Research Proposal—Design and Development of a Hydrogen Fuel Cell Electric Motorcycle as a Fully Open-Source Research Platform.

by

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Abstract

The MIT Hydrogen Bike Project extends past a platform developed for research and education (though that is a critical goal), and seeks to understand in detail Hydrogen's role in the global energy economy and the transition to net-zero by 2050. Engineering a complete vehicle is a method we are using to learn and inspire, but along the way we seek ways to make our work truly impactful. It is with this lens that we ask you to read this report. We don't seek publication past our own release because this report was more written for ourselves. To clarify our thoughts as we begin, to ensure our background research and understanding of the field was accurate, and to outline our initial steps. It's by no means final, rather it contains a summary of our current ideas at the current moment. But just because we wrote it for ourselves, doesn't mean it won't be useful to others.

The first section of this report combines the International Energy Agency's *Net Zero by 2050* plan, the United Kindgom's *Role of Hydrogen in the Energy Transition*, and the United States' *National Clean Hydrogen Strategy and Roadmap*, to understand the role of Hydrogen in the global energy transition. This lends to our understanding of how our work in Fuel-Cell Electric Vehicles (FCEVs) fits in the broader socio-economic, infrastructure, and policy contexts of a transition to clean energy, and current government action plans.

In the second section, we conduct a literature review of key areas of FCEV engineering research including energy management systems, simulation, testing, design methodology, fuel cell degradation metrology, and hydrogen combustion. We used this to identify gaps, and active areas of research for further literature review, and include our thoughts on the role of hardware testing in research. In section three, we describe the platform we hope to build. And in the final section we describe the work we hope to do in the future over a multi-year outlook.

And while the goals of this project are identified in the following pages, we acknowledge the importance of emphasizing one of them from the start. We believe that building a fully open-source FCEV, and documenting the process, the engineering, the roadblocks, the results, and our ideas for improvement with rigorous, scientific honesty is a contribution on its own. While the importance of novel scientific research cannot be overstated, accessibility of knowledge is equally important. Building a more equitable world starts by understanding the barriers to equality, and then developing tools that lower those barriers which are both context-aware, and economically attainable.

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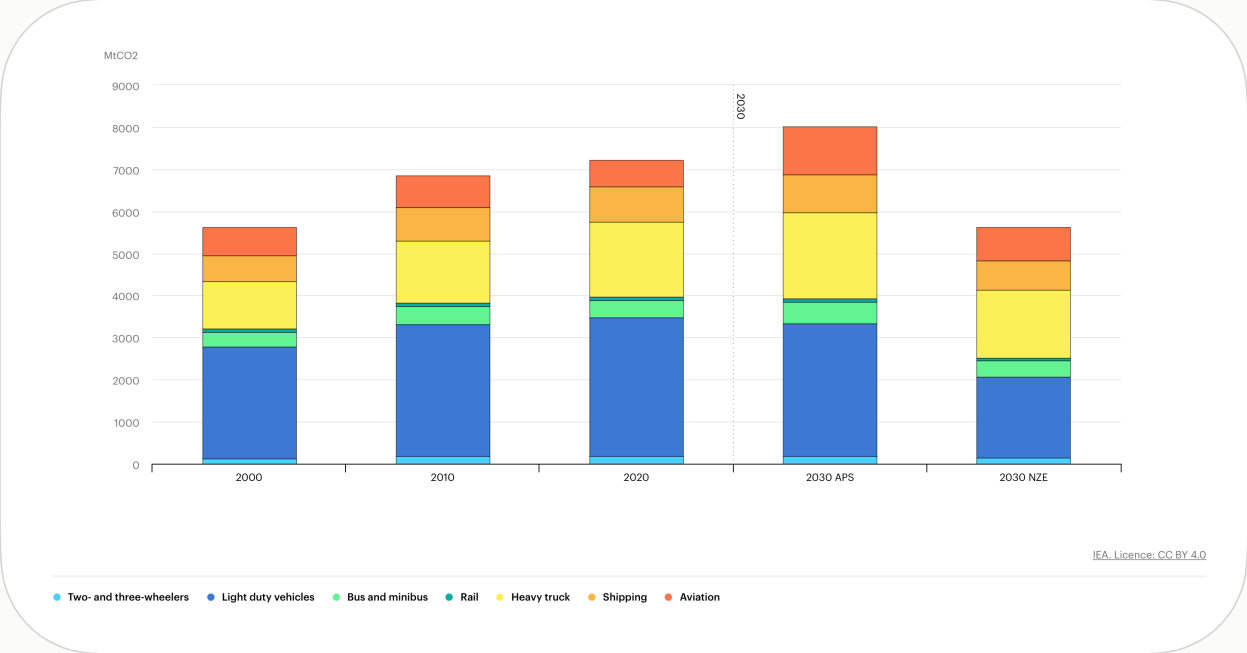
Lastly, we would like to say that we're always here for anyone looking to make the world a better place, so please reach out at any time with any questions. Additionally, we're always seeking ways to improve our work, so any feedback on our work is always appreciated, **l2f@mit.edu**.

1.

The Role of Hydrogen in the Energy Transition

The United Nations identified, in its Sustainable Development Goals[1], that a transition to affordable, clean energy[2] is one of the most urgent challenges that we need to address at a global level. According to a UN survey, only 4% of transportation was run off of renewable energy in the year 2020[3], and according to Our World in Data, it accounts for almost 24%[4] of global carbon emissions by combining data from The World Resource Institute[5] as well as the IEA.[6] More specifically, over 74.5% of those emissions come from road vehicles including both passenger cars and road freight, which makes transportation a significant sector of interest in emissions reduction.

The potential emissions reduction from a zero-emission transportation framework is around the equivalent of 7000 mega-tonnes of CO_2 as shown in data curated by the IEA in Figure 1. A combination of strategies could be used to achieve zero-emissions or 'net-zero.' But we focus on the role of hydrogen in this case.



F.1—DATA FROM THE IEA ON GLOBAL CO2 EMISSIONS FROM TRANSPORTATION BY SUBSECTOR INCLUDING PROJECTIONS UNDER THE 2050 NZE.

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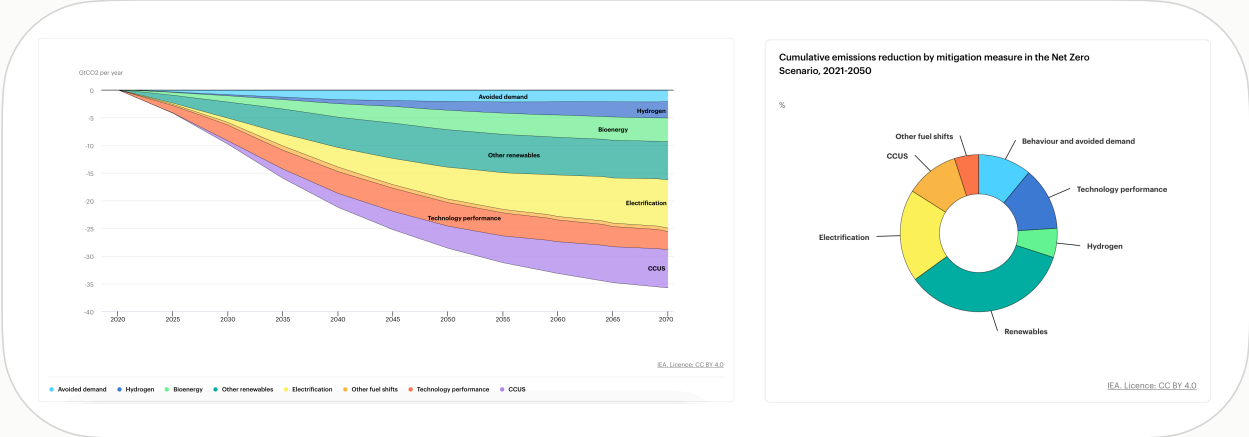
[1] United Nations Sustainable Development Goals— https://sdgs.un.org/goals
[2] Goal 7 is Affordable, Clean Energy— https://sdgs.un.org/goals/goal7
[3] United Nations SDGs Special Report 2023– https://unstats.un.org/sdgs/report/2023/
[4] Global emissions due to Transportation— https://ourworldindata.org/co2-emissions-from-transport
[5] ClimateWatch Data— Link to Data
[6] International Energy Agency— IEA Data Browser



F.2—DATA FROM THE IEA ON HYDROGEN'S ROLE IN THE GLOBAL ENERGY TRANSITION.

The International Energy Agency on Hydrogen

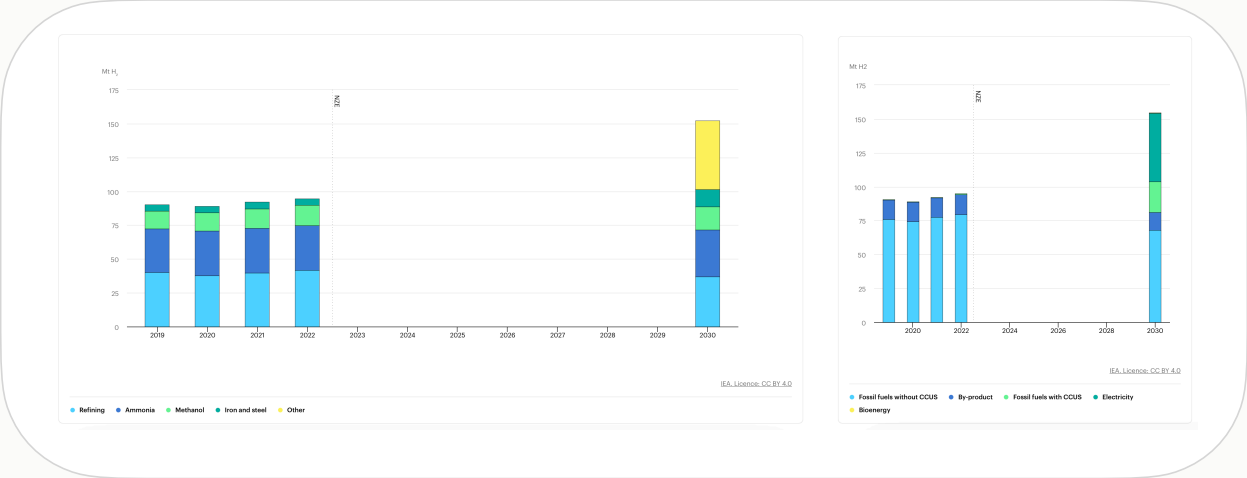
The IEA released a landmark report in 2021[7] which set out over 400 milestones that form a pathway to achieving net zero emissions by 2050. Their report accounts for the entire sector of energy, and while we'll focus primarily on the transportation side of this discussion, it's equally important to note that the principal of "net-zero" emissions could be taken as *no emissions* or that *any emissions produced are somehow off-set*.

The IEA's describes Hydrogen as having the potential to cumulatively reduce emissions by 6% in their overall plan for Net-Zero Emissions (NZE) by 2050.[8] They describe it having the most important role in reducing emissions in sectors where alternative solutions may be unavailable, or difficult to implement.

Their analysis remarks that uncertainties around "the lack of clarity about certification and regulation and the lack of infrastructure available to deliver hydrogen to end users," have stalled investments into the production of low-emission Hydrogen. Interestingly, the IEA identifies not production technologies, rather supporting infrastructure, and demand-side applications as the barrier to implementation at the moment saying, "beyond traditional uses of hydrogen in refining and industrial applications which are fully commercial, the majority of demand technologies are only at the demonstration or prototype stage... further efforts are needed to unlock the full potential demand for hydrogen in hard-to-abate sectors." The IEA argues for increased implementation of transportation and storage infrastructure rather than technological

> "Clean hydrogen produced with renewable or nuclear energy, or fossil fuels using carbon capture, can help to decarbonise a range of sectors, including long-haul transport, chemicals, and iron and steel, where it has proven difficult to reduce emissions. Hydrogen-powered vehicles would improve air quality and promote energy security. Hydrogen can also support the integration of variable renewables in the electricity system, being one of the few options for storing energy over days, weeks or months." —IEA

[7] International Energy Agency—Net Zero Emissions by 2050 Plan
[8] IEA Hydrogen— https://www.iea.org/energy-system/low-emission-fuels/hydrogen#programmes



F.3—DATA ON GLOBAL DEMAND AND PRODUCTION TECHNOLOGIES FOR HYDROGEN FROM THE IEA.

development in these areas, and indicates green generation technologies are maturing but lack of policy stimulating growth is leading to a lack of implementation. This is partially due to the fact that demand is low, and "remains concentrated in traditional applications with slow penetration in new uses."

This analysis is supported by data that shows Hydrogen's current uses are primarily in the refining, ammonia, methanol, iron, and steel industries, with transportation being a member of the 'other' category. Data also indicates that a very small fraction of Hydrogen used today is actually produced using sustainable methods.

