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INTERNATIONAL CERTIFICATION IN MANAGEMENT OF RAIL AND METRO RAIL SYSTEMS

CERTIFICAÇÃO INTERNACIONAL EM GERENCIAMENTO DE SISTEMAS FERROVIÁRIOS E METROVIÁRIOS

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FUEL CELL APPLICATION ON HEAVY HAUL RAILWAYS

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RESUMO

As fontes de energia são importantes para o funcionamento da sociedade industrializada moderna. A maioria destas fontes são oriundas da queima de derivados de combustível, como petróleo, carvão e gás natural. O principal risco de manutenção da matriz existente afeta principalmente as fontes ligadas aos combustíveis fósseis e, no caso das ferrovias de transporte de cargas, os motores das locomotivas. É sabido que em vários países alternativas mais limpas e baratas já estão sendo estudadas para o transporte de cargas e passageiros. Já estão sendo lançadas medidas para reduzir a emissão de CO2 e outros poluentes, por meio da eliminação da produção de automóveis de passageiros e outros veículos rodoviários com motores de combustão interna, com países adotando datas que vão de 2025 a 2050. Uma célula de combustível é uma célula eletroquímica que converte a energia potencial de um combustível em eletricidade por meio de uma reação eletroquímica. O escopo do projeto é desenvolver e usar uma célula de combustível como fonte de energia primária para uma locomotiva de transporte de carga. A locomotiva escolhida para este desenvolvimento é a principal locomotiva atualmente utilizada por essas ferrovias, ou seja, uma AC44i. Este trabalho tem como objetivo identificar as alternativas energéticas existentes frente às fontes de energia de combustão utilizadas atualmente pelas ferrovias de Heavy Haul. Conforme mencionado, a matriz energética atual, por se basear em combustíveis fósseis não renováveis, principalmente motores a diesel, não será sustentada por muito mais tempo, sendo necessária a busca por fontes alternativas que garantam o futuro da matriz energética destas ferrovias de carga.

Palavras-chave: Ferrovia, Locomotiva, Diesel, Célula de Combustível.

ABSTRACT

Energy sources are important for the functioning of modern industrialized society. Most of these forms come from burning fuel derivatives such as oil, coal and natural gas. The main risk of maintaining the existing matrix mainly affects sources linked to fossil fuels and, in the case of the Heavy haul railways, the engines of the locomotives. It is well known that in several countries cleaner and cheaper alternatives are already being studied for the transportation of cargo and passengers. Measures to reduce the emission of CO2 and other pollutants by eliminating the production of passenger cars and other road vehicles with internal combustion engines are already being released, with countries adopting dates ranging from 2025 to 2050. A fuel cell is an electrochemical cell that converts potential energy from a fuel into electricity through an electrochemical reaction. The scope of the project is to develop and use a fuel cell as a primary energy source for a heavy haul locomotive. The locomotive chosen for this development is the main locomotive currently used by these railways, that is, an AC44i. This work aimed to identify the existing energy alternatives in view of the combustion energy sources currently used by the Heavy haul railroads. As mentioned, the current energy matrix, as it is based on non-renewable fossil fuels, mostly diesel engines, will not be sustained for much longer, being necessary the search for alternative sources that guarantee the future of the energy matrix of the Heavy haul railroads.

Keywords: Heavy Haul, Diesel, ~~Power~~ Fuel Cell.

LIST OF ABBREVIATIONS

AC	–	Alternate Current
AC44i	–	Type of locomotive used on freight railways
AFC	–	Alkaline Fuel Cell
CO2	–	Carbon Dioxide
DC	–	Direct Current
IHHA	–	International Heavy Haul Association
IRR	–	Internal Rate of Return
MCFC	–	Molten Carbonate Fuel Cell
NPV	–	Net Present Value
PAC	–	Programmable Automation Controller
PAFC	–	Phosphoric Acid Fuel Cell
PEMFC	–	Polymer Electrolyte Fuel Cell
SOFC	–	Solid Oxide Fuel Cells
WACC	–	Weighted Average Cost of Capital

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1 INTRODUCTION

Energy sources are important for the functioning of modern industrialized society. Most of these forms come from burning fuel derivatives such as oil, coal and natural gas. As these derivatives are in carbon, the emissions of carbon gas due to the burning of such fuels have been of concern to the international community due to the fact that in addition to being non-renewable sources, the possible existence of a strong correlation with the greenhouse effect and increased concentration of carbon dioxide in the atmosphere, which could assist in raising the global temperature.

1.1 ACTUAL SITUTATION

"The world energy matrix is extremely dependent on fossil fuels. In 2014, oil, coal and natural gas accounted for approximately 80% of all fuels used in the world. In Brazil, due to the large use of alcohol and hydroelectric power, the participation of fossil fuels in the energy matrix is lower, but it raises concerns, after all fossil fuels are finite sources of energy and their use ends up generating different environmental problems and public health. With this, the development of technologies that make use of renewable fuels is central to the future of the planet. Among renewable energy sources, hydrogen appears as one of the candidates with a more promising future", says Gabriel Christiano da Silva.

Heavy haul railways are considered those that fit the following characteristics according to the International Heavy haul Association:

a) Heavy haul implies train loads over 8000 tons and axle load 25 tons or more;
b) Normally used by mining and large railways for heavy ore movement – longer loops, stations further apart, basic signaling
c) Other commodities suited to Heavy haul – paper, steel, coal and steel products
d) The record for heaviest haul train by BHP Billiton, Australia – 99734 tons (6 locos and 682 wagons)

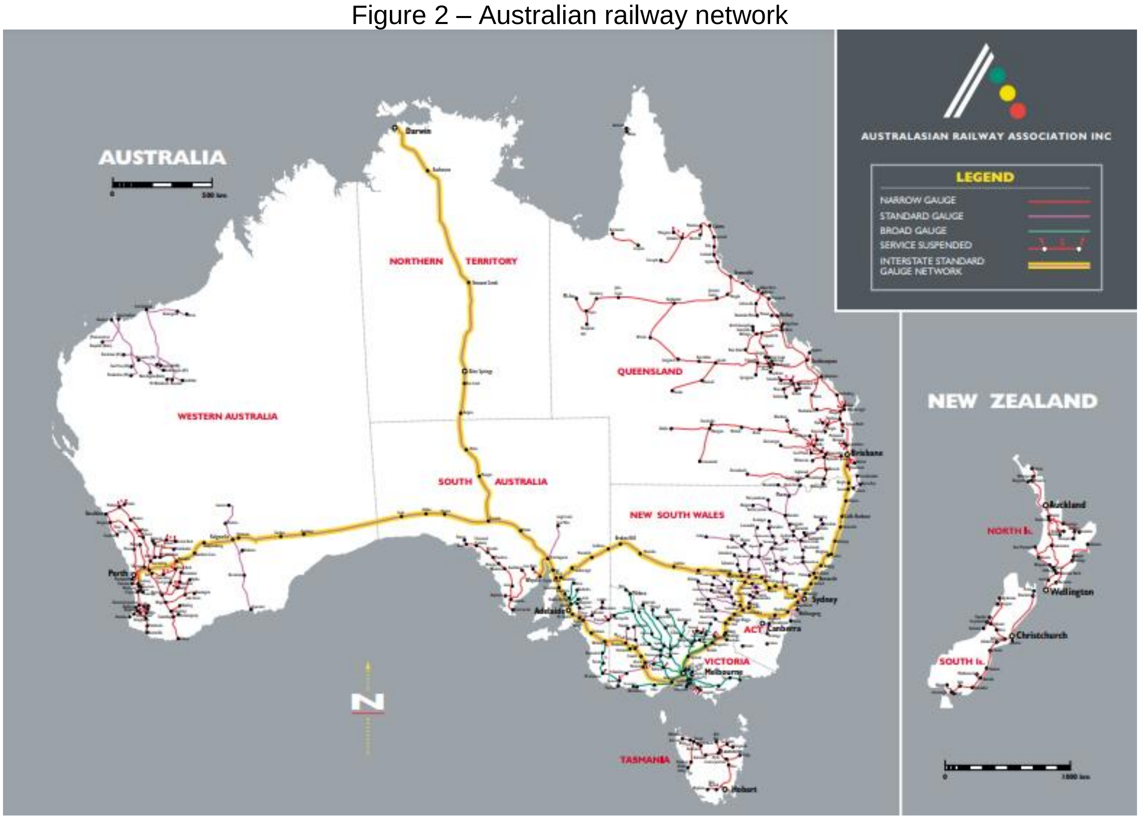
Given the conditions presented, Heavy haul railways are identified in the following countries with the main transport materials:

a) Australia (ore);
b) Brazil (ore and agricultural commodities);
c) South Africa (ore);
d) Sweden (ore);
e) United States (agricultural commodities).

As noted, the railroads classified as Heavy haul are mostly located in countries of continental dimensions, for transporting large volumes over long distances, connecting the interior of the country to its main ports, such as Brazil (Figure 1) and Australia (Figure 2).

