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Efficient and Powerful

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World’s Largest Electric Vehicle Operation in Mines

The eDumper, a gigantic dump truck, has been in operation at the La Tscharner quarry in Péry-La Heutte (Switzerland) since January 2018. It was converted from a diesel vehicle to the world’s largest electric vehicle in 18 months. Vigier commissioned Kuhn Schweiz und Lithium Storage to develop this dump truck together with research partners Bern University of Applied Sciences, NTB Interstate University of Applied Sciences Buchs, and Empa.

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MOTIVATION

In the quarry, a laden conveyor belt traveling down into the valley generates electrical energy. Might it be possible to recapture the energy generated by a dumper laden at the top of the hill (and wasted until now) during the journey down into the valley and store this energy in a battery? For this to work, the vehicle would need to be electricity-powered and it would have to be possible to use the energy obtained with around 120 t and a difference in altitude of 180 m (only half its weight without any cargo) for the next ascent.

Weighing in at 58 t when empty and with a vehicle load capacity of 65 t, Lynx, as the eDumper was christened, holds no fewer than three world records. First of all, it is the largest and strongest battery-powered electric wheeled vehicle in the world; secondly, it uses the largest battery ever produced for an electric vehicle; and thirdly, never before has a comparable vehicle been capable of saving such large quantities of CO_2 when in use. Over the next decade, the eDumper is expected to generate up to 1300 fewer t of CO_2 per year than its diesel counterpart while transporting more than 300,000 t of limestone and marl.

The eDumper, a converted diesel Komatsu HD 605-7 dumper truck, runs purely on battery power. This kind of development is all made possible by today's high-performance lithium-based batteries, which can be charged and discharged thousands of times. Sufficient energy needs to be carried in restricted installation space, as liquid fuels such as diesel or gasoline contain around ten times more energy per unit of weight than with electrical battery chemistry.

In order to realize the eDumper idea, suitable development partners needed to be found to construct the electrical drive. The conversion was performed by the company Kuhn Schweiz AG in Lommis, canton of Thurgovia, and Heimberg, canton of Bern. The components – the synchronized drive motor (Oswald Motoren GmbH), the transmission (Puls Getriebe GmbH), the batteries (Lithium Storage GmbH) and the inverter (Aradex AG) – which were custom-made based on the latest generation of industrial products, were installed in the chassis of the Komatsu HD 605-7 in the fall of 2017. Brienzer Motoren AG supplied the additional 200-kW engine, which provides the hydropump drive for the disc brake system, the tipping drive, the servo support and the prestress for the braking system. The entire 600-kWh battery pack consisting of four blocks had to be installed in place of the diesel tank and in front of the new electric engine in the engine bay.

MODELING ENERGY FLOW

In order for the eDumper's new drive, auxiliary power units and battery to be dimensioned optimally for use in the quarry, the energy flows, the maximum key figures and the load capacity of the

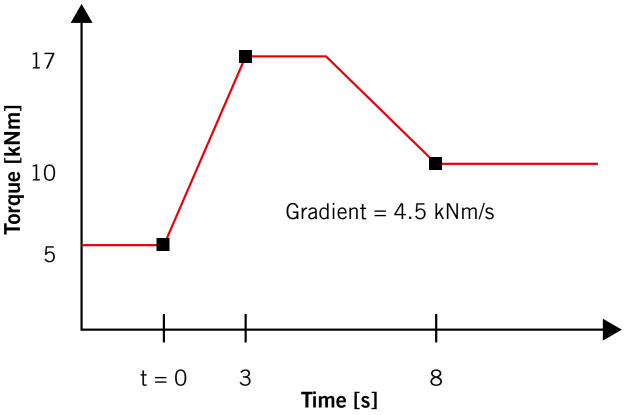


FIGURE 1 Simplified representation of the detected starting torque (© Berner Fachhochschule Biel BFH)

vehicle had to be recorded and analyzed. Calculation of the performance over time based on a reference profile enabled the drive energy footprint of the ascent and descent to be estimated. To this end, an existing diesel vehicle was fitted with a calibrated gage for the torque and number of revolutions on the drive shaft, GPS to determine the position and speed, an inclinometer and a wheel speed sensor. The readings were recorded during a second drive along a reference route in the scheduled place of use, **FIGURE 1**.

