Energy Consumption in Transportation

John C. Bean

Outline

Transportation's Energy Consumption & Environmental Impact

- Statistics on World & U.S. transportation energy consumption
- Statistics on World & U.S. transportation greenhouse gas emissions
- Unique impacts & concerns about cars OR trucks OR trains OR planes OR ships

The science behind HOW energy is spent in moving things

- Yielding predictions of how power varies with vehicle size, weight, speed, altitude . . .
  - Suggesting ways of reducing power for each mode of transportation

Energy saving technologies now proposed and/or being developed for:

- Trains, planes and ships
  - Including discussion of possible electric planes, electric & ammonia powered ships
- But with cars & trucks covered in subsequent separate note set: **Green(er) Cars & Trucks**

(Revised: March 2024)

Energy Consumption in Transportation:

For the second **Earth Day** in 1971, Walt Kelley drew this now iconic cartoon: [1]

In the immediate aftermath of 1970-80's **Gas Crises,** this view led to calls for sacrifice,

including the infamous Oval Office "sweater speech," while on America's highways:

1) Pogo, by Walt Kelly, Post Hall Syndicate

40 years later our view is more nuanced . . . and a bit more optimistic:

Why?

Because in the latter half of the last century energy consumption had grown hugely

But that growth was driven largely by astonishingly cheap oil (especially in the U.S.)

Meaning that, for almost 50 years, we'd put minimal effort into saving energy

The result?

Our homes, cars & trucks remained astonishingly inefficient (especially in the U.S.)

While, in almost every **other** area, technologies improved by leaps and bounds

But now:

Motivated by the threat of climate change (and other effects of profligate energy use),

we are **finally** seeing comparable innovation in energy-saving technologies

And, to a surprising degree, we are finding that solutions often save energy

while **enhancing** the performance, cost & comfort of our homes and vehicles

But before discussing solutions, we need to better define the challenge

To that end, I will begin with statistics about transportation energy consumption

for both the world and the U.S.

for both today and extrapolated to mid-century

Next, because consumption levels alone are an incomplete indicator of impact,

I'll add data about transport related greenhouse gas (GHG) emissions,

and explore impacts & consequences unique to specific modes of transport

Then, because they can clarify patterns & trends in transport energy consumption,

I'll develop science-based models of various forms of transportation

And finally, armed with the above data & tools, I'll explore energy saving innovations

now being discussed or explored for each of the major forms of transport,

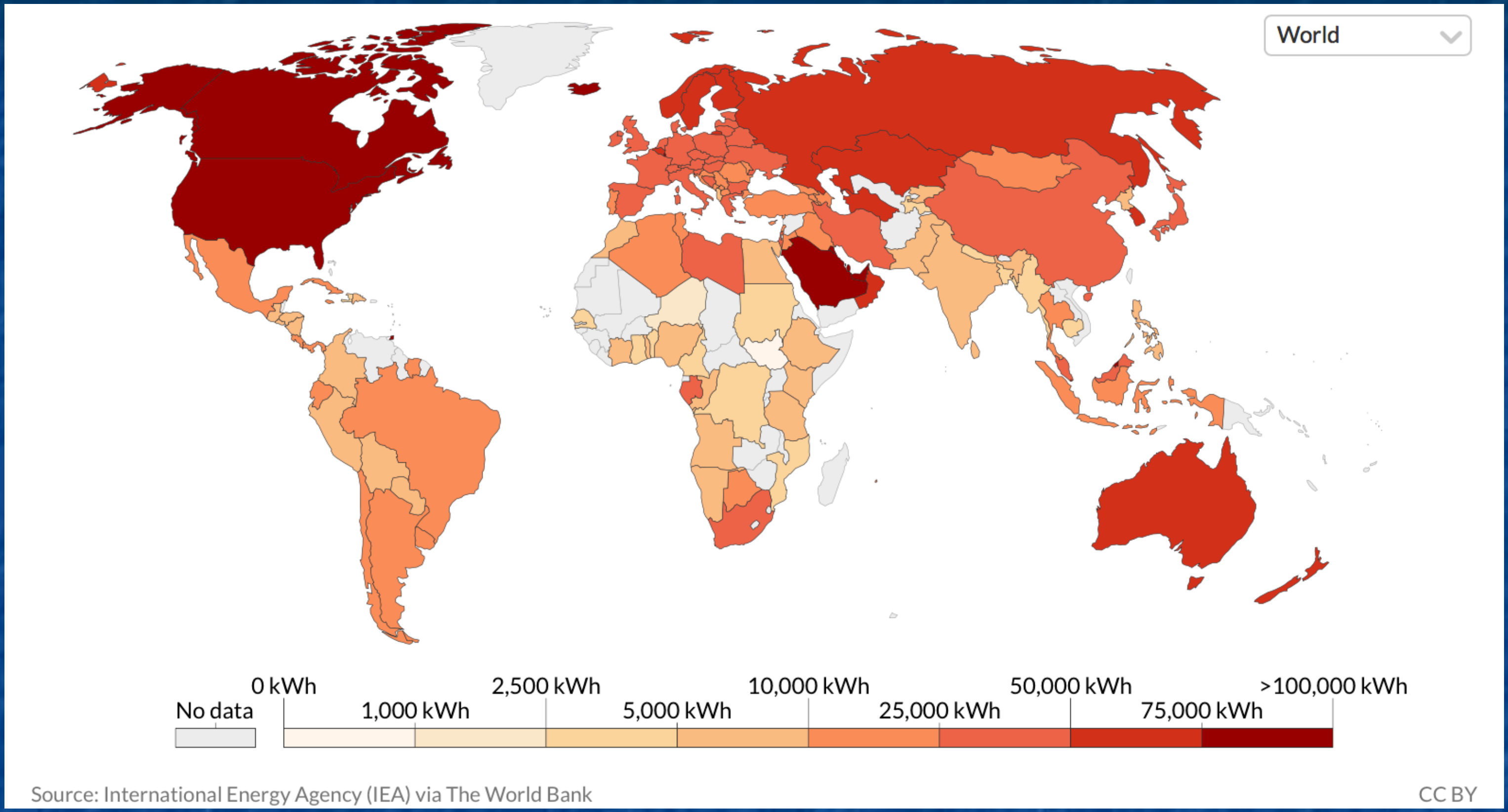
including the complete transformations now proposed for aviation & shipping

Country-by-Country Per Capita Annual Energy Use

(for all purposes, including transportation)

2015 per capita energy consumption (in units of kW-hours):

From OurWorldInData.org: [1]



NOTE: As with most such energy maps, widening color bands are used

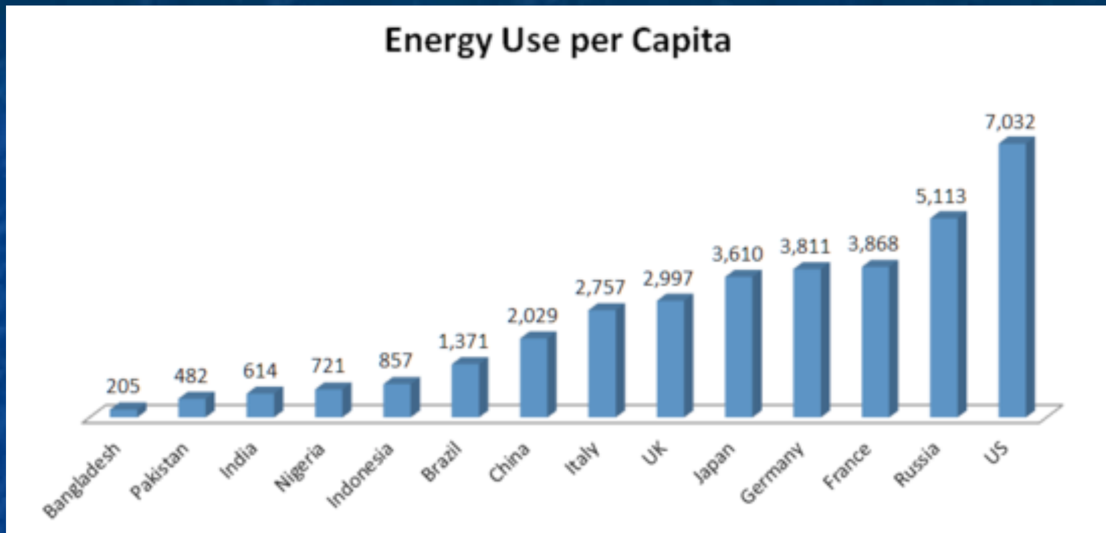
This spreads low energy color range, but compresses high energy color range

Which obscures differences between high energy consumption countries

1) https://ourworldindata.org/energy

Raw numbers reveal those differences (here in kg oil equivalent = 11.6 kW-h): [1]

2011:



2014 Rank order:

Country/Territory	kgoe/a
Iceland	17583.6
Canada	7247.2
United States	6917.4
Luxembourg	6812.2
Finland	6266.9
Norway	5854
Australia	5484.7
South Korea	5262
Sweden	4811
Belgium	4810.3
Estonia	4599.7
New Zealand	4454.7
Netherlands	4289.4
Czech Republic	3945.3
Austria	3754.1
Germany	3749.1
France	3641.1
Japan	3470.2
Slovenia	3272
Switzerland	3074.8
Denmark	2903.7
Israel	2849.5
Slovakia	2846.9
Ireland	2766.6
United Kingdom	2751.6

Range of energy consumption among affluent countries:

Canada	7247
U.S.	6917
Sweden	4811
Germany	3749
France	3641
Japan	3470
UK	2751

~ Half or less of U.S. energy use

1) https://en.wikipedia.org/wiki/List_of_countries_by_energy_consumption_per_capita

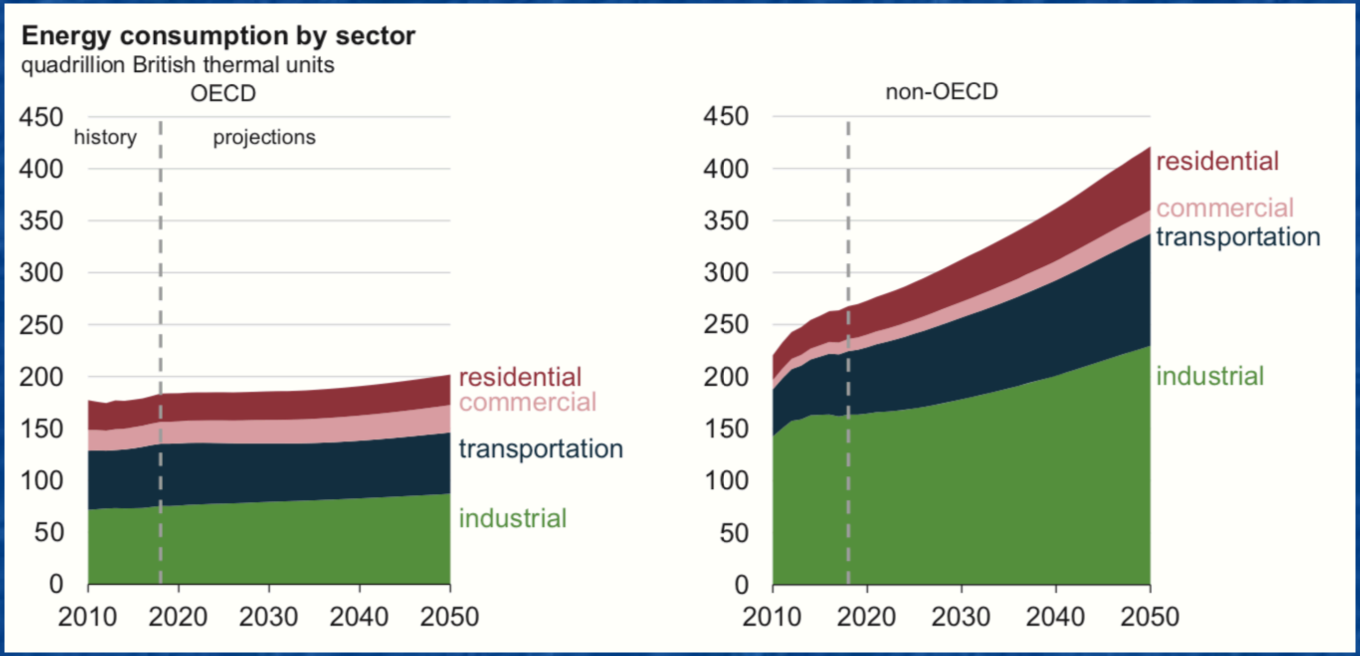
Global Transportation Energy

Global Transport Energy Consumption:

First, from the U.S. Energy Information Administration's

"International Energy Outlook 2019 - With Projections to 2050" [1]

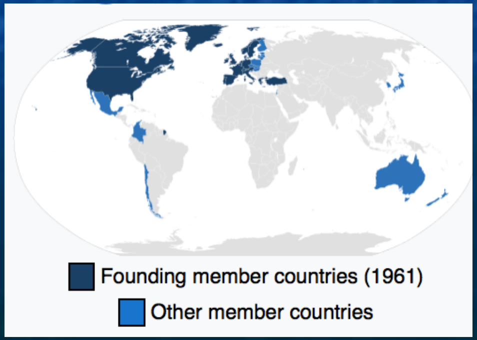
Transportation accounts for ~ 1/4 of today's global energy use



What is "**OECD**" ? It stands for the:

Organization for Economic Cooperation & Development

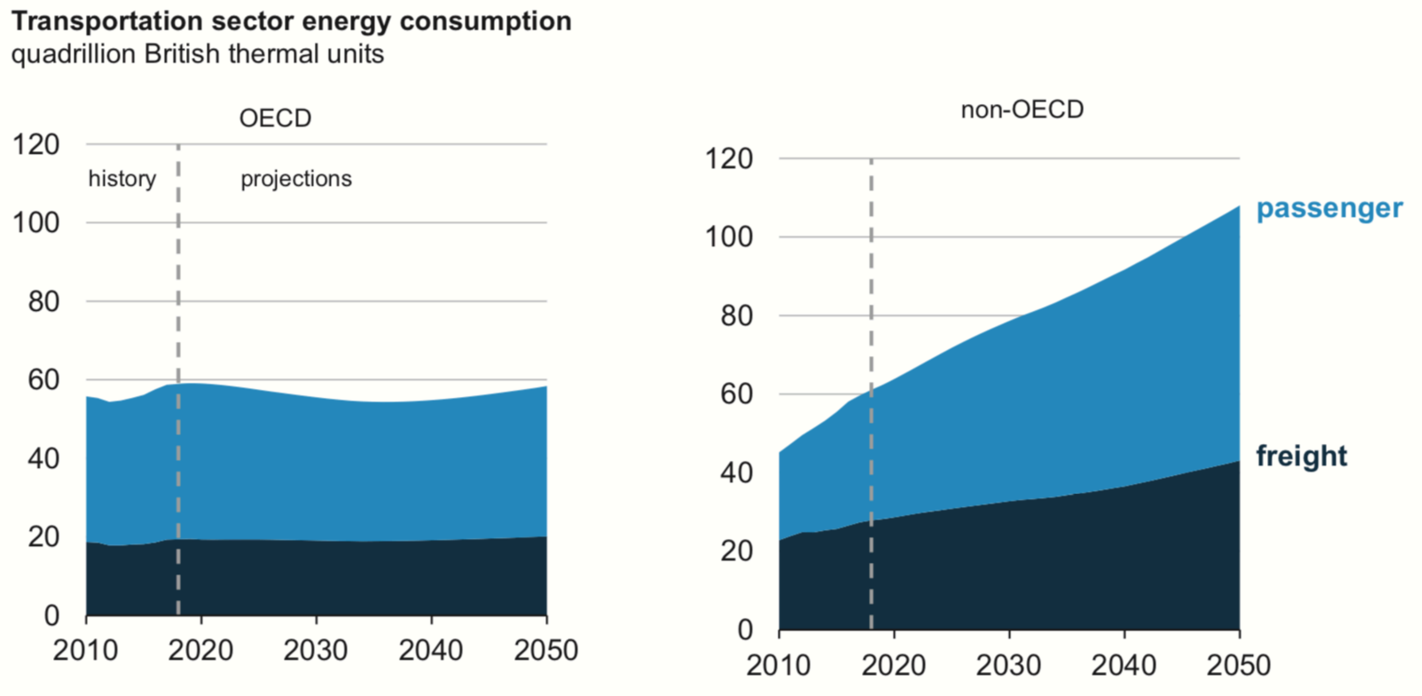
Which has these governmental members: [2]



1) Page 27 in: https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf *2) https://en.wikipedia.org/wiki/OECD*

How is global transport energy divided between passengers & freight?

From that same U.S. Energy Information Administration report: [1]



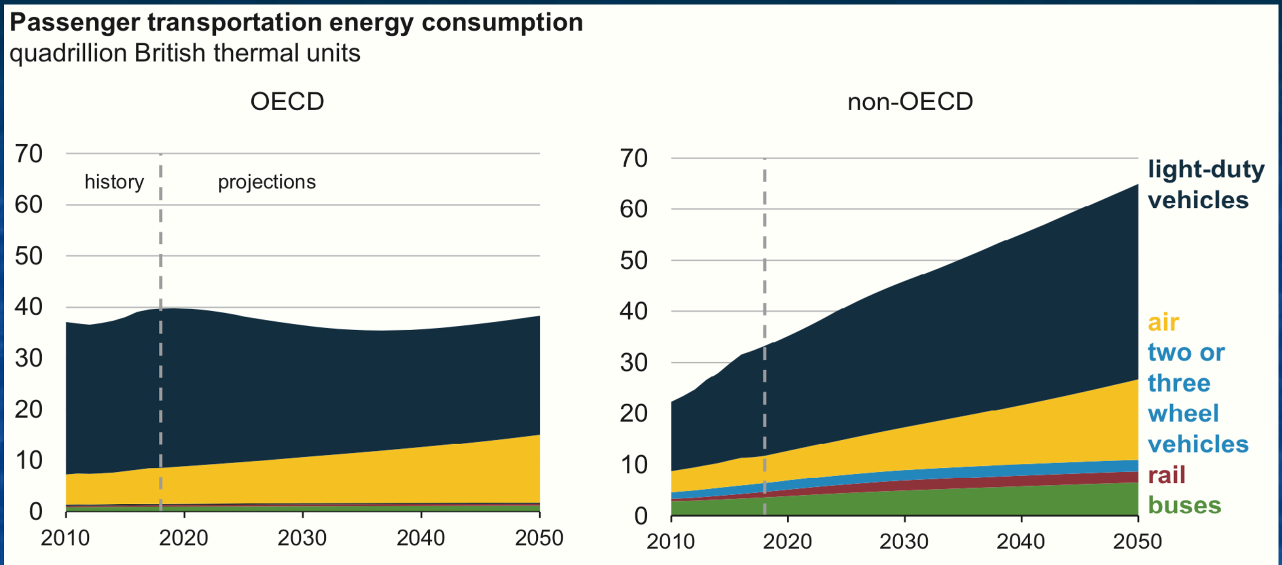
And finally:

1) Page 69 in: https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf

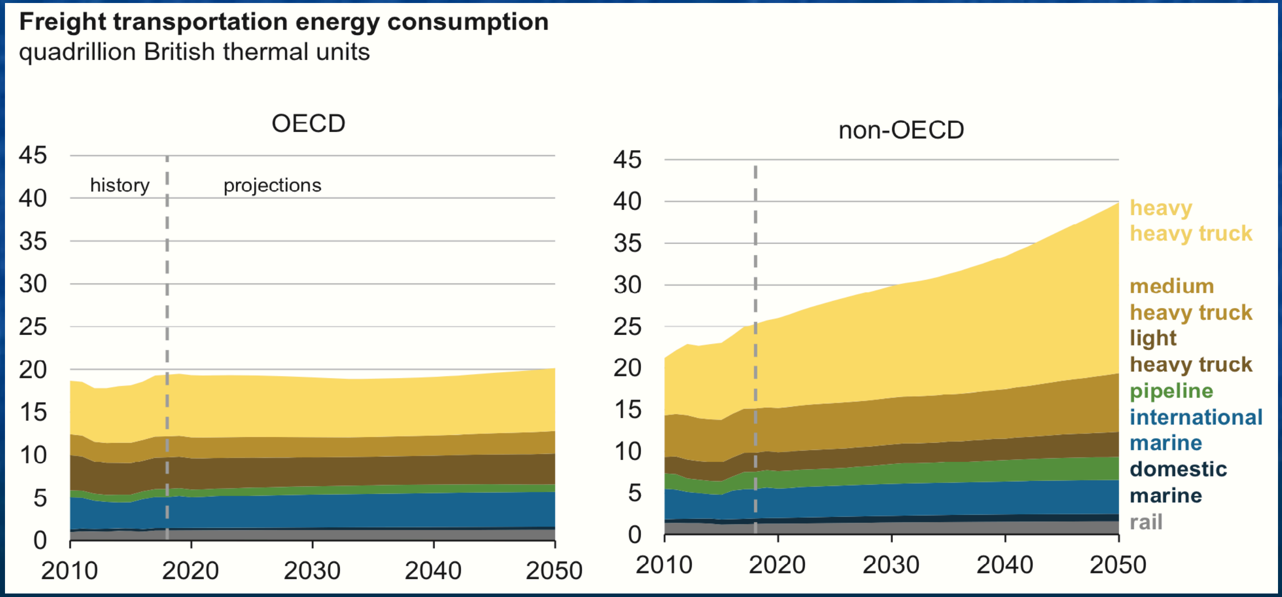
How are passengers & freight divided between transport modes? [1]

From the same report: [1]

Passenger Transport



Freight Transport



1) Ibid: pages 71 & 73

(1 BTU = 0.293 W-hr   Thus: 1 Quadrillion (10^{15}) BTU = 293 TeraWatt-hr)

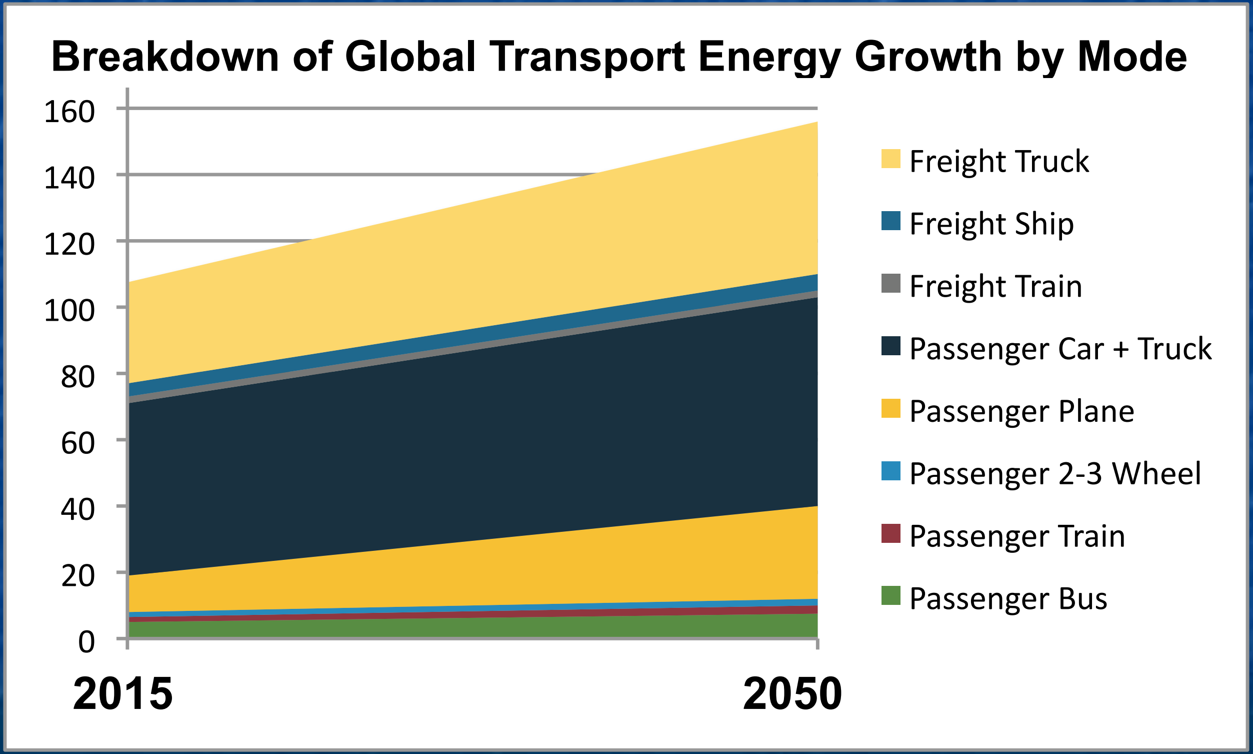
*Okay I **GET** it! The EIA **really** wants me to recognize that:*

Transport Energy growth is now overwhelming driven by "non-OECD" countries

Nevertheless, because we **all** ultimately share the world's air & climate,

I **also** wanted a plot of likely GLOBAL transport energy growth mode-by-mode,

which I've now (laboriously if crudely) created from the preceding EIA figures: [1]

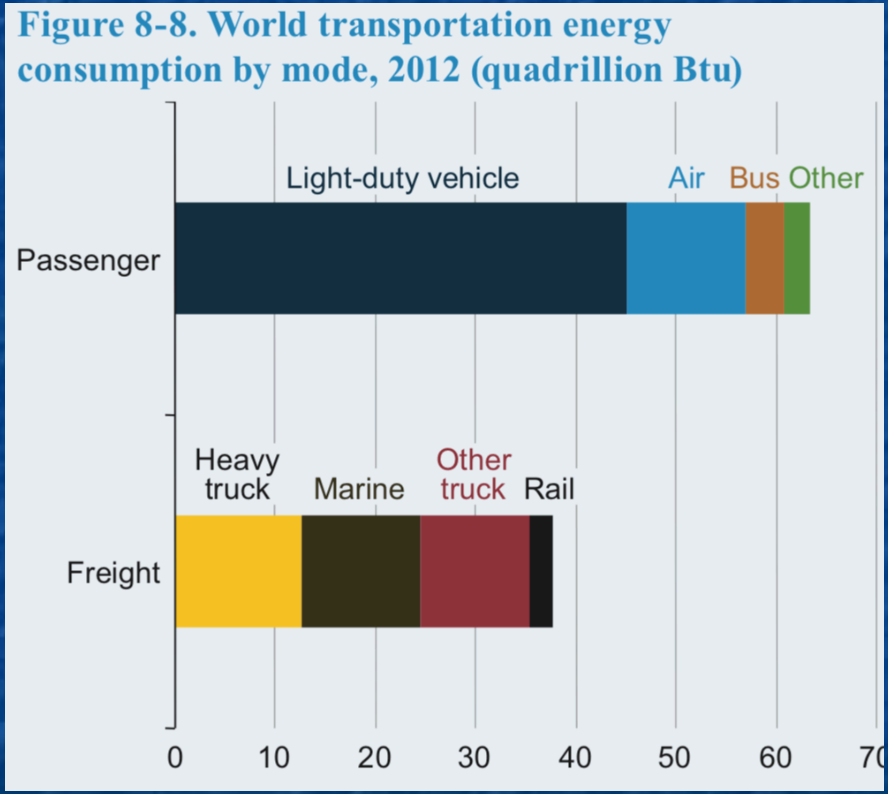


Passenger Car & Truck +20% **Freight Truck +50%** **Passenger Air +150%**

1) Excel spreadsheet in which I merged EIA's OECD + non-OECD data into this plot (link)

*But more precise **near-present day** numbers can be extracted from:*

The EIA's earlier "International Energy Outlook 2016," which included this figure: [1]



Percentages of the 100 Q-BTU total: *

Passengers (~62%):

Light Duty Vehicles (cars & trucks)	44%
Air	13%
Bus	3%
Other (e.g., trains)	2%

Freight (~39%):

Heavy truck	13%
Marine (ships & barges)	12%
Other truck	12%
Rail	2%

* (Again: 1 BTU = 0.293 W-hr   Thus 1 Quadrillion (10^{15}) BTU = 293 TeraWatt-hr)

1) Page 131 in: https://www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf

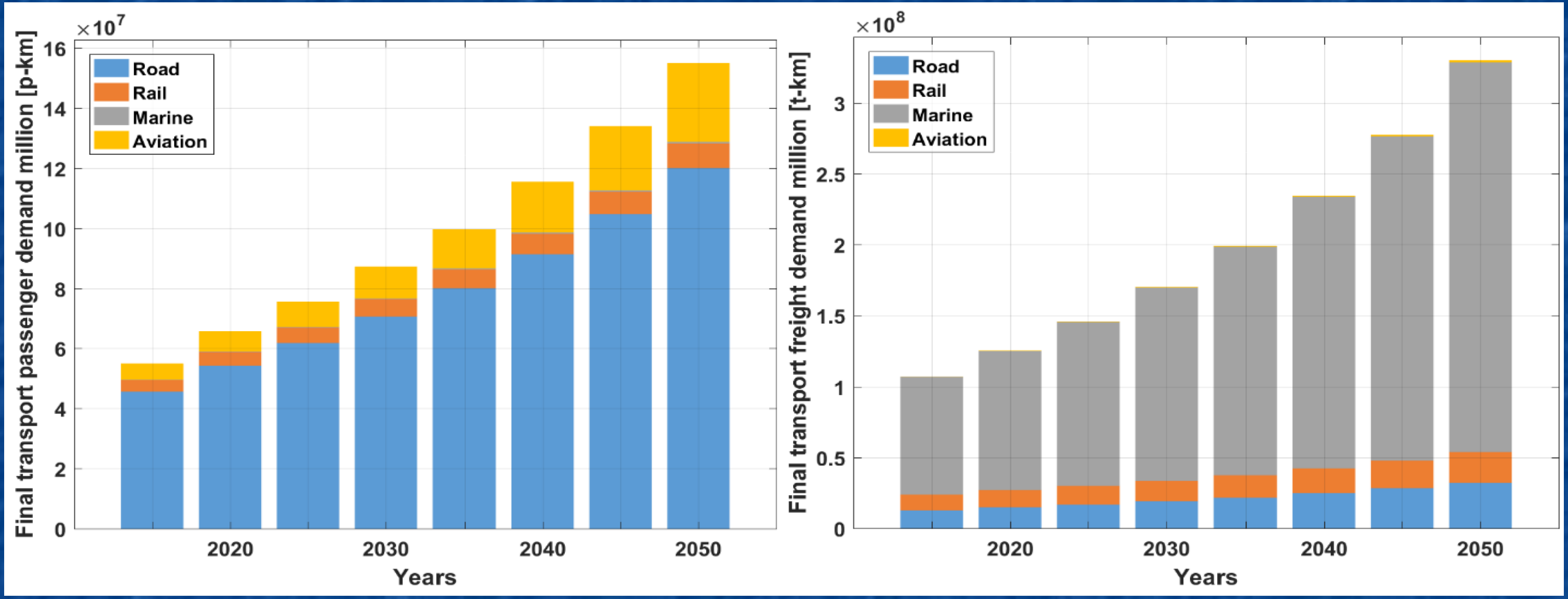
Comparing those EIA results with a Finnish academic study:

From a journal publication entitled: "Global Transportation Demand Development . . . " [1]

Net **transport load and mode** are identified for both passengers and freight:

Passenger Transport **LOAD**:
(in units of total **passenger-km** traveled)

Freight Transport **LOAD**:
(in units of total **tonne-km** traveled)



Road: 80-85%
Air: 10-15%
Rail: ~ 5%
Ship: tiny

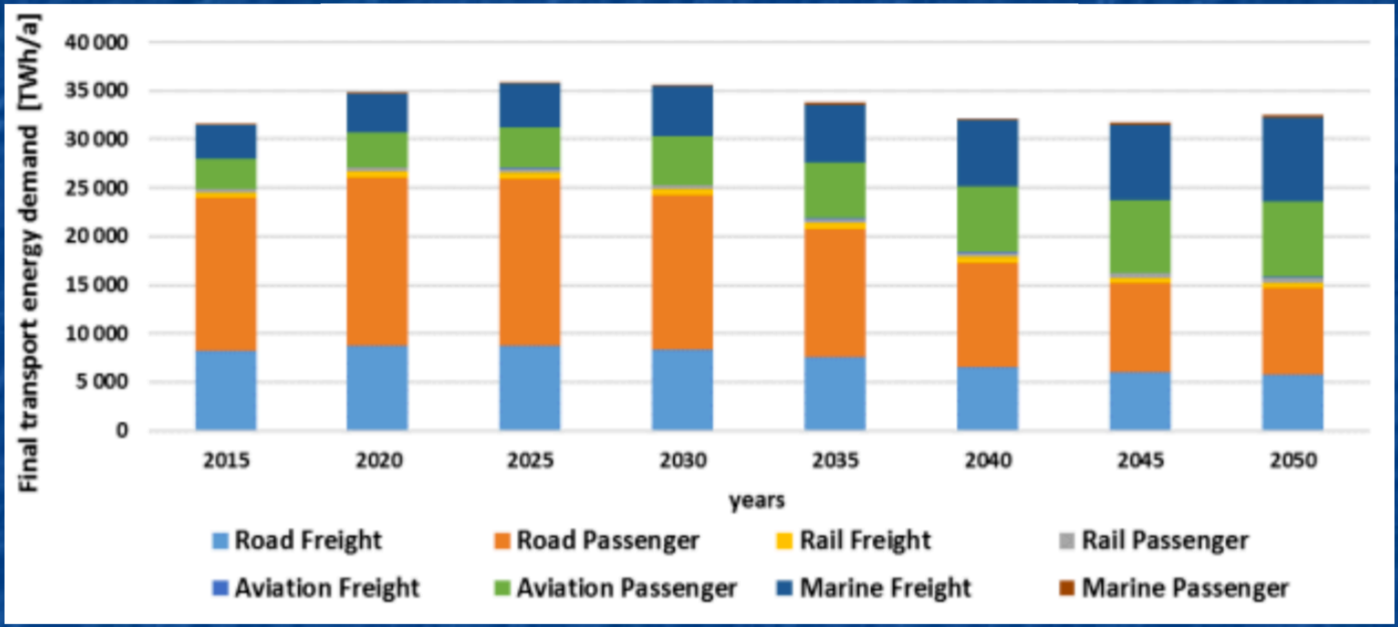
Road: ~ 10%
Air: < 1%
Rail: ~ 5%
Ship: 70-80%

1) https://www.mdpi.com/1996-1073/12/20/3870/htm#

*But it's claimed increased **loads** need NOT increase total transport **energy**:*

From that same Finnish academic study: [1]

Projected TOTAL Transportation Energy - 2015 to 2050



With growing populations AND vehicle use, HOW can this possibly be true?

It's based primarily on prediction of more efficient **road vehicles** (passenger & freight)

And secondarily on the massive introduction of **electrified airplanes** & **electrified ships**

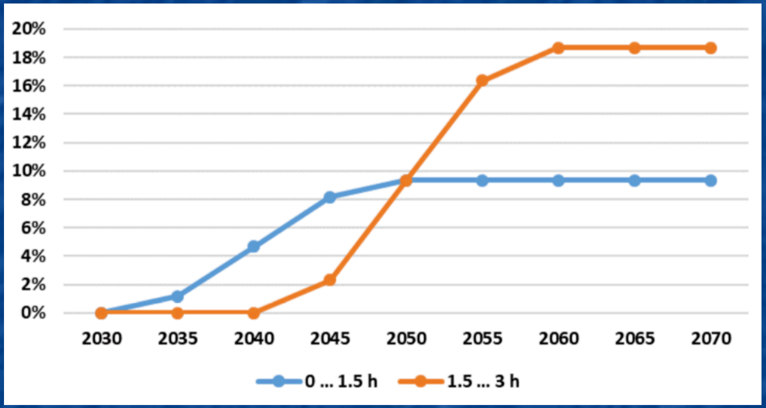
1) https://www.mdpi.com/1996-1073/12/20/3870/htm#

How plausible are such predictions?

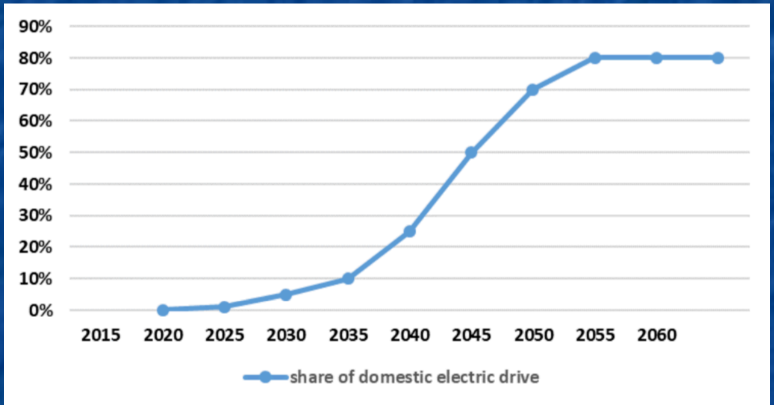
Data later in this & my subsequent **Green(er) Cars & Trucks** (pptx / pdf / key) notes support the likelihood of a dramatic decrease in energy use **per road vehicle,** but that may **not** offset the present rapid growth in **number of vehicles**

And here are the report's predictions regarding plane & ship electrification:

Projected growth of electric aviation:



Projected growth of electric shipping:



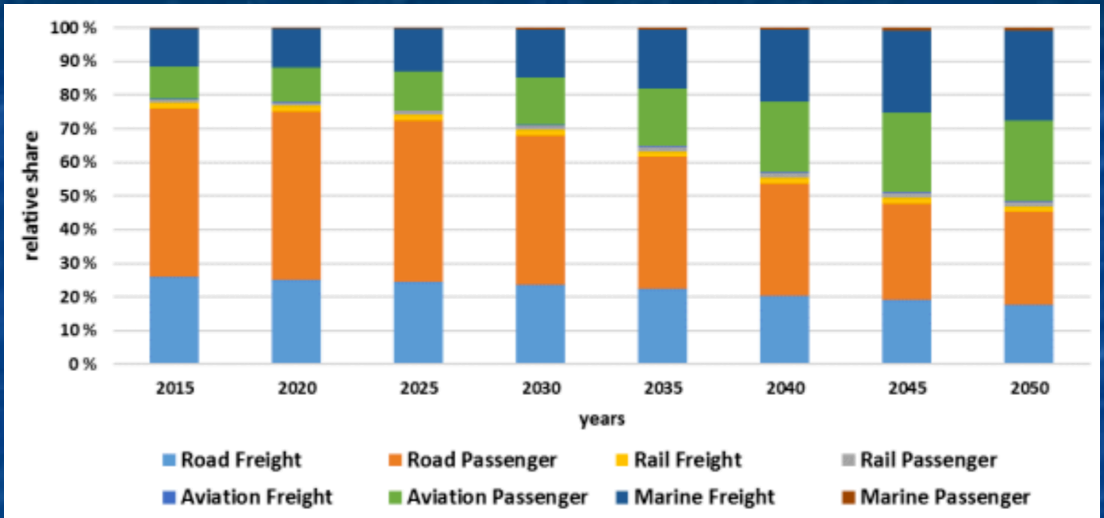
As noted in the report's text, these transitions would require technology breakthroughs

But I **know** those "breakthroughs" to be equivalent to 10-100 fold improvements

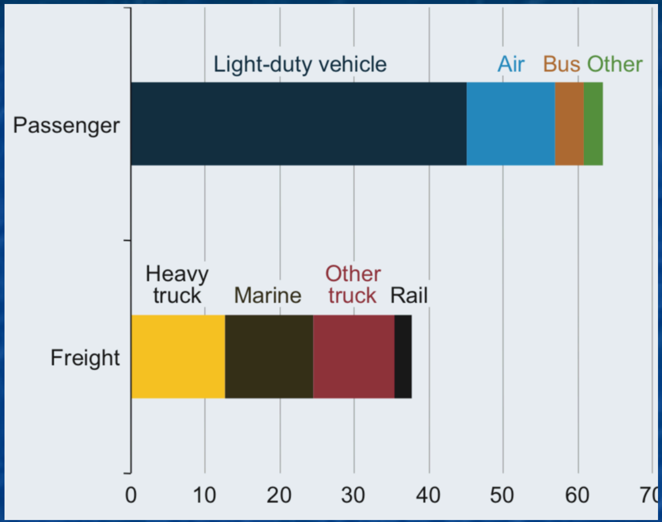
I'll thus examine BOTH scenarios in separate later sections of this note set

But is there at least agreement about TODAY's Transport Energy?

