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Sizing Direct Methanol Fuel Cells for 12/24 V Portable Backup Using a Semi-Empirical Polarization Model

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Abstract. A computational sizing tool was developed for direct methanol fuel cells (DMFC) intended for portable backup power in 12/24 V buses. A semi-empirical polarization model was implemented in MATLAB that combines the reversible term with activation, ohmic, and transport losses, and includes a penalty for methanol crossover. The algorithm delivers the design pair (N, A) that simultaneously satisfies the target power and voltage and estimates methanol consumption and autonomy using Faraday's law. Dynamic verification in Simulink, under variable load profiles, showed that the selected designs keep the bus within tolerance and avoid transport-limited operation. Temperature-concentration sweeps outlined stable operating zones useful for sizing. The workflow reduced the risk of oversizing and generated reproducible artifacts applicable to telecommunications nodes and other 12/24 V loads.

1 Introduction

Ensuring continuity of supply in power systems depends on the availability of dispatchable resources that can balance generation and demand in real time. In Honduras, system reliability has historically relied on thermal generation and reservoir hydropower to stabilize the national grid; when their participation decreases, overall stability is at risk. Recent evidence reported rationing and scheduled outages due to supply constraints delays in new capacity, low hydrology and weaker regional imports producing blackouts that disrupted productive activities and services [1]. Quality of service indicators also revealed stress: the regulator CREE reported SAIFI ranges in 2023 and higher than desirable interruption frequencies in early 2024, consistent with energy not served and economic impacts reported by the Centro Nacional de Despacho (CND) and civil society assessments [2]. This context underscores the practical need for portable, quiet, low footprint backup options that integrate with 12/24 V DC buses common in telecommunications, PLCs, and field electronics.

Within low to medium power applications, Direct Methanol Fuel Cells (DMFCs) are attractive because methanol is a liquid fuel at ambient conditions with high volumetric energy density, simple storage and refuelling, and compatibility with PEM architectures. That combination simplifies logistics relative to compressed hydrogen and supports continuous DC output as long as methanol and air are supplied, which is why DMFCs have been adopted

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in portable and remote uses and considered as complements to battery/solar systems [3]. Historically, the DMFC field has matured through milestones in catalysts, membranes and stack engineering from early demonstrations and reviews to commercial deployments and national road mapping efforts that recognize methanol pathways in broader hydrogen strategies [4], [5].

Technically, sizing a DMFC prior to prototyping is non-trivial because performance depends on coupled variables and interacting loss mechanisms. The electrical output reflects a reversible term minus losses due to activation kinetics, ohmic resistance, and mass transport, while methanol crossover can induce mixed potentials at the cathode and depress the cell voltage. Operating conditions temperature (T) and methanol concentration ([MeOH]) shift kinetics, conductivity, transport limits and crossover, thus altering the i–V curve and the feasible operating window. Design variables number of series cells (N) and active area per cell (A) must therefore be selected together with T and [MeOH] so that the stack sustains the bus voltage under load and avoids transport limited regimes [6].

Given the practical constraints of local testing infrastructure, this work adopted a computational approach to "model before building". The study implemented in MATLAB a semi-empirical polarization model that includes the reversible term and lumped losses (activation, ohmic and transport with a crossover penalty) and used it to compute the design pair (N, A) that meets power/voltage objectives for 12/24 V while enforcing operating limits [7]. Fuel use and autonomy were estimated by Faraday's law using methanol stoichiometry. To verify that a sized configuration would hold the DC bus under realistic demand, the work built a Simulink testbench with stepped and ramped load profiles, mapping stack power to bus power through a DC-DC efficiency and monitoring bus voltage, proximity to transport limit, and thermal trend in a lumped RC representation. In addition, temperature concentration sweeps were used to delineate stable operating regions and expose trade-offs between kinetics, transport margin and crossover [7] .

Various studies have examined strategies to diversify the energy matrix of the country and to explore different energy storage solutions. [8] analyzed the potential effects of residential-scale solar energy deployment on the national energy matrix. [9] investigated the potential of green hydrogen in Honduras as means to enhance grid stability. Similar to these studies, this research also aims to contribute with the diversification of the energy matrix of Honduras with the approach of employing computerized models of methanol fuel cells.

2 Context

Power-system reliability in Honduras has long depended on dispatchable capacity that balances generation and demand in real time; in practice, thermal and reservoir hydro plants provide the stability margin for the national grid, so reductions in their participation jeopardize system stability. In 2020, electricity production was 43% thermal and 54% renewables 27% hydro, 10% solar PV, 7% wind, 7% biomass, 3% geothermal highlighting, as shown in Fig. 1 below.

