The External Factors of Internal Combustion

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Christian Prestegard

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Rider W. Foley, Department of Engineering and Society

Introduction

With the past 20 years seeing major development in electric vehicles and hybrid powertrains coupled with increasing scrutiny of carbon emissions and their effect on the environment, engineers and environmentalists alike have begun to question the need for internal combustion. The major problem with this is that there is currently no equal machinery capable of doing what the internal combustion engine (ICE) does. Internal combustion engines generate power through the combustion of a fuel, which powers an element of the engine (pistons, fans, or shafts) to move. In aircraft, that movement generates propulsion; in automobiles, that movement confers onto a driveshaft that powers the wheels; in power plants, that mechanical energy is turned into electrical energy. Ultimately the effect is the same: fuel goes in, power comes out. The main drawback of internal combustion engines is the byproduct of gaseous exhaust, which is rife with hydrocarbons. The main argument for internal combustion over electric power is established infrastructure. ICE's are widely available through mass production, inexpensive to operate, easy to diagnose and repair, and relatively easy to power given the ubiquity of fuel. In terms of arguments against ICE's, their main drawback is their obvious adverse effects on the environment as well as their low thermal efficiency, which typically ranges between 30-35% in automobiles (Aaa, 2015) and 30-40% in passenger aircraft. Currently in the aviation industry there are ongoing efforts to make use of more sustainable fuels for aircraft, which may be a promising way for aircraft as they exist today to continue to operate while further development is made in the sphere of hybrid-electric propulsion (Kocal et al., 2020). Additionally, researchers around the world are developing models for assessing the benefits of possible hybrid architectures for aircraft engines, going as far as developing new sizing models for these hypothetical aircraft to prove that they can feasibly be manufactured and deployed as passenger aircraft (Jimenez et al., 2022). Conversely, electric power, while being inexpensive and producing no direct emissions through its use, is not widely available yet. Also, the argument can be made that electric power in vehicles is often just as deleterious as internal combustion because the power for these electrical systems comes largely from power plants, which use internal combustion or even nuclear power. Of course, countries like Norway generate electricity from hydroelectric plants (energifaktanorge.no, 2022), but few regions have access to the kind of tidal power required to make a genuine difference to their electrical grid. The difficulty with electric power is mainly a question of origin and availability. Another option for fuel that serves as a theoretical alternative for hydrocarbon-based power is hydrogen combustion, but research in this area is ongoing and not entirely promising (Williams et al., 2002). With all of this in mind, the most potent question now is: how will engineers reconcile modern needs currently satisfied by internal combustion with a burgeoning concern for its effect on the environment?

The main STS theory I will be using to analyze my topic will be technological momentum (Hughes et al., 1989). Hughes's theory of technological momentum proposes that technologies can take on a momentum of their own, where once they become established and integrated into society, they are difficult to displace even in the face of better alternatives. This is because technologies are not just physical objects but are also social systems that rely on institutions, standards, and infrastructures. The internal combustion engine is an excellent example of a technology that has gained significant momentum over the past century, becoming the dominant means of powering transportation and industrial machinery. Despite the growing recognition of the negative environmental impacts of fossil fuels, the internal combustion engine still holds an essential position in our society. As alternative technologies, such as electric vehicles and renewable energy sources, continue to develop, it is possible that the momentum of the internal combustion engine may begin to diminish. Nevertheless, the strength of its momentum means that the transition to a new paradigm may not happen quickly or smoothly, and may require significant institutional and infrastructural changes. As Hughes mentions in his work, large technological systems attract attention from finance, regulatory, and government bodies soon after their inception. With so many industries being directly or indirectly affected by aviation and modern transport, it is safe to say that internal combustion powers the modern world to its core in finance, government, travel, trade, and even defense. Currently, the aviation industry alone employs nearly 30 million people globally (aviationbenefits.org, 2022) and accounts for nearly $175 billion in global market share (Salas, 2022). It is undeniable that aviation plays a major role in global function today; however, what is truly astonishing is that aviation, ground transport, and shipping are only three examples of industries that are fundamentally reliant on internal combustion, with countless more just like them. If the internal combustion engine were to cease to exist tomorrow, it is no exaggeration to say that the world as we know it would collapse. This is all to say that the internal combustion's formidable momentum comes from the fact that so many facets of modern life are rooted in its use. That being said, with global warming rates more than doubling in the last century, the modern world may face new environmental threats as a result of artificially sustaining combustion power (Dahlman, 2022). Indeed, environmental concerns may be one way to reveal that internal combustion is not an "autonomous" technological behemoth, and will likely need continuous and careful upkeep in order to maintain its momentum and make the ICE agreeable to increasingly strict environmental regulations.

