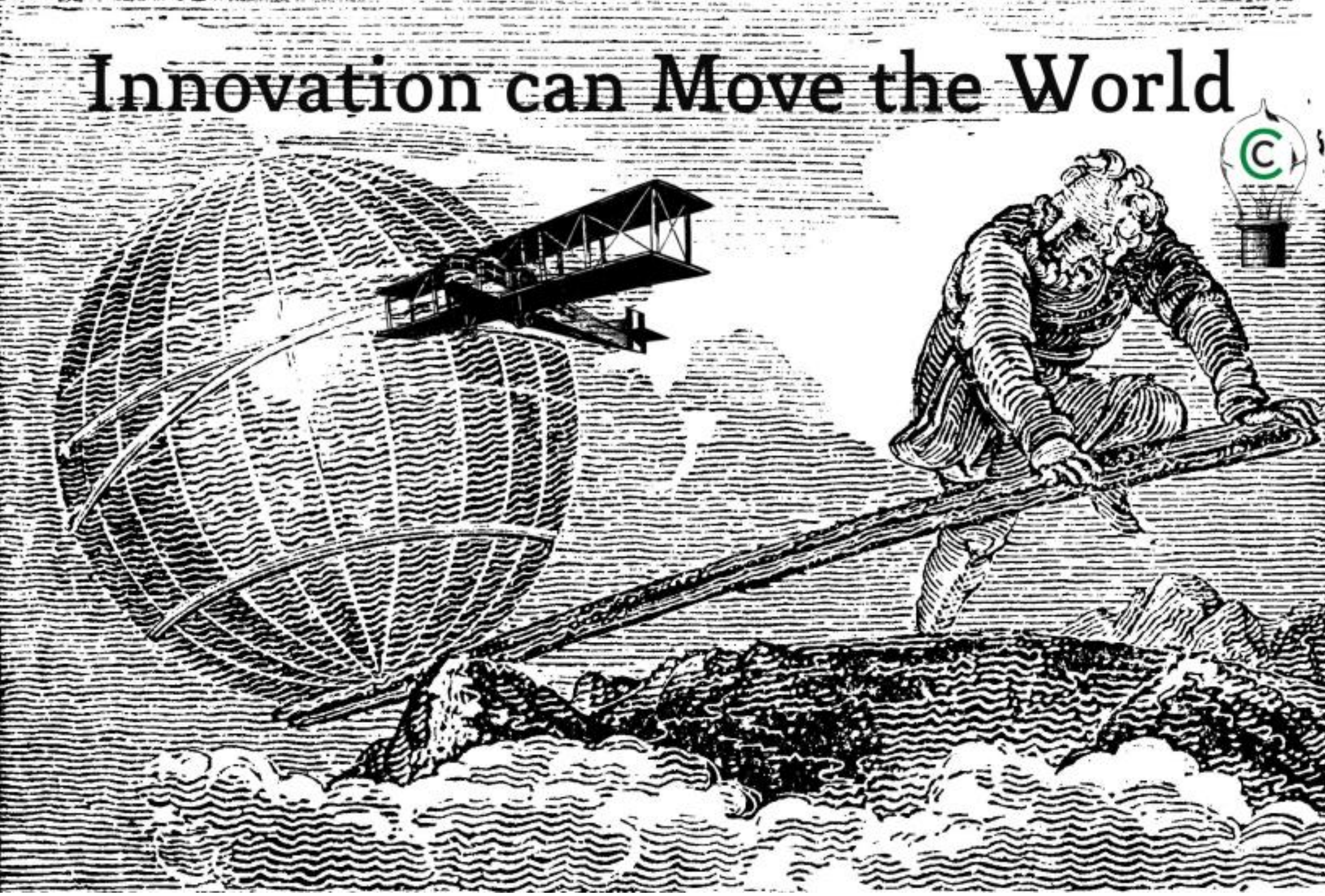

A Short History of Biofuels

Commercializing Innovation

SIXTH ELEMENT
SUSTAINABLE
MANAGEMENT

FOR PUBLIC CIRCULATION

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Introduction

In the modern world, fuels are often equated with fossil fuels: coal, oil and natural gas. However, fossil fuels only came into their own during the 20th century. From the time of the caveman until the early Industrial Revolution, biofuels - namely wood and the advanced biofuel of the day, charcoal - reigned supreme. Both fossil fuels and biofuels originate from biomass. The major difference between them is that fossil fuels are sequestered carbon, and biofuels are renewable carbon. Nowadays, the basic technologies to treat biomass for conversion into gas, liquid or solid fuels (or energy) can be logically placed into four general categories:

1. MECHANICAL: Traditional routes for woody debris are strictly mechanical treatments such as chipping or grinding the material. Greater densification takes place by pelletizing the biomass.
2. THERMOCHEMICAL: Combustion converts biomass into energy, while pyrolysis technology converts biomass into fuel. The latter process not only yields greater energy density than mechanical treatment but the fuel properties are chemically and physically more similar to fossil fuels than the original biomass. A related process is gasification which produces syngas which is a platform technology for the production of a variety of liquid biofuels, through the Fischer-Tropsch (FT) process.
3. CHEMICAL: A route for production of transportation fuels which includes biodiesel, FT, and some cellulosic ethanol processes.
4. BIOCHEMICAL: A common route for production of fuel ethanol from sugar or starch fermentation, and the production of biogas (methane) under anaerobic conditions.

Biofuel Technologies

Mechanical	Thermochemical	Chemical	Biochemical
Chips	Combustion	Biodiesel	Anaerobic Digestion
Hog fuel	Torrefaction (biocoal)	Syngas-FT	Biogas (methane)
Cubing/ Densification	Slow Pyrolysis (biochar)	Cellulosic Ethanol	Cellulosic Ethanol
Wood pellets	Fast Pyrolysis (pyrolysis oil)		Fermentation (ethanol/butanol)
	Hydrothermal (biocrude/hydrochar)		
	Gasification (syngas)		

In this review, I have attempted to identify the inventors and entrepreneurs behind the biofuel technologies listed in the table above.[1] Many are unknown in the modern biofuel literature and far pre-date the names often quoted. Though biofuels appear to have only recently emerged (in response to the threat of climate change), this review illustrates the long rich tradition of their development and utility.

[1] Where possible, hyperlinks to these references are included for the convenience of the reader.

