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Evaluation of the CO_2 Emissions and Energy Efficiency of the Train Intercidades Campinas-São Paulo with Fuel Cells and Batteries

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Abstract: This work presents a case study of the Train Intercidades project between Campinas and São Paulo, comparing, in the sense of increasing efficiency and reducing CO_2 emissions, the supply of diesel generators, batteries and fuel cells. For this, a model of the track and the train to be analyzed was developed using HOMER Pro software, and energy simulations were carried out considering the combinations of energy sources mentioned above. It was verified that the use of batteries as an auxiliary source of energy made it possible to decrease the installed power and increase the overall efficiency in simulations with diesel generators. In relation to the replacement of diesel generators by fuel cells in different scenarios, an increase in global efficiency of about 10%, the complete elimination of carbon dioxide emissions at the point of use, and an increase in operating costs of more than 300% due to the consumption of hydrogen gas were achieved. However, this financial gap is expected to narrow with the development of fuel cell technology in the coming years, making this option more economically viable in the future.

Keywords: Urban Transport; Urban Trains; Energy Efficiency; Batteries; Fuel cells.

1. INTRODUCTION

With the technological advancement, one more option is presented to compose the range of rail transportation: trains powered by fuel cells, which promise to run with renewable and clean energy, in situations in which hydrogen energy comes from renewable sources. This innovation had its first commercial implementation for passengers in 2018, in Germany, through the company Alstom Transport (Alstom. 2018).

The rising concerns about the emission of polluting gases have changed the railway market in recent years. With the desire to reduce the operating cost for this means of transport to remain competitive, diesel fuel has been put in check and the search for alternatives to replace it is growing (Hoffrichter. 2013).

With this, it is intended, through comparisons between different types of power sources for electric propulsion trains, to carry out an energy consumption assessment for a model train that can operate on the track that links the capital of São Paulo and Campinas. The technologies evaluated were: diesel-electric only, diesel-electric with batteries, fuel cells, and fuel cells with batteries. This work aims to analyze the possible solutions to reduce CO_2 emissions of trains that would operate on this line.

The altimetric profile of the track was obtained for the 102 km route, through company Alstom Transport. The simulations were carried out for the train traveling round trip, with five stops: Campinas, Jundiaí, Água Branca, Jundiaí and Campinas. The characteristics adopted for the train were: making trips of 60 to 100 minutes (round trip); 4 or 5 cars per train; seated passengers only (up to 75 per car, 300 per train); average speed of 120 km/h; maximum speed of 160 km/h; maximum acceleration of 1.12 m/s^2 and maximum braking of 1.2 m/s^2 (similar to the São Paulo Metro (Nakata *et al.* 2011)). The modeled train had its dimensions defined according to Table 1.

Table 1. Dimensions of the train model

Empty car mass (t)	44.875
Mass per passenger (t)	0.065
Full car mass (t)	49.75
Coefficient of inertia	1.075
Car length (m)	21.75
Car height (m)	3.575
Car width (m)	3.1

For this study, the fuel cell of the PEM type (Proton Exchange Membrane) was adopted, a technology with high power density and high flexibility of operation, being applied in motor vehicles and spaceships. It operates in the temperature range between 80 and 90 degrees centigrade. However, it has as disadvantages the high cost of the membrane and catalyst, and the possibility of contamination of that membrane by carbon monoxide (Gütz *et al.* 2019).

As for the battery system, its application in the railway market as a traction power source, currently, is in short stretches without electrification, or in hybrid vehicles. In these cases, the batteries act as supplementary energy sources to the main energy source, being activated occasionally to reach a certain energy demand that is above the installed power of the main medium (Hoffrichter. 2013). Therefore, batteries are used to increase the energy flexibility of the product. For the following simulations, the battery system was implemented with the objective of reducing CO_2 emissions, being used to enhance the general efficiency of the system.

The consumption curves for diesel generators and fuel cell modules used in the case study are shown in Fig. 1 and Fig. 2 respectively.

