Boston University

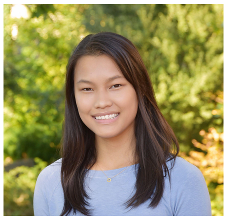
Iron Powder as a Clean Aviation Fuel Source

All team members are Undergraduate Mechanical Engineering students:

Kaylea Gaughan

Hadassah Flagg

Emily Osurman



Michelle Ramoska

Advisor: Dr. Anthony Linn

Abstract

The following will cover our research into iron powder combustion as a potential alternative fuel source for commercial aircraft. The proposed methodology utilizes iron powder as a renewable energy carrier where power is produced via combustion. The technical, social, political, and economic factors surrounding the implementation of this technology are also discussed, in addition to the current state of technology and supply chain readiness. The iron powder itself will be produced through the atomization of molten iron which is melted in induction furnaces. The combustion of iron powder will be used to produce the hot reservoir of a Brayton-Rankine heat cycle that will generate electricity to charge lithium-sulfur batteries. The iron oxide produced by the combustion of iron will be recycled using electrolysis, where the energy required for the process will be derived from renewable energy sources such as solar panels or wind turbines during times when excess powder is produced. Whenever possible, transportation will be through electric vehicles. This paper also details the safety of iron nanoparticles to humans, iron power plant locations, and the potential of retrofitting coal-fired power plants for iron powder as its fuel. Furthermore, our discussion also focuses on the installation and implementation of this technology into the current travel sector.

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Introduction

The goal of transitioning from traditional aviation fuels to alternative fuel sources with little to no emissions is an important and valuable driver for research and development on less explored fuel sources. A potential alternative fuel source involves the combustion of metal powder. Focusing specifically on iron powder, the combustion process, $4Fe(s)+3O_2(g)\rightarrow 2Fe_2O_3(s)$, produces heat that can be harnessed as energy without any carbon dioxide emissions. This makes the fuel source extremely attractive with regards to sustainability. There is ongoing research for the process of recycling iron oxide into iron via electrolysis or by reacting it with hydrogen, allowing the fuel source to be, ideally, infinitely reusable. However, iron has disadvantages as a fuel including a high density (5000 kg/m^3) and low energy density as compared to existing fuels. This particular reaction produces a solid, which would have to be captured and contained aboard the aircraft after the combustion process. For this reason, our main system would be on the ground charging batteries, which would be used to power planes. While these types of electric engines do not yet exist, it is reasonable to believe that such a design could be made in 2050.

Justification

The proposed methodology produces energy by combusting iron powder and harnessing the heat byproduct of the reaction. Iron powder will be the main fuel source of an on-site plant that will utilize a heat cycle to produce electricity, which will in turn be used to charge batteries for use on airplanes. There will also be a recycling process to convert the iron oxide byproduct back into iron powder, allowing the plant to maintain a cyclical process, as depicted in Figure 1.

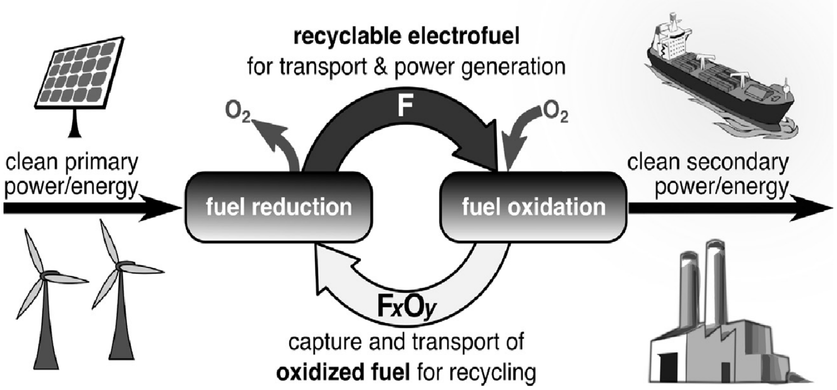

Figure 1: A graphic depiction of the cyclical life of electrofuels [1].

While narrowing our prospects of potential future fuel sources, we first decided on metal powder combustion. See Figure 2 for an energy density comparison between various fuels, including metals. Our investigation of metals included iron, aluminum, and magnesium. Each metal was researched and the selection was based on weight gain after combustion, stability as an energy carrier, cost, accessibility, and energy density. In order to find the respective weight gain of the fuels, the focus was made on the energy required to fly for two hours which was approximated to be $1.29\text{x}10^6$ MJ. See Appendix B for this calculation and comparison. The fuel that would be best based solely on weight for an on flight fuel combustion would be magnesium and the least favorable would be iron. The cost of these metals vary based on the accessibility and demand but generally iron has peaked around \$0.21 per kg [2], magnesium around \$10.62 per kg [3], and aluminum around \$3.50 per kg [4].

