Perspective│ Received 8 March 2023; Accepted 20 May 2024; Published 4 June 2024
https://doi.org/10.55092/rse20240005

A Canadian case study of carbon dioxide removals and negative emission hydrogen production

William J. Nuttall [1,*] and Ian MacGregor [2]

[1] School of Engineering and Innovation, The Open University, Milton Keynes, UK
[2] North-West Capital Partners, Calgary, Alberta, Canada

* Correspondence author; E-mail: wjnuttall@alum.mit.edu.

Abstract: This paper presents an expert perspective on a new Nature-Based Solution to contemporary problems in energy and climate policy. The paper presents an emergent industrial proposition which combines Canadian forestry technology with chemical engineering capabilities developed by the oil and gas industry. The proposition is to utilize wood fibre from otherwise surplus materials left behind by conventional forestry practices. This fibre is transported to a central facility and converted by partial oxidation to hydrogen and carbon dioxide. The process (and the resulting hydrogen) preserves the carbon capturing work of the trees because the carbon dioxide is sequestered in permanent geological storage. The project developers have coined the term Bright Green to differentiate this approach from carbon-neutral green hydrogen produced by an electrolyser. The approach discussed is carbon negative and has the potential to replace dirtier traditional hydrogen sources in industrial processes and eventually to provide a low carbon alternative to petroleum for transportation and mobility. A full range of environmental considerations is discussed in the paper. The paper does not present research, it merely provides a perspective on a new technological proposal of potential significance given its apparent potential to make a material difference on time scales consistent with the 2050 Net Zero policy horizon. In addition, the case study presented is believed to be commercially viable without need for additional public policy intervention beyond that already in place for clean fuels. Furthermore, no new technological development is required. The case study is of a project underway rather than being retrospective and historical in nature. The paper proposes a set of issues to be investigated, audited and researched as the technology moves forward.

Keywords: bio-energy; biomass; hydrogen; bio-hydrogen; carbon capture; carbon recovery; forestry; nature-based solutions; natural air capture; climate change; carbon removals

1. Introduction

The purpose of this paper is not to present primary research in energy technology and policy. Rather we offer a perspective providing context, briefing and ideas for those that might wish to conduct research into a technology which the authors believe could be of significant interest and importance in the years to come. The issues discussed represent an important possible Nature-Based Solution (NBS) to significant contemporary problems in energy use and climate protection.

While this paper will focus on developments in western Canada the implications have the potential to be global. We note the emergence of parallel, but independent, developments in California led by a company called Mote Hydrogen [1].

Canada is one of more than 110 countries worldwide that have pledged to achieve Net Zero emissions in the twenty-first century. On 29 June 2021 the Canadian Federal government enacted The Canadian Net Zero Emissions Accountability Act which underpins Canada's commitment to move to Net Zero greenhouse gas emissions by 2050 [2]. When considering Canada's journey to Net Zero - one must focus on the hard to decarbonize sectors such as cement and concrete manufacture; heavy road and rail transport and aviation. One must also consider Canada's role as a producer and exporter of fossil fuels. In addition, and separately, one must further note Canada's enormous size and its challenging geography which makes the electrification of transport particularly difficult. These challenges, and the importance of the 2050 goals, force Canada to look to negative emissions technologies as a matter of urgency. Negative emission technologies are essential if Net Zero is to be achieved, as some residual GHG emissions will always remain, however deep the policy push for emissions elimination. In addition, one potential solution to the looming difficulties for Canadian heavy transport and aviation will be the large-scale supply of hydrogen as a low-carbon fuel. Canada is fortunate in being home to Ballard, the world's leading technology developer of hydrogen fuel cell technology for vehicular applications [3]. A shift from petroleum to hydrogen, however, is a monumental task especially given the very limited time available before 2050.

Globally, approximately 95 Mt of hydrogen was produced in 2022 [4]. 98% of global hydrogen production is from fossil fuels with 76% produced from natural gas, mostly through Steam Methane Reforming (SMR) and 23% through gasification of coal. In 2022 industrial hydrogen production was responsible for 680 Mt of CO_2 emissions to the atmosphere (approaching 2% of global emissions) [4]. With the demand for hydrogen expected to grow and the global policy goal of Net Zero, the need for low emissions hydrogen is growing fast.

The consequence of these various realities is that Canada urgently needs a domestic source of hydrogen generation ideally coupled with a source of negative greenhouse gas emissions. In this paper we consider a case study that aims to address both these vital goals together. The case study is of a project underway rather than being retrospective and historical in nature. We suggest that for the journey to a Net Zero future to occur at the necessary pace, it is necessary to learn from activities while they are underway.

Globally hydrogen is of interest for two specific purposes:

First, on the one hand there is an agenda around decarbonization of heat and process emissions. This includes domestic heating (in place of pipeline natural gas), industrial process heat applications (in diverse contexts), and chemical process emissions (for example future ways of reducing of iron oxide to pig iron) [5].

Second, as regards to transport and mobility, much emphasis has been given in North America and Europe to the future potential of Fuel Cell Electric Vehicles (FCEV). This is often presented as an alternative to Battery Electric Vehicles (BEVs). Automakers such as Volkswagen and Stellantis have made massive investments based on a BEV future vision [6,7]. Such investments have overlaps with FCEV opportunity development as, it must be remembered, FCEV technologies are electric vehicles. Toyota is interesting in how it is seemingly taking a wider portfolio approach to future power trains including BEVs, FCEVs and indeed a strong continued relevance for internal combustion engines in a low carbon world [8]. It must be emphasized that while BEVs can represent a viable approach in high population density markets for personal mobility (private cars and scooters *etc*.), the case for BEV technology in heavy transportation remains less persuasive [5]. Much of the thinking around hydrogen in transportation has focused on FCEV especially for heavy transportation such as buses, trucks and rail [5].

The idea that internal combustion engines and gas turbines could continue to be a vital part of global transport and mobility including in aviation, shipping, rail and road use has, in the authors' opinion, received insufficient academic consideration in the context of hydrogen futures. We suggest that even within the domain of transportation and mobility low carbon intensity hydrogen has the potential to play a much larger economic role than simply its contribution to the roll-out, or otherwise, of FCEV technology.

It is noteworthy that in the years following the 'diesel-gate scandal' [9] local and national governments have moved to eliminate diesel cars from urban areas. In the UK the shift is particularly dramatic as only a few years ago the government was actively promoting a shift towards diesel car technology on environmental grounds [10]. For many the diesel power train appears to be dead, but it is too soon to write off internal combustion and indeed the diesel cycle in favour of EV technologies. For example, there is the prospect hydrogen related additions to the fueling of existing diesel engines. In the short term these may allow Medium Heavy-Duty Vehicle (MHDV) owners to run operate vehicles for a full 20+ year lifespan. Such a strategy would also provide a smoother energy transition. For example, biodiesels such as Hydrogenation Derived Renewable Diesel (HDRD) could be enabled by abundant low-carbon hydrogen. Such fuels might be co-combusted with low carbon hydrogen and in this manner could be a most cost-effective route to rapid and deep decarbonization. By way of example see the Hydrogen as a Service approach being pioneered for heavy truck haulage by Hydra Energy in western Canada. Such examples could be highly relevant to larger global regions such a North America, but they could be even more relevant in lower income countries where the set of economically accessible low carbon transport options is notably more limited. Separately, introducing carbon negative hydrogen at the front of the refining process will significantly reduce the carbon intensity of the resulting diesel. Currently the petroleum refining industry uses hydrogen manufactured from fossil fuels with the associated carbon dioxide vented to the atmosphere. To focus the supply of new carbon-negative hydrogen on the existing needs of oil refining avoids the problems and costs that would otherwise arise if trying to introduce the new hydrogen directly into the energy economy downstream of the refinery.

Canada's unique geography presents particular challenges for decarbonization, but it also presents opportunities. Canada with approximately 9% of the world's forests [11], is blessed with abundant forestry resources, especially in the Pacific Northwest. This paper considers a biomass-related case study.

2. Context

2.1. The authors' connections to the case study

This work is a collaborative development bringing together authors with different backgrounds and experience. One of us (IM) is directly involved in the Case Study described here, while the other (WJN) comes with a more independent perspective.

Each author brings an expertise based upon lived and professional experience. Professor Nuttall has more than twenty years as an energy technology and policy specialist with expertise in nuclear energy systems and more recently hydrogen energy systems – it is the latter set of interests that links him to the work reported here. Ian MacGregor is a Canadian engineer and industrialist known in recent years for his work associated with the successful capture and storage of more than 4 million Tonnes of CO_2 to date (March 2024) via three linked businesses all of which he has helped develop via a leadership role at one time or another. He was also involved as a significant owner in the early stages of the Weyburn project in Saskatchewan which has now stored about 35 million Tonnes of CO_2. Some of these businesses are described in Section 9.

This paper was written to introduce the academic community to a potentially important development at the interface of forestry and low carbon energy systems. It represents the authors' perspective as it reviews and describes plans and events already underway. The paper's authors intend to provide a fair and balanced assessment of the issues and the project's future potential, but we concede that, as a team, we may be too close to the project for true impartiality. Impartiality and familiarity are often in conflict when introducing innovations of this type, but the resulting perspective can be valuable. We can only suggest, and hope, that subsequently, truly independent researchers might take an interest and provide their own assessments for the future research literature.

