Graphical Abstract

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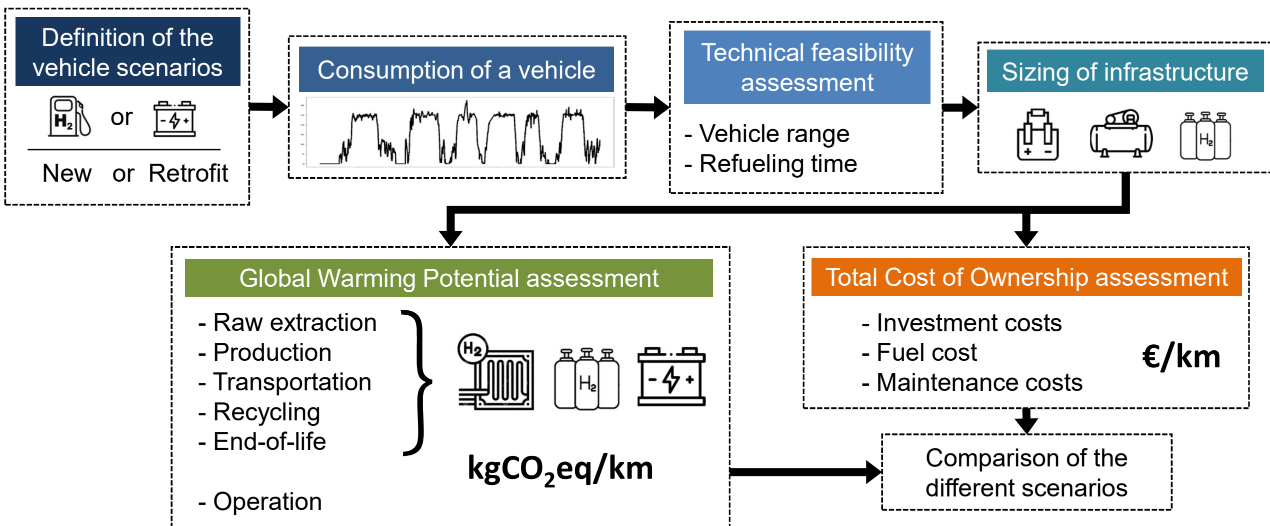

Highlights

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- GWP depends mainly on operation phase, the least on the transport of the technologies
- With marked relief, range and recharging time are a limit of battery coaches
- A battery and fuel cell coach mix results in an economic and environmental optimum
- Improvements in eco-driving and vehicle weight reduce costs and environmental impact

Investigating the use of hydrogen and battery electric vehicles for public transport: a technical, economical and environmental assessment

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Abstract

More and more territories are looking at alternatives to diesel for their public transport to decarbonise their energy mix. Electricity and hydrogen, among the most popular alternatives, are analysed in this article on the basis of various technical, economic and environmental criteria. The consumption of these vehicles is first estimated and the feasibility of their implementation validated in terms of range and recharging time. The economic criterion then evaluated is the total cost of ownership (TCO) of the vehicle fleet, and the environmental criterion is the global warming potential (GWP) of a vehicle, taking into account the life cycle of the main technologies that compose

Abbreviations: EoL, end-of-life; FC, Fuel Cell; GWP, Global Warming Potential; H2, Hydrogen; ICE, Internal Combustion Engine; LFP, Lithium-iron Phosphate; NMC, Nickel Manganese Cobalt; PV, Photovoltaics; TCO, Total Cost of Ownership

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it as well as the vehicle's operating phase. Here, coaches are analysed for the case study of Reunion Island. If the technical feasibility concludes that it is impossible to use a fleet entirely composed of electric vehicles, a fleet composed only of hydrogen vehicles would involve high TCO and GWP. A balance must be struck and improvements in vehicle consumption can be made to reduce the overall impact.

Keywords: energy transition, total cost of ownership, global warming potential, fuel cell vehicles, heavy mobility, Reunion Island

1. Introduction

Given the increasingly visible effects of climate change on the Earth, new solutions are being considered all over the world to reduce our dependence on fossil fuels. In particular, the mobility sector is at the heart of both debates and research. Indeed, it was responsible for the emission of nearly 8 gigatonnes of CO_2 worldwide in 2022 [1]. Over 73 % of these emissions come from the road sector, and 44 % from individual vehicles alone (3.53 gigatonnes of CO_2 in 2022 [2]). With their particular energy situation, combining dependence on climatic events, limited space and heavy reliance on private cars, island territories are particularly dependent on fossil imports for their mobility. Decarbonising the transportation sector is therefore a major challenge for these territories. The development of public transport is one of the plans to do so. For example, in the global transport sector in 2022, buses emitted less than 8 % of CO_2 emissions (0.45 gigatonnes of CO_2 [3]). In order to reduce global emissions, these means of transport need to be developed even further, and use low-carbon energy where this is not already the case.

The public transport sector, composed of buses and coaches, is often studied in the scientific literature for an optimal decarbonisation. While the former operate mainly in cities, with routes interspersed with numerous stops and carrying more passengers, the latter are mainly used for inter-city routes, which are longer and have fewer stops. As buses are the most commonly studied vehicles, the main solutions for decarbonising the sector include hybrid diesel-electric buses, natural gas buses, battery-electric buses or hydrogen fuel-cell buses. As a solution that has not yet been fully developed for this application sector, hydrogen-powered buses with internal combustion engines (ICE) are not widely discussed in the literature. The choice between one technology or another often depends on the application, and can be based on various technical, economic or environmental criteria. In [4], the authors analyse the total cost of ownership (TCO) of electric and hydrogen buses in public transport in a small to medium-sized city and its surrounding area in 2020 and in 2030. The same economic parameter is assessed in [5], but this time for diesel, gas, hybrid and hydrogen technologies in Australia. This criteria is also calculated in [6], centered on diesel, electric and fuel cell buses comparison, and providing an assessment of CO_2 emissions over the lifespan of the buses, and in [7], where diesel, compressed natural gas, fuel cell and electric buses from a tropical urban area are compared, with an additional criteria on bus pollutant emissions. Finally, this criteria can also be found in studies without hydrogen, like in [8], where the authors focus on the detailed comparison of two types of recharging for electric buses, depot charging or opportunity charging at terminal stops, or in [9] with a complete economic study involving the calculation of the net present value, the internal rate of return and the payback period for diesel, compressed natural gas and electric buses. Some studies do not consider an economic assessment and are interested in showing an environmental comparison, like in [10] where the carbon footprint of different fossil buses in Taiwan is calculated, with the one of electric and fuel cell buses. In [11] and in [12], a Life Cycle Assessment of different types of buses is build, considering extraction of raw materials through their utilization as fuel for the former, and total energy use by fuel type, greenhouse gases emissions and criteria air pollutants for the latter. In [13], the authors use a Life Cycle Assessment approach with a Life Cycle Inventory analysis, through an environmental model developed to assess the impact of energy carrier consumption and electricity origin on driving. Various energy sources, including wind, solar, waste, and grid electricity, are analyzed throughout the life cycles of the carriers and infrastructure. Finally, some studies compare technologies on the basis of economic and environmental criteria, like in [14], where the lifecycle costs and CO_2 emissions of diesel, natural gas, hybrid, fuel cell and electric buses are evaluated, or in [15], centered on the last two types of vehicle and assessing their emission reduction, capital, maintenance and energy costs. Sometimes other additional criteria can be studied, like noise pollution, sense of comfort or speed of traffic flow [16].

One of the main limitations of all these studies is the lack of detail in the sizing of the infrastructure required for refueling hydrogen vehicles, which is sometimes overlooked in the environmental impact calculations. This has been done in the literature, but the corresponding studies often focus on hydrogen technology and therefore do not allow a comparison with other technologies. This is the case of [17], which is investigating the sizing of the electrolyser to produce hydrogen for a bus fleet and its economic evaluation. In [18], the hydrogen fuel supply chain is optimised in order to minimise the levelized cost of hydrogen for fuel cell buses, but no environmental assessment is made. This is also the case in [19], which optimises hydrogen production in order to minimise its costs. Finally, [20] optimises the Levelized cost of driving and the Carbon Intensity of a diesel bus fleet, by optimising the proportion of vehicles converted to hydrogen, and [21] works on the configuration of the electricity supply system and the hydrogen production system to power a fleet of hydrogen-powered buses. This assessment is based on an energy, economic and environmental analysis. On the whole, economic studies offer consistent results. In the short term, they conclude that battery-powered vehicles are economically more advantageous than hydrogen-powered vehicles (still emerging sector, high costs and lack of infrastructure). In the long term, however, the conclusions are often reversed depending on the local situation. Meanwhile, environmental studies regularly fail to take into account the impact of technologies outside the vehicle's operational phase. This is often done for studies on individual vehicles, as in [22], but not for public transport. While the literature is often quite extensive concerning studies on buses, the present paper will focus on coaches, vehicles not studied in the literature. The technologies are similar, but the data may differ, as may the state of research and marketing, and the actual uses.