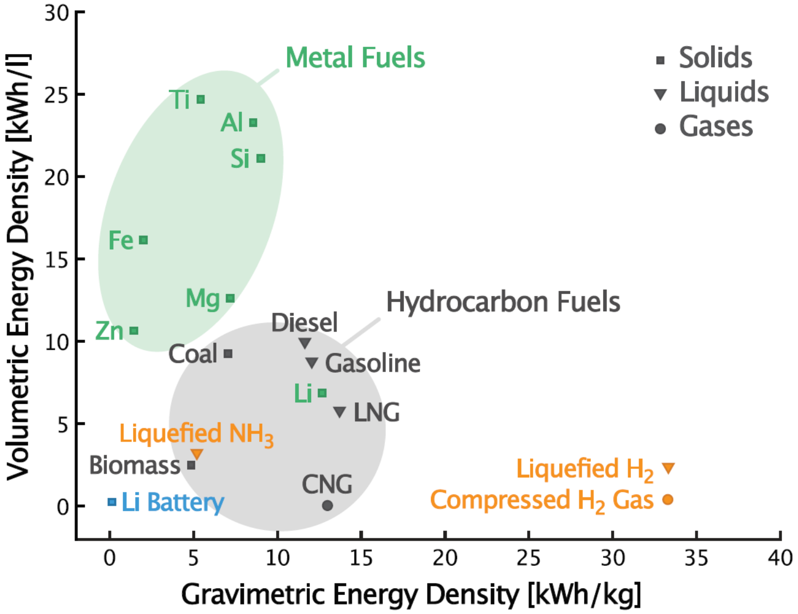

Figure 2: A graph comparing fuels by gravimetric and volumetric energy densities [5].

Iron was determined the best metal option but was further reinforced by a case study of a brewery in The Netherlands that fully relies on iron powder combustion for the heat required in its beer brewing process. Primarily created by the Eindhoven University of Technology's Team SOLID group,"Brewery Swinkels" is equipped with a megawatt-size iron fueled power plant that will be sustainable for the next twenty years. To power the facility, iron is burned ina boiler, and iron oxide is created along with steam as a by-product. This method of renewable energy is a zero-carbon source of power. The company, in addition to powering their industry on iron powder, are currently researching a clean way to regenerate the fuel through electrolysis [6]. Understanding the "Brewery Swinkels" power plant is key when considering the application of metal as a flight fuel source.

Climate Impacts

The impact that metal combustion has on the environment is the most significant factor in deciding on a new sustainable fuel source. Generally, metal oxides, the byproduct of metal powder combustion, are known to produce nanoparticles under 100 nm in diameter. These nanoparticles could potentially leach into ecosystems and disrupt the functioning and health of humans, plants, and animals. More specifically, these particles negatively influence plant metabolism which, as a consequence, can accumulate within agricultural crops that are then consumed by humans [7]. Looking more closely at the effects of Fe_2O_3, in a study involving nanoparticle exposure on zebrafish habitats, iron oxide was found to "exhibit low to no toxicity in plant seeds," but a "high toxicity… in aquatic environments" [8]. From this observation, iron (III) oxide would be a concern within bodies of water as well as bioaccumulation in the seafood that is harvested from the ocean every year. Furthermore, improper industrial disposal can worsen the spread of nanoparticles which could inadvertently impact the ocean's absorption of carbon dioxide by interfering with aquatic ecosystems. However, it is worth noting that very little research has been done on the toxicity of iron oxide nanoparticles in the environment. This study is one of the only experiments done to gain information on the effects of iron oxide nanoparticles on plants and animals. Furthermore, because the iron powder combustion would not take place on the plane there would not be as much transportation as if it did and therefore there is a reduced risk of environmental contamination.

On the other hand, the examination of jet-A fuel's harmful effects on the environment are arguably worse than those associated with iron powder combustion. The report, "Toxicological Profile for JP-5, JP-8, and Jet A Fuels," warns that "accidental releases could potentially occur at production (refineries) or storage (e.g., airport) facilities” [9], thereby contaminating air, water, and soil. Many facilities involved in the handling of Jet A fuel are not required to report releases of the fuel, so its effects can be greater than what is documented.

Source to Flight Life Cycle

The source to the flight lifecycle of iron powder starts with mining iron ore. Iron ore will be mined in the United States and Australia. While the shipment cost of CO_2 is higher from Australia, not all of the iron can be mined in the United States because of mining laws and sourcing of the iron powder. Australia will source some of the iron as well because the US has protected land that cannot be mined and therefore would not provide enough for the aviation industry. Mining of iron is typically done with an excavation of a large open pit, as each layer is excavated more iron is exposed and mined out of the site [10]. The mining industry accounts for 0.4 gigatons of CO_2 emissions world wide: including loading, hauling, and the excavation of the site [10]. From one excavation site the approximate amount of CO_2 is about 11.9 kg per 1 ton of iron [11]. After the iron is extracted, it must be transported from Australia. The iron is taken on a train and then on a bulk carrier ship. While in the United States, it is transported on a truck. International shipping accounts for 440 million metric tons of materials from bulk carriers [12]. Due to the weight of the iron ore, bulk carriers must be used over the more environmentally friendly choice of cargo ships. The iron ore is brought to ports by train which in total only accounts for 26.5 g of CO_2 on average per cargo trip [13, 14]. Once the iron is on the bulk carrier ship it accounts for approximately 16.4 g per km of CO_2 [15]. In total, an average trip from Sydney to Los Angeles for raw materials is 12,066 km resulting in a total CO_2 output of 197 kg of CO_2 per 5 tons of iron. Once iron is brought to facilities in the US via electric trucks, the iron ore is turned into usable iron powder. This process is done through combustion and the electricity provided to the iron will come from renewable energy. The iron powder will then be placed into the designed heat cycle to produce energy for the aviation batteries. Following the energy production, the batteries are taken by electric vehicles and brought to airports to fuel the plane. Overall, the approximate source to flight cost of iron is 267 kg of CO_2. This can be improved by making mining practices more sustainable and creating more efficient and clean overseas shipping options.