2.2. The need for CO_2 removal from the atmosphere

This paper explores a Nature Based Solution (NBS) to climate emissions goals. Much of the work on NBS involves establishing carbon sinks which are only good for a fixed and finite time. Eventually those plants die, and the carbon is returned to the atmosphere. As such biomass energy systems (without CCS) are merely low emission solutions when compared to historical fossil fuel alternatives. If such a system were perfectly efficient then the carbon is extracted from the atmosphere by photosynthesis, that carbon is later combusted (or used for energy purposes in some other way) and then it is returned to the atmosphere. The path of the carbon is circular from the atmosphere to the biomass and back again. Only very small quantities of additional carbon dioxide would be transferred to the atmosphere. Such a biomass combustion proposition assumes various things:

- That at 'time zero' the land in question is devoid of biomass. For zero net emissions the process must start with the extraction of CO_2 from the atmosphere.
- The process must not prompt the creation of higher greenhouse gas emissions sources (such as methane).

In such a conventional bioenergy paradigm, the carbon in the biomass is only temporarily removed from the atmosphere. In the Nature-Based Solution proposition described in this paper, the CO_2 removal is essentially permanent yielding negative emissions overall. As noted earlier, the Canadian energy system will need some technologies capable of negative emissions given that some vital activities will always produce some greenhouse gases. As such, for Net Zero to be achieved, it is not sufficient solely to develop carbon neutral technologies. To be explicit this case study explores a project bringing forward an idea in which the CO_2 gathered by the trees never returns to the atmosphere. For further information on negative emissions and NBS we recommend the work of International Energy Agency (IEA) [12].

In pointing to an NBS case study we do not wish to imply that all the physical infrastructure will itself be derived from nature. Our focus here is the process flow. It is also not our intention to enter the important philosophical debate as to whether Nature Based Solutions need to be entirely nature derived. As we shall see, we will point later to the need for third party life cycle assessment of NBS. Physical infrastructures should fall within the scope of such research. It is through such research that the complete credentials of the proposal can be explored.

3. Hydrogen Naturally—an introduction

3.1. The challenge

This paper is focused on the first large-scale activity from a new company called "Hydrogen Naturally" which publicizes its technological proposition with the trade marked phrase "Bright Green Hydrogen" [13].

The plans of Hydrogen Naturally are based on a set of fundamental aims:

- To produce hydrogen at scale with minimal, or even negative, environmental detriment to the land base using low value, residual wood fibre.
- To use residual wood fibre will mitigate wildfire risks, which are becoming more prominent in the face of climate change.
- To reduce atmospheric greenhouse gas concentrations via negative emissions'
- To be founded as a commercial proposition in ways that are scalable and replicable

- To develop and advance best practice in terms of local community engagement, indigenous reconciliation, and multi-stakeholder decision making.

Negative emissions technologies are extremely economically and technically challenging as they require extraction processing and sequestration of carbon currently residing in the atmosphere as carbon dioxide with a concentration of 0.04% or approximately 400 parts per million (ppm). Technologies attempting such a task are known collectively as Direct Air Capture or 'DAC'. While DAC approaches based solely upon the physical sciences have been proposed, it is generally the case that, where circumstances permit, far greater efficiency can currently be achieved if one is able to leverage the energy of photosynthesis inherent in all green-leaved plants. Such use of nature-based processes we term 'Natural Air Capture' or NAC.

NAC links naturally to the established term Bio-Energy Carbon Capture and Storage (BECCS), The Case Study presented here is an example of both NAC and BECCS.

Helpfully, much of this special issue will be dealing with innovations relating to 'BECCS' and the related concepts of Biomass Carbon Recovery and Sequestration (BiCRS).

3.2. The proposition

The plans of the Hydrogen Naturally team exhibit a feature common to, probably, all such projects worldwide – a sincere desire to reduce materially global atmospheric greenhouse gas concentrations through negative emissions technologies. In addition, the approach of Hydrogen Naturally is distinctive, because it is based upon five key attributes.

The company's plans have:

- A completely commercial focus.
- A project team with a track record for delivering important large-scale energy infrastructure projects.
- A goal to generate hydrogen as a new low-carbon energy product.
- A sincere desire to establish a new paradigm in community-industry relations.
- An intention to remove atmospheric CO_2 at scale.

In essence, the Hydrogen Naturally enterprise aims to use trees which grow using solar energy to extract the 400 ppm CO_2 in the air. The resulting trees are themselves 25% carbon and then Hydrogen Naturally and its partners will preserve that carbon while selling sustainable products including low emissions hydrogen and supporting the sale of lumber "saw logs". (It is worth observing that the trees are actually 50% carbon on a dry basis, but noting the mass of the water in freshly-cut trees that figure is 25%.) A key feature of the proposal is the fact that the vast majority of the carbon in the NAC biomass is not returned to the atmosphere, but rather it is sequestered safely in perpetuity.

Hydrogen Naturally proposes a "Working Forests", or "active NBS" approach as an opportunity for Canada (and in time other countries) to advance negative emissions at a material scale. In the Working Forest approach, one obtains the economic activity from harvesting of forest products and materials together with the creation of carbon negative hydrogen. This is being thought about in Canada at the landscape level as part of 'Climate

Smart Forestry'. Such approaches bring together: managed cutting and replanting, biodiversity and climate reasons, including carbon sequestration and climate change adaptation.

The company will use a process of gasification to convert the biomass into a synthetic gas (syngas) comprised of carbon monoxide, carbon dioxide and hydrogen. The syngas is then processed through a series of gas clean-up steps where the carbon monoxide is converted to CO_2. The resulting gas is then separated into pure CO_2 and hydrogen. The process to be used by Hydrogen Naturally will capture ~90% of the carbon from the wood of the remaining ~10% of the carbon, roughly half will exit via the solid product streams of ash and fines while the remainder (~5% of the carbon in the wood) will be released to the atmosphere (via the hydrogen production process or in process vents). That small gaseous release of CO_2 will be an entirely biogenic release. If one regards the solid product streams as beneficial carbon capture, then this will be an example of NAC operating at 95% efficiency (based on a carbon conversion efficiency of 95%–98%, as reported by available technology information [14]). The process will operate as a commercial enterprise producing environmentally friendly products for the market (e.g., hydrogen). The process is summarised in Figure 1.

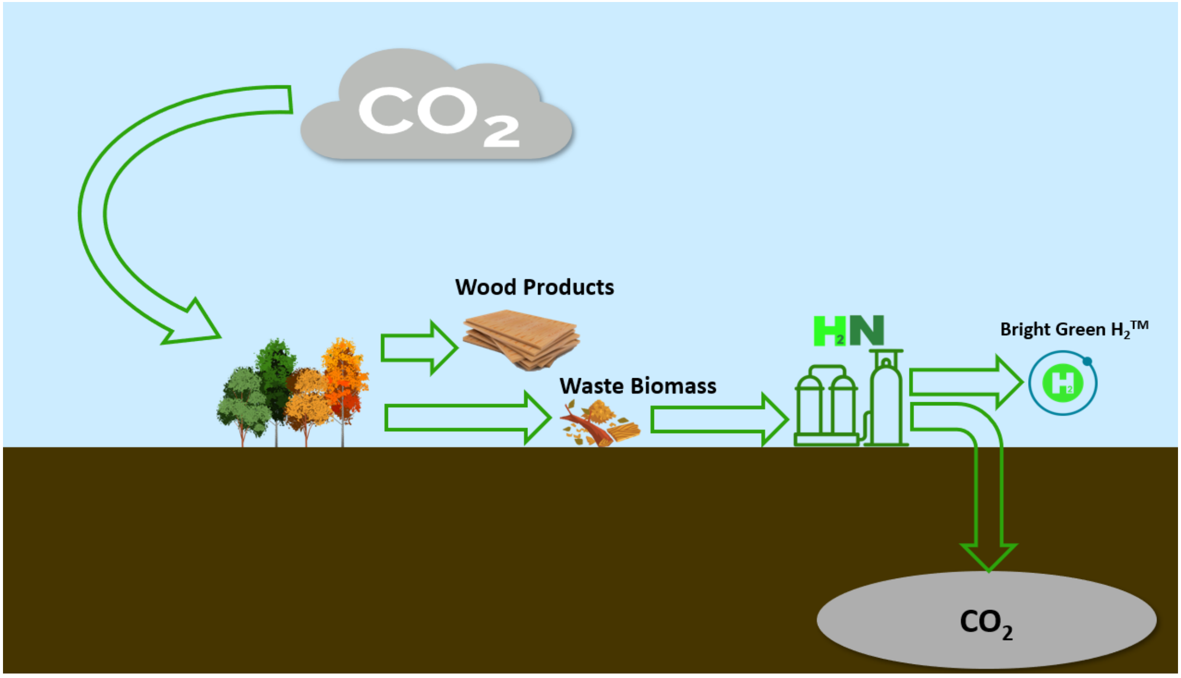

Figure 1. Hydrogen Naturally's Natural Air Capture Process (Image source: Hydrogen Naturally, with permission).

There will be two types of solid waste produced by the process: ash and fines. Both these solid products are non-toxic, non-hazardous and naturally-sourced.

