MUNK SCHOOL OF GLOBAL AFFAIRS & PUBLIC POLICY | UNIVERSITY OF TORONTO

TORONTO

Applications of Hydrogen in Support of TransformTO

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1 CONTEXT

1.1 PROJECT CONTEXT

Hydrogen has become a potential new weapon in the fight against climate change – a fuel touted by many governments, Canada included, as a major solution in their respective emissions reductions' goals. Ontario is also eager to release a provincial hydrogen strategy and has been engaging in discussions with stakeholders to determine the shape that such a strategy would take.

In response, the City of Toronto is examining if, and how, hydrogen could play a role in TransformTO, the municipal climate action strategy. The overarching target of TransformTO is to achieve net-zero greenhouse gas (GHG) emissions by 2050 or sooner. To help reach this target, the strategy has set a milestone target of 65% emissions reduction by 2030 in addition to the following goals:

- New buildings will produce near-zero GHG emissions by 2030.
- Existing buildings will be retrofitted to produce net-zero emissions by 2050.
- 100% of energy will be renewable or low carbon by 2050.
- 100% of vehicles will be low carbon and 75% of trips less than 5km will be walked/cycled by 2050.
- A zero-waste circular economy will be achieved by 2050.

As a graduate consulting team, we are exploring the feasibility of hydrogen's role in helping Toronto achieve these targets and goals.

1.2 HYDROGEN FUEL CONTEXT

Hydrogen is a colourless, odourless, zero-carbon fuel that produces only water as a by-product when burned in a fuel cell.[1] As it is not a naturally occurring fuel, like oil and natural gas, it must first be produced using energy generated by another process, such as the burning of the aforementioned fuels.[2] For this reason, it is primarily considered an energy carrier that can be used to store and move energy generated by different sources at different times.[3]

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[1] "Hydrogen Fuel Basics." *Office of Energy Efficiency & Renewable Energy*. Accessed March 2021. https://www.energy.gov/eere/fuelcells/hydrogen-fuel-basics

[2] "Hydrogen explained." *U.S. Energy Information Administration*. Accessed March 2021. https://www.eia.gov/energyexplained/hydrogen/
#:~:text=Hydrogen%20occurs%20naturally%20on%20earth,gas%2C%20coal%2C%20and%20petroleum.&text=Hydrogen%20is%20th
e%20lightest%20element.

[3] "Hydrogen Basics." Florida Solar Energy Center (FSEC) at the University of Central Florida. http://www.fsec.ucf.edu/en/consumer/hydrogen/basics/index.htm

Hydrogen fuel can be produced using a variety of methods, including natural gas reforming and electrolysis.[4] While hydrogen itself is a totally clean fuel, the production method used to generate it has a large impact on the full-cycle emissions generated in the hydrogen process. Standardized scientific definitions for the emissions generated by each production method do not exist, but industry nomenclature uses a colour coding system to classify the impact of each method. This system ranges from green hydrogen, which is produced in a fully renewable way, to brown hydrogen, which is produced using fossil fuels like coal.[5]

For the purposes of this report, the most relevant "colours of hydrogen" are green, blue, and grey. Green hydrogen is produced by using electricity generated from exclusively renewable sources to separate water from hydrogen in a process known as electrolysis.[6] Green hydrogen is considered to be entirely carbon-free across its lifecycle. Blue Hydrogen is produced by steam reforming natural gas, which means separating it into hydrogen and carbon dioxide, and although this process generates GHG emissions, carbon capture technologies are used to prevent the majority of these emissions from reaching the atmosphere, though the sequestering process is imperfect.[7] Finally, grey, sometimes called black, hydrogen is produced by steam reforming fossil fuels like natural gas and oil without capturing the GHG emissions.[8]

To achieve TransformTO, the City of Toronto is only considering the use of green hydrogen in its energy systems. As such, all recommendations in this report are dependent upon Toronto having access to a sufficient supply of green hydrogen. This issue is explored further in the *Constraints Toronto Faces* section of this report.

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[4] "Hydrogen Fuel Basics." *Office of Energy Efficiency & Renewable Energy.* Accessed March 2021. https://www.energy.gov/eere/fuelcells/hydrogen-fuel-basics

[5] "IRENA sees renewable hydrogen at least cost-possible within decade." Green Car Congress. December 18, 2020. https://www.greencarcongress.com/2020/12/20201218-irena.html

[6] "The colours of hydrogen." *EWE Group.* Accessed March 2021. https://www.ewe.com/en/ewe-group/shaping-the-future/hydrogen/the-colours-of-hydrogen

[7] Ibid.

[8] Ibid.

2 HYDROGEN APPLICATIONS AND THEIR BENEFITS

This section of the report contains an analysis of the hydrogen applications being employed in municipalities around the world, as well as the benefits derived from their usage. Our research team began by identifying, exploring, and classifying a wide range of municipalities comparable to Toronto as low, medium, or high hydrogen users - the results of which can be found in Appendix A. We then selected the four most promising hydrogen applications for further analysis, which can be found below.

2.1 TRANSIT

Hydrogen fuel cell technology has been developed to allow for vehicles to be powered by hydrogen, an emissions-free alternative to transportation fuels such as gasoline or diesel.[9] There are significant drawbacks to the use of hydrogen in the transportation sector as it requires the replacement of current gasoline or diesel vehicles and therefore involves a significant investment into new equipment to realize any meaningful reductions. Despite these challenges, it has successfully revolutionized the public transport sector of certain cities. To inform the city of Toronto's potential use of Hydrogen fuelled public transport vehicles we can look at some of the investments which have been successful in transforming different cities' public transit sector.

