archives EDF.

28 Müller, Hans-Georg: "Elektrischer Strom ist für den Nahverkehr auf der Straße eine kurzfristig verfügbare, bisher zu wenig beachtete Alternative zu Kraftstoffen aus Erdöl", Vortrag auf der Mitgliederversammlung der Deutschen Gesellschaft für elektrische Straßenfahrzeuge e.V. – DGES – am 9. Mai 1980 in Berlin, May 9, 1980, Historisches Konzernarchiv RWE.

GES's battery changing stations demonstrated at the same time across the border in Germany. With hypothetical, cheap "throw-away" batteries, limited lifetime might have been a lesser problem. The reality, however, was quite the opposite. Even with batteries reaching 400 charging cycles, as EDF managed to do by the mid-1970s, it was estimated that they would represent 20–25% of the operating costs of the vehicle. EDF was forced to conclude that such costs were "prohibitive". Moreover, real-world use of the vehicles that led to inconsistent charging patterns penalised the vehicles economically by reducing the lifetime of the batteries and therefore increasing operating costs.[29]

For GES, too, maintenance and breakdowns were above all a problem because of high cost. The bus batteries were more reliable than those of EDF's utility vehicles, but maintenance remained an important issue because the costs of upkeep pushed GES's budget to the limit. The company's contracts with local public transport operators stipulated that the latter would assume operating and maintenance costs up to the value of the equivalent needed for diesel buses. As breakdowns were much more frequent than for conventional buses, however, the operators quickly made it clear that GES would have to cover the excess maintenance costs.[30] Such a demand strained GES's budget, which was almost entirely dependent on funding from parent company RWE, and also threatened to drain resources that could otherwise have been used for development work and engineering. Moreover, for GES the problematic cost of maintenance was not the basic price of vehicle parts, but rather the cost of personnel and labour needed for maintenance. When reporting on the bus trials, a GES engineer noted that not only had the incidents "far exceeded" what had initially been thought, but also that this was mostly because specialised staff were needed to carry out maintenance and troubleshooting, and thus had to be hired in sufficient numbers. This was one more reason, therefore, to prioritise reliability when further improving the vehicles.[31]

Moreover, the battery-changing system did not help in this regard, insofar as it required GES to hold several batteries per vehicle in reserve. Not only were the batteries expensive in themselves, but the greater the number available, the

29 Heurtin/Moneuse, Expérimentation de véhicules légers et lourds; see also part 4 below.

30 GES, Ergänzung zum Besprechungsvermerk vom 30.3.1976 über den Einsatz der Elektrobusse bei den Stadtwerken Mönchengladbach, April 1976, 11142, Historisches Konzernarchiv RWE.

31 GES: "Zwischenbericht vom 17.4.1975", Zwischenberichte an das Ministerium für Arbeit, Gesundheit und Soziales, 11131, Historisches Konzernarchiv RWE.

higher the maintenance expenses. In the end, GES decided to abandon the changing stations for these reasons, and replace them with a catenary-based system that allowed short, intermediate charges at certain stops on the bus routes. Complete charges were done when buses entered the depot, usually overnight. This system ensured that from that point on, only one battery per bus was needed.[32]

CASE STUDY: A BATTERY MAINTENANCE MANUAL

To give an impression of how tedious maintenance procedures were and how carefully they had to be carried out, I will discuss a battery maintenance manual for a VW delivery van that was shared by GES with colleagues at EDF during a vehicle exchange between both companies. EDF and GES had decided to work together and sign a cooperation agreement in 1974, and as part of this collaboration, GES sent the VW vehicle to France to be tested by EDF in the Renardières research centre, while EDF sent a Renault 5 – the successor to the R4 described in this paper – to Düsseldorf in return. The manual was thus shared between the electrical engineers at both companies. This suggests that, even with the requisite knowledge and education that they possessed, battery maintenance was not a trivial process. Furthermore, the manual is revealing in that it can be used to calculate the time needed to maintain a battery, a crucial factor especially for fleet vehicles that are expected to be available as frequently as possible. Finally, by looking at the procedure in detail, it is possible to qualify the claims made by engineers about maintenance being complicated and labour-intensive.