COMPARING THE PERFORMANCE OF THE BATTERY CELLS

Due to customer requirements, the battery technology should be safe and reliable. It should also have as high an energy density as possible and offer as long a service life as possible to boost efficiency. The goal of these initial tests was to identify the best cell technology from a short and long-term performance perspective. This involved conducting a series of experiments with two different cell types. The main focus was the electrical behavior of the cells at 25 °C, as well as at high (45 °C) and low temperatures (0 and 10 °C).

For characterization, an electrical load profile which best reflected driving conditions was developed. The impact on the service life of the cells was studied in a long-term experiment. The results revealed a clear difference in performance. The best cell technology was prioritized. NTB Interstate University of Applied Sciences Buchs/SG was subsequently responsible for thermal experiments and simulations, Empa for X-ray and impedance spectroscopy analysis, Lithium Storage for the construction of a battery pack, **FIGURE 2**, and Bern University of Applied Sciences for the electrical and thermal characterization of the battery pack.

ELECTRICAL AND THERMAL CHARACTERIZATION

In order to maximize service life, battery operating temperatures of 20 to 25 °C are essential. The thermal management system was designed by subjecting a battery pack with the configuration 24s2p (24 cells serial, 2 cells parallel) to thermal and electrical measurements under controlled conditions. A second, more realistic load profile was developed with measurements on the vehicle from other work packages. In order to characterize the temperature development for the simulated journeys, 26 temperature sensors were placed at different points in the battery pack. During the measurements, temperature data was recorded and pictures were taken with an infrared camera. A plus energy factor, which reflected the vehicle's degree of self-sufficiency, was introduced for the evaluation. The influence of two air cooling systems on this plus energy factor was also examined. The results helped quantify the temperature gradient along the cooling route and configure the thermal management system in other work packages.

FIGURE 2 Assembly of the battery pack (total 16 stacks per battery) (© Lithium Storage)

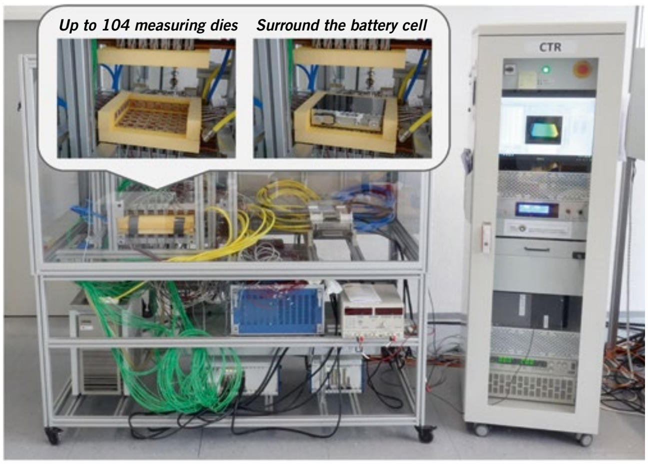


FIGURE 3 The NTB's battery cell test rig to measure the local temperature and heat flow distribution (© NTB Interstate University of Applied Sciences)

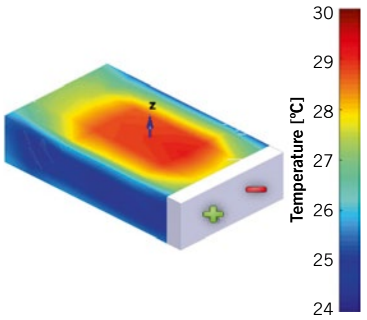


FIGURE 4 Temperature distribution on the surface of a lithium-ion cell as used in the eDumper (© NTB Interstate University of Applied Sciences)

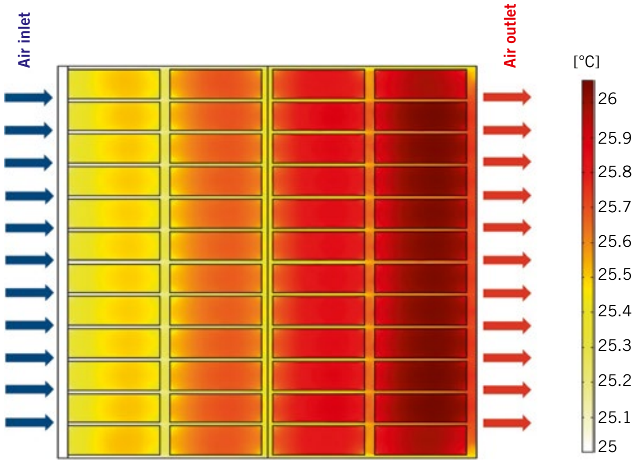


FIGURE 5 Temperature distribution of the cooling air with a horizontal through-flow of the vertical battery modules (© NTB Interstate University of Applied Sciences)

THERMAL MANAGEMENT

The thermal management of the batteries was conceived at the NTB, which boasts a test rig enabling the surface temperature and the heat flow given off by a battery cell to be determined under real load conditions at spatial resolution [1], **FIGURE 3**. Moreover, this cell test rig enables the heat capacity of battery cells to be measured. This key fundamental data is the prerequisite for dimensioning adequate thermal management.