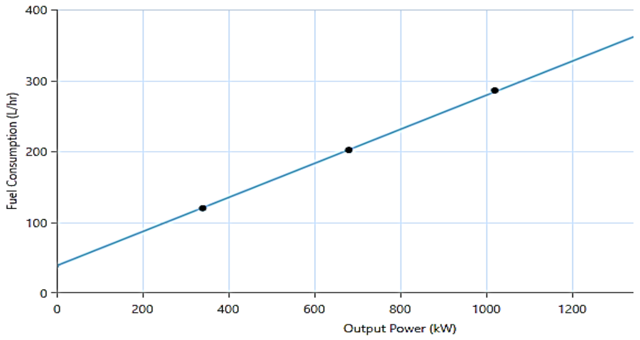

Fig. 1 Fuel consumption curve of CAT 1360 kW generator (extracted from HOMER Pro)

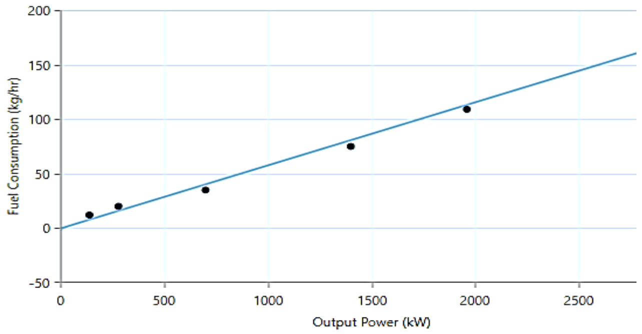

Fig. 2 Fuel consumption curve of fuel cell utilized in HOMER Pro, based on Heinzel *et al.* (2016)

Two demand curves were used, one for a train with 4 cars and the other with 5 cars. Both are following the same speed profile for the track. Fig. 3 shows these curves. They were obtained from the application of the equations presented in Pires. (2013), for modeling the movement of a train.

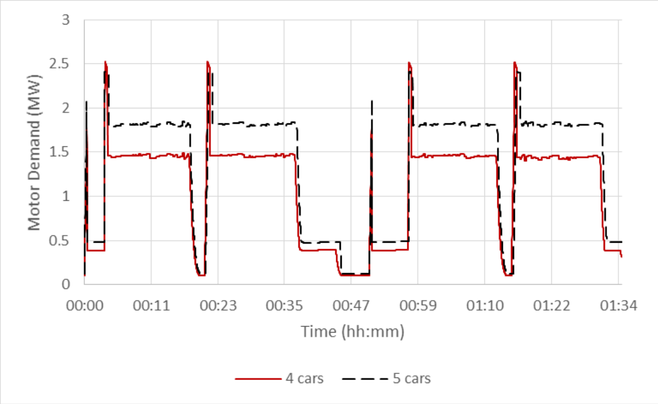

Fig. 3 Demand [MW] over time [hh:mm] for configurations of 4 and 5 cars.

2. CONSIDERATIONS

The motion simulation of the train was performed using the tools of the MS Office Excel software. To develop it, both vehicle information and track information were needed. Its purpose was to acquire the power curve required by the system over time and use it as an input for energy assessment.

A preliminary model of the train was adopted at first, which after a first round of simulations had its final shape defined in two configurations: a model with 4 cars, as foreseen in the initial specifications of the project, in which the passengers would share the space with the generators and batteries; and another model with 5 cars, one of which is exclusive for the allocation of generators and batteries, so as not to reduce the space for passengers.

It was also considered a percentage of 10% of the average power of the system for the supply of auxiliary systems (air conditioning, control and information systems, etc.) that do not depend on the speed of the train.

To control the acceleration peaks, an acceleration limiter was adopted to the train, defining the maximum limit of 2.3MW of maximum power for traction, which, added to the constant demand of auxiliary systems, does not exceed the value of 2.5MW of demand global.

