



BATTERY POWERED TRAINS FOR CROATIAN RAILWAYS

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Abstract – KONČAR - Electric Vehicles have designed and produced two prototypes of battery powered trains, Battery Electric Multiple Unit (BEMU) and Battery Multiple Unit (BMU). Alongside these trains, six stationary battery chargers are delivered and installed in six cities in Croatia: Bjelovar, Virovitica, Osijek, Varaždin, Split and Pula. The paper describes the overall system concept, including traction architecture, battery integration, control strategies, and charging infrastructure. Special attention is given to battery management functions, energy flow control between catenary, traction system, and onboard batteries, as well as the implementation of fast DC charging stations. In addition, the paper presents real operational data obtained from passenger service. Measured specific energy consumption ranges from approximately 2.4 to 3.7 kWh/km, depending on ambient temperature and route characteristics. Based on the defined state-of-charge operating window, the achievable range is estimated at 100–150 km for BEMU and 140–200 km for BMU under beginning-of-life conditions. The results confirm the technical feasibility and energy efficiency of battery-electric trains for regional transport applications, demonstrating their suitability as a replacement for diesel multiple units on partially or fully non-electrified railway networks.

Keywords – battery powered trains, 6211, 6012, NMC batteries, Croatian railways, traction converter, traction transformer, passenger trains, charging station, energy consumption, battery functions, range, kwh.

1. INTRODUCTION

Almost 60% of Croatian railway is non-electrified. In the continental part of Croatia there is a certain mix of electrified and non-electrified network, where there are local non-electrified branches of electrified mainline track. On the contrary, in the southern part of Croatia, starting from city of Ogulin, railway network is completely non-electrified, running all the way to city of Split. In Istria region there is also almost 100 kilometers of completely non-electrified rail network. Recent technological advances in battery storage systems have introduced a new type of rail vehicles, battery powered trains and locomotives. The paper is structured as follows: Section II presents the system concept, Section III describes the powertrain architecture, Sections IV and V address control and battery management functions, Section VI introduces the charging infrastructure, while Section VII presents operational results, followed by conclusions in Section VIII.

Battery-electric trains offer railway operators a clean, quiet and cost-effective way to decarbonise regional passenger services without the expense and disruption of full-line electrification. By replacing

diesel multiple units with zero local-emission traction, they cut greenhouse gas emissions and air pollution directly at the point of use, contributing to national and European climate goals. Powered largely by electricity drawn from the grid and, increasingly, from renewable sources such as on-site photovoltaic generation, these trains bring the environmental benefits of electrified rail to lines where wiring the whole route would otherwise be impractical. As demonstrated by the BEMU and BMU fleet presented in this paper, battery power is a mature, field-proven technology that lets Croatia extend sustainable, green mobility to every corner of its rail network, today rather than decades from now.

2. SYSTEM CONCEPT

KONČAR - Electric Vehicles have designed and produced two prototypes of battery powered trains; battery electric multiple unit (BEMU) and battery multiple unit (BMU). Alongside these trains, six stationary battery chargers are delivered and installed in six cities in Croatia: Bjelovar, Virovitica, Osijek, Varaždin, Split and Pula.

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2.1. BEMU 6211

BEMU Class 6211 is a 3-car train designed to run on both electrified and non-electrified tracks. It combines pantograph and traction transformer for 25 kV_{AC} line and traction batteries for non-electrified operation, making it a bi-modal train. It holds 146 seating and 158 standing passengers, being able to carry 304 passengers in total (in “normal payload working order” according to [1]). It uses a total 1,2 MVA power from 25 kV_{AC} catenary line in “electric mode” or 800 kW power from traction batteries in “battery mode”. In electric mode BEMU’s top speed is 160 kph, while in battery mode it is 120 kph. Batteries can be charged from overhead catenary line while driving or standing still, from every braking cycle by traction motors working as generators and from stationary battery chargers.

