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# Development of a solar powered hydrogen fueling station in smart cities applications<sup>☆</sup>

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## A B S T R A C T

This paper reports main criteria for design, realization and validation of a solar-powered hydrogen fueling station in a smart city application relevant to an on-site hydrogen production plant. The program has been developed by CNR-ITAE together with other industrial partners in the framework of the Italian research project called i-NEXT (innovation for green Energy and eXchange in Transportation). The i-NEXT hydrogen production plant is located in the Municipality of Capo d'Orlando, Sicily, it is fed by a microgrid able to receive energy from solar radiation by a 100 kW rooftop photovoltaic plant and connected with a battery energy storage of 300 kWh (composed by 16 sodium nickel chloride high temperature batteries). The plant is able to deliver hydrogen and electricity for an electric and hydrogen vehicles fleet. The hydrogen fueling station includes four subsystems: a hydrogen production system by electrolysis, a compression system, a high-pressure storage system and a hydrogen dispenser for automotive applications. It is able to generate in the hydrogen production subsystem through an alkaline electrolyzer of 30 kWh: 6.64 Nm<sup>3</sup>/h of H<sub>2</sub> with a gas purity of 99.995% (O<sub>2</sub> < 5 ppm and dew point < -60 °C). The compression subsystem has a three stage compressor with a rated gas flow rate of 5,2 Nm<sup>3</sup>/h and a delivery pressure of 360 bar. The compressed H<sub>2</sub> gas is stored in a high-pressure tanks of 350 L capacity allowing, in this way, a supply through a dispenser system of two automotive's tanks of 150 L @ 350 bar in less than 30 min. This paper reports the design and the development results coming from a first test campaign.

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### Keywords:

Hydrogen fueling station  
Hydrogen  
Fuel cell  
Smart city

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## Introduction

The transport sector remains a major source of air pollutants, it was responsible for about 30% of world energy-related

greenhouse gases (GHG) emissions and for around a half of all energy-related nitrogen oxide emissions (56 Mt in 2015) [1]. Hydrogen has the potential to aid in increasing the use of renewables energy resources and to contain greenhouse gases emissions by acting as an energy carrier. Then,

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*Nomenclature and abbreviations:* GHG, Green House Gases; FCEV, Fuel Cell Electric Vehicle; FCHEV, Fuel Cell Hybrid Electric Vehicle; BEV, Battery Electric Vehicle; BESS, Battery Energy Storage System; SOC, State of charge; DOD, Depth of discharge; VPN, Virtual Private Network; PLC, Programmable Logic Controller; AC, Alternating Current; DC, Direct Current; HPPS, Hydrogen Production and Purification Section; HCS, Hydrogen Compression Section; HSS, Hydrogen Storage Section; HRS, Hydrogen Refueling Section.

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European environmental policy is addressed toward the development of low emissions vehicles characterized by the installation of clean innovative devices as Fuel Cell power trains [2,3]. In order to support the deployment of fuel cell electric vehicles (FCEV) fed by hydrogen, it is important to develop a refueling network and to assess the performance, the consumption and the operation of onsite hydrogen production and fueling stations [4–7]. Within an Italian research project “i-NEXT” (innovation for green Energy and eXchange in Transportation, sponsored by PONREC - Ministry of Education, University and Research [8]), CNR-ITAE, together with other industrial partners, has developed the first Italian hydrogen production and fueling plant. Actually in Europe there are 49 hydrogen refueling stations in operation [9], but few of them exploit renewable energies. This hydrogen production and fueling plant is connected to a microgrid and it is able to receive, as input, the energy coming from solar radiation and to deliver, as output, hydrogen and electricity for refueling of an electric and hydrogen vehicles fleet. The i-NEXT hydrogen plant is located in the Municipality of Capo d’Orlando - Sicily, the hydrogen is produced by an electrolyzer connected with hydrogen storage facilities. The peculiar characteristics of this plant is that, since it is connected to a photovoltaic plant and a Battery Energy Storage System (BESS), the electrolyzer is able to generate hydrogen regardless, too, of the presence of the renewable source or refueling demand, also the entire energy system is grid connected which could facilitate their operation in electricity markets. This paper shows the design and the development coming from a first test campaign.

## Design of the solar-powered hydrogen refueling station

The plant is the first Italian solar-powered hydrogen fueling station and it was designed in order to be directly supplied by a solar renewable energy source. Solar plant and daily hydrogen production were designed for a daily fueling of one hybrid electric fuel cell/batteries minibus, one electric minivan and two electric bicycles assisted by fuel cell power system (vehicles was developed by CNR ITAE as part of the iNext project [8]).

### Design of the hydrogen refueling station

Input data for the design of the hydrogen fueling station has been mainly: daily autonomy of iNext bus used for the transportation of tourists in Capo d’Orlando municipality and therefore the amount of hydrogen for daily production. The iNext bus is a prototype of hybrid electric fuel cell/batteries having an electric drive engine with a rated power of 40 kW and a capacity of 16 passengers. Fig. 1 shows a photo of the hybrid minibus and the relevant datasheet is reported in Table 1. The selected powertrain configuration of range extender allows reducing costs, weight and recharging time of batteries and it allows to increase the range in comparison to an equivalent electric vehicle. The bus is equipped with two high-pressure tanks of 150 L each, reinforced in carbon fiber, with a total amount of about 7 kg of hydrogen at 350 bar. This volume

enables the vehicle to have a greater autonomy of 240 km in FCHEV mode. The average distance covered by iNext bus is of 200 km/day, so, in this way, it needs a daily refueling only. Therefore, the production of hydrogen in the refueling station is sized for 8.5 kg/day in order to ensure the daily utilization of the vehicle.