The Role of Demonstration Projects

The IEA defines demonstration projects as one of the **first examples when a new technology is introduced to its target market in the form it would take if it were a full scale product or solution.**[9] They note as well that the technological development of a demonstration product involves far more time, cost, and risk than a prototype, however the act of creating a demonstration product significantly reduces risk for investors. That is to say a prototype demonstrates a technology is functional, while a demonstration product improves upon the prototype implementing the technology in a market with the required rigor in safety and engineering needed for it to exist in the real world, and by doing so proves that a market exists and the solution is functional within said market. Demonstration projects focus less on technological development rather than evaluating what is needed for technologies to be implemented in the global energy economy. They enable early customer buy-in, reduce perception of risk for investors, and inform the energy community about market deployment needs. The IEA has a great guide that very clearly outlines the need for demonstration projects; we will present highlights from it here.[10]

> "By 2050, almost 50% of CO2 emissions avoided in the NZE require technologies that are not yet past the demonstration stage." —IEA

[9] Demonstration Projects in Hydrogen, IEA Paris — https://www.iea.org/data-and-statistics/data-tools/clean-energy-demonstration-projects-database?subsector=Hydrogen
[10] The Need for Demonstration Projects, IEA Paris — https://iea.blob.core.windows.net/assets/76426d5e-0c9c-4f9f-809f-feca6bde702e/Theneedfornetzerodemonstrationprojects.pdf

Country	Sector	↓ Technologies	Name	Status	Capacity	Timing	Public funding	Total funding
							million USD	
Korea	Power	Generation - Hydrogen -- High-temperature fuel cell --- Solid oxide fuel cell (hydrogen)	Bloom Energy and SK SOFC pilot	Operational	100 kW	2021		
Korea	Power	Generation - Hydrogen -- High-temperature fuel cell --- Solid oxide fuel cell (hydrogen)	Changwon RE100	Under construction	1.8 MW	2022		
United Kingdom	Power	Generation - Hydrogen -- Hydrogen-fired gas turbine --- Pure hydrogen	Keadby Hydrogen	Concept	1.8 GW	2030		
United States	Hydrogen	Storage - Aboveground physical storage -- Liquid hydrogen storage tank	Feasibility of Large-scale LH2 Storage	Feasibility study	20,000-100,000 m3	2022	6	12
Finland	Hydrogen	Transport - Conditioning processes -- Liquid organic hydrogen carriers	HySTOC	Operational		2021	2	
Germany	Hydrogen	Transport - Conditioning processes -- Liquid organic hydrogen carriers	Aquaductus-AquaPrimus	Feasibility study		2024		
Germany	Hydrogen	Transport - Conditioning processes -- Liquid organic hydrogen carriers	Hector (Storage of green hydrogen in LOHC on a tonne scale at Chempark Dormagen site)	Under construction	1.8 ktH2/y	2023	9	
Japan	Hydrogen	Transport - Conditioning processes -- Liquid organic hydrogen carriers	Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) - ENEOS	Operational	210 tH2	2022		
Japan	Hydrogen	Transport - Conditioning processes -- Liquid organic hydrogen carriers	Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) - TOA	Operational		2021		
Netherlands	Hydrogen	Transport - Conditioning processes -- Liquid organic hydrogen carriers	Project Puffin: LOHC	Under construction	1.5 tH2/d	2023	5	20.1
Australia	Hydrogen	Transport - Transport technology -- Hydrogen blending in natural gas network	ATCO Hydrogen Blending Project	Under construction		2022	2	2.6
Japan	Hydrogen	Transport - Transport technology -- Liquid hydrogen tanker	Large-scale Hydrogen Supply Chain Establishment	Feasibility study	160,000 m3	2021-2030	300 000	
Japan	Hydrogen	Transport - Transport technology -- Liquid hydrogen tanker	Suiso Frontier	Operational	1,300 m3/y	2021		
Netherlands	Hydrogen	Transport - Transport technology -- Repurposed natural gas pipelines	Netherlands Hydrogen Bakcbone	Under construction	1400 km	2024	750	1500

T.1—CURRENT DEMONSTRATION PROJECTS IDENTIFIED BY THE IEA IN THE IEA PROJECT DATABASE.

Specifically in relation to Hydrogen, Table 1 shows the current demonstration projects the IEA is tracking that relate to Hydrogen. There are 14 total projects spread across Korea, Japan, and Europe, with none present in the United States and none related to demand-

side applications of Hydrogen. This encourages a pressing need to promote demonstration projects surrounding Hydrogen in the United States, and also demonstration projects relating to heavy industry, and long-distance transportation.

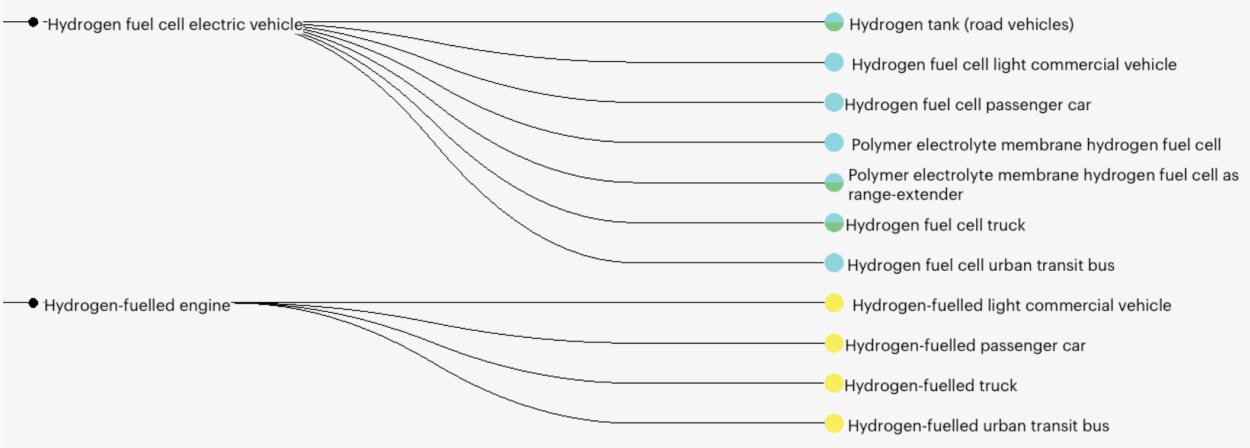
Key Technologies for the NZE 2050

The IEA tracks the progress over 400 technologies required for the clean energy transition in their ETP Clean Energy Technology Guide.[11] We filtered these technologies by the sector of road transportation, and separately energy transformation technologies relating to Hydrogen. The results are presented here. The following simplified key can be used to interpret the flow charts from the IEA.

1. **Initial Idea to Concept Validation**
2. **Early Stage Prototype**
3. **Late Stage to Prototype at Scale**
4. **Pre-commercial to Early Commercial**
5. **Integration Needed at Scale**
6. **Proof of Sustainability Reached**

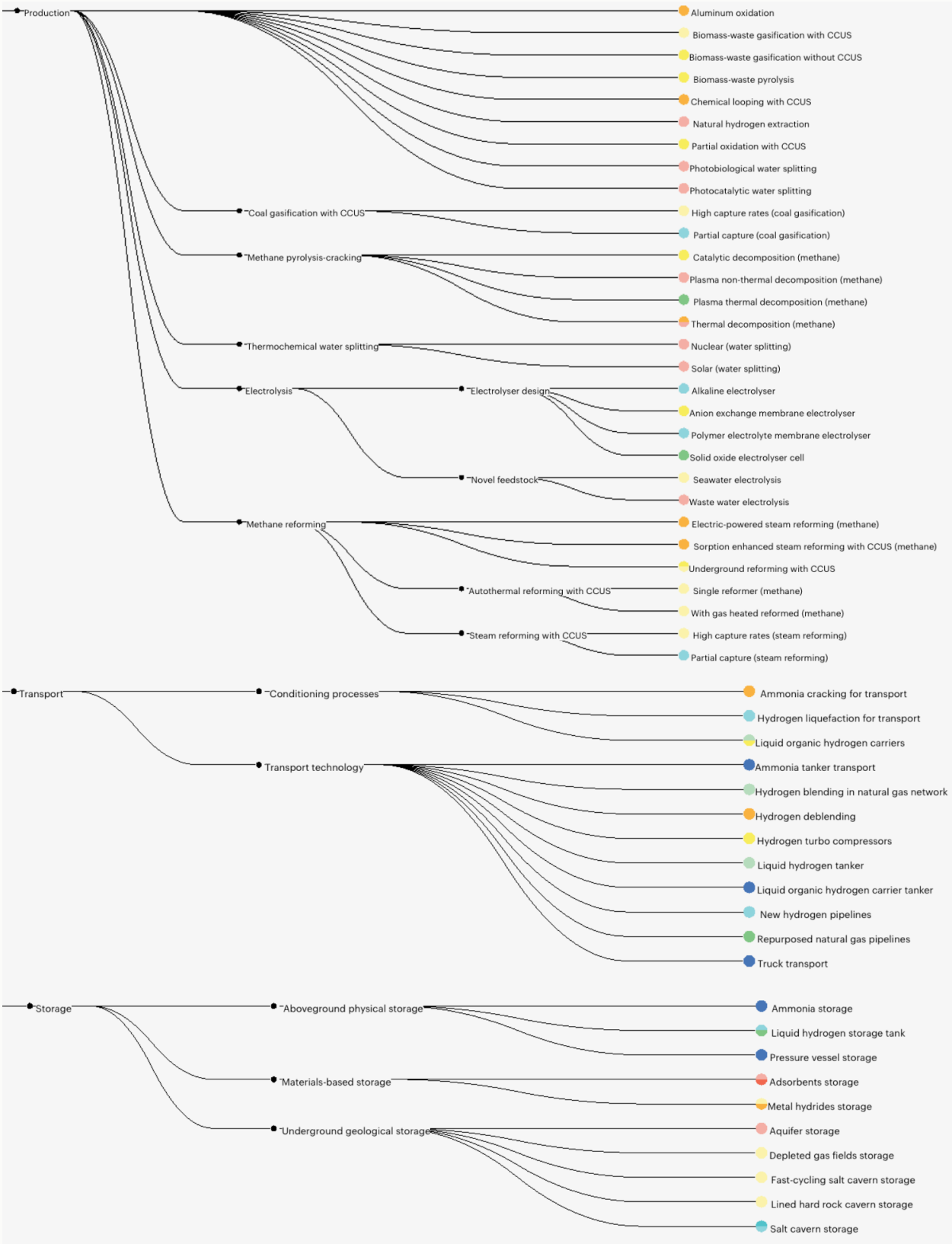
Starting with technology specific to hydrogen in transportation, a majority of applications of Polymer Electrolyte Membrane (PEM) Fuel-Cell technologies including using PEM Fuel Cells as range extenders are in the pre-commercial and early commercial, to scale-ready stage but none are in the stage where proof of sustainability has been reached. Hydrogen-fueled engines are in the late state prototype state with the IEA stating that Hydrogen combustion technology could provide a cheaper alternative to PEMFC vehicles if the challenges of safety, engine power-density, and NOx emissions are overcome.

This indicates that Fuel-Cell vehicle technology is at the stage where tools for scaling, investment in infrastructure, and projects that enable OEMs to implement the technology into commercial products may be the most applicable at this stage, with projects that can reduce the cost of PEM Fuel-Cells or replace rare material catalysts like platinum follow closely behind in importance. On the side of combustion however, it seems far more research needs to be done to bring Hydrogen combustion technology to the level required



F.4—PROGRESS ON HYDROGEN FUEL CELL AND HYDROGEN COMBUSTION VEHICLES COMPONENT TECHNOLOGIES.

[11] ETP Clean Energy Technology Guide, IEA Paris— https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide



F.5—PROGRESS ON HYDROGEN PRODUCTION, TRANSPORTATION, AND STORAGE TECHNOLOGIES.

for implementation. This indicates openings for research groups specifically to pursue projects relating to power-density, safety, and NOx capture and re-use in Hydrogen engines.

Figure 5 shows the progress on technology related to Hydrogen production, transportation, and storage. While these areas are not the focus of this proposal, they are highly relevant to integrating Hydrogen into the energy economy. The charts are presented here for identification of potential future research areas.

Review of the UK Parliament's Stance on Hydrogen

The Science and Technology Committee of the House of Commons of the Parliament of the United Kingdom released a report in 2022 entitled *The role of Hydrogen in achieving Net Zero*.[12] The report aims to define Hydrogen's place in the UK's overall decarbonization strategy while considering an international context and the approach of other countries and potential collaborations. A summary of their section on decarbonizing transportation, and a summary of their overall conclusions are both presented here.

Hydrogen's Role in Decarbonizing Transportation

According to the committee, the transportation sector is the largest emitting sector of the UK economy coving 24% of greenhouse gas emissions. They identify Hydrogen as likely being fundamental to achieving the full decarbonization of transport, patricianly in the areas of heavy transportation which agrees with the IEA's recommendations. Their analysis includes international shipping and aviation as significant areas where Hydrogen could play a significant role in decarbonization.

The report also analyzed the potential for Hydrogen to decarbonize passenger vehicles. The arguments for Hydrogen are the standard ones including improved range, faster refueling, smaller changes to consumer behavior, less peak-demand on the grid, and reduced demand for rare raw-materials for battery manufacturing. They also describe the arguments for BEVs which include the current number of electric vehicles already deployed and the indication that the growth of that sector will not slow in the near future. The Department of Transportation of the UK seemed to conclude that any move to electric vehicles must consider the environmental impact of Lead, Lithium, Cobalt, Nickel, Graphite and other major rare metals used in BEVs, and that Hydrogen technology should not be ruled out as a less environmentally-damaging alternative to consumer vehicles. Their final conclusion, however, was that **Hydrogen will play a small part in decarbonizing passenger transportation at most, but will have significant impact on decarbonization of Heavy Goods Vehicles (HGVs) provided that the wide-spread availability of Hydrogen refueling systems exists.**

Summary of Findings and Conclusions

The following summarizes the general conclusions of the committee as presented in the conclusions section of their report. Conclusions that relate directly to Hydrogen in transportation were selected and summarized while conclusions determined to be out-of-scope for this report were omitted. It is worth reading the conclusions in their entirety.

[12] The role of Hydrogen in achieving Net Zero, Science and Technology Committee, House of Commons, UK — https://committees.parliament.uk/publications/33292/documents/180198/default/

1. Hydrogen could improve resilience and energy security in certain applications, despite it being less efficient in certain scenarios when compared to alternative low-carbon technologies.
2. Hydrogen will play a small role in decarbonizing passenger transportation.
3. Hydrogen is a viable alternative to electrification for HGVs, but only if Hydrogen is widely available across the country.
4. Hydrogen has a modest but critical role in decarbonizing rail infrastructure where electrification may be not be possible in time to meet Net Zero.
5. The role of Hydrogen will be to decarbonize specific, limited areas where electrification is not possible or not optimal.

Additionally, a recurring theme throughout this proposal is a request for **the government to clearly define the role of Hydrogen in the decarbonization strategy of the UK and outline specific goals in each sector and possible application.** The United States government is endeavoring to do the same and should such a task be impractical at the national level, there are indications it may be done at the state-level (at least for some states).