2.2. BMU 6012

BMU Class 6012 is a 2-car train designed to run on non-electrified tracks, using traction batteries. It holds 102 seating and 114 standing passengers, being able to carry 216 passengers in total (in “normal payload working order” according to [1]). It uses 800 kW power from traction batteries in “battery mode”, allowing it to run with a top speed of 120 kph. Batteries can be charged from every braking cycle by traction motors working as generators and from stationary battery chargers.

2.3. Charging stations

Six charging stations are produced, installed and put into operation in six cities in Croatia: Bjelovar, Virovitica, Osijek, Varaždin, Split and Pula. Each charging station is identical. Charging station is a standalone power converter designed to be able to charge traction batteries of battery powered trains, namely 6211 and 6012 Class. Input voltage of charging station is 10(20) kV_{AC} while output is regulated DC voltage in range of $650 \div 1010$ V_{DC} with nominal output current of 695 A_{DC}. It can charge two battery groups simultaneously, each with 500 kW of power. Station is comprised of two major elements, a six meter container housing all necessary power equipment and a connection cabinet which is located near the tracks and stores charging cables, one for each battery group, used to make connection with the train.

3. POWERTRAIN ARCHITECTURE

Both trains share all major components of the powertrain, expect for traction transformer and affiliated medium-voltage gear (pantograph, main circuit breaker, instrument transformer and disconnect switch) which are used only on BEMU train. Therefore, following components are used: traction transformer

and affiliated medium-voltage gear (only on BEMU train), battery strings connected in two individual groups, traction and auxiliary converter, traction motors and gearbox.

3.1. Traction transformer

Traction transformer is a roof-mounted medium-voltage transformer made for nominal voltage of 25 kV_{AC}. It consists of a steel core with one primary winding and four secondary windings and two resonant filter chokes stored inside the same container. Secondary windings have nominal voltage of 420 V_{AC} and nominal power of 300 kVA. Filter chokes are actually part of the 100 Hz resonant filter used by the converter DC-link but are stored inside the traction transformer housing sharing the same cooling system (oil cooled by heat exchanger) as primary and secondary windings. Traction transformer is designed and built inside KONČAR Group.

3.2. Batteries

Traction Li-Ion batteries are intended for powering the main and auxiliary drives of the vehicle when it is operating on non-electrified sections of the railway. The batteries can be charged from the overhead line, from a stationary vehicle charging station located along the track, or during regenerative braking. Traction batteries enable vehicle operation on non-electrified railway lines. The traction battery system consists of three main components: battery packs, an electrical control cabinet, and a cooling unit. The battery packs contain battery cells (NMC type), connected in series and/or parallel combinations into a single unit and housed in an enclosure with integrated systems for regulating the temperature of the cells. Additionally, the enclosure includes electronic equipment for monitoring and controlling battery operation (BMS – Battery Management System) as well as power components for connecting all battery units.

The traction batteries are located on the roof of the vehicle and are divided into two groups. On the BEMU, each battery group consists of six packs (a total of twelve per train), while on the BMU, each group consists of seven packs (a total of fourteen per train). Each battery pack has nominal energy of 53 kWh, with voltage range of $720 \div 1000$ V_{DC}. This means that BEMU train has 636 kWh of available energy while BMU’s batteries hold 742 kWh of available energy.

Each battery group on the BEMU is connected to one main converter, while on the BMU, the configuration is different: both battery groups are connected to the same main converter, but to different battery converters integrated within the main converter of the BMU. This setup ensures redundancy on both types of trains, allowing continued operation at reduced power using the second battery group in case one group

fails.

The cooling unit (BTMS – Battery Thermal Management System) is responsible for maintaining the optimal temperature of the batteries. Each battery group has its own cooling unit, which independently manages the temperature of the battery coolant, separate from the other battery group.

3.3. Converter

The main drive of the BEMU consists of two main converters, each installed in one end module, sharing a common main transformer located in the middle module of the train. Each main converter includes two traction motor converters that control two asynchronous traction motors (mounted on the powered bogie), line converters, and a DC/DC converter for connection to the traction batteries. Inside the housing of the main converter, there are also two inverters for powering the auxiliary systems of the vehicle, connected to the DC-link of the main drive, and a battery charger for the control system batteries (24 VDC).