Technical, Social, Political, and Financial Factors

Technical Factors

There are challenges that come with every system. A few issues to address are the possibility of rust, high burning temperature of iron, and full combustion of iron powder. Rust is the hydrated form of iron (III) oxide. Its presence in power cycles can lead to equipment corrosion as well as particle deposits in the boiler, which reduces the rate of heat transfer and slows the water flow rate [16]. The key to mitigating the presence of rust in the system is condensation management within the combustion chamber and material selection. For example, a chromium oxide coating is currently used on stainless steel to prevent corrosion, and zinc coatings could also be applied to steel or iron.

Iron powder can theoretically burn at up to 1976℃, so the combustion chamber material would have to easily withstand temperatures of this magnitude [17]. Eindhoven University of Technology’s Power & Flow group conducted a study of burning iron powders of various sizes from five vendors and found that a quartz tube burner was adequate for the gas temperature, which reached over 1830℃. They also devised a dispersion system made up of four parts: the powder reservoir bottle, a pinch valve to control flow rate, an ejector to deliver the powder to the carrier gas line, and a scale to measure the powder mass. This dispersion system creates a fluidized mixture of iron powder and air, which allows for optimal surface area and full combustion of the powder [18].

In terms of current technology readiness, Renewable Iron Fuel Technology (RIFT) is making strides developing technology to use iron powder as a fuel source for electricity. RIFT is a start-up dedicated to commercialization of iron-fueled systems formed out of the student group Team SOLID. They are planning to launch an iron fuel boiler for testing in Helmond, Netherlands near Eindhoven in 2025, and the process is currently at Technology Readiness Level 3: proof of concept [19]. Before the commercial roll-out of the iron fuel boiler system, RIFT has plans to build a prototype of a cost-effective industrial iron fuel boiler. Then, they will optimize the boiler and scale it to size, after which a pilot program will ensue, followed by full commercial roll-out, bringing this technology to TRL 9 [20].

Social Factors

The social progress sustainable aviation fuel will have made by the 2050s depends on a number of factors including education and public awareness of the climate crisis, consumer demand for low carbon transportation options, and the accessibility and convenience of sustainably fuelled flights.

Firstly, in order to gain social support from consumers, the public must be well informed of the problem at hand. Within a United Nations article “Education is Key to Addressing Climate Change”, parties of the UN’s Framework Convention on Climate Change (UNFCCC), “undertake educational and public awareness campaigns on climate change, and to ensure public participation in programmes and information access on the issue” [21]. Other organizations and campaigns also contribute to “climate literacy” such as UNESCO, Global Action Programme, Action for Climate Empowerment. By spreading awareness of the facts of climate change, the UNFCCC can reach those who have no specific education on climate impact. This way, individuals are empowered to make well-informed decisions regarding their lifestyle, voting choices, and investments.

The effect of climate change on a community depends on socioeconomic factors as well as racial and ethnic background. In a survey given to American adults mentioned in “Gen Z, Millennials Stand Out for Climate Change Activism, Social Media Engagement With Issue,” 68% of participants who identified as Black, 55% of those who identify as Hispanic, and 38% of those who identified as White prioritize “help for lower-income communities when considering climate policy proposals.” Middle- and upper-income Black adults as well as Hispanic adults were found to have similar responses to the survey, regardless of income level. Therefore, taking into account the correlation between race and socioeconomic status within the U.S. the survey shows how marginalized communities of color and/or those of low income may be left out of the larger picture when considering policies that affect their quality of life more so than Middle-Upper class White communities.

The social progress surrounding climate change also depends on workers that make these innovations possible. In the case of iron powder, a much improved yet ongoing issue is the treatment and working conditions of those in the mining industry. The demand for iron ore would drastically increase with the implementation of iron powder as a sustainable aviation fuel source. As there is a shortage in mining employees, countries may not be able to produce enough iron ore to meet this demand. In an article outlining the major challenges within mining, it is reported that “71 percent of mining leaders are finding the talent shortage is holding them back from delivering on production targets and strategic objectives… particularly in specialized fields such as mine planning, process engineering, and digital” [22]. Going forward with this plan without changing the mining industry may hinder the quality and efficiency of production as well as worsen working conditions for those who do work in this challenging field. This presents challenges to the goal of implementing iron powder combustion as a sustainable aviation fuel source by 2050.