The process will use an inert clay consumable within a fluidized bed for the gasification stage. This material will need to be replaced at scheduled intervals. This material is the majority of the ash generated. To all intents and purposes it will be equivalent to the raw clay extracted initially. The ash has the potential to be used as a soil amendment (e.g., as a component of fertilizer) or alternatively it could be used as a component in concrete for construction. Applications in construction will require testing concerning the presence of high alkali metals in concrete. In addition, the ash has the potential to be used as an additive in landfills as an absorbent for liquids and sludges. It is important to stress that such a use for the ash is not landfill disposal itself, it is merely meeting a need that all landfills must consider.

Meanwhile the fines can be used as fuel in a cement kiln or used as a soil amendment similar to the ash. **Proposals to make good use of these two, otherwise waste, solid materials represent an appropriate area for critical independent expert assessment (Recommendation 1).** In this case-study based introduction we shall propose areas for further research investigation. This first highlighted topic is one such example. The recommendations of this paper are gathered together in Section 12.

4. Applying experience from the oil and gas sector

The oil refinery sector uses large amounts of hydrogen for two purposes. The first is the desulphurization of 'sour' crude oils. The second is to reduce the viscosity of heavy crudes (hydrocracking). Noting that Hydrogen Naturally company will be producing Bright Green negative emission hydrogen it might make sense for refiners to purchase such hydrogen as part of an incremental approach to decarbonization. Given the petroleum products will remain important for years to come it could be that Bright Green hydrogen available in Alberta will reduce provincial emissions with minimal industrial disruption. Hydrogen Naturally has the potential in the short term to displace hydrogen currently sourced from natural gas with their bio derived hydrogen. That change could reduce the carbon intensity of the resulting fuels by up to 30% [15]. In time, of course, oil refinery operations will evolve towards low carbon synthetic fuel production or face the prospect of elimination in a Net Zero world. These emerging synfuels will also need low-carbon hydrogen. On a similar timescale, demands for the direct use of hydrogen in transport and mobility and as a direct low-carbon fuel for industry can be expected to grow.

Hydrogen Naturally seeks to reduce the carbon intensity of all its derivative products by using "Bright Green" hydrogen. It is important that the carbon negative attributes of the forestry feedstock are preserved through to the end use of all the associated commercial products (both hydrogen and wood products).

5. The commercial plan

Hydrogen Naturally plans to source material from places where trees have historically been harvested for lumber and in some cases pulp. The plan is for those activities to continue providing lumber for low carbon house building and other established purposes. In a low carbon world, the demand for sustainable lumber can only be expected to grow [16]. When harvesting for lumber, typically as much as 50% of the wood fibre in the forest remains as waste. Such waste is often burned and hence returns to the atmosphere immediately as CO_2. If allowed to rot on the ground it will also return to the atmosphere as CO_2, but only if the waste wood fibre is dry as it rots. If it rots in a wetted state, then there is a risk of methane generation – a far more potent greenhouse gas than CO_2, at least in the short term [17]. The linked propositions of low carbon hydrogen and natural air capture are only applied where it can be an additional derivative of established or historical forestry operations for lumber or other wood products. It is at this point that we would like to introduce the other founding company of Hydrogen Naturally, Peak Renewables (Peak). Peak is a bioenergy and wood products company founded through the Brian Fehr Group. Brian Fehr has over 40 years in the forestry sector including founding the BID Group of Companies [18]. The BID Group is involved in all aspects of forestry including sawmill construction & maintenance work, equipment rentals, machinery fabrication & installation, and energy solutions. When BID Group was sold, Brian Fehr started the BFG group, which includes Peak Renewables and several other companies. Peak is based in British Columbia and it is committed to sustainable resource development. One of Peak's core values is its commitment to partnering with indigenous and rural communities, while working with reputable companies.

Geographical context is crucial for the case study. All aspects of geography are of relevance, including: physical geography (terrain, climate, access and infrastructure), social geography (communities and market economics) and political geography (at a local, national and global level). Sensitivity to such realities is a requirement for progress in this arena. **The social and community aspects of the case study proposition deserve a separate dedicated study (Recommendation 2)**.

We close this section with a summary of the various process inputs and outputs of the case study technology (Table 1).

Table 1. Case study technology inputs and outputs

Inputs	Outputs
Atmospheric CO_2	Permanently sequestered CO_2 meriting public subsidy
Sunshine	Commercial timber
Water	Hydrogen at commercial quality
Soil Minerals	Solid products (see main text above)
Clay	Used clay (non-toxic and non-hazardous)

In essence the goal of the Hydrogen Naturally company is to achieve NAC at a cost of approximately US$100/Tonne. This would appear to be roughly an order of magnitude lower than established approaches. When the business is seen in such terms the hydrogen is essentially a credit to the cost of extraction and sequestration. The Alberta location is important and Hydrogen Naturally notes that hydrogen destined for fossil fuel oil refining or fertilizer manufacture can command a significantly higher price than current business models based upon hydrogen as a fuel. In time the development of technology and new markets can be expected to shift these realities as the world moves towards Net Zero, but in the mid-2020s the geographic, economic and political realities of Western Canada make Hydrogen Naturally commercially viable.

It is interesting to note that for the Hydrogen Naturally company hydrogen sales will comprise less than 20% of the projected revenue. The consequence is that, as the business considers costs and revenues, greater concern is given to factors such as feedstock cost.

Feedstock cost is in turn heavily influenced by transportation distance. Other key business concerns include the cost of the engineering plant and the cost to sequester the CO_2. For the proposition as a whole the revenue side is dominated by timber sales and payments in respect of CO_2 sequestration.

6. Forest sites linked to Hydrogen-CCS facility

The fundamental factor in achieving negative emission fuels is ensuring the wood is harvested in a sustainable way and does not result in deforestation. As noted earlier, Canada has ~9% of the world's forest and it has some of the most stringent forest management practices [19]. 94% of Canada's forests are on public land and are managed by laws, regulations, and policies. Forest management practices require land-use planning, regulate wildlife habitat protection, specify harvesting and regeneration practices and prevent illegal logging. Hydrogen Naturally's plans for commercial resource production also have the following planned elements [15]:

- The local partners have secured the necessary forest tenures to sustain a harvest sufficient to furnish fibre for at least 20 years.
- All harvesting related to this western Canadian project will be conducted according to the First Nation's Land Management Framework (LMF), where applicable. The LMF is a recognized way to harvest trees that is consistent with First Nations values and sustainability.
- Local companies will benefit from jobs in the harvesting, hauling, mill, silviculture and transport aspects of the proposition.

With these policies, initiatives and practices, the carbon negativity of the hydrogen product can be realized. The concept developed by Hydrogen Naturally is based on two spatially separated components:

- Lumber production, Natural Air Capture and waste biomass utilitization in the forestry setting.
- Low carbon hydrogen production and Carbon Capture and Storage at a separate 'Hydrogen Facility'

Hydrogen Naturally plans for activity in two types of sites. The process starts with the commercial production of lumber in the forest. Wood fibre that forest producers would typically regard as waste, will now be used as a feedstock for Hydrogen Naturally's hydrogen production process. This fibre includes sawmill residuals and harvest residuals, including low-value deciduous trees with limited life spans and that are prone to rotting and forest fire, as described in greater detail below. Low-value fibre will then be transported by road, or rail, to the Hydrogen Naturally facility where advanced industrial-scale chemical engineering takes place to produce low carbon hydrogen for sale and carbon dioxide for permanent sequestration.

The business model is that each facility would have a portfolio of fibre supply from a selection of sources. Each facility can receive incoming fibre from numerous forest sites and in this way economies of scale can be achieved.

The choice to locate the first hydrogen facility in Alberta gives the project team access to fibre, a ready market for the hydrogen and exiting CCS infrastructure. Alberta has a robust forestry industry, with ~60% of the province covered in boreal forest and it is the 3rd largest lumber producer in Canada (see Figure 2 below) [20]. Alberta also has established hydrogen demand in the refining and fertilizer spaces without taking the timing risk associated with emerging direct hydrogen demand associated with transport and mobility *etc*. Once low-carbon hydrogen is available at scale, one can be confident that it will enable further shifts to lower carbon futures in the wider Alberta energy economy. The options and opportunities are too diverse and extensive to describe here, but readers are recommended to consult the Alberta Hydrogen Roadmap [21].