The main drive of the BMU also consists of two main converters; however, in this case, each converter controls one traction motor. Additionally, each main converter includes one DC/DC converter for the traction batteries and one inverter for the auxiliary power supply. One of the two main converters include a battery charger for the control system batteries.

The cooling of the main converter is achieved through forced circulation of coolant, which is air-cooled in a heat exchanger located on the roof of the vehicle. The drive system also includes electrodynamic braking, where the regenerated energy is primarily used to supply auxiliary systems, charge traction batteries (both BMU and BEMU), and/or return energy to the overhead catenary line (BEMU). Braking resistors or voltage limiters for the DC-link are mounted on the roof of the vehicle. Each main converter contains embedded computers that monitor the drive system's status (processing data and measuring current, voltage, and axle speed signals), act in the event of wheel slip, and communicate with the vehicle's main computer.

Converter is designed and built inside KONČAR Group

3.4 Traction motor and gearbox

Traction motor is a squirrel cage asynchronous three phase motor, designed to be powered by frequency inveter and housed inside powered bogie of a railway vehicle. It is a self-ventilated type and is equipped with temperature and speed sensors. Nominal ratings in S1 are as follows: voltage 540 V_{AC}, current 376 A_{AC}, power 300 kW and torque 1069 Nm. During vehicle starting, maximum allowable current is 690 A_{AC}.

Gearbox is a two stage gearbox with gear ratio of

1:4.822 and nominal power of 401 kW. Maximum design speed is 5772 rpm which enables the train to run up to 176 km/h.

Both train types use identical traction motors and gearboxes. BEMU has two powered bogies, each containing two powered axles with motor and gearbox set. This means tha in total BEMU has four traction motors and gearboxes. BMU however, has only one powered bogie, meaning in total it only has two traction motors and gearboxes.

3.5. Traction motor and gearbox

The control system of the KONČAR BEMU 6211 and BMU 6012 is centered around the Vehicle Control Unit (VCU), which supervises and coordinates all traction and energy-related functions of the train. The VCU collects real-time signals from propulsion equipment, converters, batteries, and driver inputs, and manages traction power, braking effort, and energy flow across the vehicle. It interfaces directly with the main propulsion system and ensures coordinated operation of all energy sources under both catenary and battery supply modes.

Traction control is implemented through dedicated microprocessor-based control systems integrated into each motor converter. Each traction converter independently regulates the associated asynchronous motor, controlling torque, speed, and adhesion conditions based on continuous measurement of current, voltage, and axle speed. These control units also implement anti-slip and anti-skid functionality, ensuring optimal traction utilization under varying adhesion conditions. Additionally, they provide built-in protection, diagnostics, and fault recording functions, while maintaining communication with the VCU.

A key element of the control concept is the management of energy flow between the catenary, traction converters, and onboard lithium-ion batteries. The control system dynamically switches between power supply sources and optimises energy usage depending on operating mode. During braking, the traction control system operates the motors in regenerative mode, and the recovered energy is either stored in the traction batteries or, when operating under overhead line and battery capacity is saturated, fed back into the catenary network.

4. BATTERY MANAGEMENT FUNCTIONS

The battery-electric multiple units BEMU 6211 and BMU 6012 are equipped with advanced battery management functions that are fully integrated into the overall traction and energy control system. The battery management system (BMS), in coordination with the vehicle control unit (VCU) and DC/DC converters, ensures safe, efficient, and lifetime-optimized

operation of the lithium-ion traction batteries under all operating conditions.

4.1. State-of-charge window operation

A key element of the battery management strategy is the controlled limitation of the battery state-of-charge (SoC) operating window. During normal operation, charging is typically limited to approximately 85–90% SoC, while discharge is restricted to around 20% SoC. This approach significantly reduces battery degradation and extends service life. In addition, the system enables a dedicated range extension mode, in which controlled discharge to approximately 10% SoC is permitted under predefined conditions, such as missed charging opportunities or degraded infrastructure availability, thereby ensuring operational flexibility and safe return capability. During this extended operation mode, VCU performs automatic traction power deration based on BMS current and voltage limits. Below 10% SoC, traction power is cut-off and batteries are disconnected.