Figure 1 – Brazilian railway network

Figure 2 – Australian railway network

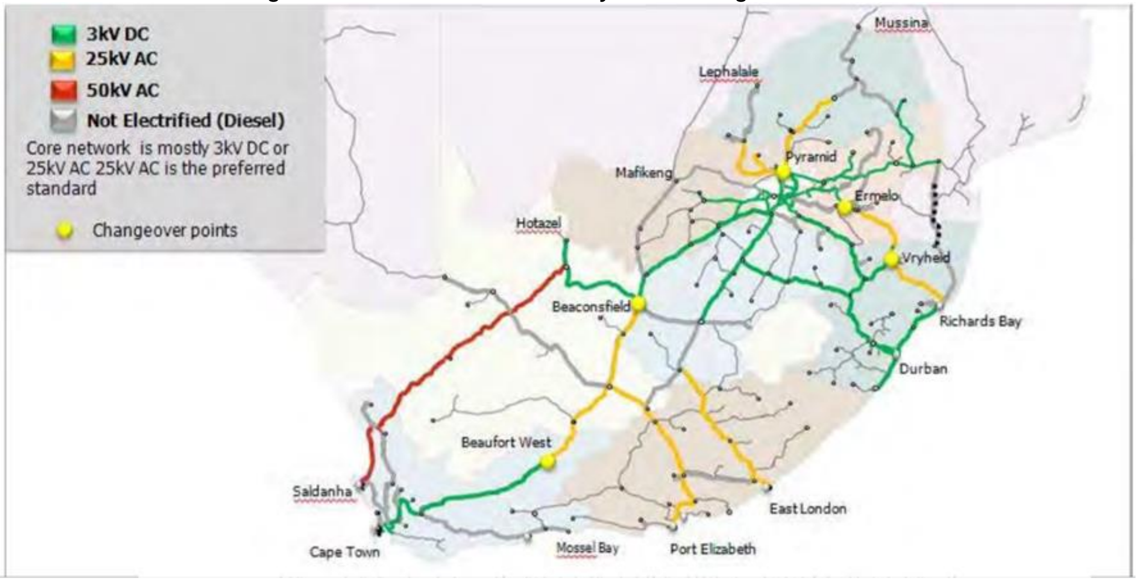


In addition to the geographic issue, the Heavy haul railroads, given the majority nature of their cargo, did not specialize in auto energy generation with the wagons, since their cargo does not require energy supply during the trip.

These railways require an extensive railway network, dispersed in several regions and with long routes of origin and destination, many of these places lacking energy sources, either for the traction of trains, as for the communication systems and other auxiliary systems dependent on energy.

For the case of developing countries, the situation of railways of large purely electric extensions generates a more complex condition, given the lack of standardization of the national electrical system, as observed in South Africa (Figure 3):

Figure 3 – South Africa's rail system voltage distribution



When we consider all the processes for generating electricity, such as chemical, mechanical, hydraulic, thermal and photoelectric, we see that factors such as availability, efficiency, cost and aggression to the environment strongly influence the choice of the system to be adopted. Given the complexity of power supply for rail transport, heavy haul railways have historically chosen to distribute their energy matrix as shown below:

a) Traction systems: diesel-electric;
b) Communication systems: electrical;
c) Field signaling and auxiliary equipment: electrical in regions with availability or capacity to use solar energy, mechanical in regions without electricity.

The main justification for adopting electric diesel traction systems refers to historical models, in addition to economic and infrastructure conditions as follows:

a) Capacity to generate high power output for traction of heavy (> 25 tons per axle) or long trains;
b) Inexistence or instability of electric energy sources in regions of the railroad path, requiring high infrastructure investments;
c) The diesel engine was the natural evolution of steam locomotives, with better power controls and more suited to the culture of the Heavy haul railways.

In other words, electric diesel traction meets the need for power generation in regions where this resource is not available. This innovation has drastically altered rail transport, and the locomotive can even generate enough energy to power the wagons and other systems if this demand exists (Figures 4 and 5).

Figure 4 – Main diesel electric locomotives used by the Heavy haul railways

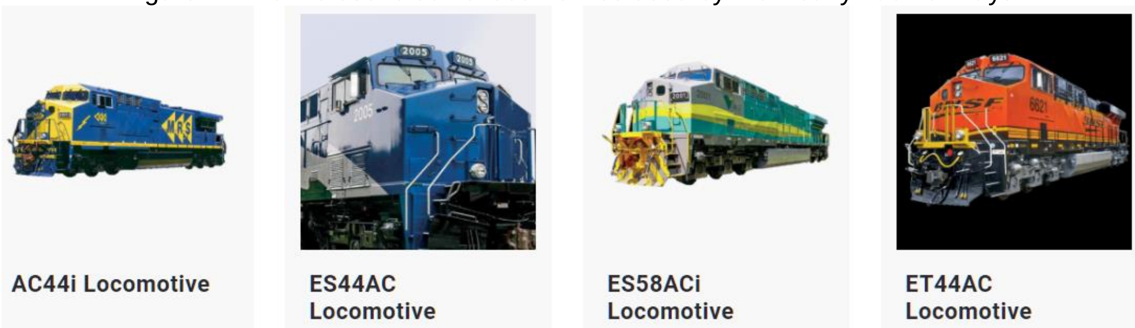


Figure 5 – Electric locomotive used on Heavy haul railways in Sweden.

However, in the last 10 years, the call for sustainable energy sources and political pressures to reduce emissions into the atmosphere have provoked the search for alternatives. Meanwhile, existing alternatives cannot pose a risk to lost productivity as efficiency is an intrinsic characteristic of Heavy haul railways, as stated by Michael Roney, special advisor to the International Heavy haul Association (IHHA): “Heavy-haul railways are under constant pressure to optimize operational efficiency, a factor that has led the sector to spearhead many new technologies ”.

1.2 RISK OF MAINTAINING THE CURRENT MATRIX OF POWER SUPPLY

The main risk of maintaining the existing matrix mainly affects sources linked to fossil fuels and, in the case of the Heavy haul railways, the engines of the locomotives. Internal combustion engines transform chemical energy from the fuel into mechanical energy and only then transform it into electrical energy. As a result, we have low energy efficiency and environmental pollution. The fuel used (diesel) is currently available and inexpensive. But because it is a fossil fuel, not renewable, its days are numbered and as it becomes scarce, its price will tend to rise, making rail transport unfeasible. The manufacture of synthetic fuels may slightly increase the survival of diesel engines, but at a much higher cost [12][12] (Graph 1 and Figure 6).

Graph 1 – Diesel x Price trend [16]