As for the masses of generators and batteries, product values (Toromont CAT Power Systems. n.d; NEC. n.d) were used, which were references for all simulations performed. The masses of the analyzed models were adapted to consider that there will be a battery bank installation in the supply system and that only a diesel generator will be responsible for the generation of energy. For the battery, the product DSS NEC 510 kWh was used as the base. Therefore, the corrected mass of the two configurations is shown in Table 2. It was considered the maximum limit of 50% of discharge depth of the batteries, necessary to ensure the maintenance of its useful life (Hoffrichter. 2013).

Table 2. Mass of models used for Motion Simulation

Configuration	4 cars	5 cars
Mass of empty cars (t)	134	167.5
Mass of cars with passengers(t)	199	232.5
Mass of batteries (t)	7.88 (DSS NEC 510 kWh)	7.88 (DSS NEC 510 kWh)
Mass of generator (t)	15.14 (Cat® 3516B)	18.27 (Cat® 3516C)
Total mass (t)	222.02	258.65

The equation of the dynamic resistances of the train followed Davis' formulas, the predominant method in the application of railway models, as seen in Pires. (2013) and Hoffrichter. (2013). For the two models generated, Table 3 shows the updated Davis Equations.

Table 3. Davis Equations of models used for Motion Simulation

Configuration	Davis Equation
Distributed generators (4 cars)	$R=1.59+0.014v+0.0009v^2$
Concentrated generators (5 cars)	$R=1.61+0.013v+0.0009v^2$

The efficiency curves for diesel generators and fuel cell modules used in the case study are shown in figures Fig. 4 and Fig. 5 respectively.

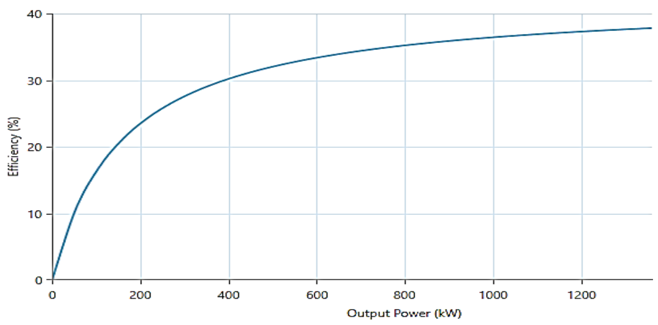

Fig. 4 Energy efficiency curve of CAT 1360 kW generator (extracted from HOMER Pro)

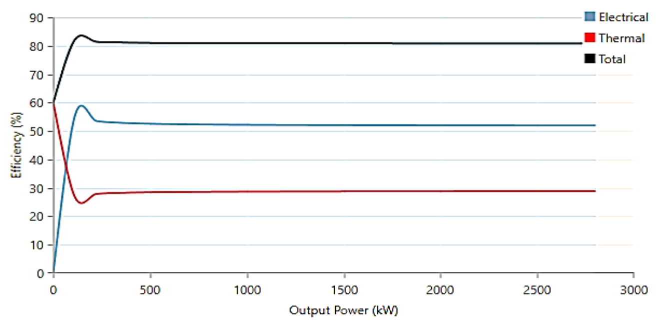

Fig. 5 Energy efficiency curve of fuel cell, based on Heinzel *et al.* (2016).

The energy simulations were carried out using the HOMER Pro software, which imported the demand curves acquired previously from the MS Excel software. Such software is generally used to meet the needs of simulations with static loads, as is the case of the study by Mansilha *et al.* (2015), making it possible to carry out energy simulations with different energy sources, including photovoltaic and wind power, for homes, buildings and other types of static loads.

Due to the data discretization limit, of a minimum of one minute in HOMER Pro (while the motion simulations show discretization of one second), it was necessary to analyze the results again after the energy simulations were performed. The acquired indicators were imported back to MS Excel, so that they are consistent with the time scale adopted outside of HOMER Pro.

Several types of results were obtained, such as fuel consumption, the amount of gas emission, the energy efficiency of the train over time, the intervals at which the generators operated with low efficiency, the identification of which generators operated, accelerations, among others.

