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Comparison between hydrogen and electric vehicles by life cycle assessment: A case study in Tuscany, Italy

I. Bartolozzi *, F. Rizzi, M. Frey

Scuola Superiore Sant'Anna, Istituto di Management, Piazza Martiri della Libertà, 33, 56127 Pisa, Italy

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ABSTRACT

The use of hydrogen produced from renewable energy sources is often reported as an attractive strategy to address the issue of urban environmental sustainability in automotive sector, and a potential alternative to fossil fuel-fed vehicles. The project 'Filiera Idrogeno' (Hydrogen Chain) has investigated the potential realisation of hydrogen production chains from renewables and its use as automotive fuel in Tuscany Region (Italy). In this context, life cycle assessment was used for evaluating the environmental sustainability of such chains, applied to a fleet of hydrogen vehicles for urban commercial delivery.

From the energy supply side, renewable wind and biomass energy sources were considered for hydrogen production either by electrolysis or direct separation from biomass gasification syngas, according to specific simulations. Benchmarking with hydrogen produced by using Italian electricity mix was carried out. From the transport side, vehicles equipped with either fuel cell or internal combustion engine were evaluated.

A benchmarking analysis with standard electric vehicles supplied with electricity produced from the same renewable energy sources was also carried out.

The results give some indications on the environmental aspects of the different alternatives and on the contribution of the chain phases to the overall impacts.

1. Introduction

Transport sector is responsible for a significant contribution to greenhouse gases emissions (GHG) and to the climate change, as well as for local air pollution, being quasi dependent (up to 95%) on liquid fossil fuels derived from crude oil, and accounting for more than 60% of total world's oil consumption.

A shift towards a more sustainable transport system is therefore considered to be crucial to reduce the use of fossil fuels, by adopting alternatives such as eco-driving [1], coal based alternative vehicle fuels, second generation technology biofuels [2], electricity or hydrogen. Source-sink modelling reveals that, in case of biofuels, there are trade-offs between their production and food markets and, in case of carbon capture and storage, there are trade-offs between their high capital intensity and investments in a variety of evolving solutions [3]. The last two alternatives have instead positive aspects such as no tailpipe emissions as well as the potential to integrate with renewable energies.

Electric vehicles (EVs) are considered to potentially have the lowest fuel costs and GHG emissions, due to their high efficiency throughout the fuel supply chain and the vehicle fuel consumption. EVs can benefit from the flexibility of electric technologies that, as an example, allow satisfactory integration within hybrid diesel-electric vehicles [4]. However, the foreseen massive emergence of EVs brings along the growing need to address potential problems related to it and much research has been undertaken in order to put forward solutions to such critical aspects. For instance, in order to solve problems occurring when a large number of plug-in hybrid electric vehicles/electric vehicles (PHEVs/PEVs) add energy load to current power grids, the implementation of suitable algorithms for the optimal management of a large number of PHEVs/PEVs charging at a municipal parking station has been proposed [5]. Also efforts to provide optimisation for EVs charging and discharging, given variations in electricity spot prices and driving patterns of the vehicle fleet, has been undertaken [6]. Suitable integration of power and road transport system, with the introduction of electric drive vehicles, has been investigated by applying a model to find the optimal configuration for instance in Northern Europe, i.e. Denmark, Finland, Germany, Norway, and Sweden [7]. Indeed the development of electric vehicles is considered not only as a cleaner and more energy efficient source of transportation but also as a flexible electricity storage option. For instance, the potential impact of EVs with vehicle to grid (V2G) capability to power system operation has been investigated in Spain in function of the power system considered, the number (and type) of EVs, and the scenarios for renewable energy sources (RES) generation [8]. Also

* Corresponding author. Tel.: +39 050 882781; fax: +39 050 883936.
E-mail addresses: i.bartolozzi@sssup.it (I. Bartolozzi), f.rizzi@sssup.it (F. Rizzi), m.frey@sssup.it (M. Frey).

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significant attention should be paid to the power generation mix and its CO_2 intensity, used to feed EVs or PHEVs. The CO_2 models indicate that the best options among EV, PHEV and internal combustion engine (ICE) vehicles depend on the CO_2 intensity of the energy mix and therefore varies upon the country [9]. Low CO_2 intensive countries are able to fully take advantage of the ability of EVs and plug-in hybrid EVs to reduce the CO_2 emissions from automotive transport. Coherently, the future integration of power and road transport system due to the introduction of electric drive vehicles influences the economically optimal investments and optimal operation of the power system [3].

Hydrogen has also been reviewed recurrently as a suitable alternative to fossil fuel based transport and both advantages to its use and barriers to its diffusion have been analysed [10].

Being a secondary energy carrier that can be produced from any (locally available) primary energy source, hydrogen can contribute to a diversification of automotive fuel sources and may offer the long term possibility of being produced from renewable energies and, at the same time, it may be used as a storage medium for electricity from intermittent renewable energies, such as wind power [11]. Hydrogen, battery and hybrid hydrogen/battery system are the options that have to be considered for lightweight electric vehicle application [12].