Review of the US National Clean Hydrogen Strategy and Roadmap

In June 2023, the United States released its Clean Hydrogen Strategy and Roadmap[13], with combined recommendations from all sectors of the United States Government to outline a plan for Hydrogen in the United States. The plan focuses on prioritizing three key areas for maximum benefit.

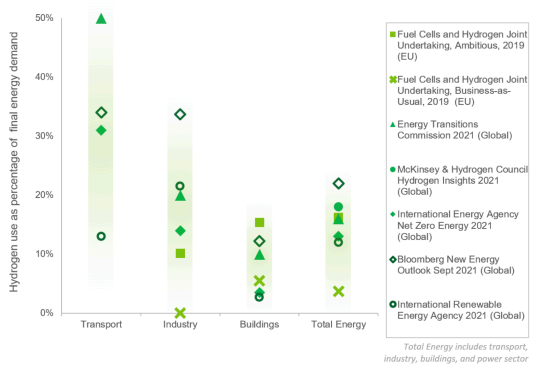
1. Targeting the chemical sector, steel, refining, heavy-duty transportation, and long-duration energy storage.
2. Reducing the production cost and delivered cost of clean Hydrogen by addressing vulnerabilities in material and supply chain.
3. Focusing on promoting regional hubs that place Hydrogen production close to the high priority users.

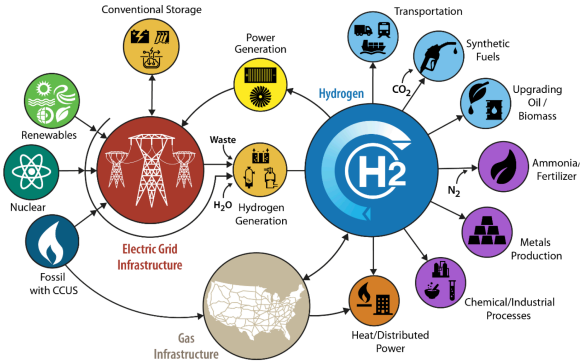
As with previous reports, we will focus on the role of Hydrogen in transportation while including other information we feel to be critical to a comprehensive understanding of the field and the plan.

Clean Hydrogen in Transportation

As of 2019, 31% of greenhouse gas emissions in the US were due to transportation and over 50% of that due to light-duty vehicles. The report indicates that this sector of light-duty vehicles is covered by battery technologies in industry, but for long-range, fast refueling, or heavy payload applications Hydrogen will be an important solution. It indicates the potential for Hydrogen as an alternative in medium and heavy-duty trucks and busses, which account for 20% of transportation-related emissions. It indicates the DOE has plans to demonstrate medium and heavy-duty fuel cell trucks in real world operating conditions within the next few years. Parcel delivery and public transportation busses are also listed as examples.

[13] US Clean Hydrogen Strategy and Roadmap — https://www.hydrogen.energy.gov/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf





F.6—(LEFT) COMPARISON OF HYDROGEN'S ROLE IN THE ENERGY TRANSITION FROM VARIOUS SOURCES. (RIGHT) DECARBONIZATION ACROSS SECTORS USING GREEN HYDROGEN FROM THE DOE.

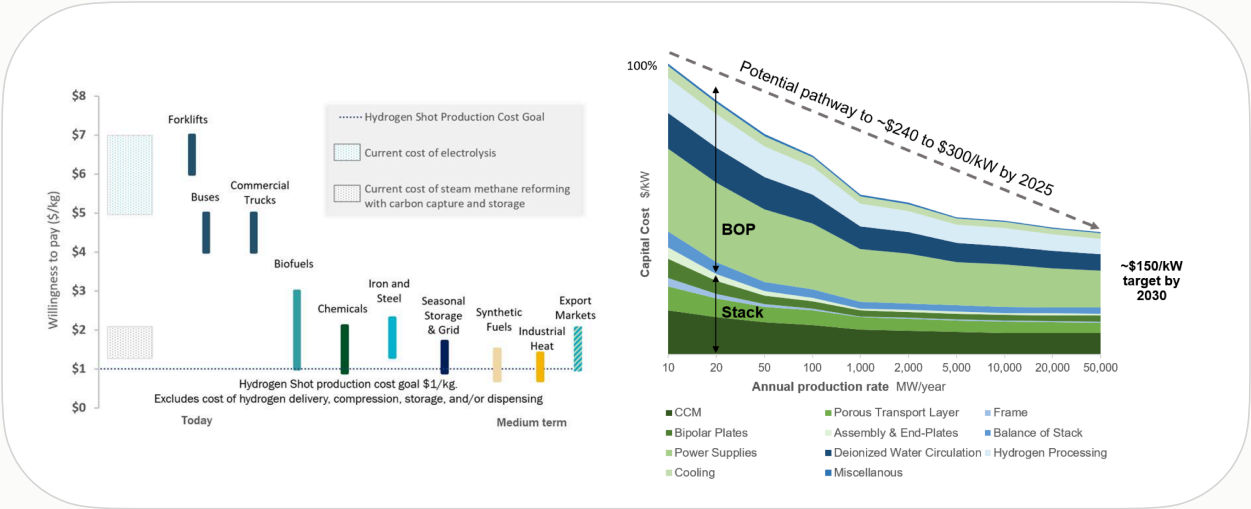
	Industrial feedstocks	Transportation	Power generation & energy storage	Buildings and hydrogen blending
Existing demands at limited current scales	• Oil refining • Ammonia • Methanol • Other (e.g. food, chemicals)	• Forklifts and other material-handling equipment • Buses • Light-duty vehicles	• Distributed generation: primary and backup power • Renewable grid integration with storage and other ancillary services	• Low percentage hydrogen blending in limited regions
Emerging demands and potential new opportunities	• Steel and cement manufacturing • Industrial heat • Bio/synthetic fuels using hydrogen	• Medium- and heavy-duty vehicles • Rail • Maritime • Aviation • Offroad equipment (mining, construction, agriculture)	• Long-duration energy storage • Hydrogen low NOx combustion • Direct/reversible fuel cells • Nuclear/hydrogen hybrids • Fossil/waste/biomass hydrogen hybrids with CCUS	• Mid to high percentage hydrogen blending in certain regions with limited alternatives • Building or district heating, including fuel cells and combined heat and power, for hard to electrify or limited options

F.7—DEMANDS FOR HYDROGEN IN THE US FROM THE ROADMAP.

The Role of Hydrogen in Light-Duty Vehicles and Material Handling

The report also analyzes current uses of Hydrogen as well as future uses, and indicates that forklifts and material-handling equipment currently apply Hydrogen as an alternative fuel in a limited capacity at a limited scale. It also indicates the light-duty material handling applications are willing to pay more for Hydrogen per kilogram (7USD/kg as opposed to commercial trucks at 5USD/kg), which might make them viable at a large-scale far sooner than other technologies.

According to the report, there are over 50,000 Fuel-Cell forklifts in operation in the United States and over 15,000 fuel cell cars. This



F.8—(LEFT) WILLINGNESS TO PAY FOR HYDROGEN BY INDUSTRY. (RIGHT) COST BREAKDOWN OF FUEL CELL AND BALANCE-OF-PLANT FOR INCREASING ACCESSIBILITY OF HYDROGEN TECHNOLOGY.

indicates the potential for growth in these areas especially as Hydrogen production cost decreases and technology advances. This also indicates the potential for research into alternative light-duty applications including mobility, and industrial applications.

Cost Reduction of Hydrogen and Analysis at Scale

Significant cost reduction analysis was conducted within the report as cost is one of the major barriers to adoption for Hydrogen technology. However, even at a large scale Hydrogen is not expected to meet the 2030 cost targets set by the US for sustainability and integration into the energy economy. Therefor further cost reduction steps are necessary to meet 2030 targets.

Figure 8 shows the cost breakdown of an Electrolyzer and Balance of Plant (BoP) system. Significant potential is available to reduce the cost of Electrolyzer systems and therefor Fuel-Cell systems due to the similarities in the technology. The report doesn't identify specific methods to reduce cost, further research and academic literature review would be needed.

Both of these indicate the cost reduction of Hydrogen from production to implementation is a significant area of active research, however potential exists and cost should not be a deterrent against the use of Hydrogen in decarbonization as technology and scaling efforts progress.

Current Hydrogen Refueling Infrastructure

The Alternative Fuels Data Center of the US Department of Energy maintains a database on clean refueling stations around the country.

F.9—HYDROGEN FUELING INFRASTRUCTURE IN THE US ACCORDING TO THE ALTERNATIVE FUELS DATA CENTER.

There are only 62 Hydrogen stations in the US concentrated in areas of demand. This is compared to the 64,000 electric vehicle charging stations.[14] As demand-side applications rise in other areas of the country, fueling stations may follow but the development of fueling stations is difficult due to the lack of consumer demand. This is one of the reasons for the establishment of regional Hydrogen Hubs as outlined in the Clean Hydrogen Strategy and Roadmap. We estimate that pilot projects which introduce Hydrogen uses into communities and sectors of the nation where it is currently lacking may help to speed the development of Hydrogen infrastructure by creating demand.

Summary of Potential Research Directions

In this section we present an itemized summary of identified research directions based on the NZE 2050, UK, and US Green Hydrogen plans.

1. Decarbonization of long-haul, heavy-duty, transportation, trucks, and busses.
2. Development and implementation of Demonstration Projects surrounding clean Hydrogen in the US (and abroad).
3. Scaling of PEM Fuel-Cell technologies in transportation.
4. Safety, power-density, and NOx reduction, capture, and re-use for Hydrogen combustion.
5. Cost reduction for Hydrogen systems including replacement of rare material catalysis, cost reduction of manufacturing and BoP.
6. Hydrogen in light-duty material handling, identification of similar small-scale, niche uses cases.
7. Increasing demand and infrastructure through regional implementation of Hydrogen in the energy economy.

In the following sections specific, technical areas of research are identified through literature review of active areas of Hydrogen energy research. However, an understanding of the broader context of Hydrogen in the global energy economy is critical to building robust, impactful solutions.

[14] US DoE Alternative Fuels Data Center — https://afdc.energy.gov/stations/#/find/nearest?fuel=HY

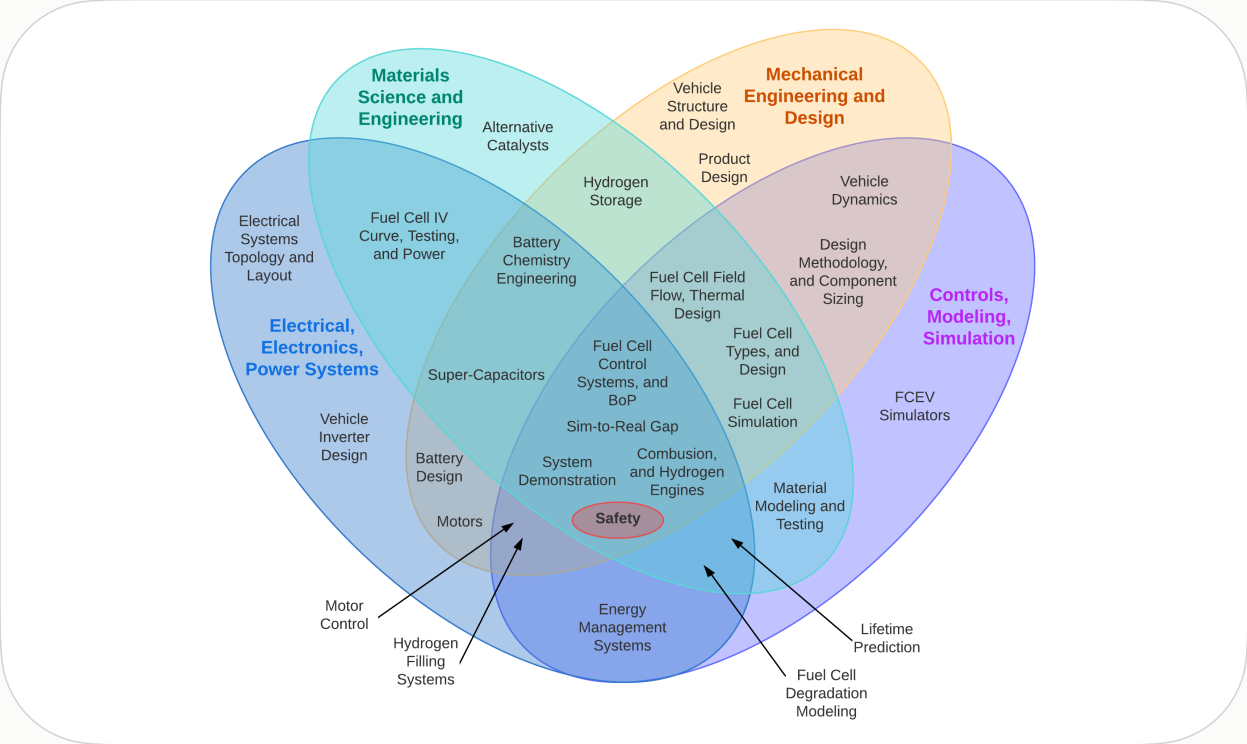
2.

A Review of Academic Research into Hydrogen on the Demand-Side

The field of Fuel-Cell Electric Vehicles is large and complex due to its dependance on infrastructure, policy, consumer opinions, and global energy strategy. For this reason, we'll break up the field into categories to discuss, focusing primarily on vehicle engineering but expanding to other areas that are critical to the understanding and development of FCEVs.

Vehicle Engineering

By curating various literature reviews from the Malaysia Fuel Cell Institute[15], the Combustion and Sustainable Energy Lab[16], a joint paper between multiple global energy research centers[17], and additional papers referenced below, we developed a map of the field of Fuel Cell Electric Vehicle engineering research



F.10—RESEARCH AREAS INTO HYDROGEN-POWERED VEHICLE ENGINEERING BROKEN DOWN BY DISCIPLINE BASED ON LITERATURE REVIEW.