3. SYSTEMS ANALYSIS

In all 22 simulations, the number of passengers, the travel time and the maximum speed of the train were maintained. For this reason, different solutions were used, such as adding another car, even if it is more financially expensive, in order not to change these parameters. The result of each case is treated below to verify the performance of the power system.

3.1 Diesel Only Simulations

All diesel generator models used are from the company Caterpillar (CAT) (Toromont CAT Power Systems, n.d). As there are only diesel generators and in points of low demand these would act with low efficiency, compromising their lifespan, in all simulations a smaller capacity generator was adopted, called “sacrifice generator”, to operate with a minimum load rate of 0% in moments that the others would be inoperative. This allowed to reduce energy waste and avoid high costs in the event of a need for replacement. Ten (10) different simulations were carried out regarding the type of train and the combination of generators.

Fig. 6 shows an example of the operation of the system in this case, where the 1825 kW generator is the main source of power through the simulation, while the secondary generator of 680 kW is activated only when it’s necessary to achieve the maximum speed, or during low speed phases.

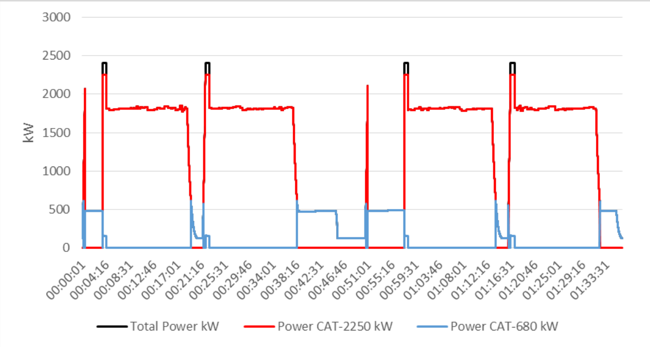

Fig. 6 Energy simulation for a 5-car train powered by a Cat® 3516B diesel generator (1825 kW) and two Cat® C18 diesel generators (500 kW).

3.2 Diesel and Battery Simulations

The sets of batteries aim to reduce the energy capacity installed in the system, making it possible to use generators optimized for the most frequent demands observed along the track, while peak demands will be achieved simultaneously by the energy dispatched by the generator and the batteries. With this, the performance of the energy simulations with different configurations of batteries and cars was analyzed.

Fig. 7 shows an example of the operation of the system in this case in which it can be seen that the batteries are used exclusively as the traction power source on low speed, where the diesel generation efficiency is lower (as shown in Fig. 4), and simultaneously with the diesel generator during acceleration phases. On the other hand, when the speed is maintained constant, the diesel generator operates at the same time to traction the train and to recharge the battery bank.

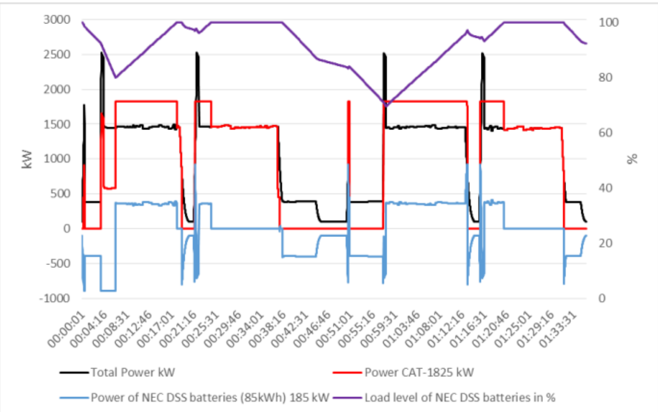

Fig. 7 Energy simulation for a 4-car train powered by a Cat® 3516B (1825 kW) diesel generator and 4 NEC DSS 85 kWh (185 kW) batteries.

The generations systems used in the study were selected aiming for capacities, from the generator and the battery system, which guarantee, with certain tolerance, the complete power of the train throughout its journey, thus optimizing the use of the installed power.

3.3 Fuel Cell Only Simulations

The train is powered only by PEM type fuel cell modules (Gütz *et al.* 2019). That is an atypical case because in the bibliographic researches, no trains in commercial operation were found being powered only by fuel cells, but trains powered by fuel cells also having some other type of source for the purpose of optimizing the feed.