Internal combustion has become synonymous with automotive and aviatic travel and no extensible alternatives had been developed until the 21st century. As such, even bearing in mind the adverse environmental effects caused by the use of internal combustion, how could society even begin to move away from it? I believe that this generation is in the nascent stages of a technological revolution that will seek to answer that question and I am excited to play a part in that through my analysis of this topic.

As a future aerospace engineer as well as an automotive fanatic, the question of how engineers will be able to adapt the ICE to modern requirements for reduced emissions and increased efficiency will likely define the futures of both my career and my passion. The answer, I suspect, will take many decades of incredibly hard work by many brilliant engineers to fully materialize. Although the solution to this problem is clearly far from simple I would like to start my own work towards it through this research.

In terms of my approach to this topic, I intend for my main source of information to come from interviews with experts in the areas of aviation, combustion power, and alternative fuels. I currently have three individuals in mind for my interviews: Kurt Prestegard, a Norwegian aerospace engineer (and my grandfather) with over 50 years of experience in the industry as well as a refined perspective on sustainability being from one of the world's "greenest" countries; Keith Williams, a professor of electrical engineering at the University of Virginia who has done extensive research and published works on the feasibility and scalability of hydrogen power; and Jesse Quinlan, a professor of aerospace engineering at the University of Virginia and branch head of the systems analysis and concepts directorate at NASA Langley, who is the director of my technical project and is uniquely qualified to discuss the state-of-the-art regarding hybrid-electric propulsion. I believe each of these gentlemen will provide extremely valuable information regarding my STS topic and I look forward to discussing it in depth with them.

Methods

The information I have gathered in order to answer this question has come from a comprehensive literature review as well as the three personal interviews with individuals covering various areas of my question. Additionally, I have pooled much information from my own literature research as well as from these individuals, all of whom I asked to provide me with any articles or other resources that they thought would be helpful in my research. Finally, throughout the course of my capstone project, I have learned a lot with regard to the projected state-of-the-art in hybrid-electric aviation and was able to incorporate some of that information into this research. The analysis stage of my research took place mostly throughout my collection phase, as I was reading documents and/or charts and speaking with my chosen experts.

I was able to keep the theory of technological momentum in mind throughout my research, especially during my interviews. Many of my questions were geared toward the potential changes to the engineering landscape regarding internal combustion and whether or not they would happen at all as a result of the formidable significance of the internal combustion engine in today's industry. Without even necessarily prioritizing it in my mind, technological momentum was a central idea throughout my data collection.

Results

In terms of my research question, the qualitative, basic answer that has crystallized over the course of my research is that engineers may seek to make ICE's more environmentally friendly rather than completely replacing them, which is seemingly the goal of many industry leaders. My results have not only shown that ICE's are deeply ingrained in our global infrastructure, but also that many common alternatives today are either equally harmful to the environment in the aggregate or simply not practical for widespread use. Indeed, these findings are closely aligned with the theory of technological momentum, which I had suspected would be the case.