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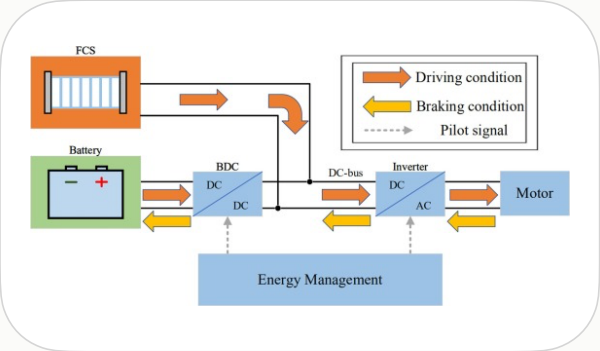
[15] Current Progress on Hydrogen Fuel Cell Vehicles, IJHE — https://www.sciencedirect.com/science/article/abs/pii/S0360319922048534
[16] Hydrogen Fuel Cell Vehicles: Current Status and Future Prospects, Applied Sciences — https://www.mdpi.com/2076-3417/9/11/2296
[17] Fuel Cell Electric Vehicles—A Brief Review of Current Topologies and Energy Management System Strategies, Energies — https://www.mdpi.com/1996-1073/14/1/252

presented in Figure 10. This map shows that Engineering an FCEV (from scratch) requires a complex overlap of Material Science, Mechanical Engineering, Electrical Engineering, and Control/Simulation Theory; and that few components of FCEVs touch less than two of these disciplines at minimum. In this report, we will review some of the most active areas of research in FCEV engineering.



F.11—ENERGY MANAGEMENT SYSTEM DIAGRAM FROM [18].

Energy Management Systems

The Energy Management System (EMS) of an FCEV controls how much power the fuel-cell and battery (or similar storage system) should output based on power demand from driver input. This can be done in many ways including through optimization, rule-based systems, or learning.[18] But, in general, the system attempts to maximize range of the vehicle, and minimize degradation of the fuel-cell. Frequency separation and decoupling approaches have been used where high-frequency components are absorbed by the storage elements (such as batteries), so the fuel-cell may experience a more steady power draw.[19] Model-Predictive Control has been used as a strategy in application to large trucks and vehicles.[20]

The approaches to energy management are usually topology dependent, with some topologies working better for certain implementations than others, and some not working at all. Fully-active systems are complex and generally require multiple DC-DC converters to accurately manage power from each source component to the main vehicle inverter.[21] It has been generally settled upon that at least one DC-DC converter (either with its input connected to the battery, and output connected in parallel to the battery and inverter like in Figure 11, or the same but with the battery and fuel-cell switched) is required for some level of active power management. In these cases, it is usually advantageous for the converter to perform closed-loop current control and have the EMS output a current set-point.

The accurate modeling of fuel-cell degradation is critical to the success of the EMS. Fuel-cell degradation can be caused by a variety of factors[22], including electrical dynamics and load variation.[23] While the validation of these models on hardware is outside the scope of most Energy Management System papers (as they pull these models from previous literature), an understanding of how the model was validated and under what conditions it is

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[18] Energy Management Strategies for FCEVs: Classification, Comparison, Outlook, Energy Conversion and Management — https://www.sciencedirect.com/science/article/abs/pii/S019689042200958X
[19] Energy Management System for FCEVs using Multi-Objective Online Optimization, IEEE — https://ieeexplore.ieee.org/document/9756570
[20] Energy Management of Heavy Duty Fuel Cell Vehicles: Model Predictive Control for Fuel Consumption and Lifetime Optimization, IFAC — https://www.sciencedirect.com/science/article/pii/S2405896320314233
[21] Energy Management Techniques and Topologies Suitable for Hybrid Energy Storage System Powered Electric Vehicles: An Overview, Electrical Energy Systems — https://onlinelibrary.wiley.com/doi/full/10.1002/2050-7038.12819
[22] A Review of PEM Fuel Cell Durability: Degradation Mechanism and Mitigation Strategies, Journal of Power Sources — https://www.sciencedirect.com/science/article/abs/pii/S0378775308011968?fr=RR-2&ref=pdf_download&rr=8019d24a99dd4d1e
[23] Hybrid Fuel Cell System Degradation Modeling Methods: A Comprehensive Review, Journal of Power Sources — https://www.sciencedirect.com/science/article/pii/S0378775321005954?ref=pdf_download&fr=RR-2&rr=8019c4a1db074cff

accurate is critical to understanding the efficacy of an energy management system, or particular algorithm.

Hardware testing is less wide-spread in Energy Management System research, likely due to the complexity and cost of hardware required to properly evaluate concepts experimentally. But while simulation is common, some research focuses on Hardware-in-the-Loop[24], or even full-system testing on real vehicles.[25] We believe this kind of research will provide key insights that simulation results cannot. Within a vehicle system, computational power is generally limited, and sensor noise, latency, bandwidth issues, and various other factors could cause any system, including the EMS, to underperform. Some interesting research from the robotics field using FPGA-based hardware acceleration to speed up computation[26], could aid in solving computational challenges in low-cost, low-energy situations such as a vehicle. But we want to highlight the importance of getting these algorithms to work on hardware, in real vehicles.

Heavily intertwined with this is the idea that it is difficult to compare EMS algorithms and strategies if they are evaluated on different vehicle platforms with different simulation frameworks. Therefor, we advocate for more studies that compare different topologies and algorithms on the same vehicle, in the same high-fidelity simulation to make various recommendations on both the type of hardware, and algorithmic approaches to use for FCEVs under various conditions, for various applications.

	Stakeholders	Model and Data Access	Applications	Licensing	Toolchain
AUTONOMIE	Vehicle system engineers (developers)	Open model and data. Can change any vehicle parameter	Develop new vehicle / powertrain / component / controls	Free for US Gov projects and teaching, Paid license for others,	Matlab, Simulink, and Stateflow
LITE AUTONOMIE LITE	Vehicle & component engineers (users)	Closed model and open data. Can change any vehicle parameter	Estimate impact of new component technology, powertrain sizing, parameters…	Free	Matlab only
AUTONOMIE EXPRESS	Non-vehicle experts	Closed model and data. 5000+ predefined vehicles available	Simulate large number of real world driving cycles either from simulation (e.g. SUMO, AimSun, VISSIM) or test data	Free	Matlab only
AUTONOMIE ML	Non-vehicle experts	Closed ML model and data 5000+ predefined vehicles available	Real-time deployment (e.g., Apps), large scale optimization (e.g., traffic light), co-simulation	Free (first release upcoming TBD)	None / Python (free)

Autonomie Versions

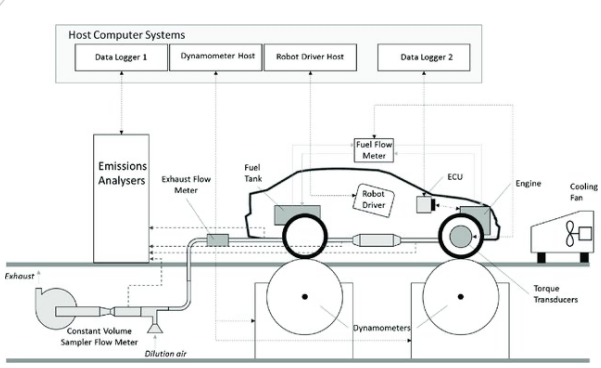
F.12—AUTONOMIE PRICING STRATEGIES FROM ARGONNE NATIONAL LABS.

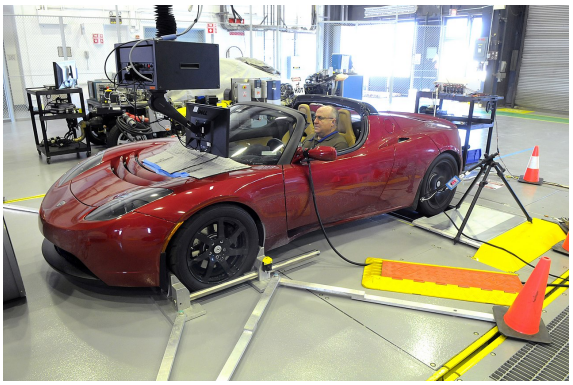
Simulation and Sim-to-Real Gap

Simulation is a critical technology used in the development of FCEVs from general system-level performance estimation, down to detailed modeling of stack and fluid performance. It's critical in efficiently and cost-effectively iterating on design ideas and control algorithms, but relies heavily on its accuracy in modeling real-world conditions.

A large portion of academic research focuses on using simulation tools that were designed and developed to accurately estimate the performance of specific vehicles, hence minimizing the concerns around sim-to-real gap for research. The Honda FCX Clarity[27] simulation framework, as well as the Toyota Mirai FCV[28] parameters are often used for energy management system development. A few projects have tried to develop a more "universal" framework for FCEV simulation. Argonne National Lab's Autonomie[29] software allows users to simulate a number of different representative FCEV platforms on the market,

[24] Real-Time Implementation of Improved Power Frequency Approach Based Energy Management of FCEV Considering Storage Limitation — https://www.sciencedirect.com/science/article/abs/pii/S0360544222006466
[25] A ROS-Based Energy Management System for a Prototype FCEV, Energies — https://www.mdpi.com/1996-1073/14/7/1964
[26] Accelerating Robot Dynamics Gradients on a CPU, GPU, and FPGA, IEEE — https://ieeexplore.ieee.org/abstract/document/9350173
[27] The Study on the Power Management System in a Fuel-Cell Vehicle Hybrid, International Journal of Hydrogen Energy — https://www.sciencedirect.com/science/article/abs/pii/S0360319911026279
[28] Modeling, Simulation and Control Strategy Optimization of FCEV, Vehicles — https://www.mdpi.com/2624-8921/5/2/26
[29] Autonomie, Argonne National Lab — https://vms.taps.anl.gov/tools/autonomie/





F.13—(LEFT) DYNAMOMETER TYPICAL SETUP FROM [34]. (RIGHT) DYNAMOMETER TESTING AT ARGONNE LABS.

and allows vehicle developers access to the core software to be used in custom vehicles. It is available in Matlab, Simulink, Stateflow, and Python, and is the only commercially available software to include control algorithms developed from dynamometer data.[30] Virtual-FCS[31] was a project funded by the Clean Hydrogen Partnership[32], that sought to create an open source Hydrogen-hybrid vehicle simulation tool in OpenModelica with integrated data from real powertrains. The example FCEV in Virtual-FCS is the Toyota Mirai, but continued development of the framework could enable accurate simulation for a wider range of vehicles.

A number of other simulation platforms and frameworks exist, including reference applications by Matlab/Simulink[33], however their performance as compared to hardware is unclear as it depends on the specific parameters, conditions, and behaviors the simulation is attempting to capture.

Dynamometer Testing

Dynamometer Testing[34] is one of the most common methods for vehicle characterization as well as reduction of sim-to-real gap in vehicle design. Dynamometers allow users to test critical performance metrics of vehicles in a controlled environment without the need for a test track, and separate the powertrain performance from other characteristics (such as aerodynamics) allowing powertrains across vehicles to be compared easily. Argonne National Labs maintains a large database of dynamometer data on alternatively fueled vehicles[35], and has publicly released detailed documentation on their testing setup, and procedures[36] which also follow the US Department of Transportation procedures on emissions testing.[37]

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[30] Argonne National Labs, Autonomie — https://www.anl.gov/taps/autonomie-vehicle-system-simulation-tool
[31] VirtualFCS Open Modelica Library for FCEV Vehicle Simulation — https://www.sintef.no/projectweb/virtual-fcs/
[32] Clean Hydrogen Partnership — https://www.clean-hydrogen.europa.eu/index_en
[33] Matlab Simulink FCEV Reference Application — https://www.mathworks.com/help/autoblks/ug/fuel-cell-electric-vehicle-reference-application.html
[34] A novel use of multivariate statistics to diagnose test-to-test variation in complex measurement systems, Measurement — http://dx.doi.org/10.1016/j.measurement.2018.07.059
[35] Dynamometer Database, Argonne National Labs — https://www.anl.gov/taps/downloadable-dynamometer-database
[36] Vehicle Dynamometer Testing Procedure and Setup, Argonne National Labs — https://publications.anl.gov/anlpubs/2021/08/167512.pdf
[37] Federal Regulations, Vehicle Testing Procedures, Air Pollution Controls — https://www.govinfo.gov/content/pkg/CFR-2018-title40-vol37/xml/CFR-2018-title40-vol37-part1066.xml

Hardware testing enables the creation of detailed powertrain models using data, leading to more accurate predictions in the performance of both individual components, and vehicles as a whole.[38] This yields to better estimates on vehicle performance during the early stage design process providing general estimates on power consumption, range, system efficiency, and more. Dynamometer tests are usually done on drive cycles, which are velocity-versus-time graphs (developed based on consumer data) a vehicle must adhere to.[39] Drive cycle selection is critical to both early stage development, and testing of FCEVs, and generally multiple are used in the dynamometer data collection process.

