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Integrating a hydrogen fuel cell electric vehicle with vehicle-to-grid technology, photovoltaic power and a residential building

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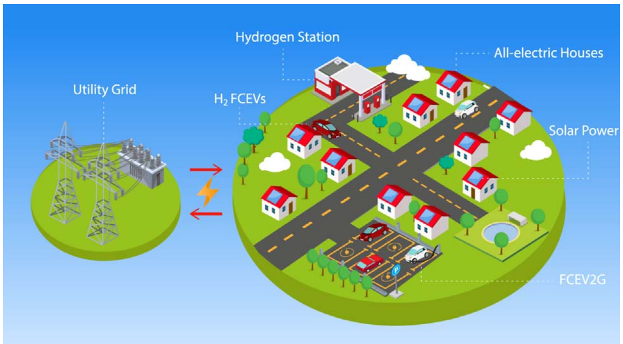
HIGHLIGHTS

- First time vehicle-to-grid measurements with a hydrogen fuel cell electric vehicle.
- Case study based on a Dutch pilot project.
- 2-week pilot living experiment in an all-electric house and using FCEV2G power.
- 52 h and 9 h of interrupted V2G at 1 kW and 10 kW power output, respectively.
- FCEVs can integrate transport and electricity sectors in a sustainable energy system.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents the results of a demonstration project, including building-integrated photovoltaic (BIPV) solar panels, a residential building and a hydrogen fuel cell electric vehicle (FCEV) for combined mobility and power generation, aiming to achieve a net zero-energy residential building target. The experiment was conducted as part of the Car as Power Plant project at The Green Village in the Netherlands. The main objective was to assess the end-user's potential of implementing FCEVs in vehicle-to-grid operation (FCEV2G) to act as a local energy source. FCEV2G field test performance with a Hyundai ix35 FCEV are presented. The car was adapted using a power output socket capable of delivering up to 10 kW direct current (DC) to the alternating current (AC) national grid when parked, *via* an off-board (grid-tie) inverter. A Tank-To-AC-Grid efficiency (analogous to Tank-To-Wheel efficiency when driving) of 44% (measured on a Higher Heating Value basis) was obtained when the car was operating in vehicle-to-grid (V2G) mode at the maximum power output. By collecting and analysing real data on the FCEV power production in V2G mode, and on BIPV production and household consumption, two different operating modes for the FCEV offering balanced services to a residential microgrid were identified, namely fixed power output and load following.

Based on the data collected, one-year simulations of a microgrid consisting of 10 all-electric dwellings and 5 cars with the different FCEV2G modes of operation were performed. Simulation results were evaluated on the factors of autonomy, self-consumption of locally produced energy and net-energy consumption by implementing different energy indicators. The results show that utilizing an FCEV working in V2G mode can reduce the annual imported electricity from the grid by approximately 71% over one year, and aiding the buildings in the microgrid to achieve a net zero-energy building target. Furthermore, the simulation results show that utilizing the

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FCEV2G setup in both modes analysed, could be economically beneficial for the end-user if hydrogen prices at the pump fall below 8.24 €/kg.

1. Introduction

Wind and solar photovoltaics are currently the fastest growing sources of electricity globally. Electricity generation from both technologies is constrained by the varying availability of wind and sunshine, which causes fluctuations in electricity output over time [1]. Their integration into current power systems, combined with the increased environmental and security concerns regarding energy supply is leading to a profound transformation in the current fossil-fuel based energy system. Distributed energy sources and energy storage are both becoming key components in this new system. The evolutionary trend of this transition is towards smart energy networks that are characterized by widespread deployment of renewable energy technologies and intelligent energy management systems [2]. Until now, the electricity system has developed independently from other energy-related systems. The recent trend seeks the integration of the electricity, heat and transport sectors in order to conceive a single energy system, or what is known as a Smart Energy System, Smart Urban Energy Network or Smart Cities [2–4]. Integrating power, heat and fuel networks can increase the utilization of the system, reduce total costs and offer national electricity systems greater flexibility [5].

While Smart Energy Systems are explored on a global level, Smart Grids are the basic underlying unit on the local level. Different energy products and services that are involved in Smart Grids include microgenerators, storage systems, smart appliances, time variable prices and contracts, and energy monitoring and control systems [6]. All of these are bound to or located near buildings; thus, in this framework, the integration of buildings into smart grids is fundamental [7]. On average most people in the developed world currently spend 90% of their lives indoors [8–10], relying on heating and air conditioning. This leads to buildings being the largest energy consumers worldwide, accounting for about 40% of global energy and approximately one-third of greenhouse gas (GHG) emissions [11].

