



Research Article



Life cycle assessment of hydrogen-powered city buses in the High V.LO-City project: integrating vehicle operation and refuelling infrastructure

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Abstract

During the project High V.LO-City, which ended in December 2019, 14 hydrogen fuel cell buses were operated in four European cities. This paper aims at presenting total emissions through the lifetime of fuel cell buses with different hydrogen production options, including the refuelling stations. The environmental assessment of such bus system is carried out using the life cycle assessment methodology. Three hydrogen production pathways are investigated: water electrolysis, chlor-alkali electrolysis and steam methane reforming. Fuel economy during bus operation is around 10.25 KgH₂/100 km, and the refuelling station energy demand ranges between 7 and 9 KWh/KgH₂. To support the inventory stage, dedicated software tools were developed for collecting and processing a huge amount of bus data and refuelling station performance, for automating data entry and for impacts calculation. The results show that hydrogen-powered buses, compared to a diesel bus, have the potential to reduce emissions during the use phase, if renewables resources are used. On the other hand, impacts from the vehicle production, including battery pack and fuel cell stack, still dominate environmental load. Consequently, improving the emission profile of fuel cell bus system requires to promote clean electricity sources to supply a low-carbon hydrogen and to sharpen policy focus regarding life cycle management and to counter potential setbacks, in particular those related to problem shifting and to grid improvement. For hazardous emissions and resource use, the high energy intensity of mining and refining activities still poses challenges on how to further enhance the environmental advantages of fuel cells and battery packs.

Article Highlights

- This paper aims at presenting a comprehensive LCA case study that uses real-world operations data to investigate the environmental impacts of the High V.LO-City hydrogen fuel cell bus system (i.e. H₂FC bus, integrating hydrogen production and delivery options and refuelling stations operation) against a conventional Euro-6 Diesel bus.
- The High V.LO-City project consisted of the integrated testing of new generation hydrogen buses and their hydrogen production and refuelling infrastructure in some European cities. It differs from other demonstration projects because it intends to evaluate both the operation of the vehicles and the production and supply of hydrogen to use them as substitutes for conventional diesel buses and trolleybuses.
- Fuel economy during bus operation is around 10.25 KgH₂/100 km, and the refuelling station energy demand ranges between 7 and 9 KWh/KgH₂. The results clearly indicate that it is advantageous to promote such mode of transport.

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tation in areas where electricity is primarily produced from renewables (i.e. wind power as an alternative to fossil fuels). However, potential setbacks, in particular those related to problem shifting and to grid improvement, should be addressed accordingly.

Keywords Low-carbon mobility · Fuel cell buses · Hydrogen · Life cycle assessment · Climate change policy

1 Introduction

1.1 Policy context

The urgent need to curb emissions from transport sector has led the European Union (EU) to set forth policies and related supportive measures. The EU Communication "Strategy for smart, inclusive, and sustainable growth" [18] highlighted the importance of a modernized and sustainable European transport system for the future development of the Union and underscored the need to address the urban dimension of transport.

In December 2019, the EC presented the "European Green Deal", an ambitious roadmap for making Europe the first climate-neutral continent by 2050 [23]. The European Green Deal covers all sectors of the economy—notably transport, energy, agriculture, buildings, and industries—to foster the efficient use of resources by moving to a clean, circular economy and to stop climate change. In July 2020, the EC unveiled its strategy to upscale hydrogen as a clean solution to the environmental crucible [26]. According to the EU strategy hydrogen can support the decarbonization of industry, transport, power generation and buildings across Europe. The parallel Communication no. 299 [25] set out a vision on the transition towards a more integrated energy system and poses hydrogen as one of the pillars capable of supporting climate change and energy security goals.

1.2 Hydrogen fuel cell bus in urban transport

Hydrogen fuel cell (H₂FC) buses are relatively mature at Technology Readiness Level (TRL) 7 to 8 [27]. Therefore, hydrogen-powered buses are the logical first step for introducing fuel cells because they can handle larger and heavier ones, can store large amounts of compressed hydrogen gas in tanks on the roof, and can be refuelled at central locations. According to Martin Pehnt [56–59] the platinum group metals (PGMs, which act as catalysts, account for most of the greenhouse gas) climate change, sulphur (acidification), and nitrogen (eutrophication emissions). The author suggests several options for improving the ecological impact of fuel cells. PGM requirements can be further reduced, and the metals recycled, the electricity source can be shifted to renewable energy; and

components of the fuel cell stack can eventually be eliminated or recycled. The above challenges triggered significant efforts in researching and developing PEM FCs, which could fit a variety of applications.

The Decision No 1982/2006/EC [12] of the European Parliament and of the Council of 18 December 2006, concerning the Seventh Framework Programme (FP7) of the European Community (EC) for research, technological development and demonstration activities (2007–2013), identified key issues and priorities for accelerating deployment of a wide range of applications (from portable to stationary and transport). This led to the formation of a Public Private Partnership—the "Fuel Cells and Hydrogen Joint Undertaking" (FCHJU)—between the European Commission, industry and the research community [16]. FCHJU is responsible for implementing the Fuel Cells and Hydrogen Joint Technology Initiative (FCH JTI), the political initiative proposing this public–private partnership in fuel cell and hydrogen technologies.

Under the FP7, FCHJU funded several projects in the application area of "Transport and Refuelling Infrastructure". Work has been encouraged at local level through a succession of hydrogen bus demonstration projects [4].

Three flagship European fuel cell bus demonstration projects paved the way for hydrogen transportation system in the urban context: Clean Urban Transport for Europe (CUTE), Ecological City Transport System (ECTOS) and HyFLEET:CUTE. CUTE [37] and ECTOS projects ran from 2001 to 2005 and demonstrated 30 fuel cell buses in 10 European cities (Amsterdam (NL), Barcelona (ES), Beijing (CN), Hamburg (DE), London (UK), Luxembourg (LUX), Madrid (ES), Perth (AU), Reykjavik (ISL)), in addition to providing buses to partner programmes in Perth and Beijing. The project showed that fuel cell buses could be delivered using series production and used safely and reliably in public transit routes. Refuelling stations were constructed and operated in each of the project cities, incorporating on-site renewable production of hydrogen and achieving station availability of 80%.

HyFLEET:CUTE was the next bus project run in the EU, from 2006 to 2009 [37]. It built upon the work done in CUTE/ECTOS, using the existing station infrastructure (plus one additional station built in Berlin) to demonstrate 47 hydrogen-powered buses in public transit in 10 cities on three continents. The project also covered the design,

construction and testing of next-generation fuel cell buses, in addition to improvements of the existing refuelling stations.

Although the project did show significant improvements in the performance of the technologies, government-funded projects were still necessary to carry the technology forward towards commercialization. The Clean Hydrogen in European Cities (CHIC) project was, therefore, launched in 2010 to address these challenges and leading to full commercialization starting in 2015. Throughout the project lifetime, 54 fuel cell buses operated in the canton of Aargau (CH), in Bolzano (IT), London (UK), Milan (IT), Oslo (NO), Cologne (DE), Hamburg (DE), and Whistler (CA) (during 2010 Winter Olympics Games).

By leveraging the experiences of past fuel cell bus projects, the High V(Flanders).L(Liguria) O(Scotland)-City (High V.LO-City) project aimed at significantly increasing the "velocity" of integrating these buses on a larger scale in European bus operations [36, 38]. The project consisted of the integrated testing of new generation hydrogen buses and their hydrogen production and refuelling infrastructure in some European cities. It differs from other demonstration projects because it intends to evaluate both the operation of the vehicles and the production and supply of hydrogen to use them as substitutes for conventional diesel buses and trolleybuses.

The project runs from 2012 to 2019. Fourteen fuel cell buses operated in Aberdeen (UK), Sanremo (IT), Antwerp (BE) and Groningen (NL). Beside the operation of the vehicles and the deployment and operation of refuelling infrastructure, the project also included the showcase of different routes for hydrogen production and delivery within the demonstration locations.

Since the start of the project, more than 900,000 km have already been travelled by the buses, saving more than 900 tons of carbon dioxide (see S1 for the calculation formula).

1.3 Alternative fuel vehicles literature survey

The assessment of emerging transportation modes, fostered by the afore-mentioned policies, is addressed at different levels of analysis.

