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Impact of fuel cell and battery size to overall system performance – A diesel fuel-cell APU case study

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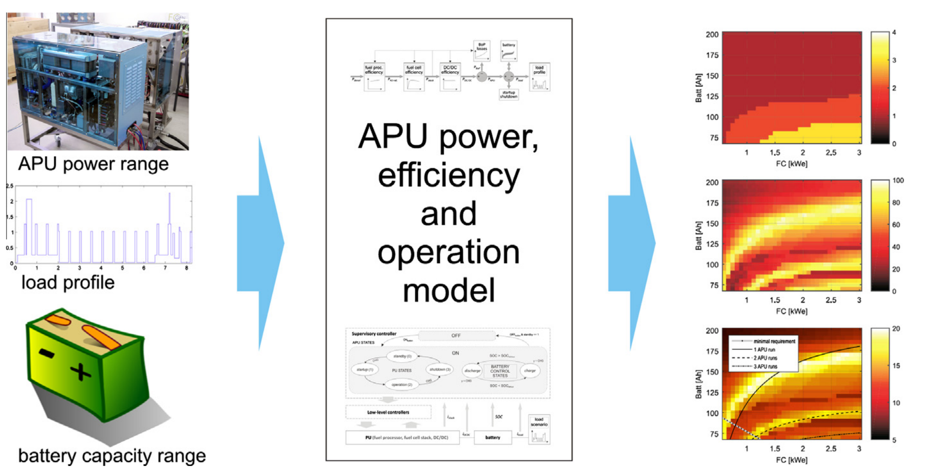
HIGHLIGHTS

- Evaluation of optimal pairing of power unit and battery for predefined load profile.
- Model-based approach employed for component sizing brings essential insight.
- Case study of truck on-board diesel fuel-cell based APU for anti-idling application.
- 0.6–3.0 kW APU power and 70–200 A h battery capacity ranges investigated.
- Relation for optimal battery size given APU power, load demand and duration derived.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper a data-validated power-efficiency model of a diesel-powered fuel-cell-based auxiliary power unit (APU) system is used to investigate the various sizes of the power unit and the battery and to evaluate the optimal choices for specified load profiles. The challenge comes from the FCGEN (Fuel Cell-based power GENeration) EU FP7 project, where such an APU was developed. The system consists of a fuel processor, a PEM stack, and a battery providing power for the startup, shutdown, and for covering load transients; however, the developed prototype system is not optimised. Before redesigning it for mass production, the optimal size of the main components needs to be identified to enable the best possible exploitation of the technology. In this work a case-specific load profile was used and a mesh grid of scenario simulations has been performed using various sizes of the fuel cell with fuel processor as a power unit and the batteries of various capacities as an energy storage unit. For this purpose a scalable APU model, including the BoP component consumption, has been developed. Upon the analysis results, the relation for optimal combinations in terms of efficiency and degradation is proposed and the confronted tradeoffs are discussed.

1. Introduction

Recently, ever more often, new products and applications based on fuel cells with a *Polymer Electrolyte Membrane* (PEM FC) [1,2] are being launched, and this attractive technology [3,4] is gathering

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further momentum. Recently, the FC-based auxiliary power units (APU) have also received increased attention. There is an interest noticed in such products in the vehicle (trucks [5–7], caravans, busses [8]) and maritime field (yachts [9,10] and sailboats [11]), as well as in the stationary application market (mCHP, telecom base stations [12], remote, mountain houses, etc. [13]). Such APUs can be fuelled directly by hydrogen as well as by commonly available LPG/CNG or gasoline/diesel fuel [14–17]. They operate at higher efficiency and with lower noise and pollutant emissions compared to ICE-based units [18]. In the case using one of the ubiquitous fuels, the system has a wide application area but requires the expensive and complex reformer part [19,20]. Several research projects (e.g., FCGEN [21], DESTA [22], PURE [23], etc.) have been initiated to overcome further obstacles to commercialization and to demonstrate such APUs in real use cases. However, to be successful, several aspects of these systems, namely, economics [24], reliability, and sustainability [25], still require to be further optimised. The cost of initial investment is high, and despite its lower consumption and very low pollutant and noise emissions, the total cost of ownership[1] (TCO) [26] is still too high. Despite recent advances in fuel-cell and reformer technologies and, in part, also in industrialization [27], as well as control [28–31] and monitoring [32,33], the current implementations still have some margins in efficiency and durability but predominantly exceed cost and size targets, owing mostly to two reasons:

- Prototype or small series production
- Suboptimal components matching

An important design phase, addressing the latter, is the selection of system components, the main parts as well as BoP components. Only by selecting the operating-condition adapted and closely-matched components, power-wise, can all parts of the system be exploited optimally, enabling the system as a whole to approach the theoretically optimal performance and durability level. In recent studies, the issue has been tackled for the fuel cell vehicle [34,35] and for the solar/wind power generation [36–38] applications, but with other incentive and approach.