Political Factors

Political factors affecting implementation of sustainable fuels play a large role in the hesitations of remodeling energy as we know it. Oil and gas trade is a driving factor for many countries' economies and interpersonal relationships with other nations. Given the immense weight that fuel carries on various factors, many political figures and entities oppose the timeline of transitioning to sustainable fuels [23] or oppose the shift entirely. In addition to the opposition of sustainable flight practices, this cannot be a transition that is done within one state in the United States or one individual country because the airline industry is a global business. If one airline company changes their fuel source then there has to be a shift and commitment by all private companies to start the transition to a new fuel as well. This is when coalitions like the Federal Aviation Administration would need to become involved to discuss fuel would need to be established. In order to regulate this process and mediate the implementation, another commission should be formed that has its priority in the fuel industry. The integration of a new fuel worldwide will require many policy changes and global community action; however, with time and compromise, a new sustainable fuel source would benefit all. The Head of Energy Efficiency at the International Energy Agency states, “an estimated 14 million new jobs are generated in energy supply by 2030. Over the same period, fossil fuel production could lose 5 million positions, resulting in a net gain of 9 million in this pathway” [24]. While jobs will be lost from the shift away from fossil fuels, more jobs will be gained because of the installation, upkeep, and research that will go into renewable energy.

Australia, The United States, Canada, and Brazil [25] are countries with the largest amount of iron ore accessible. Of all the iron ore mined from these countries the largest exported amount of iron is in China which consumes about 70% of all the iron [26] mined in the world. From a political standpoint many issues can arise with trade issues. Since the end of World War II, China and the US have had high political tensions [27] regarding trade, supply chain, and the overall economy of each nation. This change in fuel will eventually impact the world; however, the focus for the 2050 timeline is on China, the United States, and Australia. As Australia is the largest producer of iron in the world, their country sets the cost and amount exported. Australia’s economy has been strengthened by this export since June 2019 [28] and is predicted to have a steady increase because of their access to natural resources. Today in 2023, the demand for iron in the United States is significantly less than China’s and will continue to rapidly increase as the initial iron is bought for the fuel source. The iron combustion is a recyclable process, once the US has purchased necessary iron powder for the fleet the purchase of iron will rapidly decrease. The initial rise of demand for iron will greatly impact the price of iron as well as the tensions between the US and China, potentially for 20 - 50 years.

Financial Factors

In terms of economic feasibility, the competition between metal combustion and fossil fuels would be the largest challenge that this energy source would face, similar to many other sustainable fuel sources. Fossil fuels offer a low cost to energy ratio, which is why they are globally mainstreamed. However, the long term benefits of flying on metal combustion powder outweigh the short term convenience of fossil fuels considering the detrimental effects caused by the production of greenhouse gasses such as CO_2. To go into further detail, iron has an energy density of 5.2 MJ/kg [29] and a cost per unit mass of roughly \$0.06/lb (\$0.12/kg) in February 2023 [30]. Although there are economic disadvantages to using metal powder rather than conventional jet fuel, iron (III) oxide is recyclable and thereby has a longer energy life cycle than fossil fuels, whose byproducts remain in the atmosphere for hundreds to thousands of years. Other metals such as magnesium, boron, and aluminum were considered, but they either were not plentiful enough in their elemental form, too expensive, or energy inefficient, and therefore would not be economically feasible. Iron is also plentiful and is a mass-manufactured material, making it a large contender as a sustainable fuel source within commercial flight.

Safety Considerations

Iron oxide nanoparticles are becoming more commonly used in biomedical, electronic, cosmetic, and environmental applications. However, the potential and actual adverse health outcomes are widely debated. The few studies on iron oxide nanoparticles that exist have contradictory results due, in part, to exposure to other substances in addition to iron oxide and uncontrolled experimental environments. As of 1988, the Occupational Safety and Health Administration (OSHA) recommends a permissible exposure limit of 10 mg/m^3 for iron oxide fumes over the course of an 8-hour work day, while the American Conference of Governmental Industrial Hygienists (ACGIH) and National Institute for Occupational Safety & Health (NIOSH) recommend 5 mg/m^3 over the course of a 10-hour work day [31].

In a study involving 14 workers in an iron oxide pigment production facility, workers were exposed to iron oxide nanoparticles over the course of about 10 years with 80% of those particles less than 100 nm in diameter. The study showed elevated oxidative stress and inflammatory biomarkers in exhaled breath condensate and urine [32]. This suggests that iron oxide nanoparticles can be harmful with long-term occupational exposure. However, a more thorough evaluation with a larger sample size is necessary for further exposure limit recommendations to be made.

