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Hydrogen-based APU for refrigerated vans. A turnkey solution for freight transport

M. Martínez*, F. J. Vivas, F. Segura. J. M. Andújar
Research Centre on Technology, Energy and Sustainability (CITES). Universidad de Huelva, Spain
* (macarena.martinez@diesia.uhu.es)

ABSTRACT

The increase in refrigerated food demand, due to increase on urban population is involving the replacement of conventional diesel-powered transport refrigeration units (TRUs) by electrical-based auxiliary power units APUs, in an imperious. This paper presents a turnkey solution of a hydrogen-based APU for a refrigeration unit integrated in short haul trucks, for its use in the food industry.

Keywords: refrigerated vans, freight transport, hydrogen-based APU, turnkey solution

NONMENCLATURE

Acronyms

APU	Auxiliary Power Unit
BoP	Balance of Plant
CU	Cooling Unit
EMS	Energy Management System
ESS	Energy Storage System
GHG	Greenhouse Gas
HL	Hydrogen Level
ICE	Internal Combustion Engine
P&OM	Modified Perturbation and Observation
PEFC	Polymer Electrolyte Fuel Cell
SOC	State of Charge
TRU	Transport Refrigeration Unit

Symbols

δ	DC/DC boost converter duty cycle
I_{FC}	PEFC operating current (A)
$P_{Aux}(t)$	Auxiliary elements operating power (W)
$P_{Bat}(t)$	Battery operating power (W)
$P_{CU}(t)$	Cooling unit operating power (W)
$P_{DCAC}(t)$	DC/AC converter input power (W)
$P_{DCDC}(t)$	DC/DC converter output power (W)
$P_{FC}(t)$	PEFC operating power (W)
$P_{FC_{SP}}(t)$	PEFC power set-point (W)
T_{amb}	Ambient cooling air temperature (°C)
T_{DCDC}	High power converter operating temperature (°C)
$T_{DCDC_{max}}$	High power converter operating maximum temperature (°C)
V_{Bat}	Battery pack voltage (V)
$V_{Bat_{FC}}$	Battery pack minimum preset value (V)
$V_{Bat_{max}}$	Battery pack maximum preset safety value (V)
$V_{Bat_{min}}$	Battery pack minimum preset safety value (V)
V_{FC}	PEFC operating voltage (V)
$V_{PEFC_{SP}}$	Preset voltage limit (V)

1. INTRODUCTION

At the beginning of the millennium, the rural population was 1,16 times the urban population. This relation, between rural and urban population has been kept since 1960, when the historical data are available [1]. But this trend was inverted in 2007 [2], when urban population was the 50% of the total world population, and it is expected that by 2050, urban population achieves 68%. Urbanization will be one of the 21st century's most transformative trends. With increase in world population and a general improvement in living conditions, it is predicted that food, water and energy demand will increase by 50%, 30% and 45%, respectively [3]. The increase in food demand will be accompanied by a proportional growth in food transportation.

Food quality and safety cold chain is maintained by TRUs driven by the diesel engine in short to large vehicles. Refrigerated transport has been recognised as one of the main processes in terms of energy saving potential and greenhouse gas (GHG) emissions reduction in cold chains. Replacing the diesel TRU with an electric TRU is a strong recommendation for the coming years. [4]. The environmental impacts of cooling systems for the transport of food powered by diesel engines can be up to 40% of the impacts of the vehicle engine [5]. Additionally, refrigerated transport uses additional

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diesel to power the refrigeration system, increasing the consumption by 12% and fuel cost by 6,000€/y (up to 40% of direct costs), [6].