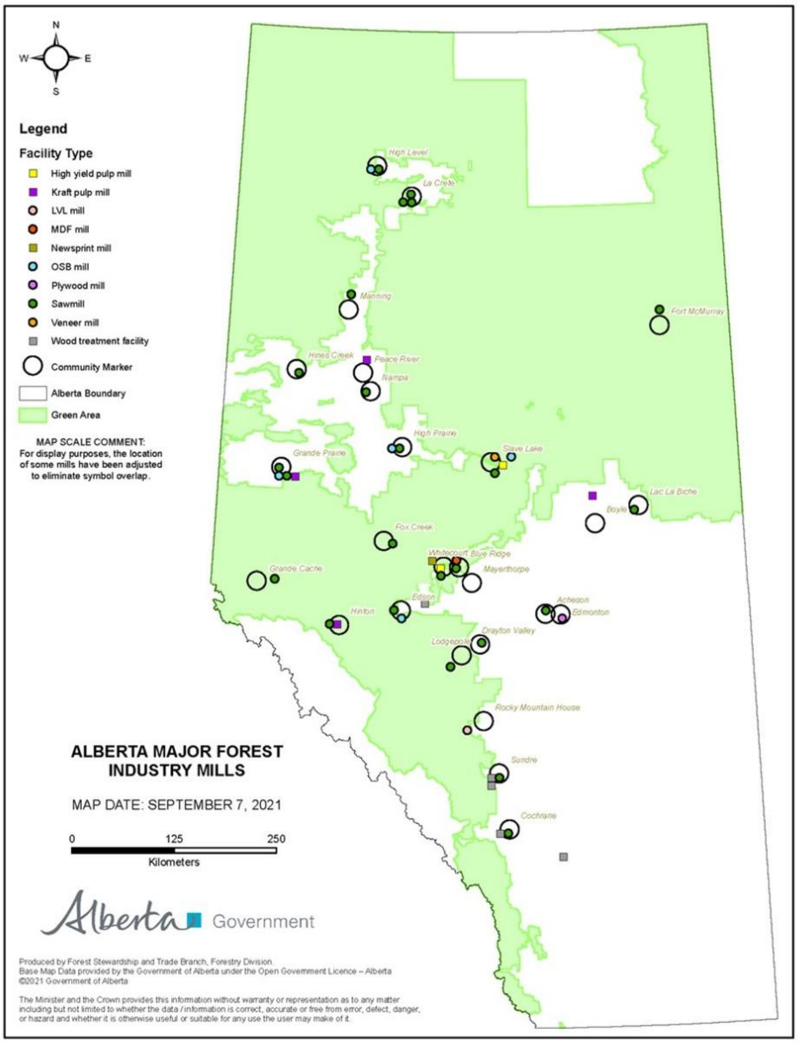

Figure 2. Fibre opportunities in Alberta, Canada (Image: Source [22] copyright: Canada Open Government Licence).

Utilising waste fibre in remote locations such as northern Alberta, British Columbia (BC) and Saskatchewan will also play a major role in supporting employment and developing worker skills in Western Canada. Fibre will be collected near the harvest location and transported for processing at a site in Alberta where the team has access to a currently operational Carbon Capture and Storage (CCS) system. It must be remembered that it takes a long time to build a CCS system, but the timescale of the 2050 policy imperative is short. It is hugely beneficial that investment has already been made by the project team and their past collaborators in developing the necessary CCS infrastructure in Alberta. Members of the project team, and indeed one of the authors of this paper, were the inventors of the CCS system in Alberta, called the Alberta Carbon Trunk Line (ACTL). Economic collection and transport of the fibre is a crucial element of the commercial proposition. Access to fibre at further distances from the site should be studied with established forestry players.

We suggest the possibility of a follow-on analysis of low carbon haulage models (**Recommendation 3**). We note that it may be possible to improve the carbon economy of the proposition still further by using low carbon rail haulage based on biodiesel, or even hydrogen-fuelled, locomotives in the future. This analysis should also consider opportunities to extract and collect waste residual fibre at the time of harvest.

The boreal forest in Alberta, and Western Canada is a mix of deciduous and coniferous trees. The conifers represent the greatest commercial value. Once cut, coniferous trees need to be replanted as, unlike the local deciduous trees, they will not grow back from the root system. The dominant value from the coniferous trees comes from the trunks. Typically, the coniferous trees are used as saw logs in saw-mills. Once the saw logs have been made, much wood fibre remains (tree-tops, small deciduous trees, side branches *etc.*) Currently some of this material may be used to make pulp (e.g., for paper) or chip board if there is a plant close enough, or else it is burned (with the CO_2 vented) or, simply allowed to remain and rot. In recent years a larger proportion of the wood biomass has been left as residual, rather than converted into wood chip or pulp due to a declining pulp industry in Canada [23]. Those long-standing secondary products are now so low in value that, in large parts of Canada at least, when considered in the context of local logistical, market and geographical factors, it becomes clear that such products are not worth extracting [15]. Such wood fibre can be as much as 70% of the wood fibre cut in the forest [15].

However, looking to the future some residuals (e.g., wood chips and sawdust) could be used to make wood pellets which can be:

- Burned in biomass power plants overseas, such as Drax in North Yorkshire, England, once again releasing the CO_2
- Burned or otherwise used in smaller biomass power plants in Canada (similarly releasing the CO_2), or
- Used for other value-added industries, such as Oriented Strand Board, pulp and paper.

Importantly some of these other potential residual-use examples manage to reduce the global release of CO_2, such as through the avoidance of the use of fossil fuels in power generation. Right now, however, pelletization remains an economically challenging proposition. That reality is not an obstacle to Hydrogen Naturally which has the potential to build a successful business based on wood chips in the near term. That early forward movement enables a focus on low carbon fuel (hydrogen) production that is both timely and novel. In time it will allow for a push to even stronger environmental benefits than seen in biomass-based power generation and forest products.

In the past the use of wood pulp for paper was important in Canada, but in recent decades it has become more challenging for two reasons:

- In North America printed newspapers have been in decline for many years as people increasingly get their news from online resources. Other uses of paper for printing have also declined.
- There are places in the world where pulp trees grow faster than they do in Canada.

Earlier we referred to residual forest material. This is especially important noting the decline of the Canadian wood pulp industry. We earlier referred to the idea that it might be left on the forest floor to decay, but currently in select areas of Western Canada it is burned in slash piles to reduce forest fire risk. The established practice of slash pile burning emits CO_2 and reduces the risk of methane release generated from fibre rotting, as mentioned earlier. Hydrogen Naturally plans to remove essentially all the non-log wood fibre material and to transport the fibre to the hydrogen facility to produce hydrogen and then to sequester the vast majority of the carbon from the fibre used (noting that the high-quality timber logs will remain in architectural use for decades).

It is important to stress that in Canada forest trees begin to slow their carbon uptake capabilities between 30 and 80 years of age, after that the benefits of forest growth in respect to carbon sequestration begins to decline [15]. Hydrogen Naturally plans to follow climate smart forestry practices and to align the growth cycles with well-planned managed harvesting. Such an approach supports maximum carbon uptake and sequestration by the forests, as well as sustainable lumber production supported by Natural Air Capture using harvest residuals all based around a more rapid growth cycle.

Hydrogen Naturally has commissioned two independent Life Cycle Assessments (LCA) based on the inputs and outputs shown in Figure 3. The first considered the Hydrogen Naturally proposition with respect to a Provincial Canadian Fuel standard (British Columbia Low Carbon Fuel Standard) using the GHGenius model [24], while the second considered a Federal Canadian standard (Canadian Clean Fuel Standard) using the FuelLCA model [25]. Both these independent third-party assessments demonstrated that the hydrogen produced by Hydrogen Naturally should achieve carbon intensities ranging from −137 to −172 g CO_2/MJ. Note the negative signs.

The process of independent commissioned assessments has included consideration of all forest practices, biomass transportation, hydrogen production and carbon capture and sequestration. Specifically, it estimated the emissions from the collection, processing and transport of the fibre to the hydrogen facility. This is based on using wood fibre to dry the biomass and the use of diesel fuel for the transportation of inputs such as fibre, chemicals or inert clays. These emissions were accounted for in the accounting of the carbon intensity noted above. Looking ahead, **we recommend an independent life-cycle analysis of natural air capture including greenhouse gas emissions and the soil nitrogen cycle based on the Hydrogen Naturally business once in operation** (**Recommendation 4**). Comparisons to best alternative technologies and business models in each respect would be appropriate. The metrics of this independent study should cover both global and local environmental impacts.

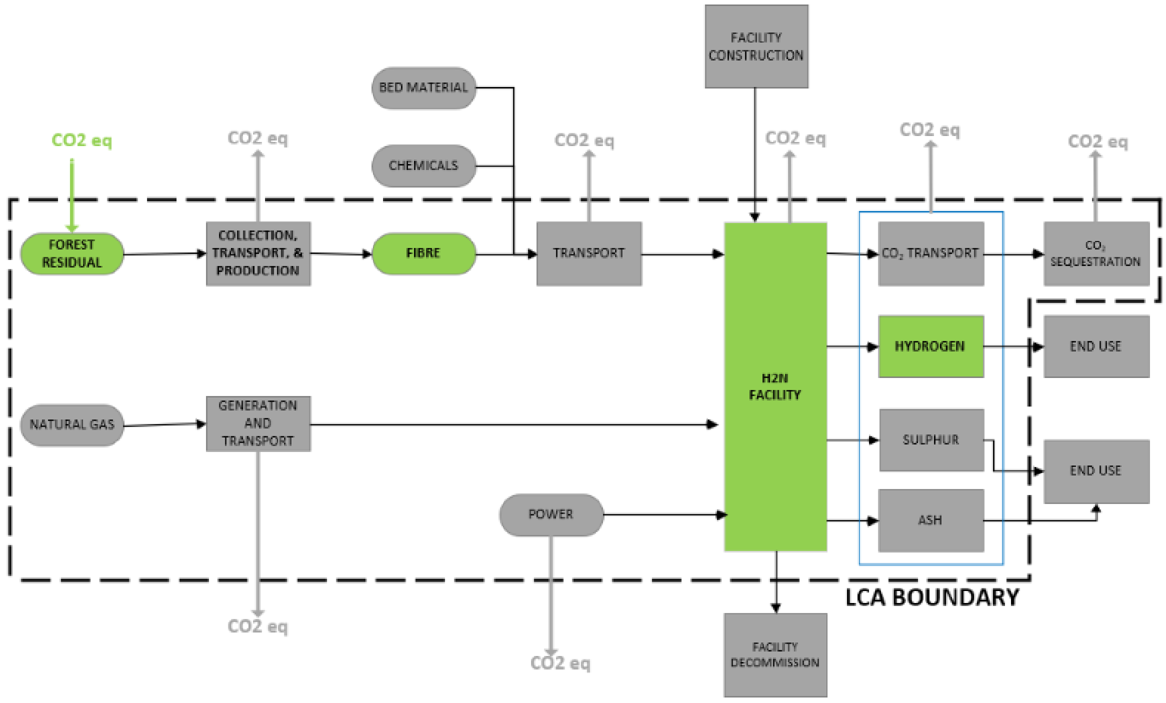

Figure 3. Life Cycle Analysis Overview for Hydrogen Naturally Facility. (Image source: Hydrogen Naturally, with permission).

