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Selection of Parameters for the Hydrogen Power-Supply System of an Auxiliary Rail Vehicle

Abstract: The article presents a concept concerning a hydrogen power-supply system for an auxiliary rail vehicle. The selection of key component parameters was based on the expected energy consumption and power balance of the vehicle. The research work discussed in the article involved the identification of traction characteristics and the simulation of theoretical rides, constituting the basis for the development of optimum vehicle control algorithms.

Key words: rail vehicle, hydrogen fuel cell, control system, emission-free drive system, traction characteristic

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1. Introduction

The purpose of the analyses and calculations presented in the article was to determine the basic parameters for the components of the hydrogen power supply system intended for installation in a railway auxiliary vehicle [1, 2].

The object of research, constituting the basis for calculations and simulations, was a WM-15A rail vehicle (motor car).

The vehicle was equipped with a high-pressure internal combustion engine [3, 4]. The engine, along with the necessary equipment, was placed in a compartment located between the cabin and the cargo box. The drive was transferred to the wheel sets mechanically.

The basic vehicle parameters are presented in Table 1.

Table 1. Basic parameters of the WM-15A vehicle [3]

Parameter	Value
Vehicle kerb weight	20000 kg
Load capacity	15000 kg
Maximum weight of wagons	120000 kg
Maximum speed	80 km/h
Combustion engine power	147 kW

The vehicle conversion involved placing drive unit components in the combustion engine compartment and under the chassis. It was assumed that the traction characteristics would not be compromised in comparison with those of the vehicle before the conversion.

The main circuit of the vehicle was built on the basis of the main power supply bus (DC link), to which the individual components were connected [5].

The parameters to be determined within the presented drive system are:

- electric traction motor power,
- hydrogen fuel cell power,
- battery energy storage capacity,

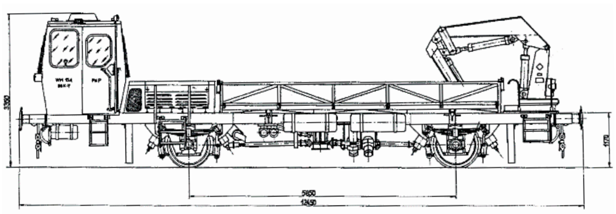

Fig. 1. Side view of the WM-15A rail vehicle [1]

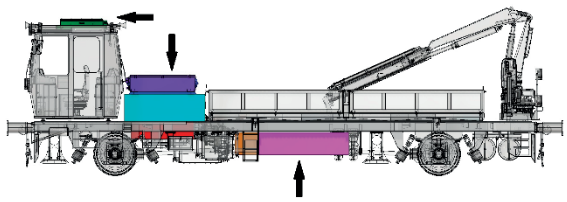

Fig. 2. Proposal for component installation

- maximum charging power and discharge power of the battery energy storage.

2. Traction characteristics

Using generally accepted motion resistance formulas for draisines [6, 8], freight cars [7] and the adhesion curve [6, 9], traction characteristics were determined for individual vehicle operating states (empty, loaded, driving with trailer cars). The power available at the wheels was assumed at 150 kW.

Figure 4 presents the traction characteristics against the motion resistance curves for a vehicle in a mass state of 35,000 kg (vehicle mass – 20,000 kg, load 15,000 kg). This power allows the vehicle to move at its maximum speed of 80 km/h on a track with an inclination of up to approximately 10 ‰. In terms of an inclination of 25 ‰, the maximum speed of the loaded WM-15A vehicle drops to 50 km/h.