A stream of research directs attention to environmental impact assessment, performing comparative analysis of alternative powertrain technologies and associated fuel pathways. The Life Cycle Assessment (LCA) and Well-to-Wheel (WTW) approaches are the preferred methodologies to calculate the magnitude of a system's emissions through its entire life cycle (the former) or use phase (the latter). For instance, Lozanovski et al. [41] assessed the sustainability of H₂FC bus system against environmental, economic and social criteria. Nava-Anguita et al. [48]

compiled a techno-economic database for road transportation fuels, with focus on alternative fuels (such as hydrogen, biomass and electricity). Orsi et al. [54] performed a WTW analysis of different passenger vehicles and associated fuel supply infrastructures, while [34] concentrated solely on natural gas vehicles in Denmark. Offer et al. [52] argued that a combination of electricity and hydrogen as a transport fuel could reduce the carbon emissions and bring also economic advantages to the end user. Nordelöf et al. [50] explore life cycle environmental impacts of city buses, depending on the electricity supply mix, for chargeable options, and on diesel or hydrogenated vegetable oil (HVO), a biodiesel, for options with combustion engine. Saxe et al. [61] reported the main operational results of the fuel cell buses operated in the CUTE project. Additionally, relevant updated reports are usually released in specialized groups of interests [30, 31]. A dedicated internet repository summarizes all the main projects that promote hydrogen fuel cell buses in many European cities [32] and (3EMOTION) [1]. Ajanovic et al. [2] analysed prospects and barriers for fuel cell buses focussing on their economic-, technical- and environmental performance. They evidenced that the major barrier, for a faster penetration of fuel cell buses, is their high purchase prices, which could be significantly reduced with the increasing number of buses through technological learning. Additionally, from environmental point-of-view it has to be ensured that hydrogen is produced from renewables. Therefore, a tougher transport policy framework is needed to finally live up to their potential [65].

Doyle et al. [8] modelled H₂FC bus and Battery Electric bus in Simulink® for a comparative well-to-wheel assessment, highlighting that the relative suitability of each from an environmental perspective is sensitive to geographical and fuel production method pathways.

A recent review study on LCA of electrified vehicles, carried out by Marmioli et al. [43], has showed a plethora of diverging and conflicting results. The main hurdle identified is the absence of a compete goal and scope definition, leading to an incorrect or delusive interpretation of results. The authors identified electricity production as the most impactful phase when it adds up to climate change and agreed on the need of finding consensus on the appropriate electricity mix Marmioli et al. [43].

However, many significant issues relevant to city bus mobility remain to be explored. Two issues emerged from the above:

- *Lack of bus operational data on H₂FC buses, integrating the production/supply of hydrogen:* for example, until now no studies in the research literature examine hydrogen-powered bus fleet's life cycle assessment impacts with alternative hydrogen production

options, including the refuelling stations operation, and based on vehicle's real performance data. Previous articles point out the general lack of data for bus operation [6, 10] and for refuelling stations as well [72]. For example, Harris et al. [35] conclude that there is a need for additional LCA studies covering the full vehicle equipment life cycle, while underscoring the difficulties in acquiring component composition and manufacturing data.

- *Absence of available computational tools:* to this date, no software has successfully implemented or provided an approach to facilitate the collection and processing of bus operational data, namely distance and fuel consumption, in an automated or semi-automated manner, to calculate the fuel economy. Additionally, the lack of available and recognized tools for automating data entry and impact calculations could hinder the inventory setup.

1.4 Aim and content of the article

The aim of this paper, in addressing the above gaps in the research field, is twofold.

The first is to develop and implement an elaboration pipeline useful to handle hydrogen bus data more conveniently and to automate data collection and data entry in the software tool. Such innovative approach can be adapted to different context where an integrated system of bus fleet and production/supply of energy vector is considered.

The second is to report a comprehensive LCA case study that uses real-world operations data to investigate the environmental impacts of High V.LO-City hydrogen fuel cell bus system (i.e. H2FC bus, integrating hydrogen production and delivery options, and refuelling stations operation) against a conventional Euro-6 Diesel bus. Specifically, three methods of hydrogen production are considered: electrolysis of water, chlor-alkali electrolysis and steam methane reforming process.

Following the introduction, this paper presents: the case study's goal and scope definition; a description of the inventory analysis, underlying the proposed elaboration strategy; impact assessment results discussion; and interpretations as commented answers to the research questions of the study. A Supporting Information (SI) integrates this article, presenting tables and figures complementary to the presentation of the impact results.

2 Materials and Methods

2.1 Goal and scope definition

The goal of the presented study is to assess the life cycle environmental impacts of High V.LO-City H2FC bus system. Three main questions are set forth:

- (1) How do the environmental impacts of H2FC bus system depend on the hydrogen production methods and on the energy need to operate the station during the refuelling process?
- (2) How does the electricity mix affect the hydrogen production and provision processes?
- (3) How do the environmental impacts of H2FC bus operation compare with a Euro-6 diesel bus?

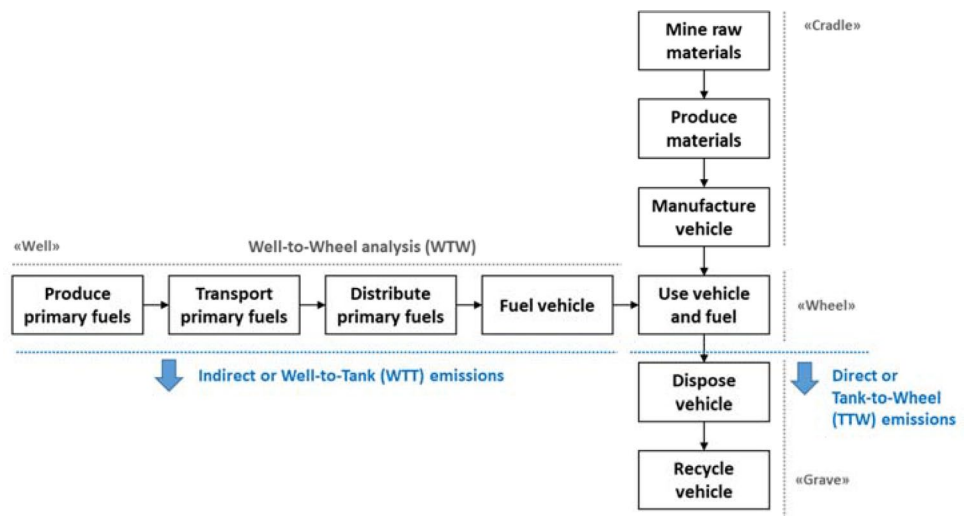
2.2 Presentation of the case study

Demonstration projects are necessary to showcase transport technologies in action and to implement EU energy policy commitments [13]. According to FCHJU [29], demonstration "*provides evidence of the viability of a new technology that offers potential economic (and societal) advantage but cannot be commercialised directly*".

The High V.LO.-City project addresses the integration of H2FC buses in the public transport (HighVLOCity), evaluating key environmental and operational concerns that local transport authorities are facing today. The project's context comprises four demonstration sites for hydrogen refuelling stations and fourteen hydrogen fuel cell (H2FC) buses:

- Aberdeen (UK) site operational since March 2015 (four buses). The bus fleet is operated by First Group a British multi-national transport group, based in Aberdeen, Scotland. The refuelling station hosts an electrolyser system for on-site hydrogen production.
- Antwerp (BE) site operational since December 2014 (five buses). The bus fleet is operated by De Lijn, the local transport authority. The hydrogen is produced using residual hydrogen as a waste product from existing industrial activities in the Solvay Antwerp plant.
- Groningen (NL), site operational since November 2017 (two buses). The bus fleet is operated by Qbuzz (owned by Italian railways), the local transport authority. The hydrogen is produced using by-product hydrogen as a waste product from adjacent Akzo-Nobel chlorine plant (located in the Delfzijl Chemical Cluster).
- San Remo (IT) site operational since November 2018 (three buses). The bus fleet is operated by Riviera

Fig. 1 Concepts of well-to-wheel (WTW) and life cycle assessment (LCA), elaborated from Nordelöf et al. [49] and Roland Berger [60]



Trasporti, the local transport authority. The hydrogen is produced via SMR from industrial activities in the Air-Liquid plants and transported to the refuelling station via tube-trailer truck.

2.3 Methodology

2.3.1 Life cycle assessment

In this article, a comparative and attributional Life Cycle Assessment (LCA) [39, 40] is performed to assess energy consumption and relevant emissions during H₂FC bus system's lifetime, based on the three abovementioned alternative hydrogen production pathways.

A vehicle's LCA is comprised of two cycles: a vehicle life cycle that includes vehicle assembly, maintenance, dismantling and recycling, and a fuel life cycle that involves all processes from harnessing a primary energy flow or stock to different forms of conversion, distribution, storage and use in the vehicle [49].

The functional unit is "1 km driving distance". The system boundary includes the production of the H₂FC bus, the refuelling infrastructure, hydrogen production and usage as well as maintenance through to the end of life. Therefore, the study is based on average data, unless specified otherwise. Foreground H₂FC bus system data include: PEMFC, lithium-ion battery and vehicle manufacturing, refuelling station components supply and operation. Other stages in the life cycle, which comprise the background system, include the extraction and production of materials, generation of electricity and treatment of materials consequent to "End-of-Life" (EoL). This analysis is substantiated in the vehicle life cycle represented by the vertical flow in Fig. 1.

2.3.2 Life cycle calculations

The life cycle analysis relies on software package OpenLCA 1.10.2 [53], integrating Ecoinvent database v 3.5 [69]. This version of the Ecoinvent database was released in August 2018. In terms of geography, the background data are generally global averages, or European averages where the former were not available.

The electricity supply inventory is calculated from EU electricity mix ("group market" for electricity from Ecoinvent database), as described in Treyer et al. [66, 67]. The "green" electricity supply from renewables is modelled from label-certified electricity which represents a special market for renewable electricity supply in Ecoinvent [66, 67].