In Scotland, the city of Aberdeen has developed H2 Aberdeen: an initiative working to bring about a hydrogen economy in the Aberdeen city region.[10] The city has developed a cluster of hydrogen activity with two publicly accessible hydrogen refuelling stations (Kittybrewster and ACHES) and one of the largest and most varied fleets of hydrogen vehicles in Europe including buses, cars, vans, road sweepers and waste trucks. The city will be the first deployment location for the world's first fleet of fuel cell double decker buses from Wright Bus, due to be delivered in Autumn 2020.[11]

In Norway, the Oslo-Akershus city council aims to be among the leading regions in the world for early use of fossil-free hydrogen for transport solutions. The region has been working on the consolidation of national and international hydrogen infrastructure, as an important step in the phasing out of fossil fuels. The highest emphasis has been placed on establishing hydrogen refuelling stations to facilitate the creation and efficiency of a future fuel-celled fleet.[12] The plan also considers the

[9] "Fuel Cell Electric Vehicles." *US Department of Energy*. Accessed March 2021. https://afdc.energy.gov/vehicles/fuel_cell.html

[10] "Aberdeen City Region Hydrogen Strategy & Action Plan." *City of Aberdeen*. March 2015. http://archive.northsearegion.eu/files/repository/20150918111637_AberdeenHydrogenStrategy_March2015.pdf

[11] "H2 Aberdeen." Aberdeen City Council. Accessed March 2021. https://www.aberdeencity.gov.uk/services/environment/h2-aberdeen

[12] "Climate and Energy Strategy for Oslo." *Oslo Kommune*. June 22, 2016. https://www.klimaoslo.no/wp-content/uploads/sites/88/2018/06/Climate-and-Energy-Strategy-2016-English.pdf

importance of stimulating the demand in order to improve the economy of the station network operation.[13]

In the Canadian context, BC Transit considered the implementation of 20 Hydrogen buses for the city of Vancouver before abandoning the project. The 20 vehicles were part of a high profile, $90-million plan to showcase hydrogen power during the 2010 Winter Olympics in Whistler.[14] These buses did not prove to be cost efficient as, according to Burnaby's Ballard Power Systems, which manufactures fuel cell engines, Whistler's hydrogen buses cost $1.34 per kilometre to maintain, versus 65 cents per kilometre for diesel-powered buses.[15] Considering that Vancouver did not have a hydrogen fuel supplier of its own, fuel had to be trucked in using diesel powered trucks from Quebec which ultimately stifled the feasibility and efficiency of the project.

There are thus extensive constraints to consider before contemplating such a project for Toronto. While Hydrogen fuel cell vehicles have proven to be very successful in cities like Aberdeen or Oslo, the timing of adoption and proximity to hydrogen production has been key in these advancements. The city of Toronto, being closer to Vancouver in terms of access to hydrogen and investment, might not find public transport to be a sector in which investment in hydrogen technologies would be beneficial at all.

2.2 GAS BLENDING

Gas blending is a process where small amounts of hydrogen are injected into natural gas lines to reduce the overall amount of natural gas being used in a system. The hydrogen is generated at production plants using processes like electrolysis, sent to a blending station connected to existing natural gas infrastructure, and then pumped into the pipes carrying natural gas to create a hydrogen-natural gas blend. This blend can then be used for the same end-use applications as natural gas, such as heating, cooking, and transportation.[16]

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[13] Ibid.

[14] "BC Transit's $90M hydrogen bus fleet to be sold off, converted to diesel." *CBC News*. December 04, 2014. https://www.cbc.ca/news/canada/british-columbia/bc-transit-s-90m-hydrogen-bus-fleet-to-be-sold-off-converted-to-diesel-1.2861060

[15] "Vancouver Ends Hydrogen Bus Program Amid High Costs." *Energ.io*. March 10, 2015. https://enrg.io/vancouver-ends-hydrogen-bus-program-amid-high-costs/

[16] "Renewable hydrogen." *Enbridge*. Accessed March 2021. https://www.enbridgegas.com/Natural-Gas-and-the-Environment/Enbridge-A-Green-Future/Renewable-hydrogen#:~:text=Hydrogen%20blending%20is%20when%20small,customers%2C%20resulting%20in%20fewer%20emissions.

Blending hydrogen into natural gas pipelines offers a multitude of benefits, ranging from energy storage to grid resilience to emissions reductions.[17] As a clean burning fuel that emits only water, hydrogen's potential to reduce the carbon intensity of existing natural gas infrastructure is the benefit most relevant to TransformTO.[18] By reducing reliance on natural gas, a fossil fuel, gas blending can reduce overall emissions and drastically improve air quality.[19] The use of hydrogen production and blending facilities also offers the opportunity to store excess energy as hydrogen, which can then be injected into the natural gas pipelines on an as-needed basis - creating an opportunity for effective grid balancing and resilience.[20]

Gas blending combining hydrogen and natural gas has already been employed in numerous jurisdictions around the world, albeit while incorporating very different proportions of hydrogen. A review by S&P Global found that projects in Germany achieved a 30% hydrogen blend, projects across France and the UK a 20% blend, and on the lower end of the spectrum countries like the USA, Switzerland, and Japan have blending limits between 2 and 5%.[21]

Highly relevant for The City of Toronto are reports by the City of Edmonton and Alberta's Transition Accelerator. Neither have initiated full-scale blending programs, but both organizations are confident in the technology's potential. The City of Edmonton believes a blend of up to 25% may be possible in the region, while the Transition Accelerator has identified a 15% hydrogen blend as being ideal for residential and commercial use.[22][23] A similarly relevant pilot project has been launched in Fort Saskatchewan, Alberta, by ATCO. This project, launching in 2021, is blending hydrogen into a subsection of Fort Saskatchewan's grid at a 5% level in an effort to reduce carbon emissions.[24]

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[17] "HyBlend Project To Accelerate Potential for Blending Hydrogen in Natural Gas Pipelines." *National Renewable Energy Laboratory.* November 18, 2020. https://www.nrel.gov/news/program/2020/hyblend-project-to-accelerate-potential-for-blending-hydrogen-in-natural-gas-pipelines.html#:~:text=Blending%20hydrogen%20into%20the%20existing,%2C%20resiliency%2C%20and%20emissions%20reductions.

[18] "Renewable hydrogen." *Enbridge.* Accessed March 2021. https://www.enbridgegas.com/Natural-Gas-and-the-Environment/Enbridge-A-Green-Future/Renewable-hydrogen#:~:text=Hydrogen%20blending%20is%20when%20small,customers%2C%20resulting%20in%20fewer%20emissions.

[19] Ibid.

[20] Melaina M. W., O. Antonia, and M. Penev. "Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues." *National Renewable Energy Laboratory.* March 2013.

[21] "Injecting hydrogen in natural gas grids could provide steady demand the sector needs to develop." *S&P Global.* 19 May 2020. https://www.spglobal.com/platts/en/market-insights/blogs/natural-gas/051920-injecting-hydrogen-in-natural-gas-grids-could-provide-steady-demand-the-sector-needs-to-develop

[22] "Role of Alternative Fuels." *City of Edmonton.* Accessed March 2021. https://www.edmonton.ca/city_government/documents/PDF/AlternativeFuels-PolicyBrief.pdf

[23] Layzell, David B., Jessica Lof, Cameron Young, Jonathan Leary. "Building a Transition Pathway to a Vibrant Hydrogen Economy in the Alberta Industrial Heartland." *Transition Accelerator Reports* 2, Issue 5. November 2020.

