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Hydrogen fuel cell power supply for hybrid electric multiple unit train

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Abstract: In European countries, electrified routes amount for 40% to 65% of the total railway networks length. Some of those routes are only partially electrified, and construction of a catenary network might not be viable on all routes. Consequently, operators run diesel trains under catenary or require both an electric and diesel vehicle, increasing costs of operation. Dual-mode vehicles exist, but they are mostly equipped with diesel generators, adding to the pollution and resulting in reduced movement dynamics. In this article, the authors present a hydrogen-hybrid electric multiple unit (HEMU), as an environmentally friendly vehicle for partially electrified railway lines. Insight into technologies utilized by both hybrid and hydrogen rail vehicles based on the literature review allowed for the formulation of requirements for such a vehicle. Furthermore, an approach to a modelling hybrid vehicle is described, including an energy management algorithm. A series of simulations were conducted, showing an operation of an HEMU on a partially electrified suburban/regional route. The presented simulation results show potential for the future introduction of hydrogen hybrid electric multiple units as a viable solution for partially electrified local and regional routes.

Key words: battery pack, energy storage, fuel cell, hybrid vehicle, rail transportation

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1. Introduction

Currently, many European railway routes are still non-electrified. Moreover, many train services operate on routes that are partially electrified [1]. Because of this, diesel-powered vehicles are extensively used, often under catenary. However, their operation has a negative impact on the local natural environment as a result of the toxic exhaust emissions. In addition, especially in touristic and recreational areas, passenger diesel multiple units (DMUs) are burdensome due to noise generated by diesel engines and their ventilation systems, especially when starting from a standstill on lines with a large number of stops. With a conservative approach, the only alternative to internal combustion vehicles is the costly electrification of the line and the equally costly subsequent maintenance. This is considered an economically viable approach for routes with large numbers of transported passengers and cargo [2, 3]. There are also bi-traction vehicles, where electric traction drive can be powered by the diesel generator outside of electrified sections, but such a solution often results in reduced performance, while the exhaust and noise pollution problems persist. Increased mass is a concern too, especially on local lines that are not prepared for increased axle loads. Therefore, introduction of electric vehicles equipped with onboard energy storage might be beneficial, and in some cases – cheaper than operating diesel trains or electrification, especially considering forecasted future hydrogen price decrease [4].

Because electric multiple units (EMUs) are already widely used for suburban and regional railway services, research into equipping such vehicles with onboard energy storage allowing for operation on non-electrified routes was the logical outcome. In Japan, vehicles equipped with electrochemical battery storage were developed based on a diesel railcar chassis intended for a local passenger line. The train began its operation in 2014 on a 31 km route, 20 km of which is non-electrified [5]. Since then, vehicles with battery storage were introduced into service in Japan, and Austria, with vehicles for operators in Germany being currently delivered. Those independently powered electric multiple units (IPEMUs) are able to run with velocity up to 140 km/h, with a range of about 80 km relying on batteries. Vehicles equipped with battery storage to run on non-electrified route fragments are widely used in urban transit, like trams or trolleybuses [6].

The latest advancement in hybrid rail vehicle technology is the implementation of hydrogen fuel cells. Because of the high specific energy of hydrogen, it is possible to extend the range of such vehicles beyond what is achievable with batteries alone. There are, however, two major limitations to the fuel cells: maximum output power and unfeasibility of transient state operation [7, 8]. Currently, fuel cell modules are available with a nominal power of up to 200 kW, and a further increase in power can be achieved by installing multiple such modules. The requirement of steady-state operation of fuel cells is typically satisfied by equipping the vehicle with another energy storage. Thus, fuel cells are designed for the average power required by the train, while the additional storage covers the peak power requirement or absorbs energy from regenerative braking [9, 10]. Because of this, the storage can have a capacity smaller than those in pure battery vehicles. Consequently, such vehicles can be equipped with batteries better suited to frequent charge-discharge cycles, despite their lower specific energy. Therefore, lithium-titanate-oxide (LTO) batteries or supercapacitors are used [11, 12]. Control strategies seeking methods of fuel cell control without significant negative impact on their lifespan are under consideration as well, as this could improve the efficiency of hydrogen use [13].

Most of the vehicles mentioned above are entirely reliant on their onboard energy storage. While this approach allows the vehicle to operate completely independently of the catenary, it is not applicable when the vehicle has already been installed [14, 15]. A vehicle able to operate and recharge its batteries under catenary would have a longer range and consume less hydrogen, lowering operation cost. The potential of such a solution was recognized, as multiple manufacturers began the development of hydrogen hybrid electric multiple units (HEMUs). In the United Kingdom, research focusing on hybrid railway vehicles for local and regional routes is motivated by environmental considerations, especially seeking ways to replace diesel vehicles [15]. In Spain, a prototype HEMU vehicle based on existing regional EMUs has already been built and is undergoing testing within the FCH2RAIL program. Document [16] shows that the introduction of this vehicle on any of the partially electrified routes in Spain, Portugal or Germany is feasible, while the considerations related to the analysis were described in a paper published by the same authors [17]. A similar vehicle was developed by Alstom, who already has experience in the production of hydrogen-battery multiple units, Coradia iLint. A new HEMU, based on a Coradia Polyvalent family is expected to enter regular service in France and Italy in 2025. In Japan, a similar vehicle is under development [18], however it differs in performance in relation to its European counterparts, as it is designed for local commuter services. It is worth noting that the design of those vehicles was aided by computer simulations in order to ensure satisfactory performance on prospective routes.