All these studies cover the techno-economic and life-cycle assessment aspects of zero-emission vehicles. Overall, coaches have been largely overlooked in public transport studies, as has hydrogen combustion in the consideration of new vehicle technologies. Moreover, very few studies take into account real speed profiles when estimating vehicle consumption, or the appropriate sizing of vehicle recharging technologies. Finally, there are very few articles comparing electric and hydrogen vehicles on the basis of TCO and global warming potential (GWP). Moreover, no literature article measures the impact of the latter criterion on in-vehicle technologies (batteries, fuel cells, hydrogen storage) for public transport.

In this way, the work proposed in the present article will address these previous shortcomings by proposing a complete comparison of hydrogen and battery electric coaches for public transport. This comparison will take into account hydrogen production infrastructure and their sizing will be detailed in the article. A technical, economic and environmental assessment of different coach technologies will be made, by evaluating the total cost of ownership and the global warming potential of these technologies. This last criterion will take into account all the stages in the life cycle of the technologies used in the vehicles and the operation phase of the vehicles. In particular, hydrogen retrofitted coaches and new hydrogen coaches will be compared with electric retrofitted coaches and new electric coaches. Vehicles with hydrogen ICE will also be considered in the study. The TCO of coaches will be studied on a real fleet over a period of 8 years (half the lifetime of the coaches studies). The methodology presented, although replicable to other case studies, will be applied to the local case of Reunion Island, a French island seeking to move closer to energy self-sufficiency and currently considering hydrogen as a solution to decarbonise its mobility. Considering an island territory as a case study offers a number of specificities: for example, terrain and climatic conditions may involve higher vehicle consumption than found in most of the literature. In addition, it is possible to model the entire electricity network and consider the impact of vehicles on it. Finally, as mentioned at the beginning of the introduction, the transition of these territories is a major challenge that needs to be studied. The work will enable the advantages and disadvantages of the technologies studied to be presented in terms of different criteria, so as to provide an overall view of each possible solution for the area in question. The results obtained will therefore be specific to the case study, and if one technological solution stands out, this may not be the case elsewhere.

Following the introductive section, the methodology is presented in Section 2. In this section, the modelling of vehicle consumption is described as well as the sizing of hydrogen vehicle refueling infrastructures. The two economic and environmental criteria assessed in the work, the TCO and the GWP, are also presented. In Section 3, the case study is described, with every local data and assumptions detailed. Finally, Section 4 presents the obtained results and discusses them. This section starts with a subsection on the technical feasibility of every scenario studied, then details the economic and environmental assessment of the two criteria introduced above. The article concludes in section 5.

2. Methodology

The objective of the present article is to compare different technologies of public transportation, over different criteria. In particular, different technologies of coaches will be studied: electric ones, composed of a battery and refueled by electricity, hybrid ones, composed of a battery and a fuel cell and refueled by hydrogen, and hydrogen ones, composed of a battery and a combustion engine, and refueled by hydrogen. Scenarios involving retrofits and investment in new vehicles will be considered.

The first aspect to assess is the technical feasibility of the different modelled scenarios compared to local characteristics. In particular, local energy production, range of the vehicles and refueling time will be studied. To do so, the consumption and the distances traveled by the different vehicles are required. Then, the size of the infrastructure required to supply them are investigated, before starting the comparison over economic and environmental points of view. The total cost of ownership (TCO) in euros per kilometre for a whole fleet are first calculated to make an economic comparison of the technologies. Then, the global warming potential (GWP) is assessed to make an environmental comparison. If the final results obtained are contradictory in the case of the economic assessment and in the case of the environmental one, the choice of one technology over another can be made in relation to other criteria (water consumption, consumers acceptance, etc.). A summary of the followed methodology can be seen in Figure 1.

2.1. Energy consumption estimation

The first step before assessing the technical feasibility of the different modelled vehicles is the estimation of their average energy consumption. To do so, the power consumption of a vehicle at each timestep of its journey is studied, and one or more speed and elevation data profiles are required. These can be taken from real data or simulated, but are necessary to estimate the fuel consumption of the vehicle at best. The different forces applied to

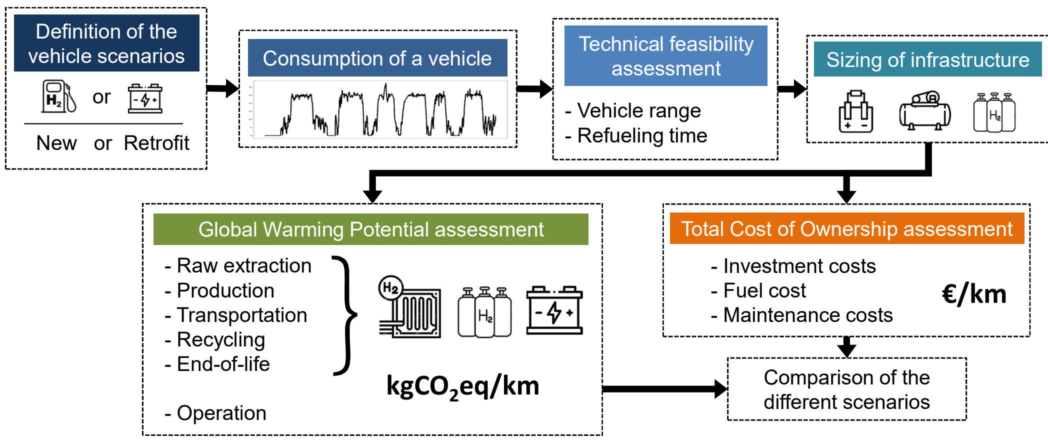

Figure 1: Methodology of the present study.

the vehicle are calculated at each timestep [23]:

$$F_a(t) = \frac{1}{2} \times \rho \times A \times C_x \times v(t)^2 \tag{1}$$

$$F_r(t) = m \times C_r \times g \times \cos\alpha(t) \tag{2}$$

$$F_g(t) = m \times g \times \sin\alpha(t) \tag{3}$$

with F_a the aerodynamic resistance (N), F_r the rolling resistance (N), F_g the climbing resistance (N), ρ the air density taken at 1.21 kg/m^3 [24], g the gravitational acceleration taken at 9.81 m/s^2 and m the mass of the vehicle (kg). A stands for the vehicle frontal area (m^2), C_x the vehicle drag coefficient and C_r the rolling resistance coefficient, three parameters specific to the modelled vehicle. Finally, v the speed (m/s) and α the slope (radians) are two variables changing at each timestep. To obtain power at the wheels P_{wheels} (W), all the forces introduced previously are summed [25]:

$$P_{wheels}(t) = v(t) \times \left(m\frac{dv(t)}{dt} + F_a(t) + F_r(t) + F_g(t) \right) \tag{4}$$

The instantaneous power $P_{traction}$ (W) is then calculated [8]:

$$P_{traction}(t) = P_{AC} + \begin{cases} \frac{P_{wheels}(t)}{\eta}, & \text{if } P_{wheels}(t) \geq 0 \\ P_{wheels}(t) \times \eta \times r, & \text{if } P_{wheels}(t) < 0 \end{cases} \quad (5)$$

with P_{AC} the additional power required for the air conditioning or heating in the vehicle (in W, assumed constant during the journey), η the drivetrain efficiency taken at 0.8 [23] and r the percentage of energy recovered during downhill. Finally, the energy consumed in kWh during the journey of the vehicle is obtained by integrating the power profile:

$$E_{elec} = \int P_{traction}(t)\, dt \quad (6)$$

For a comparison between electricity-powered vehicles and hydrogen-powered ones, the hydrogen consumption is obtained from the global energy consumption:

$$E_{hydrogen\_FC} = \frac{E_{elec} \times 3.6}{LHV \times \eta_{FC}} \quad \text{or} \quad E_{hydrogen\_ICE} = \frac{E_{elec} \times 3.6}{LHV \times \eta_{H2ICE}}, \quad (7)$$

depending if the hydrogen is used to power an electric motor or a combustion engine. In Eq. 7, LHV is the low heating value of hydrogen taken at 120.1 MJ/kg [23], η_{FC} is the efficiency of the fuel cell taken at 0.47 [24] and η_{H2ICE} is the efficiency of the combustion engine taken at 0.40 [26]. Both efficiencies were considered constant for the consumption estimates of this work. The 3.6 factor is used to convert E_{elec} from kWh to MJ. To simplify estimates, the operation of the battery in hydrogen-powered vehicles has not been modelled. Hydrogen consumption results will therefore be slightly overestimated.