7. Manufactured solution for hydrogen production and permanent carbon sequestration

Hydrogen Naturally plans to standardize its hydrogen production facilities to facilitate fast deployment and to achieve meaningful carbon removals based on the Natural Air Capture process as described above. The first hydrogen facility will be in Alberta, Canada receiving wood fibre from Alberta, British Columbia and Saskatchewan. Western Canada has numerous opportunities to build subsequent facilities that would be replicated from the first location in Alberta. Through this approach of standardization and replication, Hydrogen Naturally can reduce capital and operating costs to lower the CO_2 abatement costs. The design and execution of each facility will be identical. The manufactured facilities will then be deployed across Canada and the United States. Each facility will consume 100,000 Tonnes of fibre (dry basis) and produce about 10,000 Tonnes of hydrogen and, as a gross figure, sequester approximately 195,000 Tonnes of CO_2 annually and further avoid 100,000 Tonnes of CO_2 annually through the displacement of fossil fuels (based on displacement of diesel). Through deployment across North America, there is potential to remove megatonnes of CO_2 per year.

Once the first facility is operational there will be much interest in auditing the quantities involved as a matter of commercial and public policy importance (Recommendation 5). The focus here will be more commercial and financially oriented. It is an area where academic research investigation would not be most appropriate.

The wider block flow process for a Hydrogen Naturally facility is shown in Figure 4. The wood-fibre, as delivered from the forest locations, is first sent through a gasification step.

In this step, the biomass is thermochemically converted into a synthetic gas (syngas) through the use of industry standard partial oxidation technology [5]. The production of the syngas is an exothermic process and the heat generated is used to generate steam which will then later be used in downstream unit operations. In the water gas shift process: carbon monoxide in the syngas is reacted with water to create additional hydrogen and carbon dioxide. Chemical absorption (amine) is then used to separate the carbon dioxide and hydrogen streams leaving a highly concentrated gaseous CO_2 residual that is near perfect for CCS. A portion of the hydrogen product is consumed in the facility to generate heat and avoid the requirement for burning natural gas and also avoid the release of anthropogenic CO_2.

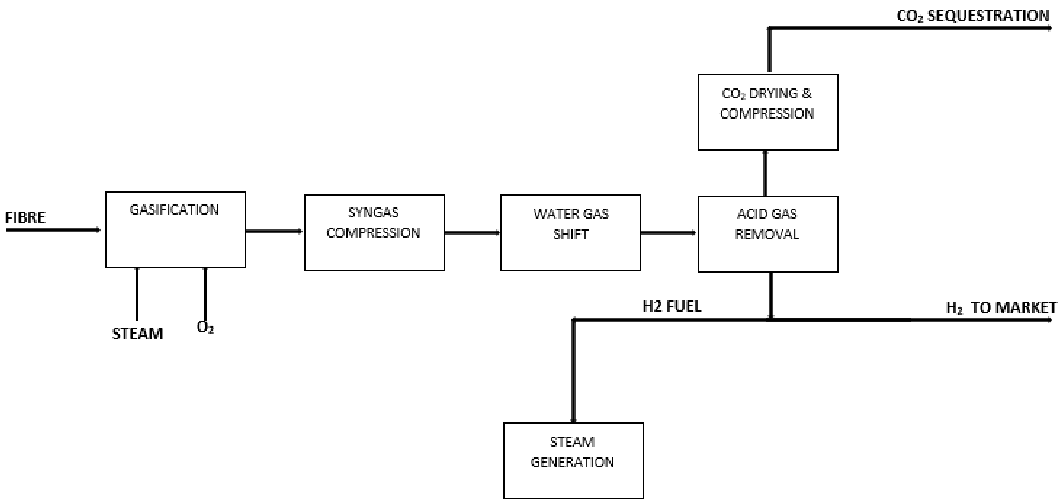

Figure 4. Block Flow Diagram for the Hydrogen Naturally process. (Image source: Hydrogen Naturally, with permission).

Importantly all of the energy produced will have its origins in renewable solar energy collected via forest photosynthesis. And all of the CO_2 sent for sequestration will have been taken from the atmosphere via the carbon in wood-fibre.

8. Wider considerations

Hydrogen Naturally as a company is joining an emerging industry based around principles of BECCS/BiCRS. This emerging sector has much potential to benefit the global climate. The UK Chief Scientific Adviser commissioned an important study on such matters that reported in August 2023 [26]. It concluded that such local approaches can indeed give rise to negative emissions.

Around the world several third-party BECCS projects are dedicated to biomass combustion for electrical power generation. Such projects are certainly moves to goodness, but we suggest that such globally dispersed plans involve particular challenges. The relevant considerations include:

- Very long (in some cases inter-continental) logistics
- The need to ensure combustion with low NO_X and SO_2 pollutant emissions
- The challenging need to achieve carbon capture via retrofit smokestack emissions.

Another resource that is to be considered when evaluating carbon dioxide removal pathways or BECCS is the consumption of water. Some industrial direct air capture technologies need significant amounts of water particularly for cooling purposes [27]. For this case study the authors understand and expect that the NAC approach will see considerably less water consumed. Water usage should be considered in the proposed academic Life Cycle Assessment (Recommendation 4).

9. Relevant local infrastructures and links to the case study

To fully appreciate this case study it is important to point to key infrastructures of the Alberta energy economy and to the past experience of the Hydrogen Naturally project team.

9.1. North-West Refining

The North West Redwater Partnership describes its Sturgeon Refinery with the following words [28]:

"The NWR Sturgeon Refinery is the world's only refinery designed from the ground up to minimize its environmental footprint through carbon capture and storage while producing the high-value, low-carbon products needed to meet North America's demand for energy."

Having been commissioned through 2018, the Sturgeon Refinery was the first new complex, greenfield, oil refinery constructed in North America in more than 40 years. The upstream feedstocks are Alberta Oil Sands – the heaviest and, if unabated, one of the environmentally worst crude oil resources in the world. It is important to stress, however, that the North-West Refinery operates as a true refinery and not as an 'upgrader'. It does not take in tar sand product and convert it into a crude oil equivalent – it produces low sulfur diesel for direct retail distribution. Of course, that diesel fuel is likely to be combusted in trucks and buses across North America and essentially all of the carbon in that fuel will find its way into the atmosphere in the form of CO_2. In terms of end use 'tail-pipe' emissions it is similarly harmful to any other diesel fuel in the North-American retail market. Importantly, however, from the start the North West Refining project had an ambitious agenda to put in place the option of significant greenhouse gas mitigation measures. These included carbon capture and storage, but also the possibility of using low or negative, carbon emissions hydrogen (such as might in future be produced by the Hydrogen Naturally project) in fossil fuel hydrocracking and hydrotreating. As such one can argue that sustainable hydrogen production can act as an enabler of unsustainable fossil fuel practices. As noted earlier, this is an important critique relating to complex considerations some of which lie beyond the scope of this case study. In response one can only add that the Canadian fossil fuel industry must move to reduce greatly its emissions impact. NAC, sustainable hydrogen production, and CCS are all technologies that have the potential to enable such environmental progress by, or in place of, the fossil fuel industry.

Concerning progress by the fossil fuel industry, based on the progress made in all areas of oil sands processing, the carbon intensity of the product from the Sturgeon Refinery is now lower that many of the equivalent petroleum products produced in the world. That is, the diesel fuel produced by North-West Refining can now surpass the environmental performance of more conventional refining operations [15].

The Alberta context provided a sufficiently attractive business case to favor the building of an entirely new refinery and even more importantly to make a material contribution to CCS development. The realities were such that North-West Refining could help propel the low carbon agenda, for Alberta and for Canada as a whole, by seeking to marry the new refinery with carbon capture and storage (CCS).

The North West Sturgeon Refinery is approximately 50 km northeast of Edmonton. The CCS capability at Clive is roughly 200 km south near Red Deer. That is, the Clive Facility is roughly midway between Calgary and Edmonton. The 200 km distance between the refinery and the Clive facility necessitated that a new CO_2 pipeline be constructed in order for CCS to be achieved. This takes us to the second of three businesses that require introduction.