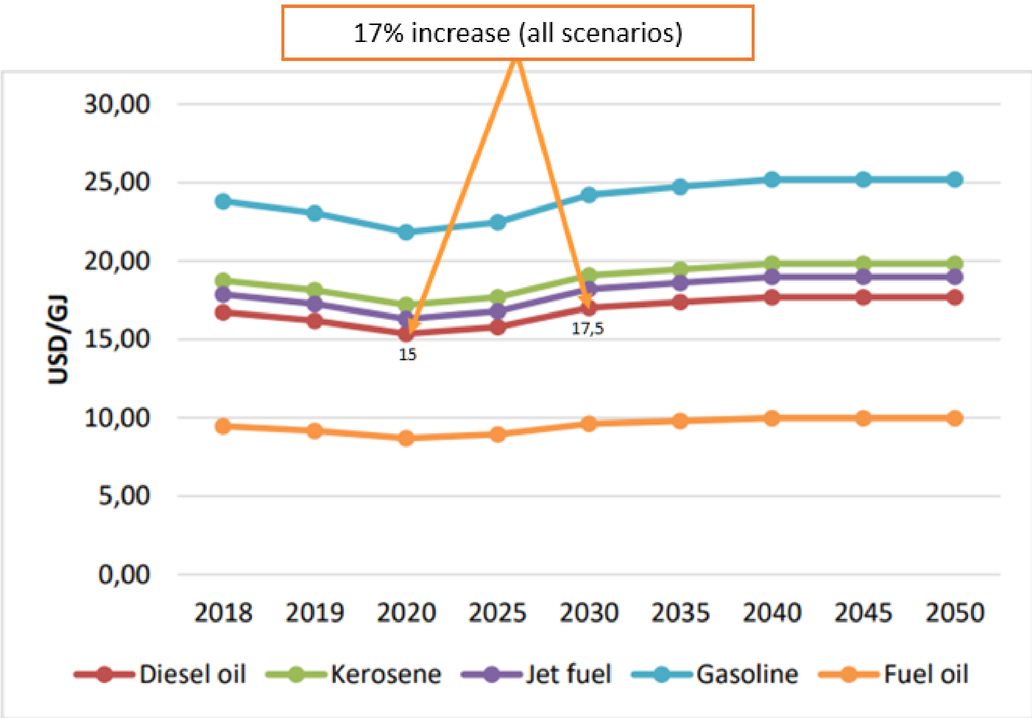
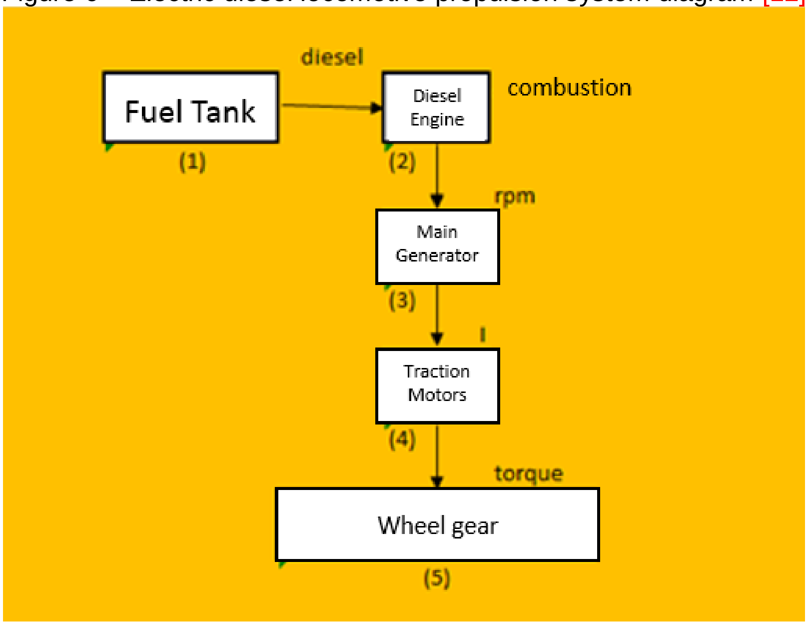
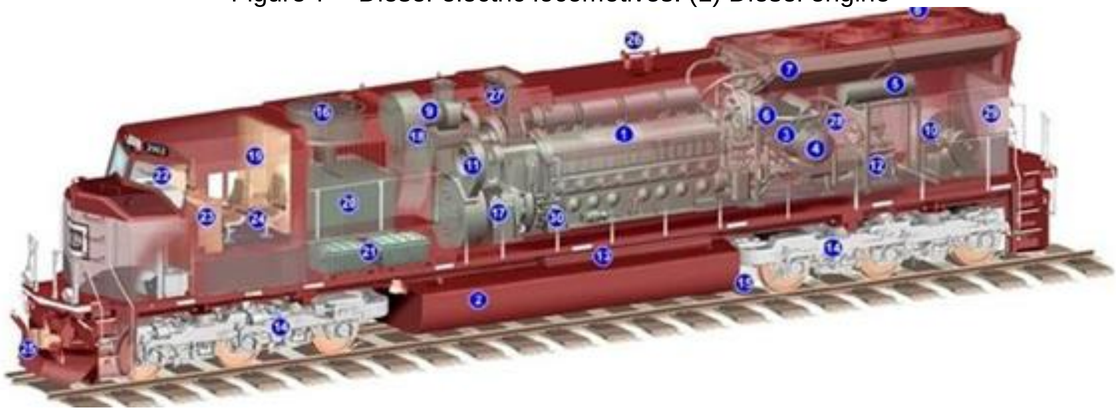


Figure 6 – Electric diesel locomotive propulsion system diagram [12]



Environmental laws tend to become much restrictive and very accelerated due to the meteorological phenomena that currently occur around the world as a result of the greenhouse effect. These threats can quickly make internal combustion engines obsolete and another primary source will need to be found quickly to replace them. The cargo locomotive is a mobile variable power generator that needs a primary source that is long-lived, has high efficiency, reduced costs, uses renewable fuel, is environmentally friendly and has high energy density to provide autonomy from relatively small storage on the locomotive [12] (Figure 7).

Figure 7 – Diesel-electric locomotives. (1) Diesel engine



The fuel cell acts as a continuous flow machine, receiving hydrogen gas and oxygen gas (existing in the air) and through an electrochemical reaction, generates electric current to perform work and rejects only water vapor and heat. Other electric current generation processes come from fixed installations (thermoelectric or hydroelectric) that depend on a distribution network that, as explained above, does not exist on most Heavy haul railroads. Other sources depend on external factors such as solar and wind energy, high-risk elements such as nuclear energy, or through energy storage that requires constant and slow recharging such as batteries [12]. In the case of the use of batteries, it is important to bring the vision of autonomy, supply time and loss of efficiency according to the supply cycles. In addition, the replacement of batteries due to their useful life (Figure 8).

Figure 8 – Why not just batteries [16].

With these considerations, the fuel cell option becomes the most advantageous. Within the various types of cells, we can eliminate those that use only pure hydrogen, as it requires a fuel that, in order to produce it, makes it expensive, and the energy used in its production is very polluting and of low efficiency, in addition to the danger to transport and store it and the high price of the internal components of the fuel cells to receive pure hydrogen (PEMFC, AFC, PAFC) [12].

1.3 INITIATIVES AROUND THE WORLD

It is well known that in several countries cleaner and cheaper alternatives are already being studied for the transportation of cargo and passengers. Measures to reduce the emission of CO_2 and other pollutants by eliminating the production of passenger cars and other road vehicles with internal combustion engines are already being released, with countries adopting dates ranging from 2025 to 2050. However, actions are still needed more concrete so that the deadlines can be met.

The Southeastern Pennsylvania Transportation Authority (SEPTA) has implemented a pilot project to capture the energy produced by braking on the rails of one of its main lines and direct it to the regional power grid of Philadelphia, the largest city in the state. a special system of lithium-ion batteries to store the captured energy.

A study by the University of Ontario, Canada, and the University of Oil and Minerals in Saudi Arabia analyzed the performance of hybrid locomotives, which use hydrogen and diesel as fuels. In comparison with the performance of traditional diesel-electric locomotives, the hybrid system performed better. The aim of the study was to analyze the viability of hybrid locomotives as a clean rail transport option, since the impact of using fossil fuels is a worldwide concern. The hydrogen production for the locomotive is done by the thermal decomposition of ammonia, using the exhaust gases as a heat source. This reduces diesel consumption and increases the use of energy from the fuel burning of the locomotive's primary engine. The researchers assessed energy efficiency, fuel consumption and the environmental impacts generated. Due to the results of the thermodynamic and environmental impact analyzes with 50% of the fuel supplied by ammonia, the environmental performance of the hybrid locomotive was superior compared to traditional diesel locomotives. The reduction in greenhouse gas emissions reached 53%, but energy efficiency did not increase as significantly. It was also found that the heat recovery by ammonia processes increased the efficiency of the locomotive.

In Germany, in September 2018 the first hydrogen-powered train, the “Coradia iLint”, started operating. Developed by Alstom in partnership with France and Germany, today it is in operation between the German cities of Cuxhaven, Bremerhaven, Bremervörde and Buxtehude (Figure 9).

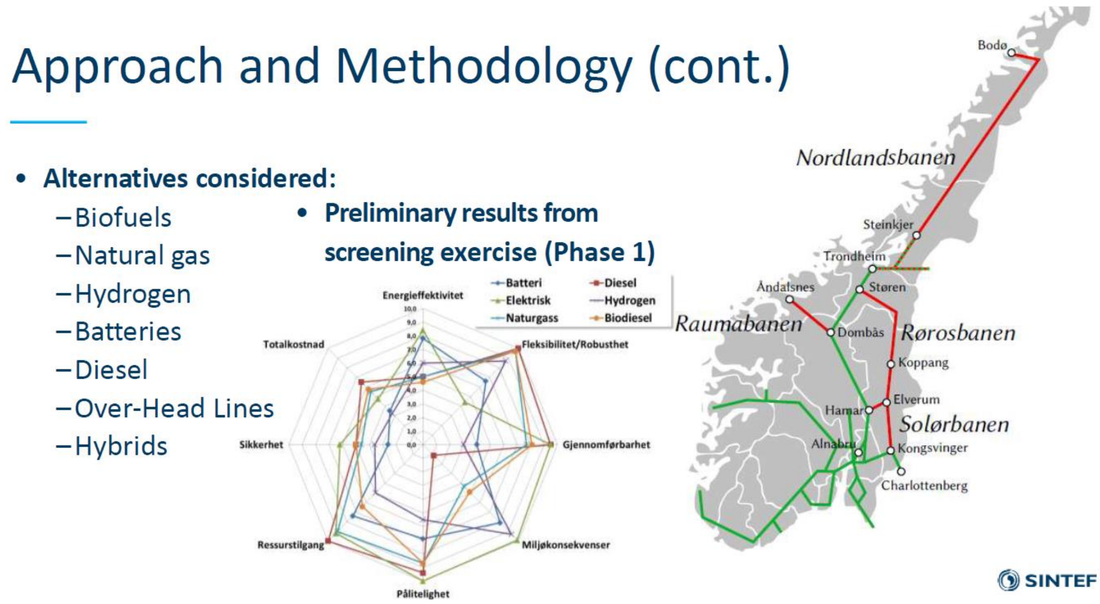
Figura 9 – The Coradia iLint na InnoTrans em Berlin em 2016

Subsequently the train was also tested in the Netherlands and went into operation in Austria in September 2020, for a 3-month demonstration period in a challenging geography stretch.