2.3.3 Elaboration pipeline for inventory compilation

The energy demand of the hydrogen dispenser unit is calculated from actual collected data. The fuel economy is a key consideration for analysing the environmental and economic impacts of H₂FC bus system and is especially crucial because the use phase of the total lifetime effects mainly consists of fuel consumption. The information on the fuel economy is obtained from the ratio between the total hydrogen consumed and the actual kms driven by the bus fleets. To facilitate the elaboration of the bus data, a LabVIEW® application has been developed to import the distance and consumption vectors, allowing the user to select the data points. Such data points are saved into an XML file format to easily exchange information with other software programmes. Figure 2 shows the application front panel window with the main control widgets that allow the selection of the data points to calculate the performance index.

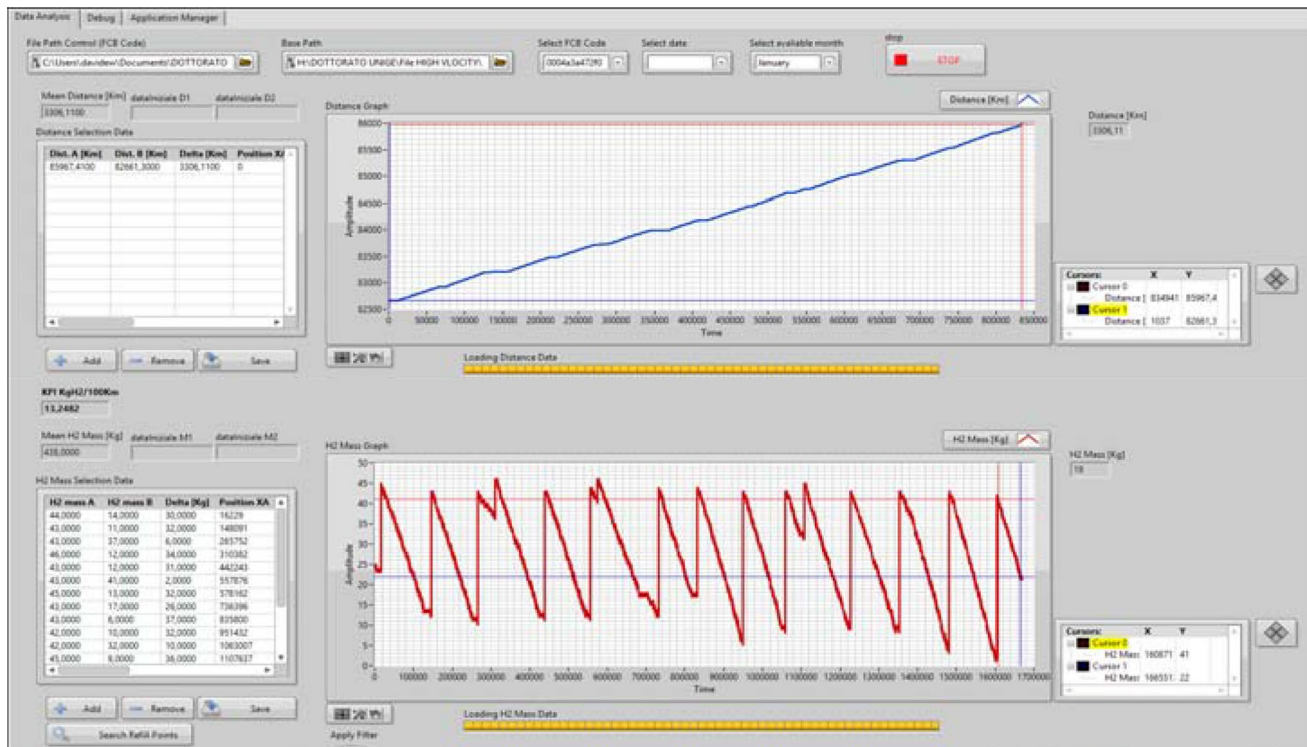


Fig. 2 Front panel of the LabVIEW® application developed to calculate the fuel economy

The compiled inventory is converted into a suitable format for OpenLCA. Such software tool integrates Application Program Interface (API) to run Python code. The JSON (JavaScript Object Notation) format is considered fit for facilitating the data entry. Therefore, individual process (including exchanges, parameters) comprising the system has been mapped on to a JSON file format and imported into OpenLCA via Python code. This approach eases all the repetitive tasks for data entry and, above all, automates the impact calculations, exporting the results in customized text files that can be further elaborated in a spreadsheet tool to make charts or other visual medium. The possibility to automate and customize the entire processing task is conducive to an improvement of the inventory compilation. Supporting information S1 provides further insight on the calculation model.

2.3.4 Selection of the impact assessment method

The potential impacts are evaluated for magnitude and significance in the life cycle impact assessment (LCIA) phase, using Environmental Footprint (EF) method which is the impact assessment method of the Product Environmental Footprint (PEF) framework, established in 2013 with a specific Recommendation no. 2013/179/EU [20], within the framework of the “Single Market for Green Products” communication no. COM(2013) 0196 (EU 2013c).

The PEF is a multi-criteria measure of the environmental performance of a good or service throughout its life cycle. PEF information is produced for the overarching purpose of seeking to reduce the environmental impacts of goods and services considering supply chain activities (from extraction of raw materials, through production and use, to final waste management). The PEF has been developed in the context of one of the building blocks of the Flagship initiative of the Europe 2020 Strategy—“A Resource-Efficient Europe” no. COM(2011) 571 (EU 2011b) aimed at establishing a common metric to assess and benchmark the environmental performance of products, service and companies: “based on a comprehensive assessment of environmental impacts over the life cycle (‘environmental footprint’)” (in (EU 2011b) at page 7).

A detailed description of the methodology is provided by [28]. For a better overview and comparability, the impact categories shown are limited to the ones that are the most widely used within studies: Climate change (GWP100), Acidification potential (AP), Photochemical ozone formation potential (HOFPP) and Eutrophication potential (EP), Ozone depletion (ODP). Supporting Information S1 and Supporting Information S2 provide results for a wide range of impact categories.

Fig. 3 Schematic of system boundary which includes hydrogen supply chain and H2FC bus transport service

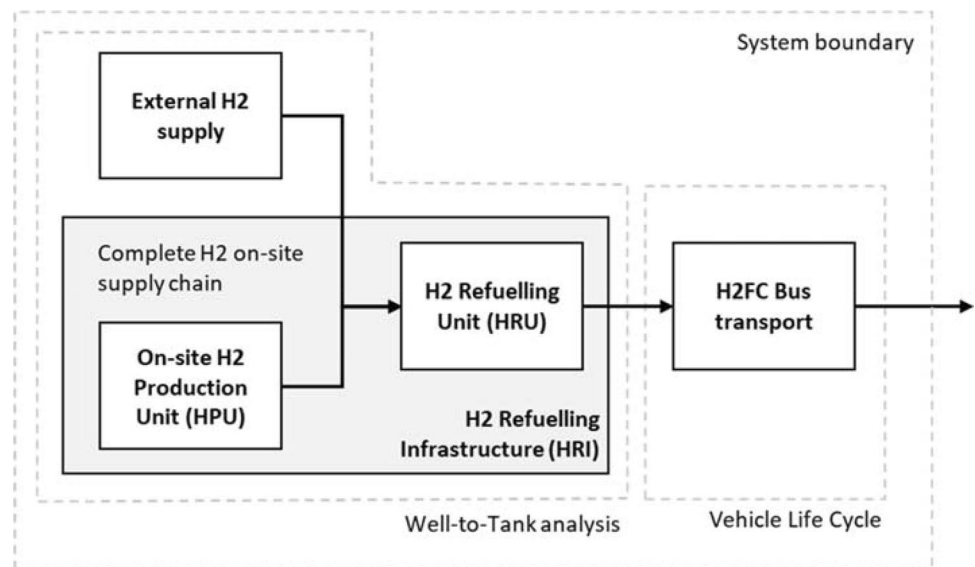
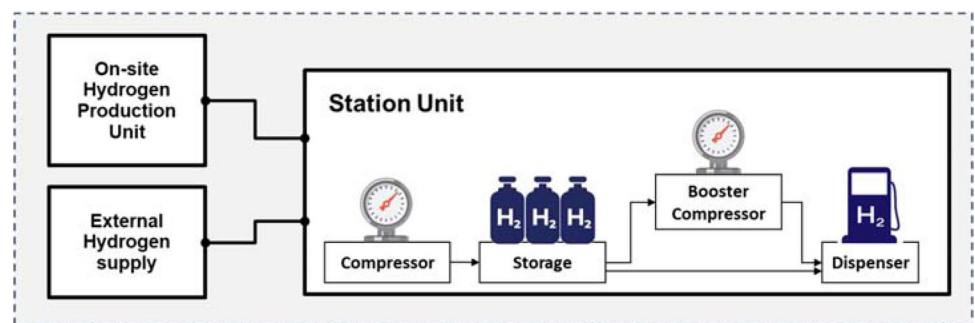


Fig. 4 Generalized schematic of the hydrogen refuelling infrastructure



2.4 Description of unit processes

The first step, as for ISO 14040 standard [39, 40], is to define what belongs to the product system [33]. Two aspects have been considered: definition of the boundaries between the H2FC bus system and the environment, and the distinction between relevant and less relevant processes related to the H2FC bus system.

