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Design tool for offgrid hydrogen refuelling systems for aerospace applications

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HIGHLIGHTS

- A simulation tool for offgrid CPV-based hydrogen refuelling systems is presented.
- Simulations of system configurations with specific UAS hydrogen demand scenarios.
- Regarding system size & reliability the most critical components are the CPV array and batteries.
- In terms of energy efficiency the most critical component is the electrolyser.

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ABSTRACT

To develop an environmentally acceptable refuelling solution for fuel cell-powered unmanned aerial systems (UASs) to operate in remote areas, hydrogen fuel must be produced on-site from renewable energy sources. This paper describes a Matlab-based simulation tool specifically developed to pre-design offgrid hydrogen refuelling systems for UAS applications. The refuelling system comprises a high concentrated PV array (CPV), an electrolyser, a hydrogen buffer tank and a diaphragm hydrogen compressor. Small composite tanks are also included for fast refuelling of the UAV platforms at any time during the year. The novel approach of selecting a CPV power source is justified on the basis of minimizing the system footprint (versus flat plat or low concentration PV), aiming for a containerized remotely deployable UAS offgrid refuelling solution.

To validate the simulation tool a number of simulations were performed using experimental data from a prototype offgrid hydrogen refuelling station for UAVs developed by Boeing Research & Technology Europe. Solar irradiation data for a selected location and daily UAS hydrogen demands of between 2.8 and 15.8 Nm^3 were employed as the primary inputs, in order to calculate a recommended system sizing solution and assess the expected operation of the refuelling system across a given year. The specific energy consumption of the refuelling system obtained from the simulations is between 5.6 and 8.9 $kW\,h_e$ per kg of hydrogen delivered to the UAVs, being lower for larger daily hydrogen demands. Increasing the CPV area and electrolyser size in order to supply higher daily hydrogen demands (e.g., above 10 Nm^3 H_2 per day) improves the system operability. However this can imply excessive system size and costs, jeopardizing the techno-economic feasibility of a remotely deployable off-grid refuelling solution.

1. Introduction

Fuel cells (FC) can offer enhanced mission capabilities for mini-unmanned aerial vehicles (UAVs).[1] Apart from low greenhouse gases (GHG) emissions, low noise and low thermal signature, air cooled fuel cells offer competitive advantage over conventional technology [1–5]. However, one of the main technical challenges in remote locations with no available grid connection is the availability of hydrogen fuel on-site to supply the fuel cell-powered UAVs, where the hydrogen can be produced in an environmentally friendly manner [6–8]. A prototype offgrid solar-based hydrogen refuelling solution for mini-UAVs developed and tested by Boeing Research & Technology Europe (BR&T-Europe) was presented in previous publications [9,10], where hydrogen is produced on-site from concentrated photovoltaic modules (CPV) according to the UAVs

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[1] Mini-UAVs have a Maximum Take-Off Weight (MTOW) below 25 kg.

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Nomenclature

AC	Alternating Current
AGM	Absorbed Glass Mat
ATEX	Explosive Atmosphere
CAPEX	capital expenditure
CPV	concentrated photovoltaic module
DAQ	Data Acquisition System
DC	Direct Current
DNI	direct normal irradiation
ELY	electrolyser
HAZOPS	Hazards and Operability Study
FC	fuel cell
GCS	UAS Ground Control Station
GHG	Green House Gases
MPP	Maximum Power Point
MTOW	Maximum Take-off Weight
OP	number of operational days across a given year
OPEX	Operating Expenses
PE	power electronics
PEMFC	proton exchange membrane fuel cell
PLC	Programmable Logic Controller
SAPS	Stand Alone Power System
SF	safety-oversizing factor
SoC	state of charge
SoC_{BAT}	state of charge of the battery bank
SoC_{H2}	state of charge of the low-pressure hydrogen buffer store
UAV	unmanned aerial vehicle
UAS	unmanned aerial system

demand. The offgrid refuelling system proposed is based on a remote nanogrid, where a CPV array connected to an electrolyser and a compressor through an AC bus to produce and compress enough hydrogen to power a fleet of electric fuel cell-powered UAVs where the fuel cell is of the proton exchange membrane (PEMFC) type. Hydrogen fuel is generated from water through an electrolyser powered from the AC bus, stored in a buffer tank and then compressed for UAV on-board usage. The refuelling system also includes a battery bank for short-term energy storage and voltage stabilization, and the associated power electronics.