In such a complex system, the experimental trial-and-error approach cannot be efficient. The time- and cost-effective alternative is to perform this in simulation [8,12]. However, one has to bear in mind the possible offsets of the model from the real environment and the simulation results have to be evaluated properly. Experience and practice point towards more weight on simulation in the early phases and on real-world experimentation in the late development phases.

To a good effect, such approach was used in a simulation case study [39], where a diesel fuel-cell-based APU was used in an anti-idling application [40,41] to support the selection of the most suitable battery type for the FCGEN project APU. In the anti-idling case, the APU has to feed the needs of the truck, i.e. heater, air-condition, cooker, electronic equipment, etc. Its main objective is to be able to stand a full night of use independently while achieving the highest possible efficiency and requiring the least starts to minimise the degradation effect.

During the late development stages of the FCGEN APU and commissioning, it was observed that better power matching of subcomponents is possible. In this sense, to enable the exploration of the exploitable space, the similar approach has been used here to inspect the sizing of the power unit (PU) and the battery and to research the parameters that govern the selection of the most suitable combination.

To perform this study, we originated from previous work [39], which comprises the efficiency and power models of the main PU components, the battery model and the power consumption profile. The model was upgraded from its predecessor to allow power scaling, and it also features data-validated BoP component power consumption characteristics. With this setup we have investigated the operational properties of the power unit (PU) and battery size for a truck on-board diesel-powered FC-based APU system for a variety of APU and battery sizes and generated a heat-map of efficiency and number of starts to facilitate the decision.

The paper first presents the APU, the power-efficiency model, described in more detail in [39], with additional characteristics tuned from a real system operation. Follow the descriptions of the control system and of the APU loads with their profiles for the truck's onboard application. The battery and PU combinations are evaluated in the simulation and the findings are summarised relating to overall efficiency, degradation, price, and other aspects of practical use.

2. Scientific approach

The main idea of the presented work is to feed a model with the desired load profile as well as the interesting ranges of the power module and battery. After running the simulations, the residuals are generated automatically and presented in the form of informative heat-map plots. To do that, the model has to describe the interesting process parameters, i.e. power flows and efficiencies, as well as model the autonomous operational behaviour of the APU, i.e. the control system.

2.1. The APU process

The APU system, developed within the FCGEN project, is composed of two main parts. The fuel processor (Fig. 1, right unit) is used to convert the diesel into hydrogen-rich reformate gas and the fuel cell (Fig. 1, within left unit) to transform that into electricity.

The simplified PU process scheme, showing its main components and process path, is presented in Fig. 2. The diesel reforming path comprises autothermal reformer (ATR) [42–44], desulphurization unit (DS), and water-gas-shift (WGS) and preferential-oxidation (PROX) reactors for carbon monoxide conversion [45]. Thus, prepared reformeate gas enters the fuel cell (FC) anode, where it is converted to electricity with controlled H_2 utilization factor. The anode off-gas containing the residual H_2 is then combusted in the catalytic afterburner (CAB) and the generated heat is used to preheat the steam entering the reformer and to completely burn potential other combustible or harmful compounds. The electrical energy generated by the fuel cell is treated by DC/DC converter, which is controlled to perform safe battery charging and provide power to the loads.

The developed prototype unit is a complex system consisting of numerous subsystems and components:

- Fuel processor reactors for diesel reforming and S/CO treatment
- Fuel-cell stack
- Power conditioning modules (DCDC converter, power distribution board for efficient BoP power supply)
- BoP components – 38 actuators (pumps, blowers, valves) and over 60 sensors (various temperature sensors, pressure sensors, flow meters, gas sensors)
- Electronic Control Unit for overall control and remote operation/monitoring

[1] TCO is a financial estimate intended to help buyers and owners determine the direct and indirect costs of a product or system. It is a management accounting concept that can be used in full cost accounting or even ecological economics where it includes social costs.