9.2. Wolf Midstream's Alberta Carbon Trunk Line

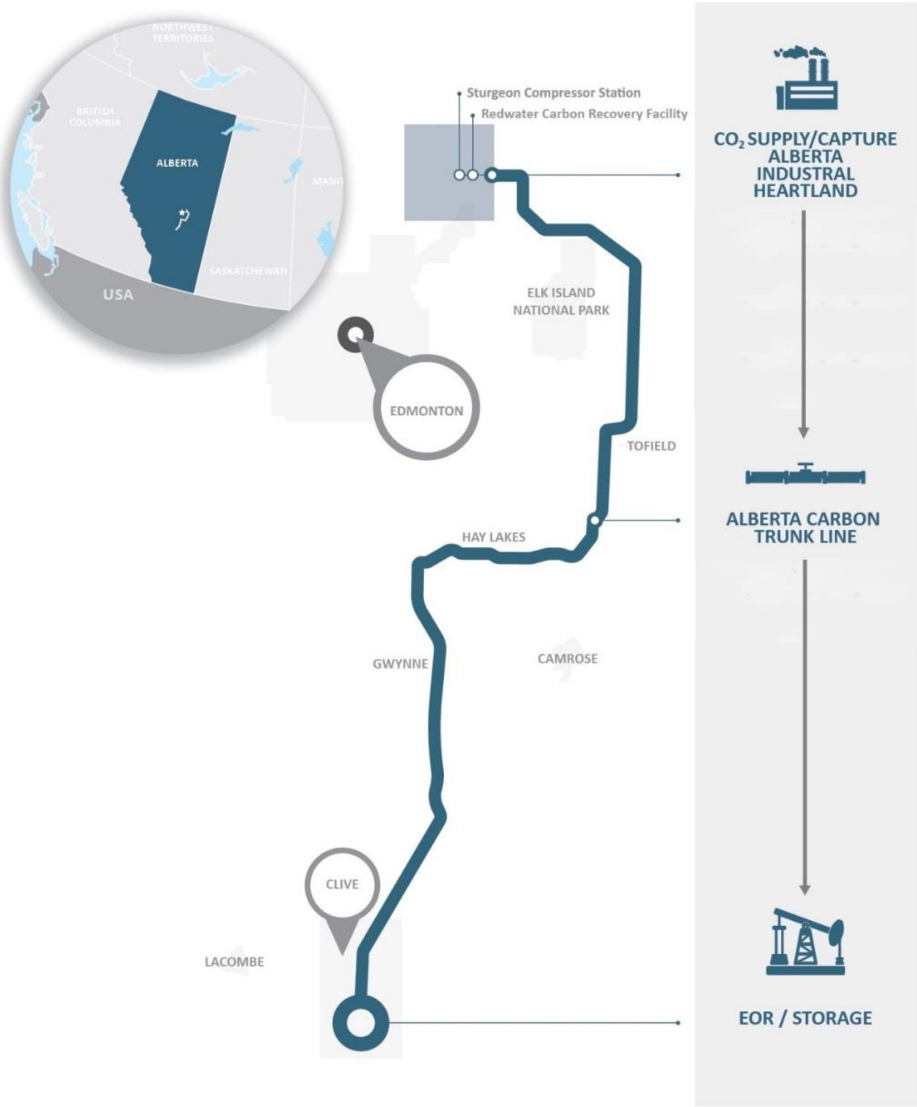

Figure 5. ATCL Map in Alberta [29] (Image: Wolf Midstream with permission).

The Alberta Carbon Trunk Line (ACTL) receives CO_2 from the North-West Sturgeon Refinery and an adjacent ammonia production facility (dedicated to fertilizer manufacture), see Figure 5. The CO_2 is dried so as to avoid the formation of corrosive carboxylic acid and compressed into a high-density supercritical state (i.e. into a fluid state that is strictly neither gas nor liquid). The CO_2 is then pumped 250 km to Clive which was previously an aging oil production facility. As the longer (250 km) length of the pipeline implies, the path of the ACTL is not direct. It meanders across the central Alberta landscape positioning itself to receive CO_2 inputs from numerous sources that should (in the journey to a low carbon future) stop venting their waste CO_2 to the atmosphere. At the time the ACTL was conceived it was routed to be in proximity to about 50% of Alberta's industrial CO_2 emissions [15]. The construction of the ACTL was a major engineering and financial undertaking involving expenditures of more than CDN 1.2 billion. The ACTL pipeline was designed specifically for CO_2 service and constructed by Wolf Midstream in 2018/2019 with operations starting in June 2020 [28]. The CO_2 in the ACTL is typically 98.5% pure as it arrives at the Clive Facility. That facility is operated by the third of the three companies that we shall consider in this section. The ACTL is believed to be the largest system in the world for managing man-made CO_2 with an installed capacity of 15 million Tonnes per year. It is currently (2023 data) operating at about 1.5 million Tonnes per year and was built with significant spare capacity to accommodate the needs of the future.

The ACTL accesses both enhanced oil recovery (EOR) reservoirs and pure CCS reservoirs that are distributed along its route. There is therefore "Giga-Tonne" CO_2 storage potential along the installed pipeline route. This future capability is of potentially global significance.

9.3. Enhance Energy

Enhance Energy at Clive produces crude oil that is shipped out by pipeline for refining. The role of the CO_2 arriving in the ACTL has thus far been to enable Enhanced Oil Recovery (EOR), but at the end of the process the CO_2 remains underground and hence can be regarded as truly being a form of CCS.

Importantly the crude oil that is produced by EOR (in ever declining quantities) is the only liquid or gas to leave the Clive site. Unless there is an emergency or safety-related problem, nothing is vented. The aversion to venting frankly suits a long-standing norm for the Albertan oil industry. It is long used to dealing with toxic H_2S as found in Albertan sour crude oil and because of these chemical concerns, it has long been the case that no H_2S venting is possible in Alberta.

It is interesting to note that the oil from enhanced oil recovery has the lowest carbon intensity of any oil in the market. Key to this reality is the observation that EOR uses infrastructures operating beyond their original design life (life plans made before EOR was envisaged). That is all the embedded carbon in construction, pipelines, roads, buildings, and drilling has arguably already been amortized in carbon terms. As the world moves away from oil, it seems likely that environmental considerations should motivate the fact that the last barrel of oil sent to the market should come from an EOR source. **Public policy should be developed to help ensure that reality and to dis-favor new exploration and drilling for oil with all the carbon intensity that such activities imply (Recommendation 6).**

As noted earlier, CO_2 from the ACTL is used to help reduce the viscosity of oil in the formation and to push crude oil out of the ground. The crude oil coming up is mixed with water, CO_2, H_2S, and some other minor components. Importantly everything at Clive, except the crude oil is returned to the ground. The water and all the CO_2 are separated and cleaned. The water is simply reinjected at Clive if not used for technical purposes. In addition, the local CO_2 arriving from underground is cleaned and mixed with the clean CO_2 arriving from the ACTL. Through such a process CO_2 that first arrived at Clive via the ACTL might be expected to rotate between the ground and the surface facility several times. As long as it ends up safely underground in the end, the circulation does not matter. In the limit that at some point in the future effectively no further crude oil emerges, then the Clive facility will have become a pure CCS enterprise. Indeed, there are clues that such a reality is approaching. The injected CO_2 is essentially cold, while crude oil should be expected to emerge hot (at about 60 ℃). The liquid emerging today at Clive is essentially cold, hence it is mostly CO_2 and, of course, much more CO_2 is going in than coming out as the EOR/CCS system operates.

The three companies referred to in this section will all have a role to play in the wider ecosystem around Hydrogen Naturally's hydrogen facility. Together and with partners, Hydrogen Naturally team members have learned a lot about CO_2 handling through their involvement in the various activities listed above. In addition, the team learned from earlier projects not directly linked to the plans for an Alberta hydrogen facility. For example, in Weyburn Saskatchewan team members learned the importance of protecting elastomer flange seals from corrosion by wet CO_2. That lesson proved extremely helpful as plans developed in central Alberta some years later.

It is important to note that at Clive, Enhance Energy are putting CO_2 where the oil has been. This links to two important geological truths. For crude oil and natural gas to have been present over millennia then we can say with confidence that the geology is definitely sealed, apart from the pin prick holes drilled by human beings over recent decades. These pin pricks from exploration and extraction should all be well recorded and indeed, at Clive they are now properly sealed and monitored. Hence Enhance Energy at Clive can be sure that its CO_2 stays in place. Indeed, the company is very careful about that. The other relevant truth is that the geology has already been extensively studied and it is relatively simple. The alternative CCS opportunity provided by saline aquifers is far less likely to be naturally sealed and is typically far less well understood than a well-managed EOR resource.

In the scenario that EOR continues to yield crude oil at Clive, one could even imagine the construction of a partial oxidation plant so that the only thing leaving the site might in future be low-carbon hydrogen rather than crude oil. In that scenario, or the more likely scenario of imminent wind down of EOR, the Clive facility will become a pure CO_2 receiver contributing greatly to Canada's, and Alberta's low carbon future [21].

It is important to be clear that two of the three companies discussed above (North West Refining and Enhance) have no direct role in the Hydrogen Naturally project, although we note that Enhance is developing a CCS site independent of Enhanced Oil Recovery and it is likely that they will be providing sequestration services on a fee for service basis which may be of future benefit to the Hydrogen Naturally company. What we can say is that central Alberta is, given its existing infrastructures, a very good place to develop low carbon hydrogen production from hydrocarbon sources (such as wood fibre).

In summary - the advanced energy infrastructure of Alberta greatly assists Hydrogen Naturally's ambitions for material NAC on a rapid timescale.

10. Case study project economics

The value proposition for the case study project relies upon:

- The value of carbon negative hydrogen in the regional economy around the hydrogen production and carbon sequestration activities.
- The value of saw logs in the forestry location.
- Acceptable transport costs from forest location to the hydrogen facility.
- Societal incentives for the sequestration of CO_2.