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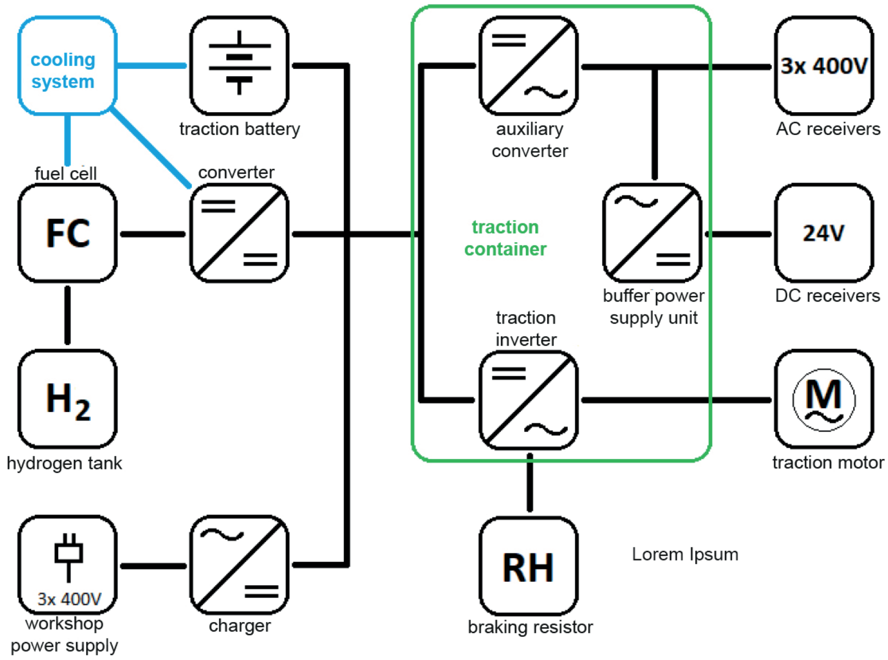

Fig. 3. Main circuit flowchart / cooling system

Figure 5 presents the traction characteristics of the vehicle in the as-loaded state and pulling a set with a trailer weight of 120,000 kg. On a straight track, such a trainset can reach a maximum speed of approximately 70 km/h, on a 25 ‰ inclination, the maximum speed drops to 13 km/h, but – importantly – the trainset is still able to go up (and down) such an inclination.

The characteristics confirmed that a power of 150 kW of the traction motor installed on the WM-15A vehicle was sufficient to perform the previously assumed traction tasks. The power was not oversized as it would negatively affect the costs of building a hydrogen power supply system.

3. Theoretical rides

The calculation of theoretical rides involved related traction characteristics. Figure 6 presents the electrodynamic braking characteristic (adopted for the calculation of the theoretical ride). Braking was performed with a constant deceleration of 0.8 m/s^2.

The simulations involved electrodynamic braking – regenerative and supported by mechanical brakes. Mechanical braking support was necessary for the obtainment of preset braking delay at higher speeds when the electrodynamic braking force was low.

The assumed electrodynamic braking power on the motor shaft amounted to 140 % × 150 kW = 210 kW (the motors could be briefly severely overloaded; an assumed overload amounted to 140 %). The simulation also took into account the electric traction motor characteristics for motor and generator operation.

Figure 7 shows the distribution of power in the theoretical ride algorithm and the designations of power between the individual energy conversion blocks.

The simulation of theoretical rides was preceded by the performance of a series of analytical calculations aimed at selecting the optimum total value of the hydrogen cell power and the capacity of the battery energy storage.

