Potential of Solid Oxide Fuel Cell-based Combined Heat and Power Systems for Commercial and Residential Applications in Alberta and Canada

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Abstract

Hydrogen is increasingly recognized as a critical component in the global energy transition, offering a versatile and sustainable solution to decarbonize multiple sectors. In this context, solid oxide fuel cells (SOFCs) demonstrate significant potential by efficiently converting hydrogen into electricity with minimal emissions, positioning itself as a promising technology for sustainable power generation in residential, commercial, and industrial applications. Given Canada's commitment to sustainable development, along with Alberta's carbon-intensive space heating and power grid, SOFC technology has the potential to substantially reduce greenhouse gas (GHG) emissions while fostering economic growth. This paper presents a comprehensive assessment of SOFC-based combined heat and power (CHP) systems, including future market penetration forecasts, capital and operating costs, associated GHG reductions, and job creation in Alberta and Canada over time. The findings indicate that by 2050, the SOFC-based CHP market is projected to reach $2.5 billion in Alberta and $15 billion in Canada, with approximately 80% of this revenue attributed to the commercial sector. Additionally, the CHP market is expected to generate around 2,300 jobs in Alberta and 13,800 jobs across Canada by 2050. Furthermore, the development of SOFC systems is projected to avoid approximately 1.7 million tons of GHG emissions annually in Alberta's commercial sector and 7.8 million tons across Canada's commercial sector, with further reductions of 690 thousand tons and 388 thousand tons in the residential sectors of Alberta and Canada, respectively.

Index terms: Solid oxide fuel cell, Combined heat and power, SOFC, CHP, Greenhouse gas emission.

1. INTRODUCTION

The transition towards sustainable energy management in the commercial and residential sectors is becoming increasingly critical to meet decarbonization goals, improve energy efficiency, and reduce reliance on fossil fuels. Among various solutions, hydrogen-based combined heat and power (CHP) systems offer a promising solution by providing a dual-function approach: a) simultaneous generation of electricity and heat, b) Utilizing hydrogen as a clean energy carrier. These systems not only support a reduced carbon footprint, but also enhance energy efficiency, making hydrogen-based CHP systems an ideal fit for diverse building energy needs [1].

Among the available hydrogen-based CHP systems, solid oxide fuel cell (SOFC)-based CHP holds particular promise due to its high efficiency, fuel flexibility, and adaptability to various applications. SOFC-based CHPs operate at high temperatures, which enables them to achieve superior efficiency by converting chemical energy directly into electricity and capturing heat as a byproduct [2]. This captured heat can be utilized for space heating, hot water, or other thermal requirements, which is particularly beneficial in cold climates or high-demand settings. By offering decentralized energy production, SOFC-based CHP systems significantly reduce transmission losses and contribute to grid stability, making them an effective tool for advancing sustainable energy management in both commercial and residential sectors [3,4].

In recent years, several studies have highlighted the potential of SOFC-based CHPs for different applications. Marocco et al. [5] analyzed the environmental impact of using SOFC-based CHPs in commercial buildings, focusing on their emissions performance under varying grid carbon intensities. Considering the unavailability of low carbon hydrogen, they found that even natural gas-fed SOFC systems become environmentally advantageous, in terms of CO_2 emissions, when grid carbon intensity exceeds approximately 300 gCO_2/kWh. Gandiglio et al. [6] evaluated the long-term performance and emissions of commercial-scale SOFC modules (10–60 kW) installed in European non-residential buildings, operating over thousands of hours. With system-level electrical efficiencies of 51%–61% and thermal efficiencies of 18%–28%, they found that, given near-continuous operation with minimal on/off cycling, SOFC-based CHPs offer a best-in-class solution for decentralized power generation in the tens to hundreds of kW range. Alns et al. [7] investigated the feasibility of installing SOFC-based CHP systems in commercial buildings in Qatar and Kuwait. Their findings indicate that SOFC-based CHP can achieve substantial emissions reductions, with up to 30% for CO_2, 90% for NO_x, and 90% for SO_2. Additionally, they estimated payback periods of 11 years for Qatar and 7.8 years for Kuwait, highlighting the economic viability of SOFC technology in the commercial sectors of these regions. Roy et al. [8] conducted a study on the feasibility of using hydrogen as a clean energy source for residential consumers in the UK via a low-carbon energy hub. They compared two configurations: a SOFC-based CHP system and a SOFC–heat pump (HP) integrated CHP system, each powered by natural gas and hydrogen. Using actual electricity and heating demand data from a UK residential cluster, they found that the hydrogen-fueled SOFC-CHP system achieved a higher energy efficiency of 92.12% compared to 66.98% for the natural gas-fueled system. Economically, the SOFC–HP system was more viable, with a hydrogen-powered levelized cost of energy (LCOE) of £0.2984 per kWh. Their environmental assessment also indicated that the natural gas-powered SOFC system had levelized CO_2 emissions of 0.308 kg/kWh, while the SOFC–HP system reduced emissions to 0.213 kg/kWh.