Additionally, at least a dozen *in vivo* toxicity studies on mice and rats have been conducted with iron particles ranging from 10 nm to 280 nanometers. The test subjects were exposed to iron oxide nanoparticles through various methods including inhalation, intratracheal instillation, intrapulmonary administration, and a dry powder nasal spray. The adverse health outcomes include inflammation, liver damage, fibrosis, liver damage, and lung damage, all resulting from varying degrees of exposure. These particles rapidly enter the circulatory system and can travel to other major organ systems, causing tissue damage at the secondary exposure sites [33]. Taking into account this lab research and existing exposure recommendations, workers should wear protective equipment like masks and goggles to limit their exposure to iron oxide nanoparticles according to OSHA and NIOSH recommendations.

Technology Readiness

Conversion from Thermal Energy to Electricity

The previously mentioned "Brewery Swinkels" project is equipped with a megawatt-size iron-fueled power plant that will be sustainable for twenty years. In order to produce the heat needed during the brewing process, they have a boiler where iron is burned and iron oxide is created with steam as a by-product. The company, in addition to powering their industry on iron powder, is currently researching a clean way to regenerate the fuel through electrolysis. The "Brewery Swinkels" power plant and Team SOLID's achievements can be further built upon to produce an iron fuel power plant.

A conventional, state-of-the-art approach is to use a steam turbine to generate electricity. The thermal efficiency of a Rankine cycle is only around 35-40% and can be improved by adding reheat and/or regenerative processes or adding a Brayton cycle for a combined cycle system. The Brayton cycle is the topping cycle with a higher working temperature. The high heat energy from the exhaust gas is transferred to the working fluid in the Rankine cycle in a waste heat recovery boiler [34]. Combined cycle gas turbine (CCGT) power plants require either nickel or cobalt alloys for high steam temperatures. By preheating the water before it enters, the system efficiency is increased. Chubu Electric Power Co., Inc. and Toshiba Energy System & Solutions Corporation have collaborated to produce the world's highest efficiency combined cycle thermal power plant as of 2017, with an efficiency of 63.08% [35]. In the 2050s landscape, the efficiency has potential to increase even more with heat loss evaluations.

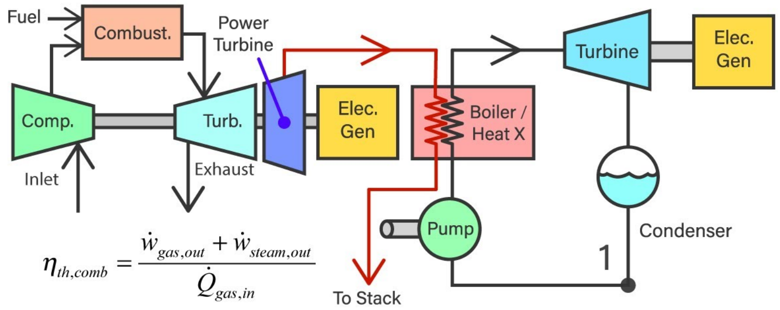

Figure 3: Brayton-Rankine Combined Cycle Diagram [36]

In addition to researching the main heat cycle, residual waste heat can be used for electricity generation. Researchers from Stanford University and MIT have collaborated to create an electrochemical system for harvesting low-grade heat and converting it to electricity. Their theory is based on the thermogalvanic effect, which is how electrode potential changes based on its temperature. This system generated current with a specific current density 7.2mA/g and electrical energy generated had a net energy density of 5.2 J/g. When heat recuperation is not used, the cycle efficiency is 3.7% as opposed to 5.5% that can be achieved with 50% heat recuperation. This type of solid-state system has a low, incremental efficiency with a low energy output in comparison to the main cycle, so for economic reasons, this would not be initially implemented in our system but could be added later for increased overall system efficiency.

Current Battery Capabilities

Once energy is generated by the combustion of iron powder, the energy will be transported to the plane using an electric battery. Various types of batteries have been tested in electrical vehicles such as lithium ion batteries, nickel-metal hydride batteries, lead-acid batteries, and capacitors [37]. Lithium ion batteries are most commonly used because of their lightweight properties, accessibility, price, and overall energy density. In addition to their design, the US government is planning on creating a recycling program specifically for these types of batteries. Nickel-metal hydrides also have high energy density but is less accessible and much more expensive. Lead-acid batteries are promising for their functionality but have many safety issues as they are very toxic. Due to the comparison of energy densities and accessibility of the various battery options a lithium battery would be the best choice. Lithium is currently in very high demand given the current need for the material in electric cars such as Tesla's [38], on a smaller scale for phone and computer batteries, and even in medical equipment such as pacemakers. Given the immense amount of research done on lithium there are even more promising batteries that will be viable in 2050.

The University of Michigan conducted research undertaking the challenge of increasing the life cycle of lithium-sulfur batteries. Their research found that the lithium-sulfur design could quadruple the energy capacity of a traditional lithium ion battery. The use of sulfur increases the batteries threshold for extreme cold or warm temperatures, are more lightweight than their lithium ion counterparts, and the batteries can have up to a 10-year life span [39]. Given the promising results from multiple sources of research, the best option for aviation usage would be a lithium-sulfur battery. Some of the further challenges of implementing this technology to aerospace can include storage, charging capabilities, longevity, and transportation.