Given a specific cooling strategy, its influence on temperature distribution on the cell surface can also be determined using the cell test rig. The goal must be to keep temperature gradients on the individual battery cells and throughout the entire battery as low as possible. Only then can a sufficient service life be guaranteed for the battery system. But this is precisely the challenge – especially with a lithium-ion battery as big as the one installed in the eDumper. **FIGURE 4** depicts the surface temperature distribution of an eDumper cell when loaded, where only the narrow sides would be cooled. The temperature increase in the middle of the large cell areas is particularly striking here. This needed to be avoided at all costs.

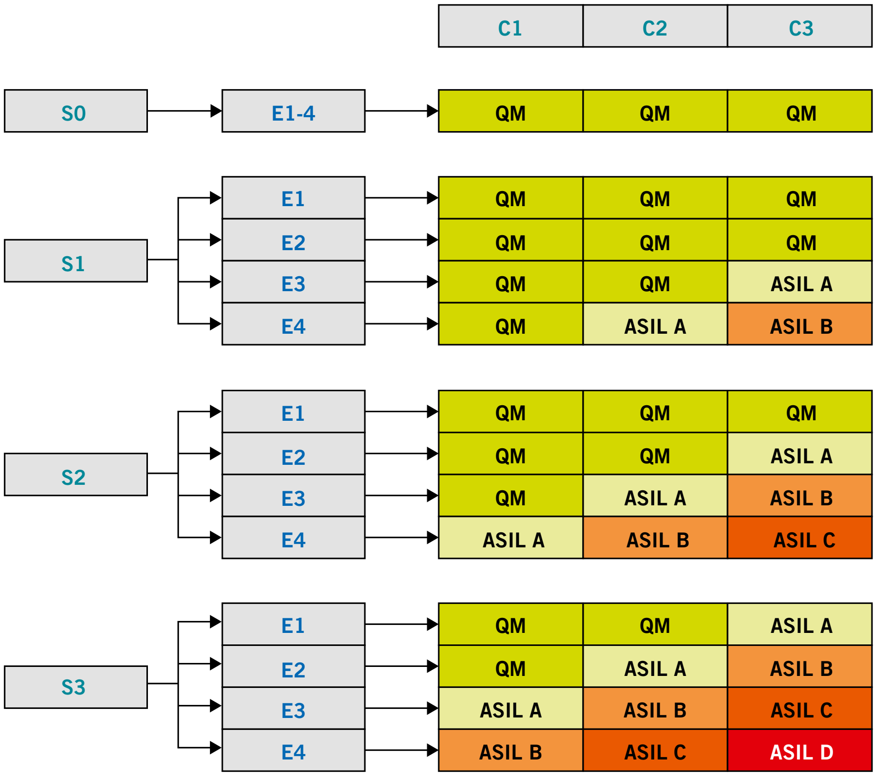
Once the thermal characteristics of the lithium-ion cells used were known, the NTB workgroup turned their attention to the battery module. In order to meet the requirement of achieving as homogenous a temperature distribution as possible, the cooling system also needs to guarantee an equally even heat supply and removal. Lithium Storage opted for cooling the battery cells with air. The challenge consisted in configuring the air distribution within a battery module and subsequently inside the battery built with the module in such a way that the same flow speed and thus the same heat transfer can be set in all cooling channels.

At the NTB, researchers used flow simulations to demonstrate that, unlike the cooling option originally planned, a horizontal perfusion of the vertical battery modules yields the best results throughout the entire battery. Although the cooling air warms up in the direction of flow, **FIGURE 5**, the warming per overflowed battery module is below 0.5 K, which means a considerably better temperature homogeneity can be achieved. In order to verify the calculations, one of the four batteries was fitted with a total of 48 surface temperature sensors and various flow probes. The results obtained previously through simulations were largely confirmed on the test rig.