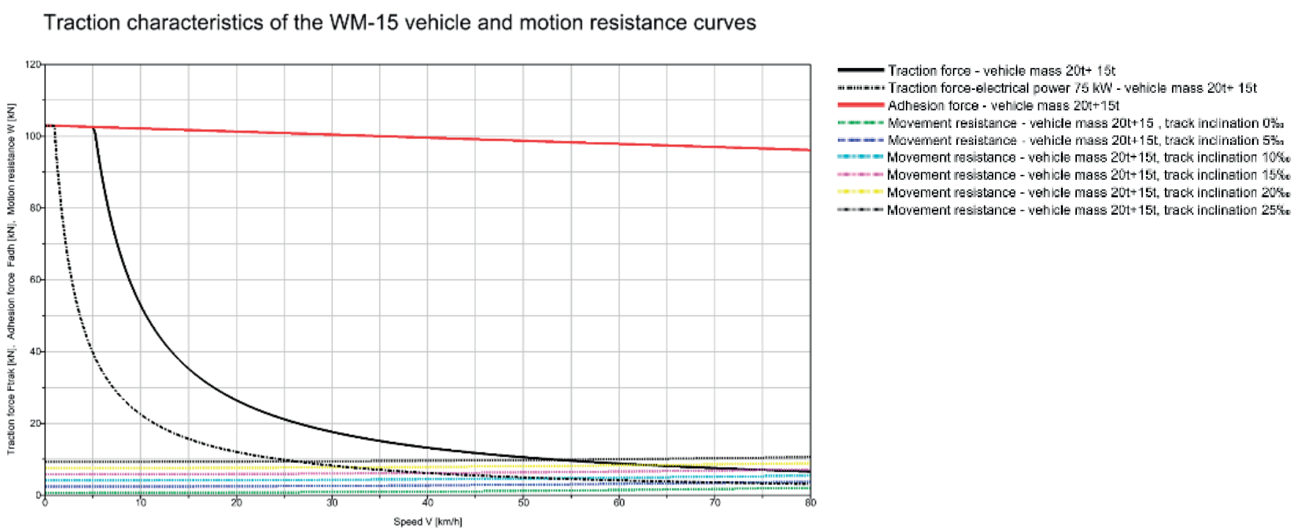

Fig. 4. Traction characteristics for vehicle weight in loaded condition (35000 kg)

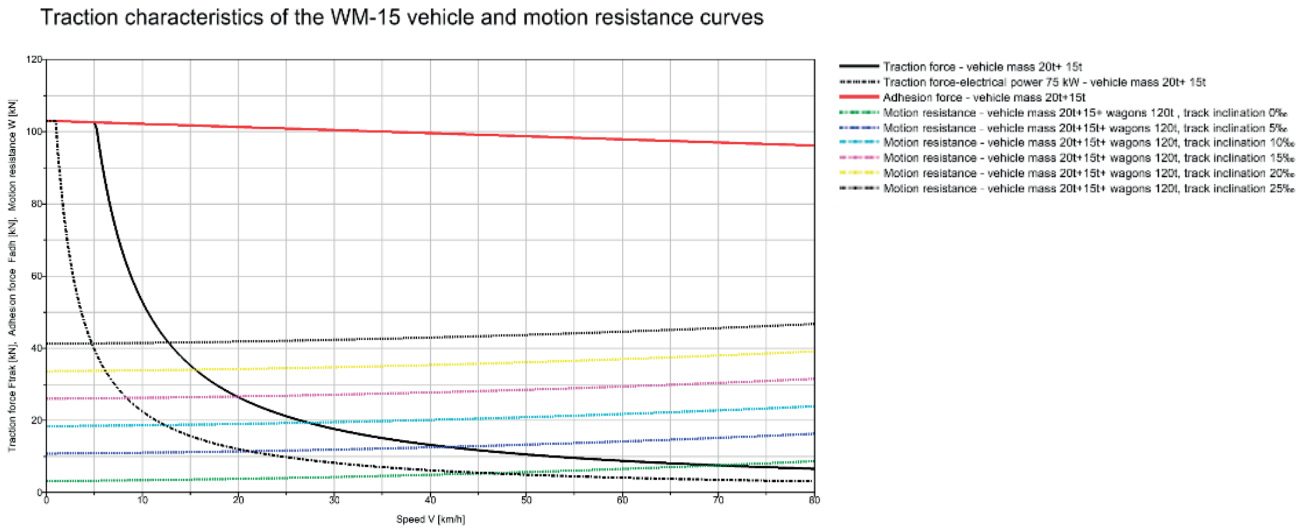

Fig. 5. Traction characteristics for the vehicle weight in a loaded condition (35,000 kg), pulling three freight cars with a total weight of 120,000 kg