The system described above can be represented diagrammatically with the main interactions shown as lines. This is done in Fig. 3 where the following unit processes are, thus, distinguished:

- (1) The hydrogen refuelling infrastructure (HRI), which, in its turn, is composed by a Hydrogen Production Unit (HPU), applicable to water electrolysis plant, and a Hydrogen Refuelling Unit (HRU) that delivers the hydrogen to the bus,

- (2) Hydrogen fuel cell bus (H2FCB).

2.4.1 Hydrogen infrastructure

Figure 4 shows a generalized schematic of hydrogen infrastructure facilities. Hydrogen is generated on site from electricity, natural gas and water, or supplied by truck from external sources. It is compressed, stored and dispensed on demand to the buses. Dispensing requires a pressure differential between the on-site storage and the vehicle tanks (decanting). Depending on the design of the station, namely the pressure level of the on-site storage, filling may have to be completed with a booster compressor (booster mode). The compressor that charges the station storage and the one for completing the filling can be the same physical unit that is able to operate in different modes.

The physical boundaries of the refuelling stations encompass relevant input flows: electricity, water supply

Table 1 Hydrogen refuelling unit (HRU) energy demand

Site	Mean value	Standard deviation
HRU (Aberdeen) [KWh/KgH ₂]	7.45	2.95
HRU (Antwerp) [KWh/KgH ₂]	2.47	2.27
HRU (Groningen) [KWh/KgH ₂]	7.10	1.60
HRU (Sanremo) [KWh/KgH ₂]	8.15	1.51

(for electrolyser), external hydrogen supply (as a by-product of a chemical plant). The amount of hydrogen dispensed to the bus is the reference flow and, hence, the functional unit of the HRI.

Table 1 shows the energy demand of individual dispensers, and Table 2 summarizes the intervening processes. The reported values are normalized with respect to 1 kg of hydrogen produced or dispensed to the bus. Three individual unit processes, one for each hydrogen path, have been conceived and implemented, based on the above-collected data. It is worth to underscore that the differences in electricity demand at the refuelling station are mainly due to different dispenser unit configuration and setup, thus leading to specific energy demand to power the station.

HRI with on-site water electrolyser. The process is modelled using project data on the electrolier performance and energy used to power the plant. The material and energy used to build the station are based on information gathered from Aberdeen site and from literature [72]. The plant consists of three HySTAT™60 electrolyser, capable of producing 360 kg of hydrogen per day, two compressors and a 420-kg storage unit. The hydrogen generating unit is based on the principles of alkaline water electrolysis. In alkaline electrolysis the reaction occurs in a solution composed of water and liquid electrolyte (30% potassium hydroxide, KOH) between two electrodes. When a sufficient voltage is applied between the two electrodes, at the cathode water molecules take electrons to make OH⁻ ions and H₂ molecule. OH⁻ ions travel through the 30% KOH electrolyte towards the

anode where they combine and give up their extra electrons to make water, electrons and O₂. The recombination of hydrogen and oxygen at this stage is avoided by means of the highly efficient and patented IMET® ion-exchange membrane. The gases produced are cooled, purified, compressed and stored. The alkaline cell inventory, including the stack arrangement, and additional balance of plant required to turn an AFC stack into a functional unit, is calculated from Staffell and Ingram [64]. The compressor data are based on [42] who elaborated the inventory for a hydrogen refuelling station from HydroStaoil assembled in Reykjavik. The energy demand of the plant is the following: the hydrogen production unit (HPU) requires 70.41 KWh/KgH₂, the dispenser 7.45 KWh/KgH₂. The values are collected from the infrastructure performance figures delivered by Aberdeen City Council on a monthly basis.

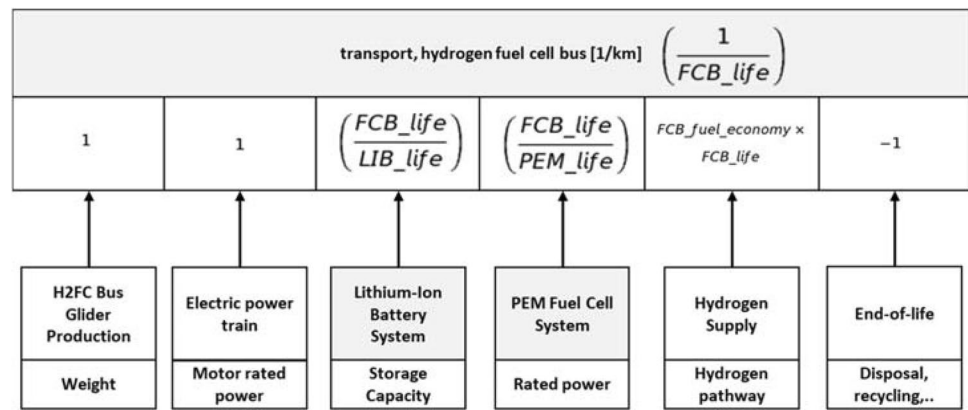
HRI supplied by hydrogen as by-product from Chlor-alkali Electrolysis. As recalled in introduction section, the main technologies applied for chlor-alkali production are mercury (19.7%), diaphragm (13.6%) and membrane (65.3%) cell electrolysis, mainly using sodium chloride (NaCl) as feed or to a lesser extent using potassium chloride (KCl) for the production of potassium hydroxide. Therefore, the result unit process is a weighted average of the above-mentioned production technologies. The gas is delivered to the station via underground pipes. The electricity demand of the station is relevant to the dispenser to fill the bus with the gas and ranges between 2.47 KWh/KgH₂ (Antwerp site) and 7.1 KWh/KgH₂ (Groningen site). The material and energy used to build and maintain the station are considered in the model.

HRI supplied by hydrogen from SMR process. The process is modelled from Spath and Mann [62], [44] and Ecoinvent database. The electricity demand, relevant to the dispenser unit, is about 8.15 KWh/KgH₂ (Sanremo site). The gas is delivered to the station via tubes trailer trucks. As mentioned above, the material and energy used to build and maintain the station are also included in the inventory.

Table 2 Hydrogen production unit (HPU) product system summary, components' demand factors and inventory data sources

Hydrogen supply components	Water electrolysis plant	Chlor-alkali electrolysis plant	Steam methane reforming
Electrolyser electricity demand (KWh/KgH ₂)	70.41	–	–
Water use (L/KgH ₂)	22.25	–	–
External Hydrogen Supply	–	As a by-product of chlor-alkali electrolysis [5]	From steam methane reforming [62]
Facility (building, operation and decommissioning)	Project data, Ecoinvent and Wulf and Kaltschmitt [72]	Project data, Ecoinvent and Wulf and Kaltschmitt [72]	Project data, Ecoinvent and Wulf and Kaltschmitt [72]

Fig. 5 Principle model structure and transport components and their relationship



2.4.2 Hydrogen fuel cell bus

The vehicle, object of the present study, is a A330 hybrid fuel cell buses from Van Hool (Belgium), belonging to vehicle category M3 as per Directive 2007/46/EC (EU 2007b). In such new buses, the fuel system and internal combustion engine have been replaced by a high-pressure (350 bar) hydrogen storage system, two polymer electrolyte (PEM) fuel cell stacks (overall 150 KW of rated power), including balance of plant components (fuel cell auxiliary systems), a lithium-ion battery (17 KWh), a DC/AC inverter, and two electric motors. The electric motors power a standard low floor rear axle through an automatic gearbox, similar to the configuration of the conventional bus. Most auxiliaries except those specific to the fuel cell system are standard.

The general model structure is illustrated in Fig. 5. The modelled transport components are linked in a unit process referred to as "transport, hydrogen fuel cell bus". To link the various transport components to the reference flow of "1 km driving distance" [68], the demand factors are determined.

Demand factors for bus components, i.e. bus glider manufacturing, electric power train supply, bus operation and bus disposal, are calculated as the inverse of the bus's lifetime transport performance, denoted by the "FCB_life" parameter. As the FC stack lifetime is less than the bus lifetime, the stack has to be exchanged twice over the bus lifetime. While the lithium-ion battery has to be replaced around four times. The ratio between the bus lifetime and their individual lifetime provides the replacement schedule number (including the item that is at the beginning of the vehicle lifecycle). Such values, rounded down to the nearest multiple, are further divided by the bus lifetime to obtain the correct demand factor on a per-Km basis. The negative demand factor in the end-of-life process is consistent with the Opposite Direction Approach (ODA) or double-negative approach implemented in OpenLCA under the use of a product flow as a quantitative reference of the waste treatment process.

H2FC bus manufacture. Data on the production of the H2FC bus are based on Ecoinvent database. The inventory of the FC systems (i.e. fuel cell stack and related balance of plant (BOP)) is obtained from Miotti et al. [46]. Their model was scaled to 150 KW of rated power. The lithium-ion battery is modelled from [45]. Though the study is based on Ecoinvent 2.2, the corresponding processes in Ecoinvent 3.5 have been found and applied to the model. The electrical powertrain is composed by two electric motors, two gear boxes, two inverters and a power management system. The inventory of the electrical motor is based on the Siemens Drive Motor 1PV5138-4WS24 technical information sheet. The gear box coupled to the motor is a Flender gear unit delivering 22,000 N torque. The electric module comprises a Siemens MONO inverter and a Siemens DICO (Digital Input Control) drive system controller. Their inventory is calculated from their datasheets.