[24] "Fort Saskatchewan Hydrogen Blending Project." *ATCOenergy.* Accessed March 2021. https://www.atco.com/en-ca/projects/fort-saskatchewan-hydrogen-blending-project.html

The use of hydrogen to reduce the carbon footprint of natural gas infrastructure is not, however, without its constraints and critics. Alluded to above, there are hard constraints on how much hydrogen can be injected into natural gas systems due to safety concerns. Too high of a hydrogen concentration in the blend can lead to pipe cracking, end-use equipment damage and malfunctioning, and an increased probability of unintended ignition and combustion.[25] Though there is variance in the academic research on this topic, acceptable ranges for gas blending tend to fall within 5-20% hydrogen - which fundamentally limits its ability to reduce overall carbon emissions from natural gas systems. Another constraint is the available supply of fully-renewable, green hydrogen, which currently accounts for less than 1% of global hydrogen production.[26][27] Again, this greatly reduces the impact gas blending can have on reducing the carbon footprint of natural gas systems, and will be explored further in the Constraints Toronto Faces section of this report.

2.3 ENERGY GRID STORAGE

Renewable energy is generated intermittently and ensuring its continuous availability to meet demand is one of the major challenges to an entirely renewable energy grid. Green hydrogen storage technology is often considered as a potential grid storage solution. This method uses surplus renewable electricity produced during periods of low energy demand to create hydrogen via water electrolysis.[28] This hydrogen is then stored until it is converted back to electricity for use during high energy demand periods or as needed. One of the greatest advantages of using hydrogen for grid storage is its capacity for long-term storage. Unlike other technologies, such as lithium-ion batteries, hydrogen does not suffer from storage degradation and is a viable option for overnight to seasonal storage.[29]

Producing hydrogen for energy grid storage is also better suited to large-scale energy storage when compared to battery technologies that require increasingly large facilities for greater storage capacity.[30] Because hydrogen can be stored at much higher

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[25] Melaina M. W., O. Antonia, and M. Penev. "Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues." *National Renewable Energy Laboratory.* March 2013.
[26] Ibid.
[27] Petrova, Magdalena. "Green hydrogen is gaining traction, but still has massive hurdles to overcome." *CNBC* Online. December 4, 2020.
[28] Sean O'Neil. "Unlocking the Potential of Hydrogen Energy Storage." Fuel Cell & Hydrogen Energy Association. July 22, 2019. https://www.fchea.org/in-transition/2019/7/22/unlocking-the-potential-of-hydrogen-energy-storage.
[29] Matthew A. Pellow, Christopher J.M. Emmett, Charles J. Barnhart, and Sally M. Benson. "Hydrogen or batteries for grid storage? A net energy analysis." Energy and Environmental Science, 2015, 8, 1938. 10.1039/c4ee04041d.
[30] Ibid.

energy densities, its footprint is significantly smaller. Green hydrogen also has environmental benefits over lithium-ion batteries, which require the use of toxic chemicals in their production phase.[31]

Given these advantages, countries and cities around the world are exploring the potential of hydrogen as energy storage in their transition from a fossil fuel economy. Canada's national hydrogen strategy notes that non-mobile applications can be stored in compressed air tanks or underground salt caverns in the event that bulk storage is required.[32] These caverns have been tested and proven to be reliable storage facilities in projects across the United Kingdom, the United States, and Europe.[33] The Ontario government has also recognized the need for an effective mechanism to store renewable generated electricity and has noted the potential of hydrogen in its Hydrogen Strategy discussion paper.[34]

Storing excess energy as hydrogen has been explored in municipal strategies as well. However, hydrogen, like other energy storage technologies, is not yet mature or cost-effective enough to encourage a widespread adoption. Nevertheless, Ottawa examined hydrogen alongside other storage technologies in its Pathway Study on Demand Side Management and Energy Storage.[35] While Ottawa appears to be pursuing the development of other storage technologies with higher efficiency and maturity, Aberdeen sees hydrogen production as a key tool in energy grid storage and resilience and has outlined its importance in managing energy demand in the city's hydrogen strategy.[36] Thus, while the promise of hydrogen storage technology is widely recognized, there are limited cases of its application available for analysis.

2.4 NICHE INDUSTRY APPLICATIONS

In addition to the broader hydrogen applications outlined above, our research team also identified a number of smaller-scale, bespoke applications that could be relevant for the City. These applications are targeted and case specific, meaning they

[31] Ibid.
[32] Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen. Natural Resources Canada. December 2020. https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf.
[33] Ibid.
[34] Ontario Low-Carbon Hydrogen Strategy: Discussion Paper. Environmental Registry of Ontario. November 19, 2020. https://ero.ontario.ca/notice/019-2709.
[35] Pathway Study on Demand Side Management and Energy Storage in Ottawa. Sustainability Solutions Group. January 2019. https://documents.ottawa.ca/sites/documents/files/pathway_study_demand_manage_en.pdf.
[36] Aberdeen City Region Hydrogen Strategy & Action Plan 2015-2025. H2 Aberdeen. March 2015. http://archive.northsearegion.eu/files/repository/20150918111637_AberdeenHydrogenStrategy_March2015.pdf.

offer fewer emissions reductions and environmental benefits. In spite of that, they may still be useful for facilitating the broader adoption of hydrogen as a clean energy source.

One such application can be found in the San Francisco Bay Area. The City of San Francisco and the Government of California have been partnering with the Golden Gate Zero Emission Marine to pursue the development of a hydrogen powered ferry boat for cross-bay transit. If powered by green hydrogen, this would be an emissions-free water-transit solution for the Bay Area - replacing ferries which currently run on diesel and other fossil fuels. These efforts have culminated in the development and approval of the Water-Go-Round, a hydrogen fuel cell vessel scheduled for launch in 2021.[37] Once launched, it will become North America's first hydrogen powered ferry and a pilot example of a feasible, innovative, environmentally responsible water transit solution.

Another application can be found in a project closer to Toronto. The Canadian Tire Corporation has begun using forklifts powered by hydrogen fuel cells in two of its Ontario-based distribution centres.[38] In doing so, they have replaced the lead-acid batteries previously used to power the fork-lifts and achieved major emissions savings and environmental benefits.[39] Crucially, Canadian Tire is not just using fuel cells in their forklifts, but they are also producing their own green hydrogen to power these forklifts at their Brampton and Bolton distribution centres.[40] To do so, they have ordered and installed three electrolyzers on-site - a cost-effective and environmentally friendly method of producing green hydrogen.[41] However, it should be noted that this project has received some criticism and push-back from councillors and residents of Caledon, one of the municipalities close to the Bolton distribution centre.[42] Citing safety concerns and zoning issues, the project was delayed several times before ultimately moving ahead.[43] Since implementation, there have been no safety issues with the electrolyzers and hydrogen-powered forklifts.