The maintenance procedure described in the manual had to be carried out at least every 15 (+/-1) charge/discharge cycles of the battery. Assuming one charging cycle per day, this implies that the battery had to undergo maintenance every two weeks. In total, the manual contains 16 steps, eight of which refer to measurements and note-taking while the rest concern actually handling, cleaning and charging the battery.[33] At the beginning of the maintenance process, after some initial measurements (steps 1–4), the battery first had to be fully charged (5). This took 3 to 8 hours, depending on the type of charging equipment and charging procedure being used. This was followed by insulation measurements (6). The values were to be measured manually using a multimeter or an insula-

32 Döring/Thomas, “Vom Pfennigspaß zum Milliardengrab”, p. 146.

33 GES: “Dossier d’information sur les batteries de traction. Communication technique N°18. Entretien des batteries de traction”, 1975, 060110, D0000252644, Archives EDF.

tion monitoring device, and then calculated using a specified formula depending on the equipment used. Individual battery cells then had to be topped up with distilled water (7) according to specifications.[34] The next steps (8–10) had to do with cleaning the battery and tray: first, the maintainer had to check whether there was water in the battery tray and remove it if needed. The maintainer then had to clean dust and oxidation off cables and contacts and grease them to prevent them from getting dirty. If the previously measured insulation value was below a certain threshold, the entire battery had to be washed carefully, making sure non-distilled water would not enter the individual battery elements. Once cleaned, meters and indicators had to be checked to make sure they functioned correctly (11). In the next step the battery had to undergo an equalising charge, in other words a slow charge in order to ensure that all cells were charged as equally as possible (12). The manual states that with a standard electric outlet, this charge would take a minimum of 24 hours. Contrary to the initial charge, where an optimised charging curve was possible, no faster options are mentioned. The equalising charge was considered successful once acid density between cells and voltage remained constant for two hours; if not, the process had to be started again after a one-hour break. Final measurements and note-taking were then required (13–15). The last step (16) of the manual specifies how batteries held in storage were to be handled.

Given the large number of steps, different areas to pay attention to, specialised measuring equipment needed, calculations to be made and overall knowledge required, it is sensible to conclude that this procedure could not be carried out by just anyone driving the cars, but that it required skilled personnel. To borrow an image from Gijs Mom, the batteries needed "the constant attention of a physician and a trained nurse".[35] Moreover, correct maintenance and charging were crucially important in order to guarantee the maximum life cycle of the batteries. It is therefore understandable that it was an important cost factor to hire the staff needed, which in turn served as a guarantee that the procedures would be carried out as diligently as possible. More importantly, however, the process was very long and had to be carried out very frequently. As mentioned above, this was especially a problem for vehicles used in fleets. Using the times

34 As is standard for high-capacity batteries, the lead-acid traction batteries used in the VW Transporter were composed of a number of individual cells arranged in a tray and connected to each other.

35 Mom, Gijs: The Electric Vehicle: Technology and Expectations in the Automobile Age, Baltimore: Johns Hopkins University Press 2013, p. 287.

given in the manual, it appears that under ideal conditions, the charging time alone would be 27 hours. If only a standard outlet was available, the initial charge time would increase to 8 hours, and it can be assumed that equalising charges took longer in most cases than the minimum duration of 24 hours. In this more realistic scenario, charging time during maintenance was at least 32 hours. To this had to be added the time needed for topping up with water, taking measurements and cleaning the tray, for which no precise durations are specified in the manual but which can be estimated to have taken several additional hours. In total, a safe estimate would be that the maintenance process left a battery out of service for at least two full working days every other week, tying up specialised maintenance personnel. If the battery was fixed in the vehicle and could not be removed, this would mean that the vehicle was unavailable during this time. If, as in the case of GES while the changing stations were in use, the battery was removable, another one had to be made available as a replacement during the maintenance process.

