Tough to Decarbonize Transportation: MIT Climate Grand Challenge

by Steven Barrett and Bill Green, 09/30/22

Yen-Chu Wu

Part I. Literature


Part II. Recent News


Part III.

Jinhua questions

(For Steven)

Q: You mentioned that there is a technology that can significantly cut contrail by 80% with a marginal increase of the cost, and a decrease in the fuel efficiency. Since you mentioned that you worked with a few industries to start to implement this, could you give us a little bit update on where we are in that?

A: We currently think that the best way to reduce contrail warming is contrail avoidance. Essentially, contrails only form in very particular meteorological conditions when it’s super saturated and cold, which happens around 10% of the time at cruise altitudes. These super-saturated regions are vertically thin but laterally wide. To avoid them, you would reduce your altitude slightly for a while and go back up. We are now working with airlines on trying this in the US airspace. It will take time to prove that out and to verify the fuel burn costs, but at least the modeling early on suggested 1% or 2% more fuel burn to mostly eliminate contrail, so I think that looks very promising.

Q: There is recent controversy about Google Flights to carbon calculator. It does not count the contrail as part of the warming. If we look at the whole warming effect, contrail needs to be incorporated, but it is hard for Google to do. What is your opinion on how should Google do in informing the public?

A: Different countries or organizations have different recommendations for the value of the multiplier. Any individual flight can vary massively in contrail warming by probably a
factor of 100, so using an average factor is a pretty good thing to do. Personally, I think it would be good to keep that in there and caveat the uncertainties in that clearly. What I would like to see is a case when you book a flight, you can know the estimation of the flight’s warming. Then, your flight can be tracked and provide actual information on fuel burn and contrail forming, and finally the estimated warming.

(For Bill)

Q: In the private car sector or urban transportation sector, it seems that electrification is a dominating solution. Will there be a spillover effect if the infrastructure of electrifying cars can be shared with trucks?

A: Trucks are very efficient actually. Charging electric trucks with grid electricity probably will produce more CO₂ emissions because diesel engines are so efficient. So, it is not trivial to figure out a solution that is significantly better.

Q: From a scientific point of view, trying all three can provide us robustness, but if considering costs, we need to just make one decision. How do you trade off between this diversity versus a clear focus? Also, please give us a sense of the different options in science, engineering, and industry practice faces.

A: Trucking is very complicated because there are millions of independent factors in different countries that all have different business situations. Also, many countries do not have regulations at all. Forcing people to use new trucks might raise some social science problems since drivers would like to save costs by using old trucks. In fact, engineers have not come up with any solution that is cheaper than the current system.

(For both)

Q: What do you observe as the industry's effort in pushing this? Do you see there is enough attention to this? What is the state of the mindset of the industry?

(Bill) A: I think the industry in rich countries (e.g. Europe, USA, Korea, and Japan) do pay attention to truck decarbonization. I think for the short-range trucks electrification is going to happen in the rich countries for sure. There are also a lot of efforts in projects with hydrogen-powered trucks. However, both of these solutions are not so obvious in other countries. One possible way is that rich countries to find a solution, implement it, and then let the rest of the countries follow. But we need to think about it carefully because both the hydrogen and the electricity solutions depend on very expensive infrastructure developments.
(Steven) A: Europe has had a strong commitment for several years now to get towards net zero, and the US, within the past year or two, has committed to that as well. The thing that is lacking now is policy support.

**Audience’s question**

(For Steven)

Q: Are contrails currently accounted for in our general greenhouse gas inventory?

A: No, the US only considers carbon now, but this might change in the coming few years.

(For both)

Q: Given the breakdown of the missions and the challenges to decarbonize, which of these three should we prioritize? At what point will companies and governments start consolidating on technology and focus time and resources on one of the options as opposed?

(Bill) A: For aviation, the community is definitely on the way to trying. For the ships, we are in the way early days that a few ship lines are seriously considering this, but a lot of shippers are only considering costs. For the trucks, in a few of the rich countries, we are starting to move towards trying to do demonstration projects, even showing that there is a solution. Until the technical problems are overcome, no policymakers are going to require people to adopt a technical solution that does not work.