Supply Chain Readiness

Iron Powder Supply Chain

The iron supply chain manages the inbound and outbound logistics and warehousing of metal powder manufacturing. The first step of the metal fuel's life cycle is mining the iron in its raw form. Those raw materials are then processed, labeled as inventory, and sent to the customer where the manufacturing process takes place.

The dominant businesses within the iron supply chain are BHP Billiton, Vale, and Rio Tinto which are able to produce iron efficiently. Since they are large companies, they can afford to increase their production and decrease per unit cost, which decreases the company's operating cost, thereby creating an economy of scale [40]. BHP Billiton and Rio Tinto have ore mines in Australia and Vale has mines located in Brazil. These two countries had the highest iron ore production in 2019, with Australia at 906 MMT and Brazil at 405 million metric tons.

Metal powder can be manufactured through a number of different methods including, atomization, solid-state reduction, electrolysis, and chemical processes. Atomization is commonly used to make commercial iron powder. In this process, molten scrap metal is poured between jets of high-pressure fluid, usually water, causing the metal particles to disintegrate and solidify into solid powder [41]. It is important to consider the type of furnace used to melt the iron before the atomization process. Industrial furnaces that are fueled by natural gas or coal would produce carbon dioxide. However, induction furnaces work by passing alternating current through a coil that surrounds a metal chamber. This changes the magnetic field within the metal thereby inducing Eddy currents which convert the energy from electricity into heat [42]. Induction furnaces are considered a green technology as they do not produce CO_2 or any hazardous waste.

The countries involved in the supply chain also have varying degrees of demand for iron with China consuming roughly 75% of the global trade in 2020. Therefore, the price per ton of iron depends heavily on China's demand for it. The unit cost of iron has fluctuated in the past decade largely due to the COVID-19 pandemic that started in 2020. At the end of 2015, the unit mass price was $40.88, then pre-pandemic in 2019, the cost went up to a high of $119.59, only to decrease to $83.75 in 2020 due to oversupply and a halted economy. It then increased to $215.82 in 2021 after the effects of the pandemic started to die out and demand for iron ore increased [43]. A current challenge within the supply chain may be overcoming the rise in unit cost for iron ore and navigating future fluctuations in these prices since the supply and demand of iron is largely dependent on only a handful of countries and large businesses. However, because metal combustion is a closed loop process, the majority of the iron powder will be recycled if the cycle has a high efficiency, thereby making the initial investment in the material the bulk of the cost.

Battery Supply Chain

Battery production consists of four main stages: raw material extraction, raw material processing, cell component production, and battery pack production [44]. Lithium-sulfur batteries require less rare metals than traditional lithium-ion batteries, which simplifies the production process. The lithium, sulfur, and aluminum used in the batteries must first be harvested via mining. Lithium can be sourced from either brine or hard rock, while sulfur is typically harvested as a byproduct of natural gas production or oil refinement [45]. For the purpose of this discussion, the more traditional source of sulfur via mining in volcanic regions or on salt domes is preferred as the use of fossil fuels goes against the purpose of the entire endeavor. After raw materials are acquired, they are processed to extract the needed materials in a pure form. Heat or chemical treatments, typically pyrometallurgy or hydrometallurgy, are the processes involved. Cell components are then produced using specialized processes or synthesis, which can finally be combined into cells through energy intensive, highly controlled processes to avoid impurities that would have significant impact on the battery performance.

Looking at the economics of the battery supply chain in terms of lithium-ion batteries, as that is the technology which currently dominates the market, the key country involved is China. China produces three quarters of all lithium-ion batteries in addition to having 70% of global cathode production capacity and 85% for anodes. China is also the site of over half of the world's lithium, cobalt, and graphite processing and refining. Other major regions are Europe which conducts 20% of global cobalt processing, Korea with 15% of global cathode material production, Japan with 14% of cathode production and 11% of anode production, and the US with 7% of the global battery production capacity. Most mining is concentrated in Australia, Chile, and the Democratic Republic of Congo. Russia, Canada, Indonesia, the Philippines, and New Caledonia are also sources of key metals [44].

Necessary Technological Advances by 2050s

Power Plant Locations

The primary focus of the location of the iron plants requires an investigation of the current use of American land use. Only 2% of America's land accounts for its sprawling urban areas [46]. The rest of the land is allocated towards forests accounting for 27%, shrubland for 24%, and 17% is used for agriculture. About 12% of land in the US is protected for national parks and protected wildlife [47]. Since the task at hand is to limit the amount of carbon dioxide produced by the aviation industry, trees and forests will not be cut down for the combustion powder plants. The iron powder combustion chamber would require approximately 32 m^3 of volume per flight. Taking into account that the iron is recyclable and the area of the plant would also have to include several elements of a heat cycle, battery recharging stations, and having additional back-up supplies, the space needed for the plant will be approximately 5,000 square meters per airport. Projecting plans into 2050 there is no comparison today to have an exact value for the size of the combustion plants; however, based on space approximations an estimate could be made. In order to choose where these sites will be located the use of land, location of airports, and transportation of energy will be factored in.