The Biofuel Chronicles[2]

1,000,000 B.C.[3] – **Bioenergy** - *Homo erectus* discovered bioenergy when wood was first burnt. The oldest Greek myths tell of this great invention that was so important it was a proprietary secret of the gods:[4]

> *But Zeus in the anger of his heart hid it, because Prometheus the crafty deceived him; therefore he planned sorrow and mischief against men. He hid fire; but that the noble son of Iapetus* [Prometheus] *stole again for men from Zeus the counsellor in a hollow fennel-stalk, so that Zeus who delights in thunder did not see it. But afterwards Zeus who gathers the clouds said to him in anger:*
>
> > *"Son of Iapetus, surpassing all in cunning, you are glad that you have outwitted me and stolen fire – a great plague to you yourself and to men that shall be. But I will give men as the price for fire an evil thing in which they may all be glad of heart while they embrace their own destruction."*

The "evil thing" that Zeus gave mankind as the "price for fire" was not climate change, but Pandora.[5] By 1875, wood still was the fuel for 75% of the world's energy supply.[6]

30,000 B.C. – **Biofuels** – The first man-made biofuel was **charcoal**, which is formed by the slow pyrolysis of wood. The earliest evidence of charcoal comes from cave paintings, and the first historic references were in the early 6th century B.C. by Theodorus of Samos[7] and Anacharsis.[8] By the time of Alexander the Great, charcoal was already well known in the smelting of ores:[9]

> *The best charcoal is made from the closest wood...for these are the most solid, so that they last longest and are the strongest; wherefore they are used in silver-mines for the first smelting of the ore… But different kinds of charcoal are utilized for different purposes… thus in iron-mines they use that which is made from sweet chestnut when the iron has been already smelted, and in silver-mines they use charcoal of pine-wood… Smiths require charcoal of fir rather than oak.*

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[2] Please forward other early references to the attention of the author.

[3] Hirst, K.K., *The Discovery of Fire – Two Million Years of Campfire Stories*.

[4] Hesiod *Works and Days* 47-59. The most famous rendition of this tale on stealing trade secrets of the gods is *Prometheus Bound* by Aeschylus (c. 525-c. 456 B.C.). The tale begins with a discussion with the god of fire (Hephaestus), Power (*Kratos*) and Force (*Bia*).

[5] Hesiod *Theogony* 507-616.

[6] Victor, N.M., and Victor, D.G. 2002, *Macro Patterns in the Use of Traditional Biomass Fuels*,; also see Victor, D.G., *Biomass Use in the Developing World*.

[7] "He it was who advised laying charcoal embers under the foundations of the temples" (Diogenes Laertius 2.103); Theodorus was known to Herodotus (1.51, 3.41).

[8] "And he declared the strangest thing he had seen in Greece to be that they leave the smoke on the mountains and convey the fuel [charcoal] to the city" (Diogenes Laertius 1.104).

[9] Theophrastus *Enquiry into Plants* 5.9.1-3.

Theophrastus (371-287 B.C.) also described coal, which he called *stone charcoal* (*lithos anthrakos*),[10] and the great Roman naturalist Pliny (23-79) utilized similar terminology: *There is also a stone 'anthracitis,' which is dug up in Thesprotia* [northwest Greece] *and resembles charcoal*.[11] These brief descriptions present coal as not much more than a curiosity and demonstrate the priority of charcoal (and wood) as the ancient fuels of choice. The word "coal," itself, is derived from the Old English word *col* (pronounced "kohl"), but *col* only referred to charcoal originally; coal, as we now know it, was first referred to as "sea coal,"[12] and the modern understanding of the term did not come into routine use until the 17th century.[13] World charcoal production is now over fifty million tonnes per year.[14]

Charcoal is best known today as a barbeque briquette. An early patent on the briquetting of charcoal (using treated bitumen as a binder) was filed in 1888 by Charles Rave of Malines, Belgium.[15] Since his discovery was an "improved" binder, such briquetting must have been well known at this time. A pioneer in the charcoal briquette business was Ellsworth B. A. Zwoyer (1862-1946). He had opened the Zwoyer Fuel Company around 1900.[16] The company first made briquetting equipment, which produced the traditional pillow-shaped briquette; Zwoyer had patented the design back in 1897,[17] and the company was reported to be producing charcoal briquettes just after World War I.

4000 B.C. – **Liquid Biofuels** – The first liquid biofuel, **straight vegetable oil**, was used as a fuel for pottery lamps since the beginning of civilization. Such traditional fuels include olive, castor, rapeseed and other plant oils. Herodotus (484-25 B.C.) described the ancient Festival of Lamps in Egypt:[18]

> *At Sais, on the night of the sacrifices, everybody burns a great number of lights in the open air, with a floating wick which keeps burning throughout the night. The festival is called the Festival of Lamps, and even the Egyptians who cannot attend it mark the night of the sacrifice by lighting lamps, so that on that night lamps are burning not in Sais only but throughout the country.*

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[10] Theophrastus *On Stones* 16.

[11] Pliny 37.27; also see 37.73.

[12] William Shakespeare (1564-1616), for example, mentioned sea coal in *Henry IV* (Part 2, line 87). The term persisted into more modern times, appearing, for example, in *Don Juan* (X, verse 82) by Lord Byron (1788-1824), and *Moby Dick* (chapter 118, paragraph 8) by Herman Melville (1819-91).

[13] Nef, John Ulric 2005, *The Rise of the British Coal Industry*, Abingdon, Frank Cass & Co; Volume 1, p. 4.

[14] UN Data

[15] U.S. patent 425,905, April 15, 1890; Rave also had a patent related to torrefaction, UK patent 3270, November 4, 1872; for other early patents on charcoal briquettes see U.S. patent 695,210, March 11, 1902; 741,728, October 20, 1903.

[16] Malcolmson, C.T. 1911, *Briquetted Coal*, *The Armour Engineer*, Vol. 3 (1).

[17] U.S. patent D27,483, August 3, 1897; however, a similar design had been patented earlier by G. Hutteman and G. Spiecker on January 4, 1895, Luxemburg pat. 2213. For a later patent of Zwoyer see U.S patent 1,632,052, June 14, 1927.

[18] Herodotus 2.62; Herodotus also mentioned the extraction of oil from the castor-oil plant, which was also used in lamps in Egypt (2.94) and the only oil in Babylon was sesame oil (1.193).

In fact, the word "oil" comes from the Greek word for "olive tree" (*elaia*). According to Greek mythology, a famous contest was held between Athena and Poseidon over who would be the protector of Athens; Athena won because she had been the first to plant the olive tree.[19] A ceremony took place in Athens to honour this event:[20]

> *Kallimachos [fl. 5th cent. B.C.] made a golden lamp for the goddess. They fill this lamp with oil, and then wait for the same day in the following year though it shines perpetually night and day. The wick in it is Carpasian flax, the only kind of flax fire will not consume.*

By the late 18th century, there was still a large energy market for vegetable oils. Thomas Jefferson (1743-1826)[21] and John Adams (1745-1826)[22] commented on the major vegetable oil market in Europe; their reference to vegetable oil is likely rapeseed oil (*Brassica campestris*), also known as colza oil in France and Spain. During the Napoleonic War, France adopted colza oil as a fuel, because whale oil shipments had been cut off. It became a favorite of lighthouses, and afterwards its use spread throughout Europe.[23]

400 B.C. - **Biochar** - Although not a biofuel, an interesting application of charcoal especially in agricultural applications is called biochar. The use of charcoal as a plant growth promoter (a component of *terra preta*) in South America may date back to 400 B.C.[24] One of the first modern studies on the impact of charcoal on agriculture was carried out by Arthur Young (1741-1820) in 1770. During the 19th century, many references appeared on the use of charcoal as a soil additive,[25] and the first observation that charcoal increased crop yields was made by John Lawes (1814-1900).[26] The most famous scientist examining biochar at the time was Justus Liebig (1803-73), "the father of the fertilizer industry."[27]