Fig. 8 shows an example of the operation of the system in this case, with the fuel cells discharging a bit more of power than needed to traction the train due to the conversion of power from direct current to alternating current.

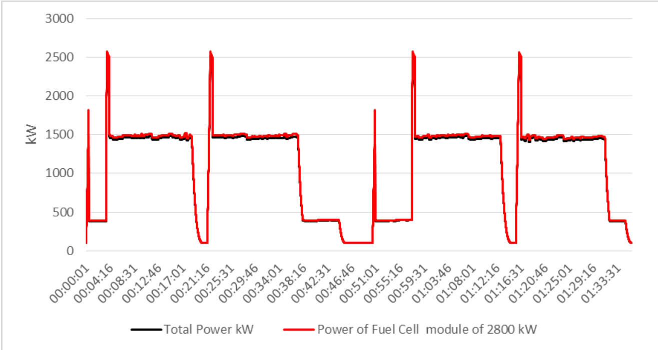

Fig. 8 Energy simulation for a 5-car train powered by a 2800 kW fuel cell bank.

3.4 Fuel cell and Battery Simulations

Altogether, 6 simulations were carried out, different in relation to the types of train configuration and according to the proportions of installed power: "Similar Capacities", "Predominance of Batteries" and "Predominance of Fuel Cells". Fig. 9 shows an example of the operation of the system in this case.

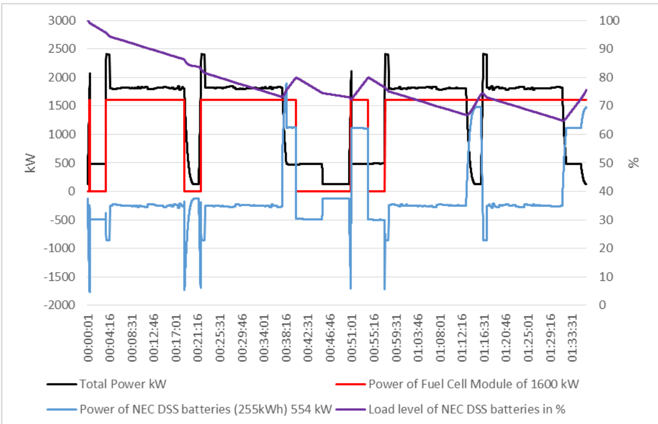

Fig. 9 Energy simulation for a 5-car train powered with a 1600 kW fuel cell bank and 3 NEC DSS 255 kWh (554 kW) batteries.

In this simulation, the fuel cells are not capable of maintaining the maximum speed by itself. Therefore, the battery bank installation needs to complement the power system throughout the simulation, being recharged only at low speeds and reaching the end of the simulation with a load level near its half.

3.5 Choice of viable operating car composition

From samples of some simulations, it was observed that the space occupied by generators and batteries, but mainly diesel generators, is not negligible in relation to the volume of the cars. Thus, it is unlikely to guarantee the disposition of the generators in the 4 passenger cars without affecting the number of passengers on the train.

However, the use of fuel cells uses less space than diesel generators. As the installed power passes from the batteries to the fuel cells, the total volume of the electricity generating system becomes less and less significant in the total volume of the car.

Therefore, the option that presents itself as the safest for a product implementation is the one that proposes a train with 5 cars in total for cases with diesel generators and a large number of batteries. For configurations that exclusively use fuel cells, or where there is a predominance of these over batteries, the option of a 4-car train becomes more guaranteed.

3.6 Performance Comparison

It was possible to organize, in Table 4, Table 5 and Table 6, the values obtained for each indicator.

Table 4 presents all simulations that were done and your respective results obtained. Meanwhile Tables 5 and 6 focus on the fuel consumption of the simulations. First for the Diesel simulations, then for the Fuel Cell simulations.