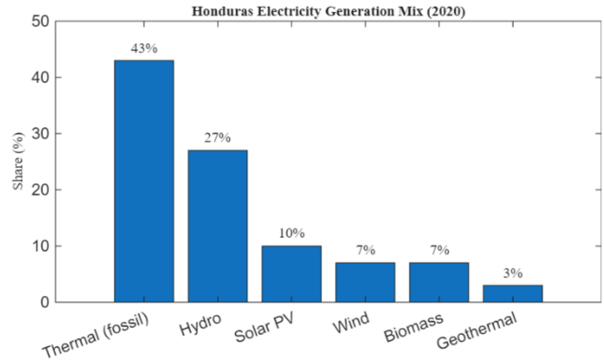

Fig. 1. Combination of renewable energy generation in Honduras

Source: [10]

Recent rationing and scheduled outages linked to delayed capacity additions, low hydrology, and weaker regional imports affected productive activities and services; quality of service indicators reported SAIFI values in 2023 between 43.5 and 83.6, and 1H-2024 figures of 24.84 (CREE) versus 12.47 (UTCD) as show in Fig. 2 below, consistent with 92.5 GWh of energy not served and an economic impact near L 7,408 million [10]. In this environment and with thunderstorms that frequently trip feeders' telecommunications infrastructure (radio base stations, microwave links, PLC/SCADA remotes) becomes a priority use-case for site level backup at 12/24 V DC that is portable, quiet, low-footprint, and capable of sustaining the DC bus beyond typical battery only autonomy.

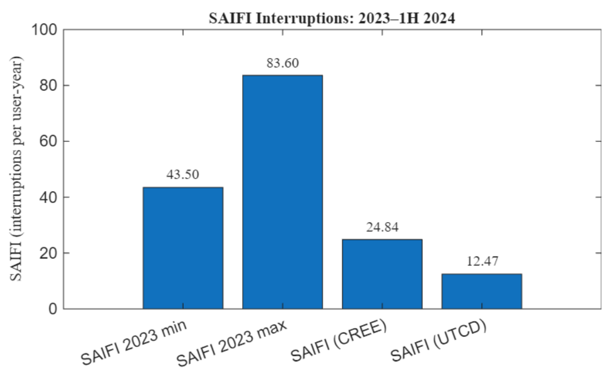

Fig. 2. Reliability indicators for Honduras.

Source: [10]

Electrochemically, Direct Methanol Fuel Cells (DMFCs) fit these constraints because methanol is a liquid at ambient conditions with high volumetric energy density and straightforward logistics. At the anode, the methanol oxidation reaction produces carbon dioxide, releasing protons and electrons; protons cross a PFSA proton-exchange membrane (e.g., Nafion), electrons power the external circuit, and at the cathode oxygen is reduced to water. The overall reaction converts methanol and oxygen into carbon dioxide and water. This stoichiometry directly links current to methanol consumption via Faraday's law, allowing autonomy to be sized from tank mass. Practical performance, however, depends on coupled operating and design variables temperature (T) and methanol concentration ([MeOH]) shape kinetics, conductivity, transport limits and crossover, while number of series cells (N) and active area (A) determine bus voltage and current density. Because methanol crossover can induce mixed potentials at the cathode and depress the i–V curve, feasible operation must balance activation, ohmic and mass-transport losses with acceptable crossover levels [11]. In telecom sites exposed to grid outages and storms, DMFCs can be hybridized with existing battery banks: the battery handles fast transients, and the DMFC extends autonomy quietly and with a smaller on-site fuel footprint than a diesel genset while natively matching the 12/24 V DC buses common in telecom equipment.

To reduce oversizing risk and provide actionable guidance before prototyping, this work adopts a computational sizing workflow consistent with the DMFC literature: a semi-empirical polarization model in MATLAB—reversible term minus activation (lumped Tafel), ohmic and transport losses with a crossover penalty returns the design pair (N, A) that jointly meets power/voltage targets at 12/24 V, enforces a minimum per-cell voltage and a cap on j/j_{lim}, and estimates methanol consumption and runtime from Faraday's law. Additionally, a BOP factor is applied to reconcile the ideal stack level fuel rate with system level consumption (L/kWh) reported by commercial datasheets, so that fuel use reflects auxiliaries and conversion and is directly comparable to vendor figures. The same datasheets are used to corroborate nominal operating points (voltage, bus power, and L/kWh) predicted by the model. A Simulink testbench with stepped/ramped load profiles also includes intervals with I load=0 to emulate battery only segments or deep discharge; these tests verify that the sized configuration re-establishes the 12/24 V bus upon resuming load, while DC-DC efficiency mapping, j/j_{lim} proximity, and the lumped thermal trend (Cth/Rth) remain within bounds. Overall, the calibration and checks reflect the technology's maturation from early studies to commercial deployments and national road mapping.