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19 Apollodorus 3.14.1; Herodotus 8.55.
20 Pausanias 1.26.7; also see Herodotus 8.54.
21 Jefferson, T. 1830, *Memoirs, Correspondence, and Miscellanies from the Papers of Thomas Jefferson*, Volume 2, p. 390.
22 Adams, J., and Adams, C.F. 1853, *The Works of John Adams, the Second President of the United States*, p. 108.
23 Hains, P.C. 1877, *Lighthouse Illumination*, Johnson's New Universal Cyclopaedia, p. 31.
24 King, Ryan 2013, *Biochar a Brief History and Developing Future*.
25 Lehmann, J., and Joseph, S. 2012, *Biochar for Environmental Management: Science and Technology*, Routledge, pp. 3-5 (also see 2nd edition, 2015); an early modern researcher into *terra preta* was Wim Sombroek (1934-2003).
26 Spokas, Kurt 2015, History of Biochar Use.
27 For an excellent review, see Wilson, Kelpie, Justus von Liebig and the Birth of Modern Biochar, *Ithaka*.

A.D. 50 – **Biomass Power** – The principle of using of biomass to fuel a steam engine dates back two thousand years. Vitruvius (c. 80 B.C.–10 A.D.) described the aeolipile:[28] "the water begins to boil, a violent wind issues forth. Thus a simple experiment enables us to ascertain and determine the causes and effects of the great operations of the heavens and the winds." The use of steam to do work had been discovered by Heron of Alexandria (c. 10 - 70), who had invented the prototype of the steam engine:[29] "As the cauldron gets hot it will be found that the steam, entering the ball...passes out through the bent tubes towards the lid, and causes the ball to revolve, as in the case of the dancing figures." He also described a steam boiler.[30]

1100 – **Ethanol** – The first man-made liquid biofuel, though not originally used for this purpose, was alcohol (i.e., diluted ethanol). The production of alcohol by fermentation also goes back to the beginnings of civilization. Wine was a popular drink with the ancient Egyptians.[31] After the flood, Noah first planted a vineyard,[32] and in Greek mythology, the god Dionysus (Bacchus) was closely associated with wine and wine-making.[33] An early technical discussion on wine-making appeared from Pliny (c. 23-79) [in Book XIV of his *Natural History*], where he listed the earlier Greeks who had investigated fermentation technology:[34]

> *But it may also be proper to give an account of the method of preparing wine, as Greek authors have written special treatises on this subject and have made a scientific system for it – Euphronius, Aristomachus, Commiades and Hicesius.*

The distillation of alcohol is necessary to produce a fuel, which may have been first achieved by the noted 9th century Arabian alchemists, Abu Mūsā Jābir ibn Hayyān (c. 721-c. 815), Abu Yūsuf Ya'qūb ibn 'Isḥāq aṣ-Ṣabbāḥ al-Kindī (c. 801-73) and Abū Bakr Muhammad ibn Zakariyyā al-Rāzī (854-925). However, in a detailed study of distillation, the discovery of the process was attributed to Magister Salernus (?-1167), who called the distilled product "*aqua ardens*." Unlike simple fermented alcohol, *aqua ardens* contained a high enough ethanol content that it could be burned. Raymond Lull (c. 1232- c. 1315) was the first to produce absolute alcohol (i.e., ethanol), which was often called *aqua vitae*.[35]

[28] Vitruvius, 6.2; derived from the Greek for the "ball of Aeolus," the god of wind.
[29] Heron *Pneumatics* 50.
[30] Heron *Pneumatics* 74.
[31] David, R. 1998. *Handbook to Life in Ancient Egypt*, Oxford University Press, New York, p. 290.
[32] Gen. 9:20, 21.
[33] Nonnus *Dionysiaca* 39.63-5. For examples of wine in Homer, see, for example, Homer *Iliad* 6.623; *Odyssey* 9.
[34] Pliny 14.24.
[35] Forbes, R.J. 1970. *A Short History of the Art of Distillation*, E.J. Brill, Leiden, p. 88-90.

1630 – **Biogas**[36] – Jan Baptiste van Helmont (1580-1644) had recorded a flammable gas coming off decomposing vegetable matter in 1630, and, in 1659, Thomas Shirley (1564-c. 1634) had made the following observation:[37]

> *The people of this town* [Wigan] *did confidently affirm, that the water of this spring did burn like oyle… For when we came to said spring…and applied a lighted candle to the surface of the water; 'tis true, there was suddenly a large flame produced, which burnt vigorously.*

In 1808, the noted chemist Humphrey Davy (1778-1829) conducted a pioneering study of the fermentation of manure:[38]

> *In October, 1808, I filled a large retort, capable of holding three pints of water, with some hot fermenting manure, consisting principally of the litter and dung of cattle… in three days 35 cubical inches* [of gas] *had been formed which, when analyzed, were found to contain 21 cubical inches of carbonic acid* [CO_2]*; the remainder was a hydrocarbonate mixture.*

Starting around 1900, various ventures emerged to use the gas from the fermentation of wastes as a fuel. In a report by Arthur M. Bushwell in 1930, he concluded:[39]

> *It is believed that the completion of some developmental work now in progress will make it possible for farms and ranges to install digestion tanks in which various crop residuals may be converted in considerable amounts to a gaseous fuel of high heat value. The undigested residual can be composted and returned to the soil…*
>
> *It is also probable that small towns located in the corn belt could be supplied with gas in the same way…*
>
> *As our coal, oil, and gas supplies become exhausted the installation of pipe lines fed by fermentation plants located along them at short distances would seem the most probable line of development.*

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[36] I would like to thank Roland Schnell, lecturer on biomass, bioenergy and biogas, at SRH Hochschule Berlin, for discussions on this topic.

[37] Shirley, Thomas 1667, The Description of a Well, and Earth in Lancashire, Taking Fire by a Candle Approached to it, *Philosophical Transactions* 2, pp. 484-5. The observation of Shirley may have been from natural gas, since the site was near a coal deposit; in 1774, Benjamin Franklin (1706-90) wrote to Joseph Priestley (1733-1804) about an experiment where he had stirred up mud in a swamp and released a gas that burnt with a strong flame [Benjamin Franklin 1774, *Letter to Joseph Priestley*, April 10]. Methane, the prime component of biogas, was not discovered until 1776 by Alexander Volta (1745-1827).

[38] Davy, Humphrey 1840, *The Collected Works of Sir Humphrey Davy*, Vol. VIII, *Elements of Agricultural Chemistry*, Part II, Lecture VI, p. 31. A later study on the fermentation of manure was conducted by Ulysse Gayon (1845-1929) [Anon. 1884, Illuminating Gas from Fermenting Manure, *Scientific American* 50 (17), p. 257].

[39] Bushwell, A.M. 1930, Production of Fuel Gas by Anaerobic Fermentations, *Industrial and Engineering Chemistry*, 22, November, p. 1168; also see Boruff, C.S., and Bushwell, A.M. 1929, Fermentation Products of Cellulose, *Industrial and Engineering Chemistry*, 21, December, p. 1181; and Boruff, C.S., and Bushwell, A.M. 1930, Fermentation Products from Corn Stalks, *Industrial and Engineering Chemistry*, 22, September, p. 931.