When we talk about bringing this type of technology to freight trains on "Heavy haul" railways, the challenges are even greater. The difficulty of substitution, the necessary traction capacity, the costs of implantation and geographic dispersion make the mission of making a substitute for diesel electric locomotives complex.

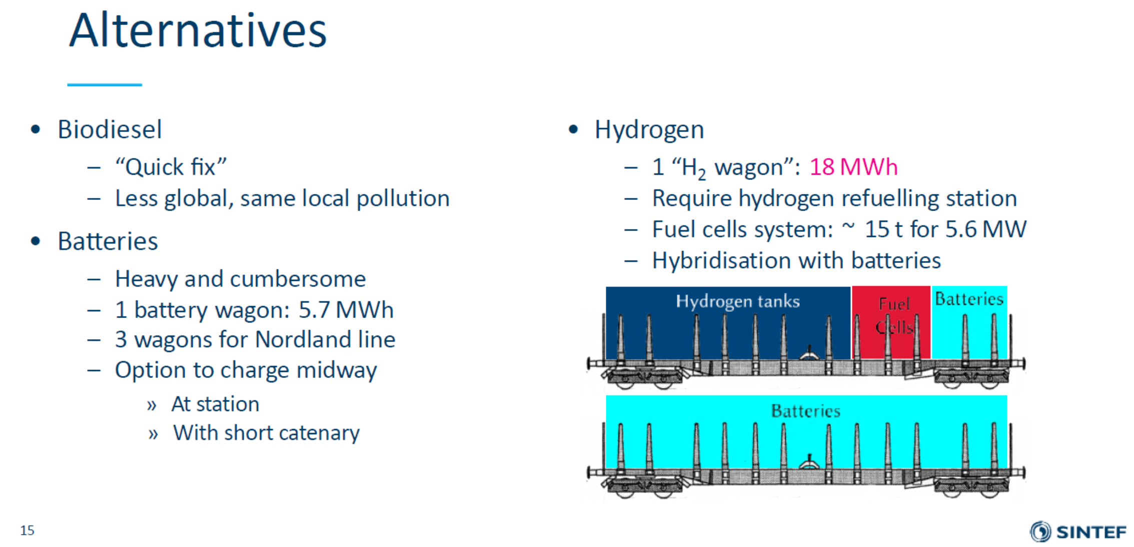
A study by SINTEF (Norwegian: Foundation for Industrial and Technical Research) on electrification of lines in Norway brought a very interesting picture in the analysis of possible alternatives for freight trains. Several alternatives were studied, including the current Diesel and electrification with upper cables (Figure 10, sections in red).

Figure 10 – Approach and methodology



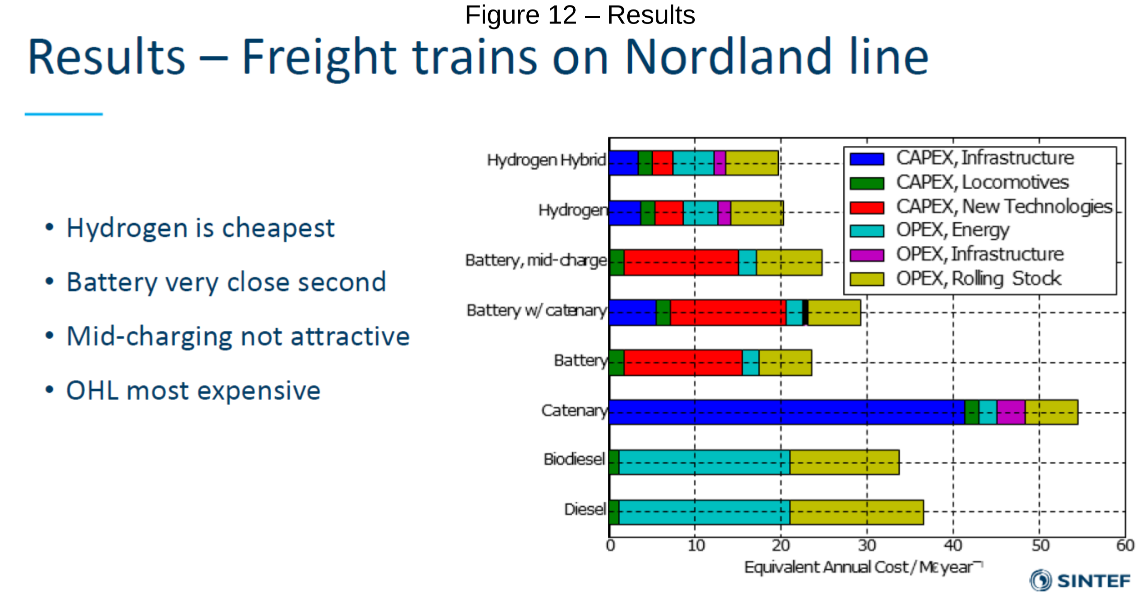
For the study, standard wagon was self-propelled, in which 3 battery wagons would be needed and in the case of hydrogen fuel cells, only 1 (Figure 11).

Figure 11 – Alternatives



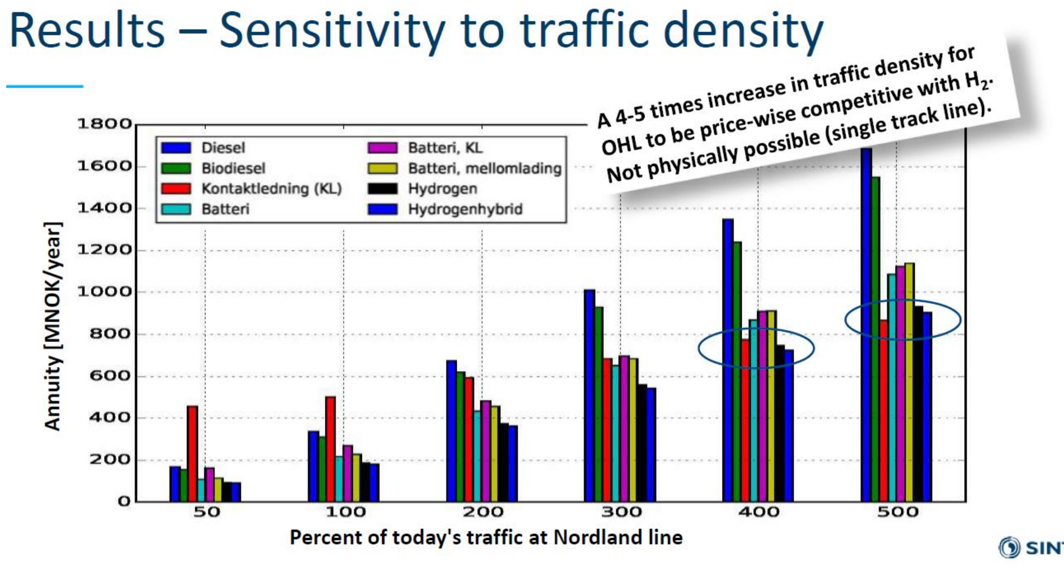
Comparing the projected costs, considering market developments, learning curves, an economically more favorable view was reached for hydrogen fuel cells combined with the use of batteries as the cheapest alternative (Figure 12).