To address the evolving sustainability initiatives at both the national and provincial levels, this paper presents a comprehensive techno-economic and environmental assessment of the potential deployment of SOFC-based CHP systems for both commercial and residential applications across Canada and Alberta.

2. SYSTEM DESCRIPTION

The proposed CHP systems for commercial and residential sectors are described in this section. The designs encompass two primary capacities: a 100 kW unit for commercial applications and a 5 kW unit designed for residential use. Initial market projections indicate a significant uptake in larger municipal commercial units, with widespread adoption anticipated to commence by 2030. As the technology advances and becomes more cost-effective, it is expected to penetrate the residential market by 2035. The key characteristics of both the commercial and residential units are detailed in Tables 1 and 2.

As shown in Table 1, the proposed CHP system utilizing SOFC technology offers significant potential for commercial applications. The initial CHP system is designed with a base capacity of 100 kW, made for commercial use. This system provides the flexibility for expansion to several megawatts (MW) by connecting multiple base units in series or parallel configurations. A base commercial unit with a capacity of 100 kW needs an initial investment cost of $400,000. According to the statistics, a 100 kW unit of commercial CHP will cover the energy consumption of a commercial unit with an area of about 2440 m^2 [9]. In addition to the commercial applications, a smaller capacity CHP based on SOFC is designed to cover the electricity and heat demand of households. According to the statistics, a CHP capacity of 5 kW will be suitable for Canadian households, including Alberta. As presented in Table 2, it requires an initial investment cost of $18,000 per household in 2035, but offers long-term environmental benefits.

Table 1. Properties of the proposed commercial CHP based on the SOFC with a base capacity of 100 kW in 2030.

Factor	Value
CHP capacity (kW)	100
Capital cost of a commercial 100 kW CHP ($) [10,11]	400,000
Daily energy production (MWh)	2.4
Annual energy production (MWh)	876
Area energy coverage per unit (m^2) [9]	2440
Annual hydrogen consumption (ton)	22

Table 2. Properties of the proposed residential CHP based on the SOFC with a base capacity of 5 kW in 2035.

Factor	Value
CHP capacity (kW)	5
Capital cost of a residential 5 kW CHP ($) [10,11]	18,000
Daily energy production (kWh)	120
Annual energy production (kWh)	43800
Daily hydrogen consumption (kg)	3

3. METHODS AND ASSUMPTIONS

This paper investigates the techno-economic and environmental potential of SOFC-based CHP for commercial and residential systems in Canada and Alberta, with key sources and assumptions summarized below:

The SOFC-based CHP market size is designed to cover 20% of the total CHP market in these regions over the time. Future capital costs for SOFC [10,11] and hydrogen are estimated based on current data and sources [12–14], while projected SOFC lifetimes derive from degradation rate data [15,16]. Direct and indirect job creation is estimated by repair and maintenance costs and the hydrogen cost required for operation ($200,000/unit creates 1 job), respectively [9]. Each commercial unit in Canada and Alberta emits 1.3 and 1.6 tons CO_2/kW annually for heating and electricity, respectively [9]. For residential households, emissions amount to 1.52 tons CO_2 for heating and 0.8 tons CO_2 for electricity in Canada, while in Alberta, they reach 4 tons CO_2 for heating and 3.6 tons CO_2 for electricity [9].