H2FC bus operation. For the H2FC bus use life cycle stage, operational energy is calculated on estimated fuel economy and on the lifetime of FC stack and lithium-ion battery. The average hydrogen use is calculated by dividing the kilometres driven in service by the hydrogen consumed. The obtained figure is 10.25 KgH₂/100 km driven. The fuel consumption decreased by around 41% if compared to CUTE project [61].

Although H2FC buses have no tail-pipe emissions, the environmental burdens depend on the hydrogen supply route chosen for the scenario assessment. The expected H2FC bus lifetime is set equal to 800,000 km as required by EU Directive 2009/33/EC [17].

H2FC bus end-of-life. End-of-life (EoL) treatment of the bus's steel and metal parts was modelled to reflect current legislation in Europe for end-of-life vehicles, namely 95% reuse and/or recycling and 5% landfilling as recalled in the Directive no. 2000/53/EC [12]. EoL treatment of all

Table 3 Characteristics of the “Hydrogen fuel cell bus” product system

Parameter	Average 13 m H2FC Bus	Inventory source
Fuel economy (KgH ₂ /100 km)	10.25	Average value computed from buses operational data
Assumed bus lifetime (Km)	800,000	EU Directive 2009/33/EC (COM 2009c)
Assumed FC stack lifetime (Km)	240,000	Miotti et al. [46]
Li-Ion battery capacity (KWh)	17	Project’s partner data
Assumed li-ion battery lifetime (Km)	150,000	Pagliaro and Meneguzzo [55]
Bus weight (ton)	15	Project’s partner data and Ecoinvent
Drive power (KW)	2 × 85	Project’s partner data

remaining vehicle components (electrical system, tyres, glazing, wood, lube oil, refrigerant) was modelled reflecting standard practice: open-loop recycling for glass, incineration for tyres and plastic mixtures, and landfilling treatment for all other parts. The recycling of spent lithium-ion battery comprises a hydrometallurgical process to extract metals [70]. Required processes are from Ecoinvent. The treatment of exhausted fuel cell stacks relies on a mechanical and chemical process, as mentioned above, to recover precious material (platinum and metals). The modelled process is built on [63] and [9]. The calculation of the environmental credits ensuing from EoL material recycling and energy recovery was performed based on the average mix of the best available technologies and applying consequential LCAs [47].

Table 3 summarizes the main characteristics of the product system which includes the H2FC bus lifetime, fuel cell system, ion-lithium battery and fuel economy.

2.4.3 Reference vehicle

The Mercedes-Benz Citaro O530 Euro-6 bus was chosen as a basis for comparison. It is a 13-m-long vehicle equipped with a 220-KW diesel engine and has an estimated fuel economy of about 34.25 L/100 km. The fuel consumption figure is calculated from the onboard monitoring system, thus providing information under real driving conditions. The bus is currently in service in the municipality of Groningen and is operated by Qbuzz. The bus model is proxied using inventory data from Ecoinvent database.

3 Results

The Life Cycle Impact Assessment (LCIA) of the H2FC bus system is articulated in three steps. The first addresses the overall environmental impacts and consumption of resources associated with the vehicle cycle. The second includes the evaluation of the potential environmental emissions and resource use stemming from fuel cycle. The third combines the above two assessments to provide the comprehensive picture of the H2FC bus system life cycle.

3.1 H2FC bus contribution analysis

Figure 6 summarizes the LCIA of the H2FC bus. The credits from recycling stage have been separated from the overall impacts. The contribution of individual hydrogen bus components, during the vehicle’s entire lifetime, are reported.

The bus manufacturing drives most of the total emissions in all the reported categories. The supply of metals and the assembly stages are energy-intensive processes in the vehicle cycle. The bus life cycle accounts for nearly 65% of the total climate change impacts. The supply of the chromium steel, the aluminium, the double-glass panels, the glass fibre-reinforced plastic, the synthetic rubber and the electronic modules represent the main impacting processes, covering almost 90% of the entire share. The trend is confirmed by previous project results (ECTOS and CHIC, for example).

The impacts relevant to lithium-ion battery are consistent with previous LCA studies [7, 45]. Most impacts from the positive electrode paste are caused by tetrafluoroethylene, lithium iron phosphate, N-methyl-2-pyrrolidone and carbon black (more than 60%). The contribution tree, reported in S2, provides further details on the relative weights of the intervening processes.

The environmental impacts of the PEM FC system show that the catalyst accounts for a large share of overall emissions in most of the impact categories. The

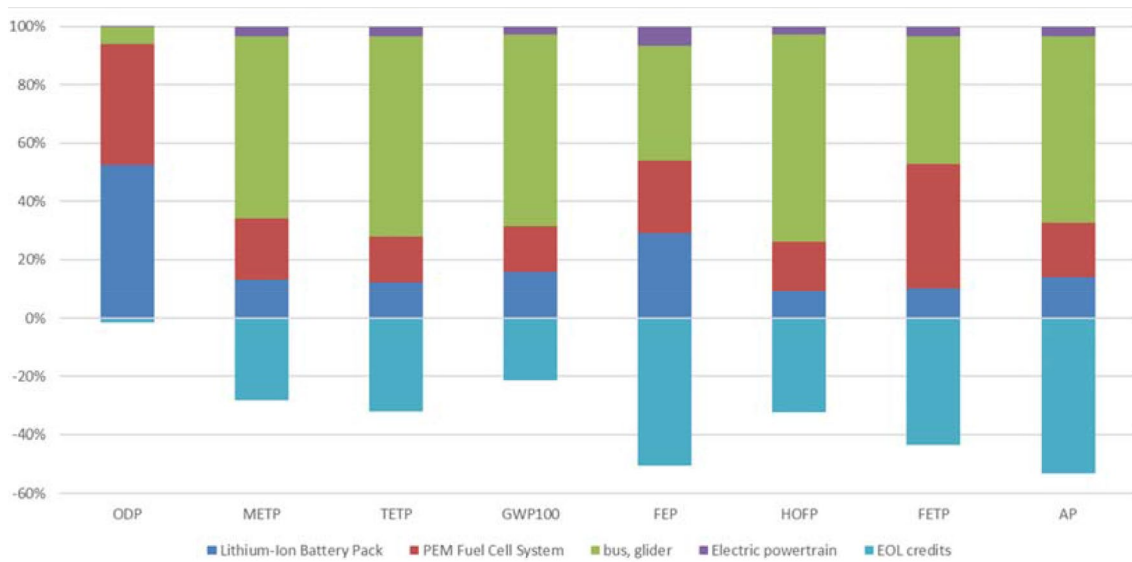


Fig. 6 Aggregated contribution of processes to midpoints categories for H2FC bus main components, including recycling credits. Impacts refer to one H2FC bus during its entire lifetime. The recycling credits are expressed as a percentage of the total burden. Impact categories: ozone depletion (ODP), eutrophication marine

(METP), eutrophication terrestrial (TETP), climate change (GWP100), eutrophication freshwater (FEP), photochemical ozone formation (HOFPP), ecotoxicity freshwater (FETP), acidification terrestrial and freshwater (AP)

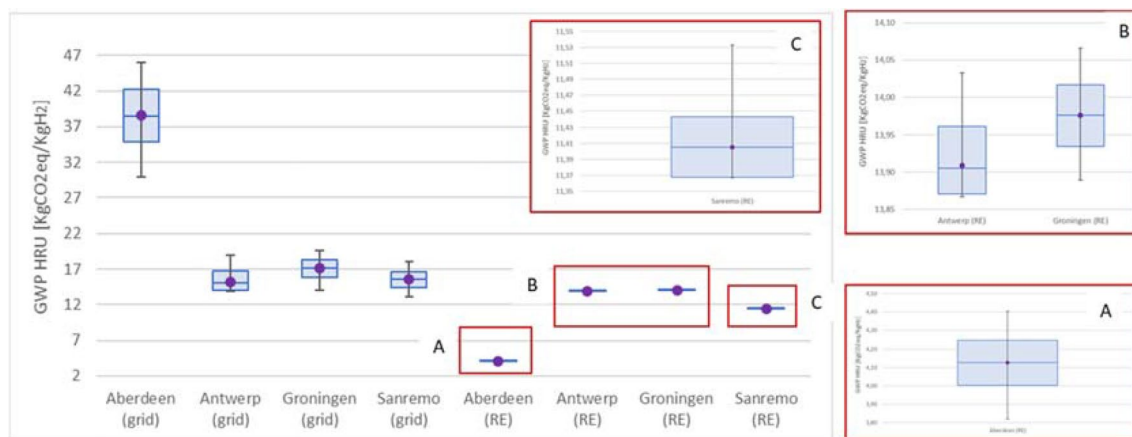


Fig. 7 GWP hydrogen production (KgCO₂eq./KgH₂ at nozzle). Grid=electricity mix from EU grid, RE=electricity generated by EU renewable sources