My literature review encompassed several of the alternatives to both combustion engines and their hydrocarbon-based fuels. To begin, the advent of electric cars in the past ten years has taken the automotive industry by storm, but while these vehicles produce no exhaust themselves, questions have been raised regarding their long-term sustainability. The two main factors contributing to this apprehension are the sources of their electric power as well as the origins of the materials required to manufacture their batteries. Firstly, EV's draw their power from the electrical power grid, which in the US is powered mainly by fuel-burning power plants. While EV's may not burn their own fuel, substantial carbon emissions can still be traced down the line to the power plants that provide the electricity required to charge their batteries. Secondly, the mining of rare earth metals, which are required for the production of the lithium-ion batteries used in EV's and other battery-powered systems, has had a massive environmental impact, specifically in the areas where these resources are found (Institute for Energy Research, 2020). It is also impossible to know the humanitarian implications of this mining. Cobalt is another key element in the production of lithium-ion batteries and it is abundant in both China and the Democratic Republic of the Congo, both of which are notorious for their dubious child labor policies (Tom Lantos Human Rights Commission, 2022), (Bureau of International Labor Affairs, 2023). Also, longevity and recycling of lithium-ion batteries is currently very low. In addition to the traceable impact of the powering of EV's, they also consume both tires and tarmac at a much faster rate than internal combustion vehicles on account of their increased weight and torque. Tires on electric vehicles wear 20% faster than their internal combustion counterparts. And while some manufacturers are looking to manufacture special tires for EV's, most on the road today just use regular market tires (M.ryu, 2022). Roads are degraded overtime as cars drive over them, mainly due to the weight and friction produced by their tires. With EV's operating in excess of internal combustion vehicles in both of those areas, it stands to reason that widespread EV use would degrade roads more rapidly. It happens that both tarmac and tire rubber require tar for their production, which produces even more CO_2 than conventional oil (US EPA, 2000). With all of these facts in mind, it becomes more difficult to think of EV's as a feasible solution to the carbon footprint of combustion-powered automobiles.

Next, research into hydrogen as an alternative fuel has been the subject of much scrutiny over the past two decades. Background information on hydrogen storage suggests that storage of gaseous hydrogen requires high-pressure tanks, whereas storage of liquid hydrogen requires cryogenic temperatures (energy.gov, 2023). Neither of these storage methods are ideal for automotive or aviatic applications, as high-pressure tanks could explode when exposed to forces in a crash or high temperatures from a fire, and cryogenic storage requires substantial energy of its own. As such, it would be ideal if hydrogen fuel could be stored at ambient conditions. For this topic, I looked to Professor Williams for insight. From my interview, he was able to provide me with some key points around hydrogen fuel. From our interview, he explained that much of his work in graduate school focused on hydrogen storage in carbon nanomaterials. These materials can have very high specific surface area, which would enable them to store hydrogen very densely in ambient conditions, provided that the hydrogen could adsorb to the carbon structure. There was literature to suggest that this was possible, which attracted funding from prominent companies like Honda, but it turned out that the research done to produce that result had encountered several errors. First of all, the hydrogen was actually bonding with metal impurities in the carbon nanostructures, and not the structures themselves. Additionally, the reharvesting of the hydrogen from these structures was performed incorrectly and was irreplicable. Ultimately, Professor Williams's research showed that hydrogen wasn't adsorbing to the nanostructures themselves and, even if it could, carbon nanostructures of the purity and in the quantity required to manufacture fuel cells at scale would be impossible to produce (Dresselhaus et al., 2013). From this, it is reasonable to conclude that hydrogen cannot replace gasoline as a fuel on a large scale until substantial developments are made in the area of storage. Also, the infrastructure for hydrogen vehicles is sparse to say the least, with hydrogen refueling stations only found in California and Hawaii, compared to the ~145,000 gas stations spread across the United States (American Petroleum Institute, 2023).

Next, I chose to look into aviation for possible solutions to its CO_2 emissions. I was able to compile the results of my literature research, interviews, and capstone design work to provide me with some insight. Firstly, the FAA suggests that sustainable aviation fuels (SAF's) are the most potent way of effecting carbon neutrality in commercial aviation. SAF's are fuels manufactured from natural sources, such as corn grain, to produce fuel that is functionally very similar to traditional jet fuel – so similar that many SAF's can be mixed with current fuels or substituted entirely with no modifications to the engines that they fuel. SAF's have been proven liable in passenger aircraft, with United Airlines conducting a passenger flight in a Boeing 737 with one of its engines being fueled entirely by SAF's (Palmer, 2021). Figure 1 shows a chart explaining the effects of different developments in aircraft on their CO_2 emissions.