1720 – **Whale Oil** - Oil was shipped around the globe a century before the first oil wells were even dug. London, Paris and other great cities of Europe used the liquid fuel to light their streets. National economies, especially that of the colonial U.S., depended on its trade. Whale oil was the first liquid fuel traded as a global commodity. Oil shipments out of Nantucket were underway by 1720.[40] The major customer for American whale oil had been Britain, and, after the War of Independence, the British slapped a duty on American whale imports, which crippled the economy of the young nation.[41] The status of the American oil industry was summarized by Thomas Jefferson in 1788:[42]

> *Whale-oil enters, as a raw material, into several branches of manufacture, as of wool, leather, soap; it is used also in painting, architecture, and navigation. But its great consumption is in lighting houses and cities. For this last purpose, however, it has a powerful competitor in vegetable oils.*

By the early 19th century, a premium market developed for sperm whale oil, which was more prized and expensive than common whale oil. So popular did this oil become that the term "whale oil" was only applied to the other whale oils, mainly from the Right Whale, in a derogatory manner; any respectable person purchased only the premium product, sperm oil. Herman Melville (1819-91) immortalized the trade in his *Moby Dick*, written in 1851, at the height of the oil industry. In his timeless work on the legendary white whale, whale oil is only mentioned once, as an "inferior article in commerce" (Book 1, Chapter 2), but sperm oil is frequently mentioned, including (Chapter 25):

> *What kind of oil is used at coronations? Certainly it cannot be olive oil, nor macassar oil*[43]*, nor castor oil, nor bear's oil, nor train oil*[44]*, nor cod-liver oil. What can it possibly be, but sperm oil in its unmanufactured, unpolluted stated, the sweetest of all oils?*

American whale oil shipments overall had peaked at this time. Supply was becoming a problem and the new product kerosene (a fossil fuel) began displacing whale oil for lamps. Whale oil, although natural, was not sustainable for the scale required; in other words, the whales were being killed off faster than they could reproduce.

[40] Starbuck, A. 1878, *History of the American Whale Fishery*, p. 20.
[41] Starbuck, A. 1878, *History of the American Whale Fishery*, p. 78.
[42] Jefferson, T. 1830, *Memoirs, Correspondence, and Miscellanies from the Papers of Thomas Jefferson*, Volume 2, p. 390.
[43] Coconut or palm oil, named after the Indonesian port of Macassar.
[44] Common whale oil.

1801 – **Biomass Gasification** – The concept of biomass gasification may have been suggested by the noted inventor John Barber (1734-1801) in his pioneering patent for the gas turbine in 1791.[45] Six years later, Philippe Lebon (or Le Bon) D'Humbersin (1767-1804) began his studies into wood gasification, and he put on a dramatic light demonstration in Paris, fueled by the gasification of wood, in 1801.[46] How far he would have taken his novel innovation, we shall never know; on December 2, 1804, Lebon was murdered. Wilhelm Lampadius (1772-1842) was reported to be working on the gasification of wood at the same time as Lebon.[47] A large wood gasifier (updraft) was built by Karl Gustav Bischof (1792-1870) in 1835, and charcoal gasifiers were opened in Audincourt, France, by Joseph-Jacques Ebelman (1814-52) in 1840, and in Lesjofors, Sweden by Gustav Ekman.[48] Fish-oil gas was first produced from a process patented by John Taylor (1779-1863) in June 1815, which was briefly popular in Liverpool, Bristol and Hull.[49]

1819 – **Ethanol-Cellulosic-Acid Hydrolysis** - Henri Braconnot (1780-1855) treated linen (i.e., cellulose) with concentrated sulfuric acid to produce fermentable sugars[50] and, later, Einar Simonsen (1867-1918)[51] conducted experiments treating sawdust with acids. The first commercial application to produce ethanol from wood was the Classen Process, developed by Alexander Classen (1843–1934) in Germany in 1900[52] (and when brought over to the U.S., it became known as the "American Process"). A facility (Standard Alcohol Company) was installed in Georgetown, SC, in 1913, and a second one in Fullerton, LA. An improved technology was invented by Heinrich Scholler in 1923, and a commercial facility was constructed in Tornesch, Germany, in 1931; by 1941, twenty such plants were operating across Germany. The Scholler Process was improved by the Forest Products Laboratory in the U.S. during the mid-1940's, which led to the Madison Wood-sugar Process.[53] Cellulosic ethanol has also been produced in the past by sulfite pulp mills, whereby wood sugars in the spent pulping liquor were fermented, which is discussed below, under "Ethanol-Cellulosic-Sulfite Pulp Mills."

[45] See, for example, *John Barber*. I could only find the abstract of his patent which does not specifically mention wood: British patent 1833, October 31, 1791.
[46] Oakes, E.H. 2002, *A to Z of STS Scientists*, Facts on File, New York.
[47] See, for example, Kaupp, A. 1984. *History of Gas Producer Engine Systems*, Springer.
[48] Rowan, Frederick J. 1886, On Gas Producers, *Minutes of Proceedings of the Institution of Civil Engineers* 84, pp. 8-11. A very detailed history of wood and charcoal gasification in Sweden during WWII (with earlier references) is presented by Reed, T.B., and Jantzen, D. (trans.) 1979. *Generator Gas: the Swedish Experience from 1939-1945*, Solar Energy Research Institute, Boulder, CO.
[49] Hughes, S. 1858, *A Treatise on Gas-Works*, John Weale, London, pp. 17-9. The Taylor patent is often listed as a reference to the use of "oil" in gasification, implying petroleum, but this is not the case, as the oil came from fish.
[50] Braconnot, H. 1819, Verwandlungen des Holzstoffs mittelst Schwefelsäure in Gummi, Zucker und eine eigne Säure, und mittelst Kali in Ulmin; *Annalen der Physik*, 63, p. 348; also see *Ann chim. Phys*., 12, p. 172.
[51] Simonsen, E. 1898, *Z. Agnew. Chem*. 195, p. 962.
[52] Ladisch, M.R., Flickinger, M.C., Tsao, G.T. 1979, Fuels and Chemicals from Biomass, *Energy* 4, p. 266.
[53] Stamm, A.J. 1955, Production of Nutrient Substances from Inedible Carbohydrates, *Proceedings, American Philosophical Society*, 95 (1); pp. 69-70.

1826 – **Ethanol-Fuel** – Samuel Morey (1762-1843) described using a mixture of ethanol and turpentine as an engine fuel.[54] One of the first renewable fuels was *burning fluid* - a mixture of ethanol blended in a ratio of 10 parts (or 4 parts) to one part camphene;[55] this product was introduced to replace whale oil in oil lamps. *Burning fluid* was excellent for lighting, except that it was highly flammable. A lamp for burning the mixture had been invented by Isaiah Jennings in 1831.[56] By 1857, one Philadelphia factory was producing more than three million liters of *burning fluid*.[57] In 1862, a tax on industrial ethanol caused the market to collapse, which was not repealed until 1906 by Teddy Roosevelt (1858-1919). The *burning fluid* market never came back but a fuel alcohol market did develop.