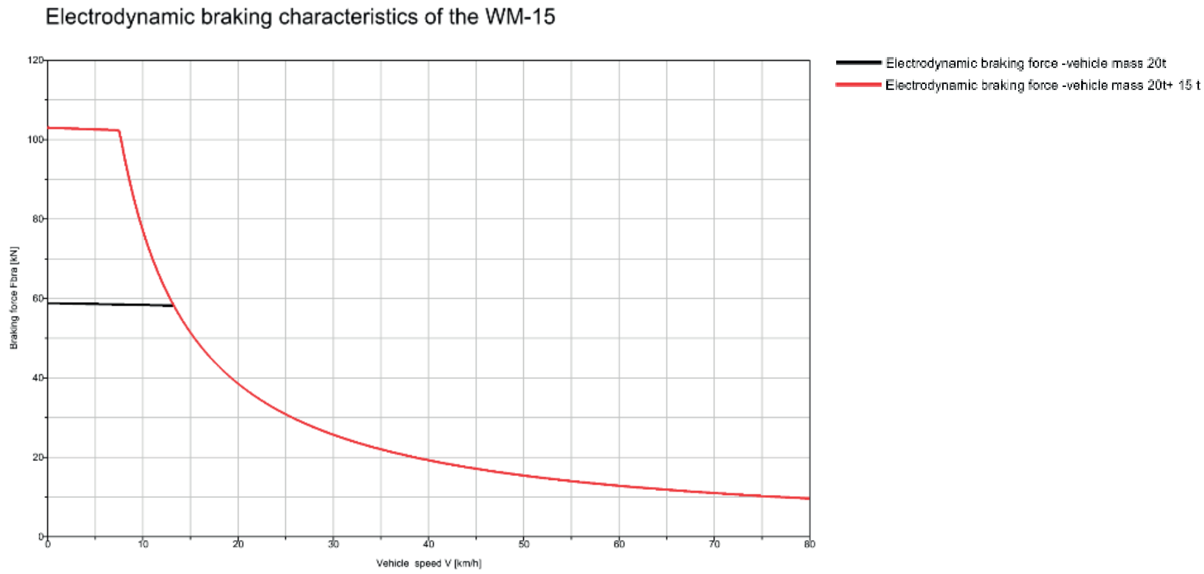

Fig. 6. Electrodynamic braking characteristics

Based on the foregoing, the hydrogen cell power was adjusted at 100 kW.

For simulation-related purposes, it was assumed that the hydrogen fuel cells could operate in two modes, i.e. in the active mode – when they generated an electrical power of 100 kW and in the sleep mode, when they did not generate any electrical power.

The assumed battery capacity amounted to 130 kWh.

The hydrogen cells were controlled by a two-position (on-off) controller, turning the hydrogen fuel cells on and off, depending on the level of energy stored. The hydrogen fuel cell was turned on when the energy level in the battery amounted to 60 kWh and turned off when the energy level in the battery was 120 kWh. There was no restriction as regards the battery charging and discharging power. During electrodynamic braking, when the battery was overfilled, the excess energy could be dissipated on the braking resistors.

The tests involved the performance of a series of theoretical rides (1A–5B) on the Łódź Fabryczna – Skierniewice route in both directions (a distance of 65,824 m, stopping at each station – 7 stops of 30 s each) and on a track with a constant inclination of 25‰ (ride 6 at the maximum speed, ride 7 speed reduced to 25 km/h). It was assumed that energy consumption for the vehicle own needs was constant and amounted to 25 kW. The results and parameters of the individual rides are presented in Tables 2, 3 and 4.

In relation to rides 1A and 1B considered together, i.e. the ride from Łódź Fabryczna to Skierniewice and back (empty vehicle), the vehicle consumed 125.15 kWh (56.64 kWh + 68.51 kWh) of electricity, while on this route the hydrogen cells generated 185.68 kWh (92.83 kWh + 92.85 kWh). The surplus energy was stored in the battery. The vehicle energy balance for rides 1A and 1B was positive, i.e. the energy stored in the battery at the beginning of ride 1A amounted to 60 kWh, whereas that stored at the end of ride 1B amounted to 114.48 kWh. During the two rides, the hydrogen cells were operating continuously, because the energy level in the battery did not exceed