Design Optimization, Methodology, and Component Sizing

Design methodology and optimization are most relevant during the early stages of design when engineers are determining component sizing, control strategy, and basic parameters to meet system-level functional requirements.[40] Applying the principals of machine design outlined in[41], the use of fundamentals physics to understand a system's key performance metrics, reliability, lifetime, and tolerance is key to a successful product. Design methodologies aid with this by combining the fundamental physics equations required for consideration in the early stages of design to provide initial component sizes, which can then be further optimized as more detailed physics models are developed. Equally important is the definition of the system functional requirements, which come from the environment the system will be implemented in.[42]

In general, FCEV component size optimization seeks to maximize vehicle range and lifetime, minimize vehicle cost and mass, while adhering to a set of performance metrics. Comprehensive energy balance while estimating component mass changes has been used as a strategy for component sizing with some success in simulation with a Nissan Leaf.[43] Multi-objective optimization[44] with performance constraints has also been used as a strategy to select the series and parallel configuration of the energy storage system, and fuel-cell stack, while accounting for mass, performance requirements, and control strategy.[45] Another strategy that has been tried is swarm, or particle-based optimization where a series of potential solutions are initialized using a parameter sweep, and these solutions are evaluated against each other while considering energy management system control strategy.[46] One interesting paper included hardware-testing in their design methodology, starting with track analysis, including hardware tests of the electric motor, and ending with track data which is compared to predicted performance.[47]

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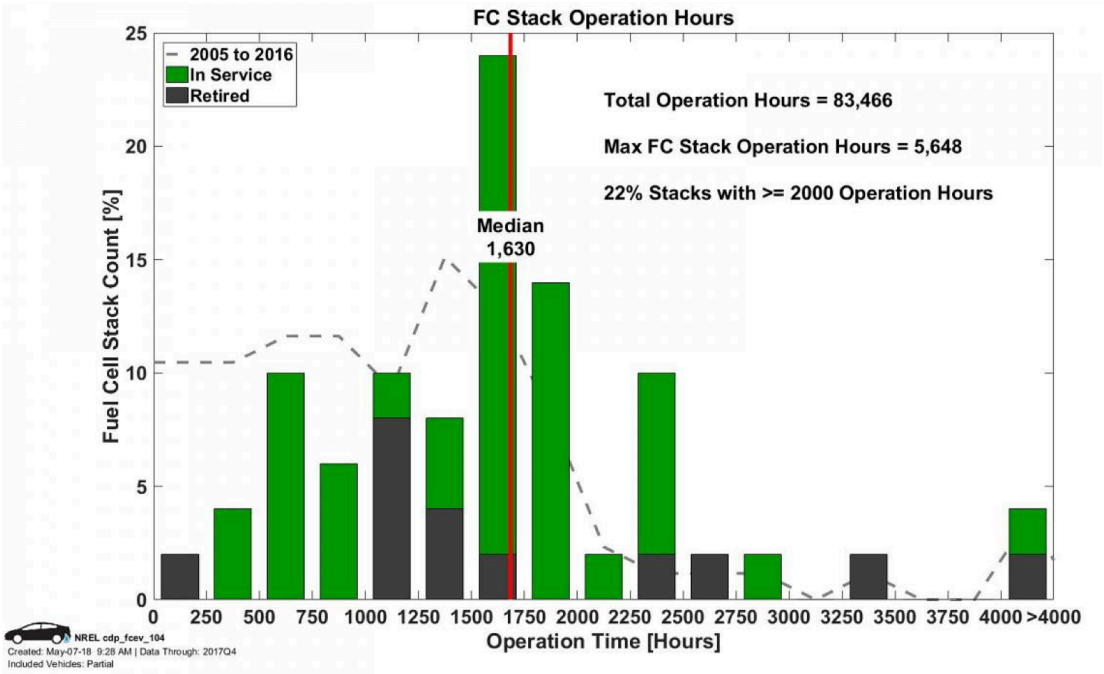
[38] Level 1 & 2 Vehicle Benchmarking, Argonne National Labs — https://www.energy.gov/eere/vehicles/articles/vehicle-technologies-office-merit-review-2015-advanced-technology-vehicle
[39] A Review of Drive Cycles for Electrochemical Propulsion, Energies — https://www.mdpi.com/1996-1073/16/18/6552
[40] Precision Machine Design, Alexander H. Slocum
[41] FUNdaMENTALs of Design, Alexander H. Slocum — http://pergatory.mit.edu/resources/fundamentals.html
[42] High-Level Design of a Hydrogen Fuel Cell Motorcycle, MIT 2.70 — https://pcb.mit.edu/lectures/lecture_01/FINAL%20PAPER%20PDF.pdf
[43] Optimal Components Design for a Fuel Cell Vehicle, SAE — https://saemobilus.sae.org/content/2015-24-2546/
[44] Multi-Objective Optimization of FCEV Powertrain Cost and Energy, SAE — https://www.sae.org/publications/technical-papers/content/2013-24-0082/
[45] Design Methodology of Fuel Cell Electric Vehicle Power System, IEEE — https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4800034
[46] Optimal Design Methodology for Sizing Fuel Cell/Battery Hybrid Power Source, Journal of Power and Energy — https://journals.sagepub.com/doi/epub/10.1177/0957650920910346
[47] Design and Testing of Fuel Cell Powertrain with Energy Constraints, Energy — https://www.sciencedirect.com/science/article/pii/S0360544211007407



F.14—FUEL CELL DURABILITY IN VEHICLES AS OF 2005-2016 FROM THE NATIONAL RENEWABLE ENERGY LAB.

However, it is similarly difficult to compare design optimization strategies developed using different input conditions, on different target platforms. We encourage studies that involve providing the same set of target functional requirements to a series of design optimization strategies in order to compare the outputs of said strategies, including evaluating their feasibility on hardware. Specifically, Hardware-in-the-Loop (HIL) testing that focuses on demonstrating methods to reach cost, lifetime, reliability, and performance targets for consumer products would greatly aid the development of Hydrogen vehicle solutions in industry.

Fuel Cell Degradation, and Metrology

Besides cost, Fuel-Cell lifetime and degradation remains to be one of the largest potential barriers for FCEVs.[48] Modeling and verifying models for stack degradation is one of the most active areas of research in the materials-side of FCEV engineering.[49] The Virtual-FCS project completed a very comprehensive review on fuel cell degradation methods outlining different mechanics for degradation based on component in a stack, as well as modeling methods and comparing their efficacies.[50]

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[48] Fuel Cell Durability and Performance, NREL — https://www.nrel.gov/docs/fy19osti/73011.pdf
[49] Durability and Degradation Issues of PEM Fuel Cell Components, Fuel Cells — https://onlinelibrary.wiley.com/doi/abs/10.1002/fuce.200700053?casa_token=LWbcTZ_6DtgAAAAA:CIfOSOcw6iTpDt9B4zxBoxWI998zEon-2bcKu6naRhgG9HAfmJfPAuZDluSHE1B-DUx3_7b_CJSUztY
[50] Hybrid Fuel Cell Degradation and Modeling Methods, Journal of Power Sources — https://doi.org/10.1016/j.jpowsour.2021.230071

In the realm of metrology, however, one paper measured voltage loss to assess degradation at the cell/stack level.[51] Another paper used a combination of SEM, IR imagery, gas permeability, ion chromatography, and contact angle to determine PEM fuel cell degradation.[52] Other methods have included Electrochemical Impedance Spectroscopy[53], and Identical Location Electron Microscopy.[54] All methods respective effectiveness depends on the exact degradation mechanism being characterized.

NOx Traps for Combustion Vehicles

On a separate vein from Fuel-Cell Electric Vehicles, NOx traps and other forms of emissions capture, reduction, and elimination could allow Hydrogen engines[55] to operate greenly while still maintaining the combustion process. Two major strategies are presented here, the first is engine control to limit NOx production during the combustion process[56], and the second is 'scrubbing' or catalytic processes that eliminate or reduce NOx emissions.[57] Research studies into the effects of combustion characteristics on NOx production have yielded that controlling the combustion process could lead to reduced NOx emissions.[58] Some interesting work has also attempted to use combustion waste products to control NOx emissions[59], some other ideas include turning NOx emissions into fertilizer for agriculture, however this research is in very early stages.[60] NOx is not covered in detail in this report as we focus on Fuel-Cell vehicles, however it remains to be one of the most significant areas of research into Hydrogen-powered systems.

Life Cycle Analysis

We conclude this section with a brief discussion on Life-Cycle-Analysis (LCA) for Hydrogen vehicles. Which is a critical area of research in determining the true, cradle-to-grave impact Hydrogen vehicles have on the environment. Two major methods for LCA exist in literature for Hydrogen vehicles, GREET by Argonne National Labs, and ISO 14040.

ISO 14040 Series for LCA

The ISO method[61] for LCA is extremely common, and in fact was used in the evaluation of the Toyota Mirai FCEV.[62] It's difficult to say exactly what the ISO standard requires[63]

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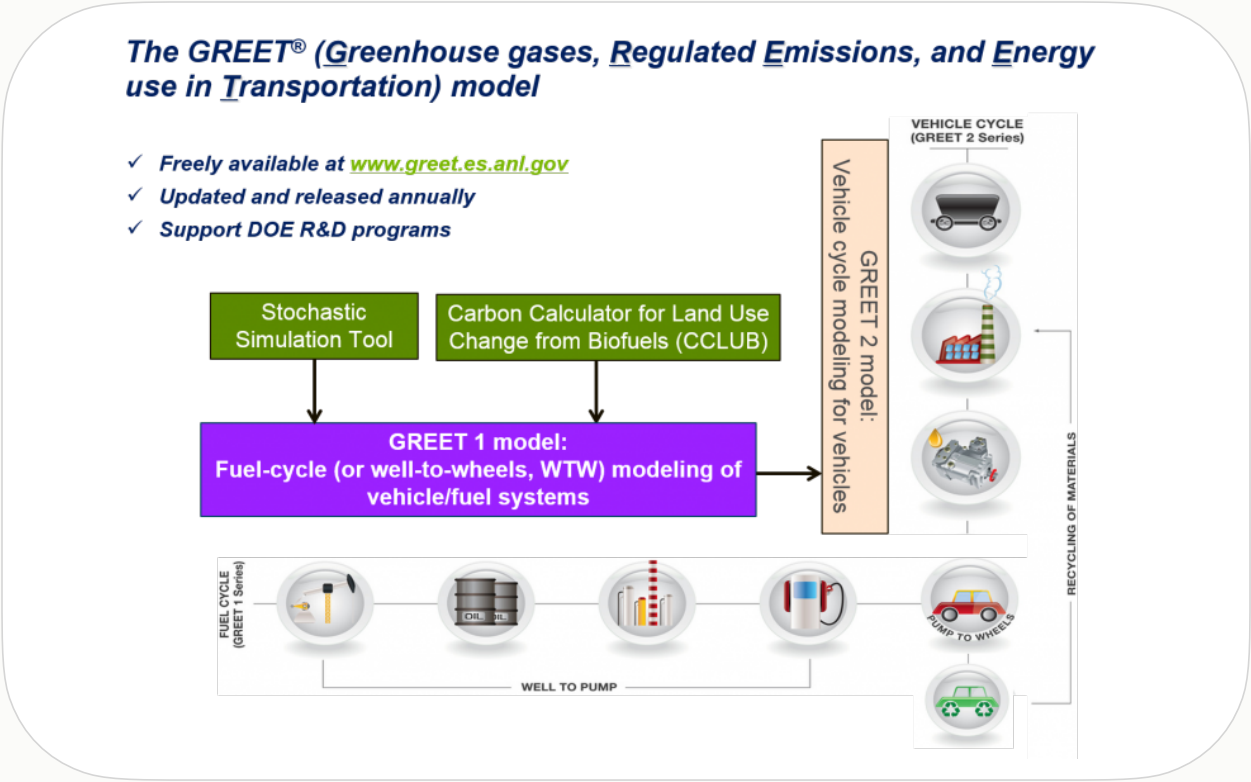
[51] Degradation Measurement and Analysis for Cells and Stacks, Journal of Power Sources — https://doi.org/10.1016/j.jpowsour.2008.06.047
[52] Ex Situ Diagnosis of PEM Fuel Cell, Journal of Power Sources — https://doi.org/10.1016/j.jpowsour.2012.01.074
[53] Performance Degradation of Direct Methanol Fuel Cell by EIS, Electrochimica Acta — https://doi.org/10.1016/j.electacta.2007.06.063
[54] Catalyst Degradation of Fuel Cells based on Identical Location Electron Microscopy, Nano Energy — https://doi.org/10.1016/j.nanoen.2016.04.027
[55] Hydrogen use in Internal Combustion, International Journal of Automotive Engineering and Technologies — https://www.researchgate.net/profile/Murat-Ciniviz/publication/267711346_HYDROGEN_USE_IN_INTERNAL_COMBUSTION_ENGINE_A_REVIEW/links/5527bd7c0cf29b22c9b93d51/HYDROGEN-USE-IN-INTERNAL-COMBUSTION-ENGINE-A-REVIEW.pdf
[56] Engine Control and low-NOx Combustion for Hydrogen Gas Turbine, IJHE — https://doi.org/10.1016/S0360-3199(97)00115-8
[57] Mechanistic Modeling of NOx Reduction Reactions after Hydrogen or Ammonia Combustion, Renewable and Sustainable Energy Reviews, https://doi.org/10.1016/j.rser.2023.113666
[58] NOx Reduction and NO2 Emissions Characteristics in Rich-Lean Combustion of Hydrogen, IJHE — https://doi.org/10.1016/j.ijhydene.2008.05.034
[59] Synthesis of Zeolites from Waste Combustion Fly Ash and Application in NOx Emissions Control — https://erepo.uef.fi/bitstream/handle/123456789/25754/urn_nbn_fi_uef-20211082.pdf?sequence=1
[60] Turning NOx into Money — https://www.unep.org/news-and-stories/story/changing-approach-turning-nitrogen-pollution-money
[61] ISO 14040 Life-Cycle-Analysis (LCA) — https://www.iso.org/standard/37456.html
[62] Toyota Mirai FCEV LCA — https://global.toyota/pages/global_toyota/sustainability/esg/challenge2050/challenge2/life_cycle_assessment_report_en.pdf
[63] Best Practices of the ISO 14040 Series — https://www.apec.org/docs/default-source/Publications/2004/2/Life-Cycle-Assessment-Best-Practices-of-International-Organization-for-Standardization-ISO-14040-Ser/04_cti_scsc_lca_rev.pdf



F.15—GREET 1 AND 2 SYSTEM BY ARGONNE NATIONAL LABS FOR EVALUATING FCEV ENVIRONMENTAL IMPACT.

without getting paid access to the details, or by looking at the considerations of LCAs that implement the ISO standards, but some literature that compares ISO to GREET seems to argue that ISO is aimed at the organizational-level, and lacks the process-oriented approach to do proper cradle-to-grave evaluation on these vehicles.[64] This does not indicate that ISO should not be used to evaluate FCEVs, rather indicates that careful considerations of exactly which carbon sources an LCA method does and does not consider is important to determining the effectiveness of an LCA, especially when comparing across vehicles, production methods, fuel types, and more.