An important factor to keep in mind in order to determine location would be to factor the transportation of the batteries. In 2050, it is believed that electric trucks will be on the market for the transportation of these batteries given the development of electric vehicles by companies such as Tesla, Ford, and the Freightliner eCascadia. These trucks will be able to transport the batteries from respective power plant locations to the airport and will receive batteries to be charged and take them back to the power plants. The power plant locations will be near the busiest airports in the country to start: Hartsfield-Jackson Atlanta International Airport (ATL), Dallas/Fort Worth International (DFW), Chicago O'Hare International (ORD), and several others [48]. Starting with larger airports near open land will allow for larger combustion sites, which can later ship to smaller airports as well. Further in time, more city planning will come into play for airports that are close to share a combustion site. For example Newark Airport, Laguardia Airport and JFK Airport are within 20 miles of each other and could share resources as they are major airports. With continuous planning and several people to oversee the process and manage the implementation, there will be a successful process.

Retrofitting Coal-Fired Power Plants

Regarding the system as a whole, there is potential to retrofit coal-fired power plants to be iron-fueled power plants. A simulation was based off of a 800 MW coal-fired power plant. Changes that are required include a cleaning system, switching to a Biflux heat exchanger, and monitoring combustion temperature more closely. 10-12 cloth filters were used to separate the very fine particles from the exhaust gas and were adequate for minimizing particle emissions, and magnetized filters could have an even better result. A cleaning system must also be implemented to prevent dust deposits on heating surfaces to prevent corrosion and clogging in channels. Although iron powder is more dense than coal, it has a mass flow comparable to lignite, a type of less refined coal which is currently used to fuel power plants. Iron particles with a diameter of 10 to 20 microns is ideal based on reaction kinetics and is comparable to the current downward velocity of coal at the hopper entrance. A Biflux heat exchanger should be used to manage the temperature differential between the high-pressure and intermediate-pressure section of the boiler. Another challenge is to avoid particle agglomeration. Iron particles burned at too high a temperature will enter a liquid phase and collect in a mass. Monitoring the burn temperature will ensure that the atomization process will only have to occur once at the beginning of the process instead of repeatedly melting down the iron oxide every cycle. Otherwise, there would be a 12-18% efficiency loss in the electrolysis recycling process [49].

With the right operating conditions, an iron fuel system could have 2.3% higher efficiency than coal due to the high melting point of iron (III) oxide, which results in less fouling in the radiation heating sections of the boiler. Another benefit to retrofitting an existing coal power plant to fit the needs of iron powder combustion is that a denitrification system is already in place for possible NOx emissions that could result from combusting iron in the presence of nitrogen. This theory is at TRL 3 as of March 2023, but the research group has highlighted the motivation for this method of reusing coal power plants. To bring this technology to TRL 9, a physical demonstration would need to be done as well as prototyping with the above retrofits to a current coal power plant, concluding with successful trials.

Advancement of Battery Technology

The parameters of the advancement of the new fuel is to be implemented by 2050 which requires many technological advancements. Primarily, the main advancements that need to be made are battery capabilities which are constantly being researched and developed. In order for a battery to have the power and durability to apply to aviation, the most promising option is a lithium-sulfur battery. Over the past decade battery development has been rapid as the world becomes increasingly digitized. Many promising companies are currently working towards manufacturing and implementing lithium batteries in vehicles, devices, and aviation. Specifically, Theion, a German battery start-up, believes they will be able to commercialize their lithium battery in an electrical vehicle by 2024 [49]. The current manufacturing issues regarding this battery are preventing corrosion of the sulfur in the capsule. While this battery is not commercialized yet the developments of the battery are promising and projected to hit the market long before 2050. In addition to mobile devices and electric cars, several companies are already applying this technology to aviation leading to an even more promising development for the timeline of this project.

In addition to battery capabilities, developments of sustainable iron powder processing will need development. Currently, the process of making iron powder requires some by-product of CO_2 and connection to the current energy grid which is not sustainable in most cases. In order to update the technology of this process, the energy grid supplied to the facility needs to be from sustainable energy sources. This is possible as the United States in 2021 had approximately 21% of their energy renewable and it is predicted the energy grid will be 44% sustainable by 2050 [50]. In addition to the continual development of sustainable technology, electric trucks will have to be further commercialized in order to transport batteries. Similarly to renewable energy development, electric trucks are all ready in the market or nearing marketability. The most promising company is Freightliner with their eCascadia truck, which is both affordable and fully electric. As the United States is moving towards more sustainable solutions, the technology advancements required by 2050 will be viable for the new aviation industry to be successful.

Conclusion

Our solution to a new sustainable aviation fuel would be successful, projecting towards 2050. Another factor to consider is the impact of the new aviation technology on the current aviation market. While the new fuel would alter the fossil fuel industry forever, it is a necessary change that needs to be made in order to progress towards a sustainable world. This novel, clean fuel technology will create a new demand for jobs, investments, and trade around the world. In order to resolve many of the long lasting effects of climate change, our habits, purchases, and fuel sources need to be altered. Using iron powder as a fuel for the aviation industry would drastically alter the aviation market and contribute to the fight against climate change.