PEOPLE: ELECTRIC VEHICLES IN USE

Maintenance was thus complex, very frequent and time intensive, and batteries had to be handled with extreme care and attention. Not only did these requirements drive up costs, but drivers and mechanics with sufficient knowledge were constantly in short supply. Drivers of EDF utility vans suffered from "range anxiety"; they often used the vehicles only for very short trips, and only if they could be sure that the range of the vehicle was sufficient. As a consequence, batteries were constantly discharged by only half their capacity, and in some of the tests by just 30%, which had not been expected initially. Such irregular use of the vehicles, with partial discharges and recharges, made the charging process less efficient and could reduce lifetime further. Moreover, such a pattern of use made it difficult for EDF to draw conclusions about the maximum range to be expected from the cars, as almost no drivers ever attempted to fully exhaust their vehicles' batteries.[36]

Similar issues arose with GES buses. At the beginning, matters were again complicated by the existence of the battery changing stations. It had initially been planned that specialised personnel would carry out the changing procedure. Later on, as part of the effort to drive down costs, GES considered having driv-

36 Heurtin, J.: "Compte-rendu de la réunion du groupe de travail 'véhicule électrique' du 26 septembre 1973", 823334, Archives EDF.

ers perform the changes themselves. This led to questions about training and the operating security of the stations.[37] The problems that hindered this transition ranged from the mundane to the dramatic. GES struggled to convince the bus drivers' professional society to agree to its proposed measures to protect drivers needing to change a battery when it rained. GES's proposal to equip drivers with a "jacket and umbrella" was roundly rejected as "unacceptable", and the association demanded that either the station should be operable remotely from inside the bus or a roof should be installed.[38] At the other extreme, in February 1980, a mechanic operating a station suffered a fatal accident.[39] As a consequence, the professional association concerned suspended the operation of changing stations pending the installation of better security systems.[40] In the meantime, however, GES had decided to abandon the system altogether.

The problems did not end there. Indeed, as the buses now had fixed batteries, the drivers and regular vehicle mechanics had a greater responsibility to correctly charge them, especially at the end of the day when buses entered the depot. As a consequence, GES found that this led to new problems precisely because drivers were not correctly following procedures when buses were in the depot. Sometimes they were disconnected from chargers at a fixed hour, although they were not supposed to leave the depot until later on; they were not reconnected to chargers when they were not going out that day and used only as reserve vehicles; they were not charged immediately after entering the depot at the end of service; when they were entering the depot in need of repair, they were put on the repair track instead of being connected to a charger; and so on. As a consequence, and initially unbeknownst to GES, buses had to be towed several times with depleted batteries, although the catenary and intermediate-charging system was designed to make sure this would never happen. The problem was aggravated by frequent changes in personnel at the depots, which made it difficult to

37 GES: "Besprechungsvermerk", 25 Mar. 1976, 11142, Historisches Konzernarchiv RWE.

38 GES: "Besprechungsvermerk, Einsatz der MAN-Busse in Mönchengladbach, Auflagen der Berufsgenossenschaft zur Bedienung der Wechselstation durch die Fahrer", 3 May 1976, 11142, Historisches Konzernarchiv RWE.

39 GES: "Zwischenbericht vom 2.9.1980", Zwischenberichte an das Ministerium für Arbeit, Gesundheit und Soziales, 11133, Historisches Konzernarchiv RWE.

40 Berufsgenossenschaft der Feinmechanik und Elektrotechnik: "Schreiben an GES mit Besichtigungsbericht vom 27.2.1980", 29 Feb. 1980, 11142, Historisches Konzernarchiv RWE.

maintain a level of training sufficient for correct operation.[41] Precisely because resident vehicle mechanics lacked the specialised knowledge needed to maintain electrical components and batteries, GES reluctantly had to resort to carrying out the maintenance itself or use other electrical engineering companies for such tasks, so the related expenses remained high.

REMEDIES: GETTING TO GRIPS WITH BATTERIES

Once maintenance and reliability had been identified as being of paramount importance, both EDF and GES began to focus their research and development efforts on these areas. For GES, "incident reduction" became a mantra for the remainder of the bus tests. A task force named "Basic Battery Issues", headed by GES, brought together representatives of battery manufacturer VARTA, W. Hagen, Volkswagen and GES to identify and develop solutions to known battery problems. The group identified six problem areas and underlined the complexity of the issue. Solutions were needed in the areas of "charging, monitoring, construction, climatisation and tray, discharging, after-treatment and regeneration".[42] Apart from this research group, GES implemented solutions on the ground in cooperation with battery supplier VARTA: later generations of batteries were equipped with automatic water replenishment systems and acid circulating pumps, eliminating several steps from maintenance procedures. The tweaks were largely successful: after seven years of operation, incident rates hovered around 120 over a period of three months, down from close to 500 at the beginning. By the end of the trial, the buses were available 96% of the time, similar to what could be expected from conventional buses.[43]