4. RESULTS AND DISCUSSION

I. Commercial CHPs in Canada

A summary of important results for the installation of the proposed SOFC-based CHP in the commercial sector of Canada is shown in Figure 1-4.

As shown in Figure 1, the annual maintenance costs associated with SOFC-based CHP systems are projected to significantly decline over time, driven by the increased number of installed units across the commercial sector of Canada. This cost reduction trend highlights the growing efficiency and economies of scale anticipated as the technology matures.

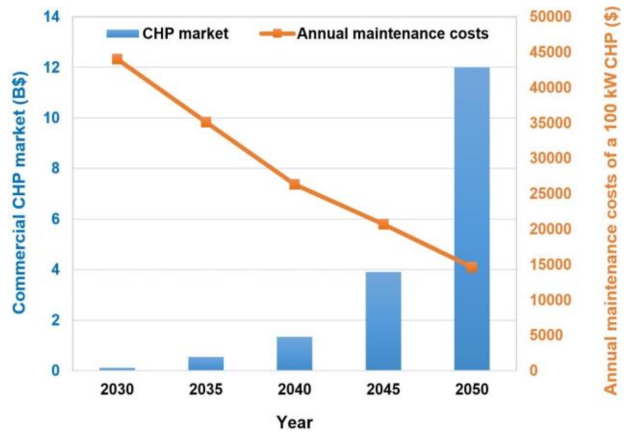

Figure 1. Commercial CHP market in Canada and annual maintenance costs per 100 kW unit.

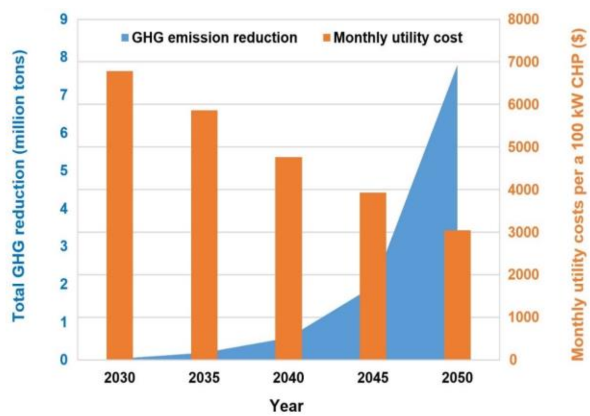

Figure 2. Total GHG emission reduction in the commercial sector of Canada and monthly utility cost per 100 kW unit.

According to the statistics, each commercial unit generates annual GHG emissions of 1.3 tons of CO_2 per kW in Canada [9]. It is estimated that the deployment of the proposed system could prevent approximately 8 million tons of greenhouse gas (GHG) emissions annually by targeting even a small portion of Canada's commercial sector, as shown in Figure 2. This substantial environmental impact underscores the system's potential to contribute meaningfully to Canada's decarbonization goals. In addition to environmental benefits, this expansion will generate considerable economic advantages, notably reducing monthly utility costs for a 100 kW system from $6,784 in 2030 to an estimated $3,050 by 2050. This reduction in operational expenses would not only enhance the financial viability of commercial enterprises but also promote broader adoption of sustainable energy solutions.

As shown in Figure 3, deployment of SOFC-based CHPs is also expected to stimulate job creation, both directly and indirectly, with projections indicating the creation of approximately 11,000 jobs by 2050, contributing to economic growth and workforce development.

Further details, including estimates of the total installation area required for commercial CHP systems and the projected capital expenditure (CAPEX) per 100 kW system from 2030 to 2050, are presented in Figure 4. As it can be seen, the SOFC-based CHPs would be able to cover the required energy for approximately 150 km^2 of the commercial Canadian sector. These estimates provide valuable insight into the scalability and cost trajectory of the proposed system over the next two decades, emphasizing its potential as a long-term sustainable energy solution for the commercial sector of Canada.