The contributions of this work include design assumptions and the presentation of a hydrogen HEMU vehicle run under challenging operating conditions, including steep gradients and a very low route electrification rate. For this analysis, a model of a hybrid vehicle powered by the catenary, battery and fuel cells was developed. The model is characterized by robustness and high computation performance. An approach to control strategy for the fuel cells was presented as well, proposing a solution for controlling fuel cell output power without negatively impacting their lifespan.

2. Inside the HEMU vehicle

A hydrogen hybrid electric multiple unit is powered by energy from three sources: overhead catenary, battery pack inside the vehicle and the fuel cells. It should be noted that there is a difference in voltage levels between the catenary and batteries and fuel cells. If the vehicle is expected to operate in e.g. a 3 kV DC supply system, catenary voltage needs to be lowered to a level compatible with the other onboard equipment. This can be achieved by use of a DC/DC input converter. Moreover, battery pack and fuel cell modules are also equipped with additional DC/DC converters to control the energy flow within the vehicle (Fig. 1).

When a catenary is available, an HEMU operates as normal EMU drawing power from the overhead contact line using a pantograph. This mode of operation allows for in-motion charging of the battery pack, thus eliminating the need for a costly stationary charger. However, charging power adds to the power required by the vehicle for its operation, so the input converter should either be designed to accommodate increased load or battery charging power would need to be limited. In this mode of operation, fuel cells are switched off.

While running on non-electrified routes, the vehicle is powered primarily by the batteries, in contrast to the approach where the fuel cells are the main power supply with the battery covering only peak power and regenerative braking, as presented in [19]. Because the battery pack is

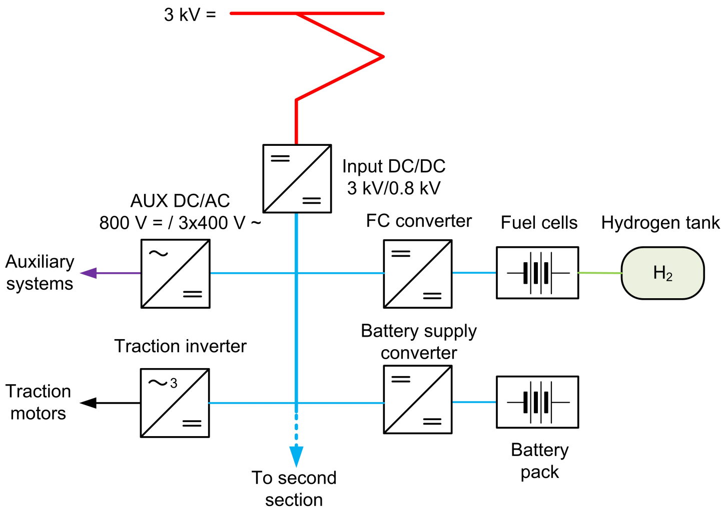

Fig. 1. Powertrain layout of the HEMU vehicle (for single section)

able to provide full traction power, the vehicle can operate as a BEMU in case of running out of hydrogen or fuel cells failure, thus improving its reliability. Moreover, operation outside of electrified fragments of the route does not need to translate into lowered movement dynamics, as the vehicle is planned to be equipped with lithium-titanate-oxide (LTO) batteries, which allow high charge and discharge currents [11]. Fuel cells are used to provide additional power while driving and recharging the battery otherwise. Because it is important to ensure the steady-state operation of fuel cells, including the elimination of frequent activation and deactivation, an adequate control algorithm should be implemented. A possible approach is based on activation thresholds (Fig. 2) When the state of charge (SOC) of the battery falls below the specified level T1_act, fuel cells are activated with lowered power P_T1. Such a solution allows for lowering hydrogen consumption and prevents frequent activation/deactivation of fuel cells. When the SOC of the battery pack