(Steven) A: I think there might be some prioritization challenges because I think they all matter to the good life. And for example, biomass is limited and lacks a market mechanism to sort everything rationally, and there will be debates on which sector should get this.

**Part IV. Summary of Memos.**

**Themes from Other Memos**

1. Spencer suggested that we should choose an option and start moving forward instead of devoting all our time on determine the best path because the time cost of inaction could be worse than choosing a suboptimal way forward.

2. Michael pointed out that in aviation, it is hard to identify the responsible country for carbon emissions since flights connect and fly over different countries. Furthermore, Michael mentioned that government policy requires a lot of
cooperation with academia and a set of different industries to decarbonize the trucking sector. This should be further investigated.

3. Manasa pointed out there is no discussion and plan on the ways to address carbon emissions from the tough-to-decarbonize sectors in the two climate action plans Manasa read, while this is critical to achieving carbon neutrality goals by 2050. Moreover, Manasa brought a perspective that the developing countries are still able to contribute to the solution of these sectors, and can potentially find alternatives with their own considerations such as finance.

4. McKenzie argued that even if we do not reduce overall demand, we should still at least recognize the unequal emissions patterns among developing and developed countries when investigating pathways to decarbonization.

5. David asked five interesting questions regarding the talk. (i) Should the de-pollution/de-carbonization of the airline industry be regulated, and if so, by whom (e.g. FAA) and how (e.g. by direct emission and contrail)? (ii) What are the major obstacles to delivering hydrogen cost-effectively to hydrogen cell vehicles? (iii) What are the advantages and disadvantages of Fuel Cell Electric Vehicles (FCEVs) that combines hydrogen and EV technology? What are the downstream effects of charging infrastructure and where are FCEVs seen as viable and sustainable alternatives to combustion engines? (iv) What are the implications for road maintenance and repair for EV trucks that weigh significantly more than combustion engine trucks? What are concurrent technologies and processes that need to be developed to solve a foreseeable increase in repairs? (v) How do we get EV or hydrogen charging to the most remote locations where trucks may travel (i.e. no urban areas), and who should invest in these stations? Should the industry itself be required to share the burden or should they be supported by taxpayers?

6. Jason mentioned that because the decarbonization of these industries requires high costs, the government needs to have corresponding policies. Otherwise, truck drivers or low-income people who take planes could be greatly affected if the legislation simply restricts the old technology, as the cost will inevitably be passed on to consumers.

7. John thought that we are trapped in the tragedy of the commons. John believed that it is valuable to adopt cleaner fuels such as solar and wind.
8. Samuel summarized the talk and concluded that everyone should make a small effort to reduce carbon emissions, and the cumulative impact can be huge.

9. Paul stated that in the short to medium term, all potential fuel options are more expensive, so the transition requires comprehensive policies. It is worth considering the impact that some mandates/adoption policies will have on developing countries.

10. If it is impossible to rely on one single method to solve the entire energy problem, as Prof. Green stated, Ao believed that it is worth spending time studying the optimal combination of strategies for each sector.

11. Tushar would like to know that at this point, given the breakdown of emissions (equal split between aviation, trucking, and shipping), and the challenges to decarbonizing requiring a massive external push (by the government?), what is the first of the three that should be prioritized towards decarbonization? This question was not clearly answered during the session.

**My Reflection**

In this mobility forum, Prof. Green and Prof. Barrett gave a presentation on the decarbonization of the aviation, shipping, and long-haul trucking sectors, which rely on high-energy-density fuels to achieve long-range travel. Passenger aviation, heavy-duty truck, and maritime cargo contributes about 14% of total fossil CO₂ emissions. There are several potential ways to decarbonize these sectors, such as using hydrocarbon fuels, H₂, and batteries. However, they all have their own science/engineering and policy/economics limitations such as energy density, costs, and required new infrastructure and regulations. Prof. Green concluded that long-haul trucking has multiple decarbonization options, and H₂ seems promising but there is no clear path forwards. On the other hand, Prof. Barrett stated that aviation’s goal is to have zero environmental impact instead of decarbonization. This is because contrails cause similar amounts of warming to CO₂. Contrail avoidance might be the cheapest and fastest way to mitigate the climate impacts of aviation.