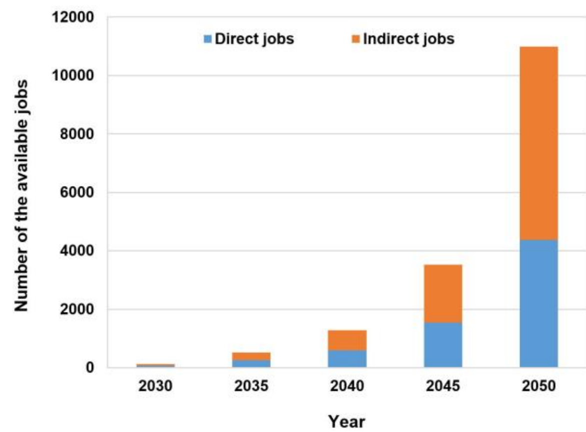

Figure 3. Number of the available direct and indirect jobs by the expansion of the SOFC-based CHP in commercial sector of Canada.

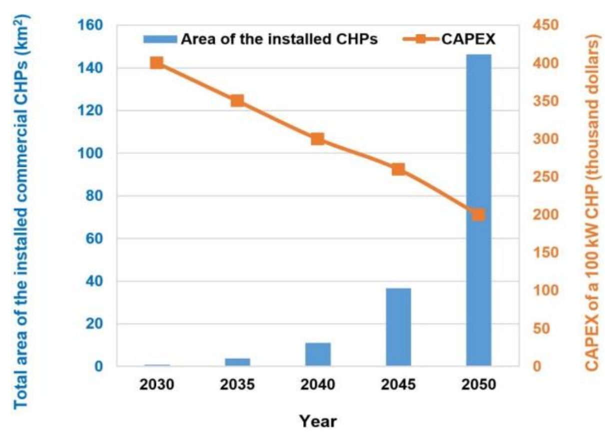

Figure 4. Total area covered by commercial CHPs in Canada and CAPEX per 100 kW unit.

II. Residential CHPs in Canada

This section provides a comprehensive overview of the results derived from the techno-economic analysis conducted for the deployment of SOFC-based CHP systems in the Canadian residential sector.

As previously mentioned, it is assumed that each CHP system, with an average capacity of 5 kW, will be sufficient to meet the entire heat and electricity demands of a typical residential unit. Furthermore, it is assumed that the growth of CHP installations in the residential sector will commence with a five-year delay following the expansion in the commercial sector. As shown in Figure 5, the market for the proposed system is projected to exceed $2.8 billion by 2050, reflecting its significant market potential and the anticipated increase in adoption across residential properties in Canada.

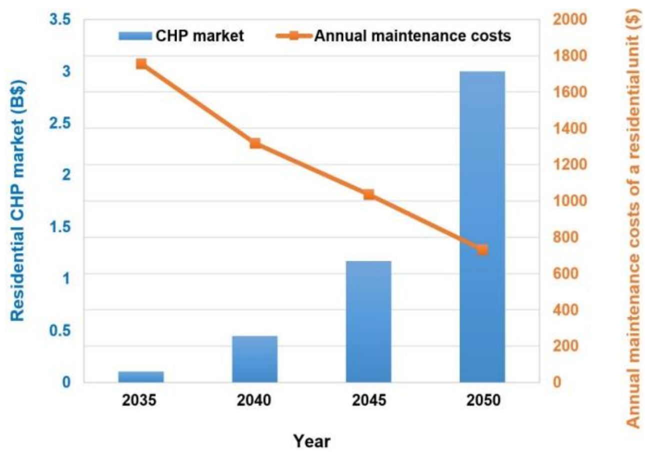

Figure 5. Residential CHP market in Canada and annual maintenance costs per 5 kW residential unit.

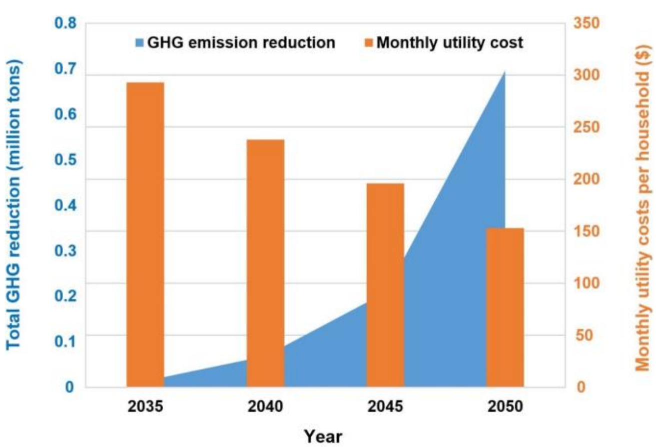

Figure 6. Total GHG emission reduction in residential sector of Canada and monthly utility cost per 5 kW unit.