The hydrogen refueling station was designed starting from this input data (needed hydrogen for day) tacking on account the availability of commercial components to minimize overall capital costs. The plant mainly includes four modules: a hydrogen production and purification module (HPPS), a hydrogen compression module (HCS), a hydrogen storage facility (HSS) and a hydrogen refueling facility (HRS). The P&ID is reported in Fig. 2.

In the first section HPPS, hydrogen is produced at 9 bar starting from deionized water by an alkaline electrolyzer and subsequently, after deoxidation and drying process, it is analyzed trough an electrochemical cell oxygen analyzer and then it is stored in a low pressure buffer tank (9 bar). In the second section HCS, the hydrogen is suctioned from low pressure buffer and through a three intercooled stage compressor it is compressed up to 360 bar and it is stored in an high pressure buffer tank. The bus refueling takes place by means of an automatic hydrogen dispenser in the HRS section. The HSS module includes a storage system of 48 vertical cylinders of 50 L at 200 bar for emergency backup of hydrogen in case of scheduled maintenance or fault of the HPPS or HCS modules.

The production, compression and refueling of hydrogen, including all operating parameters, are managed through automatic logic from the PLC control panel. The entire hydrogen fueling station is designed to be placed in three 20 ft standard ISO containers (Dimension L × P × H: 6100 mm × 2500 mm × 2600 mm) and an external view is shown in Fig. 3. In order to be compliant with the safety standards, a gas-tight wall separates the electrical system and the compressor/storage compartments. All controls and electrical power switch gear are located in the electronics compartment. A pressure discharge vent is located in the roof of the gas compartment. The refueling station is continuous monitored for leakage also in stand-by mode, hydrogen gas detection and smoke detection devices are located inside containers and an automatic emergency shutdown (ESD) shuts down station operation in case of emergency [10].

All four sections comply with the regulations:

- Directive PED 97/23/EC concerning pressure equipment [11];
- Directive ATEX 94/9/EC concerning a potentially explosive atmosphere exists when a mixture of air gases, vapours, mists, or dusts combine in a way that can ignite under certain operating conditions [12];
- Directive 98/37/EC concerning the machinery [13];
- Directive CEI EN 60079-14 concerning the electrical installations design, selection and erection in explosive atmospheres [14];
- Italian Legislative Decree 31/08/2006 concerning the technical regulation of fire prevention for the design, construction and operation of automotive hydrogen refueling stations [15];



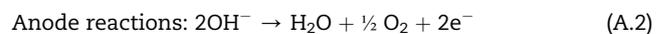
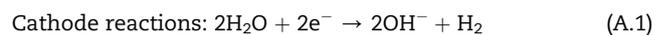
Fig. 1 – iNext FCHEV.

### Hydrogen production and purification module (HPPS)

The HPPS module is composed of a deionization water system, an alkaline electrolyzer and a deoxidation and drying gas system. The production of hydrogen by the electrolytic process is sized for a daily refueling of iNext bus. The alkaline electrolyzer (manufactured by ErreDue Spa) is designed for a rated operation reaching approximately a 54 A, at a rated operating temperature of 80 °C and a rated pressure of 10 bar. The rated hydrogen production is around 6.6 Nmc/h (~0.60 kg/h), the oxygen released in the electrolyzer is vented to the atmosphere while the hydrogen is conveyed to a purification

stage where residual particles of oxygen, through a catalyst of deoxidation, are combined with the hydrogen to produce water. Then, the purified gas comes into an adsorbent columns where it is dried. In the HPPS module the hydrogen can reach a purity of 99.999%, with an oxygen content <5 ppm and a dew point < -60 °C. The electrolyzer is able to fill the hydrogen high-pressure buffer plant's in 18 h.

The entire production process is totally managed through a PLC and it is designed to stop the hydrogen production in case of components fault or dangerous conditions. In this latter case, the entire production plant is depressurized, sending the hydrogen gas to the vent section, and it is filled with nitrogen for safety reasons. Hydrogen and oxygen gases are released by the electrochemical process into an alkaline stack with the reactions:



The electrolyte, composed by KOH and deionized water, allows the current flow from anode to cathode, which produces the water ionization and the subsequent separation in hydrogen gas by the cathode side and oxygen gas by the anode side. The single cell is composed of two electrodes assembled on bipolar plates separated by a diaphragm membrane. The bipolar plates have special internal ducts for the distribution and collection of process fluids. This feature eliminates tubular connections simplifying the plant and increasing the security of this kind of configuration reducing the risk of leaks. When hydrogen and oxygen have been released, they are separated by the electrolyte in special vessels connected with a pressure balancer, allowing the cells to work with balanced pressure between the hydrogen and the oxygen side.

Table 1 – Data sheet of iNext FCHEV.