EDF's response to problems with inefficient and partial charging cycles was a testing programme for batteries in cooperation with GES in addition to the on-road tests. Having signed a mutual cooperation agreement, the first step for the two partners was to decide on a standardised testing procedure including different charge-discharge routines. This protocol was then applied to the different

41 GES: "Vermerk T-202: Einsatz der MAN-Elektrobusse in Düsseldorf-Benrath", 11141, Historisches Konzernarchiv RWE.

42 "Besprechung des AK 'Grundsatzfragen der Batterien', 9–10.5.1983", 11135, Historisches Konzernarchiv RWE.

43 Döring/Thomas, "Vom Pfennigspaß zum Milliardengrab", p. 145; GES: "Anlage 1 zum Schreiben der GES mbh, Düsseldorf, vom 22.6.77 an Herrn Dir. Dr. G. Klätte, RWE-Vorstand", 1977, 6154, Historisches Konzernarchiv RWE.

batteries the companies were using in their vehicles. As a result, it turned out that it was perfectly possible to achieve more than 1,000 cycles with a battery under laboratory conditions. However, EDF's experience on the ground was confirmed by the fact that the charging patterns needed to achieve such a high life cycle were less than ideal for real-life use: the best results were obtained with batteries that were charged and discharged from 75% to 25% and 50% to 0%. As we have seen, however, drivers would typically discharge their batteries from 100% to 50%. Using such a pattern, even by the end of the 1970s, the best result achieved was 300 cycles.[44]

ANALYSIS: REVERSE SALIENTS, MAINTENANCE AND TECHNOLOGIES-IN-USE

As mentioned in the introduction, it is certain that if one had to identify a reverse salient holding back the development of electric vehicles tested by EDF and GES in the 1970s, it was their batteries. However, it appears that simply identifying the battery as *the reverse salient* does not do justice to the complex problems that arose and that I have described above.

The first thing to note is that batteries were highly complex systems in themselves, as the variety of battery "problem areas" identified by GES's task force underlines. Summarising its work, one engineer noted that all problem areas mutually influenced each other and that it was essential to regard batteries as a system in themselves. But more importantly, describing batteries as the reverse salient does not help us to understand how exactly the batteries had to be improved, or what criteria were used to determine when their performance was finally sufficient. What were the engineer's goals? Certainly, they were aware that batteries were the most problematic component, or subsystem, of the vehicles. But as we have seen, they could have tried to improve performance first – high speeds, long range, large carrying capacity – or decide to focus on maintenance and reliability. Why did they choose the latter? Why resolve the "technological imbalance" in this way and not another? What does it mean, in fact, to bring a reverse salient "in line" with the rest of the system, or to "balance" it?

To shed light on these questions, I believe it is necessary to employ some concepts from more recent literature in the history of technology and apply them

44 "Note d'information 79-02", 5 Apr. 1979, B0000428237, D0000259406, Archives EDF.

to the present case: first, "technology-in-use", and second, ideas specifically focused on maintenance.

David Edgerton in particular has pointed out that historians of technology have mostly focused on invention processes, and have had a tendency to neglect the use of artefacts. In other words, historians have not paid enough attention to how things are actually being used, regardless of what engineers or inventors might have had in mind when designing them or testing them under lab conditions.[45] EDF and GES engineers themselves did not see it this way: testing the vehicles, using them and subjecting them to real-world conditions was crucial in revealing the battery as the principal reverse salient. At both GES and EDF, engineers were happy with the decision to begin testing the vehicles sooner rather than later, which suggests that they were very sensitive to the importance of actually using the vehicles in order to determine further development steps. When one GES engineer reflected on the bus testing programme, he self-critically asked the question of whether it might not have been premature to put the buses out on the roads, given the high number of incidents. But his answer was unequivocal: to prove in principle that one could build an electric bus, a prototype would have been sufficient, but to "lay the groundwork" for electric road transport as a system, there was no way around testing the buses in regular service.[46] The same can be said about EDF's delivery vans. Not only were they driven on public roads; they were ultimately driven by partner companies over which EDF had no direct control, proof that getting as close as possible to real-world use conditions was crucially important for the French engineers, too. In other words, engineers understood that the final form of technological artefacts follows failure as much as it follows function.[47] For failure to occur, however, things have to be given the chance to fail, and therefore the vans and buses had to be actually driven.