While these niche use cases may currently lack opportunities for wide-spread scalability and implementation, they do offer promising evidence of Hydrogen's potential. If leveraged and adopted correctly, hydrogen can offer significant energy solutions in areas where electrification is not yet feasible.

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[37] "Water-Go-Round Project." *Golden Gate Zero Emission Marine.* Accessed March 2021. https://watergoround.com/
[38] "Canadian Tire to deploy Nuvera fuel cell powered forklifts." *Fuel Cells Bulletin* 2017, Issue 3,March 2017.
[39] Ibid.
[40] "Backgrounder: Canadian Tire Hydrogen Fuel Generation at Bolton Distribution Centre." *Town of Caledon.* July 25, 2016. https://www.caledon.ca/en/news/backgrounder-canadian-tire-hydrogen-fuel-generation-at-bolton-distribution-centre.aspx
[41] "Next Hydrogen Receives Order for Third Electrolyzer from Canadian Tire Corporation." FuellCellsWorks. June 18, 2019. https://fuelcellsworks.com/news/next-hydrogen-receives-order-for-third-electrolyzer-from-canadian-tire-corporation/
[42] Grewal San. "Caledon residents angry over re-emergence of Canadian Tire hydrogen project." Toronto.com. July 23, 2016. https://www.toronto.com/news-story/6780558-caledon-residents-angry-over-re-emergence-of-canadian-tire-hydrogen-project/
[43] Ibid.

3 HYDROGEN FEASIBILITY IN TORONTO

3.1 GENERAL RECOMMENDATION

Considering the results of our jurisdictional scan, academic and grey literature research, and conversations with subject matter experts, our team does not believe hydrogen presents a system-wide zero-emissions energy solution for the City of Toronto. Given Toronto's unique context and geography, there is simply not a strong enough case to be made for the large-scale integration of hydrogen technologies in the city.

During our stakeholder interviews, it became apparent to us that Ontario's energy grid was becoming increasingly dirty, as natural gas replaces more sustainable energy sources. This provincial move away from a clean and sustainable energy production system presents a larger concern for the city's climate goals than the identification of new zero-emissions technologies. The provincial move away from renewable energy creates an added challenge as hydrogen needs to be generated using the electricity fed into the grid. The environmental impact of hydrogen production is dependent on the environmental impact of electricity production. As such, in pursuit of it's TransformTO goals, Toronto's primary focus should be on the electrification of specific GHG emitting processes in the city and the greenification of the city's energy grid in general. At this point in time, investments into hydrogen should not be prioritized when seeking to fulfill the city's larger TransformTO goals.

In the following sections, we will outline the constraints limiting the large-scale viability of hydrogen in Toronto. Then we will outline various applications where Hydrogen could be used in smaller capacities. Though we do not recommend large, system scale investments in hydrogen, our research team has identified several smaller scale investments which may be of use in the city of Toronto.

3.2 CONSTRAINTS TORONTO FACES

3.2.1 Maturity of Hydrogen Technology

Hydrogen technologies are not mature enough to be implemented effectively in the City of Toronto. One of these maturity issues lies with the problems in the production of hydrogen as "It does not occur in nature, so it requires energy to separate".[44] Electrolysis is the technique which uses electricity to split water into hydrogen and oxygen. Today, electrolysis remains too expensive and inefficient to be

[44] Liebreich, Michael. "Liebreich: Separating Hype from Hydrogen – Part One: The Supply Side." *BloombergNEF*. https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-one-the-supply-side/#:~:text=Sadly%2C%20hydrogen%20displays%20an%20equally,it%20requires%20energy%20to%20separate.&text=It%20carries%20one%20quarter%20the,any%20given%20temperature%20and%20pressure.

used on a large scale.[45] When electrolysis-produced hydrogen is used for heating, there is only 62 per cent as much heat energy produced as the electrical energy that was involved in the production - clearly demonstrating an inefficiency in the process.[46] The immaturity of this technology contributes to the production of less clean hydrogen which the city of Toronto would not consider using.

Additionally, according to Liebreich's work for BloombergNEF, "[Green hydrogen] storage requires compression to 700 times atmospheric pressure, refrigeration to 253 degrees Celsius [...] It carries one quarter the energy per unit volume of natural gas [...] It can embrittle metal; it escapes through the tiniest leaks and yes, it really is explosive."[47] The technological challenges of using green hydrogen are thus not only related to its production, but also include storage and infrastructure issues that should not – and cannot – be overlooked considering their seriousness. The implications of the use of green hydrogen are dire and require significant development before we can efficiently produce, store, and use green hydrogen. The fuel is still very new, it is still being studied and its future remains unclear. To recommend extensive use of it by the City of Toronto would present more risks than rewards, considering the immaturity of the technologies involved.

3.2.2 Supply of Green Hydrogen

A critical constraint facing the implementation of hydrogen into Toronto's TransformTO strategy is the supply of green hydrogen. The hydrogen applications outlined above can only support Toronto's emissions reductions strategy if they are the product of a green production process. Grey, brown, and blue hydrogen are not net-zero production processes, and their use could set back climate goals. In 2018, green and blue hydrogen production represented only 1% of global hydrogen production, with grey and brown hydrogen making up the remaining 99%.[48] In 2020, green hydrogen alone was only 0.1% of worldwide hydrogen production.[49] This disparity is due to significant cost differences between grey/brown hydrogen and green hydrogen, but the costs of the latter are

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45 Ibid.

46 Robins, Jim. "Green Hydrogen: Could It Be Key to a Carbon-Free Economy?" *Yale Environment 360*. November 5, 2020. https://e360.yale.edu/features/green-hydrogen-could-it-be-key-to-a-carbon-free-economy

47 Liebreich, Michael. "Liebreich: Separating Hype from Hydrogen – Part One: The Supply Side." *BloombergNEF*. https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-one-the-supply-side/#:~:text=Sadly%2C%20hydrogen%20displays%20an%20equally,it%20requires%20energy%20to%20separate.&text=It%20carries%20one%20quarter%20the,any%20given%20temperature%20and%20pressure.