Concerning the economic value to the project from the CCS capability: that value is monetized via a Canadian Federal Investment Tax Credit (ITC) for clean hydrogen production. That tax credit is currently a nominal 40% of capital equipment costs. If this project were officially regarded as a direct air capture and storage scheme under the terms of the federal policy (Capture, Utilization and Storage ITC) then the subsidy would be worth a nominal 60%. As things stand EOR linked CCS is not eligible for the higher subsidy despite the fact that eventually an EOR operation can be expected to become a pure CCS proposition. The tax credit, whatever its value buys down the capital cost of the facilities to be constructed [30].

The value associated with the operation of CO_2 capture systems or from negative emission hydrogen production comes from the regulations or carbon pricing imposed on carbon-intensive fuels. In Canada these include the BC Low Carbon Fuel Standard (LCFS), Federal Clean Fuel Regulations, BC Renewable Gas Mandates, Federal and Provincial carbon pricing schemes and voluntary offset markets. Bringing in the value of the logs, the potential for process heat utilization, and the hydrogen the economic case for such a scheme begins to look viable.

The reality is that for its first forest location, Hydrogen Naturally will not own the lumber logs and it will not directly participate in that part of the value chain. Hydrogen Naturally will be buying the harvesting residuals that are currently struggling to find a market, burned, or left on the ground, as described earlier.

11. Some NAC project criticisms addressed

Arguably this case study project brings together two key industries that have previously existed almost entirely independently. The first is forestry and the second is the oil and gas sector. The project is founded on the notion that the new linkage of these sectors can help meet a most serious global challenge (climate change) while being based upon commercial principles.

Some arguments against the proposition must be considered.

i. Will the forestry cycle be accelerated?

Looking at some earlier examples of commercial forestry for energy applications one might ask whether the Hydrogen Naturally project will fell trees at a younger age than would be the case for a traditional forestry business. For example, in some BECCS business plans, there are implicit incentives that trees are cut in order to be burnt more rapidly than would otherwise be the case. In such scenarios the trees would be returning their carbon to the atmosphere on a more rapid cycle. We understand that in many markets, including Canada, regulations or policy militate against any such incentives. In addition, today's unabated biomass combustion for renewable electricity generation does not yield the permanent removal of CO_2 from the atmosphere only merely the temporary storage of the greenhouse gas during the life of tree. That is conventional biomass is, at best, only attempting to reach carbon neutrality. If trees are felled more rapidly any inefficiencies in the carbon management are amplified compared to conventional forestry.

ii. Will Hydrogen Naturally's activities disturb local flora and fauna?

As regards the impact on flora and fauna, while such impacts are inevitable the return of sustainable forestry can have positive consequences including for forest fire management. Forest fires, while natural and in some ways beneficial for forest renewal, are devastating for local fauna and a source of large uncontrolled CO_2 emissions and other environmental pollutants. Furthermore, and as stated earlier, once the forest gets to a certain age it is no longer sequestering, the growth is offset by the dying and rotting. At that point if the forest is replanted it starts to sequester again. Sustainable managed forestry can deliver these benefits. It must be stressed that the forest proposed by Hydrogen Naturally are existing sites of historic commercial timber production. They have been harvested previously and the plan is to go back now that the trees have again become mature.

The Hydrogen Naturally proposal entails the idea that it will prompt an expansion of climate smart, sustainable forestry, with the concomitant economic and social benefits for local communities and investors, while also actively reducing atmospheric carbon dioxide. Some might seek to oppose the idea simply on the grounds that it is connected to the cutting of trees causing disturbance to local flora and fauna, but in that case the question becomes where else might we obtain the social, economic and environmental benefits? The lack of any economic value at present for the deciduous trees in parts of Western Canada has caused a cessation of logging activity in some remote communities. That reality has weakened social sustainability.

iii. Is this greenwash for Alberta's fossil fuel economy?

Turning now to the other characteristic of the Hydrogen Naturally proposal. It brings experience gained in the Alberta oil and gas industry. Some may question Alberta's credibility as a low carbon leader and perhaps suggest that there is an intention here to 'greenwash' the Alberta fossil fuel industry. In such contexts it is perhaps relevant to point out that Hydrogen Naturally is a free-standing business with no branding or marketing linkage to any fossil fuel incumbents. In the future fossil fuel companies may be customers for the hydrogen produced, noting that the fossil fuel industry is today a user of large amounts of emission intensive hydrogen, but such entities have no involvement in the Hydrogen

Naturally business. The future evolution of fossil fuel companies into low carbon energy companies is likely to involve much interest in low carbon hydrogen [5]. By making affordable negative carbon hydrogen available, Hydrogen Naturally can help encourage such shifts by third parties. Whether the fossil fuel industry should be assisted in its moves to decarbonize, remains however, for some, a contentious issue.

One might also argue that the Hydrogen Naturally enterprise will give a boost to CCS and hence in that way facilitate the continuation of fossil fuel extraction at the expense or renewables deployment, but to that it must be said that Hydrogen Naturally's plans are an example of a carbon negative renewables deployment and that if it does in some indirect way perpetuate the continuation of fossil fuel extraction, well it does so through the reduction of emissions from such activity. One can see that in both fossil fuel extraction and in refining, the Hydrogen Naturally proposition acts as a spur to emissions reduction. Again the question remains: is that a good thing?

It must also be pointed out that if Hydrogen Naturally could in the long-term shift to using saline aquifer sequestration. If it were to do that it would enjoy the highest level of public subsidy and eliminate any historical links to fossil fuel activities.

One can challenge the proposition of environmental benefit by arguing that despite producing negative emissions hydrogen, Hydrogen Naturally is extending the life of oil sands refining in Alberta, but the reality is that in the longer term the company plans to transition to direct uses of hydrogen in, for example, low carbon transportation and mobility. That is, the company's long-term plan and subsequent phases and sites are not predicated on the supply of low-carbon hydrogen to the refinery sector, but instead look to its use as a direct environmentally benign transportation fuel, a negative emission fuel for industrial decarbonization, or as a negative emission feedstock into the chemical or fertilizer industry.

Any allegation of 'greenwash' challenges the credibility of the project proponents, one of whom is an author of this paper. It can be hard to engage further with such criticism, except to say that both authors are of the opinion that this project is best judged by its actions than by its rhetoric. We further remind that this paper is not a research article – it is a perspective. The intention is to encourage independent interest and research. It is important to the project proponents (one of whom is an author here) that the environmental benefits are indeed as substantial and rapid as they hope.

It is important to consider the fact that Alberta has advanced the cause of sequestration both for enhanced oil recovery (EOR) and pure CCS further than any other place in North America and perhaps the world, if measured by action. As 2050 comes ever closer it is important, wherever possible, to move to action at scale.

Of course, there may be other criticisms not addressed here. The intention of this case study is in part to raise awareness and to prompt debate. We raise these ideas so that the global roll-out of beneficial ideas at scale might be better understood and, if appropriate, appreciated. As noted above, the authors are keen to see all good NAC ideas imitated as widely and as quickly as possible, consistent with key values of safety, environmental responsibility and social sensitivity. In commenting on application of NAC to low-income countries one needs also to be alert to the risk of deforestation. It is essential that all regions proposed for activity of this type already have in place robust forest management practices grounded in principles of sustainability.

12. Recommendations for independent research

As noted at the outset: The purpose of this paper is not to present primary research in energy technology and policy. Rather, it is hoped that this paper might prompt deeper academic interest in NAC coupled with hydrogen production. As we have explored the proposition we have pointed to various recommendations for further research, investigation and audit based on this case study. We reproduce those recommendations here:

1. Proposals to make good use of two, otherwise waste, solid materials (ash and fines) represent an appropriate area for critical independent expert assessment.
2. The social and community aspects of the Hydrogen Naturally proposition deserve a separate dedicated study. We suggest that it is currently too early to unpack such issues, but they are clearly of significant importance. Social science insights and research could, in due course, be most helpful.
3. The emissions associated with transport and logistics of fibre movement merit scrutiny. A study on the benefits of moving to low carbon fuels to transport fibre and how this improves the value proposition. What will such emissions amount to initially, and in the long term? Hydrogen Naturally advises that it has some initial information that might be helpful to such research [15].
4. Complete an independent life-cycle analysis of natural air capture including greenhouse gas emissions and the soil nitrogen cycle based on the Hydrogen Naturally business once in operation.
5. Once the first facility is operational there will be much interest in auditing the carbon accounting and quantities involved as a matter of commercial and public policy importance. This may be an area where academic research investigation will not be so necessary, as the main focus will be a technical audit. With that said, some techniques and ideas that have emerged from scholarly research may be helpful (e.g., on matters relating to CO_2 leakage and 'fugitive emissions' as seen around the world).
6. As the world moves away from oil, it seems likely that environmental considerations should motivate the fact that the last barrel of oil sent to the market should come from an EOR source. Public policy should be developed to help ensure that reality and to disfavor new exploration and drilling with all the carbon intensity that such activities imply.

13. Closing comments

Looking more widely, we note the growing interest in deploying the established skills of petroleum chemical engineering to the opportunities provided by biomass feedstocks, see for example [31].