3 Methodology

This study followed a quantitative, model-based approach to size Direct Methanol Fuel Cell (DMFC) stacks for 12/24 V DC backup applications. The workflow comprises: (i) cell-level modeling with a semi-empirical polarization equation; (ii) a sizing routine that selects the pair (N, A) number of series cells and active area per cell that meets bus power/voltage targets within operating constraints; (iii) fuel-use estimation by Faraday's law and a BOP correction to reconcile system-level consumption (L/kWh) with commercial datasheets; and (iv) dynamic verification in Simulink under stepped and ramped load profiles, including zero-current intervals to emulate battery-only segments. The formulation aligns with established DMFC and PEMFC modeling practice.

3.1 Polarization model used for sizing: fast, calibratable, physics-aware

The procedure used to translate the technical data collected, using an operational mathematical representation of the DMFC. The objective is to have a cell V-i curve that responds to the operating variables (temperature and methanol concentration), which, when scaled up, allows the stack to predict voltage and power underload with the accuracy required by the dimensioner (±5% in power and voltage). The model adopted is semi-empirical, combining a reversible term with activation losses, ohmic losses, and mass transport limitations [12].

$$V(j,T,[MeOH]) = E_O - \frac{RT}{\alpha F} * \ln\left(\frac{j}{i_o}\right) - j * R_\Omega - \frac{RT}{nF} * \ln\left(1 - \frac{j}{j_{lim}(T,[MeOH])}\right) \quad (1)$$

The final product is a computational implementation that validates the previously established operating range to feed the scans required for the dimensioner, enabling the recommendation of battery configurations compatible with 12/24V.

3.2 Operational sweeping and Maps

The objective of this stage is to define the operational advantage in which the DMFC can simultaneously meet the power/voltage requirement, taking into account the physical and operational considerations of the model. To do this, factorial sweeps are performed on temperature T and methanol concentration [MeOH], the dimensioner solves a problem (N, A), and verifies feasibility [13].

$$\left|\frac{P_{stack}-P_{obj}}{P_{obj}}\right| \leq \varepsilon P \tag{2}$$

$$\left|\frac{V_{stack}-V_{bus}}{V_{bus}}\right| \leq EV \tag{3}$$

$$V_{cell} \geq V_{cell,min} \tag{4}$$

$$j_{nom} \leq f_{max} \cdot j_{lim}(T,[MeOH]). \tag{5}$$

The output of the sweep is a feasibility map highlighting the regions where the (power, voltage) constraints and the cell/transport limits are met, along with derived layers (e.g., iso-contours of j/jlim, bus-voltage deviation, or the minimal (N, A) found per grid point). Practically, this map (i) identifies preferred operating pockets that balance activation/ohmic losses and transport headroom, (ii) guides the choice of (N,A) by revealing where the target can be achieved with the smallest area and adequate per-cell voltage, and (iii) supports set-point selection (ranges of T and [MeOH]) that remain inside tolerance bands below the prescribed safety fraction.

3.3 Methanol consumption and range

When implementing the methanol consumption that the dimensioner may have, the operating point of the DMFC, the current and power required on the bus, and the fuel flow rate are taken into account. Based on these factors, the range with the given tank is estimated using the stoichiometry of the DMFC and Faraday's law. To directly link electricity and chemical reactions in a DMFC, we know that the anode reaction (methanol oxidation) releases 6 electrons per mole of methanol, and that electric current is a flow of electrons. Faraday's law is the physical bridge used to connect the measured current with the fuel actually consumed without relying on commercial assumptions. From the current, Faraday allows us to calculate a target methanol flow rate and, with that, estimate range and the size of the methanol tank to be used depending on consumption [14].

$$\dot{m}MeOH = M_{MeOH}\frac{\phi FI}{nF} \tag{6}$$

3.4 Dynamic verification in Simulink

To verify that the configured system can sustain the electrical requirements (12/24V bus) under variable load profiles, without violating operational restrictions where they are affected (minimum voltage per cell, transport limit, power ceilings), and with stable transient behavior (without sustained peaks or critical dips). A script was programmed to build the model, resolving the necessary routes and configurations. The configurations of the different DMFCs that were validated were processed using a temporary current profile from the stack, passing through the DMFC_CORE block, which takes into account the implementation of the semi-empirical model per simulation step. At all times, the current density is calculated, the transport limit is evaluated, and operation is limited to a safe fraction [15].

$$P_{bus}=n_{conv}P_{stack} \tag{7}$$

The verification consisted of reproducing demand profiles (steps and ramps) and checking that the dimensioned configuration was able to maintain the 12/24V bus within tolerance, without violating the minimum voltage and consumption consistent with the autonomy calculated by Faraday.