Finnish breakdown (using 2015 data at far left):



vs. EIA 2016 breakdown



Passengers (~60%):	
Road Passenger	50%
Aviation Passenger	9%
Rail Passenger	1%
Marine Passenger	< 1%
Freight (~40%):	
Road Freight	26%
Aviation Freight	< 1%
Marine Freight	12%
Rail Freight	2%

Passengers (~62%):	
Light Duty Vehicles (cars & trucks)	44%
Air	13%
Bus	3%
Other (e.g., trains)	2%
Freight (~39%):	
Heavy truck	13%
Other truck	12%
Marine (ships & barges)	12%
Rail	2%

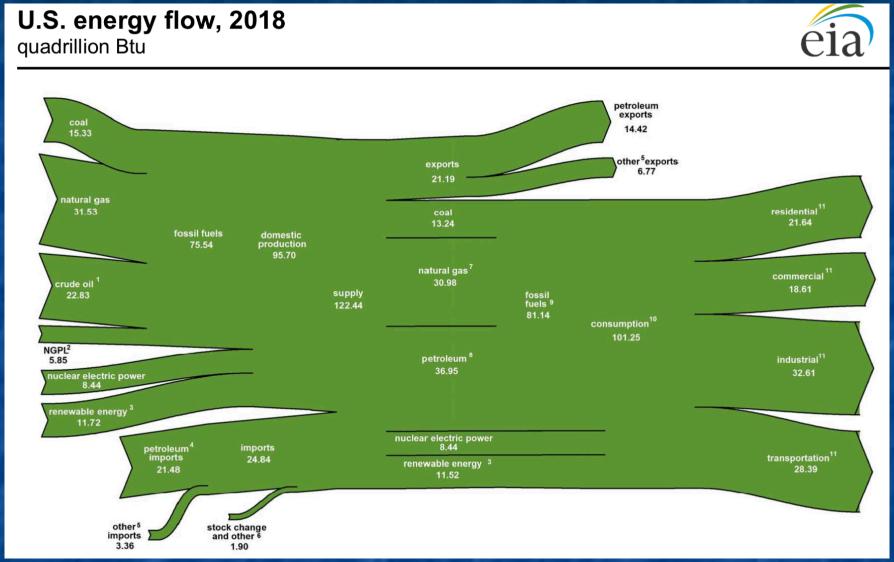
Which IS good agreement about ***Today's Global Transport Energy:***

	Global	
Transport fraction of TOTAL ENERGY:	**25%**	
Fraction of TRANSPORT ENERGY used by:		
Fossil-fueled cars & trucks	**70-85%**	
Fossil-fueled ships	**~12%**	
Fossil-fueled airplanes	**10-15%**	
Fraction of TRANSPORT ENERGY used by:		
Passengers:	**45-50%**	**in Cars & Trucks**
	9-13%	**in Airplanes**
	1-2%	**in Trains or Buses**
	< 1%	in Ships
Freight:	**25-26%**	**in Trucks**
	12%	**in Ships**
	2%	**in Trains**
	< 1%	**in Airplanes**

U.S. Transportation Energy

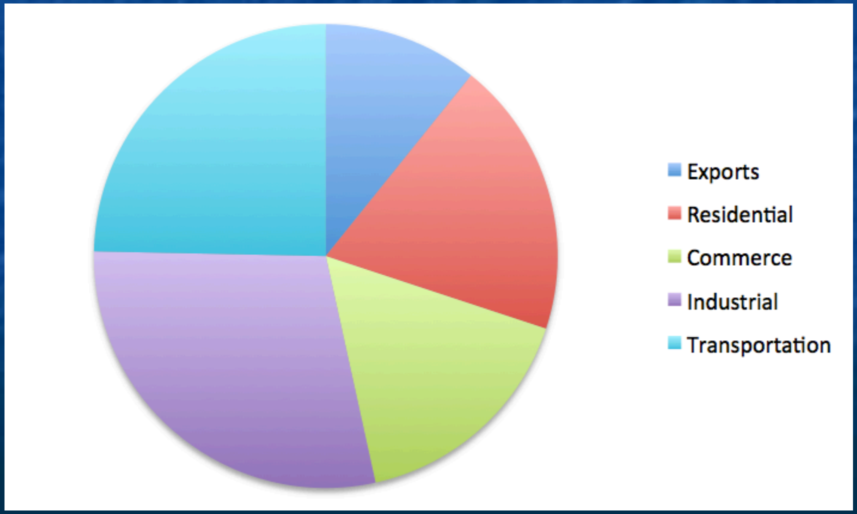
Transportation's contribution to total ***U.S. Energy Consumption:***

From the U.S. Energy Information Administration (EIA)'s 2018 "U.S. Energy Flow" [1]



"Outputs" translated into my pie chart:

Exports (fuels):	17.3%
Commerce:	17.7%
Residential:	15.2%
Transportation:	**26.6%**
Industrial:	23.2%

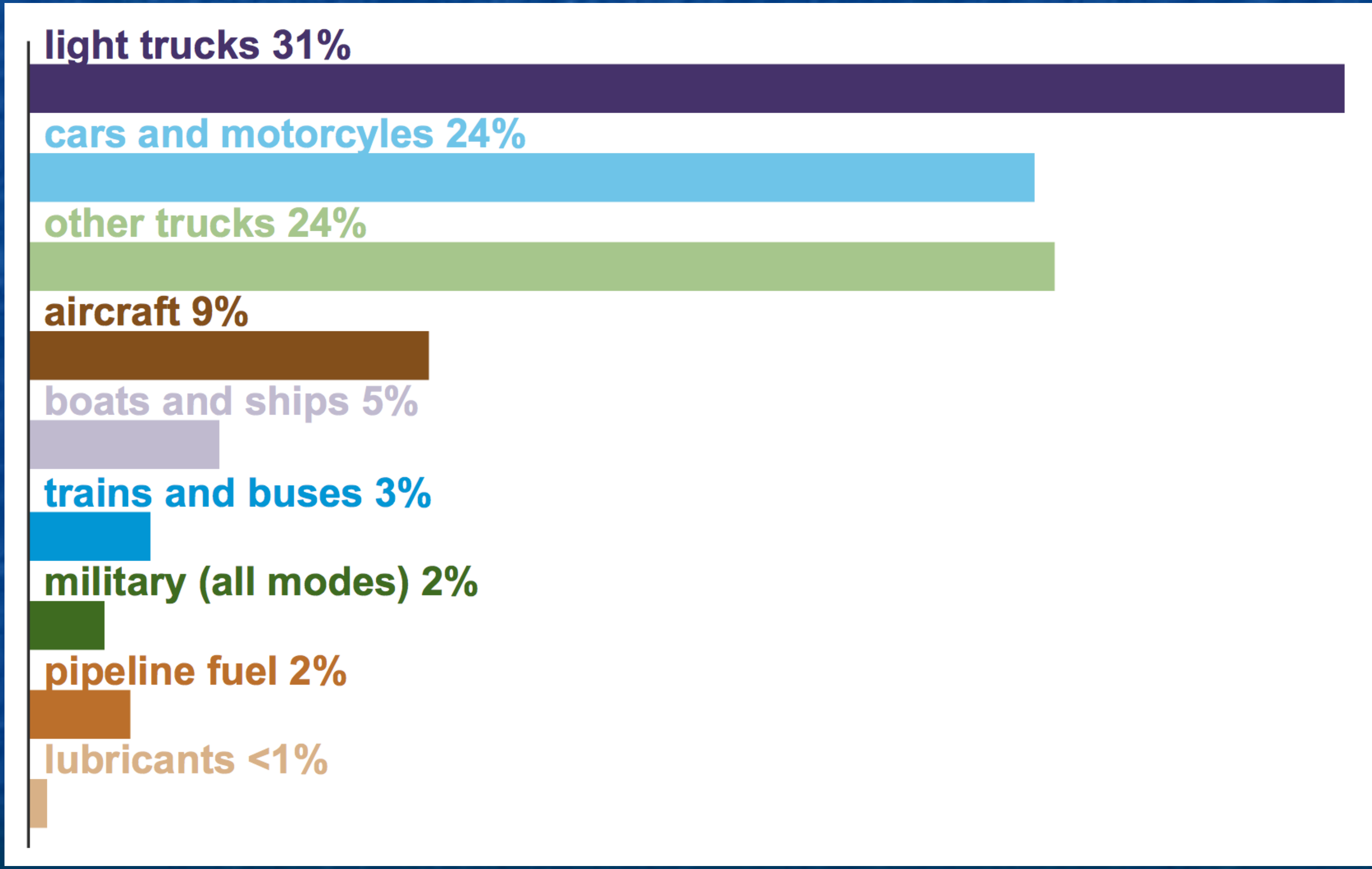


1) *EIA U.S. Energy Flow 2018: https://www.eia.gov/totalenergy/data/monthly/pdf/flow/total_energy.pdf*

Breakdown of that U.S. Transportation Energy use by mode:

From a U.S. Energy Administration (EIA) webpage (accessed June 2020):

"Use of Energy Explained - Energy Use for Transportation (In Depth)" [1]

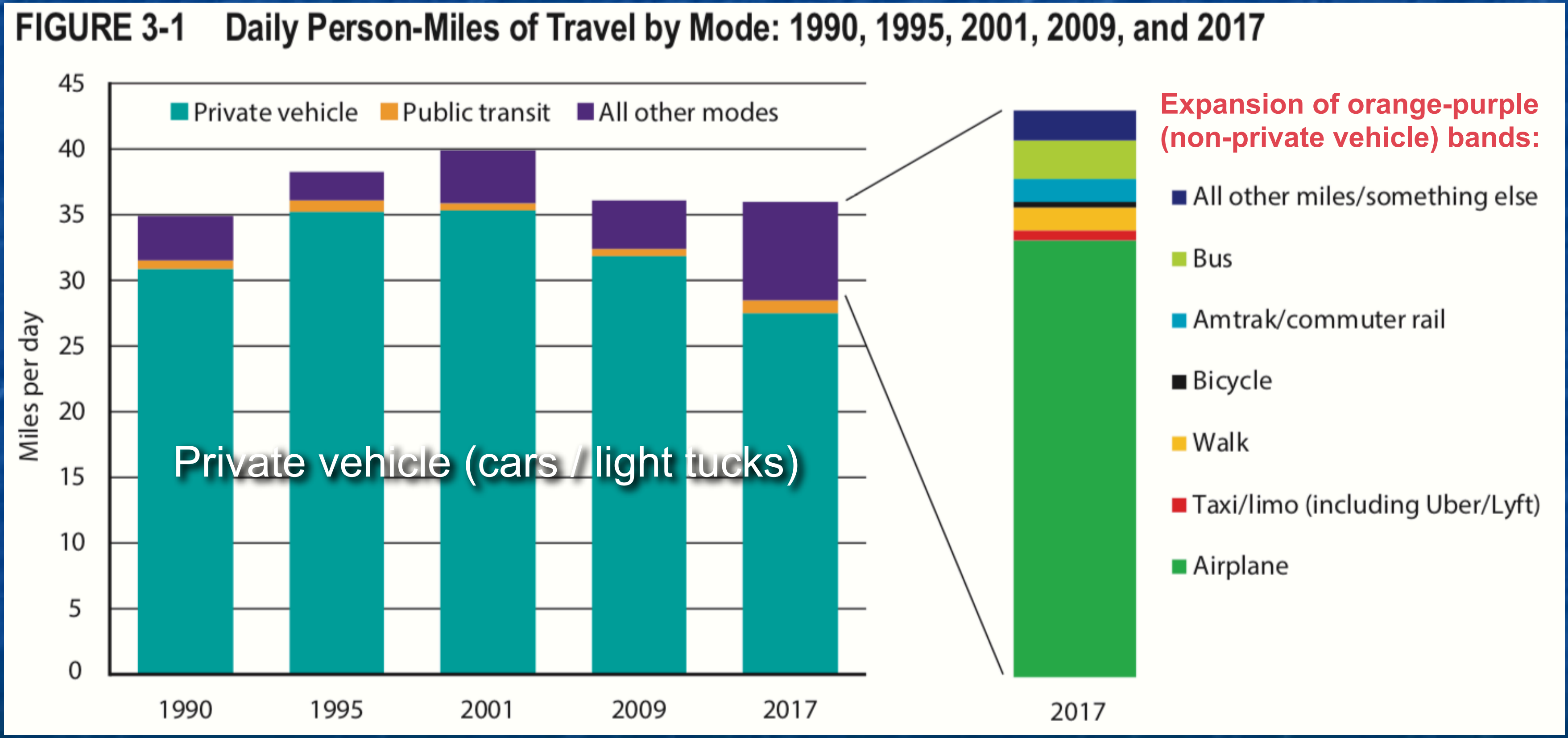


1) https://www.eia.gov/energyexplained/use-of-energy/transportation-in-depth.php

*Pertaining to **only** U.S. **Passenger** Transport:*

From the U.S. Department of Transportation (DOT)'s

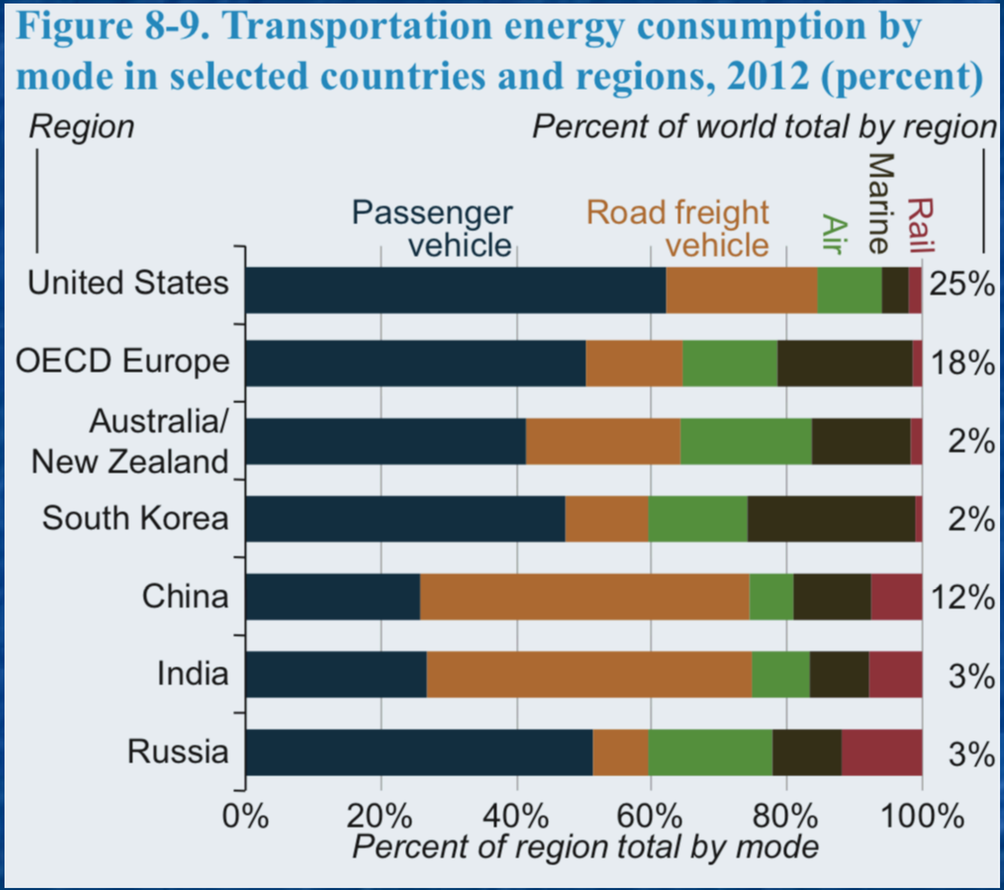
"Transportation Statistics Annual Report- 2018" [1]