Once an average consumption obtained, it is possible to first assess the technical feasibility of the different scenarios, considering the range of the vehicles, their refueling time and the average distances traveled every day. For hydrogen-powered vehicles, considering a normal refuelling rate at 3.6 kgH_2/min [27] and one or more tanks onboard for a total between 25 and 73 kgH_2 [28], the refueling time of one coach will not exceed 20 minutes, thus not constituting a strong constraint on the feasibility of the technology. Daily demand can then be generated, using a profile from [20] and adapting it according to local constraints (working hours mostly). However, for electricity-powered vehicles, the charging time will depend on the charging power chosen, influencing directly power demand on the grid and lifetime of the embedded batteries [29]. To deal with this specific constraint, the network considered must be studied more precisely, in order to establish whether several charging per day are necessary, and if so whether fast charging is necessary.

Once the technical feasibility is confirmed, it is possible to model a demand profile for one year, in order to simulate the operation of the whole electricity grid with an additional consumption for the mobility, and to size the refueling infrastructures at the same time. Indeed, these data will be required for the economic and environmental comparison.

2.2. Infrastructure modeling

To assess the impact of hydrogen mobility on the case study, it is essential to consider the entire hydrogen production process. In this section, the modelling used to size the infrastructure (electrolyser, compressor, stationary hydrogen storage) is detailed. For electric scenarios, there is no charging infrastructure that needs to be sized, as the vehicles are powered directly from the grid and the charging power will be fixed considering the required

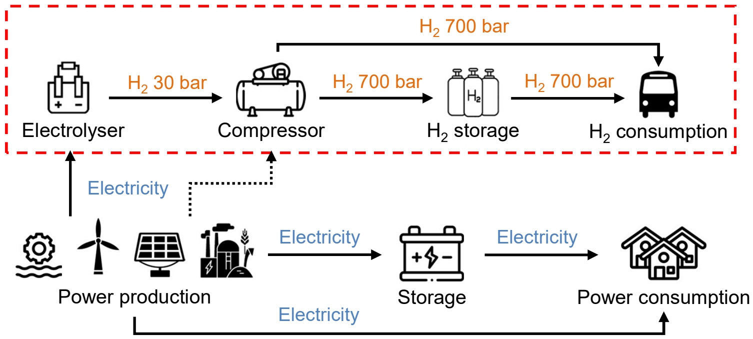

Figure 2: Modelling of a substation of the grid with a hydrogen refueling station framed in dots.

charging time.

The hydrogen necessary to refuel the coaches is produced locally by electrolysis of water, using electricity from the grid. Each refueling station is linked to a substation of the grid, as can be seen in Figure 2. Several refueling stations can be considered and placed near substations with high installed power generation capacities [30].

It is therefore important to take an interest in the grid and consider the energies that will make it up. The whole electrical system is modeled with PyPSA [31], which will allow the sizing of the refueling infrastructures. Moreover, line reinforcement is investigated with the model, as well as additional batteries at every substation, necessary to allow the operation of an electrical system with a high percentage of renewables, which is the aim of many territories in the coming years. The following notations are adopted: n for the different substations of the grid, k for the different refueling stations, s for the different technologies installed at the same station and t for the timesteps (every hour of the year simulated). The optimization of the sizing of refueling infrastructure is made with a minimization of the investment and operating costs, as defined in the objective function below:

$$min \sum_{n} c_{n,bat}\bar{e}_n + \sum_{k,s} \left[c_{k,s}\bar{gh}_{k,s} + c_{k,h2}\bar{eh}_k\right] + \sum_{l} c_l F_l$$
$$+ \sum_{t}\sum_{n,s} \left[o_{n,s,t}g_{n,s,t} + o_{n,bat,t}h_{n,t}\right] + \sum_{t}\sum_{k,s} \left[o_{k,s,t}gh_{k,s,t} + o_{k,h2,t}hh_{k,t}\right] \quad (8)$$

with $c_{n,s}$ the investment costs of a new technology, $\bar{e}_n$ the size of new batteries at every substation (MWh), $\bar{gh}_{k,s}$ the nominal power of electrolysers and compressors (MW), $\bar{eh}_k$ the size of stationary hydrogen storages (MWh), c_l the costs of electrical line reinforcement, F_l the line reinforcements (MVA), $o_{n,s,t}$, the operation costs of the technologies, $g_{n,s,t}$ the operation of electricity production technologies, $h_{n,t}$ the operation of batteries, $gh_{k,s,t}$ the operation of electrolysers and compressors and $hh_{k,t}$ the operation of hydrogen tanks, all in MW. Even if line reinforcement and additional batteries are included in the objective function, they will not be considered in the following economic assessment. Indeed, some previous study showed that line reinforcement and additional batteries are required in the medium term in order to aim for a more self-sufficient electricity grid [32]. Their sizing obtained in the present optimisation is thus not directly related to the presence of hydrogen vehicles and their impact will not be considered for the present study, focusing on the implementation of hydrogen refueling stations and the corresponding technologies.

The main constraints of the optimisation problem is the satisfaction of both electric (Eq. (9)) and hydrogen (Eq. (10)) demands:

$$\sum_{s} g_{n,s,t} + h_{n,t} - \sum_{l} K_{nl} f_{l,t} = d_{n,t} + gh_{n,ely,t} + gh_{n,comp,t} \cdot \beta_{comp.} \tag{9}$$

$$gh_{k,ely,t} \cdot \eta_{ely} + hh_{k,t} = dh_{k,t} \tag{10}$$

with η_{ely} the efficiency of the electrolyser, taken at 50 kWh/kgH_2 [33], $\beta_{comp.}$ the electric consumption of the compressors, taken at 1.68 kWh/kgH_2 [34], $d_{n,t}$ the electrical demand at a substation and $dh_{k,t}$ the hydrogen demand at a refueling station. The operation rate of electrolysers and compressors is imposed over the year with Eq. (11):

$$\sum_{t} gh_{k,s,t} \geq \sum_{t} 1 \times CF \times \bar{gh}_{k,s} \tag{11}$$

with CF a capacity factor taken at 0.9. Removing this constraint would lead to the electrolysers and compressors being oversized for economic optimum, and to highly intermittent operation, mainly at full power for less than ten hours a day. Decreasing the value of the capacity factor will also mean an increase in the size of the technologies and a more intermittent operation. The operation of hydrogen storage units is defined with the following equations:

$$eh_{k,t} = eh_{k,t-1} - hh_{k,t} \tag{12}$$

$$eh_{k,tinitial} \times (1 - 10\%) \leq eh_{k,tfinal} \leq eh_{k,tinitial} \times (1 + 10\%) \tag{13}$$

$$\bar{eh}_{k,s} \geq max \sum_{24\text{h}} dh_{k,t} \tag{14}$$

$$eh_{k,s,t} \geq max \sum_{24\text{h}} dh_{k,t} \tag{15}$$

Eq. (12) determines the stored energy with standing loss considered at zero and Eq. (13) defines a soft cyclical operation of the storage over the simulated period. Eq. (14) enforces a minimum size for every hydrogen storage $\bar{eh}_k$. At each station, these must be large enough to cover the maximum hydrogen demand $dh_{k,t}$ for a whole day. This one-day demand is not identical over the year, and can vary between a working day and a public holiday. Moreover, Eq. (15) enforces the state-of-charge of these storages to be at least equal to this same demand. This measure reinforces the previous constraint, and makes it possible to locally store the demand for a full day for the whole fleet, to minimize the risk of not being able to run the fleet due to an issue on the electrolyser or the compressor [35]. This constraint directly influences the size of optimized storage.