48 Maddy Ewing, Benjamin Israel, Tahra Just, Hoda Talebian, Lucie Stepanik. "Hydrogen on the path to net-zero emissions: Costs and climate benefits." Pembina Institute. July 2020. https://www.pembina.org/reports/hydrogen-climate-primer-2020.pdf.

49 Anmar Frangoul. "Canada is set to have one of the world's biggest green hydrogen plants." CNBC. January 19, 2021. https://www.cnbc.com/2021/01/19/canada-is-set-to-have-one-the-worlds-biggest-green-hydrogen-plants.html.

expected to fall by almost two thirds by 2040.[50] If a hydrogen strategy is pursued before a green production process is guaranteed, it could result in a rise in emissions and be harmful to Toronto's climate strategy.

Plans for green hydrogen production projects are underway across the world from the United States to the European Union. In Canada, Hydro-Quebec is preparing for the installation of an 88 megawatt water electrolysis plant, set to be one of the largest green hydrogen plants in the world.[51] However, in the absence of dedicated hydrogen pipelines, hydrogen is transported in steel tube trailers or cryogenic tanker trucks.[52] The cost of this method of transportation increases with distance travelled. [53]Given this, transporting hydrogen from Quebec to Toronto will add significant financial and environmental costs to its use. Depending on the need in Toronto, these distribution costs may outweigh the benefits. Enbridge Gas is also producing hydrogen from surplus renewable energy-generated electricity at its Markham power-to-gas facility to blend into the natural gas system.[54] While this facility currently does not produce enough hydrogen for other projects, an increase in demand could prompt an expansion.

3.2.3 Hydrogen Efficiency

Another large constraint holding back the adoption of hydrogen applications is the energy efficiency of hydrogen. Pure hydrogen does not occur naturally on Earth, and as such we cannot simply harvest it and burn it for energy in a manner similar to how we use fossil fuels like oil and natural gas.[55] Instead, we have to first produce energy, store it as hydrogen, and then convert that hydrogen back into energy at the time and location we need it - all of which leads to large efficiency losses.[56]

On average, most research suggests that the round-trip efficiency of hydrogen, which is the amount of energy left after storing energy as hydrogen and then converting

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[50] Ibid.
[51] Ibid.
[52] Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen. Natural Resources Canada.
[53] Ibid.
[54] "Renewable hydrogen." *Enbridge*. https://www.enbridgegas.com/Natural-Gas-and-the-Environment/Enbridge-A-Green-Future/Renewable-hydrogen.
[55] "Hydrogen explained." *U.S. Energy Information Administration*. Accessed March 2021. https://www.eia.gov/energyexplained/hydrogen/#:~:text=Hydrogen%20occurs%20naturally%20on%20earth,gas%2C%20coal%2C%20and%20petroleum.&text=Hydrogen%20is%20the%20lightest%20element.
[56] "Hydrogen cars won't overtake electric vehicles because they're hampered by the laws of science." *The Conversation* June 3, 2020. https://theconversation.com/hydrogen-cars-wont-overtake-electric-vehicles-because-theyre-hampered-by-the-laws-of-science-139899

that hydrogen back into energy for use, lies between 30 and 40%.[57][58] First, generated energy must be used to produce hydrogen, typically by passing it through water in a process known as electrolysis, which is around 75% efficient.[59] Then, the hydrogen must be compressed, chilled, and transported, a process that is roughly 90% efficient.[60] Finally, once the hydrogen reaches its end-use application, it must be burned to convert back into electricity with approximately 60% efficiency.[61] When combined with varying efficiency losses in end-use technologies, you arrive at a total efficiency falling between 30 and 40% depending on your application.[62]

When contrasted with more conventional energy technologies, like lithium ion batteries, which have round-trip efficiencies between 70 and 80%, the poor efficiency of hydrogen represents a major constraint to its adoption.[63][64] When considering any potential hydrogen applications, city staff will need to keep these large efficiency losses in mind, especially given the reality that hydrogen is only as green as the energy used to produce it.

3.2.4 Prior Investments into Alternative Technologies

Toronto's investments into other competing sources of renewable energy production, storage, and usage also pose a massive hurdle for the adoption of hydrogen technologies in the city. Specifically, prior investments into alternative technologies pose a significant barrier for Toronto's transit sectors and departments, such as Fleet Services.

The city's Fleet Services department has already developed a *Pathway to Sustainable City of Toronto Fleets* program, which aims for net-zero greenhouse gas emissions from all forms of city transit by 2050, in alignment with TransformTO.[65] As part of this program, Toronto has invested heavily in EV technology. These investments

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[57] Pellow, Matthew A., Christopher J. M. Emmott, Charles J. Barnhart and Sally M. Bensonaef "Hydrogen or batteries for grid storage? A net energy analysis." *Energy & Environmental Science*. 2015.

[58] "Fact Sheet | Energy Storage." *Environmental and Energy Study Institute*. February 22, 2019. https://www.eesi.org/papers/view/energy-storage-2019

[59] "Hydrogen cars won't overtake electric vehicles because they're hampered by the laws of science." *The Conversation* June 3, 2020. https://theconversation.com/hydrogen-cars-wont-overtake-electric-vehicles-because-theyre-hampered-by-the-laws-of-science-139899

[60] Ibid.

[61] Ibid.

[62] Ibid.

[63] Muelaner, Jody. "Where Are We With the Hydrogen Economy?" *Engineering.com*. March 26, 2020. https://www.engineering.com/story/where-are-we-with-the-hydrogen-economy?__hsfp=81092585&__hssc=212727627.1.1615852800104&__hstc=212727627.6fa385653ecd7c9674ba06f08984886d.1615852800101.1615852800102.1615852800103.1&utm_source=relart-etips

[64] "Hydrogen cars won't overtake electric vehicles because they're hampered by the laws of science." *The Conversation* June 3, 2020. https://theconversation.com/hydrogen-cars-wont-overtake-electric-vehicles-because-theyre-hampered-by-the-laws-of-science-139899

[65] "The Pathway to Sustainable City of Toronto Fleets." *City of Toronto*. 2019. https://www.toronto.ca/wp-content/uploads/2019/11/9188-SustainableCoTFeets.pdf

include a partnership with TorontoHydro to build 17 on-street EV charging stations within the city, the replacement of light duty city vehicles with EVs, the planned replacement of 220 passenger vehicles in the city's fleet with EVs over the next 5 years, and the procurement of 60 all-electric transit busses via the TTC Green Bus Program.[66]

Through conversations with city staff, our research team also learned that Fleet Services is intending to continue down this investment path in EVs. They have worked closely with TorontoHydro to ensure the city's grid will be capable of handling the increased capacity of a fully electric fleet and have even begun developing a potential smart grid load management system to support their EV ambitions.[67] Further, their analysis at this stage shows that EVs are simply a more cost effective and viable investment for fleet replacement, all costs considered, as compared to hydrogen powered vehicles.[68] Ultimately, while Toronto is not fully locked-in on EV technology for all its transit needs, the level of city investment and planning centred on EV technologies represents a significant impediment to the adoption of hydrogen technologies in this area.