2. H2-BASED AUXILIARY POWER UNIT

The technological proposal includes the definition and design of the APU sized to meet the energy

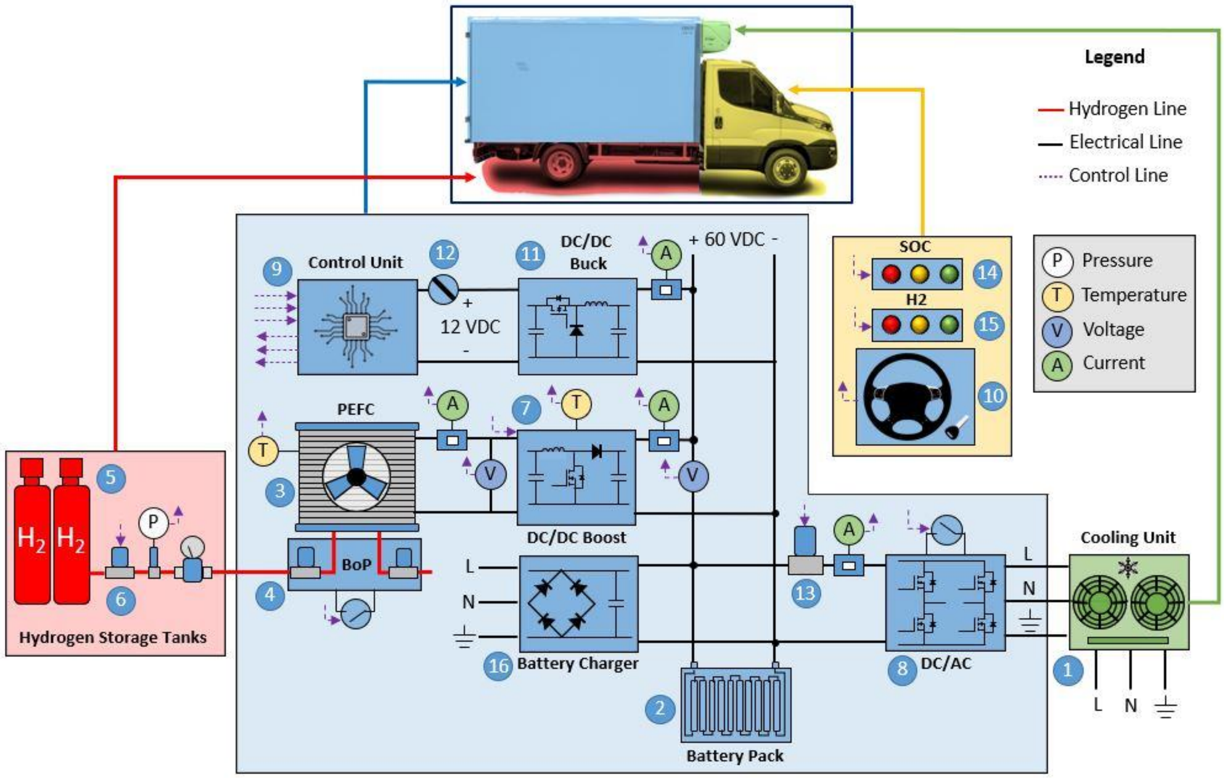


Fig. 1. Hydrogen-based APU for refrigerated van. Component layout

This paper presents a comprehensive hydrogen-based auxiliary power unit (APU) solution for an integrated refrigeration unit in short-haul trucks for use in the food industry.

For this purpose, several parameters must be considered due to their influence into the truck container:

- Container dimensions,
- Route distance,
- Ambient temperature, solar irradiation and humidity during transit,
- Number and size of refrigerated box opening doors,
- Insulation, walls and lining material properties, transmission and radiation coefficients, surface area, thickness, temperature gradient, etc.),
- Infiltration through gaps or holes,
- Thermal loads: fruits, vegetables, meat, fish, frozen products, etc.

The objective of the PU development is to validate the deployment of hydrogen technologies in transportation applications.

requirements defined for the cooling system under study. The developed solution proposes the replacement of the mechanical compressor with an electric one, eliminating the truck's fuel consumption to generate cold, and consequently reducing its overall emissions.

Regarding the power system, the central core of the APU will be a polymer electrolyte fuel cell (PEFC). There is also an energy storage system based on a battery bank, which can cope with the start-up and cold unit cycles, allowing a more conservative use of the hydrogen system.

The APU incorporates all the electrical conversion elements, as well as the auxiliary power control and management equipment, so that its design is based on the "Plug & Play" philosophy.