The main results obtained from this optimisation are the size of the electrolysers, compressors and hydrogen storages, as well as the quantity of electricity produced used for the hydrogen refueling of the coaches and the composition of the electricity mix. The installed capacities of electricity generation technologies are not optimisation variables, but parameters of the optimisation problem. In addition, electricity production models for intermittent energy sources (photovoltaics and wind), have been determined on the basis of historical production and meteorological data, and the resulting hourly production is therefore not directly optimised. Once the results collected, the economical and environmental comparison of the different scenarios can be implemented.

2.3. TCO calculation

To start with the economic comparison of the technologies, their total cost of ownership will first be calculated. This criterion groups together all the direct and indirect costs involved for a fleet of vehicles, and is expressed as a function of the travelled distance [36]. It is often used in the literature and therefore enables different technologies, different models or different case studies to be compared. The TCO of a scenario j (kind of coach technology) is calculated as follows:

$$TCO_j = \frac{(IC_j + II_j) \times CRF_j - RV_j + FC_j + MC_j + MI_j}{KM} \tag{16}$$

with IC_j the investment costs for the vehicle, II_j the investment costs for new infrastructure, RV_j the residual value of the vehicles if the end of their lifetime has not been reached at the end of the simulated period, FC_j the fuel costs for a year of operation, MC_j the vehicle annual maintenance cost and MI_j the infrastructure annual maintenance cost. Finally, KM stands for the number of kilometres travelled during a year by the whole fleet. CRF_j stands for the capital recovery factor, calculated as follows:

$$CRF_j = \frac{i \times (1+i)^{n_j}}{(1+i)^{n_j} - 1} \tag{17}$$

with i the discount rate taken at 4.5 % [37] and n_j the lifetime of the technology.

A few assumptions were taken for the calculations. Fuel cost is determined with electricity cost, as well as operation cost of electrolyser for hydrogen-powered coaches. If one scenario includes a retrofitting operation, no residual value has been considered for the old elements. Vehicle insurance and labour costs are not included in the calculations, because of a lack of data and an assumption of a small influence in the comparison. No national purchase aid was considered, whether for the retrofitting, the purchase of a new coach or the installation of new infrastructure. The obtained results can therefore be considered as an upper bound compared with costs that can be found in

Parameter	Value	Unit	Reference
Hydrogen retrofit cost	400	k€	Manufacturer
Hydrogen coach	620	k€	[20]
Electric retrofit cost	300	k€	[40]
Electric coach	440	k€	[38]
Maintenance cost of coaches	0.11	€/km	[4]

Table 1: TCO parameters for coaches.

return on experience reports. As electricity-powered coaches have a smaller range than hydrogen-powered ones [37, 38, 39], the possibility of fast charging at the terminus will be considered, with a comparison with a full charging at a charging station a few times a day. Data that can be used generically are detailed in Tables 1 and 2. Case-specific data will be detailed in section 3. It is assumed that a hydrogen station is based on an electric station, with some cost requirements for the depot charging station, the grid connection, the planning and the transformer.

2.4. GWP calculation

After the presentation of the criterion used for the economic assessment, the calculation of the global warming potential can be presented for the environmental comparison of the vehicles. This criterion, expressed in $kgCO_2eq$ or $kgCO_2eq/km$, represents the impact of a single unit of greenhouse gas on the greenhouse effect, and allows to take into account CO_2 but also other greenhouse gases, converted into their equivalents in terms of carbon dioxide. In the present study, this criterion is calculated for the fuel cells, hydrogen

Parameter	**Value**	**Unit**	**Reference**
Electrolyser	410	€/kW	[41]
Electrolyser operation	0.154	€/kWh	[33]
Electrolyser maintenance	2	% of investment / year	[41]
Compressor	550	€/kW	[41]
Compressor maintenance	4	% of investment / year	[41]
Hydrogen tank	1350	€/kgH_2	[27]
Hydrogen tank maintenance	3	% of investment / year	[4]
Hydrogen dispenser	65	k€	[20]
Hydrogen dispenser maintenance	3	% of investment / year	[20]
Electric station (depot charging station, grid connection, planning, transformer)	34	k€	[4]
Electric dispenser	35	k€	[38]
Electric dispenser maintenance and operation	0.14	€/kWh	[4]
Fast charging station (with coupling system and transformer)	515.5	k€	[4]
Fast charging station maintenance	5	k€/year	[4]

Table 2: TCO parameters for infrastructure.

Technology	GWP from raw material extraction, production and EoL	GWP with recycling	Reference
LFP battery	227.72 $kgCO_2eq/kWh$	127.45 $kgCO_2eq/kWh$	[43]
NMC battery	160.85 $kgCO_2eq/kWh$	128.48 $kgCO_2eq/kWh$	[43]
Fuel cell	42.94 $kgCO_2eq/kW$	29.47 $kgCO_2eq/kW$	[42]
Hydrogen tank	8.49 $kgCO_2eq/kWh$	x	[42]

Table 3: GWP data.

tanks and batteries of the different vehicles. This is done on different life cycle steps: raw materials extraction, production, transportation, recycling and end-of-life (EoL). The recycling phase will have an impact on the extraction and production of raw materials, thereby reducing emissions from the corresponding stages. This step is however not considered for the hydrogen tanks, as it is not possible yet to recycle them because of their high carbon fibre content [42]. Data used for all life cycle steps except transportation can be found in Table 3. Impacts of infrastructure, like electrolysers, compressors or dispensers are not considered as the assessment of the GWP focuses on the technologies inside the vehicles.

For the transportation step of the assessed technologies, it is possible to consider different countries of origin and different ways of transport. Methodology from [44] is followed and Eq. (18) from [43] is used to calculate the GWP of this step:

$$GWP_{transport,s} = \frac{1}{E_s} \times \sum_i F_i D_i \tag{18}$$

with E_s the specific energy or power of a technology (data used are sum-

Technology	Value	Reference
LFP battery	151.3 Wh/kg	[43]
NMC battery	207.4 Wh/kg	[43]
Fuel cell	650.0 W/kg	[45]
Hydrogen tank	1400.0 Wh/kg	[46]

Table 4: Specific energy and power densities data.

Transportation mode	Value ($gCO_2eq/t.km$)
Truck (26 tons)	161.00
Truck (40 tons)*	94.00
Container ship	10.70
Electric train in France	1.55
Diesel train	28.10

* Used when main mode of transport is container ship

Table 5: Emission factor data from [43] for transportation mode.

marised in Table 4), F_i the emission factor of a mean of transportation per ton transported and per kilometre travelled (in $gCO_2eq/t.km$, data used are summarised in Table 5) and D_i the distance travelled by this mean of transportation in km. Different scenarios can then be simulated, with different transportation modes and different countries of origin when the exact place of origin of the technology was not given by the manufacturer. As this step has usually a small impact over the whole GWP, the worst case can be taken for each technology; for the transportation mode, a transport by truck is often the most impactful. For the scenarios with a retrofitting operation, it

Technology	Value (gCO_2eq/kWh)
Onshore wind	14.1
Photovoltaics	43.9
Hydroelectricity	6.0
Biomass	228.3
Biogas	342.4
Fossil	730

Table 6: Emission factor data for electricity generation facilities used, from [47].

is assumed that all elements have to stop at the place where the company selling the kit is located.

Finally, the emissions generated by the operation of vehicles are the last component of the GWP. Data used to estimate the impact of the electricity mix can be seen in Table 6.

3. Case study

The present article focuses on the case study of Reunion Island, a French overseas department located near Madagascar. With a population of nearly 900 000 inhabitants, the territory must import most of its energy, either for electricity production or mobility. In 2021, Reunion Island was dependent at 88.2 % on fossil fuel imports for its primary energy consumption [48]. In particular, the mobility sector represents a major challenge. Indeed, of all the fossil fuels imported each year, almost half are allocated to the transport sector, of which 70 % are for the road sector only. This represented 450 ktoe in 2021 [48]. This amount has been increasing every year since 2000, and one of the main causes is the inhabitants' heavy dependence on private cars. Traffic jams on the island's various roads are a daily occurrence, and the private car fleet numbered almost 400,000 vehicles at the end of 2019, i.e. almost one car for every two inhabitants [48]. With the aim of the territory to reach energy self-sufficiency by 2030 [49], public transport, already present on the island, will need to be further developed in order to reduce fossil fuel imports in the years to come. Moreover, new technologies will need to be considered, such as electric or hydrogen vehicles, in order to achieve a complete decarbonisation of the road sector.