At first, when I saw the title of this talk “Tough to Decarbonize Transportation”, I thought this would center around the barriers of passenger electric vehicles. I was amazed and really excited to learn more about the challenges and opportunities of these three transportation sectors. It is sad to know that we still do not have enough knowledge of which fuel and method are the best. I am curious about the government’s attitude and plans. When reviewing some cities’ climate action plans in another course, I found that even though they set a carbon neutrality goal, they do not have discussions or policies on these
transportation modes. Besides, I am surprised that decarbonizing aviation with electric aircraft is not enough, and I am wondering if shifting flights to other public transit like high-speed rail would be helpful if it is so hard to have zero environmental impact in aviation.
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Santosh Shanbhogue
Zolti Spakovszky
Ray Speth
Gregory Stephanopolous
Kripa Varanasi
Ian Waitz
Emilia Williams
Oscar Wu

https://t2dt.mit.edu/
<table>
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<tr>
<th></th>
<th>Total</th>
<th>2019</th>
<th>2040 (eia projection)</th>
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<tbody>
<tr>
<td><strong>Passenger air</strong></td>
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<td>12.7 quad</td>
<td>22.4 quad</td>
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<td>0.3 Gt/y fuel</td>
<td>0.5 Gt/y</td>
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<td></td>
<td>~67% long-haul &gt;1500km</td>
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<td><strong>Heavy-duty truck</strong></td>
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<td>31.4 quad</td>
<td>37.0 quad</td>
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<td></td>
<td>0.8 Gt/y fuel</td>
<td>0.9 Gt/y</td>
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<td></td>
<td>~50% in US &amp; EU long-haul &gt; 400km/day</td>
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<td><strong>Maritime cargo</strong></td>
<td></td>
<td>10.8 quad</td>
<td>12.2 quad</td>
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<td></td>
<td>0.3 Gt/y fuel</td>
<td>0.3 Gt/y</td>
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<tr>
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<td>87% international, mostly long-haul</td>
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Together: $6 \times 10^{10}$ GJ LHV/y (≈1900 GW running 24x7)
comparable to total global electricity consumption = $10 \times 10^{10}$ GJe/y
1.4 Gt/y of fuel gives ~5 Gt/y of CO2, ~14% of total fossil CO2 emissions
Today’s fuels cost $600/ton ($13/GJ) wholesale, i.e. ~$900 B/yr market today.
Decision #1 Hydrocarbon fuel or not?

Hydrocarbon fuels:

- Minimal changes to vehicles or refueling infrastructure required.
  - Minimal organizational / regulatory / business changes
  - Saves a lot of capital and eases implementation.
- To avoid climate disaster, need to change from fossil to low-Greenhouse hydrocarbons
- Would need huge new industry manufacturing low-GHG hydrocarbon fuels (1.2 billion tons of fuel Carbon per year).
  - Comparable to total Carbon in all harvested foodstuffs on earth
Nutrition Carbon for Low-GHG Hydrocarbons

- Fuel from biomass is relatively inexpensive.
- Unlikely enough biomass could be sustainably harvested to meet **all** the demand for hydrocarbons from trucks + aviation + ships.
- Inadvertently set up incentive for massive deforestation?