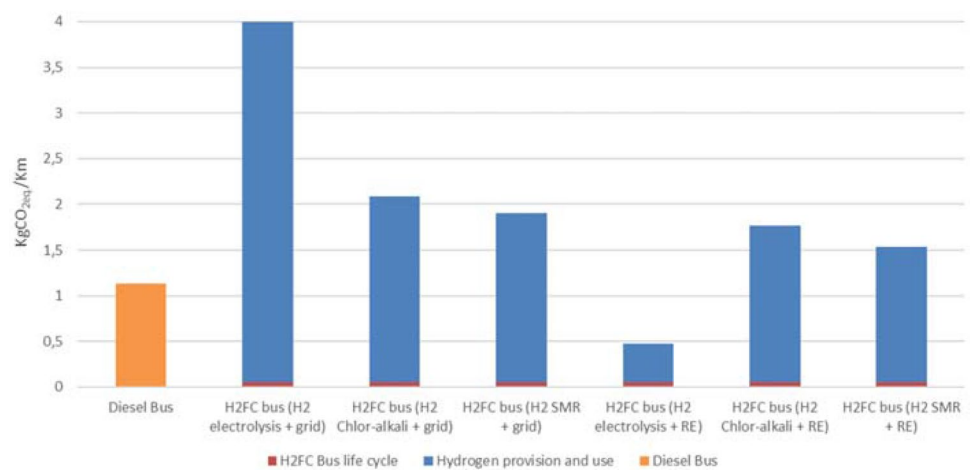
Proton Exchange Membrane (PEM), Catalyst, Bipolar Plates (BPP) and Gas Diffusion Layer (GDL) are the main contributors. The use of tetrafluoroethylene, polyethylene, sulphur trioxide, platinum, organic solvent and carbon black results in such high impacts. The main causes are the emissions originating from the mining of platinum [46]. Furthermore, as underscored by [51], metal refining to sufficient purities frequently requires energy-consuming and precisely controlled melting stages, often powered by fossil-fuel inputs.

3.2 LCIA results of the refuelling infrastructure

The stages classified in the fuel cycle are the following: feedstock production, feedstock transportation, fuel production and fuel distribution via HRU.

The carbon dioxide emissions dominate the GWP, and they are mainly related to the energy conversion process (production of electricity, chlor-alkali electrolysis and steam reforming) of non-renewable energy resources. Figure 7 summarizes the above. The use of renewable energy source significantly reduces the emissions related

Fig. 8 Global warming potential 100 year, GWP100 ($\text{KgCO}_{2\text{eq}}/\text{Km}$). Diesel bus = standard Euro-6 diesel bus. Grid = electricity mix from EU grid, RE = electricity generated by EU renewable sources. H2 electrolysis = hydrogen from water electrolysis, H2 Chlor-alkali = hydrogen as by-product from Chlor-alkali processes, H2 SMR = hydrogen from steam methane reforming processes



to electricity generation, but not remarkably in chlor-alkali and SMR plants. In the latter two production paths, the renewable energy is mainly used in the refuelling stations to fill the buses with the gas. However, the use of "green" electricity in such plants could further reduce the emissions by 85% (see S1 for the statistical assessment of the hydrogen consumption and S2 for details on hydrogen production impact assessment).

The non-methane volatile organic compounds (NMVOC) in hydrogen production stages are emitted during the electricity generation and by the chlor-alkali electrolysis and steam reforming process.

The hydrogen production by electrolyser using the EU grid mix has the highest acidification potential ($38.48 \text{ KgCO}_{2\text{eq}}/\text{KgH}_2$ at nozzle). This is related to the H_2S emissions, which is responsible for more than 90% of the AP from electricity generation. The chlor-alkali electrolysis process accounts for nearly 75%. The steam reforming reaction holds the 14% of the total impacts, while the remaining 86% is due to electricity that is mainly used to power the filling station.

The main contribution to the eutrophication potential of all considered scenarios is related to NO_x emissions, nitrogen (N) and phosphorus (P), while for electrolyser the NO_x emissions originate from energy production, in the case of steam reformer approximately 55% are direct emissions by the reforming process, and 44% are related to the consumed electricity for utilities and compression. In the chlor-alkali processes the NO_x emissions are driven by the electrolytic process (83%) and by the electricity supplied to the plant and to the filling station (17%). In aquatic systems, the addition of nutrients is mainly caused by the electricity generation processes (99% and 85%). Relevant information on the above percentages is reported in S2.

3.3 LCIA results integrating vehicle cycle and refuelling infrastructure

Figure 8 summarizes the H2FC bus system environmental impacts, expressed in $\text{KgCO}_{2\text{eq}}/\text{Km}$, combining the bus life cycle and the hydrogen supply pathways. The comparison is carried out arranging the three patterns of hydrogen production, parametrized by electricity stemming from EU average mix and from renewable sources. The contribution of the different lifecycle stages to the total score is presented by the stacked elements inside the bars.

The electricity-based hydrogen bus system produces significantly higher GWP than the reference Euro-6 Diesel bus ($1.14 \text{ KgCO}_{2\text{eq}}/\text{km}$). As shown in Fig. 8, the full life cycle greenhouse gas emissions of the production of electricity-based hydrogen depend on how the electricity is produced. The GHG emissions using the average EU electricity mix (Ecoinvent 3.5 data) are around $4 \text{ KgCO}_{2\text{eq}}/\text{Km}$, while those from the production of renewable hydrogen are significantly low, around $0.5 \text{ KgCO}_{2\text{eq}}/\text{km}$, so almost halving the emissions compared to a EURO 6 Diesel bus. On the other hand, the emissions from fossil-based and by-product hydrogen range between $1.5 \text{ KgCO}_{2\text{eq}}/\text{km}$ and $2 \text{ KgCO}_{2\text{eq}}/\text{km}$ (values depend also on the electricity mix used in the process). When looking into the local emissions that are emitted inside EU boundaries, the H2FC bus has a better performance against a diesel bus, mainly because of zero tailpipe emissions and high energy efficiency. However, the fuel cells and lithium-ion batteries manufacturing triggers high impacts for most of the concerned categories (see Fig. 6: ODP 94%, FEP 58%, AP 38% and FETP 29%). Please refer to S2 for further contribution breakdowns). Moreover, from the chart, displayed in Fig. 8, the vehicle life cycle impacts seem to be negligible (between 3 and 10% of the overall impacts), thus potentially misleading the assessment. Therefore, in considering these benefits, it is important to address concerns of problem shifting.

Fig. 9 Global warming potential 100 year, GWP100 ($\text{KgCO}_{2\text{eq.}}/\text{Km}$). Diesel bus = standard Euro-6 diesel bus. Grid = electricity mix from EU grid, RE = electricity generated by EU renewable sources

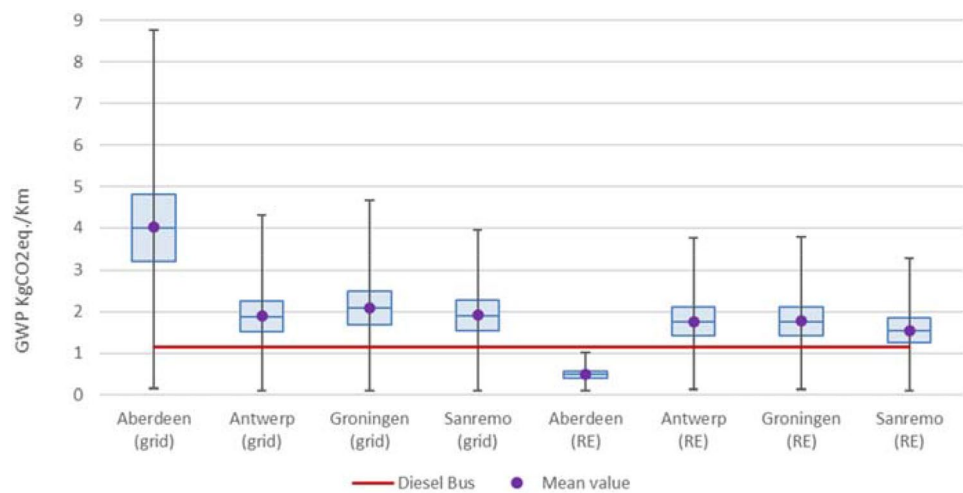


Figure 9 reports results by parallel boxplots with uncertainty information, thus evaluating the stability of the result that may be affected by the underlying uncertainty. In this study, H₂FC bus fuel economy (amount of hydrogen consumed per km) and refuelling station energy demand uncertainties¹ are considered dominant. S1 contains a detailed explanation on the statistical assessment of the hydrogen consumption data and the fuel economy of the High V.LO-City bus fleets collected during the project.