Wind and solar-based hydrogen refuelling systems for energy and road transport applications have been developed, along with system modelling tools, although most of them are at least partially connected to the grid to supply the electrical requirements, mainly to the booster or compressor and other auxiliary loads [11–18]. The main novelty of the prototype system developed by BR&T-Europe is the selection of high concentration PV technology for hydrogen production in an offgrid system exclusively dedicated to refuel UAS. For remote applications at locations with abundant direct solar irradiation across the year, a CPV power source vs. conventional PV can be justified on the basis of an overall yearly higher energy production (kW h_e supplied per year) per unit surface area. The adoption of a CPV power source is then justified on the basis of minimizing the system footprint, ultimately aiming for a containerized remotely deployable UAS offgrid refuelling solution. For reference, the footprint area of the CPV array for an offgrid UAS refuelling system similar to that developed by BR&T-Europe, may amount to half of the total system footprint including electrolyser, compressor, hydrogen stores, battery, and all system auxiliaries. Therefore, minimizing the size of the CPV array is paramount.

System design & simulation tools are required in order to develop a systematic approach for the design of CPV-based offgrid UAS hydrogen refuelling systems. A Matlab-based simulation tool was specifically developed by BR&T-Europe to approach this challenge. The simulation tool, named H2UAS-Sim, allows testing different refuelling system configurations while simulating specific UAVs operating scenarios, including different flight missions (with varying hydrogen fuel requirements) and operation in different geographical locations following the solar resource conditions.

The simulation tool has two main functions:

(i) Pre-designing an offgrid hydrogen-based refuelling system able to meet specific UAV flight missions. The design criteria are based on minimizing the system footprint and maximizing the system efficiency (minimum energy consumption per kg of hydrogen delivered to the UAVs), while maximizing the system reliability and lifetime.

(ii) Evaluating the technical feasibility of specific refuelling systems to provide enough hydrogen to perform different UAV flight missions across different locations, according to the local solar resource available and a set of operational criteria introduced by the user.

The main inputs to H2UAS-Sim are: solar irradiation data across the year for the location selected and daily UAVs hydrogen demand. The minimum number of days across a given year during which the refuelling system must be fully operational (OP_U), is also an input to the simulation tool. The main output of H2UAS-Sim is a system preliminary design, in terms of CPV size and peak power output and battery capacity. To test different system configurations, the electrolyser and compressor size, the low-pressure hydrogen stores and the power consumption of all auxiliary loads, can also be modified. Other outputs from the simulation tool are the system efficiency, the total energy and the water consumption operating in offgrid mode, as well as operating performance of the energy storage subsystems across a given year (i.e., main hydrogen stores and battery bank).

2. Overview of the prototype off-grid sustainable refuelling system for UAV_s developed by BR&T-Europe

An autonomous solar-based off-grid hydrogen refuelling station for UAVs was developed by BR&T-Europe as part of the SINTONIA project [9,10]. The system design selected is based on an off-grid CPV array. The proposed refuelling system comprises a CPV array, an electrolyser to produce hydrogen from water electrolysis at 3 MPa, a low pressure buffer tank that sores hydrogen at a maximum rated pressure of 3 MPa and a diaphragm hydrogen compressor, and a bank of small composite type III tanks (operating pressure of 30 MPa). These tanks are then installed in the UAVs for the flight mission.

A common electrical AC bus is included to act as a "backbone" to integrate the CPV modules, battery bank, electrolyser and compressor with their associated power electronics, and to manage the power and energy flows. A battery bank, with its associated bidirectional power converter for charging/discharging, is required to power the critical loads during periods of low CPV generation and also to keep the voltage stability of the AC bus. An additional inverter extracts power from the CPV array and supplies power to the AC bus. A schematic of the prototype offgrid UAS hydrogen refuelling system developed by BR&T-Europe is shown in Fig. 1.

The basic function of the refuelling system is as follows: the CPV output and water supply from the H_2O tank installed in the electrolyser are conveyed to the electrolyser to produce hydrogen