The present study focuses on the coaches of the island's regional bus network. A project for several hydrogen-powered coaches is currently being studied for this network; hydrogen can be seen as a solution for replacing fossil fuels in buses, allowing a better range and a shorter refueling time than with an electric vehicle. In France today, at least four cities are already equipped with hydrogen-powered buses [50]. In the present case, the studied vehicles are coaches, and not buses, more used for long distances and for inter-city travel. For hydrogen vehicles, fuel cell ones (with retrofitting operation or not) will be considered here, as well as vehicles with internal combustion engine, even if nothing is currently available on the market. Also part of the comparison, electricity-powered coaches (with retrofitting operation or not) will be studied.

The present work will compare the different technologies installed in the considered vehicles. These are detailed in Table 7. The chemistry of the batteries used is detailed because of their differing impact on the environment; the acronym NMC stands for Nickel Manganese Cobalt, while LFP stands for Lithium-iron Phosphate.

To estimate the hydrogen demand of the coaches of the regional network, a scenario with a higher daily bus mileage than today is proposed: a 12 % increase in annual mileage, from almost 8 Mkm to almost 9 Mkm [30]. The same number of coaches composing the fleet as today is considered, assuming that they travel more kilometres per day (about a hundred vehicles). Then, three different speed and elevation profiles were recovered, for three different lines of the studied network: two for two regular lines, travelling along the coast, and one for a line with a more marked relief. These data are visible on Figure 3. Speed, latitude and longitude data were collected with the GPS logger application inside one coach during its journey. Elevation data were obtained with GPS Visualizer [52]. In order to deal with measurement errors, the data recorded per second were averaged every 5 seconds. Data with too high elevation differences per second were also corrected. Finally, to estimate energy consumption of the vehicles, data specific to the case study from Table 8 were used. The percentage of recovery on downhill sections was taken to be lower than what is used in the literature, because the roads travelled included a large number of curves, making brake use high and recovery low.

To produce the energy that will power the coaches, a 100 % renewable electricity mix is simulated. Given the strong political will to reduce carbon emissions, this objective could be achieved in the years to come. The electricity mix is composed of photovoltaics, hydroelectricity, wind turbines, biomass and biogas. Installed capacities were determined considering current local projects, potential studies and existing planning decisions [32]. Two other short-term scenarios (named Scenario 2 and 3) were simulated in order

Technology	Fuel cell	Hydrogen tanks	Batteries	Reference	Refueling infrastructure
Hydrogen retrofit	150 kW	36 kgH_2	84 kWh (NMC)	[51]	Electrolyser, compressor, hydrogen stationary storage
Hydrogen coach	180 kW	72.8 kgH_2	160 kWh (NMC)	[28]	Electrolyser, compressor, hydrogen stationary storage
Electric retrofit	x	x	192 kWh (LFP)	[28]	Slow charging at depots, fast charging at main stops
Electric coach	x	x	375 kWh (LFP)	[28]	Slow charging at depots, fast charging at main stops

Table 7: Data on technologies used in the vehicles.

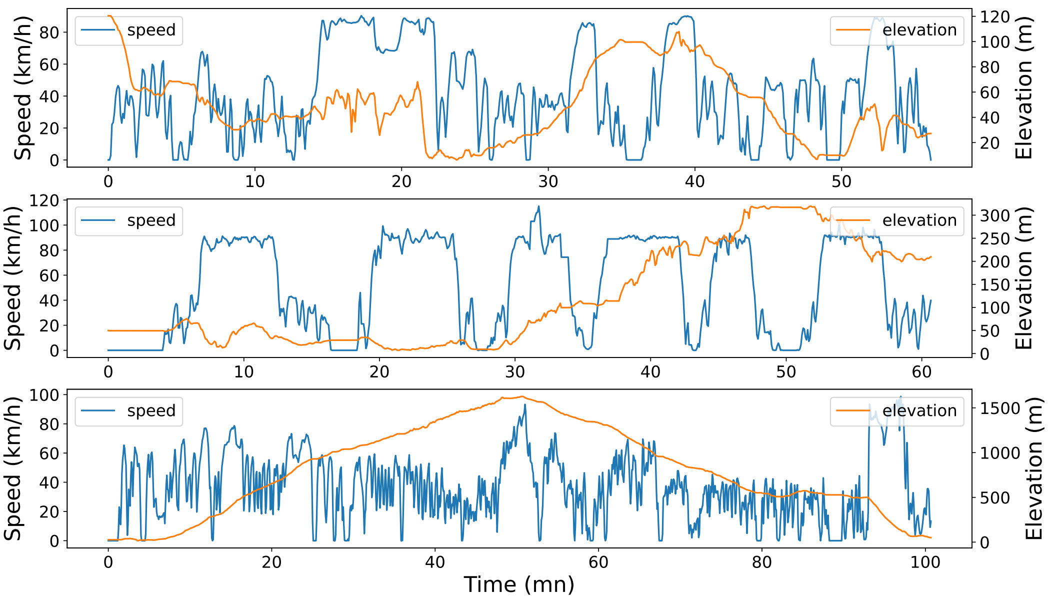

Figure 3: Speed and elevation profiles for three lines of the studied coach network. First line will be called "Regular line 1" in the following, second line "Regular line 2" and third line "Line with marked relief".

Parameter	**Symbol**	**Value**	**Unit**	**Reference**
Full vehicle mass	m	23	tons	[53]
Frontal area	A	8.59	m^2	[53]
Drag coefficient	C_x	0.66	-	[54]
Rolling resistance coefficient	C_r	0.0075	-	[8]
Air conditioning power	P_{AC}	6 800	W	[55]
Energy recovery	r	20	%	Assumption

Table 8: Parameters used for the estimation of energy consumption.

to quantify the impacts of electricity mix on results. Details of these scenarios (installed capacity and electricity mix resulting from the simulations) are shown in Table 9.

In parallel, for the modelling of the whole electrical system, the base electricity consumption consists of the Energy Efficiency (EE) scenario from [32]. This scenario assumes a rather small increase and non-trend consumption in electricity compared to current and historical data, assuming better demand management and energy performance. Moreover, the electricity consumption of individual electric vehicles was not considered as the focus of the paper is on public transport, and the greening of other bus networks' fleets of Reunion Island was not studied as the focus is on the regional lines. Concerning the sizing of the hydrogen infrastructure, two refueling stations with three dispensers each are considered for the modeling of the hydrogen-powered coaches scenario, to be able to charge in coaches in the North and South areas of the island.

The fact that the average age of the vehicles in the current fleet of the regional network is less than seven years was obtained from the network operator. Considering that the lifetime of a coach is sixteen years [37], the two economic and environmental criteria will be calculated in the present study for a period of eight years, from year 8 to year 16, following the methodology of [56]. The different scenarios compared are the following:

- hydrogen retrofit with an electric motor of the diesel coaches (after eight years of operation),
- scrapping of the diesel coaches (after eight years of operation) and purchase of new hydrogen coaches of a sixteen years lifetime,

- electric retrofit of the diesel coaches (after eight years of operation),
- scrapping of the diesel coaches (after eight years of operation) and purchase of new electric coaches of a sixteen years lifetime.

The only cost needed that is specific to the case study is electricity price, which is taken at 0.1166 €/kWh as current average electricity price excluding taxes in Reunion Island for local authorities with a contract power of more than 250 kVA. This choice was made because this price is common to all French territories and its evolution over time is difficult to predict. The impact of the 100 % renewable electricity mix is taken at 123.3 gCO_2eq/kWh, calculated with the average electricity mix resulting from the simulations, visible in Table 9. The other two electricity mix scenarios give impacts of 124.7 and 126.2 gCO_2eq/kWh. Scenario 2 represents the island's current situation, with a final combustion turbine using fuel oil. As this turbine only is used for peak demand or when other means of power generation are shut down, the carbon impact of the electricity mix is barely affected. The difference in consumption from one coach integration scenario to another only affects the production of biomass and biogas plants, because of intermittent resources depending on weather conditions, and hydropower resources being often used to the maximum because of its low cost. With data from Table 6, it can be seen that the calculated carbon impact is deteriorated by the high use of biomass and biogas resources on Reunion Island. The emissions on the operation step will be calculated over eight years.