4.2. Charging strategy

The battery charging process is actively managed to accommodate various operating scenarios, with particular emphasis on operation under overhead contact line. When the BEMU operates on electrified sections, its traction system enables continuous charging of the onboard batteries directly from the catenary. In driving mode, the control system automatically manages the energy flow from the overhead line, distributing power between traction motors, auxiliary inverters, and battery charging in accordance with the current driving profile and operational requirements. Depending on the instantaneous power demand, the system can supply traction directly while simultaneously charging the batteries, or prioritize one function over the other. In this way, combined operating modes are possible, where part of the energy is used for propulsion and onboard systems, while the remaining portion is directed to battery charging. In stationary mode under the catenary, the available power can be utilised more efficiently for charging purposes, as only auxiliary systems represent the remaining onboard load. As a result, higher charging power levels can be achieved compared to driving conditions, enabling faster replenishment of battery energy. In addition to catenary-based charging, the system also supports energy recovery through regenerative braking and charging from stationary charging infrastructure. All charging processes are continuously monitored and adjusted in accordance with battery condition, temperature, and operating constraints, ensuring efficient energy transfer while preserving battery lifetime.

4.3. Battery pack connection and system formation

At vehicle start-up, a dedicated battery system initialization sequence is executed in order to form a unified traction battery system. Individual battery packs are first checked with respect to voltage levels, general status, and insulation conditions. Subsequently, the packs are connected via controlled switching devices using pre-charge circuits, allowing gradual voltage equalisation and preventing inrush currents. Through this process, multiple battery packs are safely connected in parallel and combined into a single functional battery system. This connection algorithm ensures reliable energization, balanced load sharing, and provides the capability to isolate individual packs in the event of a fault

5. CHARGING STATIONS

Alongside the BEMU and BMU trains, six charging stations were built, in the cities of Bjelovar, Vinkovci, Varaždin, Osijek, Pula and Split.

5.1. Concept

These charging stations are based on the KONČAR KonCharge 1000 concept, designed as high-power stationary energy conversion units enabling efficient charging of battery-powered rolling stock. Each charging unit converts medium-voltage grid supply (10 or 20 kV) into a controlled DC output suitable for direct battery charging, using IGBT-based power converters with integrated transformer and switching equipment. The system allows parallel charging via two physical DC charging cables, each connected to an independent charging output rated up to 500 kW, enabling flexible and high-power charging operation adapted to timetable requirements.

5.2. Charging interface and handshake

The charging interface between the train and the station is designed to ensure both electrical and functional compatibility, including dedicated pilot connections for safety verification, controlled energisation sequences, and communication channels for real-time data exchange. Establishment of the charging process follows a structured handshake protocol between the vehicle and charging station. This process includes user authorization, selection of charging sequence, initialization of the converter, and physical connection of the charging cables. Once the connection is established, communication between the onboard control system and the charging station verifies readiness for charging, including confirmation of battery status, insulation conditions, and system availability. Only after successful validation are the power contactors closed and charging enabled,

ensuring safe and controlled energy transfer.

During the charging sequence, continuous data exchange is maintained, including parameters such as state of charge, voltage, current, and temperature, enabling adaptive control of the charging process. Upon completion, a controlled disconnection sequence is executed, in which charging current is reduced to zero, power contactors are opened, and the interfaces are safely disconnected following operator confirmation. This structured protocol ensures a high level of operational safety, prevents improper connection or disconnection, and enables reliable integration of the charging infrastructure with the battery-electric train fleet.