Through Table 4 it's possible to observe that the diesel simulation had a fuel cost per trip between R$857.14 and R$1470.00, considerably less than the simulations with fuel cells, that had a minimum cost of R$3839.56 per trip. The results for the Capacity Factor ranged from 0.28 to 0.56.

For diesel simulations, the use of batteries promoted a reduction in installed power and a reduction in carbon dioxide emission, consumption and fuel costs compared to simulations powered only by diesel. Considering the most viable configuration of cars, the simulation that presents the best results, with a capacity factor of 0.56 and lower fuel consumption and gas emission among trains with 5 cars, is the simulation with a Cat® diesel generator 3516B (1825 kW) and 4 NEC DSS 85 kWh (185 kW) batteries.

Table 4. Summary of the obtained indicators

Cars No.	Diesel	FC	Battery	Generator Power (Diesel or H_2) (kW)	Batteries Power (kW)	System Efficiency (%)	CO_2 Emissions (kg/trip)	Fuel Cost (R$/trip)	Capacity Factor
4	X			2725	-	28.1%	1661.87	1297.85	0.43
4	X			2250 + 680	-	36.3%	1287.52	1005.62	0.40
4	X			2250 + 500	-	36.6%	1277.37	997.67	0.42
4	X			1825x2 + 500	-	40.7%	1146.58	896.91	0.28
4	X			1825 + 500x2	-	40.8%	1144.33	895.11	0.41
5	X			2725	-	30.9%	1882.30	1470.00	0.53
5	X			2250 + 680	-	37.5%	1551.97	1212.15	0.49
5	X			2250 + 500	-	36.4%	1597.63	1247.78	0.52
5	X			1825x2 + 500	-	40.3%	1440.75	1127.12	0.35
5	X			1825 + 500x2	-	40.9%	1421.08	1111.54	0.51
4	X		X	1825	4x185	39.3%	1095.60	857.16	0.45
4	X		X	1825	3x369	37.9%	1095.58	857.14	0.40
5	X		X	1825	4x185	41.7%	1301.40	1018.17	0.56
5	X		X	1825	4x369	40.1%	1266.18	990.61	0.44
4		X		2800	-	51.1%	0.00	3934.48	0.41
5		X		2800	-	51.3%	0.00	4877.33	0.52
4		X	X	1400	2x1108	46.3%	0.00	3749.56	0.32
4		X	X	1600	3x554	49.8%	0.00	3592.05	0.36
4		X	X	1600	1x1108	50.1%	0.00	3839.56	0.43
5		X	X	2000	3x923	47.8%	0.00	4744.70	0.30
5		X	X	1600	3x554	48.0%	0.00	4774.95	0.44
5		X	X	1600	1x1108	48.9%	0.00	4829.88	0.53

The cases with fuel cells ensured the nullity carbon dioxide emission at the point of use, a very significant result, considering the emission of at least 1095.98kg of CO_2 per trip. It was also noted that the greater the installed capacity of fuel cells, the greater the global energy efficiency. It ranged from 28.1% on a diesel only simulation, to 51.3%, when powered with power cells. As for fuel consumption and costs, both are directly related to the capacity of the fuel cells, so for a reduction in these parameters, it is necessary to increase the capacity installed in batteries, which would lead to the need, in a broader analysis, to consider the lifespan of the systems and the costs of purchasing and replacing batteries, compared to the costs of purchasing and preserving fuel cells.

Table 5 indicates the positive effects of using an auxiliary generator with smaller capacity to operate during situations that would lead to low efficiency on the main generator, such as on the departure of the train. It's possible to note, for example, that the use of only one generator of high potency, as the 2725kW diesel generator, increases the overall consumption of the simulation in comparison with simulation operating with a 2250kW and a 680kW generator.

The same effect is seen on Table 6. There the difference is smaller, but the consumption of a Fuel Cell only simulation with 5 cars decreases from 126.52 l/trip to 123.86 l/trip when batteries systems are implemented.