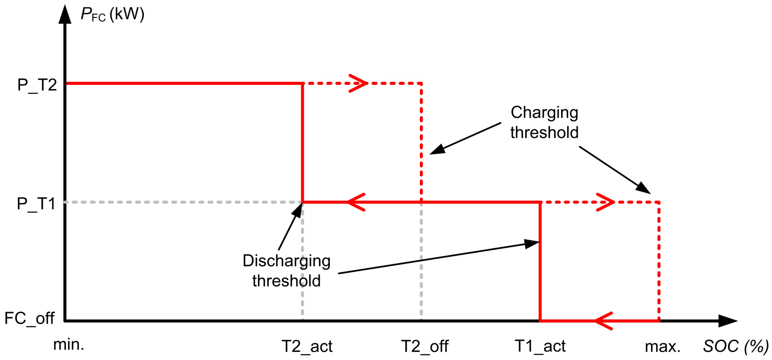

Fig. 2. Implementation of activation thresholds of the fuel cells

falls below the second threshold (T2_act), fuel cells output is increased to P_T2, equal to the nominal power of the fuel cells. Power output can be lowered when battery SOC increases above the T2_off threshold (or switched off when the battery is recharged up to set maximal value). Those charging thresholds are specified as higher than discharging to avoid frequent fuel cell output power changes, improving their reliability.

Such design allows for the reduction of hydrogen consumption, as the efficiency of the FCs operating under full power is sub-optimal. While the vehicle is able to utilize regenerative braking, recuperation back into the battery is possible only, when its state of charge is below the specified level (in this case 90%). Otherwise, the vehicle will try to regenerate energy into a catenary (if available) or dissipate it into the resistor. Electrodynamic brake is complemented by pneumatic friction brakes, used to provide additional braking force when stopping or at high speeds when electrodynamic brake alone would not be able to decelerate the vehicle with the desired rate.

3. Basis for the simulation analysis

For the sake of this analysis, run of a single 55WE-class hybrid electric multiple unit (HEMU) was assumed. The two-section vehicle is designed to be able to operate under a 3 kV DC overhead catenary, as well as using batteries and fuel cells on non-electrified lines. The vehicle is expected to be able to operate on non-electrified routes without the loss of performance, as the onboard energy storage is designed to be able to provide full traction power at all times. The prototype is currently under development, with the beginning of regular operation planned for 2027. The parameters of the vehicle used in this analysis are shown in Table 1.

Table 1. Basic parameters of the 55WE-class HEMU assumed for the analysis

Parameter	Value	Unit	Comments
Axle layout	Bo’2’ + 2’Bo’	–	
Nominal power	1000	kW	4 motors@250 kW
Axle load	18	kN	Full load/per axle
Top speed	160	km/h	
Acceleration	0.8	m/s^2	
Passenger places	140/280	–	Seated/full capacity
Fuel cells output power	400	kW	2 modules@200 kW
Usable battery capacity	270	kWh	LTO battery pack
Hydrogen capacity	150	kg	
Designed range	600	km	

Hybrid vehicles are expected to be introduced as a replacement for diesel trains. Therefore, they should be able to run on the same routes without additional technical stops or prolonged station dwelling time for battery recharge, offering the same or better level of versatility. Consequently, preliminary analyses conducted for scaling of the drivetrain elements and energy storage capacity should be carried out assuming the most challenging operating conditions. In this paper, authors assumed a 117 km long route with a very low electrification ratio of 16%. This route is located in northern Poland, connecting the Tricity agglomeration (including the international airport) with Hel and seaside resorts. Because the route crosses the nature reserve and runs along the seashore, electrification might be unfeasible, and currently used diesel trains are contributing to the noise and exhaust pollution. The most challenging part of this route is 36 km long non-electrified mountainous section, located between stations Gdańsk Wrzeszcz, Gdańsk Osowa and Gdynia Główna (4.18 km to 40.2 km). The elevation profile along with electrification availability and station location on the route is shown in Fig. 3.

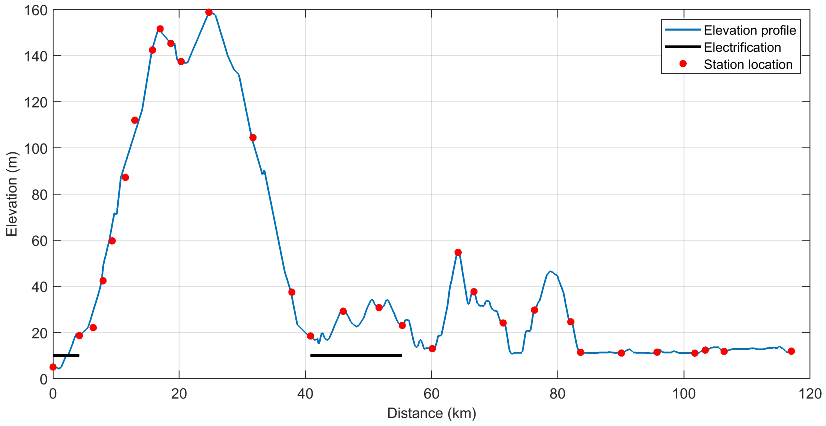

Fig. 3. Route electrification, elevation profile and stations location

The current timetable is formulated for DMUs and requires the vehicle to complete a one-way trip in time no longer than 2 h 15 min. The shortest terminal dwelling time is 1 h 30 min. The highest velocity reaches up to 120 km/h under catenary and 100 km/h on a non-electrified section. However, those times can increase, as beginning from 55.4 km the line is single-track, which may require prolonged stops for passing trains traveling in another direction.

