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The role of residential micro-cogeneration fuel cells in the energy transition

A case study in Belgium

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Abstract

Through theoretical, simulation, and experimental work, this thesis investigates the role of fuel cell micro-cogeneration systems in driving the energy transition. The thesis begins by defining the 'decarbonization' though the notion of carbon budgets, drawing insights from IPCC's latest work (AR6), which is then contextualized at both local and individual scales, with the examples of Belgium, Wallonia, and France serving as frequent case studies throughout this research. Considering imported emissions, the current commitments of those regions/countries is in fact not compatible with IPCC's +2°C recommendations. Also, since some greenhouse gases emissions could never be fully mitigated, 2050 carbon neutrality could only be reached by increasing carbon sinks to at least 1 tCO_{2eq}/year per capita, which will be highly challenging for France or Wallonia as it represents +370% and +300% increases against respective current (natural) levels.

Introducing the concept of fuel cells, the thesis provides comprehensive descriptions of main existing fuel cell types and their respective characteristics. Furthermore, the future performance of micro-cogeneration fuel cells is reviewed according to their underlying technology. PEMFC (Polymer Electrolyte Membrane Fuel Cell) systems performance are not expected to be significantly increased. This is not the case for SOFC (Solid Oxide Fuel Cell) systems, that exhibit no Carnot limit and could offer theoretical electrical LHV (Low Heating Value) efficiency close to 100% (DC) for the dry electrochemical oxidation of biochar or methane, which can be a renewable hydrogen carrier. Maximum demonstrated LHV electrical efficiency (AC) of any commercially available fuel cell systems is already of 65%, for a utility scaled methane-fed SOFC system launched on the market in 2023.

The thesis then presents experimental and simulation work performed on two presently available fuel cell systems, namely the BlueGEN SOFC and the Vitovalor PT2 PEMFC. The experimental work encompasses both laboratory test campaigns and in-situ field-test monitoring in real applications, yielding dedicated performance models that can be integrated into building performance simulation or energy planning tools. The tested PEMC system exhibits a high-level of hybridization with a classical condensing boiler, which is assumed to prevent both sub-systems to operate as optimally and reliably as they would have as standalone units. Oppositely, the tested SOFC system exhibited no troubleshooting and a reliable electrical efficiency always close to 60% (LHV) at its nominal power outputs, which can also easily even be modulated in the 33-100% range.

Building on those experimental performance and anticipated advancements of fuel cell systems, the thesis demonstrates that their greenhouses gases mitigation potential over the average individual carbon footprint remains quite unsignificant if their fuel is not decarbonized. Even so, their mitigation potential would still be way insufficient, and other actions, including behavioural changes, would still have to be implemented.

However, emerging technologies, such as Direct Carbon Solid Oxide Fuel Cells (DCSOFCs) or Direct Formic Acid Fuel Cells (DFAFCs) offer the capability of facilitating pure CO_2 capture at their anode exhaust and thus allow for potential negative emissions. With the case study of an average Belgian dwelling's electrical demand and the use of an electric car (for about 20000 km/year) provided by a DCSOFC with an electrical LHV efficiency of 80% fed by biomass, those negative emissions could be up to about 3 $MtCO_{2eq}$/year. In view of the minimal carbon absorption level implied by the carbon neutrality target (reported above), which will unlikely rely only on natural sinks in densely populated western countries, the negative emissions potential of such fuel cell systems shall absolutely be further developed and implemented (in addition to the maximization of natural sinks).

Résumé

Cette thèse examine le rôle des systèmes de micro-cogénération à piles à combustible dans la transition énergétique via un travail théorique et expérimental. La thèse commence par définir la ‘décarbonisation’ à travers la notion de budgets carbone, en s'appuyant sur les derniers travaux du GIEC (AR6), qui sont ensuite contextualisés à l’échelle locale et individuelle, avec les exemples de la Belgique, de la Wallonie et de la France. En tenant compte des émissions importées, les engagements actuels de ces régions/pays ne sont en fait pas compatibles avec les recommandations du GIEC visant à limiter le réchauffement à +2°C. De plus, étant donné que certaines émissions de gaz à effet de serre ne pourront jamais être complètement atténuées, la neutralité carbone en 2050 ne pourrait être atteinte qu'en augmentant les puits de carbone à au moins 1 tCO_{2eq}/an par habitant, ce qui représenterait une augmentation de +370% et +300% par rapport aux niveaux actuels (naturels) respectifs pour la France et la Wallonie, ce qui sera extrêmement difficile.

La thèse fournit des descriptions complètes des principaux types de piles à combustible existantes et de leurs caractéristiques respectives. De plus, les performances futures des piles à combustible de micro-cogénération sont étudiées. Les performances des systèmes PEMFC ne devraient pas augmenter de manière significative. Ce n'est pas le cas des systèmes SOFC, qui pourraient offrir une efficacité électrique théorique (DC) de 100% (LHV) pour l'oxydation électrochimique de biochar ou du méthane, qui peut être un vecteur d'hydrogène renouvelable. Par ailleurs, l'efficacité électrique LHV maximale démontrée (AC) d’une SOFC disponible commercialement depuis 2023 est déjà de 65%.

Ensuite, la thèse présente des travaux expérimentaux et de simulation réalisés sur deux systèmes actuellement commercialisés, à savoir le SOFC BlueGEN et le PEMFC Vitovalor PT2. Les travaux expérimentaux comprennent à la fois des campagnes de tests en laboratoire et un suivi des tests in situ, sur le terrain, dans des applications réelles, débouchant sur des modèles de performance qui peuvent spécifiquement être intégrés dans des outils de simulation de bâtiments ou de planification énergétique. Le système PEMC testé présente un niveau élevé d'hybridation avec une chaudière à condensation classique, ce qui est présumé empêcher un fonctionnement optimal et robuste de ces deux sous-systèmes. En revanche, le système SOFC testé est fiable et offre une efficacité électrique toujours proche de 60% (LHV) à sa puissance nominale, qui peut par ailleurs facilement être modulée dans la plage de 33% à 100%.

En s'appuyant sur ces performances expérimentales et sur les progrès anticipés des systèmes de piles à combustible, la thèse démontre que leur potentiel de réduction des gaz à effet de serre sur l’empreinte carbone individuelle moyenne reste relativement insignifiant si leur combustible n'est pas décarboné. Même dans ce cas, la réduction resterait insuffisante, et d'autres actions devraient encore être mises en œuvre.

Cependant, certaines piles, telles que les SOFC à ‘Direct Carbon’ (DCSOFC) ou les PEMFC à ‘Direct Formic Acid’ (DFAFC), offrent la possibilité capturer du pure CO_2 à leur échappement anodique. Avec l'étude de cas de la demande électrique moyenne d'un logement belge et de l'utilisation d'une voiture électrique (pour environ 20000 km/an) fournie par une DCSOFC avec une efficacité électrique LHV de 80% alimenté en biomasse, ces émissions négatives pourraient atteindre environ 3 $MtCO_{2eq}$/an. Vu le niveau minimal d'absorption de carbone requis par l'objectif de neutralité carbone (spécifié plus haut), le potentiel d'émissions négatives de ces systèmes de piles à combustible devra absolument être davantage développé et mis en œuvre en parallèle d’une augmentation significative des puits carbone naturels.

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