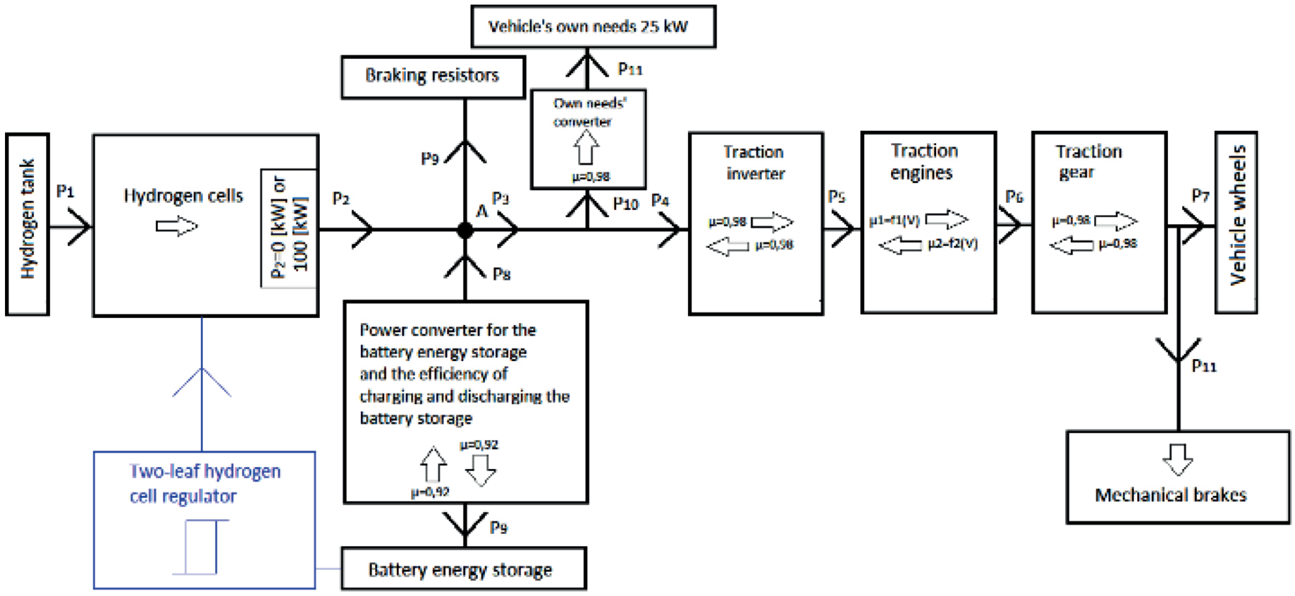

Fig. 7. Energy distribution assumed in the theoretical ride algorithm

Table 2. Energy consumption during theoretical rides

Ride	Vehicle weight [kg]	Ride time [min]	Total energy consumption [kWh]	Mean energy consumption [kWh/100 km]
1A	20000	55.71	56.64	95.0654
1B	20000	55.71	68.51	
2A	35000	56.71	67.26	118.4845
2B	35000	56.84	88.72	
3A	75000	61.08	144.63	253.2877
3B	75000	63.47	188.82	
4A	115000	66.10	174.19	305.0465
4B	115000	74.13	227.39	
5A	155000	71.21	204.48	359.5688
5B	155000	84.82	268.89	
6	35000	74.37	254.87	387.2018
7	35000	158.11	259.16	393.7124

Table 3. Energy balance in the battery energy storage

Ride	Initial value of energy [kWh]	Minimum value of energy [kWh]	Final value of energy [kWh]	Reduction of energy in the storage [kWh]
1A	60.00	58.83	92.57	-32.57
1B	92.57	91.50	114.48	-21.91
2A	60.00	56.86	84.52	-24.52
2B	84.52	80.13	89.93	-5.41
3A	120.00	44.56	46.70	73.30
3B	120.00	14.65	17.30	102.70
4A	120.00	60.65	62.37	57.63
4B	120.00	24.86	26.54	93.46
5A	120.00	41.43	42.78	77.22
5B	120.00	3.79	5.22	114.78
6	120.00	1.25	2.17	117.83
7	60.00	59.75	63.92	-3.92

120 kWh, which means that the on-off controller did not switch off the cells. The changes in power on the individual elements of the drive system and power supply system for rides 1A and 1B are presented in Figures 8 and 9.