If smokestack capture... emitting fossil carbon.
- Air capture will probably be expensive (?)
- To make 1 Gt/y fuel, need to capture ~3 Gt/y CO2, by processing about 2 billion cubic meters of air every second.
Huge low-GHG H₂ production needed to make fuels

Renewable electricity + Water Electrolysis → Low-GHG H₂

NREL estimate: > $4/kg H₂ if $70/MWh

Carbon source (e.g., biomass, captured CO₂) → Low-GHG H₂ → Drop-In “Low Carbon” Hydrocarbon Fuel

Steam methane reforming (SMR) of natural gas + Carbon capture & sequestration (CCS) → Low-GHG H₂

< $2/kg H₂ in USA (at locations with gas and CCS)

Nitrogen source (e.g., air, sedimentary nitrogen) → Low-GHG Ammonia

Huge Amount of H₂ required: need much more electricity and/or natural gas than today. Needs to be inexpensive and very low greenhouse gas emissions.
Need High Energy Density for Range

To travel long distances, vehicles have to carry stored energy (fuel).
+ Need fuels with high specific energy and energy density, else fuel cuts into payload.
  + Batteries have low energy density, not good for long range travel

Long-Haul Jets: Only Hydrocarbons have high enough specific energy.
Long-Haul Ships: A handful of options:
  Hydrocarbons, Liquid H2, Ammonia
Long-Haul Trucks: Many fuel options, including batteries. Unclear what is best.
Zero-CO$_2$ fuel options interesting but **challenging**

Zero-CO2 options are appealing for climate, avoid need to obtain a billion tons of non-fossil Carbon, but unlike drop-in fuels require...

+ complete replacement of vehicles
+ all new refueling infrastructure
+ all new regulations & emission controls

H2 as Fuel? Liquid (cryogenic) and high pressure H2 hard to handle, greatly increases vehicle + refueling system expense, esp. for trucks. Producing H2 much cheaper than supplying it retail.

How viable are other zero-CO2 options? Maybe NH3 or Liquid Organic H2 carriers? What are their downsides? Emissions?
Likely that different sectors or sub-sectors will use different fuels

- Hydrocarbon Fuels from biomass, like SAF (Sustainable Aviation Fuels) have big advantages, but probably insufficient quantity to fuel all sectors.

- Batteries won’t work for most aviation or shipping, but may be best option for some trucking applications.

- Some fuels, like NH3, are safe enough for ships, but probably will be considered too smelly/dangerous for most trucking.

- Some mode-switching, e.g. from airplanes and trucks to trains?
Overall: Challenging multi-disciplinary problem

**Big Science & Engineering Problems:**
In some sectors not yet clear **which fuels are viable** options.
Some plausible proposed solutions have **not been demonstrated yet**.
Most proposed solutions have **unresolved environmental questions / issues**.
Even where consensus on fuel + vehicle, **not yet clear how to reach needed scale**.

**Big Policy/Economics Problems:**
All solutions will **noticeably increase cost** of Freight & Air Transportation.
  - Transition will **need to be pushed by policies**.
  - **Equity implications** of the increased cost.
Tricky to manage competition between old and new vehicles/fuels during transition, while keeping freight moving smoothly.
Currently Trucking is regulated (or not regulated) locally, not globally.
  - Does this need to change, to force transition in every country?

Quite a lot of R&D & Policy work needs to be done.... and **Quickly**!
Need the solutions to be **deployed on huge scale within next ~20 years**.
Decarbonizing Trucking: Hydrogen & Other Options

Prof. William H. Green
Dr. Robert Jones
Ms. Kariana Moreno Sader
Mr. Sayandeep Biswas
Medium & Heavy-Duty Trucks emit ~7% of USA CO2. Long-Haul Trucks ~3% & growing

Trucks not dominant source of greenhouse gas emissions, but too big to ignore
Many Options for Decarbonizing Trucking

**Low-GHG Diesel and Renewable Hydrocarbons**
- Made from low-GHG hydrogen
- **Carbon Source**: Biomass and captured CO₂
- No refuelling infrastructure change necessary – customers ready if you can provide the fuel
- **Limitation**: Scale to match entire fuel demand??