4. Simulation of the HEMU operation

Therefore, the authors developed a model of the vehicle using MATLAB/Simulink programming environment. The model can be divided into two parts:

- Traction system that calculates vehicle movement dynamics, which serve as a basis for computation of required electrical power,
- Energy system, which purpose is energy management using available sources: overhead contact line, traction battery and fuel cells; implemented control algorithm takes into account charging of the traction battery.

The traction system simplifies the vehicle, with the assumption that all parameters are lumped into a single point. Therefore, an equation of motion based on Newtonian mechanics can be applied (1):

$$k \cdot m \cdot \ddot{x} = \gamma(x,t) \cdot F_t - (a\dot{x}^2 + b\dot{x} + c + F_{rr}(x,A)), \tag{1}$$

where: k is the rotating mass coefficient (–), m is the vehicle mass (kg), x is the absolute vehicle location (m), γ is the movement control function used for schedule execution (–), F_t is the maximum motive force (N), a, b, c are the coefficients of the Davis equation of fundamental motion resistance (N, N/km/h, N/(km/h)^2), F_{rr} is the additional movement resistance force (N), dependent on location of the vehicle and elevation A(m).

The motive force of the vehicle is set by the control algorithm, which arguments are the time and the location of the vehicle. Typically, the vehicle is accelerated using the maximum available motive force, which can be limited by either wheel adhesion or power limitation. The maximum is determined by the motive force curve, computed on the basis of the maximum motive force, rated power of the motors and mechanical transmission efficiency. During cruising, the motive force is controlled to match the movement resistance forces value, thus achieving constant velocity. Coasting phase requires the motive force to be equal to zero, however, control algorithm will prevent exceeding the speed limit while running downhill – in such case, constant velocity will be retained using an electrodynamic brake.

Deceleration and braking are executed using the blended mode, with electrodynamic brake being assisted with electro-pneumatic friction brakes. During the deceleration phase, the motive force is controlled to satisfy a constant deceleration rate, with conformation to braking curves specified in European Railway Agency (ERA) standards and IEEE standards on train braking [20]. For this model, an equation determining required velocity in relation to vehicle location and target location was formulated (2):

$$v_{\text{set}} = \sqrt{2 \cdot d \cdot \left(x_{tgt} - x\right) + v_{\text{limit}}^2}, \tag{2}$$

where: v_{set} is the set velocity (m/s), d is the constant deceleration rate (m/s^2), x_{tgt} is the location of speed limit (m), v_{limit} is the velocity limit (target; it equals zero if braking for the station; m/s).

The last part of the traction system is used for computation of power required by the vehicle. For this task, energy dissipated by the drivetrain elements needs to be approximated. With designed range of 600 kilometers, the vehicle presented in this paper is designed to cover routes of hundreds of kilometers in length, and such a journey takes hours to complete – so implementation of detailed models of traction inverter or motors is not justified because of the difference in time step requirements. Consequently, for the purpose of robust efficiency evaluation, authors implemented efficiency maps for traction motors and inverters, computed using a dedicated traction drive model. Thus, the required power of the electric traction drive can be computed as (3) or (4), depending on the motive force value:

$$P_e = F_t \cdot v \cdot \frac{1}{\eta\left(T, \omega\right)}, \quad F_t \geq 0, \tag{3}$$

$$P_e = F_t \cdot v \cdot \eta\left(T, \omega\right), \quad F_t < 0, \tag{4}$$

where: P_e is the required electrical traction power (W), η is the traction drive efficiency (–), T is the traction motor torque (Nm), ω is the angular velocity of traction motor shaft (rad/s).

The energy subsystem contains models of energy sources used by the vehicle. Those comprise of catenary, battery pack and fuel cells. Activation of those subsystems is dependent on catenary availability and energy management algorithm. Catenary was implemented in simplified form – the constant value of voltage was assumed, as the analysis is focused on the vehicle. Such an assumption will not significantly influence final results, because the vehicle is expected to consume most of the regenerative braking energy using its battery pack. Batteries were modelled as energy storage, which can both absorb and send out energy. The maximum value of stored energy is limited by the pack parameters, while the minimal stems from the physical properties of the battery. In principle, stored energy is considered as a value, that can increase or decrease by integration of power flowing in or out the storage. This can be described as (5):

$$E_{\text{bat}} = E_0 + \int P_{cdc} \cdot e_c \cdot \mathrm{d}t, \tag{5}$$

where: E_{bat} is the energy stored in the battery (J), E_0 is the initial energy stored (J), P_{cdc} is the power of charge/discharge of the battery pack (W), e_c is the efficiency coefficient of the charge/discharge process (–).