1) Page 3-5 (with labels added) in: https://www.bts.dot.gov/sites/bts.dot.gov/files/docs/browse-statistical-products-and-data/transportation-statistics-annual-reports/Preliminary-TSAR-Full-2018-a.pdf

*The DOT conspicuously omitted a comparable **freight** ton-miles summary*

But the earlier EIA "International Energy Outlook 2016" included this figure: [1]



Assuming:
U.S. "Rail" is ~ all freight,
U.S. "Air" is ~ all passenger,
U.S. "Marine" is ~ all freight
Figure would imply:

Passengers (by all modes ~ 71%):

Cars & light trucks	~ 62%
Air	~ 9%
All other	< 1%

Freight (~ 29%):

Heavy truck	~ 22%
Marine	~ 3.5%
Rail	~ 2%

But U.S. marine freight of 3.5% is **much smaller** than the earlier Global value of 12%

(Compare the 2nd-from-right dark brown "Marine" bands top to bottom in figure above)

1) Page 131 in: https://www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf

*Two reasons why U.S. ship transport energy **might** be lower:*

1) **Relative Distances:**

The size of most countries is **much smaller** than the size of the world's oceans

Distance traveled by goods from Asia in **ships** is thus **much longer than**

distance traveled in **trucks & trains** to distribute goods **within** the country

But the continental U.S. is ~ 1/2 as wide as the Pacific Ocean

Which shifts the distance balance away from ships towards trucks & trains

2) **Deceptive Reporting:**

Nations want to polish their image by minimizing their apparent energy footprint

which the U.S. **might** be doing by omitting or sharply discounting the

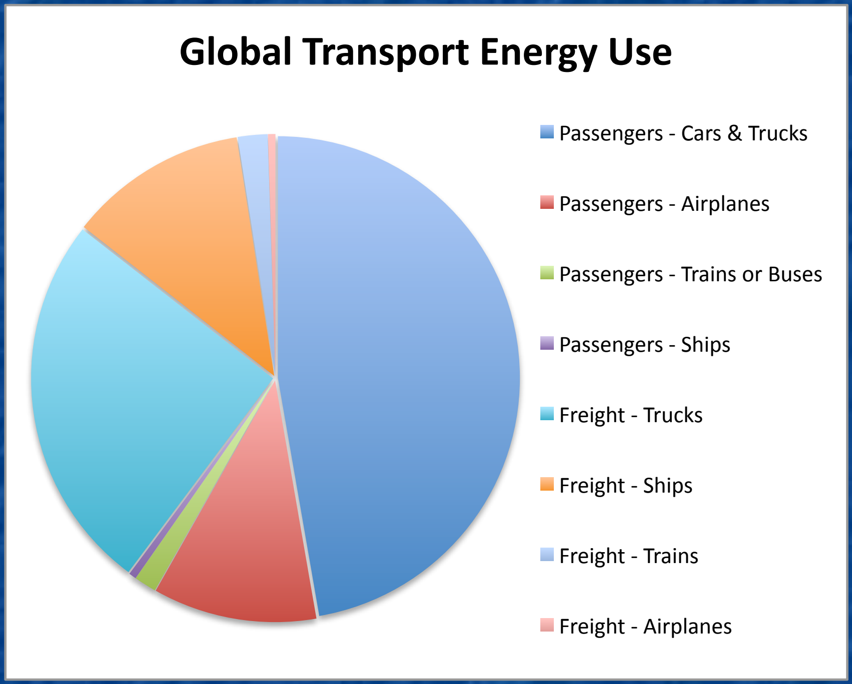
energy used transporting goods **TO** the U.S. via internationally flagged ships

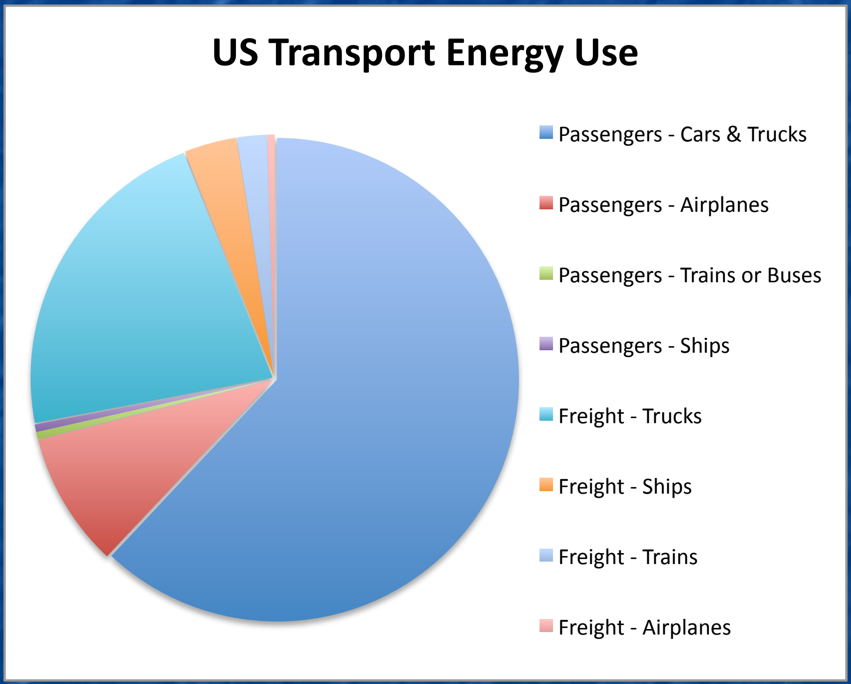
(which, while it might be legally defensible, strikes me as deceptive)

Summary comparison of Global vs. U.S. Transport Energy:

	Global		U.S.	
Transport fraction of TOTAL ENERGY:	25%	vs.	26.7%	
Fraction of TRANSPORT ENERGY used by:				
Fossil-fueled cars & trucks	70-85%	vs.	~84%	
Fossil-fueled ships	~12%	vs.	3.5-5%	
Fossil-fueled airplanes	10-15%	vs.	~9%	
Fraction of TRANSPORT ENERGY used by:				
Passengers:	45-50%	vs.	~62%	in Cars & Trucks
	9-13%	vs.	~9%	in Airplanes
	1-2%	vs.	<1%	in Trains or Buses
	< 1%	vs.	<1%	in Ships
Freight:	25-26%	vs.	~22%	in Trucks
	12%	vs.	~3.5%	in Ships
	2%	vs.	2%	in Trains
	< 1%	vs.	< 1%	in Airplanes

Transport Energy breakdowns in the form of pie charts:





Greenhouse Gas Emissions

Energy Impact vs. Greenhouse Gas Impact?

The above energy expenditures have huge economic & environmental consequences

But while economic impact may scale roughly with AMOUNT of energy used

Environmental impact may also vary with HOW that energy is used

Why?

Because, depending on HOW energy is used, it ultimately liberates:

Heat alone - as mostly occurs when energy drives **electric motors** OR

Heat + innocuous gases - as occurs when **hydrogen is burned** OR

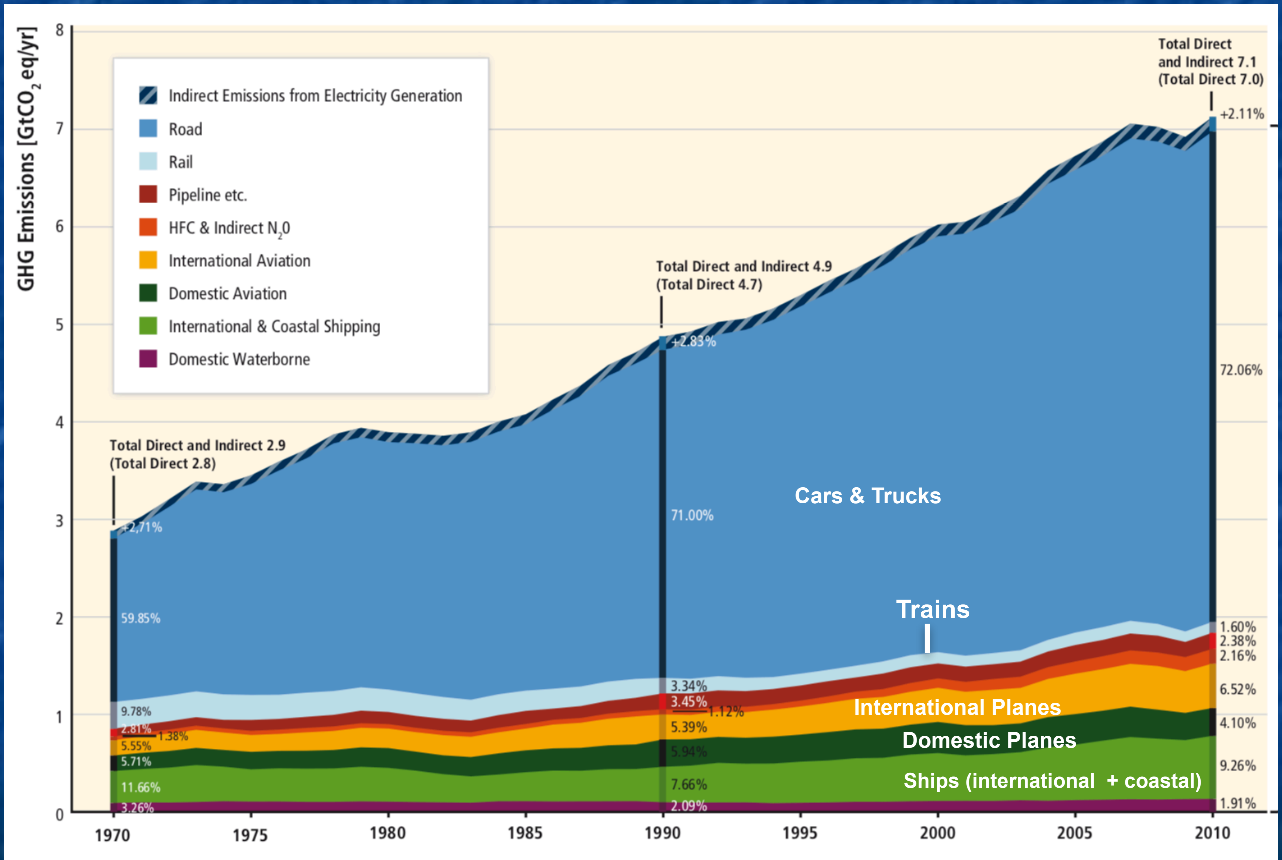
Heat + greenhouse gases - as occurs when **fossil fuels are burned**

So we must now examine the GHG emissions of each transportation mode:

*Transportation's contribution to **Global Greenhouse Gas Emissions**:*

From: Transport - Chapter 8 - Climate Change 2014 - IPPC Fifth Assessment [1]

(Note: Unlike earlier **projection** figures, in this **history** figure TODAY is at RIGHT END)



GHG Emission Share:

Transportation:

Cars & Trucks:	72%
Ships (intl/coastal)	9.2%
Planes (intl)	6.5%
Planes (domestic)	4.1%
Ships (domestic)	1.9%
Trains	1.6%

Non-transportation:

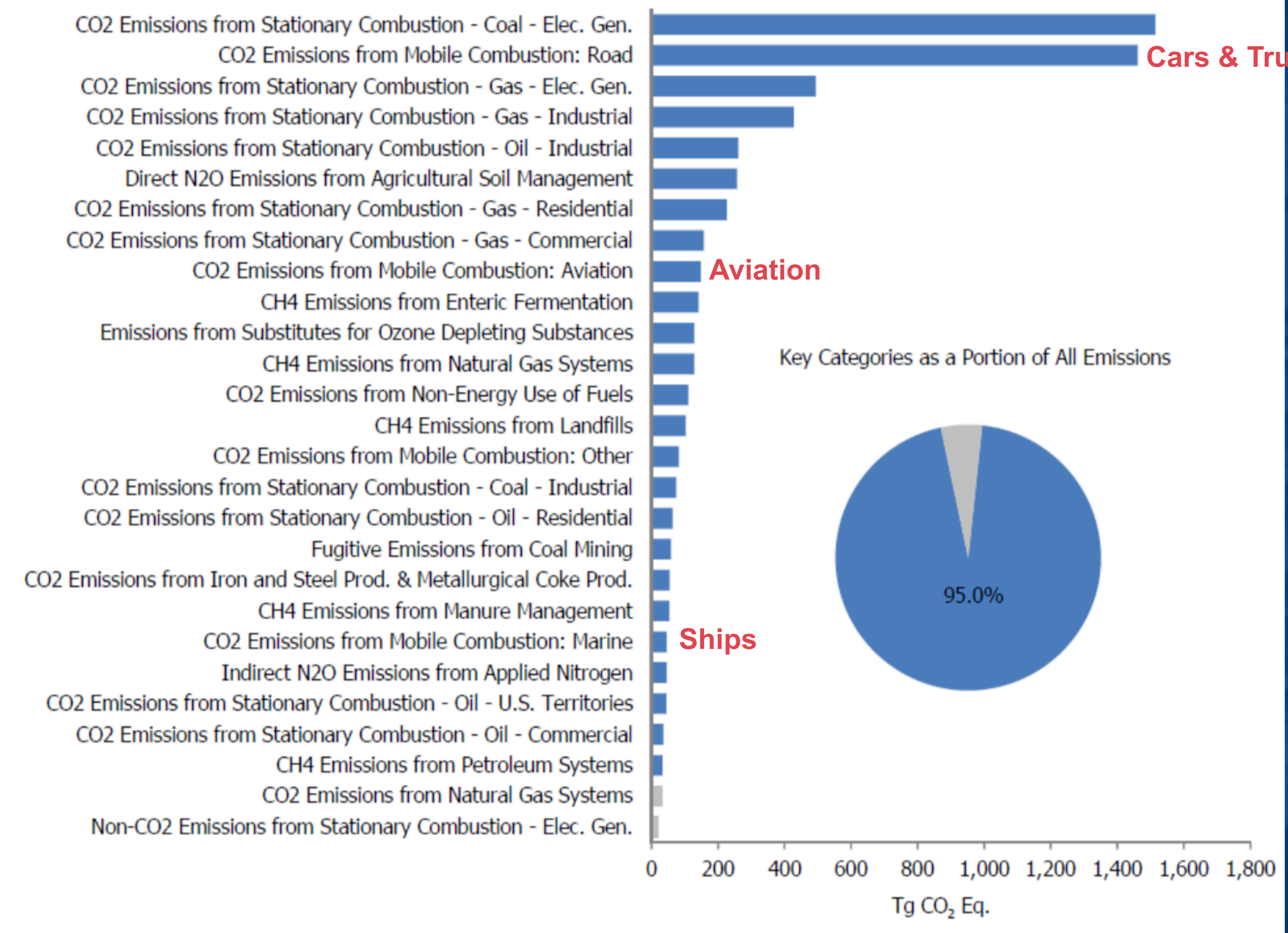
Power Plants (indirect)	2.1% *
All Other	~ 4%