One of the most compelling benefits of this system is its substantial potential to reduce GHG emissions. Currently, statistical data shows that each residential unit in Canada contributes approximately 1.52 metric tons of CO_2 annually from heating, with an additional 0.8 metric tons of CO2 produced from electricity consumption [9]. The adoption of SOFC-based CHPs can dramatically curtail these emissions.

As shown in Figure 6, installing the proposed system, with an average monthly utility cost of $150 per 5 kW system, across a portion of the Canadian residential sector (covering approximately 300,000 units), it is estimated that about 0.7 million tons of GHG emissions could be avoided annually by 2050. This represents a significant step toward achieving Canada's environmental targets, particularly in reducing the carbon footprint of residential energy use.

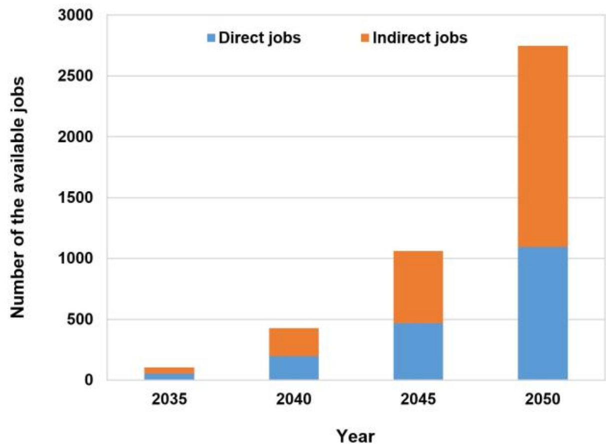

Figure 7. Number of available direct and indirect jobs by the expansion of the CHPs in the residential sector of Canada over time.

In addition to environmental benefits, the widespread implementation of SOFC-based CHPs will create significant economic opportunities. As shown in Figure 7, the installation of these systems is expected to generate over 2,700 direct and indirect jobs nationwide by 2050, spanning various sectors including manufacturing, installation, maintenance, and supply chain services. These job creation figures underscore the broader socio-economic advantages of transitioning to cleaner and more efficient energy solutions for residential homes.

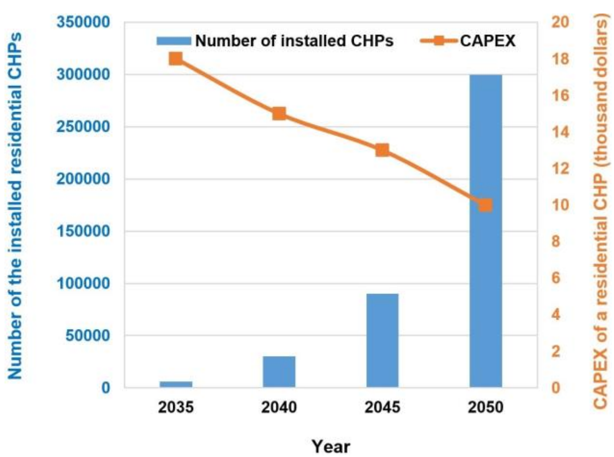

Figure 8. Number of the installed residential CHPs in Canada and CAPEX per 5 kW unit.

From a financial perspective, the CAPEX per 5 kW system is also expected to decrease considerably over time. Current projections indicate that CAPEX will decline from approximately \$18,000 per unit in 2035 to about \$10,000 by 2050, as shown in Figure 8. This reduction reflects both technological advancements and economies of scale, making the proposed system more financially accessible for widespread residential adoption in the coming decades. These cost reductions, coupled with the system's efficiency and environmental benefits, position the SOFC-based CHP technology as a transformative solution for sustainable energy in Canada's residential sector.