Fuel cells were implemented similarly; however, they can only discharge accumulated energy. Stored energy is computed directly based on the mass of hydrogen inside the tank. The efficiency of energy conversion depends on the fuel cell output power and has been assumed in the form of an efficiency curve. Parameters of fuel cells were set based on data provided by the manufacturer. Losses resulting from the DC/DC converter were also considered and implemented in the model in the form of a constant efficiency factor equal to 0.95.

The key factor in ensuring hybrid vehicle operation is the energy management algorithm. Such an algorithm decides which sources will be used to provide energy to the vehicle. Because this is a preliminary study, a simplified approach was adopted. The diagram is shown in Fig. 4.

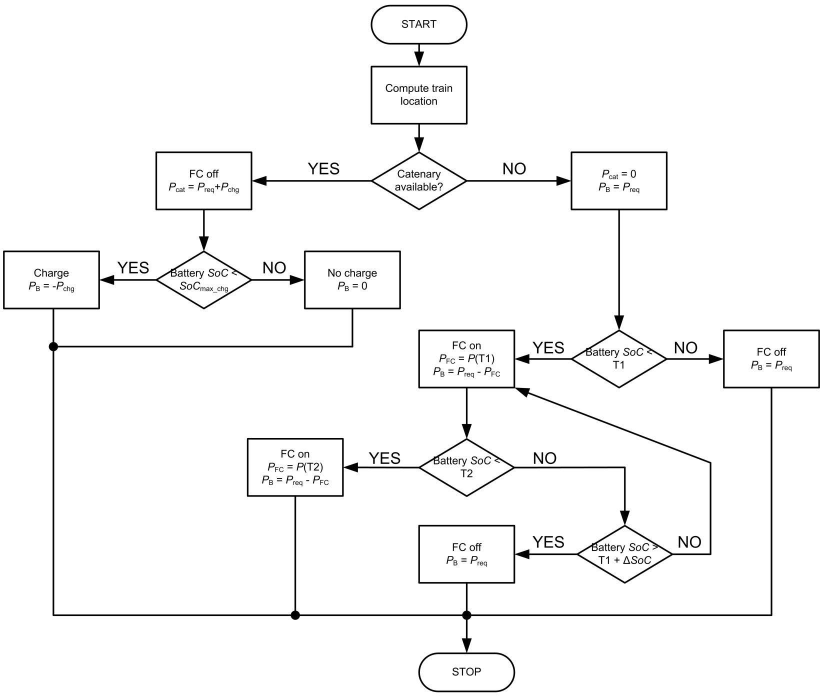

Fig. 4. Implemented energy management algorithm

In this case, thresholds of fuel cells activation were specified at 90% and 60% of usable energy stored in the battery pack and 250 kW and 400 kW of fuel cells output power for T1 and T2 respectively. Fuel cells were used only on non-electrified parts of the route. In future work, further development of energy management algorithms is planned, as the authors recognize the potential for hydrogen and energy savings shown in research papers [21–23].

Simulations were carried out assuming regenerative braking was used to recharge the battery. While operating under catenary, recuperation over maximum battery charging power is omitted, as the analysis is focused on the vehicle (influence on energy recuperation on electrified fragments that the traffic has was not considered).

5. Results analysis

The simulation was conducted assuming run in both directions, including terminal dwelling, where the battery pack is recharged using fuel cells. The run begins with a short (4.18 km) electrified section. Then, the vehicle enters a 36 km long non-electrified mountainous section, with 10 stops located on an uphill part. The speed limit was assumed at 80 km/h. The next downhill part is covered at 90 km/h, until arrival at the major station where the electrified section begins. On the electrified section, the speed limit is set at 120 km/h. The rest of the route is non-electrified, with a top speed of 100 km/h (with the exception of one fragment containing tight curves). The velocity profile of this run is shown in Fig. 5.