In relation to the jointly considered rides 2A and 2B, the energy balance of the vehicle was also positive, i.e. the energy stored in the battery at the beginning of ride 2A amounted to 60 kWh, whereas that at the end of ride 1B amounted to 89.93 kWh. In both the above-named rides, the hydrogen fuel cells worked throughout the entire ride simulation.

The most unfavourable of the cases considered was the situation connected with attaching three wagons with a total weight of 120,000 kg to the vehicle (rides 5A and 5B). Because of the line profile, ride 5B turned out to be more critical. In spite of the fuel cells working throughout the simulation, the energy level in the battery dropped from 120 kWh at the beginning of ride 5B to 5.22 kWh at the end of the ride. The vehicle consumed 268.89 kWh of electric energy on this route, whereas the hydrogen fuel cells

Table 4. Fuel cell operation

Ride	Fuel cell operation time [min]	Generated energy [kWh]	Mass of hydrogen consumed [kg]	Mean hydrogen consumption [kg/100 km]
1A	55.71	92.83	6.98	7.1478
1B	55.71	92.85	6.98	
2A	56.71	94.51	7.11	8.9086
2B	56.84	94.73	7.12	
3A	37.92	63.19	4.75	19.0442
3B	47.18	74.71	5.62	
4A	66.10	110.17	8.28	22.9358
4B	74.13	123.55	9.29	
5A	71.21	118.68	8.92	27.0352
5B	84.82	141.36	10.63	
6	74.37	123.94	8.67	27.0770
7	158.11	263.51	19.81	29.6024