By the beginning of the 20th century, ethanol was already a popular automobile fuel. In 1902, there was an automobile race in France for only ethanol-fueled vehicles, and in the same year, there was a conference held in Paris, *Congress des Applications de L'Alcool Denature*, by the Automobile Club of France and the Ministry of Agriculture. During the 1920's, fuel blends had reached 50% ethanol, but engine problems were reported and blends were cut back to 25%. Germany was also an early pioneer in fuel alcohol. In 1899, the *Centrale fur Spiritus Verwerthung* established a tariff-subsidy program to allow ethanol to be price-competitive against regular gasoline. Between 1887 and 1904, German ethanol production rose from 40 million liters to 100 million liters, and reached 250 million liters by the beginning of World War I. And when oil supplies were cut off during the War, most vehicles were switched over to pure ethanol. By 1935, fuel ethanol in Europe totaled 500 million liters: France – 290 million liters, Germany – 47 million liters, Czechoslovakia – 41 million liters.[58]

The country that would lead the world in fuel ethanol during the second half of the 20th century was Brazil. In 1931, the first law was passed requiring gasoline importers to purchase 5% of their volumes as ethanol. And two years later, the *Instituto do Assucar e do Alcool* was established to promote fuel alcohol. At this time, there was only one ethanol producer in Brazil, who was producing 100,000 liters. By 1939, there were 31, with an annual production of more than 50 million liters. During World War II, production reached 77 million liters and fuel blends were as high as 50%.[59]

The great American ethanol-fuel entrepreneur was Henry Ford. When he designed his first car in 1896, the Quadricycle, it was designed to run on pure ethanol, as was the original Model-T. Henry Ford also supported the Agrol Company, a grain-to-ethanol facility, as it rolled out a 10% ethanol-fuel blend across 2,000 service stations during the Depression. In 1925, Ford stated:[60]

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[54] Morey, Samuel 1826, Morey's Explosive Engine, *American Journal of Science and Arts*, 11, p. 104; also see U.S. patent 4378, 1826.
[55] Russell, L. and Holmes, J. 2003, *A Heritage of Light: Lamps and Lighting in the Early Canadian Home*, p. 93.
[56] Isaiah Jennings, U.S. patent X6680, 1831, U.S. patent 29, 1836, U.S. patent 31, 1836, U.S. patent 1453, 1839; also see John Ratcliff, Canada patent 25, 1831.
[57] Russell, L. and Holmes, J. 2003, *A Heritage of Light: Lamps and Lighting in the Early Canadian Home*,, p. 94; also see Kovarik, W. 2001, *Ethanol's First Century*.
[58] Kovarik, W. 2001, *Ethanol's First Century*.
[59] Kovarik, W. 2001, *Ethanol's First Century*.
[60] Ford, Henry 1925, Ford Predicts Fuel from Vegetation, *New York Times*, September 20; see also see Kovarik, W. 1998, Henry Ford, Charles Kettering and the Fuel of the Future, *Automotive History Review* 32, p. 7. For a review

The fuel of the future is going to come from fruit like that sumach out by the road, or from apples, weeds, sawdust — almost anything. There is fuel in every bit of vegetable matter that can be fermented. There's enough alcohol in one year's yield of an acre of potatoes to drive the machinery necessary to cultivate the fields for a hundred years.

Eight years earlier, similar words had been spoken by another entrepreneurial visionary, Alexander Graham Bell (1847-1922):[61]

There is, however, one other source of fuel supply which may perhaps solve this problem of the future. Alcohol makes a beautiful, clean, and efficient fuel, and, where not intended for consumption by human beings, can be manufactured very cheaply in an indigestible or even poisonous form. Wood alcohol, for example, can be employed as a fuel, and we can make alcohol from sawdust, a waste product of our mills.

Alcohol can also be manufactured from corn stalks, and in fact from almost any vegetable matter capable of fermentation. Our growing crops and even weeds can be used. The waste products of our farms are available for this purpose and even the garbage from our cities. We need never fear the exhaustion of our present fuel supplies so long as we can produce an annual crop of alcohol to any extent desired.

The world will probably depend upon alcohol more and more as time goes on, and a great field of usefulness is opening up for the engineer who will modify our machinery to enable alcohol to be used as the source of power.

1835 – **Torrefied Biomass** - Adéodat Dufournel (1808–82) had proposed torrefied wood in metallurgical processes to replace charcoal which was first put it into practice by Jean-Nicolas Houzeau-Muiron (1801–44). Other pioneers in this area were Leonce Thomas (1812–70), Camille Laurent and François-Clément Sauvage[62] (1814–72). France was the early centre of research in torrefied wood, where it was called "red charcoal" (*charbon roux*; in Germany, it was called *Rothkohl*; another early name was "brown charcoal").[63] Torrefaction trials had been carried out in Senuc,[64] and at Dupont and Dreyfus[65] in Chéhéry. In 1839, Dupont and Dreyfus were issued a French patent on the torrefaction (and carbonization) of wood. The year before another torrefaction patent had been issued to Belgium metallurgist F.G. Echement, and this technology was installed at Chéhéry in 1839. Torrefied wood saw limited commercial use at

of the fuel ethanol business in the U.S. during the 1920's, see Kitman, Jamie 2016, The War Against Ethanol, Part I, August 18; The War Against Ethanol, Part II, September 26, *Automobile Magazine*.

[61] Bell, Alexander Graham 1917, Prizes for the Inventor, *National Geographic* 31 (2).

[62] Sauvage, François-Clément 1839, *Sur la Fabrication du Charbon Roux en Foret*, *Annales des Mines*, 3rd Series, Volume 16, pp. 657-62; Sauvage, François-Clément 1840, *Sur la Fabrication en Foret du Bois Torrefie*, *Annales des Mines*, 3rd Series, Volume 18, pp. 3-38, 677-706.

[63] Saint-Ange, W. de 1838, Metallurgie du Fer,, Part I, p. 217.

[64] Saint-Ange, W. de 1838, Metallurgie du Fer, Part II, p. 194.

[65] Founded by Auguste Dupont (1792–1883), his son Mayer (1816–84), and son-in-law, Adolphe-Isaac Dreyfus (1802–84) in 1836.

iron works in France, Belgium and Germany, but was generally not successful.[66] Later, a commercial operation by the metallurgical industry opened again in France: a 10,000 tonne-per-year facility was built by Pechiney at Laval-de-Cère, France, in 1985, but the facility was closed after a few years, but was reopened in 1997, under the name Arôbois,[67] which still manufactures specialty torrefied oak products for the wine industry.

The self-binding property of torrefied wood was discovered later in the 19th century. For example, a U.S. patent on torrefaction from 1901 states.[68]

> *The first period of carbonization, which is only partial and will give a brown* [wood] *dust suitable for briquetting…when the dust comes out brown all the pyroligneous acid is vaporized and the fiber of the sawdust is left intact and can be readily pressed into briquets of any desired shape without requiring binder.*

Another early American report of torrefaction was by Cleburne Ammen Basore (1893-1974) in his *Fuel Briquettes from Southern Pine Sawdust* in 1929.