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Appendix B: Flight Energy and Metal Mass Calculations

How much energy does a 2hr flight use?

1. Stages
    a. Takeoff: ~2000 kg fuel (Average between Boeing 737-800, and both 747-400 models) [B1]
    b. Cruising: 2h*1gal/s (high estimate, according to [B2] & [B3]) = 7200 gal =~ 27.25m^3
    c. Landing: likely negligible, maybe 30min*1gal/s = 1800 gal =~ 6.81m^3

BP Jet A-1 has a density of 804 kg/m^3 (at 15C) [B4]:
2000 kg takeoff, 21909 kg cruising, 5475 kg landing → ~30000 kg fuel → 1.29x10^6 MJ

Metal	Atomic Mass (g/mol)	Reaction	Oxide Atomic Mass (g/mol)	Atomic Mass Difference (g/mol)
Fe	55.845 [B6]	$4Fe+3O_2 \rightarrow 2Fe_2O_3$	159.687	103.842
Mg	24.305 [B7]	$2Mg+O_2 \rightarrow 2MgO$	40.304	15.999
Al	26.982 [B8]	$4Al+3O_2 \rightarrow 2Al_2O_3$	101.961	74.979

Metal	Specific Energy (MJ/kg) [B5]	Mass For 2h Flight (kg)	Mass After Flight (kg)	Mass Gain (kg)
Fe	5.2	248,077	354,684	106,607
Mg	24.7	52,227	86,605	34,379
Al	31	41,613	78,625	37,012

Mass for flight: $1.29x10^6 MJ/(Specific\ Energy,\ MJ/kg)$

ex. Iron: $1.29x10^6 MJ/5.2MJ/kg = 248,077\ kg$

Mass after flight: $(Oxide\ mass)/(Pure\ mass) * (Flight\ mass) * (Mol\ Oxide)/(Mol\ Pure)$

ex. Iron: $159.687/55.845 * 248,077 * 2/4 = 354,684\ kg$

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Appendix C: Thermodynamic & Electrolytic Calculations

When burned in oxygen, iron powder oxidizes to form iron oxide (Fe2O3) which has an enthalpy of formation of approximately 5,000 kJ per kg of iron oxide, or 7150 kJ per kg of iron [C1, C2]. When burning 1 kg of iron powder in a 10 cubic meter chamber filled with air, the temperature of the chamber would increase by approximately 578 degrees Celsius as calculated below. The temperature of the flame itself can reach up to almost 2000 degrees Celsius, as the adiabatic flame temperature of iron is 2250 K [C4].

$$10\, m^3\; air\, *\, \frac{1.2\, kg}{1\, m^3} = 12\, kg\; air \text{ [C3]}$$

$$7150\, kJ\, *\, \frac{kg\; air * K}{0.7\, kJ} \simeq 10200\, kg\; air\; *\; K \text{ [C3]}$$

$$\frac{10200\;\; kg\; air * K}{12\, kg\; air} \simeq 851\, K\, =\, 578\, C$$

For the electrolysis process, the energy required is governed by the standard change in free energy of the reaction (G) which is calculated using the number of electrons (n), Faraday's constant (F), and the applied voltage (E):

$$\Delta G\, =\, nFE$$

The reduction of iron oxide involves the transfer of 3 electrons per mole of iron :

$$\frac{1}{2} Fe_2 O_3 \rightarrow Fe + \frac{3}{2} O_2(g) \text{ (overall)}$$

$$Fe^{3+} + 3e^{-} \rightarrow Fe \text{ (cathode)}$$

$$\frac{3}{2} O^{2-} \rightarrow \frac{3}{2} O_2 + 3e^{-} \text{ (anode)}$$

The free energy of the reaction with an electric potential of 1.8 volts is calculated:

$$\Delta G\, =\, 3\, *\, 1.8\, *\, 96,485.3321\, =\, 521021\, kJ/kmol\; of\; Fe$$

Converting from kJ/kmol to kWh/kg Fe:

$$521021\, kJ/kmol\, =\, \frac{521021\, kJ/kmol\; of\; Fe}{56\, kg/kmol\; Fe * 3600s} = 2.58\, kWh/kg\; Fe$$

As previously discussed, the enthalpy of formation of iron oxide is approximately 5,000 kJ/kg Fe_2O_3. Converting to kWh/kg Fe:

$$5,000\, kJ/kg\; Fe2O3\, =\, \frac{160\, kg\; Fe2O3}{1\, kmol\; Fe2O3} \frac{1\, kmol\; Fe2O3}{2\, kmol\; Fe} \frac{1\, kmol\; Fe}{56\, kg\; Fe} \frac{1}{3600s} = 1.98\, kWh/kg\; Fe$$

Which results in an efficiency of approximately 77% for electrolysis via:

$$\frac{1.97\, kWh/kg\; Fe\; via\; burning}{2.58\, kWh/kg\; Fe\; to\; recycle} = 76.7\%\; efficiency$$

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