The input to the fuel cell unit is provided by a hydrogen gas supply line with the purity and pressure conditions required by the fuel cell manufacturer.

The APU output is provided by a single-phase 220 VAC, 50 Hz power outlet, capable of supplying up to 3 kW of steady-state power, sufficient to meet the requirements of the cooling unit.

Hydrogen is supplied and stored in two 20-liter tanks, each with hydrogen compressed to 200 bar, and a system of valves, piping and regulators that allow safe operation during loading, unloading and storage.

2.1 Design and development

The objective of the developed APU is to guarantee the power supply to the cooling unit (CU) (1, Fig. 1) throughout the successive stops during the delivery route.

The philosophy employed during its design ensures the lowest impact on the TRU. The sizing of the APU was calculated to guarantee the energy demand during a working day, about 8 hours.

In this case, the APU is based on a hybrid energy storage system (ESS) composed by a 60 VDC Li-ion battery pack (2, Fig. 1), and a hydrogen-based ESS as a range extender. This consists of a 2 kW stack (PEFC) and its balance of plant (BoP), [7] (3 and 4, Fig. 1), and two high-pressure hydrogen tanks with a storage capacity of 20 L at 200 bar (5, Fig 1). To guarantee the supply pressure of the PEFC (0.5 bar), a two-stage pressure regulator is used (6, Fig. 1). In addition, as the PEFC supplies unregulated power, an interleaved boost converter has been developed for proper integration and management of the PEFC on the DC bus (7, Fig. 1). Finally, the power conversion stage to supply the cooling unit from the DC bus is performed by an isolated single-phase DC/AC converter (8, Fig. 1).

For its part, the control unit (9, Fig. 1) performs the tasks related to the acquisition of the variable of interest, the management of the local APU controllers and the implementation of the energy management system (EMS). For this purpose, the APU has all the necessary sensors and actuators to carry out the proper control actions (see Fig. 1). In addition, the control unit monitors the status of the van ignition key (10, Fig. 1), to command the start or stop status of the APU.

To ensure proper power supply to the APU auxiliary equipment (fans, control unit, BoP, etc.), there is a 12 VDC buck DC/DC converter (11, Fig. 1) with direct power supply from the battery pack. In addition, to ensure electrical and personal safety during operation, the APU is equipped with auxiliary elements that allow safe disconnection of the electrical power system. Specifically, a rotary main switch (12, Fig. 1), and a DC contactor (13, Fig. 1).

From the user interface point of view, the APU integrates in the van cabin two indicator panels that inform the driver about the battery state of charge (SOC) and hydrogen level (HL) (14 and 15 respectively, Fig. 1), as well as an alarm associated with the ESS maximum discharge limit.

Finally, the APU has an integrated battery charger (16, Fig. 1), which allows external recharging of the battery pack if necessary, which can be done simply from a usual 230 V AC outlet.

2.2 EMS (Energy Management System)

The developed EMS responds to a multi-objective proposal in which three fundamental design premises are considered, [8]: to guarantee of the power balance according to eq. 1 in DC bus, the maximum availability of the APU, as well as the conservative use of the battery pack and PEFC, [9].

$$P_{Bat}(t) + P_{DCDC}(t) + P_{DCAC}(t) + P_{Aux}(t) = 0 \quad (1)$$

The proposed solution is based on a hierarchical operation in which the battery pack assumes the power balance and the demand profile fluctuations in the first instance, preserving the charge of the battery pack and maintaining its operation in a stable state regardless of operating conditions.

Taking into account the above assumptions, and the system architecture shown in Fig. 1, the EMS strategy is described as follows (Fig. 2): First, during internal combustion engine (ICE) operation, the APU will be in standby until the start condition (ignition key disconnection) occurs. Next, it will be the battery pack, via the DC/AC converter, that will supply the required power to the CU. This operation will continue indefinitely until its SOC reaches a preset minimum level, after which the PEFC will start up in a controlled manner, using a stepped profile, which is essential to ensure proper humidification and thermal management of its stack.