#### Fuel cell hybrid electric minibus data sheet

|  |  |
|--|--|
| Vehicle platform                       | IVECO DAILY  |
| Dimension<br>(Length × Width × Height) | 7348 × 1996 × 3100 [mm]                                    |
| Laden mass                             | 5600 [kg]  |
| Seating capacity                       | 16 + 1 [B Class on Italian Regulation]                     |
| Traction                               | Asynchronous electric engine 3 phase AC with IGBT inverter |
| Nominal engine power                   | 40 [kW]  |
| Power Peak                             | 80 [kW] @ 2950 [rpm]                                       |
| Battery                                | Li-Ion polymer   |
| Battery energy                         | 70 [kWh]   |
| Battery nominal power                  | 30 [kW]  |
| Battery peak power                     | 120 [kW]   |
| Fuel cell type                         | PEM  |
| Fuel cell system power                 | 20 [kW]  |
| Hydrogen storage                       | 300 [liters] @ 350 [bar]                                   |
| Consumption (average)                  | 0,75 [kWh/km]  |
| Range FCHEV                            | >240 km  |
| Range BEV                              | >100 km  |

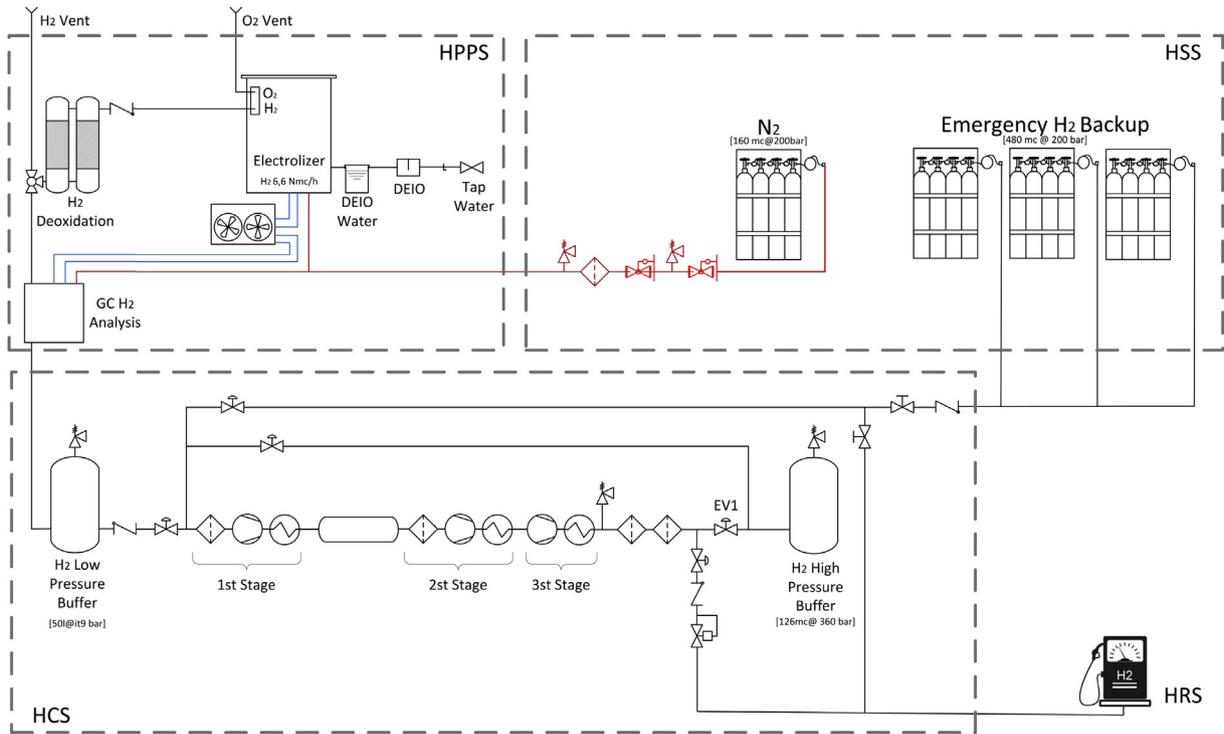


Fig. 2 – P&ID of Hydrogen filling station.



Fig. 3 – Hydrogen filling station.

Then the hydrogen is sent to the deoxidation and drying gas system, where it is purified by means of a deoxidation catalyst (deoxo). In this device the oxygen contained therein is combined with hydrogen to release water (water vapor). Subsequently, the purified gas comes into a drying system consisting of two tanks containing activated alumina (dryers): the first tank works in operation mode and the other tank works in regeneration mode. The regeneration mode is split-up in two macro-phases: during the first phase, air is used as carrier fluid to remove from the column the humidity. During the second and last phase, the regeneration is completed by means of nitrogen to ensure complete purification with inert gasses and reduction of oxygen below the flammability limit.

After the deoxidation and drying, the hydrogen is analyzed by continuous oxygen gas analyzer (designed for oxygen analysis in pure gases and for measuring the residual oxygen

concentration) and a residual moisture analyzer so as to comply with the fuel cell gas specifications.

#### Hydrogen compression module (HCS)

The HCS module is composed of a hydrogen low-pressure buffer tank (9 bar rated operating pressure of electrolyzer), a three stages booster compressor, manufactured by Idromeccanica Srl, and a high-pressure buffer composed of 7 cylinders of 50 L@360 bar (126 Nm<sup>3</sup>). The hydrogen booster compressor has three intercooled stages, the piston is driven by a hydrostatic transmission unit in order to reduce the rated power to 5.5 kW. The maximum suction flow rate is of 5.2 Nm<sup>3</sup>/h and the operating pressure is 360 bar. The refrigeration system is fed by glycolated water and has an overall power duty of 0.75 kW.

The HCS is designed to work in two different ways; the first, during “normal operation”, the booster draws hydrogen gas from the low-pressure buffer and send it towards the high-pressure buffer, using all three compressions intercooled stages, up to 360 bar. Conversely, in “refill operation” when a vehicle will be refueled, after the first phase of hydrogen transfer from high-pressure buffer to FCHEV tanks, during the second phase, only the last stage of the booster compressor works in top-up operating mode pumping the hydrogen up to a 350 bar into the FCHEV tanks.