The eDumper is currently undergoing field trials. The initial measurement results are available and now have to be evaluated in detail. During the bitterly cold winter months and the current summer temperatures, it has already become evident that the required maximum temperature homogeneity of 5 °C – gaged via a battery – cannot be achieved without active thermal management. As expected, the measurements revealed that the external thermal energy input

Number	Source of danger	Hazards
G1	Smoke/gas outlet in the area	Smoke poisoning driver
G2		Smoke poisoning bystanders
G3	Deflagration	Pressure on driver
G4		Pressure on bystanders
G5	Battery outside hot	Combustion driver
G6		Combustion bystanders
G7	Battery is burning	Smoke poisoning driver
G8		Smoke poisoning bystanders
G9	Battery is burning	Combustion driver
G10		Combustion bystanders
G11	Vehicle is burning	Smoke poisoning driver
G12		Smoke poisoning bystanders
G13	Vehicle parts under high voltage	Electric shock driver
G14		Electric shock bystanders

TABLE 1 Sources of danger and hazards (© Empa Dübendorf)



		C1	C2	C3
S0	E1-4	QM	QM	QM
S1	E1	QM	QM	QM
	E2	QM	QM	QM
	E3	QM	QM	ASIL A
	E4	QM	ASIL A	ASIL B
S2	E1	QM	QM	QM
	E2	QM	QM	ASIL A
	E3	QM	ASIL A	ASIL B
	E4	ASIL A	ASIL B	ASIL C
S3	E1	QM	QM	ASIL A
	E2	QM	ASIL A	ASIL B
	E3	ASIL A	ASIL B	ASIL C
	E4	ASIL B	ASIL C	ASIL D

FIGURE 6 ASIL, determined in accordance with ISO 26262 (© Empa Dübendorf)

required to raise the cooled eDumper to its operating temperature within a suitable timeframe after a lengthy downtime will be considerable in the wintertime. The cold lithium-ion batteries with their significant thermal masses especially needed heating beyond their self-heating via the operating electricity. Moreover, it is already safe to say that heat input from the surroundings also has a sizeable influence on the temperature distribution within the battery.

SAFETY ANALYSIS

The safety analysis concerns additional risks to people caused by using the battery as a power source, **TABLE 1**. It is conducted based on the ISO 26262 standard "Road vehicles – Functional safety." The following eleven operating types were defined: driving on the flat or uphill (B1), driving downhill (B2), vehicle (Vh) being loaded (B3), Vh being unloaded (B4), Vh feeding energy into the grid (B5), Vh taking energy from the grid (B6), Vh when parked (B7), Vh when serviced (B8), Vh when shut down (B9), Vh accident during operation (B10, driver able to act), Vh accident during operation (B11, driver incapacitated).

Two worst-case scenarios which could cause personal hazards through smoke, mechanical pressure, thermal impact or electricity are defined. In scenario 1, it is assumed that a cell in a battery module malfunctions catastrophically, i.e. fuses thermally. This can lead to the development of potentially toxic smoke and the warming of the battery casing. Deflagration is also conceivable, where the concentration of the gases formed lies within the explosion limits and they are ignited by a spark. In the worst case, the thermal fusing of a cell spreads to neighboring cells, with the end result that the entire battery module and also the vehicle catches fire. Moreover, it is assumed that the battery is no longer active as an energy source. In the second scenario, electric current hazards that could be caused by the battery, which is powered with voltages of up to 750 V, are studied.

The potential hazards are then examined for all operating types and their risk assessed. The risk assessment divided potential hazards in the categories Exposure probability, Severity and Controllability into three or four levels. This yields the following ratings: S0 No injuries; S1 Minor to medium injuries; S2 Serious injuries, likely to the survive; S3 Life-threatening injuries, unlikely to survive; E1 Very low probability; E2 Low probability; E3 Medium probability; E4 High probability; C1 Easily controllable; C2 Normally controllable; C3 Difficult to bring under control or uncontrollable. Based on these classifications, ASIL (Automotive Safety Integrity Levels) for the hazards considered are determined in accordance with **FIGURE 6**. This involves totting up the figures according to the letters (for example S3/E4/C3), in this case producing a score of 10 points. As this is the worst-case scenario (the highest score in all