**Electricity**
- Ideally, obtained through renewable sources – Wind and Solar
- Existing and projected grid (2050)[1] is not completely renewable – “Dirty” electricity
- Spill over benefits from the light-duty market – passenger vehicles
- **Limitations**: Long recharging times, large battery required for trucks: expensive and reduces payload

**Hydrogen**
- Production: Electrolysis of water or steam methane reforming with carbon capture
- Storage and Transport: Compressed gas, Cryogenic liquid, or solid/liquid hydrogen carriers
- Benefits include fast refueling, high energy density
- **Limitations**: Presently, cost of delivered hydrogen is prohibitively high

Many Options for Decarbonizing Trucking, But...

Low-GHG Diesel and Renewable Hydrocarbons

- Made from low-GHG hydrogen
- Carbon Source: Biomass and captured CO₂
- No infrastructural changes necessary — high market readiness
- Limitation: Scale to match entire fuel demand

Electricity

- Effective implementation of alternative fuels could dramatically reduce trucking-associated greenhouse gas emissions.

But required Scale is Enormous! ~0.8 Billion Tonnes / year of truck fuel

For scale: total sustainable biomass possible in USA ~1 Billion Tonnes/y (and less than half of that mass could be converted to diesel fuel)

Current cost of truck fuel ~$1 Trillion / year

Alternative Fuel will probably Cost More

Hydrogen

- Production: Electrolysis of water or steam methane reformation with carbon capture
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Long-Haul is different from other Trucking

Trucks for “short-haul”:
- Do not travel very far each day
- Many fuel/powertrain options can work

Trucks for “long-haul”:
- Travel several hundred miles each day.
- Lot of fuel burnt and lot of CO2 emissions
- Lot of energy (e.g. as fuel) needed on the truck. Batteries are possible, but so large & heavy they displace significant payload

Fixed routes
- Truckers sleep at home
- Could refuel/recharge at the depot

Flexible long-hauling
- Truckers sleep in their trucks
- Could refuel/recharge at many locations
Long-Haul Trucking Economics

Present-day trucks:

- Labor cost: in rich countries ~ half the cost of long-haul trucking (mostly the driver’s wages). Less in low-wage countries
- Cost of delivered diesel fuel: Next biggest cost

- Capital cost of truck: significant but less, ~10-20% of total cost in USA
Future trucks: similar, but costs shift

Operating cost:
- Labor cost: still the biggest cost in rich countries in most scenarios
- Cost of delivered low-Greenhouse fuel or electricity: significant, could be much higher than cost of diesel from petroleum.

Capital cost:
- Expensive to build new fuel/electricity production and delivery system.
- Biomass: lower capital but high labor and land cost
- Some new trucks, particularly battery trucks, are much more expensive than today’s vehicles.
Unclear which decarbonization option is really the best in long-term for long-haul trucking.

None of the deep decarbonization options are clearly cheaper than sticking to Diesel.

Large costs in short term during transition to decarbonized trucking system.

Analysis done for USA long-haul, but conclusions are similar for other countries with long-haul trucks. Short-haul is a different story.
Decision #1 Stick with Hydrocarbon Truck Fuel, or Change to Something Else?

• If you think sufficient biomass will become available, this is the cheapest / easiest option.
• But unclear if so much biomass is really going to be available....
• Since likely we will be short on biomass Carbon, need R&D on methods to improve Carbon-Efficiency of Biomass-to-Fuel Processes
## Decision #2: Electric vs Hydrogen