Regarding scenarios with electricity-powered vehicles, some additional assumptions were made. Following the data used in [57], it will be assumed that the batteries of the electric vehicles cannot be discharged below 20 %,

Technology	Scenario 1	Scenario 2	Scenario 3
Onshore wind	50 MW 153 GWh	50 MW 153 GWh	91.5 MW 280 GWh
Photovoltaics	600 MW 780 GWh	600 MW 780 GWh	470 MW 600 GWh
Hydroelectricity	150 MW 800 GWh	150 MW 800 GWh	146 MW 778 GWh
Biomass	429 MW 1 200 GWh	429 MW 1 200 GWh	429 MW 1 300 GWh
Biogas	48 MW 210 GWh	48 MW 210 GWh	48 MW 210 GWh
Fossil	0 MW 0 GWh	80 MW 10 GWh	0 MW 0 GWh

Table 9: Details of the installed capacity and average electricity mix resulting from power system simulations.

Scenario	Regular line 1	Regular line 2	Line with marked relief
Electricity consumption	152.1 kWh/100km	176.7 kWh/100km	206.7 kWh/100km
Hydrogen consumption (FC)	9.7 kgH_2/100km	11.3 kgH_2/100km	13.2 kgH_2/100km
Hydrogen consumption (ICE)	11.4 kgH_2/100km	13.2 kgH_2/100km	15.5 kgH_2/100km

Table 10: Results of the consumption study.

nor charged above 80 %, this to preserve their lifetime. Moreover, to estimate the number of fast charging stations required, it will be assumed that the maximum power charging at these stations is 300 kW per dispenser [57].

4. Results and discussion

The technical comparison of the vehicles will first be detailed, with the results of the estimation of their consumption and the sizing of the refueling infrastructures. The calculated TCO and GWP will then be presented.

4.1. Technical comparison

Following the study of the consumption of different types of vehicles, different results were obtained. These are visible in Table 10. In the case of a regular line, it can be seen that the obtained results are close to the data usually used in the literature, whether for electric [58] or fuel cell [11] vehicles. A sensitivity analysis was carried out to assess the uncertainty surrounding the various parameters used to calculate consumption, the results of which

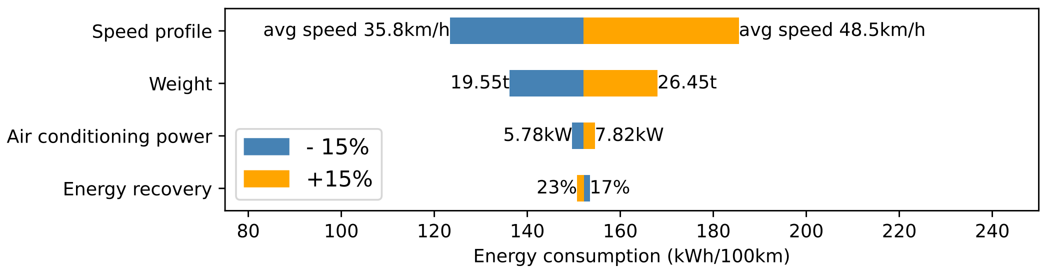

Figure 4: Tornado chart on Regular line 1 consumption showing a $\pm 15\,\%$ sensitivity analysis on energy consumption of a vehicle.

are visible in Figure 4. If this validates the importance of using a real speed profile and the impact of the mass of the vehicle, it also shows that the uncertainties on the consumption of the air conditioning and the energy recovered in downhill are small. Finally, the results obtained in the case of a line with marked relief show the impact of it on the consumption of the vehicle, with an increase of 36 % of the latter. With regard to the fuel consumption of hydrogen-powered vehicles, a 15 % improvement in the efficiency of the fuel cell (0.54) and the thermal engine (0.46) would lead to fuel consumption of 8.4 $kgH_2/100km$ and 9.9 $kgH_2/100km$ respectively (-13 %) for Regular line 1. It is important to first remember that the operation of the battery inside the hydrogen vehicles has not been simulated and to then specify that the obtained results allow us to estimate an average consumption, but would not be sufficient in the case of sizing on-board technologies. To do that, a more precise study should be carried out.

With this consumption data, the range of the vehicles can be assessed. According to the network operator, some vehicles travel around 400 km per day. In the present study, it is assumed that all the coaches travel an average

Scenario	Electrolysers	Compressors	Hydrogen tanks
FC coaches	3.09 MW / station	2.04 MW / station	2.23 tH_2 / station
	Total: 6.18 MW	Total: 4.08 MW	Total: 4.46 tH_2
ICE coaches	3.58 MW / station	2.39 MW / station	2.61 tH_2 / station
	Total: 7.16 MW	Total: 4.77 MW	Total: 5.22 tH_2

Table 11: Results of the hydrogen infrastructures sizing. The electricity mix used for the simulation does not have an impact.

of 400 km per day. By grouping the results of Tables 7 and 10, the following conclusions can be drawn. First, if the coaches were all equipped with fuel cells, around two refuelings per day would be required (range of around 300 km). In the case of a vehicle with large on-board storage, such as a new hydrogen coach or one with a combustion engine (without on-board fuel cells, there is more space for storage), two refuelings for three days of operation would be necessary (range of more than 600 km). The results of the hydrogen station refueling infrastructure sizing are shown in Table 11. These data are necessary to evaluate the TCO and GWP of the entire hydrogen chain. It is important to note that the size of the technologies is directly proportional to the total demand for hydrogen on the island. For the same number of stations, if demand is halved, then the size of the technologies will be halved. However, if the number of stations were to change (e.g. 3 stations installed or 4), the total installed hydrogen storage would vary slightly, as shown in [30].

It can be seen that in both scenario a hydrogen storage capacity of more than two tons of hydrogen would be required. This would involve cumbersome administrative procedures in France, as such project must be subject to authorization. Thus, it could be more beneficial to install more refueling stations to spread consumption and reduce administrative procedures. Another solution could be the removal of the constraint minimizing the size of the storages in order to ensure a minimum supply (Eq. 14 and 15). Finally, a last solution could be the evolution of current regulations, taking the example of Germany, where hydrogen storage can reach 3 tons on the same site before undergoing heavier procedures [59].

For electricity-powered vehicles, the problem is addressed from another side. It is assumed that batteries cannot be discharged below 10 %, nor charged above 95 % [8]. This constraint directly impacts the range of the vehicles considered. Thus, for a retrofitted vehicle, the range will be around 117 km for a regular line and around 93 km for a line with marked relief. For a new electric coach, the range will be around 228 km for a regular line and around 181 km for a line with marked relief. Regarding the vehicles recharging time, it is assumed for the case study that a vehicle should not have to stop for more than 5 minutes during a race to charge its battery. This would mean that a maximum of only 25 kWh could be charged with a power of 300 kW. With the consumption data obtained in Table 10, this corresponds to 15 km on a route with little relief. Considering the lengths of the different lines composing the network and although the consumption of the vehicles was overestimated by taking a full coach and a high consumption of air conditioning, it seems technically difficult to consider vehicles with electric retrofit for the entire studied network (longest journey is 110 km long and has very few stops). Indeed, if it is assumed that a vehicle cannot be fully recharged during the day (because of charging time, availability of operators, impacts on the grid or impacts on battery lifetime), the use of retrofitted electric coaches is not possible. The implementation of new electric coaches could be possible with the use of fast charging stations and with a reduction in the daily mileage of some vehicles, but seems difficult in the case of lines with marked relief. Therefore, from a technical point of view, it is better not to implement the transition of Reunion Island's coach network using only electric vehicles, as they are currently available on the market and with current charging technologies.

However, the optimal composition of the fleet between electric and hydrogen vehicles, as well as the daily mileage of each vehicle will not be studied here. This would require more data on the network, such as the number of vehicles per line or the location of depots and the distances travelled by the vehicles between their commercial journeys. In this way, the total cost of ownership of fleets composed of a single type of vehicle will be evaluated. This will enable to set limits on the TCO of an optimum fleet. The GWP of the different types of bus will then be evaluated.

4.2. TCO

For the assessment of the total cost of ownership, coaches burning hydrogen will not be considered because of missing data. The obtained results are visible in Table 13.