Between us, as authors, we have much experience of a diverse range of energy technologies including fossil fuels, nuclear energy and hydrogen futures. In this paper we focus on a case study based on biomass renewables for "Bright Green" hydrogen coupled with CCS. In summary, we suggest that such developments have the potential to be material, commercial and beneficial environmentally and socially; but such a biomass-based solution is not sufficient to address the climate challenge as a whole. It is merely one of a range of technological approaches that may be necessary, but which in isolation are each insufficient. One consideration for the future is that, just as Hydrogen Naturally brings together forestry and chemical engineering, so we might see beneficial synergies at interfaces of other previously distinct sectors (such as synergistic collaboration between the nuclear power and natural gas sectors, around process heat applications of nuclear energy [32]). As regards good low carbon ideas, frankly we will need them all, if we are to meet the very challenging goals of decarbonization policy on time.

One distinctive characteristic of this case study is that all the required technologies exist already, the forest feedstock material exists in abundance and is otherwise effectively waste. Finally, and this is important for rapid progress at scale, the whole proposition appears to make sense in commercial terms as guided by existing public policy. There would appear to be no policy or market changes required in order to permit rapid forward progress with the project at scale and as described here.

With all that said this paper has pointed to matters of future concern, that will deserve investigation and reporting if this technology is indeed to have maximal impact globally.

Acknowledgments

We would like to record our thanks to Adam Couillard, Neil Dobson, Brett Jackson, David Nikolejsin and others at Hydrogen Naturally for information, informal advice, guidance and numerous insights. Of course, the authors alone are fully responsible for the work presented here. We are also most grateful to Hydrogen Naturally for providing Figures 1, 3 and 4. With thanks to Wolf Midstream for providing Figure 5. This paper contains no investment advice and should not be used as the basis of any commercial decisions. Information and opinion is presented by the authors in good faith, but without liability.

Conflicts of interests

Ian MacGregor has a significant equity stake in Hydrogen Naturally and is part of the team leading the case study project described in this paper. In addition, Ian MacGregor was previously much involved in several of the companies discussed in Section 9. The importance of his expert and engaged perspective is described in the paper. William J. Nuttall is an academic entirely independent of all companies and activities named in this paper. He has no equity stake and thus far has not acted as an employee of, or consultant to, Hydrogen Naturally. He visited Alberta in June 2022 and December 2023 as a guest of Ian MacGregor and North West Capital Partners. Nuttall's travel in 2022, prior to this work, was funded by a UK Higher Education Innovation Fund via The Open University. At no time was travel funding provided by his Canadian hosts. The HEIF award concerned industry, policy and academia knowledge transfer relating to hydrogen energy. Nuttall expresses his thanks for that funding support but it has no direct connection to this work.

Authors' contribution

Conceptualization, W.J.N. and I.M.; methodology, W.J.N.; investigation, W.J.N. and I.M.; writing—original draft preparation: W.J.N. and I.M.; writing—review and editing, W.J.N. and I.M. All authors have read and agreed to the published version of the manuscript.

References

[1] Mote Hydrogen. Available: https://www.motehydrogen.com/ (accessed 10 September 2023).
[2] Government of Canada. Canadian Net-Zero emissions accountability act. Available: https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050/canadian-net-zero-emissions-accountability-act.html (accessed on 4 March 2023).
[3] Ballard Power Systems. We are ballard power. Available: https://www.ballard.com/about-ballard (accessed on 4 March 2023).
[4] International Energy Agency. Global hydrogen review 2023. Available: https://www.iea.org/reports/global-hydrogen-review-2023 (accessed on 3 April 2024).
[5] Nuttall WJ, Bakenne AT. *Fossil Fuel Hydrogen*, 1st ed. Switzerland: Springer Cham, 2019.
[6] Peter Valdes-Dapena, CNN Business. Volkswagen increases spending on EVs to $100 billion (9 December 2021). Available: https://edition.cnn.com/2021/12/09/business/volkswagen-electric-vehicle-investment/index.html (accessed on 4 March 2023).
[7] Michael Wayland, CNBC Autos. Electric Dodge muscle car and Ram pickup part of Stellantis' $35.5 billion EV plans (8 July 2021). Available: https://www.cnbc.com/2021/07/08/stellantis-to-invest-35point5-billion-in-evs-and-new-technologies-by-2025.html (accessed on 4 March 2023).
[8] Michael Wayland, CNBC Autos. Toyota CEO Akio Toyoda talks about why he isn't all-in on EVs - and what made him do a 'happy dance' (2 October 2022). Available: https://www.cnbc.com/2022/10/02/toyota-ceo-akio-toyoda-electric-vehicles-happy-dance.html#:~:text=Toyota%27s%20hesitancy%20to%20launch%20all,rankings%20the%20past%20two%20years (accessed on 4 March 2023).
[9] BBC News. Volkswagen: The scandal explained (10 December 2015). Available: https://www.bbc.co.uk/news/business-34324772 (accessed on 4 March 2023).
[10] Ian King. Sky Views: Pushing drivers to diesel was a fraud that is hitting jobs (21 January 2019). Available: https://news.sky.com/story/sky-views-pushing-drivers-to-diesel-was-a-fraud-that-is-hitting-jobs-11604101 (accessed on 4 March 2023).
[11] Statistics Canada. Human activity and the environment 2017: Forests in Canada, 14 March 2018. Available: https://www150.statcan.gc.ca/n1/pub/16-201-x/16-201-x2018001-eng.htm (accessed on September 2023).
[12] International Energy Agency. Going carbon negative: What are the technology options? (31 January 2020) Available: https://www.iea.org/commentaries/going-carbon-negative-what-are-the-technology-options (accessed on 10 September 2023).
[13] Hydrogen Naturally. Hydrogen naturally makes bright green™ hydrogen. Available: https://www.h2naturally.com (accessed on 4 March 2023).
[14] SunGas Renewables. Available: https://sungasrenewables.com/ (accessed 13 September 2023).
[15] Hydrogen Naturally. Private communications, June 2022–March 2023.
[16] Stephanie Burrell, World Economic forum. 5 Reasons why sustainable timber must become a core global building material (24 January 2023). Available: https://www.weforum.org/agenda/2023/01/sustainable-timber-core-building-material/ (accessed on 4 March 2023).

[17] United Nations Climate Change. Global warming potentials (IPCC second assessment report). Available: https://unfccc.int/process/transparency-and-reporting/greenhouse-gas-data/greenhouse-gas-data-unfccc/global-warming-potentials (accessed on 5 March 2023).
[18] BID Group. Available: www.bidgroup.ca (accessed 13 September 2023).
[19] Government of Canada. Canada's forest laws. Available: https://natural-resources.canada.ca/our-natural-resources/forests/sustainable-forest-management/canadas-forest-laws/17497 (accessed on 3 April 2024).
[20] Alberta Government, Economic Dashboard - Key Indicators. Softwood lumber production. Available: https://economicdashboard.alberta.ca/dashboard/softwood-lumber-production/ (accessed on 3 April 2024).
[21] Alberta Government. Alberta hydrogen roadmap (5 November 2021). Available: https://open.alberta.ca/publications/alberta-hydrogen-roadmap (accessed on 4 March 2023).
[22] Alberta Forestry and Parks, Government of Alberta. Alberta's forest economy 2023: A handbook of public economic and socioeconomic Accounts (28 September 2023). Available: https://open.alberta.ca/publications/albertas-forest-economy (accessed on 4 March 2023).
[23] IBIS World, Wood Pulp Mills in Canada - Market Size, Industry Analysis, Trends and Forecasts (2023–2028).
[24] (S&T)2 Consultants Inc. Carbon Intensity for Hydrogen Naturally Inc. Private communication, Hydrogen from Biomass, 24 November 24 2022.
[25] BMO Radicle. Private communication, Hydrogen Naturally CFR Estimated Carbon Intensity, 21 April 2023.
[26] UK Government (DEZNZ), The Ability of BECCS to Generate Negative Emissions Task and Finish Group Report, Available: https://www.gov.uk/government/publications/ability-of-bioenergy-with-carbon-capture-and-storage-beccs-to-generate-negative-emissions (accessed on 1 May 2024).
[27] World Resources Institute. 6 things to know about direct air capture (2 May 2022). Available: https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal (accessed on 13 September 2023).
[28] Northwest Redwater Partnership. Sturgeon refinery. Available: https://nwrsturgeonrefinery.com/ (accessed on 5 March 2023).
[29] Wolf Midstream. Operation - Carbon. Available: https://wolfmidstream.com/carbon/ (accessed on 3 April 2024).
[30] Government of Canada. Investment tax credit for carbon capture, utilization, and storage (2021). Available: https://www.canada.ca/en/department-finance/programs/consultations/2021/investment-tax-credit-carbon-capture-utilization-storage.html (accessed on 13 September 2023).
[31] Forsberg CE, Dale BE. Can large integrated refineries replace all crude oil with cellulosic feedstocks for drop in hydro carbon biofuels? (January 2023). Available: https://www.hydrocarbonprocessing.com/magazine/2023/january-2023/biofuels-alternativerenewable-fuels/can-large-integrated-refineries-replace-all-crude-oil-with-cellulosic-feedstocks-for-drop-in-hydrocarbon-biofuels (accessed on 5 March 2023).
[32] Nuttall WJ. *Nuclear Renaissance*, 2nd ed. Routledge Abingdon UK: CRC Press, 2022, Chapter 7, pp. 165–187.