1846 – **Biodiesel** – Straight vegetable oil (SVO) was the first known liquid fuel and had been known since the beginning of civilization (see above). Freidrich Rochieder (1819-74) in 1846[69] and the Irish chemist Patrick J. Duffy (1829-87) in 1853[70] discovered the **transesterification** of such oils, and the process was patented to produce a fuel by Georges Chavanne (1875–1941) in 1937.[71]

Returning to SVO, Rudolph Diesel (1858-1913), himself, built a model of his engine which ran on peanut oil in 1900, and he later proudly espoused SVO for the Diesel engine:[72]

> *But it is not yet generally known that it is possible to use animal and vegetable oils direct in Diesel motors. In 1900 a small Diesel engine was exhibited at the Paris exhibition by the Otto Company, which, on the suggestion of the French government, was run on Arachide oil, and operated so well that very few people were aware of the fact. The motor was built for ordinary oils, and without any modification was run on vegetable oil. I have repeated these experiments on a large scale with full success and entire confirmation of the results formerly obtained. The French Government had in mind the*

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[66] Early reviews in this area are by Ronalds, E., and Richardson, E. 1855, *Chemical Technology*, Vol. 1, Part 1, Fuel and its Applications, p. 90; Percy, J. 1875, *Metallurgy: the Art of Extracting Metals from their Ores*, p. 408; Fernow, B. 1879, *Transactions of the American Institute of Mining Engineers*, Vol. 6, The Economy Effected by the Use of Red Charcoal p. 201.
[67] Anon 2000, La torréfaction à l'export, *La Dépêche du Midi*, January 22; I wish to thank Roland Schnell of SRH Hochschule Berlin for bringing this article to my attention.
[68] U.S. patent 683,268, September 24, 1901; also see U.S. patent 683,269.
[69] Demirbas, A. 2010, *Biorefineries: For Biomass Upgrading Facilities*, Springer, London, p. 82.
[70] Duffy, P. 1853, On the Constitution of Stearic Acid, *J Chem Soc*, 5, p. 303. This reference is often erroneously cited as "E. Duffy and J. Patrick."
[71] Belgium patent 422,877, August 31, 1937.
[72] Diesel, Rudolf 1916. *Diesel Engines for Land and Marine Work*, D. Van Nostrand, New York, p. 4; also see p. 7.

utilization of the large quantities of arachide or ground nuts available in the African colonies and easy to cultivate, for, by this means, the colonies can be provided with power and industries, without the necessity of importing coal or liquid fuel,

Similar experiments have also been made in St. Petersburg with castor oil with equal success. Even animal oils, such as fish oil, have been tried with perfect success.

If at present the applicability of vegetable and animal oils to Diesel motors seems insignificant, it may develop in the course of time to reach an importance equal to that of natural liquid fuels and tar oil. Twelve years ago we were no more advanced with the tar oils than to-day is the case with the vegetable oils; and how important have they now become!

We cannot predict at present the role which these oils will have to play in the colonies in days to come. However, they give the certainty that motive power can be produced by the agricultural transformation of the heat of the sun, even when our total natural store of solid and liquid fuel will be exhausted.

1861 – **Biobutanol** - Louis Pasteur (1822–95) had been the first to discover butanol from fermentation in 1861 and, in 1905, Franz Schardinger (1853-1920) found that acetone was also produced in this process. Six years later, Auguste Fernbach (1860-1939) found an organism to ferment potatoes to acetone and butanol;[73] and the technology was installed at Rainham (later moved to King's Lynn), England, by Strange and Graham, in 1913. In 1916, Chaim (Charles) Weizmann (1874-1952)[74] patented a process to manufacture acetone, butanol and ethanol (ABE) from the fermentation of starch. The King's Lynn facility switched to the improved technology of Weizmann, and it was also used at Poole, England, and Toronto, ON (Gooderham and Worts Distillery),[75] and later by the Commercial Solvents Corporation at Terre Haute, IN (1920), Peoria, IL (1923), and Liverpool, England (1935). The last ABE plant (Germiston, South Africa) closed in 1983.[76]

[73] British patent 15,203, 15,204, 1911.

[74] U.S. patent 1,315,585, September 9, 1919; in 1949, he became the first president of Israel.

[75] Gooderham, A.E. 1919. *Report on British Acetones Toronto Limited*, p. 49. The report of almost 700 pages provides exceptional detail of the process. Pictures of the facility can be found at Distillery District Heritage Website.

[76] Jones, David T., and Woods, David R. 1986, Acetone-Butanol Fermentation Revisited, *Microbiological Reviews* 50 (4), p. 484.

1903 – **Ethanol-Cellulosic-Sulfite Pulp Mills** - Sulfite pulp mills,[77] especially dissolving pulp[78] mills, have been producing cellulosic ethanol for over a century. After the pioneering studies of Gösta Ekström (1882-1949) and Hugo Wallin (1876-1946) in 1903, the first production of ethanol from spent sulfite liquor took place at Skutskär, Sweden, in 1909, followed by Donnarspet, Sweden, using the Ekström process. Ethanol production by sulfite pulp mills became common place; for example, Attisholz in Switzerland began producing cellulosic ethanol in 1915 (until 2008),[79] and, later in North America, the sulfite mill of Georgia-Pacific in Bellingham, WA (1946 to 2000, when the mill closed), and the Tembec mill in Temiscaming, Quebec [closed its cellulosic ethanol facility in October 2014, but still produces cellulose, bioenergy (CHP – combined heat and power), and lignosulfonates[80]]. Many of these mills produced more than cellulosic ethanol from the spent sulfite liquors, becoming the earliest **biorefineries**. Another notable example is the Lenzing pulp mill, which produced acetic acid, xylose, and furfural. The world's largest biorefinery operation today is run by Borregaard in Sarpsborg, Norway, which produces cellulose, cellulosic ethanol, lignosulfonates, yeast and vanillin.

1911 - **Hydrothermal Carbonization/Liquefaction** – Friedrich Bergius (1884–1949)[81] discovered a high pressure and temperature hydrogenation of biomass (or coal), in the presence of water. In 1911, he had used this reaction to convert peat into a coal-like substance. In his Nobel Lecture, Bergius stated:[82]

> *With the same apparatus we carried out extensive and systematic experimentation on the decomposition of the cellulose in wood and other plant substances at temperatures between 290 and 350°, in the presence of liquid water, i.e. at pressures of up to about 200 atm.. It would be devious to give details here about this reaction on which I worked for many years, at first with Hugo Specht and John Billwiller, and later with Paul Erasmus. In recent times, the reaction has reawakened the interest of chemists and has been studied in particular by Berl.*[83] *I would like to mention that both cellulose and lignin, treated in this manner, lead to practically the same carbonaceous end products…*

[77] There are three major processes for the pulping of wood – mechanical, kraft and sulfite. Kraft is the dominant pulping process today, which makes most of the pulp to produce high-grade paper and packaging material. Both the kraft and sulfite processes use chemicals to remove the lignin component of the wood to produce pulp: kraft - alkali (caustic soda and sodium sulfide); sulfite – acid (sulfur dioxide).