Figure 12 – Results



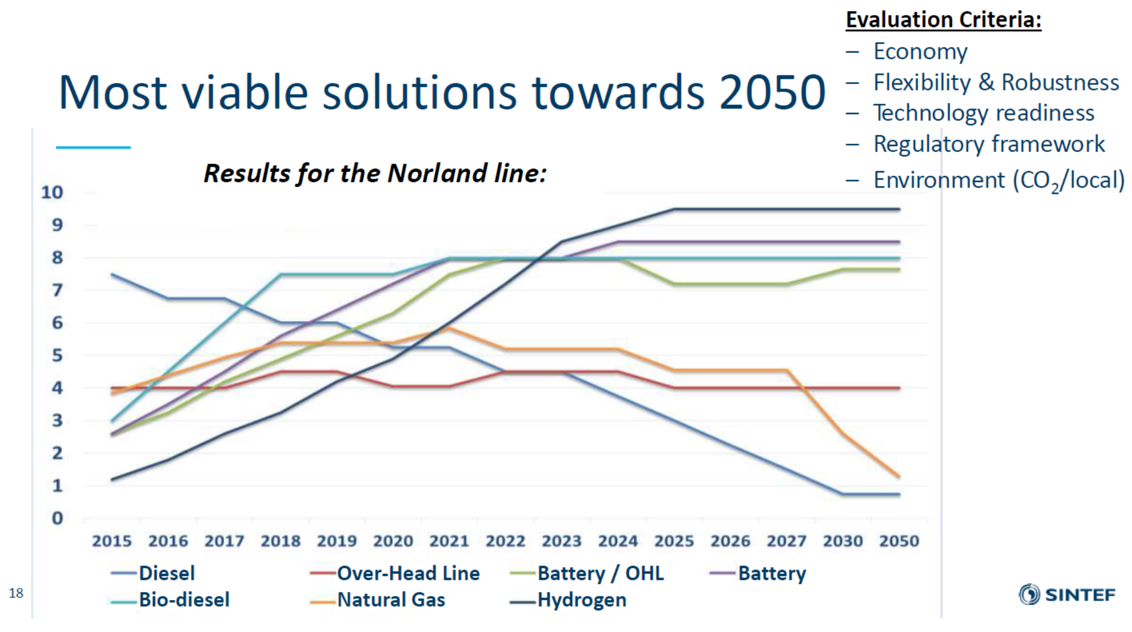
However, the study also shows considerable variation in this balance according to the volume of transport. Which shows that each case must be studied within its projections of transportation, fuel availability and technologies. But the indication of cleaner solutions as more economical is quite favorable (Figure 13).

Figure 13 – Results



Even though over time, fuel cell solutions with hydrogen and batteries have proven to be increasingly advantageous (Figure 14).

Figure 14 – Most viable solutions by 2050



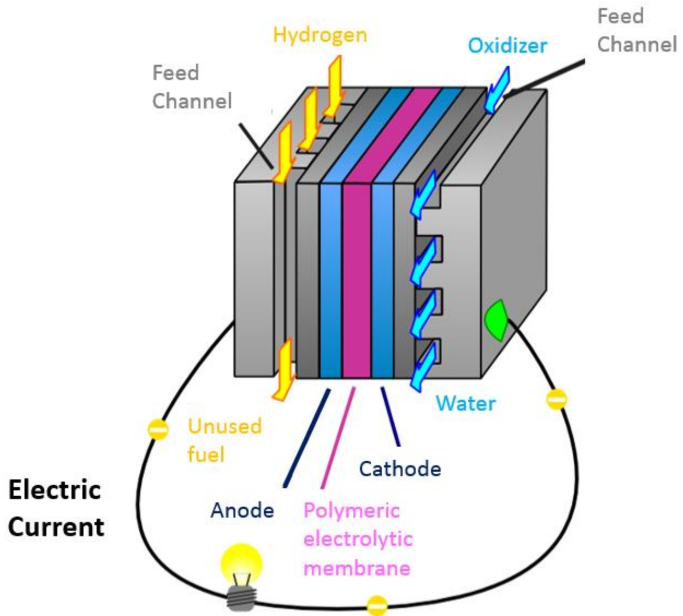
2 DEVELOPMENT

Recent studies show that fuel cells operate with greater thermodynamic efficiencies than thermal engines. Since fuel cells do not use combustion, their efficiency is not linked to the maximum operating temperature. As a result, the efficiency of converting chemical energy to electrical energy (electrochemical process) can be significantly higher.

2.1 FUEL CELL MODELS

A fuel cell is an electrochemical cell that converts potential energy from a fuel into electricity through an electrochemical reaction. Like any electrochemical cell, a fuel cell consists of two electrodes, the anode and the cathode, and an electrolyte. Two components are essential: hydrogen as a fuel and oxygen as an oxidizer. [1] In principle, fuel cells are not pollutants, since water is the product of the reaction (Figure 15).

Figure 15 – Schematic of operation of a fuel cell.



In general, the fuel cell functions as an electric current generator. The current generated operates the most diverse devices (lamps, motors, appliances, as examples) and then returns to the generator, completing what is called an electrical circuit. Its principle of operation is to use the energy generated by the reaction of hydrogen with oxygen, with water as the product. The hydrogen is fed to the anode where it is decomposed by a catalyst into protons, with a positive charge, and electrons with a negative charge. The electrons are injected into the electrical current (the useful part of the system), and the protons migrate through the electrolyte to the cathode. There, the protons combine catalytically with oxygen coming from the air and electrons returned by the electric current. [1]

There are several types of fuel cells, generally classified by operating temperature. [2]

a) Temperatures below 250 ºC:
    - Alkaline (A)
    - Phosphoric acid (PA)
    - Proton exchange membrane (PEM)
b) Temperatures above 600 ºC:
    - Molten Carbonates (MC)
    - Solid oxides (SO)

2.2 TECHNOLOGICAL DEVELOPMENT AND APPLICATIONS

The table presented in Figure 16 lists the types of fuel cells developed to date with their main characteristics, current advantages and disadvantages and their most relevant applications.

Figure 16 – Comparative table

Type	Electrolyte (transported species)	Temperature range (° C)	Advantages	Disadvantages	Applications
Alkaline (A)	KOH (OH^-)	60 - 90	- High efficiency (83% theoretical)	- Sensitive to CO^2 - Ultra pure gases, without fuel reform	- Spacecraft - Military applications
Proton exchange membrane (PEM)	Nafion® (H_3O^+)	80 - 90	- High density of - Flexible operation	- Membrane cost, power and efficiency - Contamination of the catalyst with CO	- Motor vehicles and catalyst - Spacecraft - Mobility
Phosphoric acid (PA)	H_3PO_3 (H_3O^+)	160 - 200	- Greater technological development	- Electrode porosity control - CO sensitivity - Efficiency limited by corrosion	- Stationary units - Stationary units (100 kW to some MW) - Electricity / heat cogeneration
Molten Carbonates (MC)	(CO_3^{2-})	650 - 700	- CO / CO^2 tolerance - Ni-based electrodes	- Material problems - Need for CO^2 recycling - Three-phase interface difficult to control	- Stationary units of a few hundred kW - Electricity / heat cogeneration
Solid Oxides (SO)	ZrO_2 (O^{2-})	800 - 900	- High efficiency (favorable kinetics) - Fuel reform can be done in the cell	- Material problems - Thermal expansion - Need for pre-retirement	- Stationary units from 10 to a few hundred kW - Electricity / heat cogeneration

As previously described, cells that use only pure hydrogen should be eliminated due to cost, emissions and storage risk issues. Fused carbonate cells, on the other hand, generally use fuel gas for their reactions, a fact that already represents a storage problem for Heavy haul railways. Point of attention is due to the toxicity of the fuel and the high temperature at which it operates, requiring sealing of the cell components to prevent leaks.

Thus, we relied on the solid oxide fuel cell for allowing the use of hydrogen-rich fuels that can be extracted through reform and whose materials used are of lower cost and resistant to carbon monoxide. Studies are continuing with the objective of finding even cheaper materials and manufacturing processes for the manufacture of these SOFC cells in order to reduce the cost of this technology and increase its useful life [1212].

The main attractions of this technology are the use of renewable fuel, with low pollution level and high overall system efficiency (60%). This efficiency can still be improved, if the thermal energy existing at the high temperature in which this fuel cell operates (700 - 900 °C) is used. The hybrid SOFC cycle, which integrates a SOFC with a gas turbine cycle, can offer a fuel efficiency potential to generate electricity in the order of 75 to 80% [12~~12~~].

2.3 ADVANTAGES AND DISADVANTAGES OF USING FUEL CELLS [3~~3~~]

The main advantages researched regarding the use of fuel cells in relation to existing energy sources are:

a) Operate without producing pollution when using pure hydrogen. Exhaust products are just pure water and heat. When operating with reformed gas rich in hydrogen, some harmful emissions occur, although much less than those emitted by engines that use fossil fuels.
b) Operate with greater thermodynamic efficiencies than thermal engines. Since fuel cells do not use combustion, their efficiency is not linked to the maximum operating temperature. As a result, the efficiency of converting chemical energy to electrical energy (electrochemical process) can be significantly higher.
c) Show high efficiency in partial loads and show no drop in efficiency when the cell size decreases.
d) Rigid devices (without moving parts) that react chemically and change the charge regime instantly.
e) When used as an electrical power generation device, the fuel cell requires little energy transformation when compared to a thermal engine.
f) Do not require adjustment.
g) Do not require a refill. The fuel system can be replenished very quickly and has a longer autonomy the larger the storage tank.