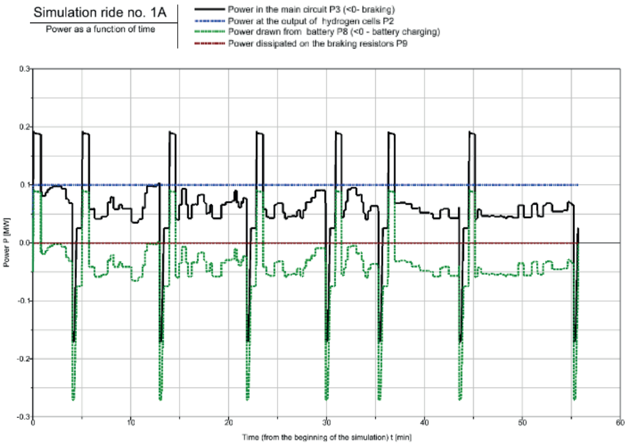

Fig. 8. Energy flow as a function of time in relation to ride 1A

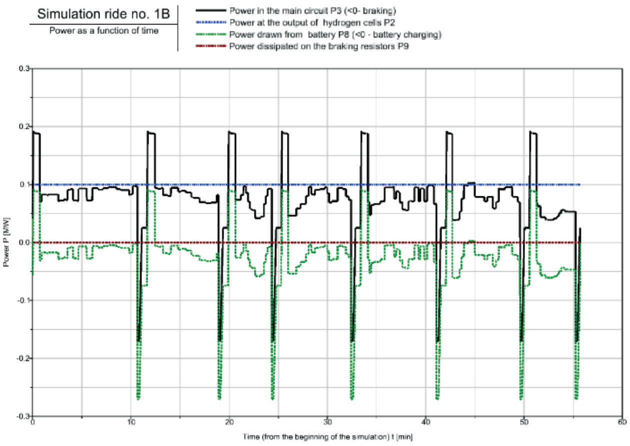

Fig. 9. Energy flow as a function of time in relation to ride 1B

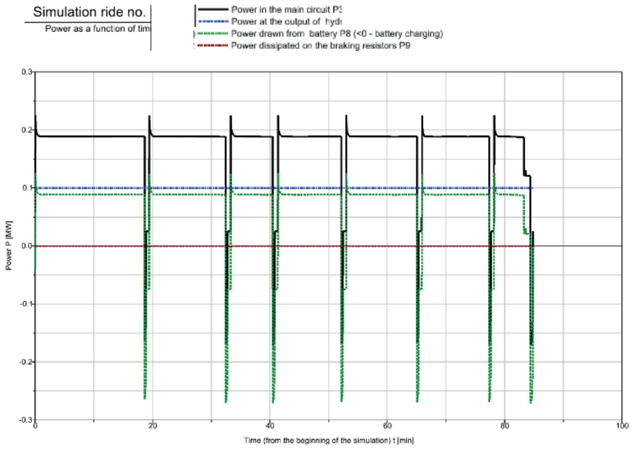

Fig. 10. Energy flow as a function of time in relation to ride 5B

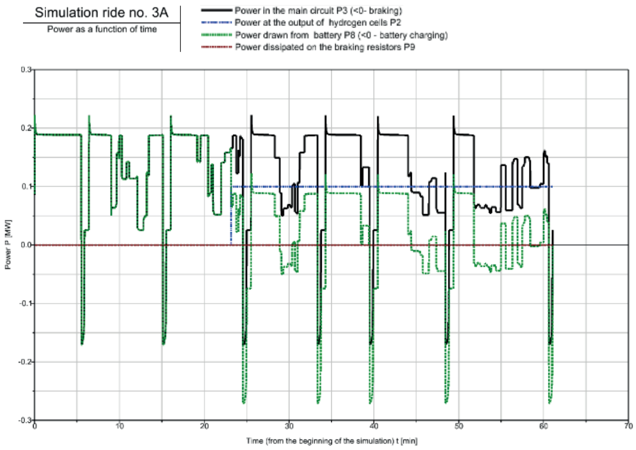

Fig. 12. Energy flow in the battery storage in relation to ride 3B

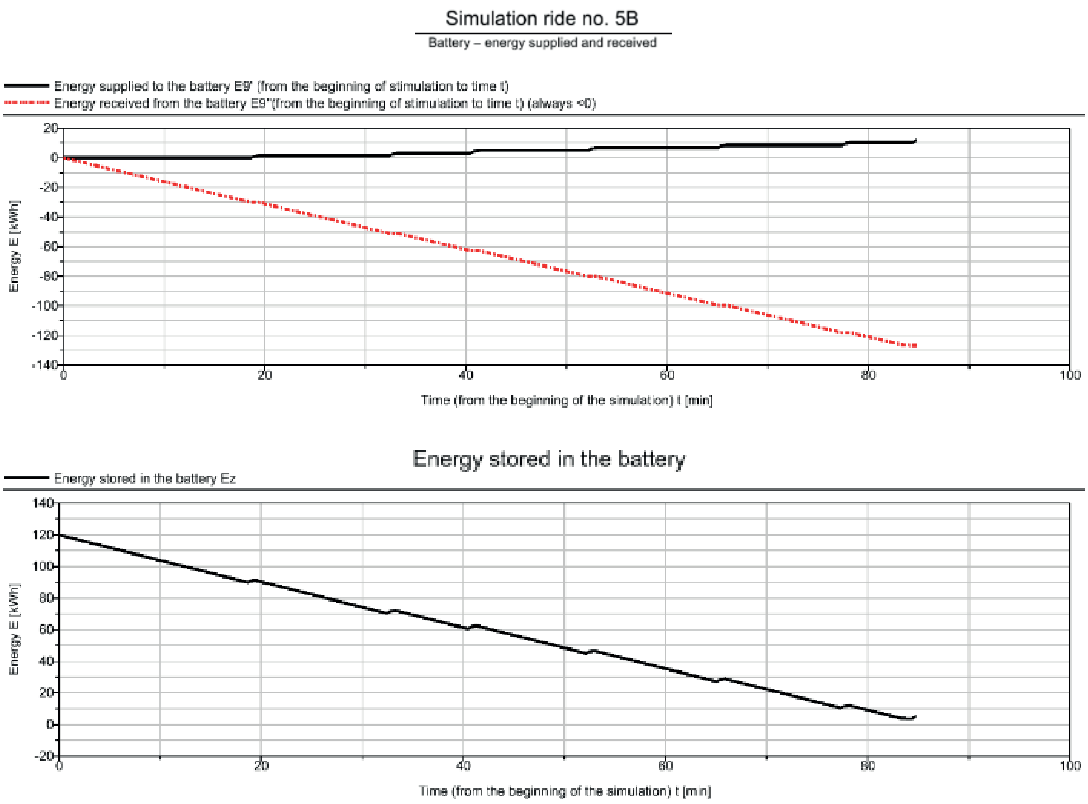

Fig. 11. Energy flow in the battery storage in relation to ride 5B

generated 141.36 kWh of energy. As can be seen, the energy balance of the vehicle on the route was negative. In order to cover the route under analysis, the vehicle had to have a sufficient energy reserve in the battery at the beginning of the ride. The courses (of energy flow) for ride 5B are presented in Figures 10 and 11.

Rides 1A–2B were balanced in terms of energy. In relation to these rides, the size of the energy storage did not have to be excessively large. The critical ride was ride 5B of the WM-15A vehicle, i.e. the run with three wagons with a total trailer weight of 120,000 kg. Because of the high energy consumption when the vehicle was pulling a 120 t train, the recommended energy storage capacity should amount to approximately 130 kW. Such a solution would enable the WM-15A vehicle (loaded 35,000 kg) with a trailer weight of 120,000 kg to cover a distance of approximately 65 km on a typical lowland route.

Figure 12 presents (among other things) the power drawn, or supplied to battery P8 during ride 3A. During the ride, in its initial phase, the hydrogen fuel cell did not work. It was switched on after approximately 23 minutes. The maximum charging power of the battery amounted to approximately 270 kW (negative values on curve P8). The power included the energy from the electrodynamic braking of the vehicle and that generated by the working (also during braking) hydrogen fuel cell. In relation to the theoretical rides, the vehicle own power was assumed at 25 kW. The power was constantly drawn from the main circuit, including electrodynamic braking, simultaneously reducing the power flowing into the battery. In the unfavourable case of electrodynamic braking with working fuel cells and own needs amounting to 0 kW, the battery charging power should be increased by 25 kW – to a value of approximately 295 kW. The ultimate recommended battery charging power should be then about 300 kW.