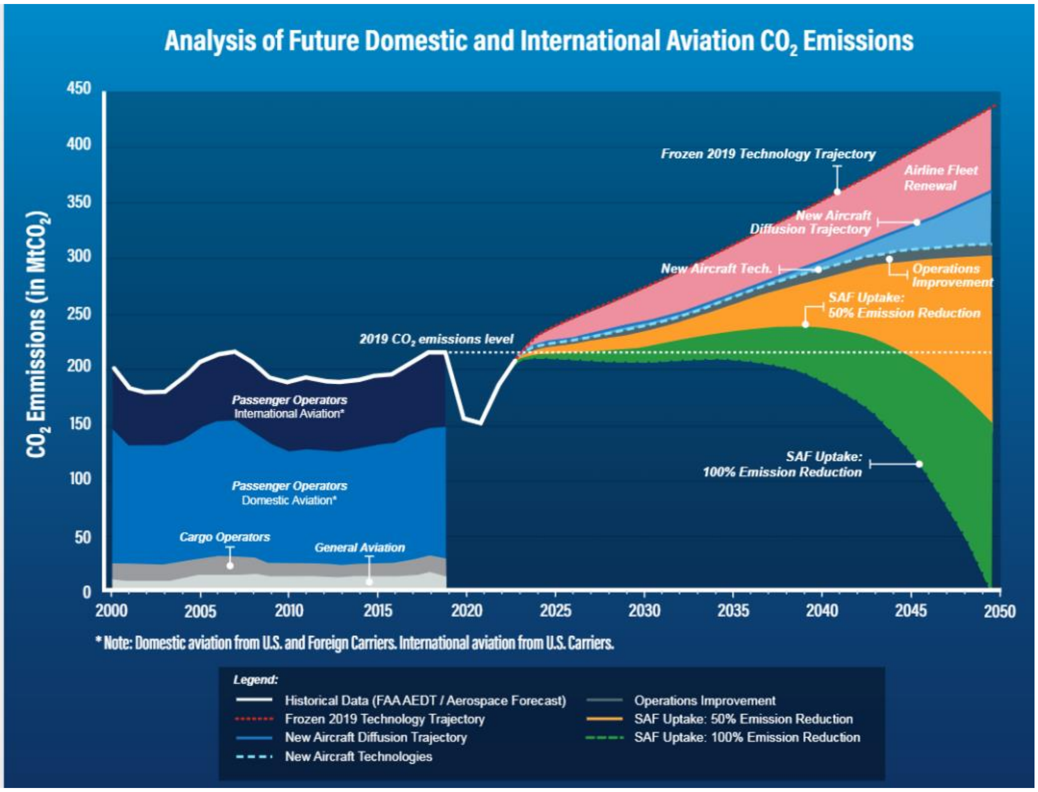

Figure 1: Analysis of CO_2 Emissions in Aviation (Federal Aviation Administration, 2023)

While continued development in efficient engine technology and hybrid-electric systems provide some tangible projected reduction in CO_2, it is SAF's that are expected to lead aircraft to carbon neutrality. In my interview with Professor Quinlan, he suggested that, while research into electrified propulsion systems for commercial aircraft is ongoing and widely backed by industry leaders including NASA, the battery technology is a long way off from ICE's, and SAF's are likely the solution for reducing aircraft carbon emissions in the short term. Apropos the topic of electrification of aircraft, my capstone group was able to perform a trade study on percent hybridization vs. reduction in block fuel burn on a 50-passenger turboprop aircraft. Our work found that a mere 1% hybridization was the optimal figure for reducing block fuel burn, as increasing the hybridization would increase battery weight in the aircraft, which rapidly increases the required fuel burn. These findings are displayed in Figure 2.