The disadvantages of using fuel cells were also researched to identify possible risks in applications on Heavy haul railroads.

a) Although the use of hydrogen benefits the environment when used in fuel cells, its responsibility is also greater due to the difficulty of making and storing it. The manufacturing processes are expensive and consume intense energy, whose origin is from fossil fuels.
b) Hydrogen gas storage systems are large and heavy to accommodate a low energy density per volume of hydrogen. Liquid hydrogen storage systems are smaller and lighter but operate under cryogenic temperatures. If hydrogen is stored as a hydrocarbon or alcohol and released on demand through a reformer, storage and handling are simplified, but some environmental benefits are lost.
c) Fuel cells require relatively pure fuel, free of specific contaminants. These contaminants include sulfur, carbon compounds and liquid fuel residue that can deactivate the catalyst, effectively destroying its ability to operate.
d) The use of platinum as a catalyst to promote the electrochemical reaction is a rare and very expensive metal.

e) Fuel cells that use ion exchange membranes cannot dry out during use and must remain moist during storage. Attempts to start or operate these cells under dry conditions can lead to membrane damage.
f) Fuel cells are rigid but depend on support systems. Among them, an air compressor is required. This imposes additional loads on the general system. The complexity of the system increases significantly when the cells are operated in conjunction with a reformer.
g) The complete fuel cell system is heavy due to the fuel support and storage systems. Systems that include a reformer are even heavier.
h) Emerging technology. Reduced cost, weight and size compete with increased reliability and service life.

Despite the listed disadvantages, the risk analysis of the project will identify the possibility of solution, being an important step for a technology under development.

2.4 IDENTIFICATION OF POSSIBLE APPLICATIONS ON HEAVY HAUL RAILWAYS

As detailed previously, fuel cells have specific applications according to energy demand and usage characteristics. Describing the main energy demands coming from a Heavy haul railway:

a) Traction systems: diesel-electric;
b) Communication systems: electrical;
c) Field signaling and auxiliary equipment: electrical in regions with availability or capacity to use solar energy, mechanical in regions without electricity.

For the systems presented, it can classify them as fixed or mobile installations, as follows:

a) Fixed installations: field signaling, auxiliary equipment, fixed communication systems (radio towers, stations, etc.);
b) Movable applications: traction systems, communication systems on board.

Fuel cells, although more efficient, have the need for refueling. Therefore, fixed installations along the railway network with the use of fuel cells at first become impracticable, since the dispersion of the equipment will require a continuous supply flow that, depending on the distance, becomes expensive and of high risk.

The application of a fuel cell to partially replace the locomotive's traction system presents a good alternative, given the condition of the locomotive to transport its fuel demand in the existing tanks. Diesel-electric locomotives depend on the diesel engine specifically for power generation through an alternator, where the generated electrical power is transmitted to the traction engines. The replacement of the diesel engine and alternator group with a fuel cell of equal power has a great chance of success, eliminating the dependence on fossil fuel and meeting environmental requirements.

Following is the comparison of the systems (Figures 17 and 18):

Figure 17 – Combustion engine and generator set [12~~12~~]

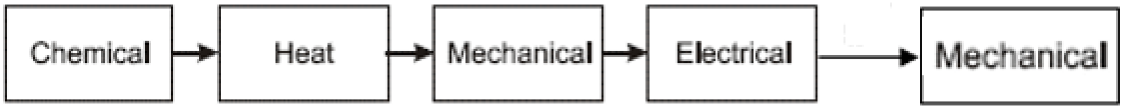
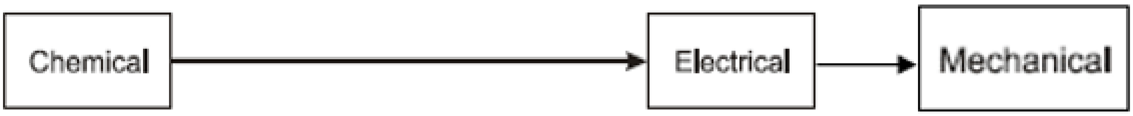
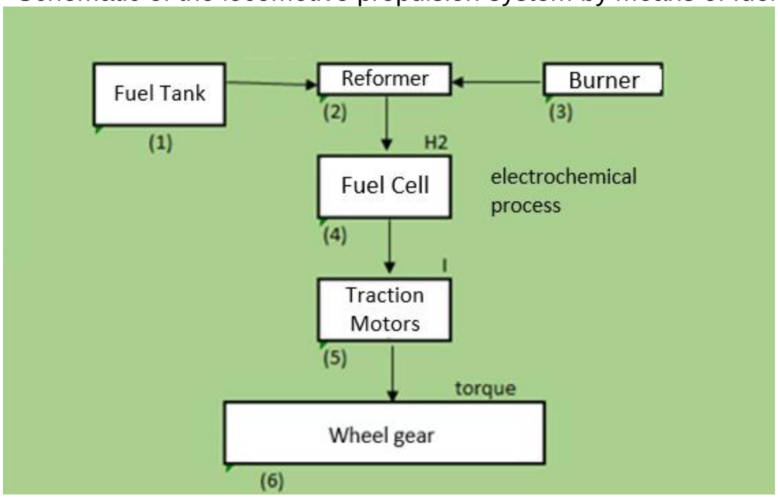


Figure 18 – Fuel cell [12~~12~~]



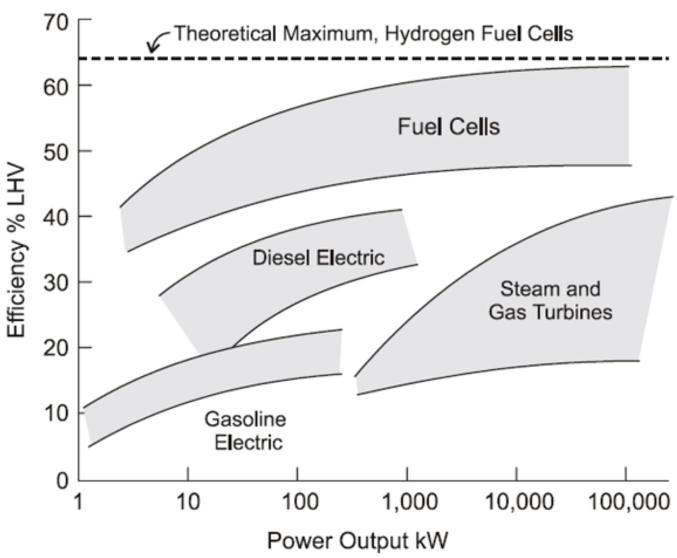
Due to the great need for power required in the traction motors of a locomotive, the fuel cell must be coupled with additional units known as reformer and burner (Figure 19):

Figure 19 – Schematic of the locomotive propulsion system by means of fuel cell [12~~12~~]



However, despite the inclusion of additional components, fuel cells continue to provide the necessary kilowatt power needed for the most efficient locomotives (Figure 20).

Figure 20 – Energy efficiency versus available power [3~~3~~].



2.5 INITIAL FINANCIAL ANALYSIS [16], [17]

As explained, the proposed technology still has an initial maturity level. However, it is possible to develop a financial feasibility study based on the researched information.

In order to present a summary of the financial analysis and following the concepts presented in the course, a prior financial analysis needs to define the following variables:

a) Scope of the project;
b) Necessary investment;
c) Internal rate of return (IRR);
d) Net present value (NPV);
e) Payback;
f) Weighted Average Cost of Capital (WACC)

The scope of the project is to develop and use a fuel cell as a primary energy source for a heavy haul locomotive. The locomotive chosen for this development is the main locomotive currently used by these railways, that is, an AC44i.

For the best financial details, the main changes in expenses with the use of technology were listed, thus developing the initial financial analysis (Table 1):

Table 1 – Financial variables used to calculate feasibility

Financial variables
(-) Investiment (delta)
AC44i fuel cell cost (CAPEX)
Diesel engine cost 7FDL + alternator AC44i (CAPEX)
Tax Credit (PIS and COFINS)
(+) Expense Reduction
Carbon credits (estimated)
AC44i fuel cell consumption (estimated)
Diesel consumption AC44i (estimated)
(-)Expense Increase (OPEX)
Preventive maintenance SOFC
TK Diesel preventive maintenance (estimated)
(+) Other Revenues

The period of analysis of return on investment was linked to the estimated useful life of a fuel cell, that is, 12 years. By entering values and calculations, the following result is obtained (Table 2):