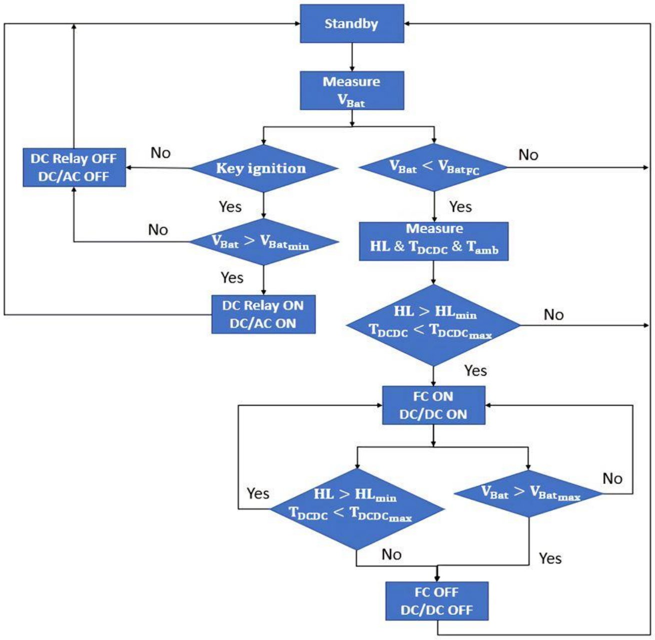
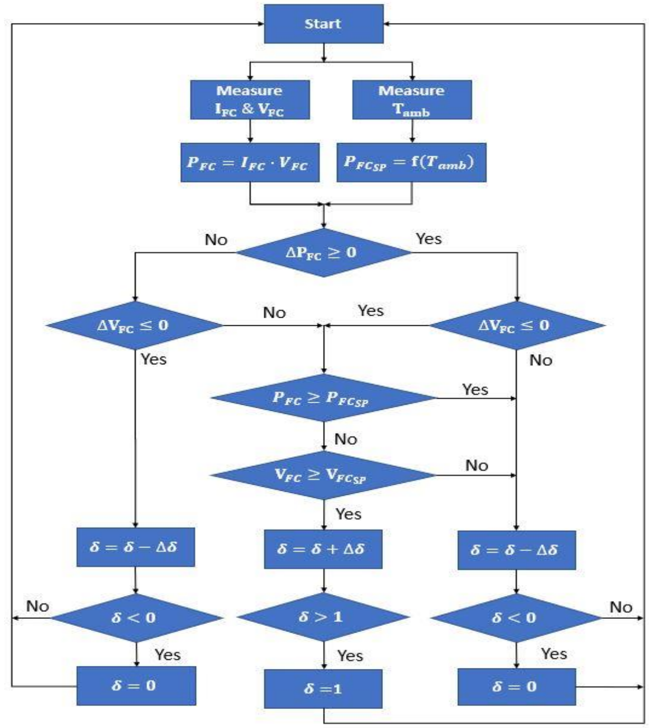
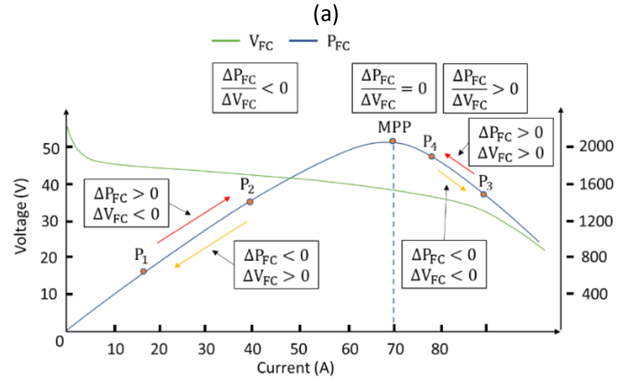


Fig. 2. EMS strategy of the developed Hydrogen-based APU.

Then, the control unit, through the DC/DC boost converter, implements a control law based on the modified perturbation and observation (P&OM) algorithm (Fig. 3), [10], which allows the maximum available power to be extracted from the PEFC. This algorithm has been slightly modified to ensure safe operation of the PEFC by setting power limitations as a function of operating voltage and ambient cooling air temperature (T_{amb}, Fig. 2). Based on this, a preset voltage limit ($V_{PEFC_{SP}}$) is set to avoid operating in the stack concentration region. To reduce thermal stress, a maximum power setpoint ($P_{FC_{SP}}$) is defined as a function of the ambient temperature inside the cabinet. This parameter was obtained experimentally under controlled conditions of ambient temperature and demand profile.