Argonne National Labs GREET Method

GREET[65] is a more 'comprehensive' methodology for evaluating LCAs developed by Argonne National Labs. GREET covers both Hydrogen product and use in vehicle operation (GREET 1), as well as cradle-to-grave vehicle manufacturing to end of vehicle life (GREET 2).[66] As compared to the ISO standard, GREET is freely-available on the web in the form of an Excel spreadsheet that can be used to calculate the environmental impact of a vehicle.[67] GREET is also constantly updated by Argonne based on latest technologies, and current research into environmental impact.[68]

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[64] LCA of FCEVs using GREET, Sustainability — https://www.mdpi.com/2071-1050/13/9/4872
[65] GREET, Argonne National Labs — https://www.anl.gov/sites/www/files/2020-10/GREET_Impact_Sheet.pdf
[66] GREET Model for Hydrogen Life Cycle Emissions, Argonne National Labs — https://www.energy.gov/sites/default/files/2022-06/hfto-june-h2iqhour-2022-argonne.pdf
[67] GREET Excel Sheet and Model, Argonne National Labs — https://bioenergymodels.nrel.gov/models/29/
[68] Summary of Expansions and Updates in GREET 2022, Argonne National Labs — https://www.osti.gov/servlets/purl/1891644

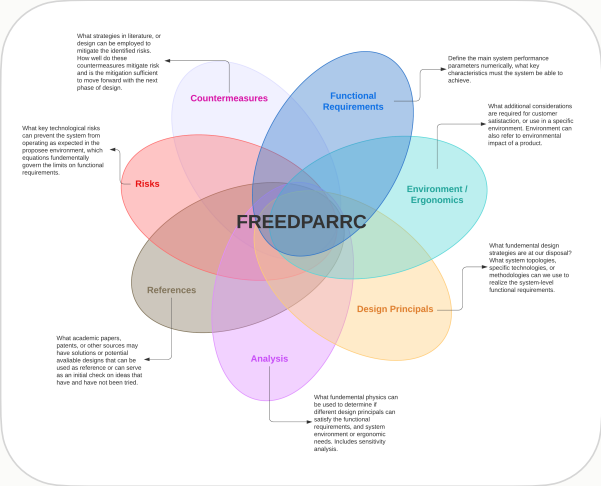
3.

Developing a Platform for Research

What falls out of an understanding of Hydrogen's role in the global energy economy, and the field of Hydrogen vehicle engineering is the need to create an accurate, versatile research platform. Our group has, for the moment, chosen to focus on the demand-side of Hydrogen according to gaps identified by the IEA. And based on a literature review of the field of Fuel-Cell electric vehicles, has further chosen to focus on energy management systems, simulation, dynamometer testing, design optimization and methodology, fuel cell degradation and modeling, and combustion with considerations of Life Cycle Analysis accounting for both Hydrogen's supply and use, as well as cradle-to-grave analysis for vehicles. Our research many also include discussions on the specifics of fuel-cell design, including the use of open-cathode[69] fuel-cells in mobility, and selection of fuel-cell technologies.

Design Overview

The following section presents an overview of the proposed hardware platform design for research and education applications. Detailed design is not presented in this research proposal, rather higher-level system functional requirements, and component descriptions. This section represents what we intend to build.



F.16—FREEDPARRC PROCESS FOR INITAL SYSTEM DESIGN AND CONCEPT VERIFICATION.

Defining Functional Requirements

In defining the system-level functional requirements, we followed the FREEDPARRC process for initial conceptual design as outlined in precision engineering literature.[70] The process is best understood with practice, however a brief description is outlined in Figure 16. In this design cycle, we placed particular emphasis on the environment and ergonomics sections of FREEDPARRC, considering features that make our system a good platform for research, in addition to a representative product for a consumer market.

Table 2 (on the next page), presents the detailed functional requirements (FRs) for the research platform that resulted from the FREEDPARRC process. Where appropriate, FRs were assigned specific numbers developed from initial analysis.

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[69] Progress on Open Cathode PEM Fuel Cells: Performance, Designs, Challenges, and Future Directions, Applied Energy — https://doi.org/10.1016/j.apenergy.2020.116359
[70] FUNdaMENTALs of Design, Alexander H. Slocum — http://pergatory.mit.edu/resources/fundamentals.html

Requirement ID	Requirement Statement	Priority	Numerical	Unit	Note
001	Platform must contain all basic components to create a representative fuel-cell electric vehicle according to DoT standards	High	N/A	N/A	https://afdc.energy.gov/vehicles/fuel_cell.html
002	Platform major components must be easily 'swappable' to allow newly developed components to be tested in a rapid fashion	High	N/A	N/A	**Major Components** is defined as the battery, fuel cell, energy management system, motor, motor controller, BMS, DC/DC converters, tank, filling system, and any other main electrical component required for vehicle function
003	All major performance-indicating datafields from all components must be logged at a speed high enough to enable viewing of transient behavior	High	10	Hz (Min Logging Speed)	**Major Performance-Indicating Datafields** includes battery current and voltage, fuel cell current and voltage, motor torque, and vehicle speed, hydrogen tank pressure, and critical system temperatures at
004	According to ergonomic parameters, test platform must fit in a typical research lab space at an R1 research university	High	16x20	ft	Based on assessment of MIT lab spaces avaliable to professors in the Mechanical Engineering Department
005	Adjustement of space allocation for based on requirements for a safe lab space	High	12x16	ft	Based on OSHA standards for minimum walkway of 4 feet around any equipment.
006	The platform must be capable of achieving similar speeds to a production vehicle.	Med	65	mph (min top speed)	https://www.iihs.org/topics/speed/speed-limit-laws
007	The platform must be capable of achieving similar accelerations to a production vehicle.	Med	0.42	g's	https://www.fdot.gov/docs/default-source/rail/publications/studies/safety/accelerationresearch.pdf
008	The platform must cost, with measurement, safety, and installtion equipment included, a resonable amount for research to be conducted	Med	200000 *cost minimization is a key target for acessibility	USD (max)	Based on the equipment grants maximum from the NSF https://www.nsf.gov/pubs/2001/nsf0193/nsf0193.htm

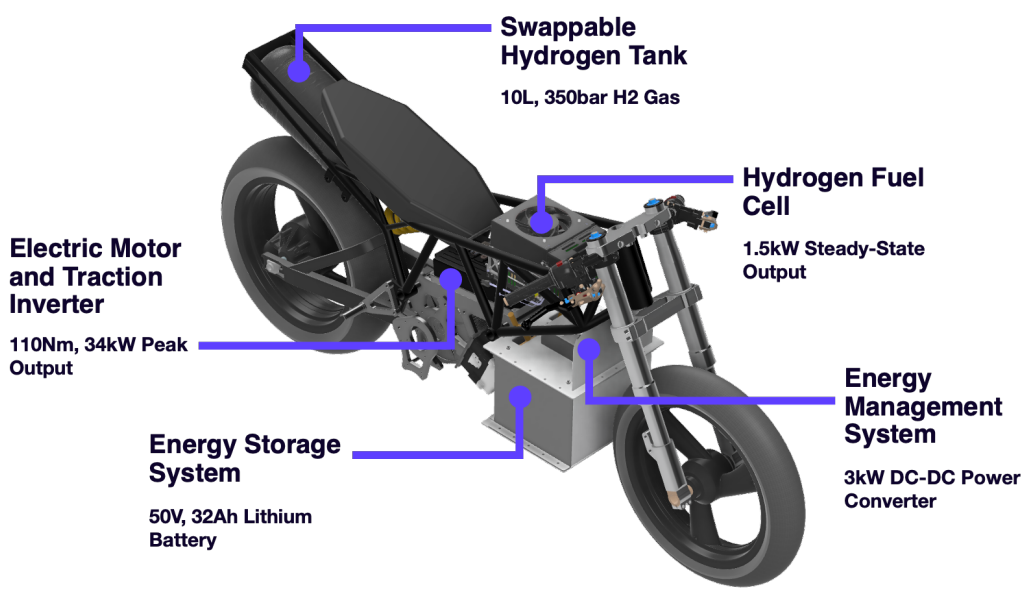
T.2—HIGH LEVEL FUNCTIONAL REQUIREMENTS FOR RESEARCH PLATFORM BASED ON FREEDPARRC PROCESS.

To maximize the accessibility of the research platform to space and resource-constrained labs, cost reduction was critical in the ideation process as was the requirement for the ability of the platform **to be installed in any room on any floor of a building with a standard sized door.** This functional requirement falls under the analysis done for FR004 and FR005, but was not explicitly stated in the table because it may be fulfilled as long as the geometric design of any individual component allows it to fit through a standard sized door. That is to say, the system itself can be assembled within a lab space, with sufficient space around it after final assembly to meet OSHA safety requirements.[71]

Platform Description

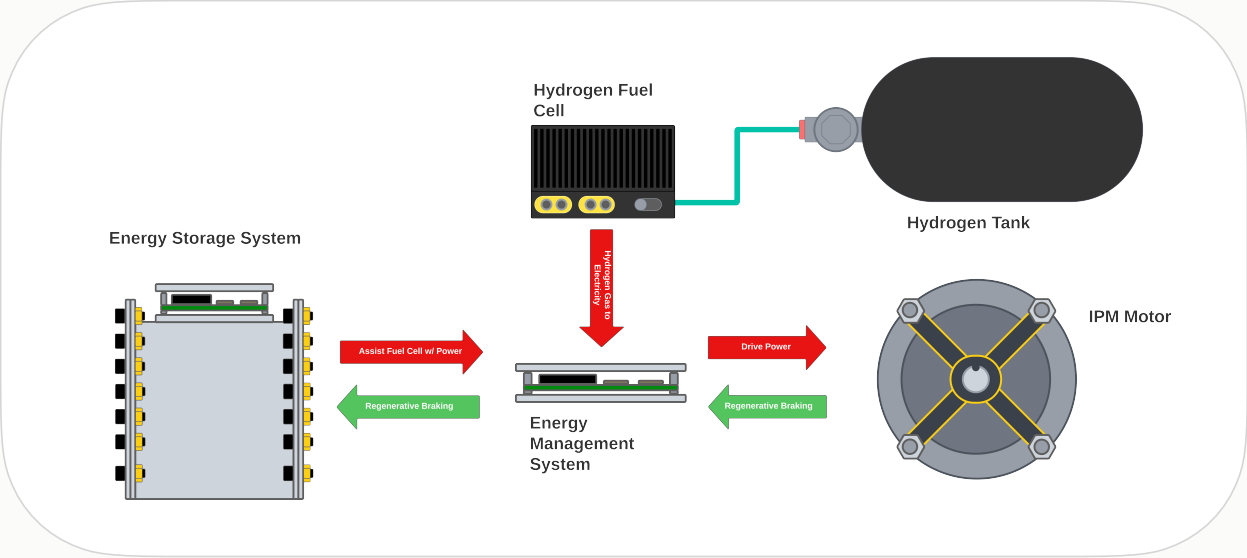
Based on the listed functional requirements, we propose a motorcycle as a starting platform due to the low starting cost, increased simplicity, and smaller space requirements than a full-scale passenger vehicle platform. In addition to the above reasons, the motorcycle platform also allows our group to focus on mobility, and small-scale, demand-side applications of Hydrogen that are often neglected. General trends indicate a sentiment that Hydrogen is only useful in heavy industry, and larger vehicles. We want to open up the possibility of more creative applications of Hydrogen as a method to reduce carbon emissions globally. A labeled, high-level diagram of the proposed system is outlined in Figure 17.

The system is laid out like a standard fuel-cell electric vehicle hybrid with a main storage component, fuel-cell, hydrogen tank, energy management system, motor, and motor



F.17—PROPOSED OPEN SOURCE HYDROGEN BIKE PLATFORM (SIMPLIFIED DIAGRAM WITH MAJOR COMPONENTS).

[71] OSHA Compliance with Aisle Markings — https://www.osha.gov/laws-regs/standardinterpretations/1972-05-15



F.18—POWER SHARING DURING OPERATION OF A BASIC FUEL-CELL ELECTRIC VEHICLE WITH MAJOR COMPONENTS IDENTIFIED.

controller (inverter).[72] In version one, this will be a combination of Commercial-Off-the-Shelf (COtS) components, as well as custom hardware. A general diagram of how power is shared by the critical components in the FCEV system is shown in Figure 18, (note that the inverter was omitted for simplicity).

Fuel Cell and Fuel Tank System (COtS)

The Fuel Cell and Swappable Tank system for the version one system will be built from COtS components. The initial system will use the Doosan Mobility Innovation DM15 Fuel-Cell, which is designed for use in drones and small aerial vehicles.[73] This cell was chosen because of its package completeness including the fuel-cell, balance of plant (BoP), hydrogen storage, and safety systems for fast integration into an initial test system.

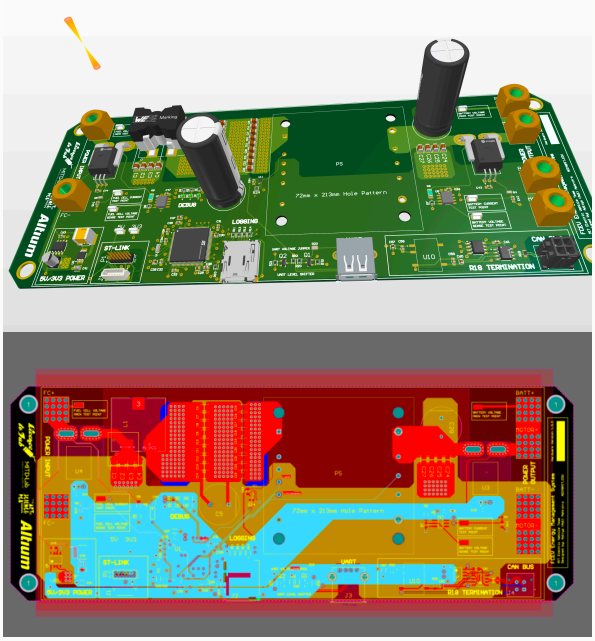
With a maximum power output of 1.5kW, it will not be sufficient for a commercial product. Future version of the system will look into larger, higher-power fuel-cells, but the single package of the DM15 is sufficient for initial research and testing. Accounting for system efficiencies, the DM15 package can provide 6kWh of energy storage and dissemination to the final platform. This is equivalent to the battery capacity on some smaller electric motorcycles.