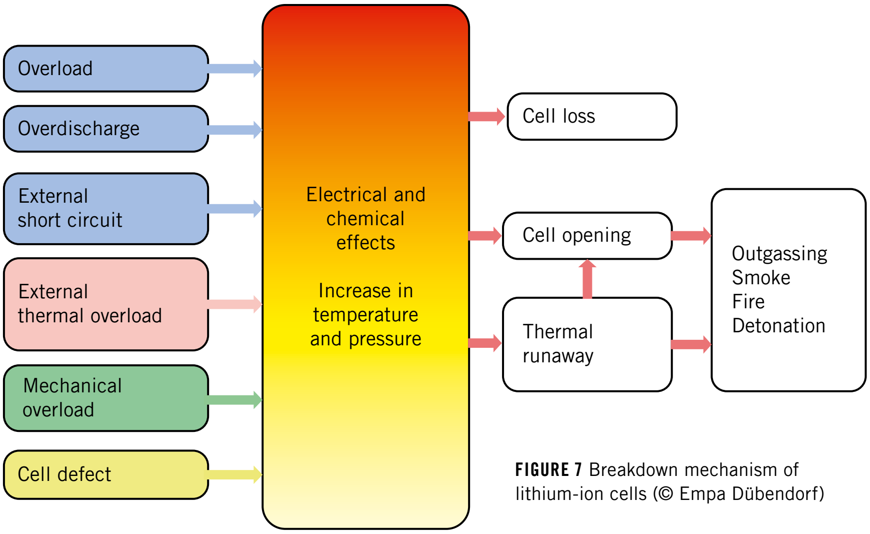


FIGURE 7 Breakdown mechanism of lithium-ion cells (© Empa Dübendorf)

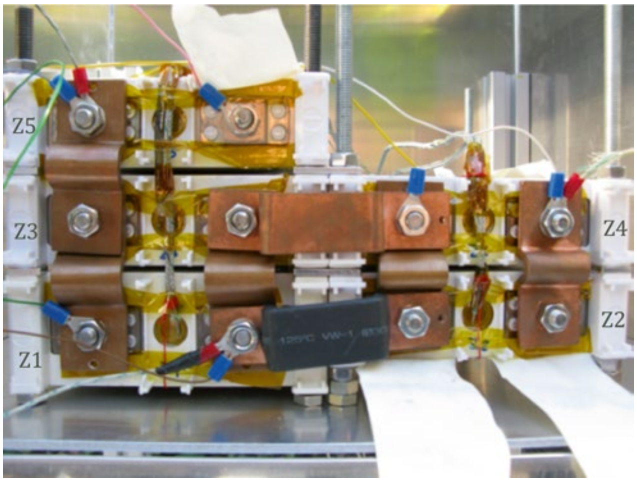


FIGURE 8 Cell arrangement for the spread test (© Empa Dübendorf)

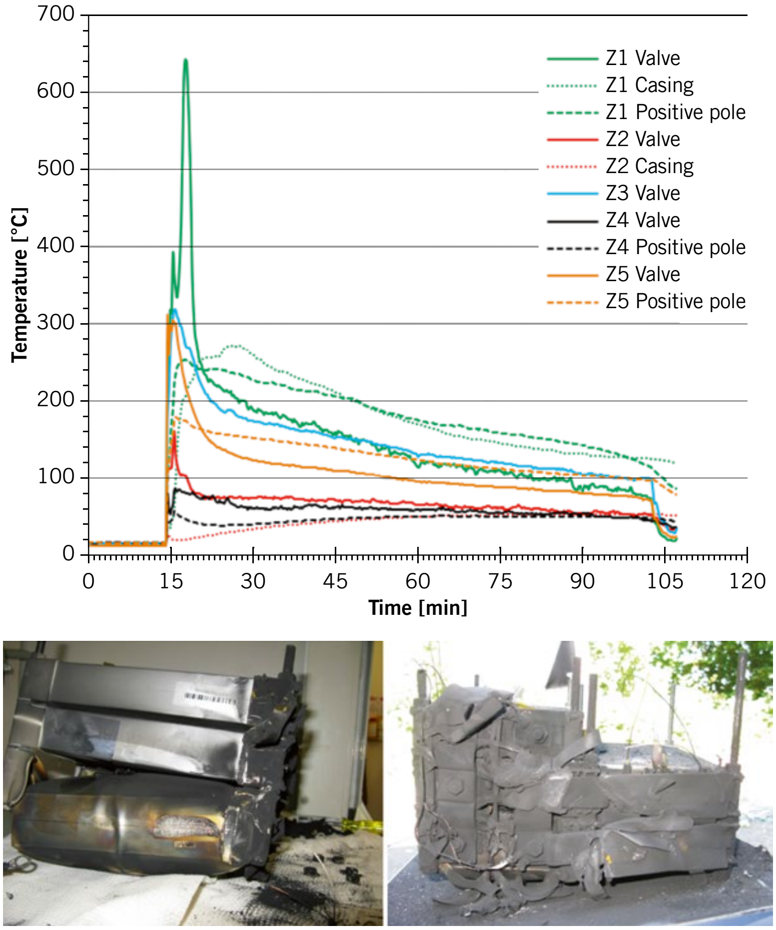


FIGURE 9 Temperatures during the spread test, cells after the spread test (© Empa Dübendorf)

three categories), this ASIL rating is D. Ratings from A to D (10 to 7 points) require special measures; QM stands for Quality Management.