Table 2 – Return on investment analysis

Reais Mil	1	2	3	4	5	6	7	8	9	10	11	12	Total	VPL
(-) Investiment (delta)	**-5.207**												**-5.207**	**-5.207**
AC44i fuel cell cost (CAPEX)	*-9.207*												*-9.207*	*-9.207*
Diesel engine cost 7FDL + alternator AC44i (CAPEX)	*4.000*												*4.000*	*4.000*
Tax Credit (PIS and COFINS)	*0*												*0*	*0*
(+) Expense reduction	**1.365**	**1.387**	**1.410**	**1.433**	**1.455**	**1.478**	**1.499**	**1.521**	**1.542**	**1.564**	**1.585**	**1.596**	**17.835**	**9.049**
Carbon credits (estimated)	*223*	*234*	*244*	*255*	*265*	*276*	*286*	*297*	*307*	*318*	*328*	*339*	*3.373*	*1.648*
AC44i fuel cell consumption (estimated)	*-1.794*	*-1.794*	*-1.794*	*-1.794*	*-1.794*	*-1.794*	*-1.794*	*-1.794*	*-1.794*	*-1.794*	*-1.794*	*-1.794*	*-21.523*	*-11.181*
Diesel consumption AC44i (estimated)	*2.935*	*2.947*	*2.959*	*2.971*	*2.983*	*2.995*	*3.006*	*3.017*	*3.029*	*3.040*	*3.051*	*3.051*	*35.985*	*18.582*
(-) Expense increase (OPEX)	**-108**	**-108**	**-108**	**-108**	**-1.057**	**-108**	**-108**	**-108**	**-108**	**-1.057**	**-108**	**-108**	**-3.196**	**-1.487**
Manutenção preventiva SOFC	*-463*	*-463*	*-463*	*-463*	*-1.411*	*-463*	*-463*	*-463*	*-463*	*-1.411*	*-463*	*-463*	*-7.452*	*-3.698*
Manutenção preventiva TK Diesel (estimada)	*355*	*355*	*355*	*355*	*355*	*355*	*355*	*355*	*355*	*355*	*355*	*355*	*4.256*	*2.211*
(+) Other Revenues														
(=) Result	**-3.951**	**1.279**	**1.302**	**1.324**	**399**	**1.369**	**1.391**	**1.412**	**1.434**	**507**	**1.477**	**1.488**	**9.432**	**2.355**
IR Base	*1.256*	*1.279*	*1.302*	*1.324*	*399*	*1.369*	*1.391*	*1.412*	*1.434*	*507*	*1.477*	*1.488*	*14.639*	*7.562*
(-) Depreciation (benf) fuel cell AC44i														
(-) Depreciation (benf) 7FDL diesel engine + AC44i alternator														
(+) Depreciation (loss) fuel cell AC44i	*425*	*425*	*425*	*425*	*425*	*425*	*425*	*425*	*425*	*425*	*425*	*425*	*5.101*	*2.650*
(+) Depreciation (loss) 7FDL diesel engine + AC44i alternator	*-500*	*-500*	*-500*	*-500*	*-500*	*-500*	*-500*	*-500*	*-500*	*-500*	*-500*	*-500*	*-6.000*	*-3.117*
(-) Income tax	**-402**	**-409**	**-417**	**-425**	**-110**	**-440**	**-447**	**-455**	**-462**	**-147**	**-477**	**-480**	**-4.671**	**-2.412**
(=) Final Result	**-4.352**	**870**	**885**	**899**	**289**	**929**	**943**	**958**	**972**	**360**	**1.000**	**1.007**	**4.760**	**-57**
PAYBACK (months)	**12**	**12**	**12**	**12**	**12**	**12**	**6**	**0**	**0**	**0**	**0**	**0**	**78**	
NPV	**-4.352**	**756**	**669**	**591**	**165**	**462**	**408**	**360**	**318**	**102**	**247**	**217**	**-57**	

As an output, the economic model generates the following results (Table 3):

Table 3 – Results of the economic model

Model	AC44i diesel vs. AC44i fuel cell
Total Investiment *(R$ mil)*	-5.207
IRR	15%
NPV *(R$ mil)*	-57
Payback (months)	78
WACC	15%
Period	12 years

In this first financial approach, the project had a positive IRR and a negative NPV close to zero (1% of total investment). Given the estimated values due to the technology used presenting a high cost because it is a conceptual project and the non-exhaustive analysis of gains, the first result is positive for the continuity of the project. However, in a more comprehensive scenario, for a large-scale implementation across the railroad, analyzes of culture change and impacts on the organizational structure of companies are necessary.

2.6 CULTURE CHANGE AND MACRO IMPACTS ON CHANGING POWER SUPPLY MATRIX IN LOCOMOTIVES

Model inclusion strategy. Main alternatives:

a) Track construction already considering the installation of the system.
b) Gradual change, considering the implantation in specific rail routes, with the systems coexisting:

- Rolling Stock: It is necessary for locomotives to be replaced or adapted, an option for adaptation was presented earlier in this work.
- Tracks: Initially, it is not necessary to make any kind of adaptation on the way. It is expected that the new locomotives, or adaptations, will maintain the characteristics like the current ones, within the same limits of vertical load, acceleration and braking, so as not to generate additional efforts on the permanent way. A change that must be evaluated to validate the current maintenance parameters of the track is the change in height of the locomotives' center of gravity. This is a very relevant factor in studies on the stability of train movement. However, this characteristic is usually more critical in wagons, and the change in the energy matrix is not expected to have a relevant impact on the maintenance parameters.
- Refueling stations: A new supply logistics is required. New stations need to be built in order to receive the new fuel flow. Very strict conditions of transport and storage. In addition to the limited number of suppliers. The fuels with the greatest potential for use are methanol and ethanol, due to their ease of storage and supply. In addition to fuels with the potential to increase the scale of production, considering the agricultural scenario of the regions crossed by the railroad in

Brazil. The gaseous state in the form of compressed gas is the most common form of hydrogen storage and transport, however, pure hydrogen was not considered a viable option as previously presented. It is necessary that the tanks are suitable for degradation by the action of hydrogen, which in contact with the air is highly reactive and can form explosive mixtures.

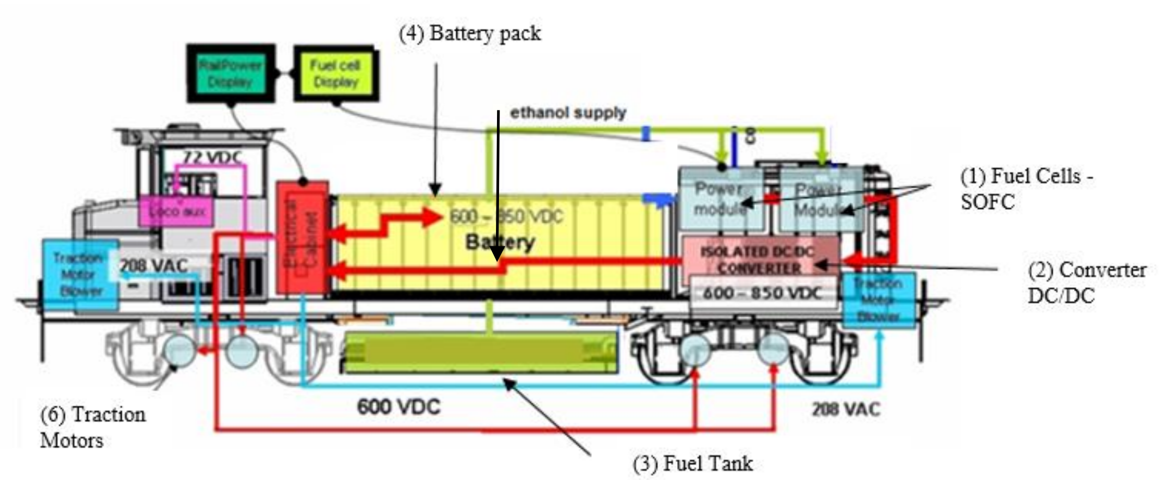
- Locomotive maintenance: New maintenance structures are not necessary, but adaptations to existing structures and spaces are needed to store and work with the new types of components, be they fuel cells and battery banks. Due to the complexity of these components, a high level of workforce training is essential, in addition to partners with mastery of cutting-edge technologies, universities and research centers. The alternatives are expected to involve lower mechanical maintenance costs, mainly because these systems have a large reduction in the number of moving parts. Changing the combustion reaction also reduces the working temperature and the total temperature delta observed by the system.
- Waysides: Enabling the use of batteries and fuel cells on the railroad opens new doors for increasing the monitoring capacity of several factors that are not viable today. Considering that structurally there will be no considerable changes in the track or in the rolling part of wagons and locomotives, the change in the energy matrix does not generate an additional need for external monitoring. However, the conventional way is to install stationary waysides, the reading being made at specific points, when the train crosses it. Today wagons in general do not have monitoring of their characteristics, which allows a deficiency to continue for a long time until it crosses a suitable wayside for that specific deficiency. Adding electrical power from the locomotive to the other cars in the process would generate an operational impact, more connecting elements between the cars, in addition to the in-line system generating an unreliable situation with possible constant need for maintenance. Considering the addition of a small set of fuel cells or batteries associated with dynamos, we can envision the adoption of continuous monitoring systems, where we no longer have only measurement points where some limits are defined, but a continuous view in which the trend can be monitored much more reliably. Some characteristics such as temperature of the whole set, integrity of axles and wheels, excessive impact / vibration, braking efficiency.

3 PROJECT SIMULATION: PROJECT OF A LOCOMOTIVE

Replacement of the diesel engine and generator group with a SOFC fuel cell. This cell must continuously provide at least the average duty cycle power.

Figure 21 shows the general scheme of the locomotive with the primary energy source (fuel cells) and the secondary source (battery pack) for situations of greater energy demand [12~~12~~].