(a)



(b)

Fig. 3. PEFC control law (P&OM algorithm); (a) flowchart; (b) P&OM principle

The operation of the PEFC will be maintained indefinitely until the full state of charge of the battery pack or the minimum HL is reached. At that time, a controlled fuel cell shutdown protocol will be established according to a power reduction profile.

Finally, coinciding with the final part of the working day (the system is calculated for that), the battery pack will be allowed to start discharging again. From here, the PEFC remains off and when the van returns to its base, the APU is ready to recharge its battery pack and hydrogen tanks in anticipation of another day's work.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The final assembly of the APU in Figure 1, the high-pressure hydrogen tanks and the pressure regulator is shown in Fig. 4. To validate the proposed design, the developed APU was tested against a demand profile corresponding to a typical 8-hour workday.

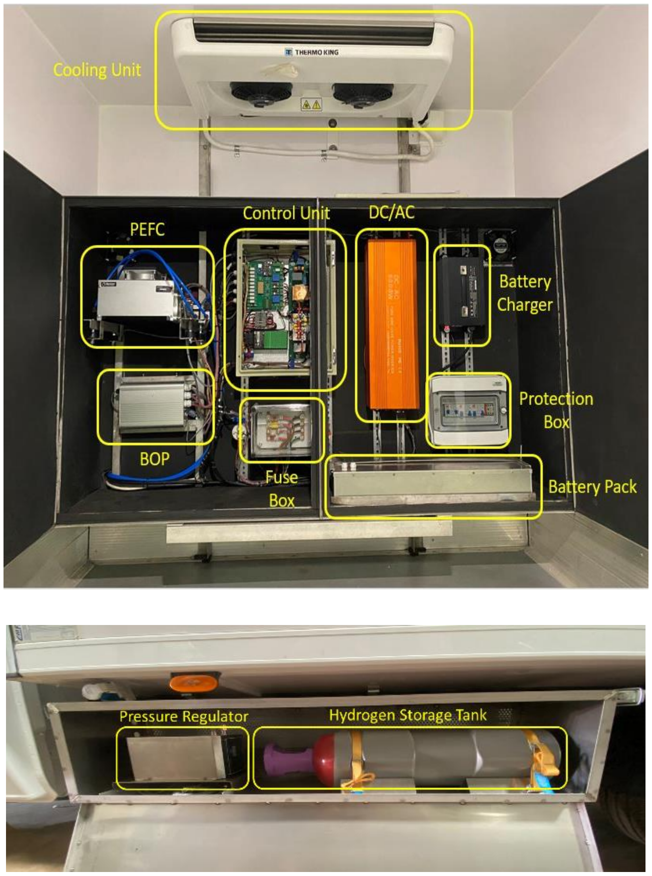


Fig. 4. Distribution and final assembly of the components inside (top) and outside (bottom) the refrigerated box of the van.

At the initial instant, the ICE is operating, supplying power to the CU, and therefore the APU is off ($P_{DCAC}(t) = 0$, Fig. 5). During delivery stops, the APU comes into operation and supplies power to the CU to counteract thermal losses ($P_{DCAC}(t) < 0$, Fig. 5).

According to the proposed EMS, it is the battery pack in the first instance which guarantees the demand profile (see P_{Bat} and P_{DCAC}, Fig. 5, $t \leq 190$ min). This operation is maintained until the SOC drops to 35% (Fig. 5 and 6, $t \leq 190$ min). At this point, the PEFC is activated (Fig. 5 and 7, $t = 190$ min).