The high-pressure buffer has been designed to ensure the daily bus hydrogen demand and the runtime of the compressor is estimated 600 min per day to fill-up the high-pressure buffer with a rated flow of 6.6 Nm<sup>3</sup>/h.

### **Hydrogen storage module (HSS)**

The plant includes a specially equipped area (HSS) where an emergency backup facility is installed, it is composed of three hydrogen storage packs which include 16 vertical cylinders each (50 L @ 200 bar) with a total amount of 480 mc @ 200 bar. The aim of this module is the supply of hydrogen in case of scheduled maintenance or fault of the HPPS or HCS modules. In the same area a nitrogen storage pack is also included, it is composed of 16 vertical cylinders each (50 L @ 200 bar) with a total amount of 160 mc @ 200 bar, which assure the right operation of the pneumatic valves plant's and to feed the deoxidation and drying hydrogen gas system in the HCS.

### **Hydrogen refueling module (HRS)**

A hydrogen dispenser able to supply a minibus refueling in 30 min composes the HRS module. The hydrogen dispenser, comply with the Directive ATEX 94/9/EC, it is equipped with a safety break-away valve WEH “TSA5”, a WEH “TK-16” fueling nozzle and a mass flowmeter. The hydrogen dispenser has been designed to perform refueling activities in automatic mode through the badge's operator. A test pulse from the high-pressure storage bank settles the initial vehicle pressure. Based on this test measurement and accounting for the ambient temperature, the final vehicle target pressure is established. The fueling process starts with the equalization of the FCHEV tanks. After fueling, the station switches automatically into the recharge mode and fills up to 350 bar the FCHEV storage tanks. The quantity of motor fuel dispensed is recorded using a mass flowmeter to calculate retail sales.

### **Microgrid concept: self-sufficient solar-powered hydrogen refueling station**

The whole plant energy system, in which hydrogen refueling station is integrated, involves the implementation of a grid connected multi-purpose system where the generation of electricity from renewable sources is dedicated to the production of hydrogen and electricity for vehicle charging (able to recharge in 22 kW AC, 20 kW DC CHAdEMO and 20 kW DC CCS). Furthermore, this plant allows energy supply safety with a reduction of electric power consumption during periods of maximum demand on the power utility (peak shaving) with a consequent knock-off of energy prices. In detail, a

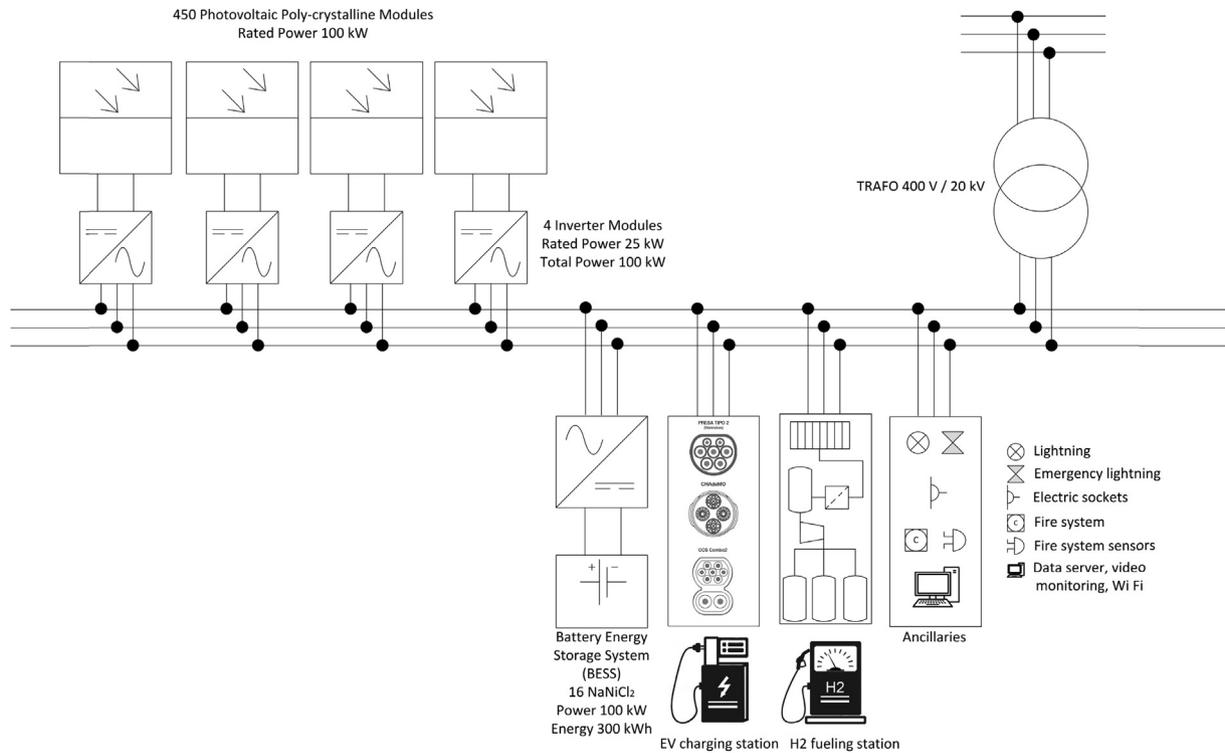
photovoltaic plant of rated power of 100 kW was installed on the roof of a shed for vehicles recovering (area of 720 m<sup>2</sup>). The Battery Energy Storage System (BESS) of 100 kW and 300 kWh equipped with 16 sodium nickel chloride high-temperature batteries is a plug and play containerized system connected through a bidirectional inverter to the 400 Vac microgrid. In the design of the plant, both solar irradiation data and daily hydrogen demand are optimized across the year for the selected location (Capo d'Orlando - Sicily). The BEES function is to balance the energy coming from renewables and loads, in order to minimize the energy exchange with the grid and supporting the energy independency of the overall system. Demand response control is active on the electrolyzer in order to make simultaneous the operation of the electrolyzer with the photovoltaic energy production. A remote agent, through VPN (Virtual Private Network) connections, allows monitoring and control of the overall system. It can send commands to BESS, in order to regulate the amount of active and reactive power delivered, supporting the local grid regulation (grid frequency and voltage). The electrical layout of the whole microgrid including the hydrogen refueling station is shown in Fig. 4.