4 Results

This section presents the results of the study conducted using the methodology explained in chapter four. It also presents the analysis performed in MATLAB and its complementary verification in Simulink, showing the calibration and validation of the semi-empirical i-V model, followed by the parametric sweep of temperature [T] and methanol concentration [Me OH]. External validation is based on commercial DMFC data sheets, which show the consistency of the simulator with respect to DMFCs already on the market, demonstrating the robustness and reliability of the simulator. The first test was performed with a commercial DMFC data sheet, as shown in Table (1).

Table 1. Data obtained from the technical specifications of DMFC S1

Variable	**Value**
Output power [W]	150
Voltage range [V]	12
Nominal current S1	12
Weight [kg]	7.25
Operating temperature	-20°C a+50°C
Fuel consumption [L/kWh]	0.8

Using the commercial DMFC S1 (12 V class, nominal 150 W, datasheet consumption 0.8 L/kWh) as an external reference, the sizing model returned a stack with 24 cells in series and an effective active area ≈57–63 cm² per cell, operating at $j_{nom} \approx 0.225\ A{\cdot}cm^{-2}$ (about 30 % of the estimated transport limit). Under the base operating point (T = 60 °C, [MeOH] = 1.5 M), the cell voltage predicted by the semi-empirical i–V model is $V_{cell} \approx 0.477$ V, giving $V_{stack} \approx 11.44$ V and $P_{stack} \approx 148$–162 W depending on the precise area selected. When the DC-DC conversion stage is included, the useful bus power reaches ≈ 145.4 W, i.e., −3.1 % relative to the 150 W datasheet rating well within the ±5 % tolerance used for design confirming that the pair (N, A) satisfies the 12 V regulated bus requirement without violating the per-cell minimum voltage constraint. The model's minimum (Faradaic) methanol consumption at that point is = 0.59 L/kWh, which is intentionally optimistic because it excludes plant-level penalties; after applying an empirically calibrated BOP factor = 1.36 (to represent purge, crossover-related losses and auxiliary loads), the adjusted specific consumption becomes 0.80 L/kWh, matching the datasheet value exactly. The predicted mass flow of methanol at the nominal point is ≈ 62–68 g/h, corresponding to I_cell ≈ 13–14 A at the declared bus voltage, as described in Table (2).

Table 2. Comparison of technical specifications vs. simulation.

Metric	Specification (SPEC)	SIM (bus)	Δ
V_bus [V]	12	12.0 (regulated)	0.0 %
P to bus [W]	150	145.4	−3.1%
L/kWh (minimum model)	-	0.59	-
BOP_factor [–]	-	1.36	-
L/kWh (adjusted)	0.8	0.80 (with BOP=1.36)	+0.0%

This agreement between datasheet targets and simulated performance validates the sizing workflow and supports its use to recommend stack sizing and operating windows for 12/24 V telecom back-up scenarios, where quiet, liquid-fuel autonomy extensions are required.

5 Conclusion

This study presented a computational sizing workflow for Direct Methanol Fuel Cells (DMFC) aimed at low-/mid-power backup applications on 12/24 V DC buses. A semi-empirical polarization model (reversible term with activation, ohmic and mass-transport losses plus a crossover penalty) was implemented in MATLAB to return the design pair (N, A) that simultaneously satisfies voltage and power targets while respecting per-cell voltage and transport-limit margins. Operating-map sweeps over temperature and methanol concentration delineated feasible regions and quantified trade-offs between kinetics, ohmic drop, transport margin and crossover. Calibration against commercial datasheets showed high consistency: for a 12 V/150 W DMFC module, the model delivered 145–148 W at the bus (−3.1% deviation) and a faradaic minimum of 0.59 L kWh, applying a balance-of-plant (BOP) factor of 1.36 reproduced the published 0.80 L kWh figure.

A Simulink testbench with stepped and zero-current segments verified that sized stacks, coupled to a DC–DC stage, hold bus voltage within tolerance and recover normally after brief load interruptions, while staying below a conservative fraction of the transport limit. Taken together, the results indicate that DMFC systems are a technically viable option to extend autonomy for telecom loads in Honduras where reliable 12/24 V DC backup is needed due to frequent outages offering a quiet, portable alternative with simpler logistics than hydrogen. The methodology reduces prototyping risk and provides actionable sizing guidance (cells in series, active area, operating window and expected methanol consumption) to support early design decisions. Remaining limitations lumped thermal dynamics, simplified crossover representation, and the absence of long-term degradation and water-management effects point to future work involving parameter identification with laboratory data, closed-loop control of fuel/thermal balance, and evaluation with low-carbon (“green”) methanol supply scenarios.

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