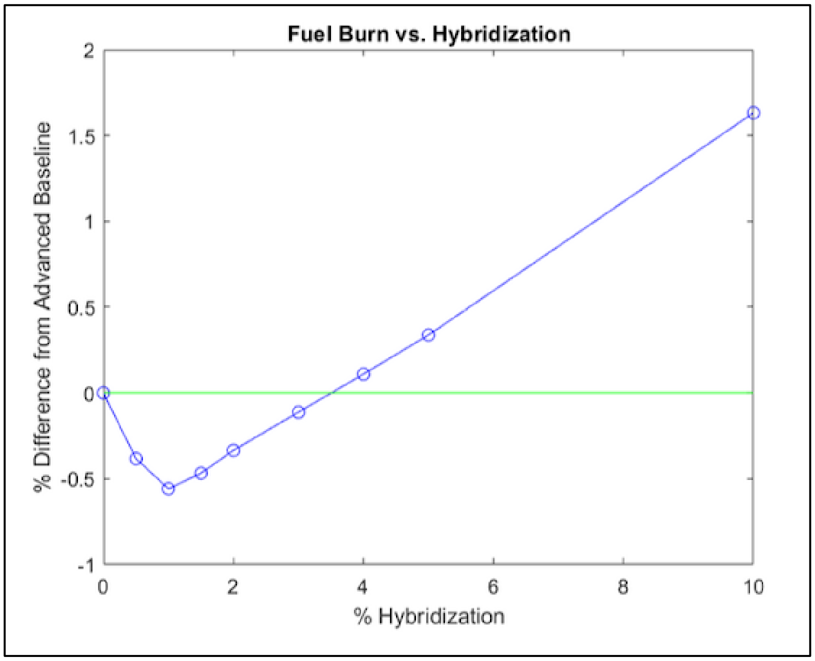

Figure 2: Effect of Percent Hybridization on Block Fuel Burn (Prestegard et al., 2023)

Both of the above figures are further evidence for the technological momentum of ICE's, as they both display a fundamental resistance to significant change in design and function. While battery power struggles to buy its way on in terms of FAA projections and actual empirical studies, the notion of incorporating sustainable fuels that are used in the same way and produce the same results as regular jet fuel while greatly reducing emissions is ever more attractive.

In my interview with Mr. Prestegard, he discussed his own thesis work when he was pursuing his degree in aeronautical engineering. His group performed studies on a new type of rotary aircraft engine, which would outperform piston and turboshaft engines in terms of efficiency. Ultimately, the rotary engine wasn't developed to the point of implementation, as the development, maintenance, and production were projected to be prohibitively expensive. In addition, most engineers in the last century are less familiar with the rotary engine than its counterparts, and expertise on their operation is sparse as a result. Mr. Prestegard also mentioned the Concorde as another trend in the aviation industry that ultimately faded due to prohibitive costs, risks, and inefficiencies. The Concorde was a supersonic passenger aircraft with a cruise speed of roughly Mach 2. Famously, if you were to fly from London to New York on one, you would arrive “before you left,” completing the journey in only 3.5 hours. While the Concorde was introduced in 1969, the last one was retired in 2003 because of the high fuel costs associated with the high-powered engines on the aircraft. Also, customers were apprehensive to board the aircraft after a deadly crash in 2000, which killed 113 people, including everyone onboard and four people on the ground.

Discussion

My research has given me a broad understanding of the development of ICE’s and alternatives in the current global environment, bringing my attention to technical, ethical, and economic concerns closely tied to every element of these technologies. Ultimately, I feel that my chosen ethical framework of technological momentum was the perfect lens through which to consider this topic, as I was able to practically derive information in the form of all of the aforementioned spheres. Additionally, sociopolitical concerns will play a major role in the rising tide of electric vehicles. One could imagine that large oil companies may attempt to lobby against restrictions on gasoline-powered vehicles in the US and abroad. Additionally, government subsidies for electric vehicles have already begun to decrease, and are headed towards zero. While artificial support for electrification continues to decrease, markets may once again be drawn to the convenience and simplicity of internal combustion.