6. OPERATIONAL EXPERIENCE

The BEMU and BMU trains represent the first battery-electric passenger trains introduced in Croatia and the broader region. During the initial design phase, extensive simulations were conducted using telemetry data and mission profiles from Class 7023 diesel trains operating on non-electrified routes—the same lines where the BEMU and BMU units are expected to be deployed. These simulations played a key role in estimating energy consumption, operating range, and charging requirements under real-world conditions. Once the battery trains entered passenger service, operational data became available and provided insight into real energy consumption, operational efficiency, and achievable autonomy under different environmental and operational conditions.

For the BEMU platform, measurements were conducted on regional routes such as Zagreb – Bjelovar. Under low ambient temperature conditions (approximately 5 °C), the recorded energy consumption was around 108 kWh over a distance of 30 km, corresponding to a specific consumption of 3.6 kWh/km. Under milder conditions (approximately 20 °C), the energy consumption decreased to approximately 86 kWh over 32 km, yielding a specific consumption of 2.7 kWh/km. Under high temperatures, recorded energy consumption was around 114 kWh over a distance of 31 km, yielding a specific consumption of 3.7 kWh/km. These results clearly indicate the influence of ambient conditions, particularly HVAC demand, on overall energy consumption.

For the BMU platform, operational measurements were carried out on the Split – Kaštel Stari route. At an ambient temperature of approximately 4 °C, the recorded energy consumption was asymmetric depending on the driving direction, with 90 kWh for one direction and 43 kWh for the return trip over the same distance of 18 km, resulting in an average consumption of approximately 3.7 kWh/km. At higher temperatures (approximately 15 °C), the energy

consumption decreased significantly, with measured values of 66 kWh and 22 kWh respectively, corresponding to an average specific consumption of approximately 2.4 kWh/km. The difference between directions is primarily attributed to track gradient and operational conditions, demonstrating the sensitivity of energy consumption to route characteristics.

Based on the available battery capacity and defined state-of-charge operating window (approximately 85% to 20%), the usable energy for traction amounts to approximately 412 kWh at the beginning of life (BoL) for BEMU and 478 kWh for BMU, with reduced values at end-of-life conditions. Consequently, the achievable operational autonomy is estimated in the range of 100 to 150 km for BEMU and 140 to 200 km for BMU under BoL conditions, with corresponding reductions over the vehicle lifecycle.

Given the diversity of routes across the network—each with varying topography, stopping patterns, and climate conditions—battery consumption varies significantly between missions. It will therefore be essential to compare the simulation results with real-world performance data on all track to validate the initial assumptions regarding range and energy efficiency.

7. CONCLUSION

The development and deployment of the BEMU 6211 and BMU 6012 units, supported by a dedicated network of high-power charging stations, represent a significant step toward the modernization and decarbonisation of regional railway transport in Croatia. Together, the battery-electric rolling stock and charging infrastructure form a fully integrated system enabling reliable operation on mixed electrified and non-electrified railway networks.

The analysis of operational data obtained from passenger service confirms that the achieved performance is consistent with design expectations. Measured specific energy consumption in the range of 2.4 to 3.7 kWh/km reflects the influence of ambient temperature, route characteristics, and operational conditions, with particularly strong impact of HVAC demand and track gradients. Based on the defined battery operating window and available energy, the achieved and projected operating ranges of 100–150 km for BEMU and 140–200 km for BMU at beginning-of-life conditions validate the suitability of the concept for regional services.

The deployed charging stations, capable of high-power DC charging via dual connections, play a key role in enabling practical operation of battery-electric trains. Their integration with the onboard control and battery management systems ensures safe, efficient, and flexible charging both in scheduled and operationally constrained conditions. The combination

of stationary charging infrastructure, catenary-based charging (for BEMU), and regenerative braking provides a robust and adaptable energy supply concept.

Overall, the presented experience confirms that battery-electric trains, supported by appropriately dimensioned charging infrastructure, are a technically viable and energy-efficient alternative to diesel-powered units on partially or fully non-electrified railway networks. Future work will focus on further optimisation of energy consumption, refinement of

charging strategies, expansion of the charging network, and continued validation of long-term operational performance.

REFERENCES

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