* Compare this 2.1% "indirect electricity generation" GHG number with data on following two slides

1) White labels added to: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter8.pdf

Transportation's contribution to ***U.S. Greenhouse Gas Emissions:***

From: "EPA Inventory of U.S. Greenhouse Gas Sources & Sinks - 1990-2012" [1]



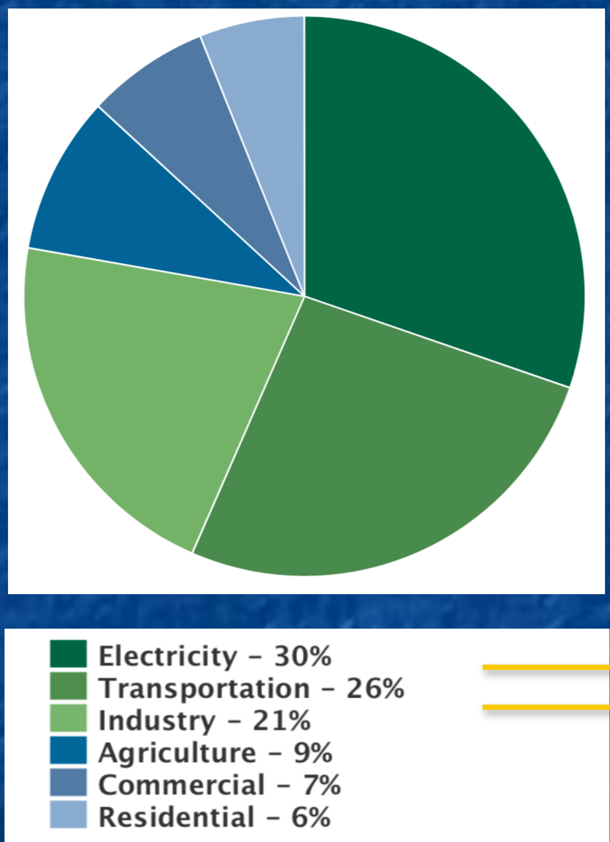
Note top line identifying coal electricity generation plants **alone** as the **top** U.S. GHG emitter

1) Now disappeared EPA document: link WeCanFigureThisOut.org cached copy: link

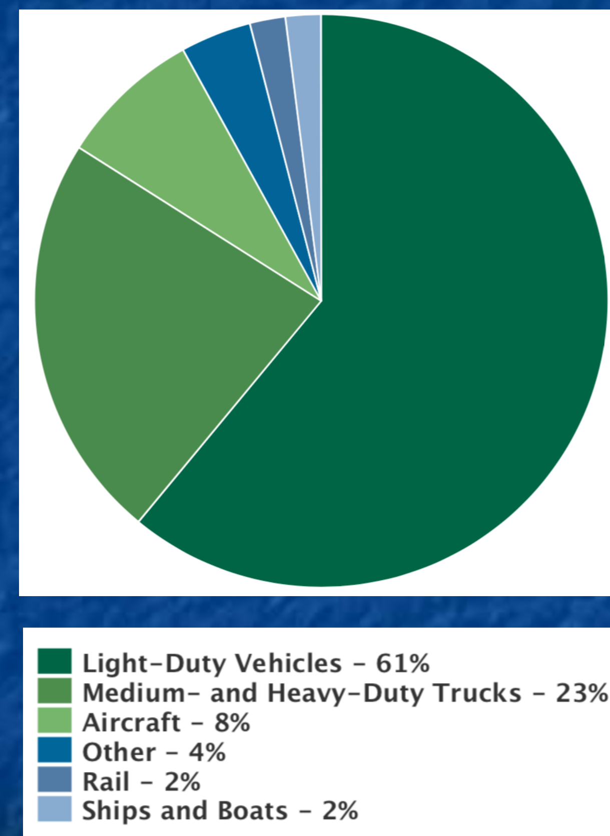
Or this enumeration of ***U.S. Greenhouse Gas Emissions****:*

From online 2017 archive of the U.S. Environmental Protection Agency's "Fast Facts on Transportation Greenhouse Gas Emissions" [1]

All U.S. GHG Emissions:



Transportation U.S. GHG Emissions:



AT LEFT: Note electricity generation's 30% GHG share - What WAS the 2.1% IPCC referred to in earlier slide?

Possibility: GHG's due to tiny fraction of electricity generation now used by electric trains & cars

1) https://19january2017snapshot.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions_.html

A possibly surprising observation / conclusion:

Car + truck **GHG emission share** = Car + truck **energy share**

Globally both are ~ 72%   For the U.S. both are ~ 84%

Similarly, airplane GHG share and energy share are both ~ 10% (Global and U.S.)

And rail GHG share and energy share are both ~ 2% (Global and U.S.)

Indicating use of a SINGLE cross-cutting technology: Fossil fuel combustion

Producing either motion directly (in cars, trucks, trains, planes, ships . . .) OR

Producing electricity then used to produce motion (in electric cars & trains)

YES: There has yet to be any recognizable reduction in GHG's due to

Electric vehicles using power from **low GHG electric power plants**

Suggesting: **Too few electric vehicles** and/or **too few low GHG electric power plants**

Indeed, the fraction of cars now powered electrically is still very very small

And even where most passenger trains **are** electric, the electricity is **not** low GHG

A possible exception: French electric passenger trains using nuclear electricity

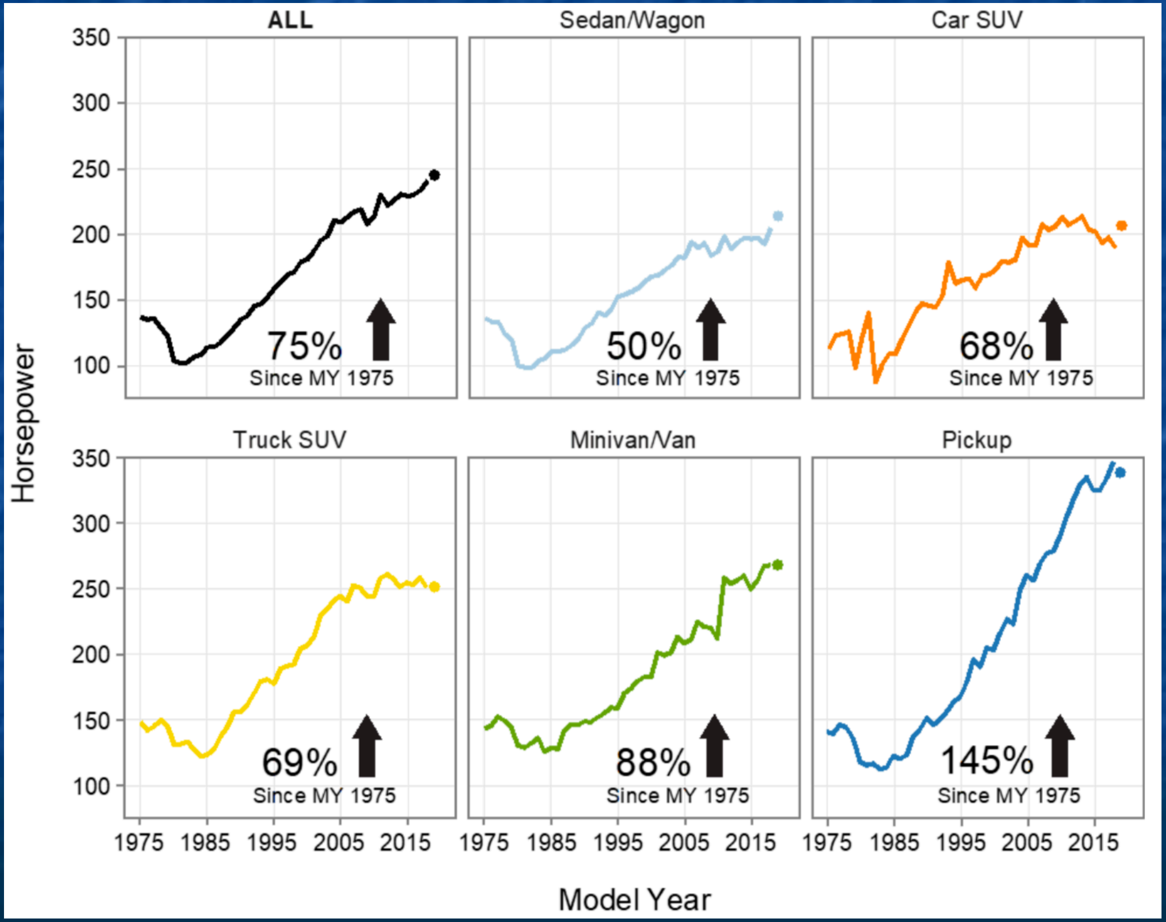
Unique Impacts & Concerns about Specific Transport Modes:

Cars & Trucks:

From the U.S. Environmental Protection Agency (EPA)'s

"2019 EPA Automotive Trends Report" [1]

The engine power of U.S. road vehicles has skyrocketed!

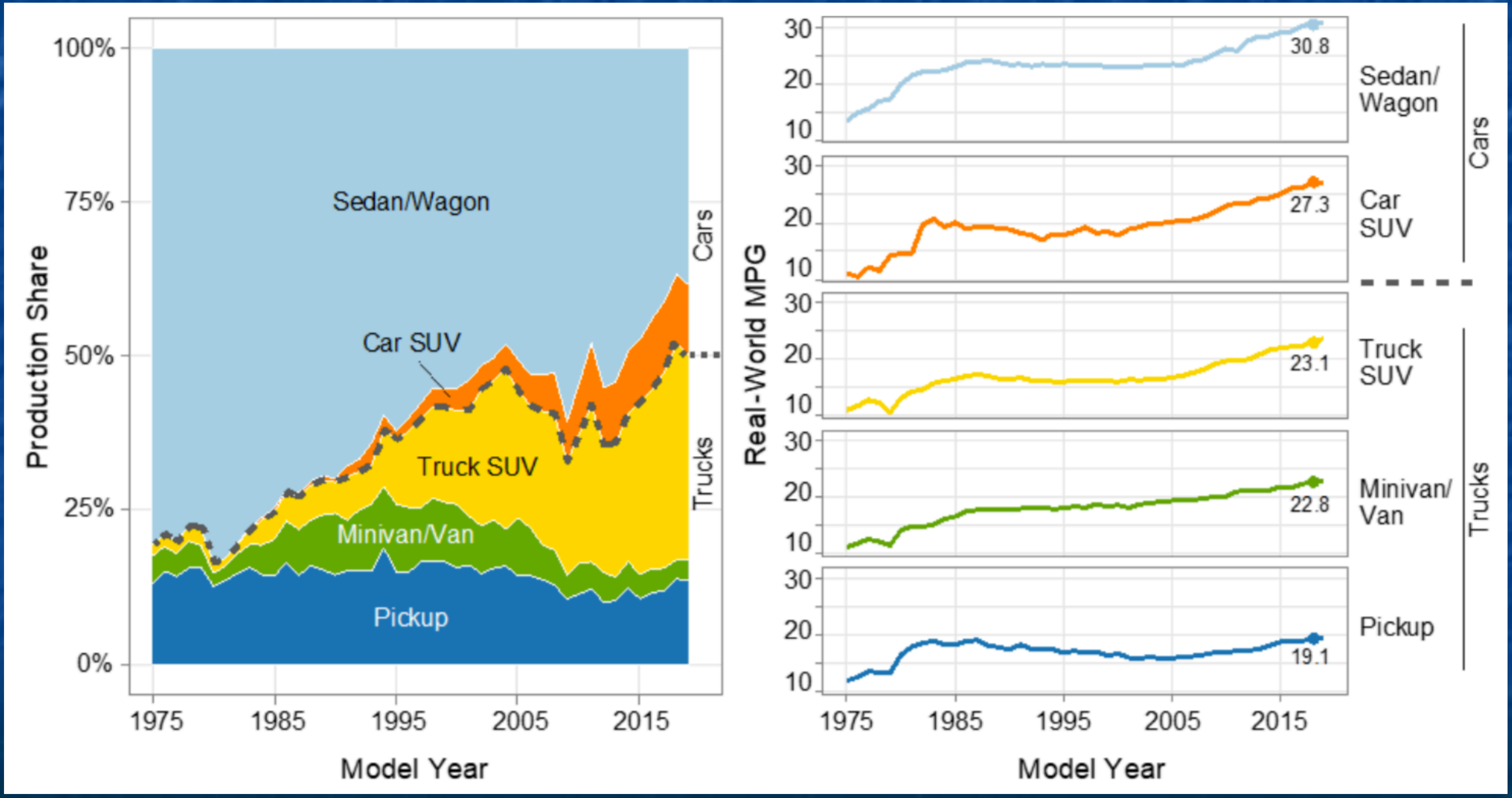


1) Page 5 in: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100YVFS.pdf

Despite which: ***Fuel mileage has improved*** *for all* ***except*** *pickup trucks:*

From the "2019 EPA Automotive Trends Report" [1]

Production share and estimated real-world average U.S. fuel economy:

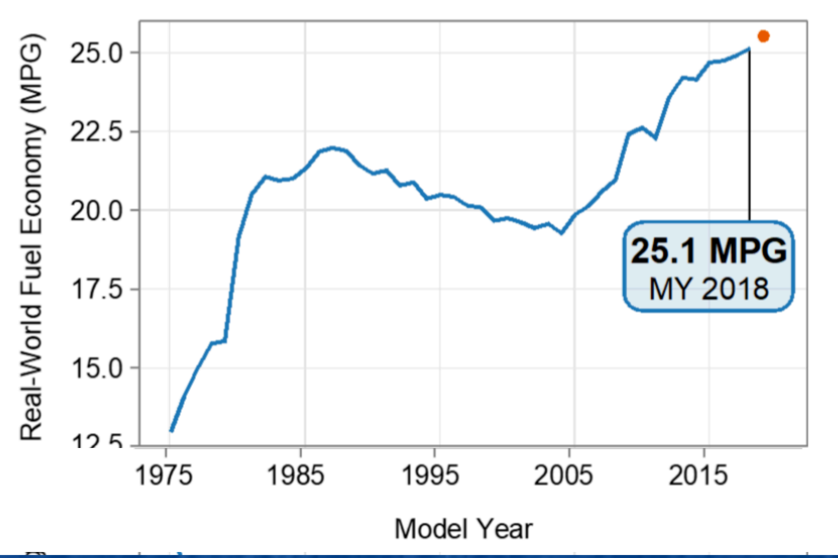


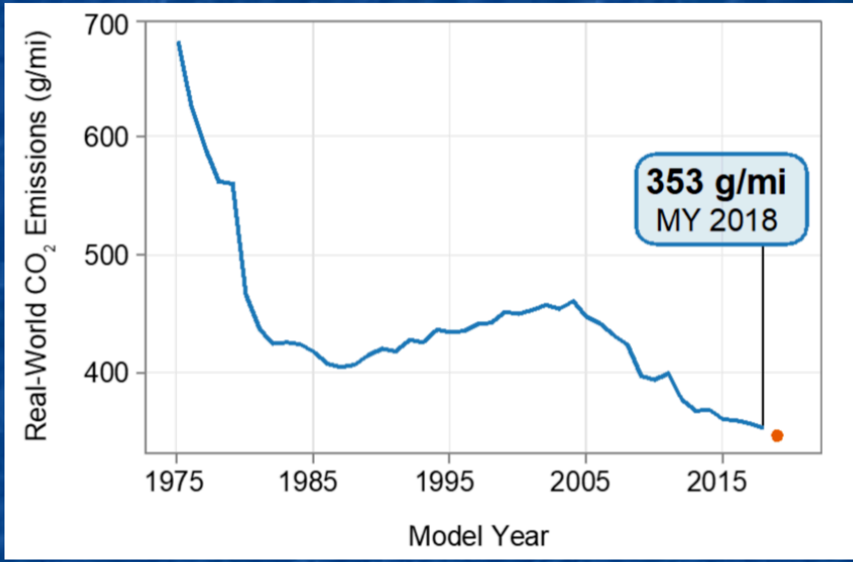
1) Page 16 in: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100YVFS.pdf

Leading to overall improvement 2005 onward:

From the "2019 EPA Automotive Trends Report" [1]

Overall real-world average U.S. auto fuel economy and CO_2 emissions:





Likely reasons for the sustained post 2005 improvement?

Market forces alone began driving the industry to higher mileage levels 2005 onward

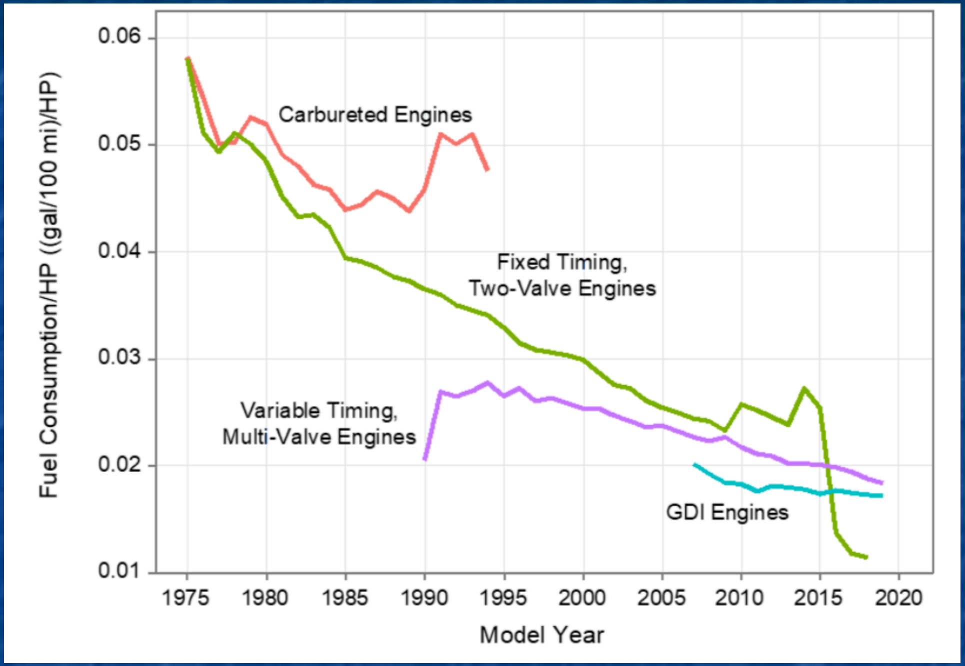
FURTHER, despite four years of rhetoric, the Trump administration has yet to replace higher mileage standards implemented under an Obama / Industry agreement [2]

1) Page 5 in: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100YVFS.pdf

2) https://obamawhitehouse.archives.gov/the-press-office/2012/08/28/obama-administration-finalizes-historic-545-MPG-fuel-efficiency-standard

All enabled by this evolution in car & truck engine technology:

From the "2019 EPA Automotive Trends Report" [1]



These ongoing improvements to fossil-fueled car & trucks are so massive,

as are the improvements promised by electrification of cars & trucks,

that I am devoting a separate entire note set to their exploration:

Green(er) Cars & Trucks (pptx / pdf / key)

1) Page 46 in: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100YVFS.pdf

Trains:

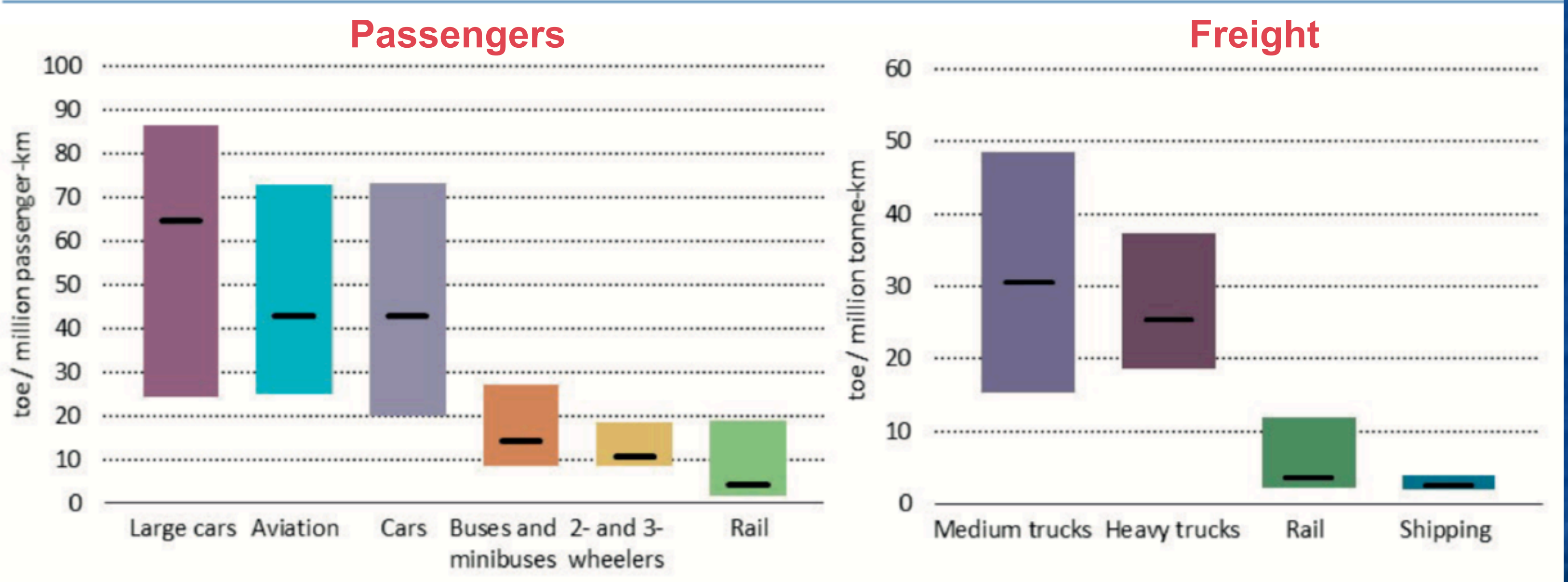
From the International Energy Agency (IEA)'s 2019

"The Future of Rail - Opportunities for Energy and the Environment"

Rail is the MOST EFFICIENT means of PASSENGER transport

And almost ties with shipping as most efficient means of FREIGHT transport

Figure 1.21 **Energy intensity of different transport modes, 2017**



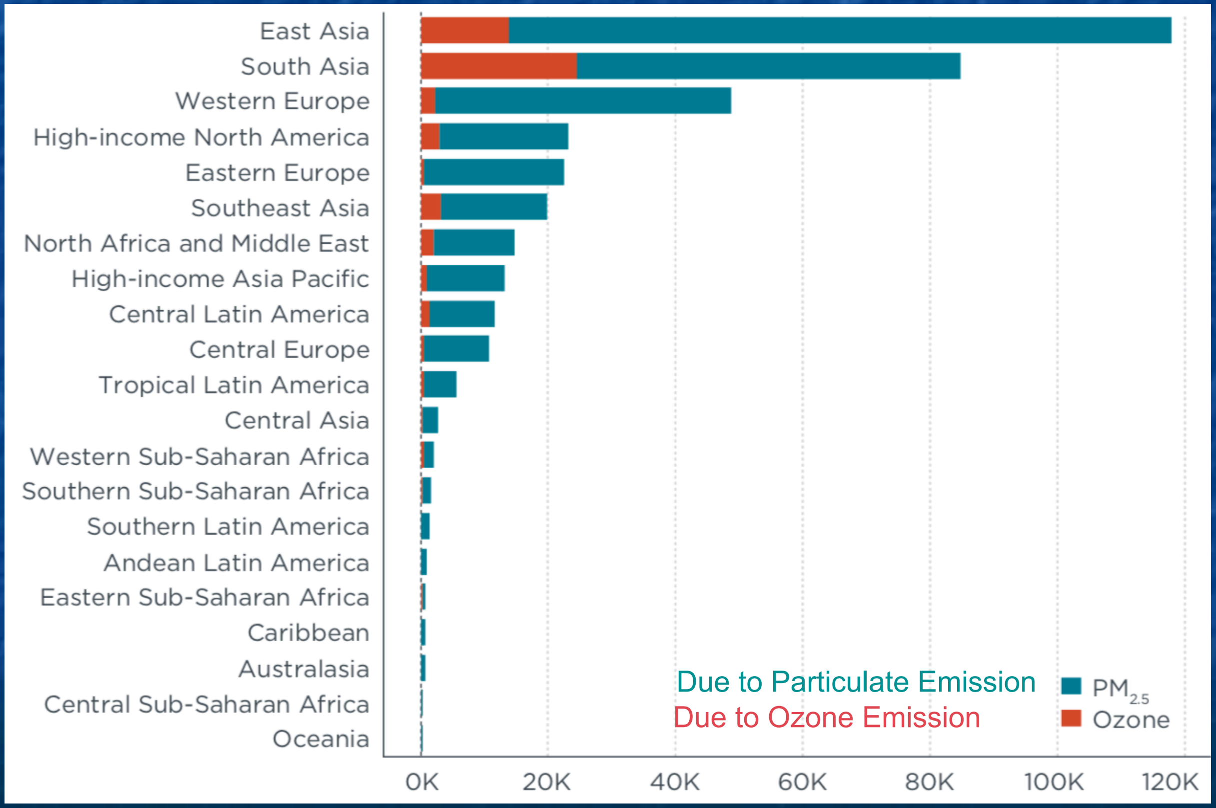
Boxes = Worldwide Range Bars = Worldwide Average

1) Page 48 (red labels added) in: https://www.iea.org/reports/the-future-of-rail

Airplanes:

Planes account for only ~ 10% of world transport energy use & GHG emissions

Nevertheless, the International Council on Clean Transportation (ICCT)'s 2019 "Global Snapshot of Air Pollution Related Health Impacts of Transportation" claims that aviation has a major worldwide health impact:



Deaths Attributed to Aviation Pollution in 2015

1) Page 17 (with labels added) in: https://theicct.org/publications/health-impacts-transport-emissions-2010-2015

Airplane GHG emissions are also of special concern:

Because of the exceptional difficulty in reducing aviation's use of fossil fuels

Which is a challenge that I will explore in depth later in this note set

Who / what is now most responsible for aviation's CO_2 emissions?