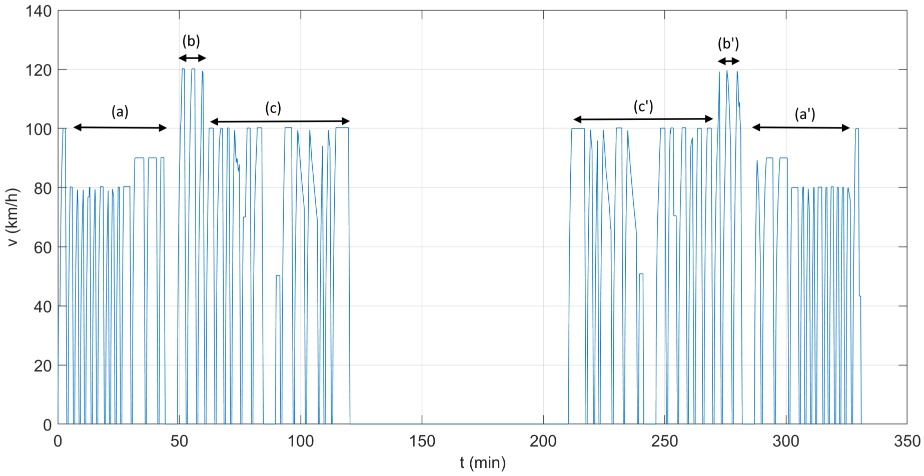

Fig. 5. Waveform of the velocity of the analysed run: (a) mountainous, non-electrified section; (b) electrified section; (c) seaside non-electrified section; sections covered during the return run were marked with apostrophe

The driving strategy was assumed to utilize the cruising phase on steeper slopes and the coasting phase otherwise. This results in slight energy regeneration while the vehicle is running downhill. The train completes its one-way run in exactly 2 hours, which is 15 minutes faster than the current timetable requirement. Waveforms of power flow are shown in Fig. 6 and energy figures are shown in Fig. 7.

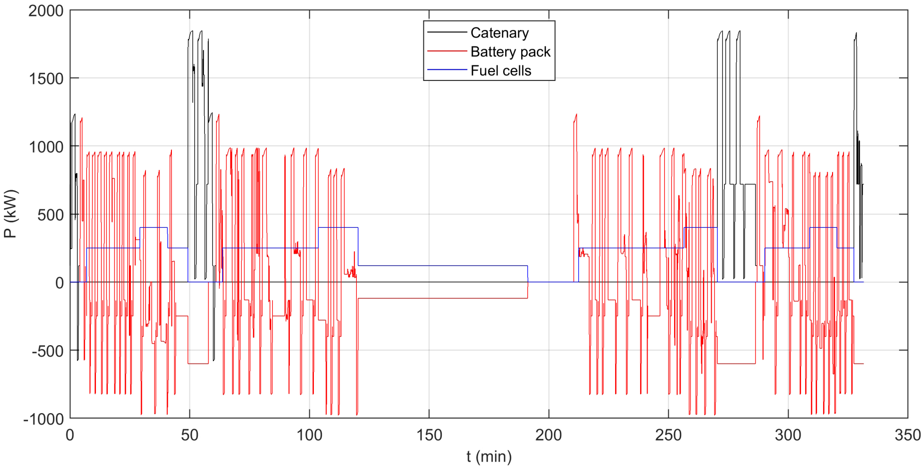

Fig. 6. Power flow between energy sources (positive value – discharge, negative – charge)

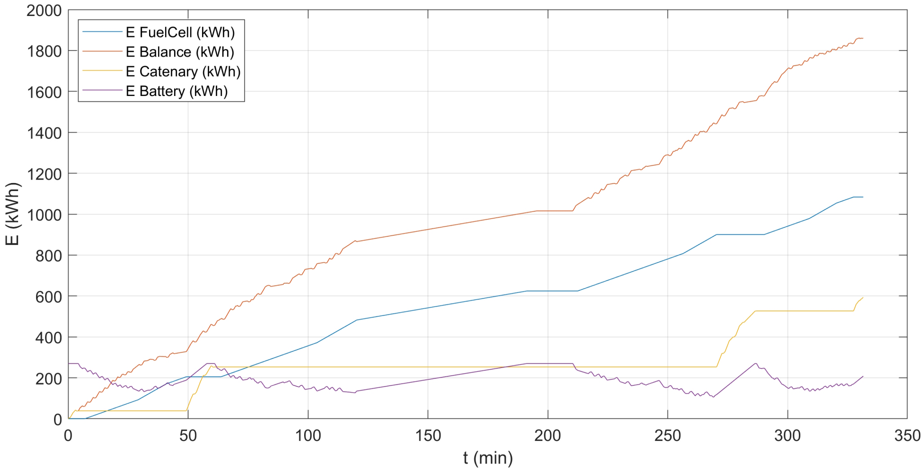

Fig. 7. Energy balance: total energy required and energy provided by fuel cells, catenary and stored in battery pack

The vehicle consumed a total of 1860.02 kWh, 632 kWh of which were used to power auxiliary equipment, including air conditioning (full power of auxiliaries was assumed). From the catenary, the vehicle used 593.76 kWh and fuel cells provided 1083.68 kWh. Energy initially stored in the battery does not decrease the final balance value – consumed energy increases the figure regardless of its source (recharging the battery using fuel cells also adds to the final energy consumption).