III. Commercial CHPs in Alberta

With Alberta's high carbon intensity and fossil fuel-dependent electricity grid, implementing SOFC-based CHP systems presents a valuable opportunity to support the province's decarbonization efforts. These high-efficiency systems generate electricity while utilizing waste heat, enabling substantial GHG emissions reductions at the point of use. This aligns well with Alberta's goals for transitioning to cleaner energy, maintaining grid reliability, and fostering economic growth. Additionally, SOFC-based CHP provides enhanced energy security and resilience for both residential and commercial sectors, offering a decentralized solution that reduces dependency on the main grid. Alberta's natural gas abundance further supports the adoption of SOFC-based CHP as a practical step toward lower-carbon energy.

Figure 9 and Figure 10 summarize the potential GHG reduction impacts for Alberta's commercial sector, with projections indicating that over 25% of the total Canadian emissions reductions from SOFC-based CHP deployment could occur in Alberta. This underlines Alberta's critical role in national decarbonization and highlights the substantial environmental benefits CHP systems offer in reducing Canada's carbon footprint.

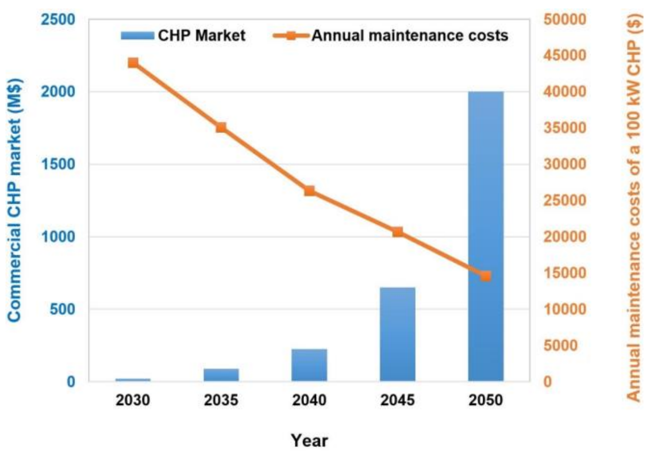

Figure 9. Commercial CHP market in Alberta and annual maintenance costs per 100 kW unit.

The economic and environmental benefits of deploying SOFC-based CHP systems in Alberta are equally impressive. By 2050, the commercial sector in Alberta is projected to encompass a market valued at approximately \$2 billion, covering a commercial area of over 24 km². Within this context, the installation of CHP systems could lead to a reduction of over 1.6 million tons of GHG emissions annually, directly contributing to Alberta's climate action targets. Furthermore, this initiative is expected to generate over 1,800 jobs, both direct and indirect, providing a substantial economic boost to the province. These jobs would span multiple sectors, including manufacturing, installation, maintenance, and associated supply chains, reinforcing the economic viability of this initiative.

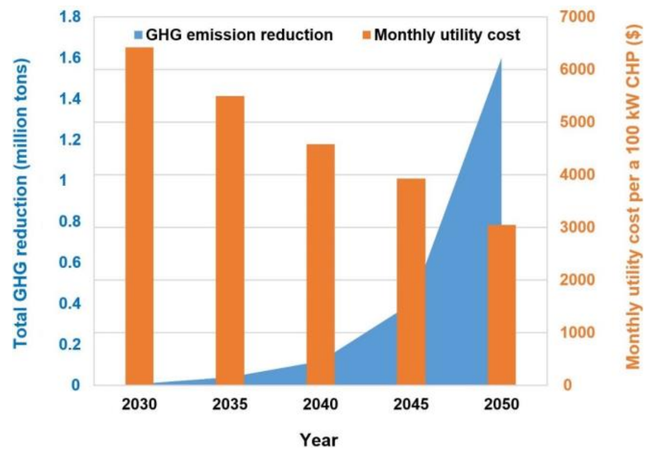

Figure 10. Total GHG emission reduction in the commercial sector of Alberta and monthly utility cost per 100 kW unit.

IV. Residential CHPs in Alberta

This section presents the results of implementing the proposed SOFC-based CHP system in Alberta. As previously highlighted, Alberta has the highest grid carbon intensity in Canada, leading to substantial GHG emissions, particularly from residential heating and electricity consumption. The statistical data indicates that the average residential unit in Alberta produces approximately 4 metric tons of CO_2 annually from heating, predominantly through the use of natural gas, and an additional 3.6 metric tons of CO_2 per year from electricity consumption [9]. These data underscore the significant environmental challenge posed by the province's reliance on carbon-intensive energy sources.