In terms of the limitations of my research, I would say it was difficult to find my own quantitative results. Although I was able to use my own trade study for percent hybridization, I was mostly reliant on outside literature for my findings. Additionally, my research question lent itself to more opinion-focused questions in my interviews with my chosen experts. Both Mr.

Prestegard and Professor Quinlan gave the caveat that they can't predict the future, and could merely give their own opinions on many of my questions. As someone who is passionate about internal combustion engines in automobiles myself and hopes to work in a motorsport division powered by internal combustion, I must admit to some inherent bias against electric vehicles.

Future work would entail more research into the state-of-the-art in sustainable fuel alternatives as well as the constantly evolving political focus on oil-based fuel, electric vehicles, and rare earth metals. More trade studies focused on the emissions, increase in land usage, and increase in processing to produce SAF's may yield interesting results.

This research has made clear to me that it isn't possible as an engineer to only consider the technical side of your work. Not only are the social and economic elements equally relevant, but in many cases they are all so closely tied together that it is epistemologically impossible not to consider the broader scope of one's work as an engineer. I now have a much clearer sense for the metacognition of engineering practice and the broad scope of all engineering work. I hope to use this knowledge to continually educate my decisions as an engineer in this new and exciting generation, during which I hope to find novel and interesting answers to my originally posed question.

Conclusion

The results of my research have ended up being as fascinating to me as the topic around which my original question is focused. Getting to talk with industry experts about various topics related to my question and hearing their own experiences as engineers striving to answer it was a privilege as well as confirmation that my research question is both valid and relevant to my field of study. In summary, the prominent upshot of my research has been that engineers must seek to find sustainable and effective way to continue to use the ICE as it exists today while also working to effect more significant changes to its design, use, and efficacy in the longer term. This answer, while not entirely surprising, does come with its own set of detailed questions as to how the “greenification” of the internal combustion engine will ultimately be accomplished and indeed how we as a society will begin to prepare for the possible large-scale replacement of ICE’s down the line.

This research has broad significance to most of the world as environmental concerns within our technological society come to a head. The path to reconciling these matters is not clear, but it begins with the inherent curiosity required to ask such questions, the desire to solve them, the technical expertise to find those solutions, and the broad view of the impact of those proposed solutions in order to make progress in this area of engineering discovery. What I’ve found is that there is seemingly always another nested question of “how?” within each solution to an engineering problem. While I have answered my original research question, I am left with the question of how that solution will come to be realized. And within that there are surely more similar questions.

References

Aaa. (2015, October 7). *How efficient is your car's engine*. AAA Automotive. Retrieved April 28, 2023, from https://www.aaa.com/autorepair/articles/how-efficient-is-your-cars-engine

Child labor and human rights violations in the mining industry of the Democratic Republic of Congo. Tom Lantos Human Rights Commission. (2022, August 11). Retrieved April 28, 2023, from https://humanrightscommission.house.gov/events/hearings/child-labor-and-human-rights-violations-mining-industry-democratic-republic-congo

Das, A. K., Kumar Bardhan, A., & Fageda, X. (2022). What is driving the passenger demand on new regional air routes in India: A study using the Gravity Model. *Case Studies on Transport Policy, 10*(1), 637-646. doi:10.1016/j.cstp.2022.01.02

Dahlman, R. L. A. N. D. L. A. (n.d.). *Climate change: Global temperature*. NOAA Climate.gov. Retrieved December 9, 2022, from https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

Dresselhaus, M. S., Williams, K. A., & Eklund, P. C. (2013, November 29). *Hydrogen adsorption in Carbon Materials: Mrs bulletin*. Cambridge Core. Retrieved April 28, 2023, from https://www.cambridge.org/core/journals/mrs-bulletin/article/hydrogen-adsorption-in-carbon-materials/10F54D8F0E3E0ACB12D0083DF1C91672

Electricity production. Energifakta Norge. (2021, May 11). Retrieved October 27, 2022, from https://energifaktanorge.no/en/norsk-energiforsyning/kraftproduksjon/

Employment. Aviation. (n.d.). Retrieved December 9, 2022, from https://aviationbenefits.org/economic-growth/supporting-employment/