<table>
<thead>
<tr>
<th></th>
<th>Electric</th>
<th>Hydrogen</th>
<th>Main Takeaways</th>
</tr>
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<tbody>
<tr>
<td><strong>Capital investment</strong></td>
<td>![Electric Symbol] $</td>
<td>![Hydrogen Symbol] $</td>
<td>New refuelling/recharging infrastructure – Expensive transition</td>
</tr>
<tr>
<td><strong>Inventory</strong></td>
<td>One day</td>
<td>Few days</td>
<td>Week</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Electric suffers from low robustness: blackout can lead to shortage of essentials e.g. food</td>
</tr>
<tr>
<td><strong>Refuelling time</strong></td>
<td>![Clock]</td>
<td>![Clock]</td>
<td>Requires truck to be off-road for several hours during charging – may not be feasible for long-haul</td>
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<tr>
<td><strong>Powertrain Efficiency</strong></td>
<td>![Bar Graph]</td>
<td>![Bar Graph]</td>
<td>Battery to wheels has 85% compared to hydrogen powertrains: Internal combustion engine - 38%, Fuel Cell - 45%</td>
</tr>
<tr>
<td><strong>Payload Penalty</strong></td>
<td>![Bar Graph]</td>
<td>![Bar Graph]</td>
<td>Battery is quite heavy and reduces the available space for goods, hydrogen has a significantly lower penalty given its high energy density</td>
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Hydrogen (or H2 carrier) might be easier to supply in places with poor infrastructure and unreliable grids – robustness becomes an important advantage. However, hydrogen has costs and problems too, complicated.
Production

Blue Hydrogen
- Emissions: 60 kg CO$_2$/MWh$_{H_2}$
- Price: $2/Kg_{H_2}$
- GHG Source:
  - Methane leaks
  - Uncaptured reactor emission
  - Plant construction

Green Hydrogen
- Emissions: 20 kg CO$_2$/MWh$_{H_2}$
- Price: $8/Kg_{H_2}$
- GHG Source:
  - Manufacturing and installation of wind turbines, solar panels

Delivery

Compressed Gas
- Pressure: 700 bar
- Transport method: Trucks
- Major Problem:
  - Compression losses ~20% of energy content

Cryogenic Liquid
- Temperature: 20K
- Transport method: Trucks
- Major Problem:
  - Boil-off losses
  - Not suitable for long-term storage

Liquid Hydrogen Carriers
- Transportation method: Truck, Pipeline – all existing diesel infrastructure
- Major Problem:
  - Regeneration of hydrogen by breaking chemical bonds

Energy Extraction

Combustion Engine
- Lower powertrain efficiencies
- Robust & Simple Design

Fuel Cell
- Higher powertrain efficiencies
- More ancillary components
What we did

Developed a Drive Cycle for USA long-haul trucks

Optimized each powertrain to minimize Total Cost (includes capital and operating cost of trucks and GHG emissions cost)

• City and highway driving modelled separately
• Our drive cycle limits driving to 11 hrs/day

For H2, most of the cost is related to refueling infrastructure and processes, so we analyzed many options to try to knock that big cost down.

There are multiple powertrain options for each fuel - not comprehensively explored

Tried to be Consistent: Honest apples-to-apples comparisons of options
Created Drive Cycle that matches how USA Long-Haul Trucks are actually driven

- Average Speed 55.6 mph
- Urban end segments
- 600 mile length
- 10 hr 47min
- Majority of grade within 3%
Diesel: Capital & Operating

- Powertrain & Tank are inexpensive
- Glider dominates capital cost for truck
Diesel: Capital & Operating

- Operating Costs dominate. Mostly Labor (Driver) and Fuel

Capital Cost of Vehicle small contribution to Diesel total cost
Diesel emissions in USA today about 1.5 kg CO2e/mile.
In future expected to drop to about 1.1 kg CO2e/mile.
Very good biomass-to-fuel processes could drop it much lower (if enough biomass is actually available…).
Main takeaways:

- Fuel Economy: 2.5 kWh/mi
- 1500 kWh battery for full range (600 miles)

Implication: if $100/kWh, battery alone costs $150,000. Roughly doubles purchase cost of each long-haul truck. Big battery is heavy, reduces maximum payload: need more trucks & drivers.
Battery Electric: Implications of 2.5 kWh / mile

- Per EPA, USA delivered electricity emits 0.43 kg CO2e/kWh. So battery electric truck in USA emits **1.1 kg CO2e/mile.** Since battery weight displaces some payload, need more truck trips to move same goods. **Net: only slightly better for climate than current diesel truck in USA.**
  
  **But in future** people expect grid intensity to drop by perhaps factor of 2, but diesel truck will not improve that much. So in future battery-electric truck would have significant greenhouse gas advantage over diesel.