Energy Storage System (Custom)

Energy Storage Systems for FCEVs employ a number of technologies including super capacitors, and batteries. Because of the low-cost, high power density, and increased energy density compared to a super capacitor, a Lithium-Ion battery was chosen. The battery can be designed to match the powertrain, fuel-cell system, and to maximize potential capacity by accounting for vehicle geometry. Specific cell selection will occur in future work, however detailed battery modeling using the Randles

[72] Fuel Cell Electric Vehicles, Alternative Fuels Data Center, US Department of Energy — https://afdc.energy.gov/vehicles/how-do-fuel-cell-electric-cars-work
[73] DM15 Fuel Cell, Doosan Mobility Innovation — https://www.doosanmobility.com/en/products/powerpack-dm15

model and load characterization will be used to select the specific Lithium-Ion cell.[74]



F.19—INITIAL DESIGN FOR OPEN-SOURCE ENERGY MANAGEMENT SYSTEM INCLUDING DATA LOGGING.

Energy Management System (Custom)

FCEVs are not popular enough, nor are Energy Management Systems (EMS) developed, and general enough for a COtS EMS product to exist on the market. Alternatives would include using a modified solar Maximum Peak Power point Tracker (MPPT)[75] or similar power electronic system with closed-loop logic. However, due to the requirement to be able to develop and test multiple EMS algorithms and techniques, a custom EMS is worth the engineering effort. The initial EMS will be rated to 3kW, which is sufficient to convert power for the 1.5kW fuel-cell chosen with a Factor of Safety (FoS) of 2. The architecture decision of placing the EMS in parallel with the battery, also does not limit the power output of the battery to the traction inverter and motor.

Traction Motor and Inverter (COtS)

The main traction motor and inverter for the version one system will be COtS components taken off a previous generation Zero Motorcycles electric motorcycle.[76] The Zero Motorcycle ZF75-7 motor and SEVCON Gen4 Size 6 paired inverter provide a peak power point of 81Nm @ 5300RPM, for a peak power of 45kW. Through initial estimates of motorcycle mass, and aerodynamic performance, we determined this powertrain (including a final-drive chain), is sufficient for a medium sized sport bike based on the listed functional requirements.

Bridging Simulation and Reality with Hardware Testing

Developing a mobile vehicle platform (as opposed to a system-on-bench test setup) enables increased opportunities for research enabling users to load the system with more realistic test conditions. Conditions like aerodynamic drag, rolling resistance, and similar energy dissipation methods are difficult to model, and while they can be simulated in hardware, track data is often important in creating opportunities to bridge simulation and reality. At the same time, dynamometer testing allows for a controlled environment for testing of the major power system components. Further, it enables research to occur without access to a test track, which can have both cost and safety concerns.

Based on this, we propose the creation of a selectable input, and model simulation

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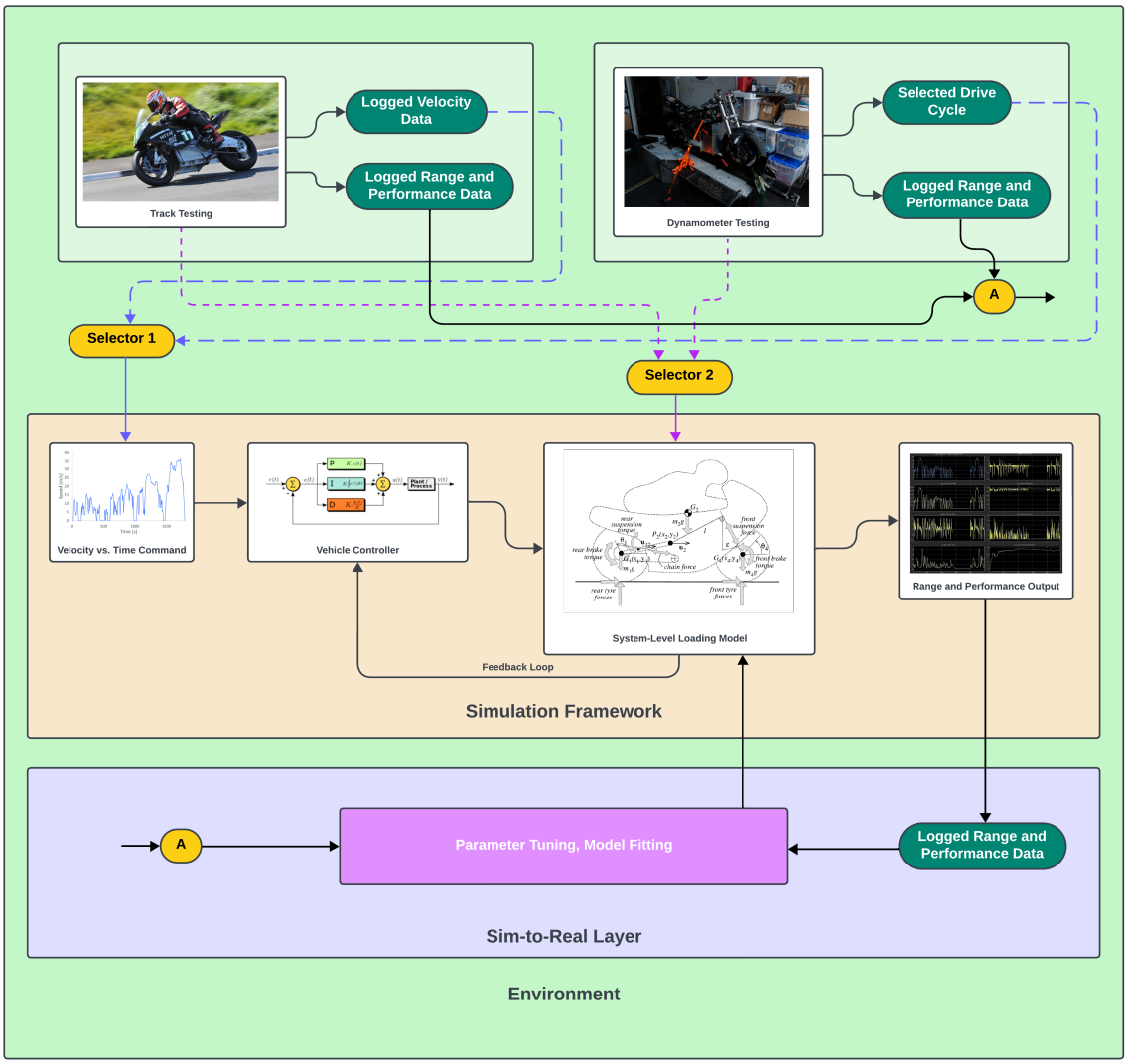
[74] A Distributed Randles Circuit Model for Battery Abuse Simulation, Ansys — https://lsdyna.ansys.com/wp-content/uploads/2022/12/a-distributed-randle-circuit-model-for-battery-abuse-simulations-using-ls-dyna-r.pdf
[75] Simulation and Design for PV MPPT, IEEE — https://ieeexplore.ieee.org/abstract/document/5571418?casa_token=mzrKfknB3kkAAAAA:MDEjsO9lffvSLIf6yzVhdm3g8ABEvuKQ1MOEXTcz8nfaLQ9pK35a9JZ2MZXkE0PXlP2oM_wmMg
[76] Zero Motorcycles Powertrain — https://zero-cms-disco.cdn.prismic.io/zero-cms-disco/372e4e04-53f3-4f30-9bf2-7e3e5fc1a901_powertrain-data-sheet.pdf



Graphics From https://www.researchgate.net/figure/WLTP-Drive-cycle-for-passenger-vehicles_fig1_354394903
https://www.researchgate.net/figure/Seven-dof-motorcycle-model_fig3_239391944
Wikipedia, PID Controller

F.20—SIMULATION FRAMEWORK AND SIM-TO-REAL COMPARISON WITH SELECTABLE INPUTS AND SYSTEM MODELS FOR TRACK AND DYNAMOMETER TESTING.

framework. This framework is shown in Figure 20, and allows the user to select either a drive cycle, or logged velocity-time data as the input to the simulator. A vehicle controller then attempts to control a model to follow the drive profile. The model can be selected as a dynamometer model, which neglects certain loss factors such as aerodynamic drag, or a full-vehicle model which is designed to be as comprehensive as possible. The output of the simulation can be compared to either real dynamometer, or track data which can be used to tune the simulation parameters to bridge sim-to-real gap. After an iterative process of parameter turning, the simulation can be used to design energy management system

algorithms, or estimate how changing major design parameters could affect the performance and range of the vehicle. It can also then be used to predict how the vehicle might fair on alternate driving routes.

This dual framework has an additional advantage in also helping researchers be able to discern which parameters are contributing most to model discrepancies. For example, should the simulation perform well on dynamometer data, but less well on track data, researchers may be able to predict that aerodynamic, rolling resistance, elevation change, or other environmental factors are likely the critical error source. Additionally, a simulator that performs well on dynamometer data could be used to predict how changes in components affect performance and range on a dynamometer, but might not scale as accurately to real-world range and performance predictions. Both are important.

It's critical to understand that a velocity-time input does not capture the entire environment being simulated. To understand this, think of two motorcycles, one traveling at constant velocity on a flat ground, and another attempting to maintain the same velocity on an incline. The velocity-time profiles may be the same, but their requested drive torques will be different. Therefor it may be necessary to include more complex inputs into the simulation framework in the future.

The Role of Open Source in Achieving Platform Functional Requirements

In our design process, we will strive to make as much of the platform's hardware and software as open-source as possible within reasonable limits. We do this for multiple reasons, many of which have been document in various forms of literature. According to the National Academy of Engineering, scientific development and engagement is often limited by expensive and proprietary equipment.[77] By open sourcing hardware, not only does this improve accessibility, enable widespread design review, and enable replication abilities even after a project's lifecycle[78], it has a significantly higher Return on Investment (ROI) as the cost to replicate work for a well-documented project approaches only the cost of physical materials.

The National Library of Medicine of the NIH also conducted a study on the economic savings of using Free and Open Source Software (FOSS) and Hardware (FOSH) including the Arduino platform, and RepRap 3D printers in academic research.[79] The study estimated that open source technologies provided an economic saving of up to 87% compared to proprietary alternatives. This is an overwhelming economic advantage for both research labs with a constrained budget, but also less-funded research labs, organizations and companies in developing nations, or any other users in resource-constrained environments or

[77] Impact of Open Source Hardware in Science and Engineering, NAE — https://www.nae.edu/174822/Impacts-of-Open-Source-Hardware-in-Science-and-Engineering
[78] Hardware: The Next Step towards Open Source Everything, NAE — https://www.nae.edu/174828/Hardware-The-Next-Step-toward-Open-Source-Everything
[79] Economic Savings for Scientific Free, and Open Source Technology (FOSH): a Review, NIH — https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7480774/

situations where the cost reduction can greatly improve accessibility.[80]

It's important to note that documentation is critical to the success of open source projects.[81] This is partially because documentation enables the ability to replicate, modify, and scale solutions, but also because the existence of documentation in itself adds value.[82] Documentation can provide knowledge that experimental hardware setups would provide even without the replication of those test setups. Meaning in resource-constrained environments, the starting point of being able to use previous work in developing a solution is already a significant value, and makes a proposed project far more feasible and attainable.

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[80] Open Hardware in Science: The Benefits of Open Electronics, Integrative & Comparative Biology — https://academic.oup.com/icb/article/62/4/1061/6590044
[81] Open Source Hardware, MIT DSpace — https://dspace.mit.edu/handle/1721.1/55201
[82] Defining Success in Open Source Hardware Development Projects: a Survey of Practitioners, Design Science — https://www.cambridge.org/core/journals/design-science/article/defining-success-in-open-source-hardware-development-projects-a-survey-of-practitioners/6DD6C830713A518971CA8AAC1458D3A0

4.

Multi-Year Project Outlook

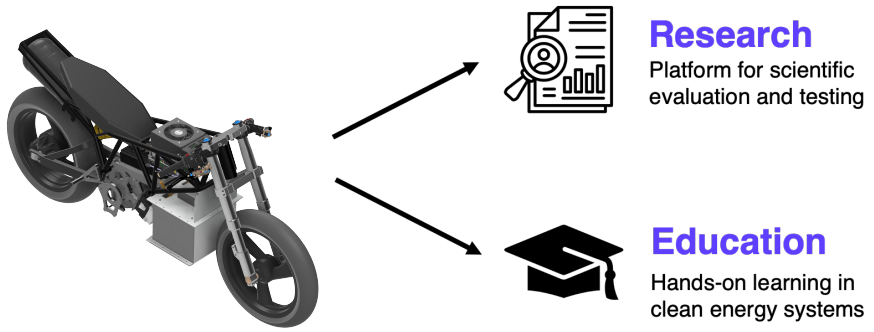
The last section of this report looks at the potential impacts this project could have in the real-world, at various scales, over a multi-year outlook. The focus being to help in building a more sustainable, and equitable global energy economy. We present these as ideas, the details of which will become clearer in future repots and publications.

Thinking of Hydrogen as a Molecular Energy Carrier

To summarize the key advantage of Hydrogen, especially compressed gaseous Hydrogen we need to look at the entire energy economy from generation to use. Hydrogen is a molecular energy carrier, meaning that it can enable access to green and renewable energy even in locations where renewable energy is difficult to implement.[83] For example, in regions where Solar, Wind, or Nuclear power is difficult to implement, Hydrogen generated from renewable sources and transported into the region may enable a green energy economy and reduce dependence on fossil fuels.

Additionally, Hydrogen can enable renewable energy systems to become more tractable in specific applications. Solar-powered vehicles have proved challenging to get working due to the area required to produce enough energy to drive a commercial vehicles. However, Hydrogen produced by solar can be compressed and stored on-board a vehicle and significantly increased the stored energy and maximum output power of the powertrain.

It's this end-to-end, context-aware mindset we hope to explore in our work. To figure out



F.21—THE OPEN SOURCE HYDROGEN BIKE CAN BE USED FOR ENABLING THE VERIFICATION OF RESEARCH ON HARDWARE, WHILE ALSO PROVIDING HANDS-ON EDUCATIONAL OPPORTUNITIES FOR STUDENTS.