Table 5. Diesel consumption per trip in simulations with diesel generators

Cars No.	Diesel	FC	Battery	Diesel Generator Power (kW)	Batteries Power (kW)	Diesel Consumption (l/trip)
4	X			2725	-	628.11
4	X			2250 + 680	-	486.68
4	X			2250 + 500	-	482.83
4	X			1825x2 + 500	-	434.07
4	X			1825 + 500x2	-	433.20
5	X			2725	-	711.42
5	X			2250 + 680	-	586.64
5	X			2250 + 500	-	603.88
5	X			1825x2 + 500	-	545.48
5	X			1825 + 500x2	-	537.94
4	X		X	1825	4x185	414.83
4	X		X	1825	3x369	414.82
5	X		X	1825	4x185	492.76
5	X		X	1825	4x369	479.42

Table 6. Hydrogen consumption per trip obtained from fuel cell simulations

Cars No.	Diesel	FC	Battery	Fuel Cells Power (kW)	Batteries Power (kW)	H_2 Consumption (l/trip)
4		X		2800	-	102.06
5		X		2800	-	126.52
4		X	X	1400	2x1108	97.26
4		X	X	1600	3x554	93.18
4		X	X	1600	1x1108	99.60
5		X	X	2000	3x923	123.08
5		X	X	1600	3x554	123.86
5		X	X	1600	1x1108	125.29

Therefore, by the results of the capacity factors and efficiencies, it is possible to conclude that the simulations configurations with greater capacity in fuel cells and with the batteries acting in an auxiliary way present the best indicators.

3.7 Variation of discharge depth

Battery simulations proved to be the best in terms of energy efficiency and fuel consumption. However, the use of them also implies an increase in cost due to their maintenance and limited lifespan.

The models used in the simulation are the NEC DSS (NEC. n.d), with 5000 operating life cycles. Disregarding the degradation of batteries over time, it was observed that more than 3 recharge cycles would be carried out daily, leading to battery lifespan below 5 years at the operating frequency proposed by the project.

Table 7. Battery lifespan summary with discharge depth sensitivity analysis

Discharge Depth	Diesel	FC	Battery	Generator Power (Diesel or H_2) (kW)	Batteries Power (kW)	System Efficency (%)	CO_2 Emissions (kg/trip)	Battery dispatch (kWh/trip)	Equivalent cycle per trip	Lifespan in years
100-50%	X		X	1825	4 x 185	41.7%	1301.40	217.97	0.64	3.56
		X	X	1600	3 x 554	48.0%	0.00	431.02	0.56	4.05
(50%)		X	X	1600	1 x 1108	48.9%	0.00	405.73	0.80	2.87
90-20%	X		X	1825	4 x 185	40.3%	1349.67	215.92	0.64	3.60
		X	X	1600	3 x 554	43.2%	0.00	388.43	0.51	4.50
(70%)		X	X	1600	1 x 1108	45.5%	0.00	383.82	0.75	3.03

The use of other battery models, such as LTO (Lithium Titanate Oxide) batteries that have a lifespan of more than 20000 cycles, would significantly increase the longevity of the system (Toshiba. 2019).

4. CONCLUSION

It was concluded that the use of fuel cells as a power source, with an auxiliary battery system for high demand moments, meets the project proposal, nullifying carbon dioxide emissions, but significantly increasing operating costs in relation to the diesel.

The full operational cost of using hydrogen gas as an energy source, including the train's storage and supply infrastructure, requires further analysis. Likewise, the study of other types of batteries, considering their degradation over the charge cycles, should also be done to verify the long-term viability of this solution.

These high costs, however, tend to be reduced in the coming years, with the improvement of fuel cell technologies, increased distribution of hydrogen gas, and cheaper batteries.

In parallel to fuel cells, combustion engines powered by biodiesel can also be a viable alternative in the sense of replacing diesel with a less polluting fuel. This option has been considered by the state government in the project in question (Exame. 2019), and it is something to be simulated.

The long-term financial matter of the solutions presented, the complete hydrogen gas processing cycle for use in the railway market, and the comparison of the results presented here with electrified routes are other options for continuity in future works. This work is just a starting point for the study of alternative sources of train power aimed at energy efficiency and CO_2 reduction.

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