

French Polytech network form for PhD Research Grants from the China Scholarship Council

This document describes one of the PhD subjects proposed by the French Polytech network. The network is composed of engineering schools/universities. The document also provides information about the supervisor.

Supervisor information	
Family name	VIAL
First name	Christophe
Email	christophe.vial@uca.fr
Web reference	https://scholar.google.com/citations?user=GiinnroAAAAJ&hl=fr
Lab name	Institut Pascal
Lab web site	www.institutpascal.uca.fr
Polytech name	Polytech Clermont
University name	Université Clermont Auvergne
Country	France

PhD information	
Title	Dynamic Modeling and Optimization of a Hybrid Power-to-Methane System Integrating Electrolysis, Biological Methanation, and Battery and Hydrogen Storage

Main topics regards to CSC list (3 topics at maximum)	V-5. Energy of hydrogen and technology of hydrogen storage
Required skills in science and engineering	Chemical engineering, and/or Energy engineering, and/or Fluid mechanics

Subject description (two pages maximum including biblio)

Context

Power-to-methane (PtM) systems based on biological methanation are emerging as one of the most promising technologies for converting surplus renewable electricity into chemical energy, as biomethane is generally easier to store and transport than hydrogen [1]. In such systems, renewable electricity is first converted into hydrogen by water electrolysis. The hydrogen is then biologically combined with carbon dioxide by methanogenic microorganisms to produce biomethane, a renewable energy carrier that can be injected into existing natural gas grids, stored over extended periods, or used as a sustainable fuel. Despite their considerable potential, both water electrolyzers and biological methanation reactors are highly sensitive to fluctuating operating conditions. Frequent load variations and intermittent operation may reduce electrolyzer efficiency and accelerate component degradation [2], while temporary interruptions in hydrogen supply can significantly impair microbial activity and reactor performance [3]. To mitigate these limitations, hybrid energy systems integrating battery storage for short-term power smoothing and on-site hydrogen storage to buffer the biological methanation process had been proposed. Such hybrid configurations enhance operational flexibility and may increase the utilization of surplus renewable electricity. However, the addition of storage technologies also increase capital and operating costs, making the optimal sizing, integration and management of each subsystem a critical challenge. The design and operation of these hybrid systems therefore require a thorough understanding of the dynamic interactions between the subsystems, which remain insufficiently investigated. Developing a comprehensive dynamic simulation framework capable of accurately capturing these coupled transient phenomena is essential for optimizing system performance, reliability and economic viability.

Background and previous works

Institut Pascal (UMR 6602 CNRS) is a French joint interdisciplinary research and training unit comprising approximately 400 researchers, engineers, technicians, and PhD students. The institute conducts cutting-edge research in engineering sciences, with a particular focus on Sustainable Mobility. Within the institute, the Chemical Engineering, Applied Thermodynamics, and Biosystems (GePEB) research group develops innovative processes and technologies for the production, conversion, and storage of renewable energy, with a particular emphasis on biohydrogen and biomethane production. Building on more than seven years of experimental research, the GePEB group has developed and patented an innovative biological methanation process [4,5]. More recently, the group has developed advanced Computational Fluid

Dynamics (CFD) models that accurately describe the complex interactions between hydrodynamics, mixing, gas/liquid mass transfer, and biochemical reactions within biomethanation reactors [6]. Although these model provide valuable insights into reactor performance, their high computational cost make them unsuitable for long-term dynamic process simulations.

Objectives of the PhD project

The main objective of this PhD project is to develop and validate an integrated dynamic model of a hybrid energy system coupling water electrolysis, biological methanation, hydrogen storage, and battery energy storage. The specific objectives are to:

- Develop a dynamic model of the electrolyzer, accounting for hydrogen production rates, electrical efficiency, transient response, and operating constraints, with and without intermediate H₂ storage;
- Develop a dynamic model of the biological methanation reactor, including gas–liquid mass transfer, microbial kinetics, methane production, and process stability;
- Develop a dynamic model of the battery energy storage system, including charge/discharge dynamics, state-of-charge evolution, energy efficiency, and degradation mechanisms;
- Integrate these models into a unified simulation framework describing the coupled flows of electricity, hydrogen, carbon dioxide, methane, and stored energy, to validate using experimental data;
- Design and optimize energy management strategies based on key performance indicators such as overall efficiency, methane production, renewable energy utilization, and system flexibility.

The proposed research will combine experimental data acquisition, process modeling, numerical simulation, and optimization techniques. The first step will consist in developing mathematical models for each subsystem based on mass and energy balances, electrochemical principles, microbial kinetics, and energy storage dynamics. Available laboratory and literature data will be complemented by dedicated experimental investigations using the facilities available at Institut Pascal: (i) a 4 NL/min PEM electrolyzer; (ii) a 22 Ah NMC battery equipped with a battery management system (BMS); (iii) a hydrogen storage reservoir; and (iv) several biomethanation reactors with liquid-phase working volumes ranging from 0.5 to 12 L. These experimental facilities will enable the independent characterization of each subsystem before investigating different coupling configurations and completing the existing datasets and provide the data required for model calibration and validation. For biological methanation, CFD-generated data will also be exploited to simulate operating conditions that are difficult or costly to achieve experimentally. The main modeling phase will involve the development of dynamic models using MATLAB or Python, first for each individual subsystem and subsequently for the fully coupled system. The expected outcome of this integrated model is a dynamic simulation tool for hybrid electrolysis–biological methanation–electricity/hydrogen storage systems, providing a better understanding of the interactions between hydrogen production, biomethane conversion, and energy storage. This tool will also support the identification and optimization of energy management strategies and provide design and operational recommendation for hybrid PtM systems under variable renewable energy sources.

Profile of the candidates

The PhD candidate will have a strong academic background in Chemical Engineering, Energy Engineering, or a related field, together with a strong interest in renewable energy systems and hydrogen technology. The ability to combine experimental data analysis with model development, as well as a willingness to work in an interdisciplinary research environment, will be essential.

References (bold name for people involved in the project)

- [1] H.C. Yörüklü, D. Kamravamanesh, E.O. Köroğlu, G.H. Patel, J. Havukainen, H. Karjunen, J. Sillman, M. Kokko, Energy Conversion and Management, 341 (2025) 120075. doi.org/10.1016/j.enconman.2025.120075
- [2] F. Maoulida, D. Guilbert, M.-B. Camara, B. Dakyo, Renewable and Sustainable Energy Reviews, 225 (2026) 116170, doi.org/10.1016/j.rser.2025.116170.
- [3] D. Strübing, B. Huber, M. Lebuhn, J.E. Drewes, K. Koch, Bioresource Technology, 245 A (2017) 1176-1183. doi.org/10.1016/j.biortech.2017.08.088.
- [4] M. Keramati, K.Erdogan, **J.-S. Guez**, **A.-V. Ursu**, **P. Dubessay**, **C. Vial**, P. Fontanille, Bioresource Technology Reports (2024) 101938. doi.org/10.1016/j.biteb.2024.101938
- [5] P. Fontanille, **C. Vial**, **J.-S. Guez**, K. Fadhlaoui, P. Dubessay, **A.-V. Ursu**, M. Keramati, Patent EP4615985A1 (2025).
- [6] H. Bournot, **A. Essid**, **J.-S. Guez**, **A. Marcati** , 20th congress of SFGP (13-15 October 2020, Clermont-Fd, France).