[83] Hydrogen Explained, US Energy Information Administration — https://www.eia.gov/energyexplained/hydrogen/

now just *which* applications Hydrogen may help decarbonize, but *where*, and *how*. Considering the supply side, while innovating on the demand side.

Applications to Research and Education

During the initial stages of project development, we will be using the platform to perform our own academic research. Our research will focus on filling gaps in FCEV vehicle engineering that we identified in the previous sections. These will serve as contributions to the field, but also demonstrations of how to use simplified hardware platforms to verify academic research on hardware.

External Research Collaborations

At this stage, we hope to provide the platform to researchers at other universities (regardless of research designation) to verify their research using the platform, as well as provide feedback on the platform. For universities that may have space, cost, or other constraints that may not enable them from receiving the full platform, we hope to establish partnerships that enable them to to verify their work on our hardware platform.

This strategy provides both the opportunity for hardware-centric approaches into filling the engineering gaps in FCEVs, but also enables increasing the technical quality and capabilities of the vehicle we are developing. Naturally in research, experiments will reveal opportunities for platform improvement, and during this stage we hope to take full advantage of these opportunities to improve the hardware, documentation, and simulation capabilities.

Hands-on Education

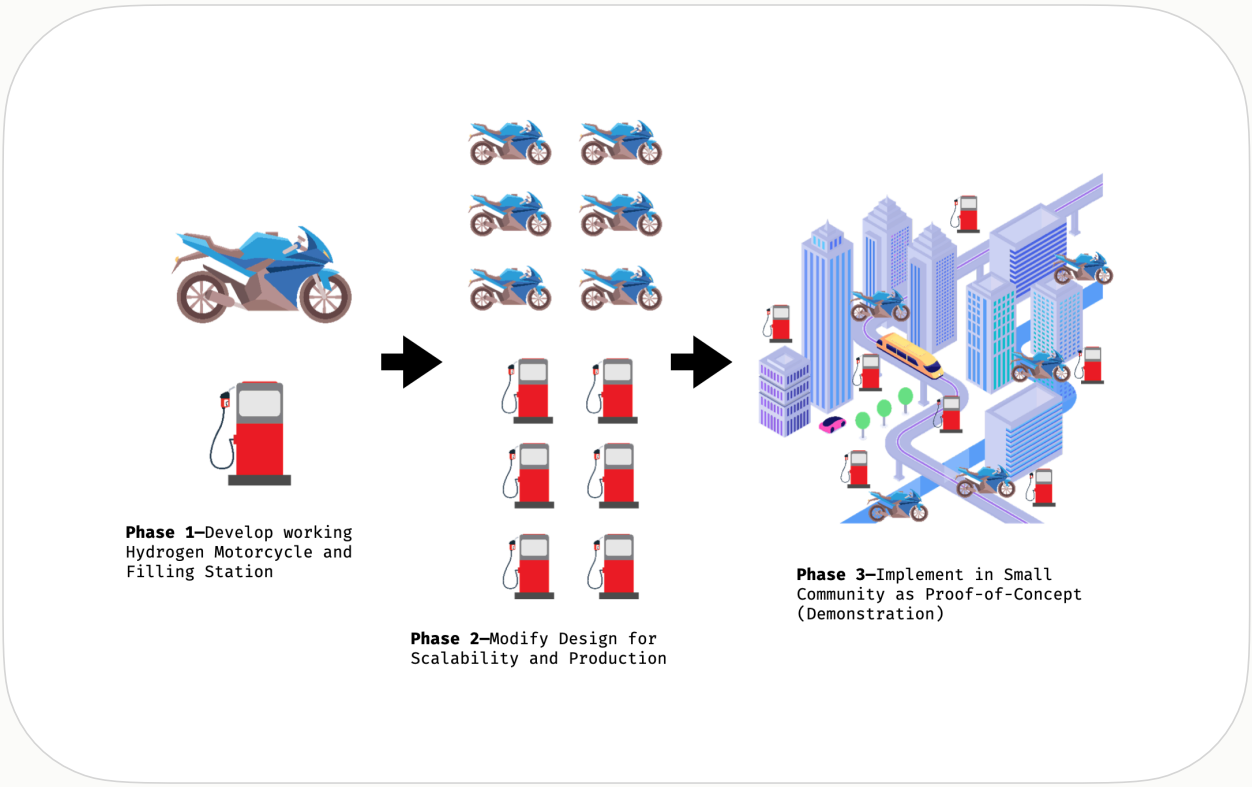
At both the 2022 Hydrogen Americas Summit[84], and the 2023 World Hydrogen Summit[85], education was identified as a critical gap in the space of hydrogen. During the development of the platform, our project provided the opportunity for a number of undergraduate students (across various departments) to gain hands-on experience in designing various aspects of Hydrogen Fuel-Cell systems. This includes volunteered time from undergraduates at MIT, as well as paid research opportunities through the MIT UROP program, with additional collaboration with the MIT Energy Initiative and the MIT Edgerton Center.[86]

We have started to collect the results of our student's projects to evaluate the skills, and experience they developed while working on various aspects of the vehicle. As an experiment into hands-on education, we hope to showcase how the platform can enable new, and creative teaching methods in energy systems, controls, mechanical design, fluids, simulation, and algorithm development but on a real hardware system. However, it is still unclear of what form our recommendations on education will take. We hope to additionally combine various literature from the science of learning to structure comprehensive educational opportunities in new renewable energy technologies.[87]

Demonstrating the Efficacy of Hydrogen at Scale

Through multiple industry partnerships we hope to explore the efficacy of Hydrogen, for now specifically in the mobility sector, but

[84] Hydrogen Americas Summit, SEC — https://www.hydrogen-americas-summit.com/
[85] World Hydrogen Summit, SEC — https://www.world-hydrogen-summit.com/
[86] UROP Program, Massachusetts Institute of Technology — https://urop.mit.edu/about/
[87] Make it Stick: The Science of Successful Learning, Peter Brown, Henry Roediger, Mark McDaniel — https://www.retrievalpractice.org/make-it-stick

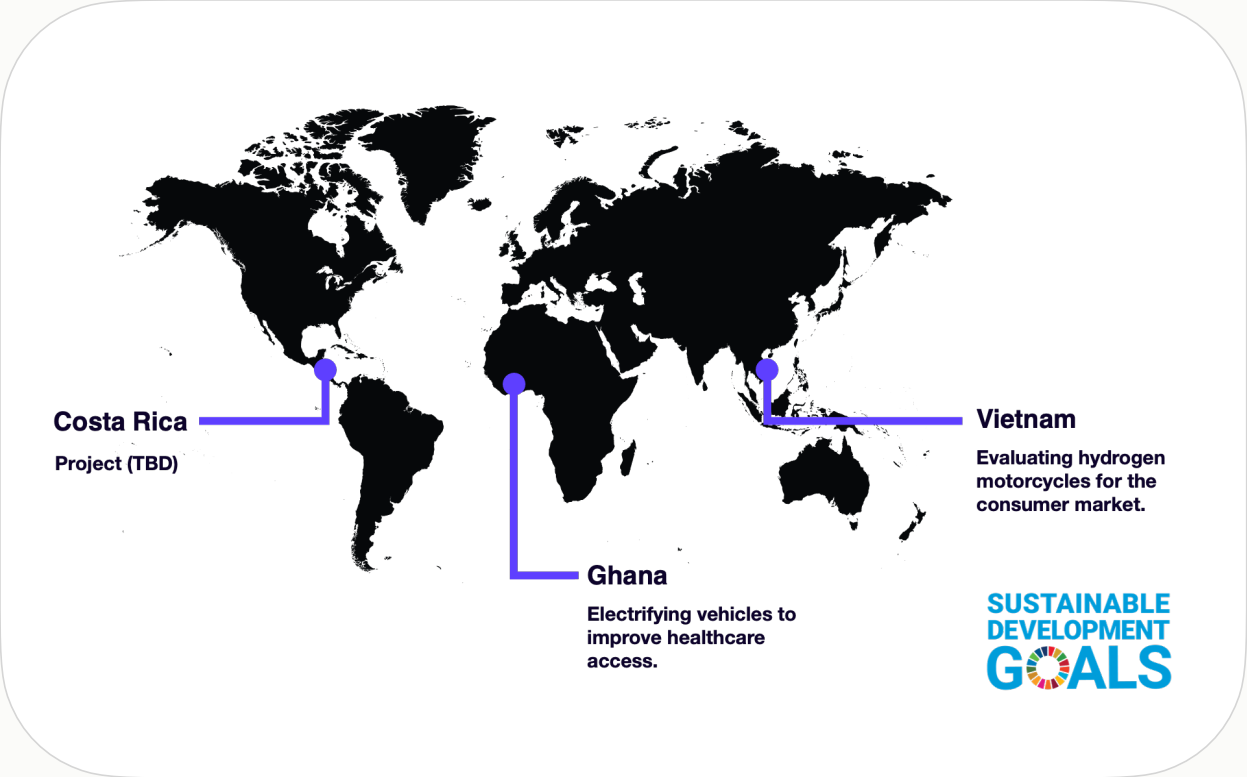


F.22—DIAGRAM OF A POTENTIAL DEMONSTRATION PROJECT, INCLUDING FEASIBILITY ANALYSIS AND IMPLEMENTATION OF A PILOT PROJECT IN A REPRESENTATIVE, REALISTIC ENVIRONMENT.

expanding to other creative applications in the future. We have partnered with two motorcycle manufacturers, as well as a fuel-cell manufacturing company to develop a Hydrogen-powered mobility solution. While the details of these partnerships are not yet public, Figure 22 showcases the envisioned project.

In the first stage, we focus on building a robust platform with our industry partners placing key emphasis on safety, reliability, and economic feasibility. In the next stage, we focus on building the resources for a pilot project implementation in stage three. In the final stage, we hope to implement a number of Hydrogen mobility solutions in a representative target market to run a full-scale pilot study to analyze the efficacy of Hydrogen to replace gasoline vehicles, or battery-electric vehicles. The selection of the target market will depend on the feasibility analysis conducted in phase one of the project, and the market research of our partners.

We hope to obtain critical data from a large-scale pilot. The methods for how Hydrogen infrastructure is implemented will vary from region to region, and a pilot would allow exploration of various methods, but also track unexpected costs, changes, and infrastructure challenges to transition to a Hydrogen-centered energy economy. Additionally, a pilot allows us to obtain critical user data that would be difficult to obtain otherwise which include barriers to adoption, unexpected required behavioral changes, direct comparisons by users between alternative solutions and Hydrogen powered solutions, and feedback on ergonomics. Data that would lower the barrier to implementation, and increase the likelihood of adoption of similar solutions in other markets



F.23—MAP OF LOCATIONS OF GLOBAL PROJECT PARTNERS AND INITIAL DETAILS ON POTENTIAL PROJECTS.

and contexts. If implementing a full-scale pilot in hardware is not feasible due to cost or infrastructure challenges, alternative methods will be explored.

Focus on Emerging Markets

Climate energy leapfrogging is becoming more commons as emerging-market countries push to transition to renewable energy before fully developing their fossil fuel infrastructure.[88] And while many sources agree that it's not fair for these nations to have to leapfrog due to accelerated climate degradation caused by western nations, it does provide some distinct advantages.[89] Many of these include the promise of increased energy security, and economic development through job creation, with the downside being the need for both significant investment into infrastructure and engineering expertise.[90] The IEA has compiled a number of resources and programs on clean energy in emerging economies.[91]

In partnership with MIT's D-Lab, both our research and education, and industrial pilot project endeavors will focus on emerging markets because of the dual climate, and social impact potential for projects. Systems in resource constrained environments often see more abuse that is far less characterizable or predictable when compared to non-resource

[88] Leapfrog to Renewable Energy in Africa, Greenpeace https://www.greenpeace.org/africa/en/press/54215/africa-climate-summit-africa-can-leapfrog-towards-a-clean-and-sustainable-energy-future/
[89] Renewable Energy Leapfrogging, Climate Reality Project — https://www.climaterealityproject.org/blog/renewable-energy-leapfrogging-better-way-forward
[90] Renewable Energy in the Developing World, OECD — https://www.oecd.org/dev/developing-countries-and-the-renewable-energy-revolution.htm#:~:text=Renewables are clean.,They enhance energy security.
[91] Clean Energy in Emerging Economies, IEA — https://www.iea.org/programmes/clean-energy-transitions-in-emerging-economies

constrained environment. As a result, the creativity and robustness of solutions often has to be higher to achieve the same system performance.[92] And because of this, while we are focusing on emerging markets, the lessons we take away can lead to more cost-effective, robust energy solutions in the US and other western nations.

Figure 23 shows some of our initial partnerships. In Costa Rica, we hope to explore more niche, demand-side applications of Hydrogen including the potential for Hydrogen powered drones to increase agricultural output. Vietnam represents one potential location for the full-scale mobility pilot study described in the previous section.

Ghana is a more interesting situation. Ghana's fluctuating oil prices render vehicles too expensive to operate on some days to smallholder farmers in the north.[93] Here, we hope to explore multiple different renewable energy methods including solar electrification, hybrid methods, and Hydrogen to potentially improve access to reliable transportation in the northern regions. The learnings from this project may be able to be used to create methods for determining how to implement context-aware renewable energy solutions in communities around the world, and how to select renewable energy technologies based on socioeconomic factors.

[92] MIT D-Lab — https://d-lab.mit.edu/
[93] Based on our own internal studies, with data to be released in future reports and projects.

Acknowledgements

The authors would like to thank our project partners listed on the partners page of our website. Additionally we would like to thank the MIT Mechanical Engineering Department, the MIT Energy Initiative, MIT D-Lab, and the MIT Edgerton Center for their continued and incredible support. Additionally we would like to thank our project advisor, Professor Alex H. Slocum, as well as our mentor and shop manager Jack Whipple. Finally, we would like to thank J. Shia and the Madhouse Motors team for giving us the 1999 Ducati 900ss that gave us our start.

Contact

We are open to working with anyone looking to build a cleaner, more equitable world for all regardless of race, gender, socio-economic status, or educational background. Please reach out to us at l2f@mit.edu at any time.

Electric Vehicle Team @ MIT.