The early emphasis on use and the decision to submit the vehicles to real-world conditions in turn revealed the central problem that I have discussed in this chapter: that the biggest challenges engineers faced were to be found in the areas of maintenance and reliability. Recently, a growing number of STS scholars have pointed out that invention and innovation have in the past too readily

45 Edgerton, David: "De l'innovation aux usages. Dix thèses éclectiques sur l'histoire des techniques", in: Annales. Histoire, Sciences Sociales 53 (1998), p. 815–837.

46 GES: "Zwischenbericht vom 14.5.1976", Zwischenberichte an das Ministerium für Arbeit, Gesundheit und Soziales, 11131, Historisches Konzernarchiv RWE.

47 "Form follows Failure" as a design principle is discussed in Petroski, Henry: The Evolution of Useful Things, New York: Knopf 2010, p. 22–33.

been identified with the creation of new and shiny things, as well as the personalities of ingenious inventors and “innovators”.[48] But more mundane activities such as repair and maintenance, “tweaking”, “hacking” and gradual improvements matter at least as much as making ground-breaking inventions. Engineering, as Walter Vincenti has remarked, is first and foremost a problem-solving activity.[49] The history of EDF’s and GES’s electric vehicles provides good evidence for this type of argument. After all, no fundamentally new components or artefacts were involved in the process, and most of the work indeed focused on solving problems that were discovered during the tests, in order to gradually eliminate them. The end result, of course, was improved, and therefore “new”, buses and delivery vans.

Recent literature on maintenance, however, tends to distinguish between innovation and maintenance as separate or even contradictory processes. In other words, it gives the impression that maintenance only begins to matter after a thing has been invented, has been used and has broken down.[50] But it is not only after innovation that maintenance begins to matter. Rather, maintenance is part and parcel of all stages of the lifetime of an artefact. Without question, electric vehicles were considered innovative in the 1970s. But the point I would like to make is that already during the innovation process, maintenance and repair were crucially important. In fact, they were even identified as the principal problems to be resolved and were considered to be “life-threatening” issues for the success or failure of electric vehicles as systems, and therefore the innovation process itself. The engineers were acutely aware that they were primarily in the business of making things that “kind of work most of the time” and that above all had to

48 Russell, Andrew L./Vinsel, Lee: “Hail the Maintainers”, in: Aeon, https://aeon.co/essays/innovation-is-overvalued-maintenance-often-matters-more (accessed 06.09.2019); McCray, Patrick: “Mo’s not all lightbulbs”, in: Aeon, https://aeon.co/essays/most-of-the-time-innovators-don-t-move-fast-and-break-things (accessed 10.09.2019).

49 Vincenti, What Engineers Know, p. 200.

50 Andrew L. Russell and Lee Vinsel explicitly deplore that the history of technology has so far “focused predominantly on the earliest stages of technological life cycles”, implying that maintenance is not (yet) part and parcel of technology at this stage. Consequently, they titled their paper “*After* Innovation, Turn to Maintenance”, suggesting that one comes first and the other follows. Russell, Andrew L./Vinsel, Lee: “After Innovation, Turn to Maintenance”, in: Technology and Culture 59 (2018), p. 1–25, here p. 4.

be just good enough to conform to real-world requirements, probably even more so than to be ground-breaking and exciting.[51]

To sum up, the case of 1970s electric vehicles suggests that understanding artefacts in all their complexity still challenges the available theoretical frameworks. Social and technological factors, invention and use, innovation and maintenance all matter simultaneously and relate to each other in ways that stark theoretical distinctions cannot always adequately capture. Historians of technology therefore have to tap into a number of different approaches simultaneously to grasp the complexities involved in working with artefacts, new or old. In this chapter, I have tried to bridge several such approaches, by considering questions of use and maintenance while describing an innovation process.

51 I am borrowing the slogan from "The Maintainers" group of researchers: http://themaintainers.org/ (accessed 04.04.2019).