The calculated TCO shows a clear difference between a hydrogen technology and an electric one. As can be seen in Table 13, in the case of the modelled coach fleet, a hydrogen fleet would have a TCO in euros per kilometre around 2 times higher than the one of an electric fleet. This result

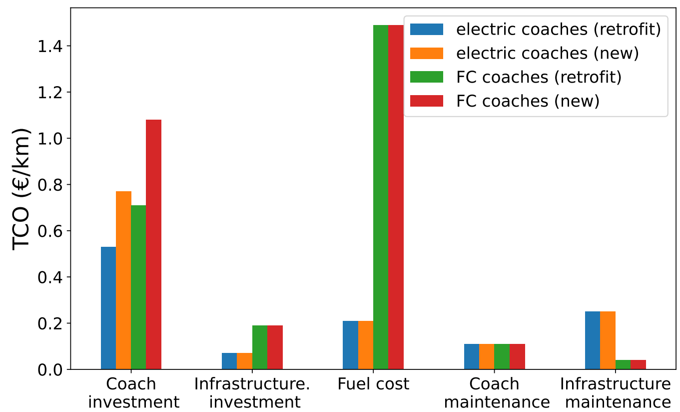

Figure 5: Details of the breakdown of the TCO. The electricity mix used for the simulation does not have an impact.

validates the economic optimality of having a fleet made up of both battery and fuel cell vehicles, so as to reduce the TCO of a fleet made up exclusively of the latter. Details of these costs are shown in Figure 5. The main difference between the two technologies lies in the cost of powering the vehicles. Indeed, powering hydrogen coaches requires more electricity, and the operating cost of the electrolysers as well as the electricity consumption of the compressors have to be taken into account. Finally, it is important to note that, as this TCO criterion depends on the kilometres travelled, the obtained results will vary according to the configuration of the network and the lines.

Given the large difference in TCO for hydrogen coaches, a sensitivity analysis was carried out to identify the parameters with the greatest influence on this criterion, and thus study the possible evolution of the obtained results in the coming years. Knowing that half of the TCO comes from fuel supply, this analysis is carried out on coach consumption (a parameter that also influences infrastructure sizing), electricity cost and operating cost of the electrolyser. Another parameter is also studied as source of uncertainty in the modelling: the investment cost of the retrofit, as well as that of the electrolyser, compressor and hydrogen tank technologies. The results of the sensitivity analysis are shown in Figure 6. As expected, the average consumption of the hydrogen coaches is the parameter with the highest impact on the TCO. To have a TCO lower than the one of electric vehicles, if only the consumption of hydrogen coaches varied, it would take a 66 % reduction in consumption, namely a consumption of 3.7 $kgH_2/100km$. As seen above, consumption can be decreased, but probably not at such a level. To have a competitive TCO, all costs for hydrogen technologies should decrease. However, while the cost of hydrogen seems set to fall [41, 60], the price of electricity could rise in the years ahead. The price of electricity in households has been rising steadily since 2007 [61], with an increasing rate of 41.8 % between January 2018 and January 2024. If the price of electricity were to rise in the same way between now and 2030, it could reach 0.1653 €/kWh excluding taxes in the medium term for local authorities with a contract power of more than 250 kVA. This would imply an increase in the TCO of 10.6 % (2.81 €/km) and 9.6 % (3.19 €/km) respectively for a hydrogen retrofit scenario and the purchase of new hydrogen coaches. For fully electric vehicles, the increase in the TCO would be 7.5 % (1.25 €/km) in the case of a retrofit, and 6 % (1.48 €/km) in the case of a new fleet.

Finally, the choice of calculating the TCO over an 8-year period may be questioned. This choice was made in order to compare both retrofit operations and new vehicle purchases. In the case of a longer-term study, more data would be needed, such as the replacement of technologies in vehicles

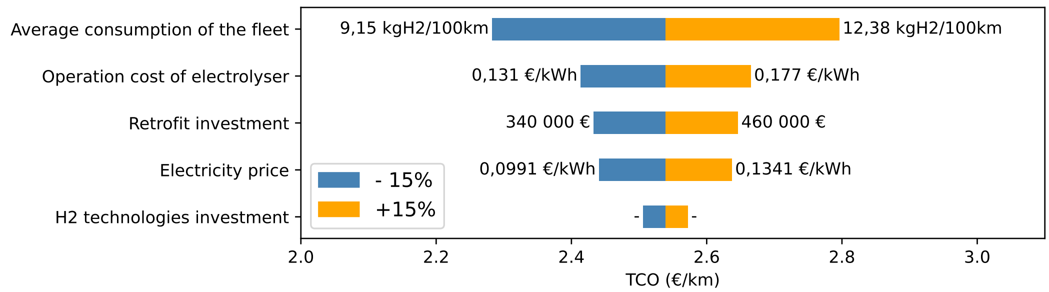

Figure 6: Tornado chart for the hydrogen coaches showing a $\pm 15\,\%$ sensitivity analysis on TCO. The low values of investment of electrolysers, compressors and hydrogen tanks are respectively 348.5 €/kW, 467.5 €/kW and 1 147.5 €/kgH_2. Their high values are respectively 471.5 €/kW, 632.5 €/kW and 1 552.5 €/kgH_2.

(battery, fuel cell). However, the obtained results are consistent with those of [6], which compares electric buses (TCO of 1.45 €/km) and fuel cell buses (TCO of 2.7 €/km) with the same methodology. Other electric/hydrogen comparison studies show quite different results for hydrogen like [4] (TCO around 0.9 €/km for electric buses and around 1.4 €/km for fuel cell buses). This could be due to the lower fuel consumption of hydrogen vehicles (taken at 8 kgH_2/100km), but other parameters could influence, explaining the difference in ratio between hydrogen/ electric vehicle types (56% in the article, 89% in the present study).

4.3. GWP

Concerning the calculation of the GWP, the impacts obtained for the transport phase of the technologies are first presented in Table 12. It is assumed that all elements of new hydrogen coaches have to stop in Portugal, place where the vehicles considered in the present study are manufactured. As expected, this step has a small impact over the whole GWP.

Technology	Application	Country of origin	GWP from transportation
LFP battery	New electric coach	China	1.962 $kgCO_2eq/kWh$
LFP battery	Electric retrofit	France	0.886 $kgCO_2eq/kWh$
NMC battery	Hydrogen retrofit	Mainland France	0.717 $kgCO_2eq/kWh$
NMC battery	New hydrogen coach	Turkey	4.418 $kgCO_2eq/kWh$
Fuel cell	Hydrogen retrofit	Mainland France	0.269 $kgCO_2eq/kW$
Fuel cell	New hydrogen coach	Japan	3.426 $kgCO_2eq/kW$
Hydrogen tank	Hydrogen retrofit	South Korea	0.270 $kgCO_2eq/kWh$
Hydrogen tank	New hydrogen coach	Japan	1.590 $kgCO_2eq/kWh$

Table 12: GWP data from the transportation step.

Then, the results obtained by calculating the GWP are presented. In each case, results presented are for one coach, not for the whole fleet, and only take into account the impact of the batteries, fuel cells or hydrogen tanks inside the vehicle, as well as the operation of the vehicle. The obtained results are visible in Table 13. As can be seen, the impact of the operation phase for eight years is far greater than the impact of the other steps: up to 17 times larger in the case of a hydrogen retrofit (with a 100 % renewable and local electricity mix in Reunion Island). This can be seen in Figure 7, where the composition of the GWP of all scenarios is detailed.

Regarding the vehicle with hydrogen retrofit, its GWP is lower than the one of a new electric vehicle, by considering only the technologies composing it, but becomes significantly superior by taking into account the operation phase over eight years. These results show the importance of having a decarbonated electricity mix, a low consumption of the coaches and a high

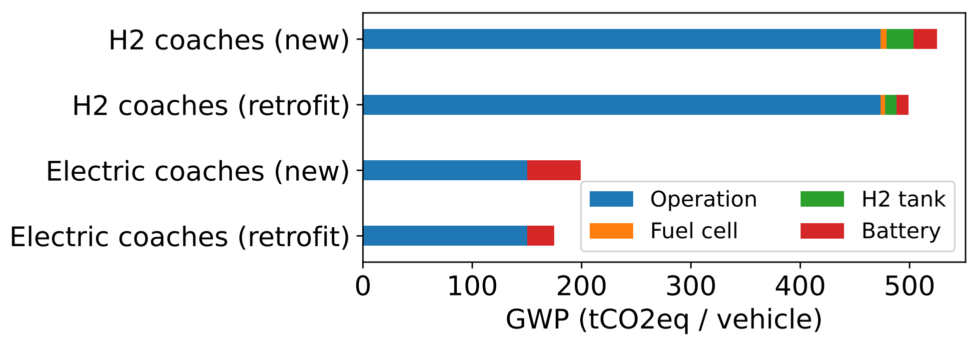

Figure 7: Details of the breakdown of the GWP with a simulation with Scenario 1 electricity mix.

efficiency of the hydrogen production chain. Indeed, all these parameters are the reason of the higher impact of the hydrogen vehicles on the operation stage; if the electricity mix used had a carbon impact of 10 gCO_2eq/kWh, the overall GWP of the two vehicles (hydrogen retrofit and new electric) would be equivalent. Scenario 2, with a slightly more carbon-intensive mix, implies a 1 % increase in GWP, while Scenario 3 implies a 2 % increase in GWP due to a greater use of biomass.