A common electrical 400 V AC bus is used to integrate the 450 photovoltaic polycrystalline modules, BESS, electrolyzer, hydrogen purification system and compressor with their associated power electronics, and to manage the power and energy flows. The BESS, with its associated bidirectional power converter used for charging/discharging, is required to power the critical loads during periods of low solar radiation and, also to, to keep the voltage stability of the AC bus. The concept is to store renewable energy and maximize self-consumption in order to exploit it when needed.

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## **Experimental: hydrogen refueling on field test**

The fleet of iNext project includes: a fuel cell hybrid electric minibus, a full electric delivery van and two total fuel cell bikes. In particular, the FCHEV Minibus (Fig. 1) is a reconfiguration of an internal combustion traditional vehicle, belonging to category M3, to an electric propulsion hybrid fuel cells and batteries vehicle. The fuel cell distributes the electrical power to the connecting line between the batteries and the traction inverter via a DC/DC converter. The minibus is length 7.3 m, high 3.1 m with a weight of 5600 kg, it is able to transport 16 passengers. The operative version of the minibus is equipped with lithium polymer batteries (16 modules with 6 cells everyone sequentially connected); the nominal voltage is 355 V and the total energy is 65 kWh. The FC system is based on a PEM Nuvera Fuel Cells 21 kW @ 252 A. The hydrogen storage is constituted by two tanks, with a total capacity of 296 L (3.58 kg of hydrogen for tanks) at 350 bar. The hydrogen tanks have been installed on the roof of the minibus, in the available area, between the air conditioning compartment and the emergency exit. The vehicle is equipped with three voltage lines: high, medium and low. The first two represent the power connection for the generation, transformation and use of the traction energy. The high-voltage line connects the battery to the traction system and the auxiliary power (inverter compressors and motors) through two contactors



**Fig. 4 – Electrical layout of global plant energy system.**

positioned on both poles. The medium-voltage line transfers the power generated by the fuel cell to the high voltage line by means of a voltage converter (DC-DC). Finally, the low-voltage line is used to power all the auxiliary devices of the vehicle; the battery 12 Vdc of this line is charged by a DC-DC converter connected to the high voltage line.

In order to optimize the operation of the solar-powered hydrogen fueling station, appropriate algorithms have been developed. These take on account: seasonal solar output availability, the SOC of the BEES, the filling of the high-pressure buffer, the operating characteristics of the electrolyzer and the hydrogen daily demand from the fleet.

The control system of the global plant energy system has been developed in order to ensure the hydrogen refueling in relation to the photovoltaic availability, specific control strategies are currently under development and will be implemented after the first year of operation for maintaining the system's high performance during the four annual seasons. For a full refill of the high-pressure storage, the operating time of the HPPS and HCS modules is estimated about 600 min. The electrolyzer load profile is shown in Fig. 5, it included the auxiliaries electrical consumption (system for deionized water, water pump, cooling system and gas purification system); hydrogen gas flow and pressure trends are shown in Fig. 6. The electrolyzer works at rated conditions (30 kW) until fulfilling of the low-pressure buffer, the time estimated for the complete coverage is 120 min, in this way the cycle is as represented below.

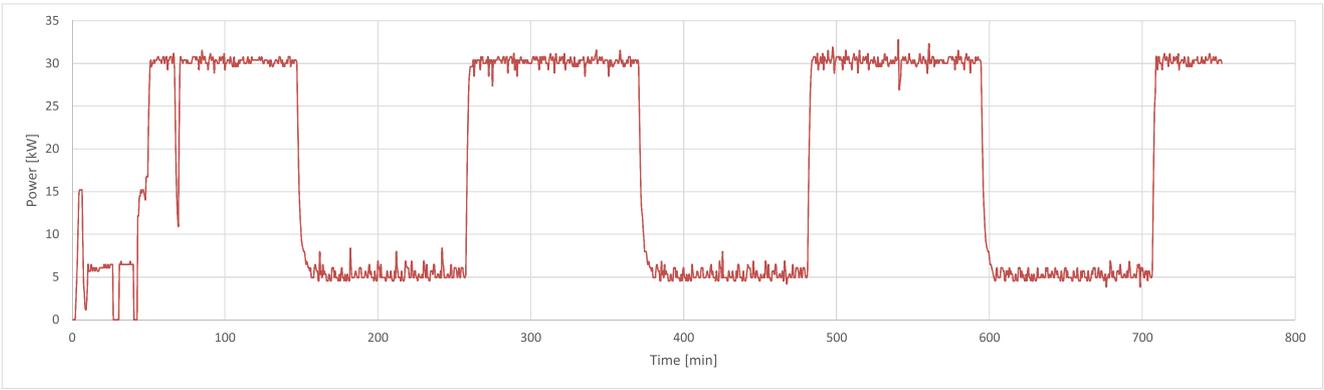
The average power requirement of the booster compressor motor is 5 kW with peaks of 7 kW on start up. The runtime to fill-up the seven high-pressure cylinders buffer is estimated in

630 min/day. The inlet of the booster compressor is connected to the low-pressure buffer storage at 9 bar and the outlet is coupled to the high-pressure storage up to 360 bar. The compressor load profile is shown in Fig. 7, while, in Fig. 8 is shown the trend of the compressor during 630 min starting from 20 bar up to 350 bar.