Figure 21 – Scheme of the hybrid propulsion system for a locomotive [6~~6~~].



3.1 REAR COMPARTMENT

The following systems will be housed in this compartment: fuel cells, the DC / DC converter, the cooling module, the air compressor (brake and other systems) and the fan for the traction motors located in the trick below this compartment.

The (1) SOFC fuel cells receive the hydrogen obtained from the autothermal reform of the fuel. This will be stored in a tank placed at the bottom of the locomotive (4). Both the fuel cells (1) and the battery pack (4) will provide electrical energy to be used by the traction motors (6) at 600 V in alternating current.

The (2) DC / DC converter is used to make use of the power generated by the fuel cell (primary source) and the battery pack (secondary source) and release it to the high voltage bus of the locomotive at the correct power and voltage level there will be a need for a DC / DC converter. There will be a need for a DC / AC inverter to supply alternating current to the traction motors.

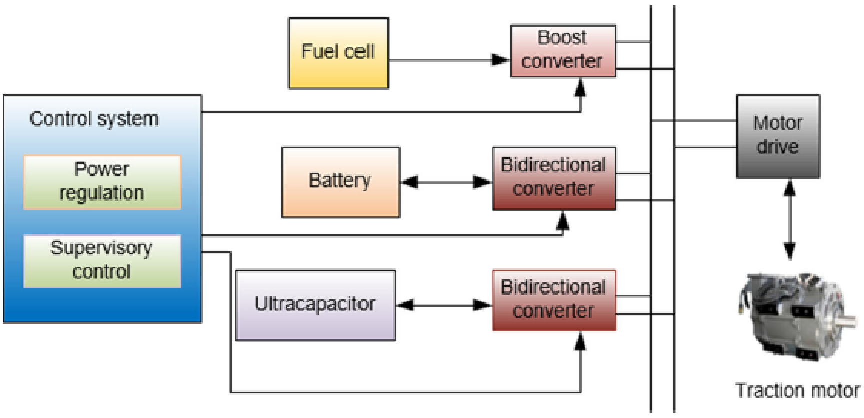
3.2 CENTRAL PART OF THE LOCOMOTIVE

The (3) Fuel tank is used for fuel storage. The material of the tank can be made of stainless steel or polymeric. The volume will need to be determined. Depending on the existing space, you can have up to 18,000 l.

The (4) Battery pack serves as a secondary source of energy, a battery pack will need to be sized to act on the power demand transients and allow their full charging through the fuel cells when the power demand on them drops.

In Figure 22, the central part of the locomotive can be seen.

Figure 22 – Scheme of the power options of a hybrid locomotive with integrated control system [7~~7~~].



3.3 FRONTAL LOCOMOTIVE [12~~12~~]

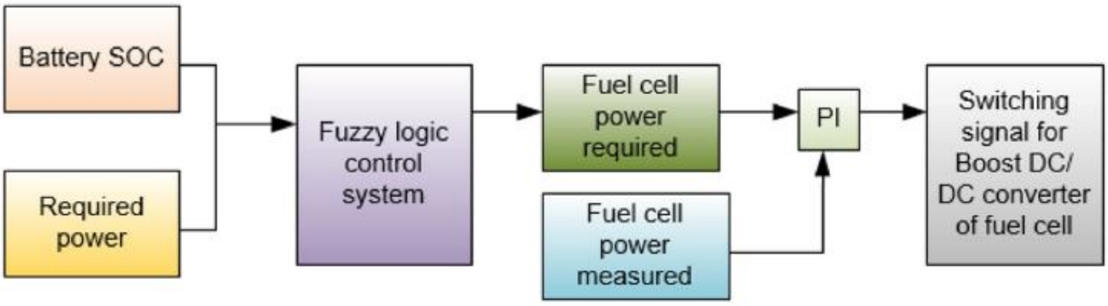
The (5) Control system will consist of: instrumentation, actuators and programmable automation controller (PAC). During normal operation, the PAC receives the power setpoint from the locomotive controller. The PAC will relay this power point to the DC / DC converter controller and will also establish the necessary conditions for the fuel cell system to generate the required power. First, the air flow required to produce the desired power will be calculated. The air compressor is controlled to release the calculated air flow. Minor corrections in this flow will be made by measuring the actual air flow released to the fuel cells. Assuming the air flow is enough, the hydrogen supply will be consumed at a rate that is proportional to the current projected for the fuel cell system.

The (6) Supercapacitor is an electrochemical capacitor that has an extraordinary energy storage capacity in relation to its size when compared to ordinary capacitors. The power system of the locomotive should be designed so that the fuel cells supply the average power demand, while the changes in power demand are complemented by supercapacitors and batteries, with the supercapacitor being used to quickly release the transient power.

A (7) Dynamic braking regeneration technology should be included in the battery energy storage system. During dynamic braking, part of the generated electric current intensity will be used to recharge the battery pack.

Regarding (8) Power control, it is noteworthy that this system will be composed of a system based on fuzzy logic. The control system should manage the power demand and provide the hybrid system with an optimized operational efficiency of the fuel cell as well as maintaining a specified range of battery charging status. The “diffuse logic” control system should provide lower minimum and maximum voltages on the DC bus, favorable to motor inverters. This will allow for a longer life expectancy for the battery pack and greater efficiency of the power system (Figure 23).

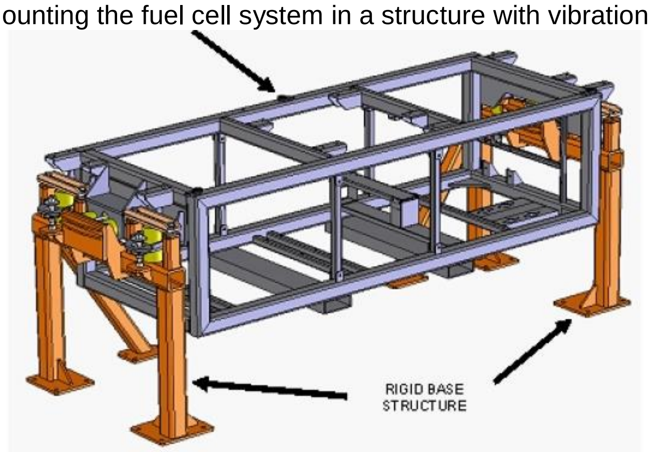
Figure 23 – Control scheme through a “fuzzy logic” system [77].



3.4 ASSEMBLY AND INSULATION OF THE FUEL CELL SYSTEM [66]

The locomotive will constantly couple wagons, which can lead to shocks above 10 g. Although these shocks are short-lived, they can lead to fatigue failures of system components or the mounting frame. To minimize this severe condition, each module must be isolated from shocks by means of rubber or synthetic springs or dampers. The shock absorber must absorb enough energy so that the components receive only the resulting part that they can support. Generally, 10 g shocks should be dampened in order to only release a maximum of 3 g into the system. The natural frequency of the assembled set must be much less than the frequency of disturbance of the system. The insulation system must absorb shocks from the 3 directions: horizontal, lateral and vertical (Figure 24).

Figure 24 – Mounting the fuel cell system in a structure with vibration isolation [66].



4 CONCLUSIONS

This work aimed to identify the existing energy alternatives in view of the combustion energy sources currently used by the Heavy haul railroads. As mentioned, the current energy matrix, as it is based on non-renewable fossil fuels, mostly diesel engines, will not be sustained for much longer, being necessary the search for alternative sources that guarantee the future of the energy matrix of the Heavy haul railroads.

Through the exposed study we have that fuel cells are presented as the best alternative so far for this change of scenario, since such cells can be developed according to the energy matrix of greatest availability in each country, in the case of Brazil studies move forward with a focus on the use of ethanol as a food source.

It was also possible to observe that it is the alternative that provides a better adaptation and conversion of the matrix for the Heavy haul railroads, since the investments are concentrated in the replacement or conversion of the locomotives, not requiring major changes and investments in other sectors as a permanent way, wagons, locomotive maintenance stations, wagon maintenance stations, as well as train licensing and circulation intelligence.

It is noteworthy that because it is a new energy generation system, it is necessary to deepen studies, analyzes, partnerships with educational institutions that can develop prototypes and perform tests, whether simulated or in the field, in order that the application fuel cells is a reality for Heavy haul railways.

It is recommended that initially the tests and applications take place in yards assisted by maneuvering locomotives, as they have a 24-hour work cycle with reduced displacements around the yards, making it possible to monitor the use of fuel cells in the reduced working radius of the patios.

This leads to the conclusion that the sector is not so far from the reality that it will no longer be necessary to use fossil fuel, Diesel, on the Heavy haul railroads. These efforts, in addition to generating savings and adapting to international expectations of reducing the use of fossil fuels and emission of polluting gases, lead the Heavy haul railroads to a new historic industrial moment, which is guided by sustainability.

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