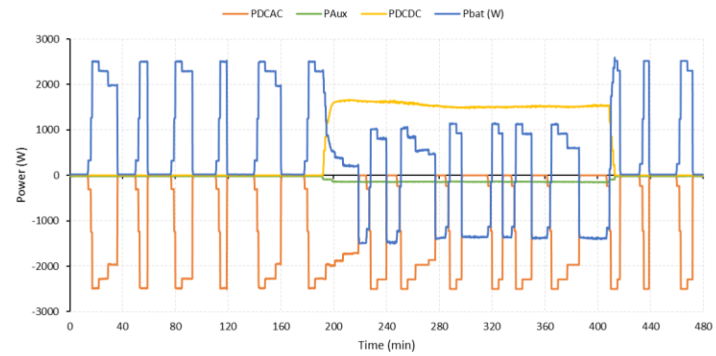


Fig. 5 Battery (P_{Bat}), DC/AC input power ($P_{DC/AC}$), DC/DC output power ($P_{DC/DC}$) and auxiliary consumption (*PAux*) power profile.

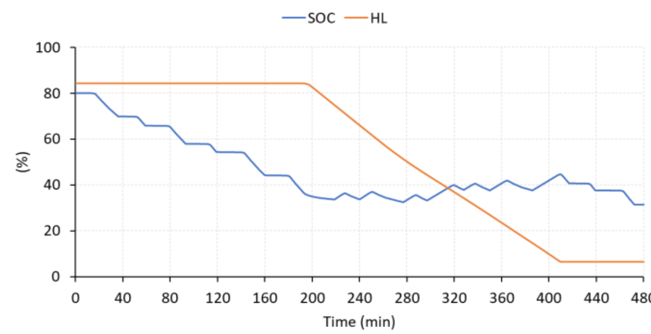


Fig. 6. SOC and HL profile.

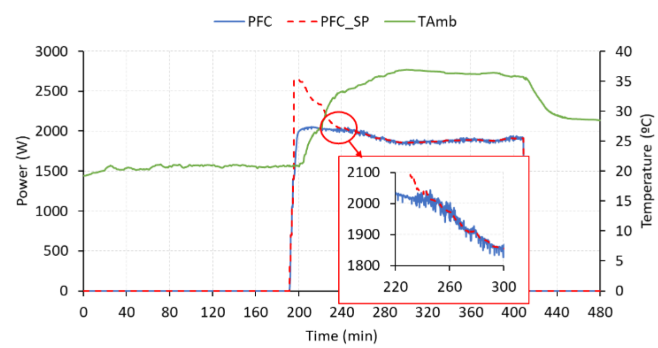


Fig. 7. PEFC generation (PFC), PEFC power setpoint (PFC_SP) and ambient temperature (TAmb) profile.

Based on the proposed P&OM algorithm, when the PEFC starts up, it charges the battery pack by transferring the maximum possible power to it; however, its continued operation causes a consequent increase in the ambient temperature inside the cabinet (Fig. 7, $190 \leq t \leq 220$ min). To reduce the thermal stress of the PEFC, this temperature increase determines a reduction of the maximum power supplied, which ensures that the ambient temperature is maintained in a safe range until the end of the PEFC operation (Fig. 5 and 7, $220 \leq t \leq 410$ min), in this case, determined by the total consumption of stored hydrogen (Fig. 5, 6 and 7, $t = 410$ min). After this, when no more hydrogen is available, the PEFC is shut down in a controlled manner. Finally, from this point on, it is the battery pack which finally ensures the demand profile until the end of the working day (Fig. 5, *t* ≥ 410 min).

From the experimental results, the correct design and development of the APU, the EMS and the P&OM algorithm are validated.

4. CONCLUSIONS

In this work, the design, development and experimental validation of a hydrogen-based APU for use in refrigerated vans has been carried out. Experimental results have demonstrated the correct functioning of the system in terms of operability, autonomy and safety. Based on the results, it is demonstrated that the developed APU is a valid solution to achieve the environmental objectives in refrigerated food transportation.

The hydrogen-based APU demonstrates an extended autonomy of more than 6 h, ensuring a trip without refuelling stops.

Taking into account that according to EU analysis, the environmental impact of refrigeration systems for food transport powered by diesel engines can be up to 40% of the vehicle's tractor engine. The proposal presented can make a significant contribution to reducing greenhouse gas emissions.

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