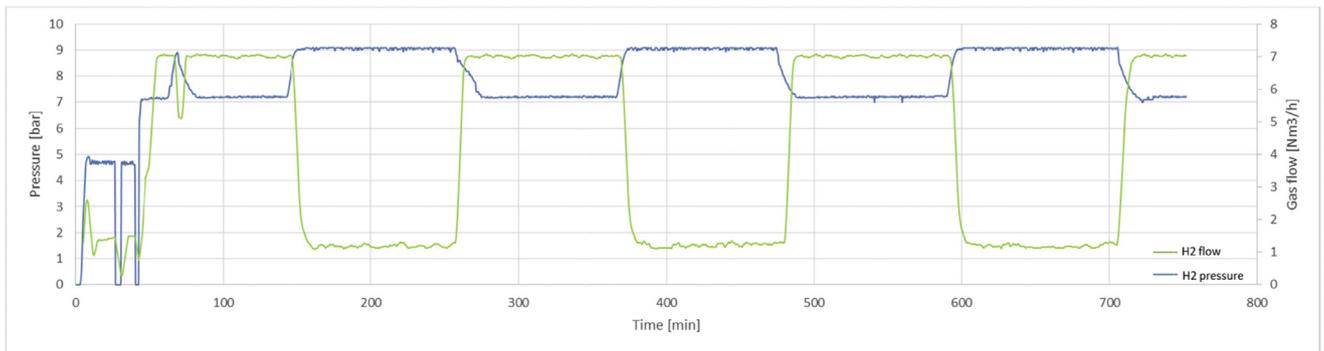
The refueling of iNext minibus takes place in a little more than 30 min and it is managed by the HRS. The refueling is composed of two stages: the first where the hydrogen is transferred from the high-pressure buffer to bus cylinders until the balance of pressures, the second phase consists of a top-up compression from the high-pressure storage directly to bus cylinders through the third stage of the booster compressor in the HCS. The two phases of the refueling are shown in Fig. 9. The blue trend is the hydrogen pressure measured in the HRS, while the red one is the pressure in the high-pressure buffer. Trends of hydrogen pressure and temperature in the bus cylinder are shown in Fig. 10.

During the first phase, hydrogen is transferred from high-pressure buffer directly to the bus cylinders up to 170 bar and the hydrogen temperature of the bus internal cylinders rises up to about 50 °C (Fig. 10).

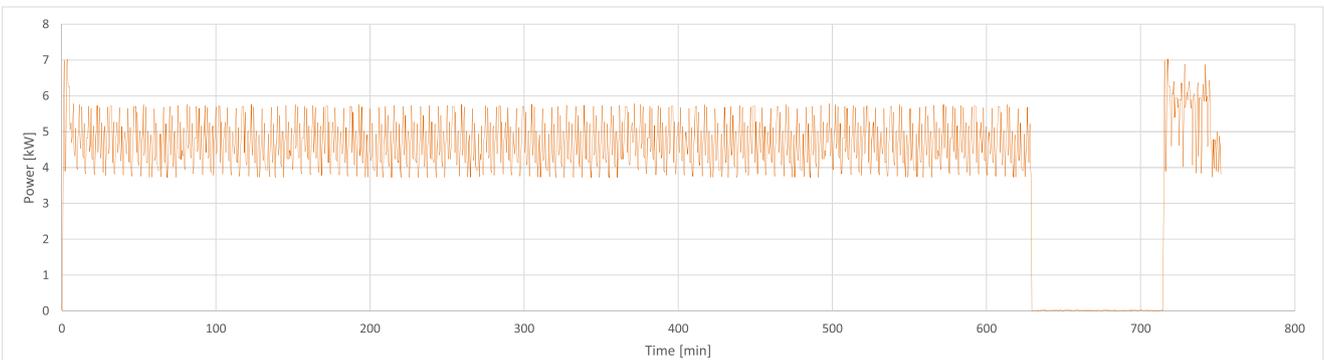
Thanks to the activation of the EV1 by-pass electrovalve (Fig. 2), hydrogen compressor pushes hydrogen up to 350 bar into the bus cylinders (top-up phase). Indeed, in this critical condition there is equilibrium between the high-pressure buffer and the pressure inside the cylinders, so the activation of the compressor is needed. Since the compressor is liquid cooled, the gas temperature during the top up compression is kept under control (about 45 °C).