[78] Almost pure cellulose used in rayon, cellophane and CMC production.

[79] For a review of the early work on cellulosic ethanol see Boullanger E. (trans. De Piolenc, F.M.) 1924, Wood Alcohol, *Distillerie Agricole et Industrielle* (note that the article is erroneously titled "Wood Alcohol," which is reserved for methanol only).

[80] I managed managed the business from 1996 to 2005.

[81] Stranges A.N. 1984, Frederich Bergius and the Rise of the German Synthetic Fuel Industry, *Isis*, 75 (4).

[82] Bergius, F. 1932, *Chemical Reactions Under High Pressure*, Nobel Lecture, May 21, pp. 260, 262-3.

[83] Ernst Berl (1877-1946); see Berl, E, and Schmidt, A. 1928, The Behaviour of Cellulose in Pressure Heating with Water, *Justus Liebigs Ann. Chem.* 461, p. 192; Berl, E., Schmidt, A., and Koch, H. 1932, Über die Entstehung der Kohlen, *Angew. Chem*. 45 (32), p. 517; Berl, E. 1944, Production of Oil from Plant Material, Science 99, p. 309. Recent reviews of hydrothermal liquefaction are: Elliot, D.C., et al. 2015, Hydrothermal Liquefaction of Biomass: Developments from Batch to Continuous Process, *Bioresource Technology* 178, p. 147; Ramirez, J.A., Brown, R.J.,

The investigations into the conversion of cellulose into coal by coalification in conjunction with our studies on the hydrogenation of heavy oils opened the way to the discovery of the process for liquefying coal. We had observed that a product forms from cellulose with splitting of certain quantities of carbon dioxide and water which we considered to be similar to natural coal, and we had further observed that the hydrogen in this so-called synthetic coal is unstable. The attempt to formulate this process of cellulose decomposition led me to a hypothetical concept of the constitution of this coal-like substance formed from cellulose. I assumed that our artificial coal is a compound of carbon, hydrogen, and oxygen…a coal obtained by cellulose coalification passed on treatment with hydrogen at about 150 atm pressure and at temperatures between 400 and 450°, into gaseous, liquid and benzene-soluble substances.

1925 – **Steam Thermal** (steam explosion) – The steam explosion process was discovered by William H. Mason[84] (discoverer of the related Masonite process). A few years later, Leon W. Babcock used the process to release fermentable sugars to produce ethanol.[85] Canadian firms, Iotech (Iogen) of Ottawa and Stake Technology of Toronto, were both early developers of the technology. Stake built a continuous pilot facility at the University of Sherbrooke and another in Italy.[86] Studies on producing pellets from the Stake process were first carried out in Canada by Staffan Melin and John Swaan in 1999.[87] Such pellets are often referred to as "black pellets" (although the term is also used for torrefied pellets). Trials on the production of pellets from steam explosion were also conducted in Norway by Cambi and then by Norsk Pellets Vestmarka, owned by Arbaflame;[88] in 2003, a demonstration plant to produce pellets from a steam explosion process was built in Grasmo, Norway by Arbaflame.

and Rainey, T.J. 2015, A Review of Hydrothermal Liquefaction Bio-Crude Properties and Prospects for Up-grading to Transportation Fuels, *Energies* 8 (7), p. 6765.

[84] U.S. patent 1,655,618, January 10, 1928; also see U.S. patent 1,578,609, March 30, 1926.

[85] U.S. patent 1,855,464, April 26, 1932.

[86] Stake subsequently became SunOpta, and in 2010, this technology was sold to Mascoma. For reviews, see Chen, H. 2015, *Gas Explosion Technology and Biomass Refinery*, Springer, New York, pp. 148-52; Lam, P.S. 2011. *Steam Explosion of Biomass to Produce Durable Wood Pellets*, Ph.D. Thesis, University of British Columbia, Chapter 1.

[87] Staffan Melin personal communications.

[88] Obernberger, I., and Thek, G. 2010. *The Pellet Handbook: The Production and Thermal Utilization of Pellets*, Routledge, London, p. 104.

1972 – **Fast Pyrolysis**[89] – The Occidental Flash Pyrolysis[90] technology was developed to convert organic solid waste (and wood wastes) into a liquid fuel called "Pyrofuel," which became a popular area of research during the 1970's. A milestone in this sector was a workshop on the "Fast Pyrolysis of Biomass," sponsored by the Solar Energy Research Institute (now NREL) in 1980.[91] Among the first commercial processes to produce pyrolysis oil from biomass was one developed by Robert Graham and Barry Freel at the University of Western Ontario.[92] They formed Ensyn in 1984 to commercialize the Rapid Thermal Processing (RTP) process. Equal credit to the founding of the modern pyrolysis field must be given to the University of Waterloo, where work began in the early 1980's. Researchers on the project formed Resource Transforms International (RTI), whose technology was used by a few companies, most notably by Dynamotive.

1976 – **Wood Pellets**[93] - an early patent on wood residual densification to produce a fuel was filed by William Harrold Smith in 1880,[94] but wood-pellet technology came a century later. Rudolf Wilhelm Gunnerman (1928 -)[95] filed a U.S. patent for extruded, self-bonding wood pellets in early 1976, and the following year, a pilot of the process was built by Woodex[96] (owned by Biosolar Research & Development; site later became Northwest Pellet Mills) in Brownsville, OR. In the later '70's, several early ventures emerged including: Western Power in CA (operated 1978 to 1982), Day Resources (Lignetics) in OR, Biomass Energy in ME, Guaranty Fuels in NC, FL and MN, and Aspen Fibre in MN. In Eastern Canada, BioShell (a

[89] For a review of the early work of fast pyrolysis, see Milne, T. 2002, Pyrolysis – The Thermal Behavior of Biomass below 600C, in Reed T.B. (ed.) 2002, *Encyclopedia of Biomass Thermal Conversion*, The Biomass Energy Foundation Press, November, pp. 91-117.

[90] See for example, Mallan, G.S., and Finney, C.S. 1972, New Techniques in the Pyrolysis of Solid Wastes, *AIChE Symp. Ser*., AIChE National Meeting, Minneapolis, MN, Aug; Longanbach, J.R., and Bauer, F. 1975, Fuels and Chemicals by Pyrolysis, *Prepr., Div. Pet. Chem., ACS National Meeting*, Philadelphia, PA, 6 Apr; Boucher, F., Knell, E., Preston, G., and Mallan, G. 1977, *Pyrolysis of Industrial Wastes for Oil and Activated Carbon Recovery*, U.S. Environmental Protection Agency, Washington, D.C., EPA/600/2-77/091 (NTIS PB270961); Chang, P.W., and Preston, G.T. 1981, The Occidental Flash Pyrolysis Process, in *Biomass Conversions Processes for Energy and Fuels*; Springer, p. 173; also see U.S. patent 3,698,882, October 17, 1972; U.S. patent 3,846,096, November 9, 1974; U.S. patent 4,147,593, April 3, 1979.