Therefore, this link between renewable energy and the transport sector, may provide global environmental benefits, although it may still have significant disadvantages such as the incapability to utilise a large part of the available energy and a low cost-effectiveness compared to hydrogen production from fossil fuels [13]. Even though at present, approximately 97% of total hydrogen production is accomplished by steam reforming of natural gas and other fossil primary energy, and therefore only 3% is based on renewable energies, the attention paid to these sources is strategic not only from an environmental point of view but also for the improvement of the process efficiency as, for instance, it has been demonstrated for a biomass-gasification-electricity-electrolysis chain [14].

However, the success of a hydrogen economy still has to overcome significant barriers, both technological and economical. Significant effort has been done in the past years to boost such development, by supporting a large number of projects aimed to solve these issues. Among the others, H2power, H2ways, HyRaMP, HyER European projects are intended to provide potential roadmaps for overcoming the technical and economic barriers that are widely discussed in the archival literature [15]. These barriers are mainly related to the implementation of hydrogen-dedicated structures and to the impacts of hydrogen policies on consumers' behaviours, both aspects being strictly connected.

Furthermore, path dependencies and competition between alternatives can determine the development of hydrogen applications in the long run. As an example, available infrastructure alternatives suffer from both external and internal concurrences. In fact, focusing on the latter, the potential refuelling methods that are in competition include cans, barrels, home refuelling outfits, parking garage refuelling facilities, mobile stations, hand carts and curb pumps. Melanina [16] argues that, due to the impossibility to determine ex-ante the optimal replication at systemic level of one of these methods, research and development strategy that can support hydrogen delivery and dispensing technologies would be adaptive, broad in scope, and would extend over a long time horizon. Similarly, since market penetration of clean vehicle technologies is an influence on people's preferences ('the neighbour effect'), not only on technical and economic performances, adaptive strategies are required also for green vehicles marketing policies. With this regard, Mau et al. [17] argue that, being the consumers' preference patterns for evolutionary technologies unlikely to apply to disruptive technologies, the development – as an example – of electric and hydrogen vehicle markets can have a mutual influence. Similar dynamics can be extended also outside the boundaries of green vehicles. Meyer et al. [18] argue that the integration and competition of a related variety of hydrogen technologies are necessary also from a wider product-oriented perspective. In particular, the authors find that a coordinated policy approach that encourages both the purchase of fuel cell vehicles and the building of hydrogen infrastructure and provides insights into related factors for technology diffusion of complementary goods is needed. On the other hand, the low level of hydrogen economy growth calls for a rational distribution of resources (i.e. to avoid the dispersion of resources on hopeless alternatives). Policy and decision makers have to be provided with an adequate technical, economic and environmental theoretical framework that takes into account also actual external costs and innovation in a long term perspective. It is often claimed that electric or hydrogen alternatives provide a simple displacement of the environmental impacts, especially when hydrogen and electricity production is based on fossil resources [19]. The integration of multicriteria perspectives into distributed generation planning and design is fundamental for supporting a paradigm shift in urban energy systems [20]. The evaluation of the environmental sustainability of such alternatives should take into account the whole life cycle of the hydrogen production process, including production from renewable energy sources, purification, storage, transportation, distribution, and final utilisation. For instance, Lee et al. examined the competitiveness of a hydrogen station based on wind energy, in both environmental and economic aspects, under two scenarios, by using life cycle assessment (LCA) and life cycle costing (LCC) methodologies [21]. Briguglio et al. applied LCA to compare a renewable hydrogen production chain applied to a urban sustainable mobility with a number of alternatives [22].

In this context, the project 'Filiera Idrogeno' (Hydrogen Chain), supported by Tuscany Region (Italy), has the general objective to evaluate the technological, economical, social and environmental aspects of renewable energy hydrogen chains at a regional scale, with the use of produced hydrogen as automotive fuel. A high-intensity last-mile service of delivery vans, used for goods distribution to commercial retail activities in the centre of a mid-size city, represents the application scenario that is here exogenously introduced as potential starter of the local green mobility market [23]. The evaluation of the environmental sustainability of such scenarios, carried out in parallel with the evaluation of the economical and technological feasibility, is an important element to support the decision making process.

To this end, life cycle assessment (LCA) is the suitable tool for analysing the whole life cycle, from hydrogen production, storage, transportation and its use as fuel in the operational phase of the vehicle. Hydrogen production based on Italian energy mix was analysed as benchmarking element. Also, in order to compare different technological alternatives, benchmarking with electric vehicles based on renewables as well as on Italian electricity mix was carried out.

2. LCA methodology

LCA is a holistic environmental management tool that determines the environmental impacts of a product or system over its entire life cycle, from production, through use and to disposal, as defined by SETAC, and coded by the ISO 14040 standards, according to which the analysis is divided into four steps [24].

– Goal and scope definition is the preliminary stage, in which we define the goal of the study, the functional unit, the system boundaries, the amount and quality of data, the assumptions and limits and the environmental issues to be considered.