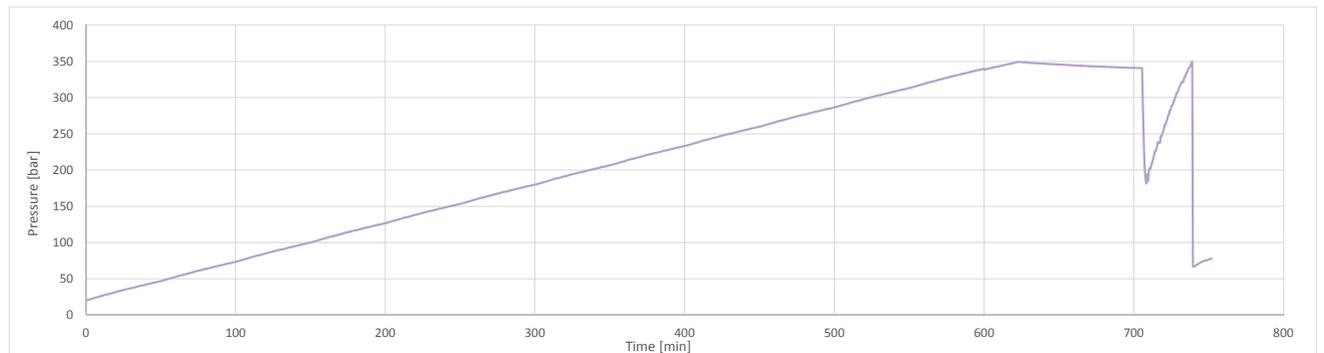
**Fig. 5 – Electrolyser load profile.**



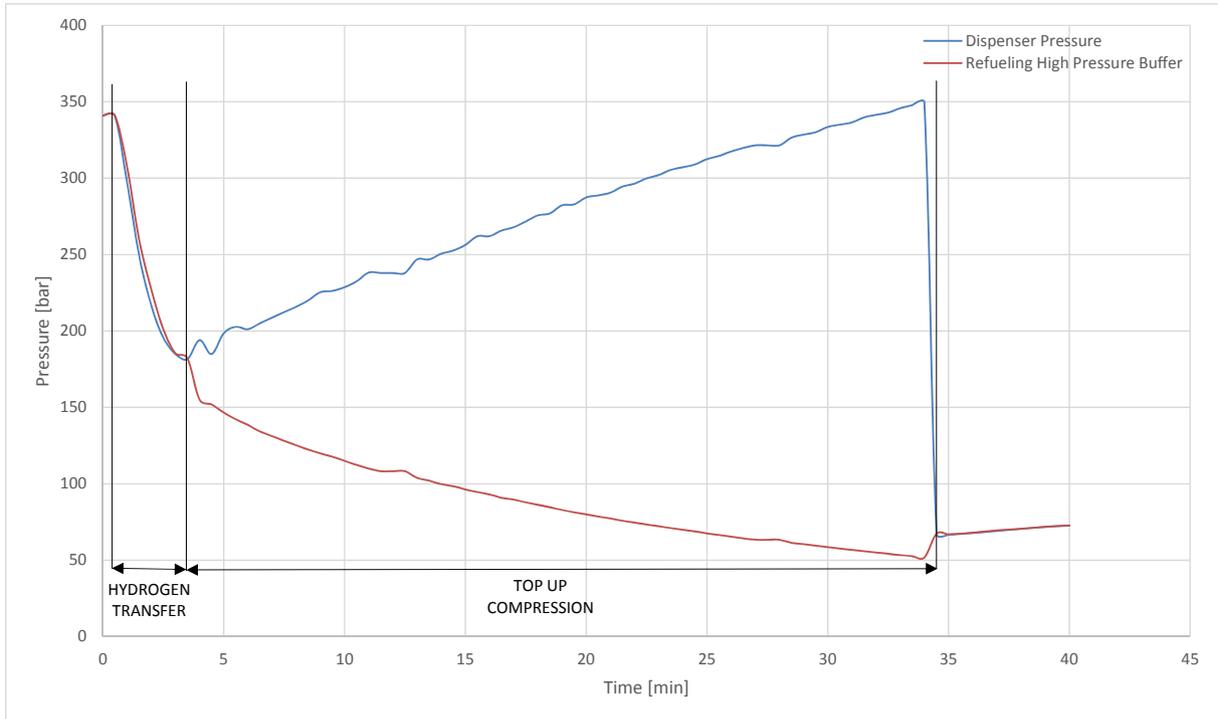
**Fig. 6 – Hydrogen flow and pressure.**



**Fig. 7 – Compressor load profile.**



**Fig. 8 – High pressure buffer: hydrogen compression trend.**



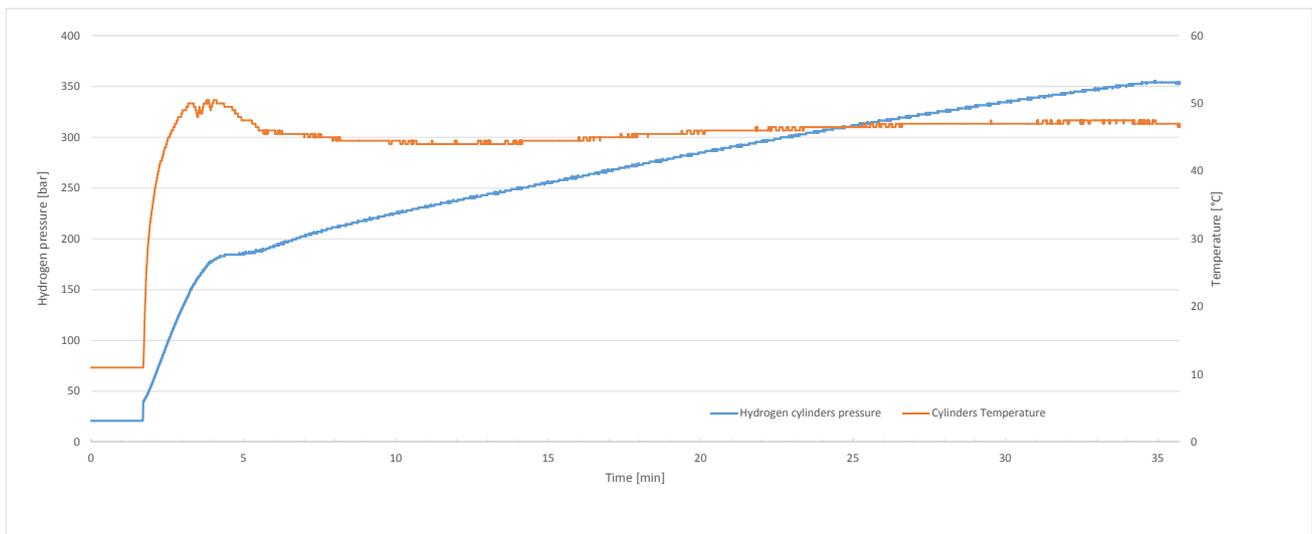
**Fig. 9 – Pressure trend of dispenser and high-pressure buffer measured during Bus refill.**