- If delivered electricity at a fast charger costs $0.35/kWh, then costs $0.88/mi for electricity, and $525 for the 600 mi daily trip.

- Compare with diesel: 7.9 mpg, if gallon costs $5, then $0.63/mile. **Smaller refueling cost than battery-electric recharge.**

- All the cost and CO2e **numbers above can vary significantly** with location and from time to time. Not so clear which option is best. Needs great care!

Need clean electricity for battery electric trucks to be green
Battery Electric: Our cost projections

- **OPEX**
  - Operating cost (thousand USD)
  - Present, Midterm, Longterm

- **Cost of Vehicle**
  - Capital cost (thousand USD)
  - Present, Midterm, Longterm

Legend:
- Glider
- Engine
- Battery
- Replacement
- Transmission
- WHR
- Aftertreatment
- Fuel Tank
- Motor
- Inverter
- DC-DC Converter

Cost projections include:
- Fuel
- Labor
- Payload Penalty
- Charging Penalty
- Maintenance and repair
- Insurance
- Fees
Fuel Cell system overall efficiency of 45% (7.6 mi/kg H2) is better than best combustion system (38%, 6.7 mi/kg H2).

Very important if delivered H2 is expensive.

But Fuel Cell system is more expensive and less robust than engine.
In the present, hydrogen powertrains are 1.4 to 2.3 times more expensive than diesel and 1.1 to 1.2 times more expensive in the long run.

High manufacturing volumes will significantly bring down the costs of the fuel cell and battery, however probably not the fuel tank.
Hydrogen: Capital & Operating

• In the present, hydrogen powertrains are 2.0 to 2.3 times more expensive than diesel and 1.3 times in the long run

• Maintenance and repair for the fuel cell powertrains is 40% less than the combustion engine

• Payload penalty more apparent in PHEV, but diminishes over time

Fuel Cell is more efficient, but still the very high price of delivered H2 increases costs
Some methods of H₂ production are cheap today, less per Joule than liquid fossil fuels.

But delivered high pressure H₂ is very expensive, about 3x cost of fossil fuel today.

Delivery + Refueling is over half the cost no matter what scheme one considers.

Projected that better delivery + refueling technology and also higher utilization rates of the capital assets will significantly drop cost by 2050.

But H₂ will likely be more expensive than diesel fuel (per Joule delivered) even in 2050.
Further work: low-greenhouse H$_2$ production

• “Blue” H$_2$ (from natural gas with carbon capture) can be inexpensive in locations where natural gas is cheap and CCS is allowed/viable.

• But the simplest Blue H$_2$ schemes have significant CO2 and CH4 emissions, not clean enough to give big decarbonization benefit. Need improved Blue process.

• “Green” H$_2$ (from electrolysis) is moderately expensive, and with normal grid electricity it is not clean at all.
  - Need a special cheap low-carbon electricity source... location dependent.

• There are several H$_2$-production schemes which have better emissions or lower costs or both, a complicated topic of active R&D.

• The location-dependence is important, since shipping H$_2$ is expensive

• Maybe best to ship H$_2$ on a chemical hydrogen carrier...but then need to deal with conversions of the carrier to release the H$_2$. 
Summary

• Long-haul Trucking is a pretty large CO2 emitter, will have to change.
• There are multiple decarbonization options for long-haul trucking.
• Several options look competitive in long-term, but they all have large short-term and medium-term costs and other problems.
• Challenging to make a full-scale affordable system with a big Greenhouse advantage over current system.
  • Simplest options add a lot of cost for only modest climate benefit.
• Most of the promising options are based on low-Greenhouse Hydrogen as the main energy source, but how best to use that H2 is not yet clear.
  • H2 as a gas or as a cryogenic liquid is quite expensive.
  • Making H2 into synfuels/biofuels instead is cheaper, but is there enough non-fossil carbon available?
Towards zero environmental impact aviation
Presented by Steven Barrett on behalf of LAE and AeroAstro colleagues
CO$_2$
NO$_x$
Contrail-Cirrus
Fuel Sulfur
Environmental Impacts ($/tonne of fuel burn)