3.2.5 Logistical and Infrastructure Costs

One logistical and cost challenge comes from having to construct and operate hydrogen fuel refilling stations. The United States has approximately 170,000 gasoline stations nationwide. As of this writing there are 45 hydrogen fueling stations in the US. 43 of these are in the state of California. For hydrogen to begin to compete with gas and electric vehicles a large investment would have to be made in building out fueling stations. For the US, the dollar estimate to replace those 170,000 gas stations was 500 billion dollars. This assumes that hydrogen stations cost between 1 million and 4 million to build each. When applying this to the Canadian context, and to the city of Toronto specifically, there's simply no feasible way to jumpstart the investment without assistance from provincial and federal governments. When taking into account the need to produce green hydrogen production facilities and logistics processes the idea becomes even more unfeasible. The city of Toronto has been looking to use existing fossil fuel infrastructure to facilitate the production of hydrogen, but to do so renewably would

[66] "City of Toronto and Toronto Hydro launch new on-street electric vehicle charging station pilot." *City of Toronto*. November 7, 2020. https://www.toronto.ca/news/city-of-toronto-and-toronto-hydro-launch-new-on-street-electric-vehicle-charging-station-pilot/
[67] City of Toronto staff: fleet services. Interview by hydrogen consulting team. Online, March 11, 2021.
[68] Ibid.

require the creation of new green hydrogen infrastructure, defeating the goal of reusing existing infrastructure at lower cost.

3.3 SPECIFIC HYDROGEN APPLICATION RECOMMENDATIONS FOR TORONTO

Given the technologies, constraints, and recommendation presented above, our research team still feels there are focused hydrogen applications the City of Toronto may want to consider implementing as they execute their TransformTO strategy. These case- and technology-specific examples are analyzed in the following section and a summary can be found in Appendix B.

3.3.1 Hydrogen Vehicles

As has been discussed in this paper, Hydrogen is not a feasible option for personal vehicles in the city of Toronto. However, it does seem to have a potentially interesting and efficient application for long haul transit. Considering that electric freight vehicles have not been extensively developed and invested in, there is a gap to be filled to make this sort of transit more sustainable. Hydrogen powered trucks are faster to fuel up than comparable electric vehicles and have significantly longer mileage.[69] However, such an investment would require the creation and development of a network of refuelling stations across the province, thus calling for investment from higher levels of government.[70]

While there are appealing elements to the application of hydrogen technologies to long haul transit, it would be a challenging transition to make. The City of Toronto would have to provide significant incentives to encourage this investment which might prove extremely difficult. According to an employee of the City of Toronto's fleet services, it would take a multi-pronged approach combining commitments at different levels which is both hard to coordinate and uncertain in terms of outcomes.[71]

Additionally, while hydrogen has sizable potential benefits in long haul transit, it is hard to compress hydrogen down to store a lot of energy which results in efficiency losses.[72] The challenges associated with producing, storing, and using hydrogen were

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[69] Danielle Bochove. "Hydrogen Key to Clean Long-Haul Transport in Canada." Bloomberg. January 29, 2021. https://www.bloomberg.com/news/articles/2021-01-29/hydrogen-could-be-key-to-clean-long-haul-transport-in-canada.

[70] Ibid.

[71] City of Toronto staff: fleet services. Interview by hydrogen consulting team. Online, March 11, 2021.

[72] City of Toronto staff: environment and energy division. Interview by hydrogen consulting team. Online, March 15, 2021.

outlined earlier in the paper and are a crucial consideration in this matter. Investing in a hydrogen-powered long haul transit system would rely on immature and unstable technologies which presents significant risks for the city and should thus be carefully evaluated.

3.3.2 Gas Blending

Enbridge has recently made a $5.2M investment into a hydrogen gas blending facility in Markham, Ontario, where a 2% hydrogen blend will be injected into the existing gas infrastructure servicing 3600 customers by fall 2021 - expected to abate up to 117 tons of CO2.[73] As part of this project, Enbridge conducted a feasibility assessment and concluded that 2% was the maximum amount of hydrogen that can be safely blended in Ontario's natural gas infrastructure, significantly less than in other jurisdictions.[74] This assessment, combined with the fact that Enbridge's current hydrogen projects use blue hydrogen, which is not fully-renewable, significantly reduces the positive environmental impact gas blending could have for Toronto.

As well, Toronto's Green Standard sets tight, zero-emissions goals for new buildings in Toronto.[75] Through conversations with city staff, our research team learned that Toronto has ambitions to ensure no new municipal buildings are connected to natural gas infrastructures, with a ban on fossil fuel furnaces even being a potential option.[76] Due to these standards and potential policies, significant investment in hydrogen blending is not an advisable action.

Though gas blending is often touted as a way to green existing natural gas infrastructure, which Toronto is currently reliant on, these issues and the constraints raised previously do not outline a strong use case in support of the goals outlined in TransformTO.[77] A low threshold for safe blending, high investment costs, and Toronto's shift away from natural gas make this technology largely inapplicable for the city. However, there may be specific industrial use cases, where infrastructure built for pure

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[73] "Groundbreaking $5.2M hydrogen blending project aims to green Ontario's natural gas grid." *Enbridge*. November 18, 2021. https://www.enbridge.com/stories/2020/november/enbridge-gas-and-hydrogenics-groundbreaking-hydrogen-blending-project-ontario

[74] "Low-Carbon Energy Project." *Enbridge*. July 20, 2019. https://www.enbridgegas.com/-/media/Extranet-Pages/Projects-tab-links/Low-Carbon-Energy-Project/Enbridge--Final-LCEP-Panels-July-4-2019--Dillon.ashx?la=en&hash=EAC569476DA6632EFCA0325B7B089E4E7C637244

[75] "Toronto Green Standard." *City of Toronto*. Accessed March 2021. https://www.toronto.ca/city-government/planning-development/official-plan-guidelines/toronto-green-standard/

[76] City of Toronto staff: environment and energy division. Interview by hydrogen consulting team. Online, March 15, 2021.