The evaluation for hazards G9 and G11 in operating state B11 where the driver is incapacitated yields an ASIL rating of A. Hazards G13 and G14 in the operating states B1 to B6 are also rated as ASIL A. For all other combinations the rating is QM. ASIL A means that the recommended breakdown probability should be lower than 10^{-6} per hour, which corresponds to a breakdown rate of 1000 FiT (Failure in Time). For hazards G9 and G11, the breakdown rate for the breakdown type "coincidental thermal fusing" of a cell, which could cause the battery to catch fire, thus needs to be determined. Moreover, whether this kind of fusing in a cell will spread to other cells should be ascertained.

Based on the conservative assumption of a breakdown rate of 1 ppm/year for high-quality cells, this works out at a breakdown rate of 164 FiT for the battery with 1440 cells, which fulfils the requirements for ASIL A. For hazards G13 and G14, ASIL A is fulfilled as permanent insulation monitoring displays a breakdown rate of less than 1000 FiT.

THERMAL FUSING AND SPREAD

The Battery Management System (BMS), which monitors the lithium-ion cells continuously, measures all the cell voltages and temperatures in the cell stacks, regulates the currents when charging and discharging, calculates the charge status and controls the balancing of the cells while charging. Together with circuit breakers, fuses and insulation monitoring, the BMS ensures the safe operation of the battery. This enables the electrical mechanisms of overcharging, overdischarging and external short circuits to be prevented or kept under control, **FIGURE 7**. Heating/cooling and a casing that is adapted to the mechanical stresses while in operation enable external thermal and mechanical overloads to be avoided. Only defects inside the cell cannot controlled with constructive measures and the best BMS. Although these defects are rare, they need to be taken into consideration on account of their potentially catastrophic effects. In particular, the spread for the thermal fusing of a cell needs to be examined.

To this end, an arrangement of cells in a casing is set up. The geometry of this arrangement, especially the horizontal and vertical distances and the cell connectors, coincides with the original battery, **FIGURE 8**. In cell Z1, a short circuit is created by penetration with a needle, which causes thermal fusing. The test revealed that the smoke escaping from cell 1 displays a temperature of over 600 °C, while the casing for cell 1 warms to around 270 °C, **FIGURE 9**. The thermal fusing, however, did not trigger a fire or any spreading to the neighboring cells.

SUMMARY

The eDumper, a gigantic dump truck, has been in operation starting January 2018 in the La Tscharner quarry in Péry-La Heutte (Switzerland). It was converted from a diesel vehicle to the world's largest electric vehicle within 18 months. With its 58 t net weight and 65 t payload, the eDumper transports rock from the mountain to the valley. The recuperated electricity allows driving up empty. Ideally, even a surplus energy operation is possible.

Based on test drives with a diesel-powered vehicle, the energetic design of the new concept and the creation of the load profile of the battery were carried out. A metrological performance comparison enabled the selection of the most suitable battery cells. With the help of test bench for measuring the local resolution of the heat flow and the surface temperature of a battery cell under real load conditions, the thermal management of the battery could be designed. An ingenious safety concept ensures reliable operation under harsh operating conditions.

REFERENCE

[1] Christen, R.; Rizzo, G.; Gadola, A.; Stöck, M.: Test Method for Thermal Characterization of Li-Ion Cells and Verification of Cooling Concepts. In: Batteries 1 (2017), No. 3, pp. 1–12

THANKS

The authors thank the Swiss Federal Office of Energy (SFOE) for funding the eDumper project. The aim of the Swiss Energy Strategy 2050 and the corresponding action plan is to promote energy research. The core element is the establishment of eight national Swiss Competence Centers for Energy Research (SCCER). These should yield the necessary innovations for the sustainable realization of the energy strategy and ensure that the research results are transferred to the market. The Mobility SCCER was launched in 2014 with the aim of finding solutions to slash the energy consumption and CO_2 emissions in the transport sector.