During ride 3A, the hydrogen cell did not work in the initial phase. The entire vehicle was then powered by the battery pack. The maximum power drawn from the batteries (in accordance with the ride) amounted to 220 kW. Characteristic power peaks at the beginning of the start-up resulted from the lower efficiency of traction motors at low travel speeds, generating an increased demand for electrical power, in relation to a constant mechanical power of the motors of 150 kW.

The recommended value of the battery discharge power should amount to 220 kW.

4. Conclusions

The performance of calculations and simulations of theoretical rides in relation to various operating conditions of the auxiliary rail vehicle enabled the confirmation of the theoretically assumed basic parameters of the hydrogen power supply system. The list of specified parameters is presented in Table 5.

The capacity of the battery energy storage unit was determined for a specific route, therefore it should be treated as the minimum value satisfying specific conditions.

The value of the vehicle own receivers was intentionally overestimated in the simulation in order to take into account the operation of the thermal conditioning system of the battery energy storage (heating and cooling of the fuel cells) as well as the need to start the fuel cell using the energy stored in the battery energy storage.

Table 5. Parameters determined of the hydrogen power supply system

Parameter	Value
Electric traction motor power	150 kW
Power of hydrogen fuel cells	100 kW
Battery energy storage capacity	130 kWh
Maximum charging power of the battery energy storage	300 kW
Maximum discharge power of the battery energy storage	220 kW

Because of the specific operation of working trains (having low priority and, as a result, being usually stopped to let passenger and freight trains pass), the theoretical rides involved a stop at each station. The increased time of stops of such a train and the related consumption of energy for train own needs are very easy to calculate.

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