The above results are consistent with those from [41]. The authors proposed two scenarios to illustrate the possible range of results. The first scenario is for "grey" H₂ produced by a central SMR. The second scenario is for "green" H₂ produced on-site using an electrolyser, powered by renewable energy available on-site. The GWP emissions on per Km-basis are the following: for H₂FC bus powered with "grey" hydrogen, they are ~1.38 $\text{KgCO}_{2\text{eq.}}/\text{km}$, while in the present study they range between $1.5 \div 2 \text{ KgCO}_{2\text{eq.}}/\text{km}$ – differences are due to hydrogen production options and filling station energy demand; for H₂FC bus powered with "green" hydrogen, they are ~0.23 $\text{KgCO}_{2\text{eq.}}/\text{km}$, while in our assessment they are around 0.5 $\text{KgCO}_{2\text{eq.}}/\text{km}$. In the latter scenario, differences may be due to the energy demand of the production site and to modelling considerations that could affect the impact assessment. In our analysis, however, we have collected data from actual consumption of the refuelling station, thus underscoring the validity of the obtained results.

¹ Energy to produce, deliver, store and supply the gas to the bus.

3.4 Interpretations and recommendations

The study shows that the H₂FC bus system could deliver significant air quality improvements over conventional diesel buses in the urban context, provided that hydrogen is "produced through the electrolysis of water and with the electricity stemming from renewable sources" [25]. A corresponding way to express the above is to answer to questions 1, 2 and 3 stated in the goal definition section. An answer to question 1—if the environmental impact decreases or increases according to the hydrogen production methods and on the energy need to operate the station during the refuelling process—is that differences between the LCIA categories depend on the selection of the production method and of the electricity mix (question 2) used to power the hydrogen supply chain.

In the climate change impact category—which is especially interesting as climate change mitigation is a key driving force for renewable hydrogen [25]—it can be noticed that the use of "clean" H₂FC bus system is beneficial. Two final important conclusions from the assessment of the climate change category can be drawn. The first is that the hydrogen production from water electrolysis presents significant savings compared to a conventional diesel bus (question 3); the second, in contrast, is that the H₂FC vehicle, which has the largest potential to reduce emissions, has the heaviest vehicle equipment life cycle burden (see Fig. 6; bus glider account for more than 60% in GWP, AP, HOFP and eutrophication categories; PEM fuel cell stack, lithium-ion battery pack together are responsible for more than ninety per cent in the ODP category).

Transportation-related emissions have a negative impact on public health because of their negative impact on the air quality [11]. The deleterious impact of air pollution on public health has long been assessed and

described as underlined by WHO [71]. Although they may seem to be two very different issues, climate change and air pollution are closely related, emissions of pollutants into the air can result in changes to the climate, and vice versa [3].

For the above reasons, we underscore that the use of H₂FC bus fleets during the entire project allowed to save potentially around 5 tons of carbon monoxide, 1.4 tons of nitrogen oxides, roughly a half ton of unburned hydrocarbons (HC) and nearly 36 kg of particulate matter (PM), if compared to a EURO 6 Diesel bus. Emission limits are taken from [22]. See S1 for details on the emissions saving calculation. Therefore, policies should involve the integration of climate change, air quality and public health benefits to provide a common ground [3].

For regional environmental impacts caused by airborne emissions, i.e. acidification and eutrophication, as well as local air pollution, renewable hydrogen option has the best potential to reduce impacts of emissions overall. In August of 2019, the EC revised their previously published Clean Vehicle Directive [24], tightening up and set a minimum target for 24% of all public transport buses in each EU member state to be "clean" by 2025, with this minimum quota increasing based on the country's Gross Domestic Product (GDP).

4 Conclusions

The outcomes of these demonstration projects have substantially proved the effectiveness of such approach, thus favouring renewables penetration and significantly improving the air quality in cities. In this context hydrogen produced through electrolysis using renewable electricity can play a particularly important "nodal" role in decarbonizing transport in a cost-effective way, addressing the whole hydrogen value chain to support economic growth and recovery.

Our results clearly indicate that it is advantageous to promote such mode of transportation in areas where electricity is primarily produced from renewables (i.e. wind power as an alternative to fossil fuels). It is noteworthy that the surge in electricity demand in transportation should be accompanied by a sharpened policy focus with regard to life cycle management and to counter potential drawbacks, in particular those related to problem shifting and to grid improvement.

Author contributions Adriana del Borghi and Maurizio Mazzucchelli helped in conceptualization, methodology, and validation; Davide Walter Pederzoli curated the data and wrote the original draft; Luca Moreschi and Michela Gallo investigated and visualized the study;

Cristina Carnevali and Riccardo Genova supervised the study. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Availability of data and material The datasets generated and/or analysed during the current study are available in the OSF repository. Supporting Information: S1 (<https://osf.io/bkr8z>), S2 (<https://osf.io/hq54a>).

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants performed by any of the authors.

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References

- 3EMOTION (2015–2022) Environmentally Friendly, Efficient Electric Motion: FCH JU Funded Project 2015–2022. Available online: <https://www.3emotion.eu/>.
- Ajanovic A, Glatt A, Haas R (2021) Prospects and impediments for hydrogen fuel cell buses. *Energy* 235:121340
- Akasha H, Ghaffarpasand O, Pope F (2021) Climate change and air pollution. In: K4D helpdesk report. Institute of Development Studies, Brighton. <https://doi.org/10.19088/K4D.2021.071>. https://opendocs.ids.ac.uk/opendocs/bitstream/handle/20.500.12413/16600/962_Climate_Change_and_Air_Pollution.pdf
- Berger R (2015) Fuel cell electric buses-potential for sustainable public transport in Europe. A study for the fuel cells and hydrogen joint undertaking. http://www.fch.europa.eu/sites/default/files/150909_FINAL_Bus_Study_Report_OUT_0.pdf
- Brinkmann T, Giner Santonja G, Schorcht F, Roudier S, Delgado Sancho L (2014) Best available techniques (BAT) reference document for the production of chlor-alkali. In: JRC science for policy report (JRC91156/ EUR 26844 EN). Publications Office of the European Union, Luxembourg. <https://doi.org/10.2791/13138>
- Cooney G, Hawkins TR, Marriott J (2013) Life cycle assessment of diesel and electric public transportation buses. *J Ind Ecol* 17(5):689–699
- Cusenza MA, Bobba S, Ardente F, Cellura M, Di Persio F (2019) Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles. *J Clean Prod* 215:634–649

8. Doyle D, Harris A, Chege S, Douglas L, Early J, Best R (2020) Hydrogen fuel cell buses: modelling and analysing suitability from an operational and environmental perspective (no. 2020-01-1172). SAE Technical Paper
9. Duclos L, Lupsea M, Mandil G, Svecova L, Thivel PX, Laforest V (2017) Environmental assessment of proton exchange membrane fuel cell platinum catalyst recycling. *J Clean Prod* 142:2618–2628
10. Ercan T, Tatari O (2015) A hybrid life cycle assessment of public transportation buses with alternative fuel options. *Int J Life Cycle Assess* 20(9):1213–1231
11. Erickson LE, Jennings M (2017) Energy, transportation, air quality, climate change, health nexus: sustainable energy is good for our health. *AIMS Public Health* 4(1):47
12. EU (2000) Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles - Commission Statements. OJ L 269, 21.10.2000. Available at: <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32000L0053>
13. EU (2006a) Decision No 1982/2006/EC of the European Parliament and of the Council of 18 December 2006 concerning the Seventh Framework Programme of the European Community for research, technological development and demonstration activities (2007–2013). *Official Journal of the European Union*, L 412, 30 December 2006
14. EU (2006b) Decision no 1982/2006/EC of the European Parliament and of the Council of 18 December 2006 concerning the seventh framework programme of the European community for research, technological development and demonstration activities (2007–2013) Statements by the Commission. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32006D1982>
15. EU (2007b) Directive 2007/46/EC of the European Parliament and of the Council of 5 September 2007 establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles (Framework Directive). <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32007L0046>
16. EU (2008) Council regulation (EC) no 521/2008 of 30 May 2008 setting up the fuel cells and hydrogen joint undertaking. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008R0521>
17. EU (2009c) Directive 2009/33/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of clean and energy-efficient road transport vehicles. <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0033>
18. EU (2010a) COM(2010) 2020. EUROPE 2020 A strategy for smart, sustainable and inclusive growth. <https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A52010DC2020>
19. EU (2011b) COM(2011) 571. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Roadmap to a Resource Efficient Europe. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52011DC0571>
20. EU (2013a) COM(2013) 179. Commission recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013H0179>
21. EU (2013c) COM(2013) 196. Communication from the Commission to the European Parliament and the Council building the single market for green products facilitating better information on the environmental performance of products and organisations. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52013DC0196>
22. EU (2014) Commission regulation (EU) No 133/2014 of 31 January 2014 amending, for the purposes of adapting to technical progress as regards emission limits, directive 2007/46/EC of the European Parliament and of the Council, Regulation (EC) No 595/2009 of the European Parliament and of the Council and Commission Regulation (EU) No 582/2011. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014R0133>
23. EU (2019a) Communication COM/2019/640: the European green deal. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN>
24. EU (2019b) Directive (EU) 2019/1161 of the European Parliament and of the Council of 20 June 2019 amending directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles. <https://eur-lex.europa.eu/eli/dir/2019/1161/oj>
25. EU (2020a) Communication COM/2020/299: powering a climate-neutral economy: an EU strategy for energy system integration. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0299&from=PL>
26. EU (2020b) Communication COM/2020/301: a hydrogen strategy for a climate-neutral Europe. <https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:52020DC0301>
27. Eudy L, Post MB (2018) Fuel cell buses in us transit fleets: Current status 2018 (No. NREL/TP-5400-72208). National Renewable Energy Lab. (NREL), Golden, CO (United States). <https://www.nrel.gov/docs/fy19osti/72208.pdf>
28. Fazio S, Castellani V, Sala S, Schau E, Secchi M, Zampori L, Diaconu E (2018) Supporting information to the characterisation factors of recommended EF life cycle impact assessment methods. In: New models and differences with ILCD, EUR, 28888
29. Fuel Cells and Hydrogen Joint Undertaking (FCHJU) (2005) European Hydrogen and Fuel Cell Technology Platform: Strategic Research Agenda. Retrieved from <https://www.fch.europa.eu/page/who-we-are>
30. Fuel Cell and Hydrogen Joint Undertaking (FCH-JU) (2017) CHIC final report. Müller, K., Schnitzeler, F., Lozanovski, A., Skiker, S., Ojakovoh, M, Brussels, Belgium
31. Fuel Cells and Hydrogen Joint Undertaking (FCHJU) (2012) Urban buses: alternative powertrains for Europe. <https://www.fch.europa.eu/node/790>
32. Fuel Cells and Hydrogen Joint Undertaking (FCHJU) (2020) Fuel Cell Electric Buses Knowledge Base. <https://fuelcellbuses.eu/>
33. Guinée JB, Udo de Haes HA, Huppes G (1993) Quantitative life cycle assessment of products 1: goal definition and inventory. *J Clean Prod* 1(1):3–13. [https://doi.org/10.1016/0959-6526\(93\)90027-9](https://doi.org/10.1016/0959-6526(93)90027-9)
34. Hagos DA, Ahlgren EO (2018) Well-to-wheel assessment of natural gas vehicles and their fuel supply infrastructures—perspectives on gas in transport in Denmark. *Transp Res Part D Transp Environ* 65:14–35
35. Harris A, Soban D, Smyth BM, Best R (2018) Assessing life cycle impacts and the risk and uncertainty of alternative bus technologies. *Renew Sustain Energy Rev* 97:569–579
36. HighVLOCity (2019) Cities speeding up the integration of hydrogen buses: FCH JU funded project 2012–2018. <http://highvlocity.eu/>. Accessed on 8 September 2019
37. HyFLEET:CUTE (2008) Hydrogen transport: bus technology and fuel for today and for a sustainable future: EU funded project 2006–2009. https://cordis.europa.eu/project/rcn/85636_en.html
38. HyTransit (2016) European hydrogen transit buses in Scotland: FCH JU funded project 2013–2018. http://cordis.europa.eu/project/rcn/106694_en.html
39. ISO (2006a) Environmental management—life cycle assessment—principles and framework (14040)