If no recycling step was considered in every scenario, the GWP of the technologies in the retrofit hydrogen scenario would be 30.6 tCO_2eq, 59.3 tCO_2eq in the new hydrogen coach scenario, 43.9 tCO_2eq in the electric retrofit scenario and 86.1 tCO_2eq in the new electric coach scenario. This shows the importance of considering battery recycling when studying the installation of new vehicles. As a reminder, the recycling phase will have an impact on the extraction and production of raw materials, by using recycled materials.

The obtained results can be compared with those of [13]. In the article, the authors propose several scenarios, considering different vehicle consumption and different electric mix. A scenario in particular is similar to the present study, with consumption of vehicles close (120 kWh/100km and 9 kgH_2/100km), and also a composition of electric mix close (half solar - half waste-energy with carbon capture). In this scenario, the GWP is equal to 26.9 $kgCO_2eq$/100km for electric vehicles, and has a value of 99.2 $kgCO_2eq$/100km for fuel cell vehicles.

If a similar study were to be conducted in a few years, the results would probably be different. Indeed, certain resources used in one technology or another could become scarce. This could be due to a number of factors: scarcity of raw materials [62], monopolies held by one country over part or all of a sector [63], diplomatic or armed conflicts that could lead to disruption of the sector or embargoes, pandemics, etc. However, these topics are difficult to predict.

4.4. Other impacts

Other environmental impacts like pollutant emissions of nitrogen oxide, carbon oxide, hydrocarbons or fine particles could have been assessed. Regarding the operation phase of the vehicles, all these emissions would be 0 in the case of a vehicle with an electric motor [58]. However, if hydrogen were to be burned in an ICE, these emissions would not be null. Indirect costs would also be generated, for example on the healthcare system [64].

As a common subject for interrogation, water consumption of hydrogen-powered coaches was evaluated. With a data of 11 liters of water required to produce 1 kg of hydrogen [65], 10 621 m^3 would be required for one year to power the whole hydrogen coaches fleet. This represents around 0.7 % of the island's daily requirements (drinking water supply, irrigation, industry)

[66]. This criterion can therefore be neglected. As a comparison, it would take 12 423 m^3 to fuel hydrogen-powered vehicles in an ICE (0.8 % daily requirements).

It is also important to have an idea of consumers attitude toward new technologies in mobility. Indeed, if collective transport using different technologies basically offers the same service at the same price, consumption choice then deals mostly with technology acceptance. In general, the literature on hydrogen technologies seems to show a high acceptance, but also that a large part of the population lack knowledge and have a volatile positioning toward hydrogen [67, 68]. Moreover, some papers study the positive willingness to pay for the air pollution reduction associated with hydrogen buses [69]. Finally, it has been shown in the literature that decision to adopt alternative fuel vehicles for public transportation does not really depend on end users. However, it would seem that the barrier for alternative fuel public transportation was more related to entrepreneurs and companies' choices [70] as they mostly consider operating and acquisition costs.

5. Conclusion

The aim of the presented work was to carry out a comparison of the technical, economic and environmental aspects of different means of electric and hydrogen public transport, applied to Reunion Island. In particular, one type of vehicle were studied, coaches. The study began by estimating the energy consumption of the vehicles with real-data profiles, in order to not have a study with underestimated consumptions. Then, the range and recharging time of the vehicles was estimated. The first conclusions ruled out

Scenario	Vehicle consumption (average)	Range (km)	Annual electricity consumption	Infrastructure required	TCO (€/km)	GWP without operation phase (tCO_2eq)	GWP with operation phase (tCO_2eq)
Electric coaches (retrofit)	178.5 kWh/100km	108	16 GWh	2 stations 6 fast-charging stations 6 dispensers	1.16	24.6	175.1 (28.4 $kgCO_2eq$/100km)
Electric coaches (new)	178.5 kWh/100km	210	16 GWh	2 stations 6 fast-charging stations 6 dispensers	1.39	48.5	199.0 (32.3 $kgCO_2eq$/100km)
FC coaches (retrofit)	11.4 kgH_2/100km	316	45.5 GWh	5.6 MW electrolyser 4.1 MW compressor 4.5 tH_2 tank 2 stations 6 dispensers	2.54	25.8	499.1 (81.1 $kgCO_2eq$/100km)
FC coaches (new)	11.4 kgH_2/100km	639	45.5 GWh	5.6 MW electrolyser 4.1 MW compressor 4.5 tH_2 tank 2 stations 6 dispensers	2.91	51.6	524.9 (85.3 $kgCO_2eq$/100km)
ICE coaches	13.4 kgH_2/100km	∼540	53.2 GWh	6.5 MW electrolyser 4.8 MW compressor 5.2 tH_2 tank 2 stations 6 dispensers	unknown	[25, 50]	[525, 550]

Table 13: Results of the assessment of the different scenarios.

electrical retrofitting operations on the vehicles of the current fleet, as well as the exclusive use of new electric coaches considering current range required for the network. The use of hydrogen-powered vehicles would make it possible to overcome the problems of both range and recharging time. Thus, the infrastructure required for hydrogen production were looked at, a step which is sometimes overlooked in the literature, yet essential if all the impacts of a hydrogen vehicle are to be taken into account. Once this sizing was carried out, it was possible to compare the electricity consumption of the vehicles, their total cost of ownership and their global warming potential. From an economic point of view, the obtained results are consistent with those in the literature, which conclude that hydrogen vehicles are more expensive today than battery-powered ones. If a fleet made up of different types of vehicles were to be optimised, it would be economically more interesting to have more electric vehicles than hydrogen ones. Then, from an environmental point of view, the comparison between the vehicles was made by considering the different stages in the life cycle of the technologies present in the vehicles, as well as the operation phase of the latter. This distinction was not necessarily relevant, given the current overwhelming impact of vehicle operation. As a result, with a lower electricity consumption, the comparison of environmental impact comes down in favour of electric vehicles. Finally, if both technologies provide the same quality of service to users, the social impact of manufacturing technologies or installing refueling stations was not assessed in the study.

In the article, the use of internal combustion engines burning hydrogen was compared to the other solutions in the majority of criteria. The advantages of such a solution lie mainly in the fact that it does not use rare materials (compared to fuel cell vehicles), is tolerant of the use of less pure hydrogen and is faster to deploy [71]. This first point has been partially evaluated with the GWP, the fuel cell being the least impacting technology compared with battery and hydrogen tanks. As hydrogen is only produced from water electrolysis in this study, the second point is not a major constraint on the deployment of hydrogen-powered mobility. Finally, as this solution is not yet deployed on the market, unlike fuel cell solutions, the last point cannot be verified. However, if this were to be the case, it is possible that it would be more attractive to deploy hydrogen ICE engines, for environmental and economic reasons.

As mentioned in the development, the transport networks scheduling has not been optimised, due to too much uncertainty about the future place that will be allocated to public transport on Reunion Island. Once this has been done, it will be possible to re-apply the methodology presented in this paper, optimise recharging times [72] and compare the new obtained results. The number of buses in the network and their routes can also be optimised to favour one type of vehicle over another. In the case studied here, it has been shown that electric vehicles alone cannot be deployed locally, because of the local topography and the daily distance covered by vehicles, and that a technological mix can be considered for economic and environmental reasons. Indeed, as discussed in [7] battery and hydrogen technologies are complementary, and can coexist in the same territory. In a future study, other fuels could be considered for the study case [73, 74].

Acknowledgements

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CRediT authorship contribution statement

Agnès François: Conceptualization, Methodology, Investigation, Software, Formal analysis, Writing - Original Draft. **Robin Roche:** Conceptualization, Supervision, Project administration, Writing - Review and Editing. **Dominique Grondin:** Conceptualization, Supervision, Writing - Review and Editing. **Nastasya Winckel:** Investigation, Writing - Review and Editing. **Michel Benne:** Conceptualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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