As depicted in Figure 11, the market for the proposed SOFC-based CHP system is projected to surpass \$500 million by 2050, underscoring its substantial market potential and the anticipated growth in adoption across residential properties in Alberta. One of the most compelling advantages of this system lies in its ability to significantly reduce GHG emissions. The implementation of SOFC-based CHP systems in Alberta, a province responsible for a considerable portion of Canada's national GHG emissions, presents a powerful solution to address these environmental challenges. As illustrated in Figure 12, deploying the proposed system—at an average monthly utility cost of \$150 for a 5 kW unit—across approximately 50,000 residential properties in Alberta could prevent around 0.38 million tons of GHG emissions annually by 2050. This represents a critical contribution toward achieving Alberta's environmental goals and reducing the carbon footprint of residential energy consumption.

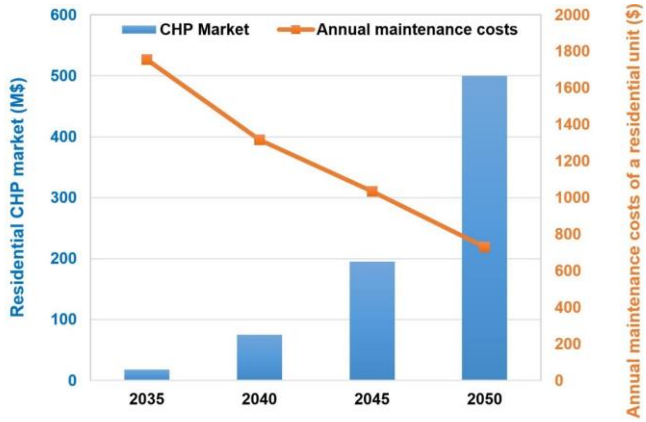

Figure 11. Residential CHP market in Alberta and annual maintenance costs per 5 kW residential unit.

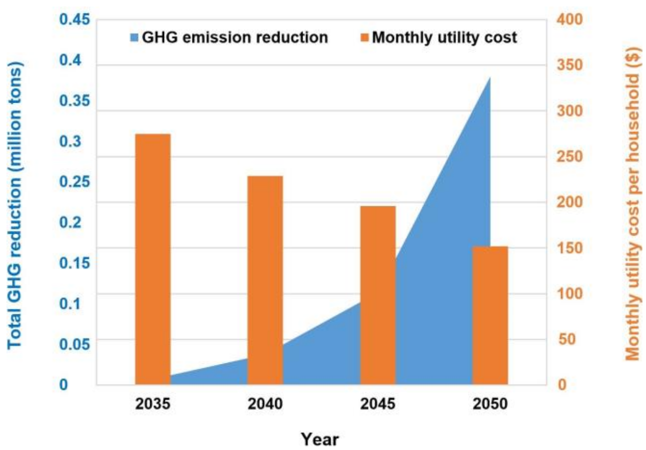

Figure 12. Total GHG emission reduction in residential sector of Alberta and monthly utility cost per 5 kW unit.

5. CONCLUSIONS

A comprehensive techno-economic and environmental analyses was conducted in this paper to assess the potential of solid oxide fuel cell (SOFC)-based combined heat and power (CHP) systems for Alberta's and Canada's commercial and residential sectors. That SOFC-based CHP systems exhibit significantly greater techno-economic feasibility for larger-scale applications, making them especially viable for commercial sectors. Consequently, market potential and associated job creation are projected to be substantially higher in the commercial sector than in the residential sector. Implementation timelines were thus set to commence in 2030 for commercial units and in 2035 for residential units. By 2050, projections estimate that SOFC-based CHP systems could have a market of around \$2.5 billion in Alberta and \$15 billion across Canada, with approximately 80% of this revenue stemming from commercial applications and the remaining 20% from residential use. Furthermore, this market expansion is anticipated to create roughly 2,300 jobs in Alberta and 13,800 jobs nationwide. Environmentally, this deployment could avoid approximately 1.6 million tons and 7.8 million tons of greenhouse gas (GHG) emissions in Alberta's and Canada's commercial sectors, respectively, while reducing emissions in the residential sectors by an estimated 700,000 tons in Canada and 380,000 tons in Alberta.

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