[77] "Groundbreaking $5.2M hydrogen blending project aims to green Ontario's natural gas grid." *Enbridge*. November 18, 2021. https://www.enbridge.com/stories/2020/november/enbridge-gas-and-hydrogenics-groundbreaking-hydrogen-blending-project-ontario

hydrogen gas blends could help to reduce emissions in Toronto - a topic explored further in the *Niche Use Cases* section of this report.

3.3.3 Energy Grid Storage and Capacity Balancing

Though the Ontario Government and the City of Aberdeen have outlined the potential for hydrogen to function as an energy storage and capacity balancing tool, discussed in the *Hydrogen Applications and Their Benefits* section of this report, the poor efficiency of hydrogen significantly dampens this potential. As discussed in the *Constraints Toronto Faces* section of this report, 30 to 40% round trip energy efficiency when using hydrogen represents a drastically higher energy loss when compared to conventional fuels or batteries. While this may make hydrogen impractical for grid-wide energy balancing and storage, our research team has identified a unique case in which hydrogen could be used to reduce the carbon intensity of Toronto's grid.

In conversations with city staff, our research team learned that back-up generators across Toronto are still powered by diesel fuel.[78] These generators are used in the event of energy shortages and grid shutdown events to ensure that critical buildings, such as hospitals, can still get the power they need. Though the use of these generators represents only a small fraction of Toronto's emissions, they will still need to be replaced for Toronto to achieve its TransformTO objectives. The city could utilize zero-emissions hydrogen back-up generators, which are already being made by companies such as Ballard Power and Plug Power, to transition away from the fossil-fuel generators currently installed.[79][80] Though these generators would need to be powered by green hydrogen and they do not represent a grid-wide energy balancing solution, they do provide the City of Toronto with an innovative opportunity to integrate hydrogen technologies to provide zero-emissions resilience to the energy grid.

3.3.4 Niche Use Cases

Our research team has also identified a few, niche areas where the City of Toronto may be able to implement small-scale hydrogen applications to reduce

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78 City of Toronto staff: environment and energy division. Interview by hydrogen consulting team. Online, March 15, 2021.

79 "Backup Power Systems." *Ballard*. Accessed March, 2021. https://www.ballard.com/fuel-cell-solutions/fuel-cell-power-products/backup-power-systems

80 "Scalable Backup Power for Critical Applications." *GenSure*. Accessed March, 2021. https://www.plugpower.com/fuel-cell-power/gensure/

emissions. Though these recommendations may lack broad applicability for system-wide use, they can still support Toronto in achieving its broader TransformTO targets.

One application we identified that was of significant interest to the City of Toronto was the use of hydrogen to power ferries in San Francisco. As Toronto has its own ferry fleet for transportation between Toronto and the Islands, hydrogen-fuel celled ferries may be a technology Toronto will want to look into adopting as it phases out the diesel powered vessels in the current fleet. Though the ferry fleet only makes up a tiny fraction of Toronto's GHG emissions, these emissions will still need to be eliminated by 2050. Producing the green hydrogen necessary to power this fleet could be a simple, closed-system opportunity for Toronto to align with the Province's hydrogen ambitions.[81] However, it should be noted that from our conversations with City staff, Toronto appears more likely to electrify its ferry fleet than to rely on hydrogen powered watercraft.[82]

Another potential hydrogen application identified by our research team is the role hydrogen could play as an energy source for high temperature industrial processes. Industrial heat is responsible for roughly two thirds of industrial energy demand and nearly a fifth of total global energy consumption.[83] Currently, these industries rely on fossil fuels, like natural gas, to generate the heat required for their production processes.[84] In our conversations with city staff, it was noted that it will be incredibly difficult for these industries, which include processes like paper and steel production, to generate the extreme temperatures they need using electricity alone.[85] The U.K.'s Climate Change Committee published a report in 2018 stressing the potential for hydrogen to replace natural gas in high-temperature industrial processes - with it being generally defined as a cheaper alternative than the pure electrification of these processes.[86] By encouraging hydrogen's use in this sector, Toronto can also incentivize the adoption of hydrogen fuel for broader business applications. This could lead to even more industry-led hydrogen implementations, similar to the Canadian Tire hydrogen powered forklifts discussed previously, helping to further reduce industrial emissions across Toronto.[87]

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[81] "Ontario Low-Carbon Hydrogen Strategy." *Ontario Provincial Government.* November, 2020. https://prod-environmental-registry.s3.amazonaws.com/2020-11/Ontario%20Low-Carbon%20Hydrogen%20Strategy%20-%20discussion%20paper%20%28November%202020%29.pdf

[82] City of Toronto staff: environment and energy division. Interview by hydrogen consulting team. Online, March 1, 2021.

[83] Bellevrat, Elie , Kira West. "Clean and efficient heat for industry." *International Energy Agency.* 23 January, 2018. https://www.iea.org/commentaries/clean-and-efficient-heat-for-industry

[84] Ibid.

[85] "Hydrogen in a low-carbon economy." *Committee on Climate Change.* November, 2018. https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/

[86] Ibid.

[87] "Canadian Tire to deploy Nuvera fuel cell powered forklifts." *Fuel Cells Bulletin* 2017, Issue 3, March 2017.

The major advantage of using hydrogen in these high-temperature and localized industrial applications is that it can be generated on-site through the use of an electrolyzer. This means it would not require large-scale infrastructure investments from the city. Essentially, these industrial use cases represent closed-system, small-scale opportunities for Toronto to leverage hydrogen without making large changes to their current TransformTO strategies.

3.3.5 The Role Toronto Can Play

To support the small-scale applications recommended above, we see two distinct roles for the City of Toronto to play. First, Toronto should lobby the provincial government for broader grid greenification. Second, the city should look for every opportunity to collaborate with the federal and provincial governments on investments into the small application areas identified above.

Since hydrogen can only be as green as the energy used to produce it, it is critical that the City of Toronto lobbies aggressively to have Ontario's grid supplied with 100% renewable energy. Currently, the proportion of energy generated by natural gas in the province is continuing to increase, a worrying trend in light of Toronto's ambitious climate goals.[88] By pushing hard for grid greenification, Toronto can support their broader TransformTO targets while also ensuring that industries willing to embrace hydrogen in the City are able to produce fully renewable, green hydrogen.