The primary energy source of the vehicle is the battery pack. Equipped batteries are designed to be discharged or charged with power up to 1200 kW, being able to provide full traction power for the vehicle. Fuel cells provide additional power to the vehicle and recharge the battery when the train decelerates or stops. During the terminal stop, heating, ventilation and air conditioning (HVAC) systems are switched off (the vehicle is not accessible for the passengers at this time), and the battery pack is recharged using fuel cells working at lowered (optimal) output power. During catenary operation, batteries are recharged at a constant power of 600 kW because of pantograph limitation (2000 kW while running, 600 kW while stopped). Maximum battery discharge power does not exceed 1200 kW, confirming the design assumptions. When the fuel cells are activated, discharge power decreases, as they feed additional power into the system. At the same time, during regenerative braking battery is recharged with a maximum power of around 1000 kW. Under the catenary, the maximum power drawn by the vehicle reaches 1800 kW, for both traction and battery charging.

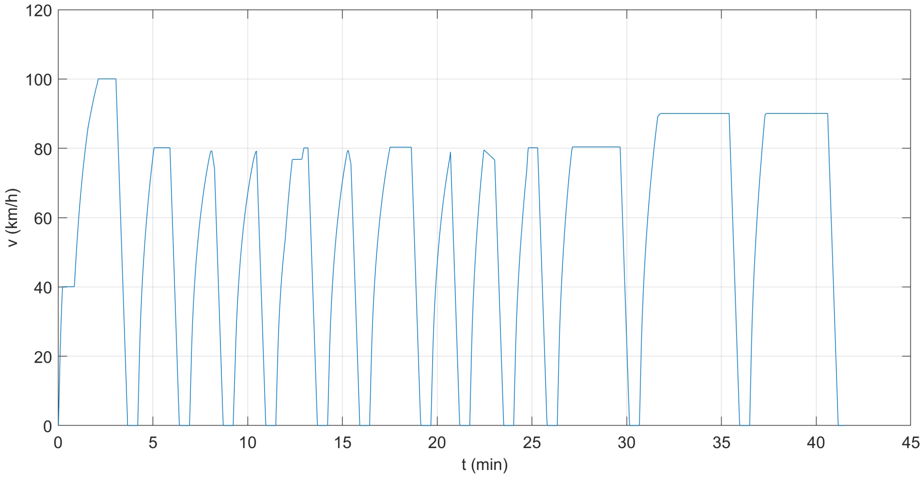

Fig. 8. Velocity on the mountainous section, marked as (a): at around 12 min, vehicle is unable to reach set velocity of 80 km/h despite operating at full power

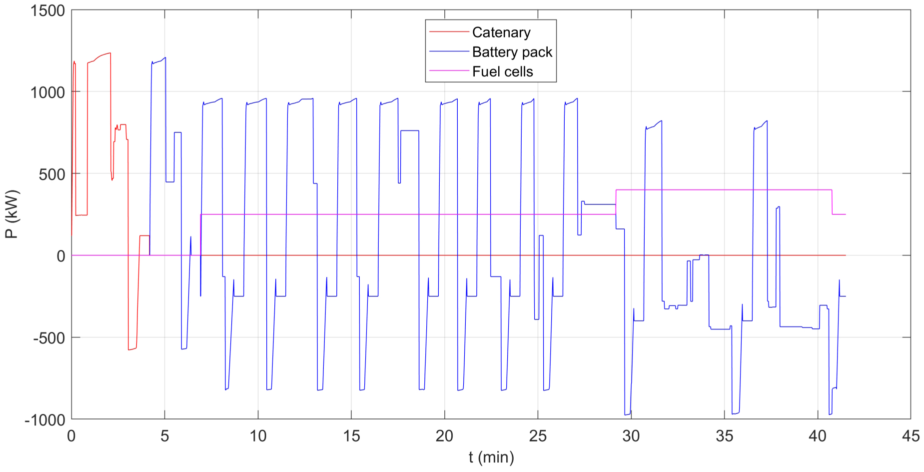

Fig. 9. Power on the mountainous section (uphill starts at 4 min, downhill from 30 min) – less power is drawn from the battery when fuel cells operate at a higher threshold. However, power of regenerative braking is visibly higher

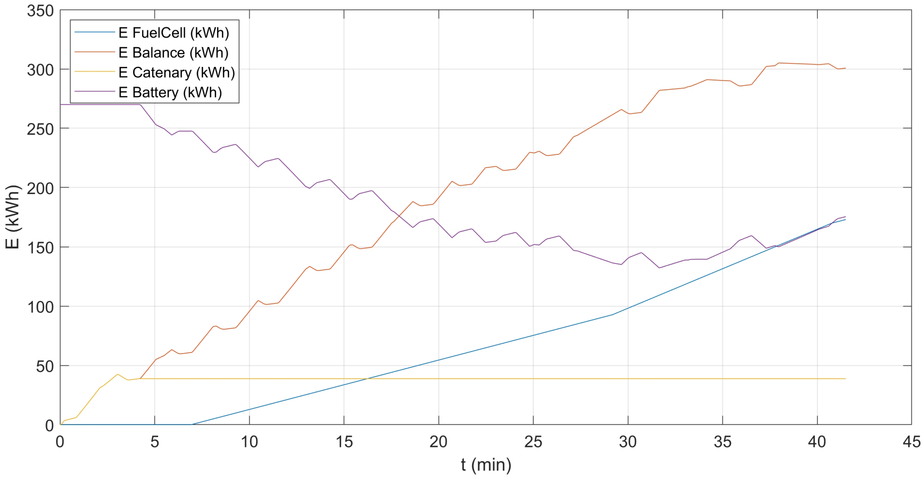

Fig. 10. Energy on the mountainous section – total energy required and energy provided by the catenary, fuel cells and energy stored in battery pack. Regenerative braking at the downhill section allows for recharge of the battery (from 30 min)