40. ISO (2006b) Environmental management—life cycle assessment—requirements and guidelines (14044)
41. Lozanovski A, Whitehouse N, Ko N, Whitehouse S (2018) Sustainability assessment of fuel cell buses in public transport. *Sustainability* 10:1–15
42. Maack M (2008) Generation, of the energy carrier HYDROGEN in context with electricity buffering generation through fuel cells. *NEEDS New Energy Externalities Developments for Sustainability*
43. Marmiroli B, Messagie M, Dotelli G, Van Mierlo J (2018) Electricity generation in LCA of electric vehicles: a review. *Appl Sci* 8(8):1384. <https://doi.org/10.3390/app8081384>
44. Mehmeti A, Angelis-Dimakis A, Arampatzis G, McPhail SJ, Ulgiati S (2018) Life cycle assessment and water footprint of hydrogen production methods: from conventional to emerging technologies. *Environments* 5(2):24. <https://doi.org/10.3390/environments5020024>
45. Majeau-Bettez G, Hawkins TR, Strømman AH (2011) Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric. *Veh Environ Sci Technol* 45:4548–4554
46. Miotti M, Hofer J, Bauer C (2017) Integrated environmental and economic assessment of current and future fuel cell vehicles. *Int J Life Cycle Assess* 22(1):94–110
47. Nakatani J (2014) Life cycle inventory analysis of recycling: mathematical and graphical frameworks. *Sustainability* 6(9):6158–6169
48. Navas-Anguita Z, García-Gusano D, Iribarren D (2019) A review of techno-economic data for road transportation fuels. *Renew Sustain Energy Rev* 112:11–26
49. Nordelöf A, Messagie M, Tillman AM, Ljunggren SM, Van Mierlo J (2014) Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment. *Int J Life Cycle Assess* 19:1866–1890. <https://doi.org/10.1007/s11367-014-0788-0>
50. Nordelöf A, Romare M, Tivander J (2019) Life cycle assessment of city buses powered by electricity, hydrogenated vegetable oil or diesel. *Transp Res Part D Transp Environ* 75:211–222. <https://doi.org/10.1016/j.trd.2019.08.019>
51. Nuss P, Eckelman MJ (2014) Life cycle assessment of metals: a scientific synthesis. *PLOS ONE* 9(7):e101298
52. Offer GJ, Howey D, Contestabile M, Clague R, Brandon NP (2010) Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. *Energy Policy* 38(1):24–29
53. OpenLCA (2020) <http://www.openlca.org/>
54. Orsi F, Muratori M, Rocco M, Colombo E, Rizzoni G (2016) A multi-dimensional well-to-wheels analysis of passenger vehicles in different regions: primary energy consumption, CO₂ emissions, and economic cost. *Appl Energy* 169:197–209
55. Pagliaro M, Meneguzzo F (2019) Lithium battery reusing and recycling: a circular economy insight. *Heliyon* 5(6):e01866. <https://doi.org/10.1016/j.heliyon.2019.e01866>
56. Pehnt M (2001) Life-cycle assessment of fuel cell stacks. *Int J Hydrog Energy* 26:91–101
57. Pehnt M (2003) Assessing future energy and transport systems: the case of fuel cells. Part I: methodological Aspects. *Int J Life Cycle Assess* 8(5):283–289
58. Pehnt M (2003) Assessing future energy and transport systems: the case of fuel cells. Part II: Environmental performance. *Int J Life Cycle Assess* 8(6):365–378
59. Pehnt M (2003) Life-cycle analysis of fuel cell system components. In: Vielstich W (ed) *Handbook of fuel cells. Fundamentals, technology and applications, vol 4*. Wiley, Chichester, pp 1293–1317
60. Roland Berger (2016) Integrated fuels and vehicles roadmap to 2030. <https://www.rolandberger.com/en/Media/Integrated-Fuels-and-Vehicles-Integrated-Fuels-and-Vehicles-Roadmap-to-2030.html>
61. Saxe M, Folkesson A, Alvfors P (2008) Energy system analysis of the fuel cell buses operated in the project: clean urban transport for Europe. *Energy* 33(5):689–711
62. Spath PL, Mann MK (2000) Life cycle assessment of hydrogen production via natural gas steam reforming (No. NREL/TP-570-27637). National Renewable Energy Lab., Golden
63. Stropnik R, Lotrič A, Bernad Montenegro A, Sekavčnik M, Mori M (2019) Critical materials in PEMFC systems and a LCA analysis for the potential reduction of environmental impacts with EoL strategies. *Energy Sci Eng* 7(6):2519–2539
64. Staffell I, Ingram A (2010) Life cycle assessment of an alkaline fuel cell CHP system. *Int J Hydrog Energy* 35(6):2491–2505
65. Staffell I, Scamman D, Abad AV, Balcombe P, Dodds PE, Ekins P, Shah N, Ward KR (2019) The role of hydrogen and fuel cells in the global energy system. *Energy Environ Sci* 12(2):463–491
66. Treyer K, Bauer C (2013) Life cycle inventories of electricity generation and power supply in version 3 of the ecoinvent database—part I: electricity generation. *Int J Life Cycle Assess* 21(9):1236–1254
67. Treyer K, Bauer C (2014) Life cycle inventories of electricity generation and power supply in version 3 of the ecoinvent database—part II: electricity markets. *Int J Life Cycle Assess* 21(9):1255–1268
68. Van Mierlo J, Messagie M, Rangaraju S (2017) Comparative environmental assessment of alternative fueled vehicles using a life cycle assessment. *Transp Res Procedia* 25:3439–3449. <https://doi.org/10.1016/j.trpro.2017.05.244>
69. Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. *Int J Life Cycle Assess* 21(9):1218–1230
70. Werner D, Peuker UA, Mütze T (2020) Recycling chain for spent lithium-ion batteries. *Metals* 10(3):316
71. World Health Organization (WHO) (2015) Economic cost of the health impact of air pollution in Europe: clean air, health and wealth. WHO Regional Office for Europe. https://www.euro.who.int/__data/assets/pdf_file/0004/276772/Economic-cost-health-impact-air-pollution-en.pdf
72. Wulf C, Kaltschmitt M (2018) Hydrogen supply chains for mobility—environmental and economic assessment. *Sustainability* 10(6):1–26. <https://doi.org/10.3390/su10061699>

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