Additionally, Toronto itself cannot mandate that industries and businesses within its boundaries switch away from fossil fuels to hydrogen.[89] As such, Toronto should look to leverage potential co-investment opportunities with the federal and provincial governments, both of which are interested in embedding hydrogen in Canada's energy make-up, to provide incentives for these industries to make the switch to hydrogen. This could come in the form of negotiated subsidies for on-site electrolyzers, joint infrastructure investments, or policy and regulatory support. Alongside broader grid greenification, this support could create the necessary environment for the small-scale hydrogen applications above to become feasible opportunities in Toronto.

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[88] McGrath, John Michael. "Why Ontario's electricity is about to get dirtier." *TVO*. September 20, 2019. https://www.tvo.org/article/why-ontarios-electricity-is-about-to-get-dirtier

[89] City of Toronto staff: environment and energy division. Interview by hydrogen consulting team. Online, March 15, 2021.

4 CONCLUSION

In exploring whether hydrogen can help Toronto achieve its emissions reduction goals, our graduate consulting team conducted jurisdictional scans, grey and academic literature reviews, and interviews with experts and city staff. With this research and analysis, we conclude that hydrogen implementation faces too many challenges and constraints to be a viable investment for the City of Toronto. The hydrogen applications being pursued by other municipalities around the world are not appropriate options given Toronto's unique context. Within transportation, there is significant momentum and investment in electric vehicles, a more mature and efficient technology. In energy grid storage, the efficiency losses make investment in hydrogen less economical than other budding storage technologies. Hydrogen-natural gas blending does not amount to meaningful emissions reductions unless significant infrastructure investments are made, which will ensure Toronto is locking into hydrogen for the long-term. Across all of these applications, hydrogen's low efficiency is a major constraint. Additionally, without a guaranteed supply of green hydrogen, these applications will only contribute to greater GHG emissions, setting Toronto back in its climate goals. These challenges create too much uncertainty around hydrogen's potential and our consulting team feel such an investment would only distract the City of Toronto from more promising paths.

However, there are opportunities for small-scale, niche investments in hydrogen. Back-up generators, forklifts, long-haul transportation, and industrial processes are all areas where hydrogen can meaningfully contribute to reducing emissions through the creation of system-wide, closed loop solutions. While implementing hydrogen in these applications does not necessarily fall under municipal jurisdiction, Toronto could consider providing incentives to industry and businesses using the recommendations outlined above.

APPENDIX A

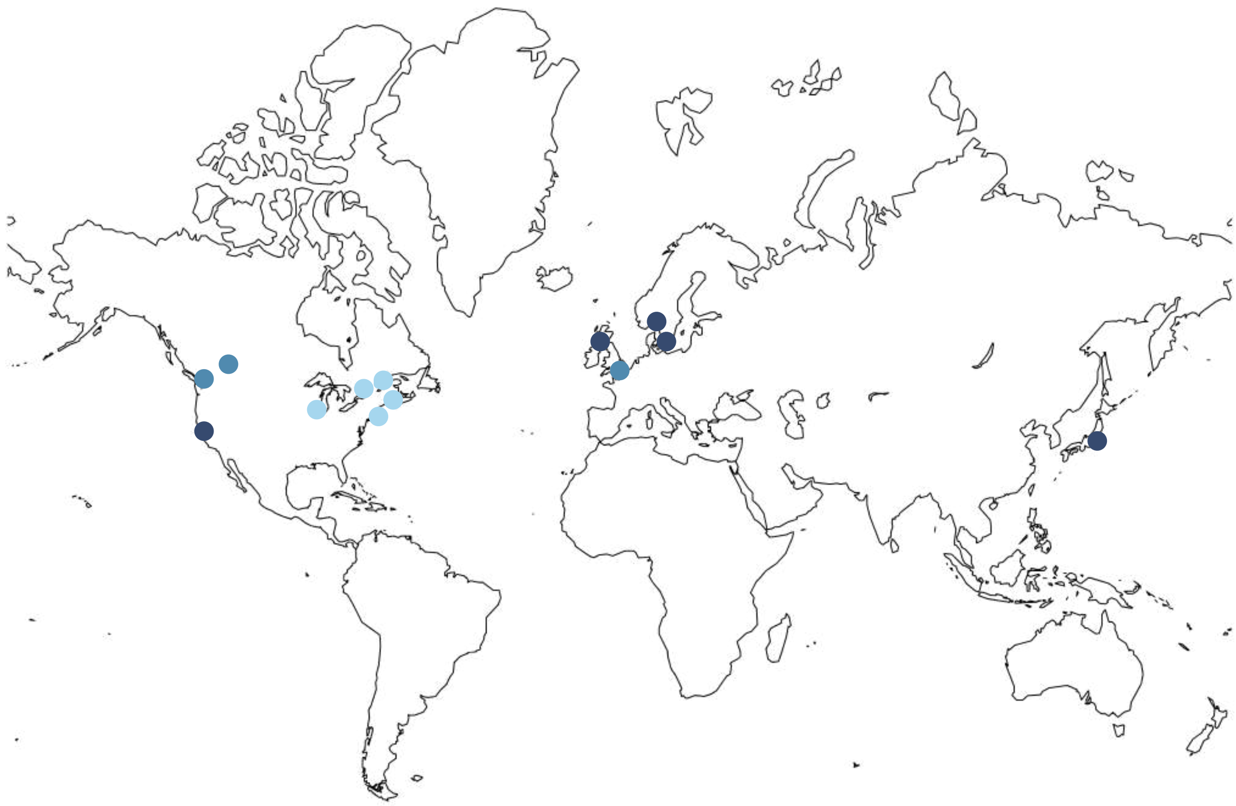

Figure 1: Degree of Hydrogen Usage

High	Medium	Low
Aberdeen	Vancouver	Chicago
Oslo	Edmonton	New York
Copenhagen	London	Boston
San Francisco		Montreal
Tokyo		Ottawa

APPENDIX B

Table 1: Specific Hydrogen Application Recommendations for Toronto

Focus Area	Recommendation
Hydrogen Vehicles	- Focus on the continued electrification of municipal and consumer fleets - Potential future opportunities for long-haul travel
Gas Blending	- Avoid the implementation of pilot hydrogen blending projects - Focus on transitioning away from natural gas entirely
Energy Grid Storage and Capacity Balancing	- Explore transitioning current diesel backup generators to hydrogen - Avoid relying on hydrogen as a general grid capacity solution - Focus on greening the broader electricity grid
Niche Use Cases	- Explore powering Toronto's ferries with hydrogen power - Support the generation and use of hydrogen in high-temperature industrial processes and on-site business applications
The Role Toronto Can Play	- Lobby the provincial government for broader grid greenification - Collaborate with the federal and provincial governments on investments into the industrial applications of hydrogen