- CO₂
- NOₓ
- Contrail-Cirrus
- Fuel Sulfur
Environmental Impacts ($/tonne of fuel burn)

- Climate
  - CO$_2$: 585
  - NO$_x$: -82
  - Contrail-Cirrus: 100
  - Fuel Sulfur: 100

Graph showing environmental impacts with categories for CO$_2$, NO$_x$, Contrail-Cirrus, and Fuel Sulfur.
Environmental Impacts ($/tonne of fuel burn)

- Climate: 585
- Air Quality: 360

- CO₂
- NOₓ
- Contrail-Cirrus
- Fuel Sulfur
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### Price/policy emphasis on feedstock availability

- **F1**: A1 - 64.8% S1, 68.1% S2, 63.3% S3
- **F2**: A2 - 60.7% S1, 65.4% S2, 26.7% S3
- **F3**: A3 - 4.1% S1, 2.2% S2, 1.1% S3

### Size of the primary bioenergy and waste resource

- **S1**: 32.3% A3, 19.8% A2, 11.1% A1
- **S2**: 41.1% A3, 26.8% A2, 10.3% A1
- **S3**: 26.8% A3, 4.1% A2, 4.1% A1

A1, A2, A3 represent different categories or variables. S1, S2, S3 represent different subcategories or conditions within each variable.
Fossil fuel → Drop-in BtL → Drop-in PtL → Hydrogen → Battery?
Example: fueling CDG with PtL

Electric power consumption of fuel production

*broken down by process step, in GW*

- Total 17.35 GW
  - Total 13.09 GW
    - E-fuel (RWGS-PEM) 12.8 GW
    - E-fuel (RWGS-SOEC) 9.0 GW
    - E-fuel (Coelec) 7.1 GW
- Total 10.00 GW
  - Total 8.36 GW
    - LH₂ 7.0 GW
    - Fuel LHV 1.3 GW
- Energy requirements are lower bounds (assume that time-varying demand to be smoothed through stored fuel)
- Advances in electrolysis and e-fuel production technology to reduce energy demand
Example: fueling CDG with PtL

Electric power consumption of fuel production
*broken down by process step, in GW*

For comparison:
- French total installed capacity: ~133 GW
- Largest nuclear plant in the world (capacity): ~7 GW
- Largest solar power plant (capacity): ~2.2 GW

How much land is needed to produce LH₂ using renewable solar?
- H₂ Gas Pipeline+ Airport Liquefaction: 490 km²
- Near CDG: City of Paris: 105 km²
- Offsite at fuel production location: 585 km²
- Cryogenic H₂ Transport from Offsite Liquefaction: 130 km²
- Electrofuel: > 700 km²
Specific energy demand and year-2019 & 2050 fuel replacement with PtL & LH₂

Specific energy demand in MJ (elec)/MJ(fuel), total electricity demand in TWh

- 15%

Renewable electricity generation
2050, IEA NZE

Renewable electricity generation
2050, IEA SDS

Global renewable electricity generation 2021*

Specific electricity demand
Total electricity demand
Specific electricity demand
Total electricity demand

0 0.5 1 1.5 2 2.5 3 3.5
Specific electricity demand [MJ elec./MJ fuel]

0 10000 20000 30000 40000 50000 60000
Total electricity demand [TWh]

2019 2050
Average year 2018/19 contrail coverage of U.S. airspace
(algorithm is entirely observational and has no information about flight routes)
Contrail avoidance:

Potentially the cheapest and fastest way to mitigate *and roll back* the climate impacts of aviation
Tough-to-Decarbonize Transportation: MIT Climate Grand Challenge

Profs. Steven Barrett & William H. Green
MIT Mobility Forum
Sept 30, 2022