[91] Anon. 1980, *Specialists' Workshop on Fast Pyrolysis of Biomass Proceedings*, Copper Mountain, CO, October 19-22.

[92] For an overall review see Radlein, D, and Quignard, A. 2013, A Short Historical Review of Fast Pyrolysis, *Oil and Gas Science Technology; Rev. IFP Energies nouvelles*, Vol. 68, No. 4. Other early pioneers in the production of pyrolysis oil from biomass were: Michael J. Antal at the University of Hawaii; Maurice Bergougnou at the University of Western Ontario; Anthony V. Bridgwater at Aston University; James P. Diebold at NREL; Jan Piskorz at the University of Waterloo; Christian Roy at Laval University; Donald Scott at the University of Waterloo.

[93] A review of the early wood pellet industry is given by Callas, B., and Haygreen, J. 1987, *An Analysis of the Densified Wood Fuel Industry in the Lake States*, Miscellaneous Publication 42, Minnesota Agricultural Experimental Station, University of Minnesota.

[94] U.S. patent 233,887, November 2, 1880.

[95] For the controversy on this entrepreneur, see Smith, S. 1978, Fuel for a Fight, *Eugene Register-Guard*, October 15, p. 1D; Smith, S. 1978, Fuel for a Fight III, *Eugene Register-Guard*, October 17, p. 1C.

[96] U.S. patent 4,015,951, April 5, 1977; for an early patent on molding sawdust, see U.S. patent 43,112, June 14, 1864; U.S. patent 959,870, May 31, 1910. A later milestone took place on February 9, 1998, when the first transoceanic shipment of wood pellets was made by Pacific BioEnergy from Prince Rupert, BC, to Helsingborg, Sweden.

division of Shell) built three wood pellet facilities, each with a capacity of 125,000 tpy: Hearst, ON (operated 1980 to 1991); Iroquois Falls, ON; Lac Megantic, QC (opened 1982; purchased by Energex in 1993). In Western Canada, Swaan Bros. (later Pinnacle) carried out wood pellet trials in Quesnel, BC, in 1988. In Sweden, plants were built at Mora which operated from 1982 to 1986 and at Vårgårda from 1984 to 1989.

1977 - **Fischer-Tropsch (**FT/syngas**)** - Franz Fischer (1877-1947) and Hans Tropsch (1889-1935) discovered the process of converting hydrogen and carbon monoxide (syngas from gasification) catalytically to hydrocarbons (i.e. oil) in 1925.[97] The first commercial facility[98] opened in Germany in 1936, and by 1940, production exceeded one million tonnes per year using coal as a feedstock. Although biomass is an obvious carbon source for syngas, there is little evidence of direct work on biomass in an FT process until the studies of James Lowell Kuester (1937-) of Arizona State University in the later 1970's,[99] and the first commercial attempt to do so was by Choren beginning in the mid-90's.

2001 – **Bioenergy with Carbon Capture and Storage** (BECCS, Bio-CCS)[100] – CCS for coal-fired power plants has been under development for a few decades. A milestone in this sector was the formation of the Carbon Capture and Sequestration Technologies program at MIT in 1989. A natural extension of this technology was to use it for carbon dioxide emissions from biomass-fired power plants. In 1998, Robert Williams of Princeton University hinted at BECCS by mentioning decarbonizing biomass fuels and the sequestration of captured carbon dioxide, but the focus of the report was the production of hydrogen from biomass.[101] The process was more clearly laid out in 2001, where Bioenergy Carbon Sequestration (BECS) and "GHG removal" were mentioned.[102] When the IPCC reviewed CCS in 2005, bioenergy was frequently mentioned, and the following was reported: [103]

[97] German patent 411216, 1925; for the early literature on FT see *Fischer Tropsch Archive*.

[98] The commercial development of FT is summarized by Leckel D. 2009, Diesel Production from Fischer-Tropsch: The Past, the Present, and New Concepts, *Energy Fuels* 23 (5), p. 2342.

[99] Kuester, J.L. 1977, *Conversion of Cellulosic and Waste Polymer Material to Gasoline*, Progress Report, US DOE, May; Kuester, J.L. 1979, *Conversion of Cellulosic and Waste Polymer Material to Gasoline*, *Preprint for the Thermal Conversion of Solid Wastes, Residues and Energy Crops Symposium*, American Chemical Society Meeting, Washington, D.C., p. 14, September; Davis, E.A., Kuester, J.L., and Dagby, M.O. 1984, "Biomass Conversion to Liquid Fuels: Potential of some Arizona Chaparral Brush and Tree Species", *Nature*, 307**,** pp. 726-8, February 23; Kuester, J.L, U.S. patent 4,678,860, July 7, 1987.

[100] For a review of the early development of BECCS, see Hickman, L. 2016, *The History of BECCS*. Also see *Scientific Background for BECCS* from the Global CCS Institute.

[101] Williams, R.H. 1998, Fuel decarbonisation for fuel cell applications and sequestration of the separated CO_2; in R.U. Ayres and P.M. Weaver (eds.) *Eco-restructuring: Implications for Sustainable Development*, United Nations University Press, Tokyo, pp. 180-222.

[102] Obersteiner, M., Azar, C., Kauppi, P., Möllersten, K., Moreira, J., Nilsson, S., Read, P., Riahi, K., Schlamadinger, B., Yamagata, Y., Yan, J. and van Ypersele, J.P. 2001, Managing Climate Risk, *Science* 294 (5543) p. 786.

[103] Metz, B., Davidson, O., de Coninck, H., Loos, M., and Meyer, L. 2005 (edit.), *IPCC Special Report on Carbon Dioxide Capture and Storage*, p. 58; bioenegy carbon capture is mentioned throughout the report; especially see section 2.5.3.2 (p. 100), 3.7.8.4 (p. 161), and 8.3.3.5 (p. 358).

Recently it has been recognized that biomass energy used with CO2 capture and storage (BECS) can yield net removal of CO2 from the atmosphere because the CO2 put into storage comes from biomass which has absorbed CO2 from the atmosphere as it grew (Möllersten et al.[104]*, 2003; Azar et al., 2003). The overall effect is referred to as 'negative net emissions'. BECS is a new concept that has received little analysis in technical literature and policy discussions to date.*

Commentary

Biofuels are the dominant renewable fuels today, bringing together the energy, forestry and agricultural sectors. The biofuel industry has undergone a renaissance of sorts in the past few decades as a result of climate change and previous oil crises. Creative engineers, scientists, mechanics, inventors, and other entrepreneurs, applying modern engineering and scientific know-how, have created a host of commercial, and not-so commercial, processes, but we should not forget the great entrepreneurs of yesteryear who are the true pioneers of these technologies.

[104] The Möllersten paper was frequently quoted in the IPCC review: Möllersten, K., J. Yan, and J. Moreira, 2003: Potential market niches for biomass energy with CO2 capture and storage – opportunities for energy supply with negative CO2 emissions, *Biomass and Bioenergy*, 273-285.