Grewe, V., Gangoli Rao, A., Grönstedt, T., Xisto, C., Linke, F., Melkert, J., . . . Dahlmann, K. (2021, June 22). Evaluating the climate impact of aviation emission scenarios towards the Paris Agreement including Covid-19 Effects. Retrieved October 17, 2022, from https://www.nature.com/articles/s41467-021-24091-y

Hot mix asphalt plants - emission assessment report - US EPA. (n.d.). Retrieved April 28, 2023, from https://www3.epa.gov/ttnchie1/ap42/ch11/related/ea-report.pdf

Hughes, T. (1989) The Evolution of Large Technological Systems. In: Bijker, W.E., Hughes, T.P. E Pinch, T.J. The Social Construction of Technological Systems. New Directions in the Sociology and History of Technology. (pp. 51-82) Massachusetts: MIT Press

Hydrogen Storage. Energy.gov. (n.d.). Retrieved April 28, 2023, from https://www.energy.gov/eere/fuelcells/hydrogen-storage#:~:text=Hydrogen%20can%20be%20stored%20physically,pressure%20is%20%E2%88%92252.8°C

Jimenez, D., Valencia, E., Herrera, A., Cando, E., & Pozo, M. (2022, January 25). Evaluation of series and Parallel Hybrid Propulsion Systems for UAV's implementing distributed propulsion architectures. Retrieved October 16, 2022, from https://www.mdpi.com/2226-4310/9/2/63/htm

List of goods produced by child labor or Forced Labor. DOL. (n.d.). Retrieved April 28, 2023, from https://www.dol.gov/agencies/ilab/reports/child-labor/list-of-goods-print?items_per_page=10&combine=china

M.ryu. (2022, August 26). *What makes EV tires different from regular tires*. Hyundai Motor Group. Retrieved April 28, 2023, from https://www.hyundaimotorgroup.com/story/CONT0000000000050465#:~:text=The%20tires%20of%20electric%20vehicles,that%20generate%20strong%20instantaneous%20power

Palmer, W. (2021, December 2). *United Flies World's first passenger flight on 100% sustainable aviation fuel supplying one of its engines*. GE News. Retrieved April 28, 2023, from https://www.ge.com/news/reports/united-flies-worlds-first-passenger-flight-on-100-sustainable-aviation-fuel-supplying-one

Prestegard, C., Taylor, R., Descisciolo, C., Fimiani, V., Hunter, K., Lattari, D., Nafis, K., Richwine, M., & Vu, N. (2023). *Hybrid-Electric Regional Turboprop*, 1–100.

Salas, E. B. (2022, July 27). *U.S. domestic market share of Leading Airlines*. Statista. Retrieved December 9, 2022, from https://www.statista.com/statistics/250577/domestic-market-share-of-leading-us-airlines/

Service station faqs. Energy API. (n.d.). Retrieved April 28, 2023, from https://www.api.org/oil-and-natural-gas/consumer-information/consumer-resources/service-station-faqs#:~:text=How%20many%20service%20stations%20are,are%20convenience%20stores%20selling%20fuel

Sustainable aviation fuel: Review of technical pathways report. (n.d.). Retrieved October 17, 2022, from https://www.energy.gov/eere/bioenergy/downloads/sustainable-aviation-fuel-review-technical-pathways-report

The environmental impact of lithium batteries. IER. (2020, November 12). Retrieved April 28, 2023, from https://www.instituteforenergyresearch.org/renewable/the-environmental-impact-of-lithium-batteries/

Williams, K. A., Pradhan, B. K., Eklund, P. C., Kostov, M. K., & Cole, M. W. (2002). Raman spectroscopic investigation of H2, HD, and D2 physisorption on ropes of single-walled, carbon nanotubes. *Physical review letters*, *88*(16), 165502. https://doi.org/10.1103/PhysRevLett.88.165502

Working to build a net-zero sustainable aviation system by 2050. Federal Aviation Administration. (n.d.). Retrieved April 28, 2023, from https://www.faa.gov/sustainability