In addition, most road transport energy consumption is due to passenger vehicles, and when they are not in use, they are usually parked close to buildings [12]. Significant energy and environmental savings could be achieved if buildings were designed and managed efficiently and passenger vehicles were integrated into the built environment. It is estimated that an energy demand reduction of 35% can be achieved for a household by incorporating thermal insulating layers, utilizing energy-efficient appliances, efficient illumination and changing from fossil-fuel based to electric cars. However, this reduction in total energy is directly connected to an increase in electricity demand of 150% [13]. For the system to be sustainable, all of these 'all-electric' households will have to be supplied with electricity from renewable sources, such as solar and wind.

The conceptual understanding of a zero-energy building (ZEB) is that it is an energy-efficient building able to generate electricity, or other energy carriers, from renewable sources in order to compensate for its energy demand. More specifically, the term *near or net* ZEB (NZEB) is used to refer to buildings that are connected to the energy infrastructure, underlining the fact that there is balance near or equal to zero between energy taken from and supplied back to the energy grid over a period of time, nominally one year [14]. The end-users living in these buildings are sometimes referred to as 'prosumers', as they not only consume energy but also produce it on-site. The term often describes consumers who rely on smart meters and solar PV panels to generate electricity and/or combine these with home-energy management systems, energy storage, electric vehicles (EVs) and vehicle-to-grid (V2G) systems [15].

In this framework, electric vehicles become a fundamental component of buildings. The great potential in reducing energy demand in the built environment is reflected globally in policy directions that are moving towards zero-energy standards [16]. For example, the European Union (EU) has established that by 2021, all new buildings must be close to ZEB, and by 2019, new buildings occupied and owned by public authorities must also be close to ZEB [17]. While in California in the United States, the California Public Utilities Commission adopted the Big Bold Initiative, which directed that all new residential and commercial construction be Zero Net Energy by 2020 and 2030, respectively [18]. The technical feasibility of such zero-energy buildings has been proven by several pilot and case studies [19]. Some of them have even proven the ability of residential buildings to become positive-energy buildings (PEB), producing more energy than they consume [20,21].

Both intraday and seasonal energy storage systems are needed to support the integration of renewable energy. Typical solutions include electrical energy storage in batteries, flywheels, compressed air energy storage, pumped storage, EVs and hydrogen as an energy carrier [22–24]. While batteries will be used for short-term energy-efficient storage, long-term (seasonal) storage will require hydrogen fuels [25]. Energy storage, in the form of hydrogen and its direct use in fuel cells, can ensure reliability to the energy system and assist in the integration of renewable energy supply into the residential and industrial sectors. Electricity, heat and water are produced when hydrogen reacts with oxygen in a fuel cell. Hydrogen can be used in the transport sector in fuel cell electric vehicles (FCEVs). It is also important to mention the positive environmental effect caused by the replacement of gasoline vehicles by FCEVs. It has recently been reported by Ahmadi et al. that a 72% reduction in total GHG emissions (in terms of gCO_2 equivalent emitted per km of vehicle travelled) can be obtained by switching from gasoline vehicles to FCEVs in the transportation sector and that they are becoming both technologically and economically viable compared with incumbent vehicles [26].

In a recent review, Alanne and Cao defined the concept of the 'zero-energy hydrogen economy' as a zero-energy system, where hydrogen is one of the key energy carriers [27]. The review focuses on the integration of zero-energy hydrogen vehicles at the level of single buildings and communities and suggests that more research is needed to understand the impact of the exchange of various energy types between these vehicles, buildings and/or communities and hybrid smart grids. In this study, we aim to bridge this knowledge gap by providing insight into the technical feasibility of integrating a fuel cell electric vehicle with a residential building of a prosumer type, in order to fulfil the zero-energy building target.

EVs are considered promising candidates to replace fossil fuel powered vehicles. They not only have the potential to yield cleaner transportation but can also provide electric storage capabilities for other applications, such as V2G, Vehicle-to-Home (V2H), Vehicle-to-Load (V2L), and Vehicle-to-Vehicle (V2V) [28]. In this way, the cars are seen as dispatchable and flexible means of power supply that can interconnect the fuel sector and the electricity sector. In 1997, Kempton et al. had already envisioned that EVs, whether fuelled by batteries, liquids or gaseous fuels generating electricity on-board, would have value to electricity utilities as power resources [29]. This opens the possibility of EVs participating in demand-side management, voltage and frequency regulations, spinning reserve, active/reactive power compensation, load balancing and harmonic filtering [30].

In the literature, V2G related research is widely correlated and usually exclusively linked to battery-run electric vehicles (BEVs)