When the refueling finishes, the hydrogen pressure into the high-pressure buffer is about 70 bar (1.5 kg of H<sub>2</sub>). It is evident the relaxation phenomenon of the gas inside the buffer due to the achievement of the equilibrium pressure conditions after the electrovalve closure.

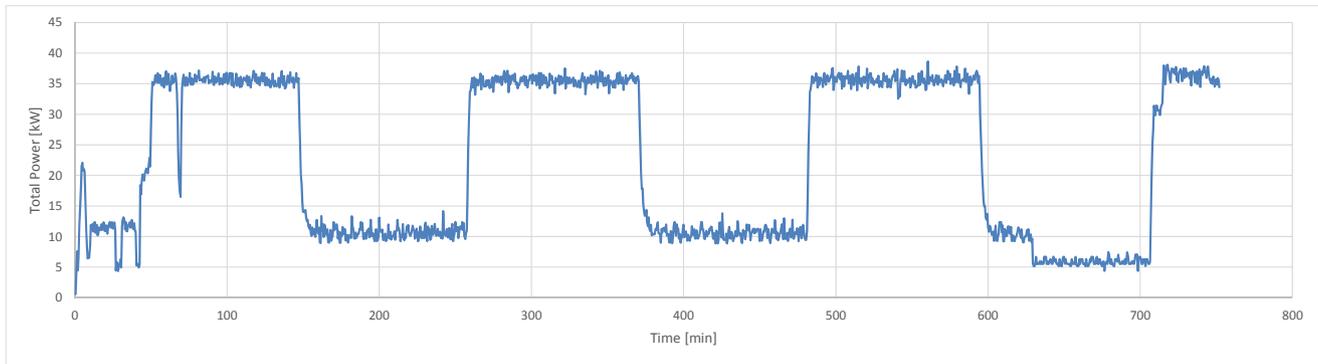
## Results and discussion

The daily urban cycle covered by iNext minibus is of 200 km/day with a consumption of hydrogen of 6,5 kg/day. This

weight of hydrogen is covered by the daily production of the HPPS as a base load during solar hours. The excess of energy production by photovoltaic panels is used for electric vehicle charging station and balanced by the BEES in order to maximize the self-consumption of the overall system. The runtime to fill-up the seven high-pressure cylinders buffer is estimated in 630 min/day. The electrical consumption trend of the entire system (refueling station) is shown in Fig. 11, it takes into account the power absorbed by all modules (HPPS, HCS, HRS and the ancillaries). In this period most of the energy is covered by the energy produced by photovoltaic



**Fig. 10 – Cylinders bus: pressure and temperature trends during refill.**



**Fig. 11 – Refueling station electrical consumption trend.**

panels. As shown in Fig. 11, the electrical consumption, during the hydrogen production and compression period, has a square wave trend, where the maximum 35 kW peaks are due to the simultaneous operation of HPPS and HCS. Instead, during the night standby period, the entire system works with an average consumption of 5 kW due to the load of standby mode of HPPS and the ancillaries of the entire system.

The optimization procedure under development, takes into account the electrolyzer and compressor power range, solar power output during the seasonal periods and hydrogen production met for each time period (24 h). The algorithm developed takes into consideration a demand side management of the overall hydrogen production and storage chain, making simultaneously the energy production and consumption. When solar radiation is present, the electrolyzer is activated in order to store hydrogen into the high-pressure buffer, making it available for bus refueling and avoiding a double conversion of energy through the BEES. The daily energy production by solar panels is estimated about 500 kWh/day during the summer season and about 300 kWh/day during the winter season. Since the energy consumed by the HPPS + HCS + HSS for a complete tankage of the high pressure buffer is about 280 kWh/day (Fig. 11), it is clear how the overall system was designed appropriately to satisfy the energy consumption of the loads.

## Conclusions

The design, development and the operation data of the first Italian solar powered hydrogen fueling station have been reported in this paper. The fully-automated refueling of a hydrogen bus and the operation of the entire production, storage and refueling system have been demonstrated in safety conditions. A complete refueling of a hydrogen bus has been performed in 35 min, reaching a maximum temperature of 50 °C.

The overall equipment is able to produce and store 8.5 kg of hydrogen at 350 bar in 630 min with a peak load of 35 kW and a base load of 10 kW. The energy consumption and the time period of the overall system operation is compatible with the on-site solar energy production, demonstrating, taking into

account the energy management from the BEES and the demand side management of the electrolyzer, the energetic autonomy of the micro-grid developed and the capability of the micro-grid to minimize the electricity exchange with the mains.

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