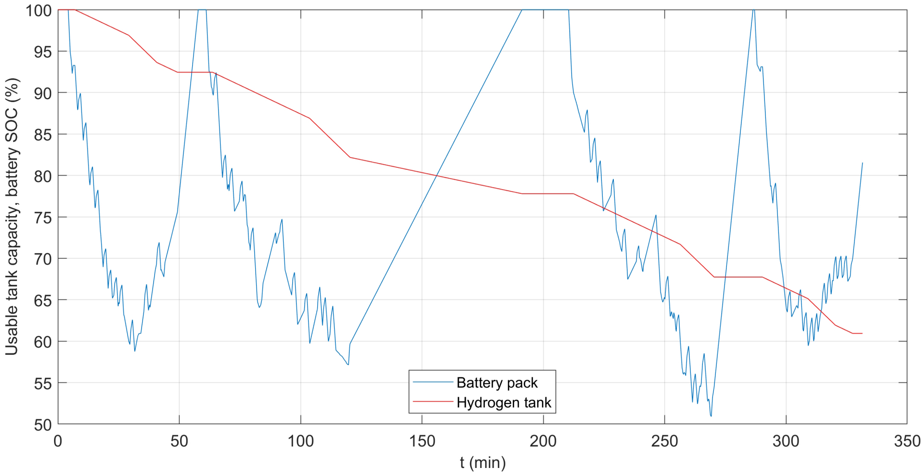

Fig. 11. Percentage of energy stored in battery pack (analogous to SOC) and hydrogen tank

It is worth noting, that this implementation of in-motion charging allows for consuming all the regenerative braking energy. Therefore, it might be beneficial not to recharge the battery up to 100% state of charge, as this is the only situation when the vehicle recuperates energy back to catenary.

Assuming a fully charged battery and full hydrogen tank, the vehicle begins its run on an electrified fragment. After entering the non-electrified mountainous section, the battery is assisted by the fuel cells which activate the second threshold (400 kW). However, at the downhill section output power of the fuel cells is reduced, as the battery recharges rapidly. A detailed view of this operation is shown in Fig. 8 (velocity), Fig. 9 (power) and Fig. 10 (energy).

In the electrified section, fuel cells are switched off; the operation of switching between catenary and storage operation is done only when the vehicle is stopped. While the vehicle is running on flat terrain, a battery supported with fuel cells operating at the first power threshold is sufficient for powering the vehicle. Percentage of stored usable energy is shown in Fig. 11.

It is worth noting that the vehicle used around 40% of stored hydrogen, which would allow it to complete two round trips on a single refill. This translates to a range of 585 km, only slightly less than the designed range of 600 km, which is expected because of the challenging route parameters. However, there is a possibility for a further decrease in hydrogen consumption through energy management, as the battery was never discharged below 50% of its usable capacity, and full power of HVAC systems was assumed.

6. Conclusions

Analysis carried out shows that an HEMU can be a viable solution for partially electrified suburban and regional railway routes. The possibility of recharging the battery under the catenary allows for the extension of the vehicle range. In relation to diesel-powered vehicles, hybrid electric vehicles have the advantage of being able to regenerate braking energy back to the battery, enabling recharge without using other energy sources. Moreover, use of the electrodynamic brakes allows for reduction of the friction brakes wear. The considered vehicle is capable of running through non-electrified routes with a mountainous profile, proving its versatility. It can also be introduced into service on the analysed route easily, as it does not require additional infrastructure. The analysis showed that the use of HEMUs is technically viable on partially electrified routes, where there is an alternation between electrified and non-electrified sections. A 3 kV DC power supply system allows not only for running the vehicle but also for battery recharging – also during station and terminal dwelling. This mitigates the need for expensive stationary vehicle chargers.

It can be concluded that despite the challenging operation regime on the presented route, the vehicle managed to retain its designed range of 600 km. It should be noted that a higher electrification percentage of the route would result in a longer range of the vehicle in non-electrified sections. Furthermore, there is room for potential further improvement, as the HEMU can complete the route up to 10 minutes faster than the scheduled time, so it is possible to reduce energy consumption through velocity reduction or velocity profile optimization.

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