From the ICCT's 2018 "CO_2 Emissions from Commercial Aviation" [1]

Global 2018 CO_2 emissions by type of air service:

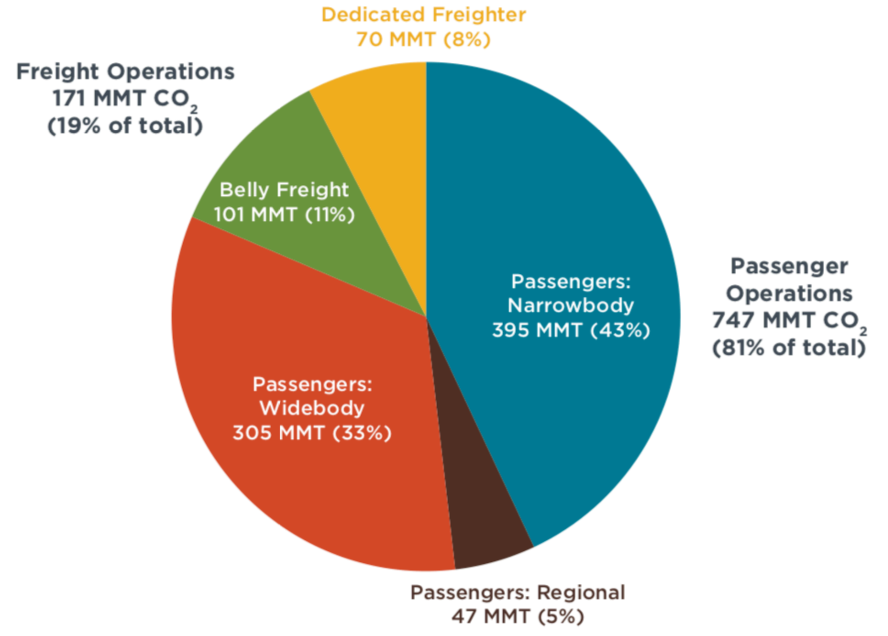


Figure 1. CO_2 emissions in 2018 by operations and aircraft class

Passenger Operations: 81%

Belly Freight: 11%

Dedicated Freight: 8%

1) https://theicct.org/publications/co2-emissions-commercial-aviation-2018

The same report suggests disproportionate role of long / international flights:

CO_2 emissions & carbon intensity attributed to passengers vs. flight distance:

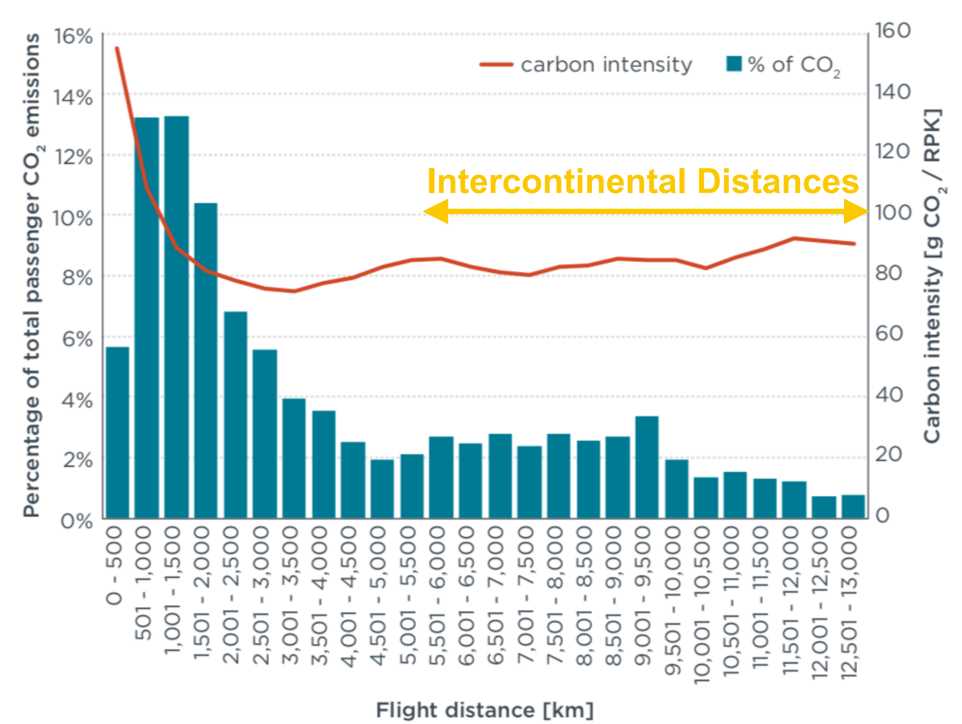


Figure 3. Share of passenger CO_2 emissions and carbon intensity in 2018, by stage length.

This CO_2 impact despite the much lower "carbon intensity" of long distance flights

Carbon Intensity = Grams CO_2 per Revenue Passenger Kilometers (flown)

Lower for long flights because fuel is burned **much** faster during ascent than cruising

1) (yellow label & arrow added): https://theicct.org/publications/co2-emissions-commercial-aviation-2018

*But oft reported surge in **middle income** air travel is **not** the culprit:*

From the International Council on Clean Transport (ICCT)' s

"CO_2 Emissions from Commercial Aviation:"

CO_2 due to passengers vs. passenger income:

As contrasted with Global income distribution:

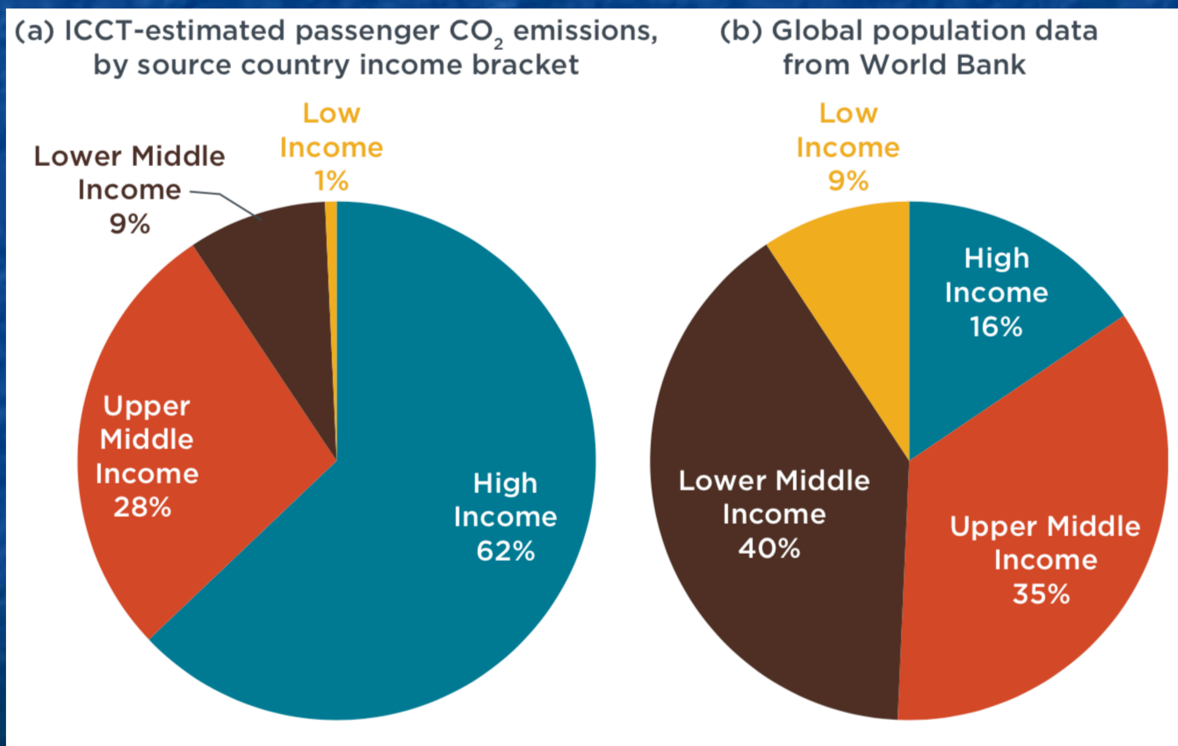
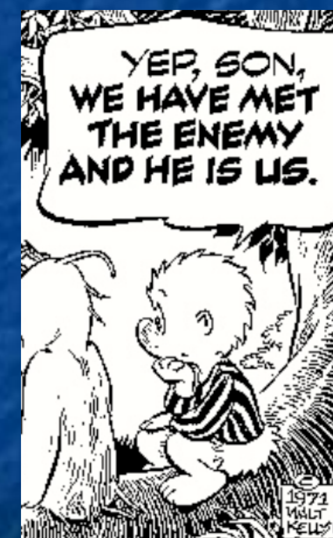


Figure 2. CO_2 emissions from passenger aviation operations and total population in 2018, by country income bracket (United Nations, 2019; World Bank, 2019)



https://theicct.org/publications/co2-emissions-commercial-aviation-2018

Shipping:

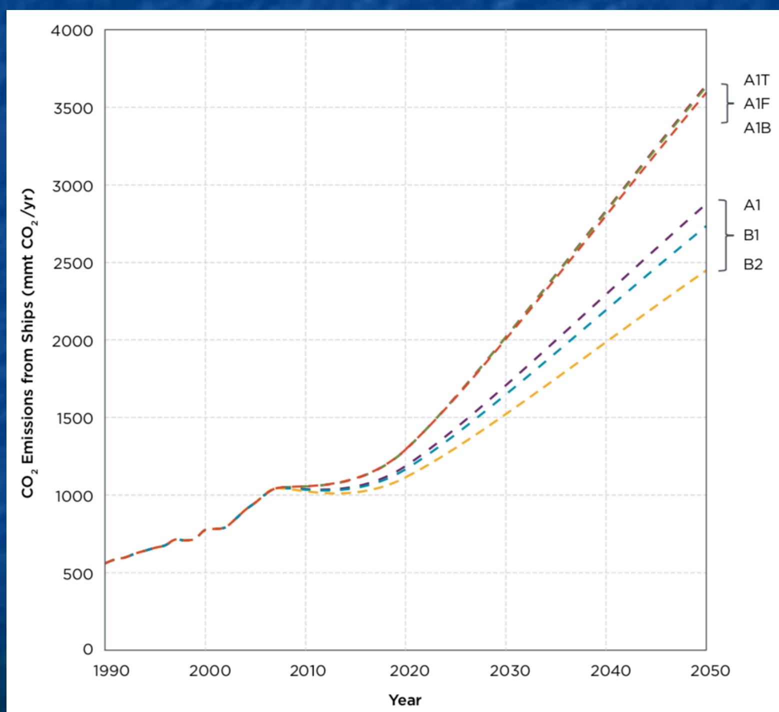
Sources above describe ships as the MOST energy efficient mode of freight transport

And note that ships now account for less than 2% of world GHG emissions

But not mentioned was the fact that today's ships use of some of the **dirtiest fossil fuels**

Or that, while now overshadowed by other modes, shipping's impact is soaring:

Projected Shipping GHG emissions



Projected Growth by 2050

From above:

Passenger Car & Truck +20%

Freight Truck +50%

Passenger Air +150%

From plot at left: [1]

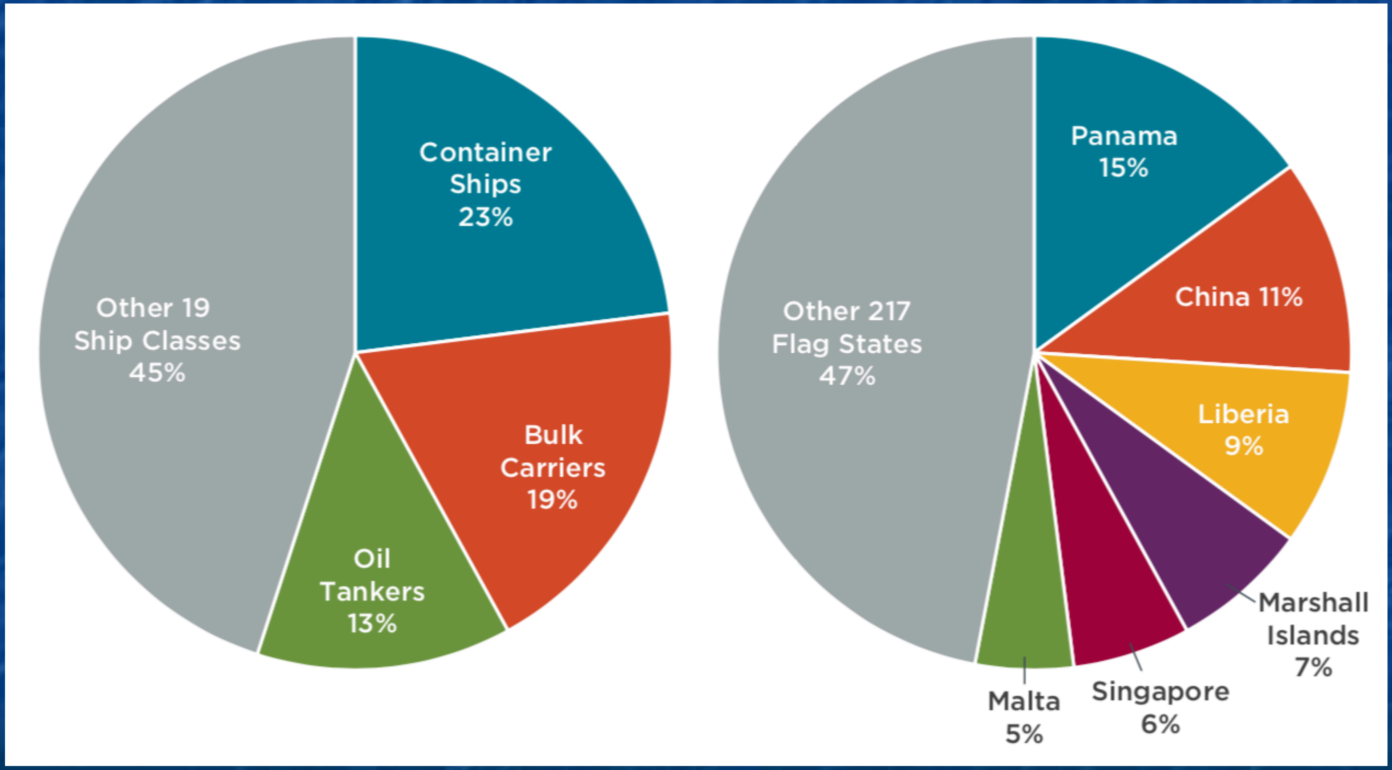
Shipping +300-500%

1) Reducing the Greenhouse Gas Emissions from Ships - Cost Effectiveness of Available Options - ICCT - 2011: https://theicct.org/sites/default/files/publications/ICCT_GHGfromships_jun2011.pdf

Impact is mostly due to just 3 classes of ship, flying just 6 national flags:

From the International Council on Clean Transport (ICCT)'s

"Greenhouse Gas Emissions from Global Shipping 2013-2015:" [1]



1) https://theicct.org/publications/GHG-emissions-global-shipping-2013-2015

"Black carbon" is identified as a particular climate change culprit: [1]

Black carbon (BC) = Particulates stemming from ship's use of low grade fossil fuels [2]

Bad news: They are unusually effective at causing global warming

Good news: As particles, they fall out of the atmosphere more quickly than gases

Meaning that IF their emission were soon curtailed, their latent global warming impact would diminish in 10's rather than 100's of years

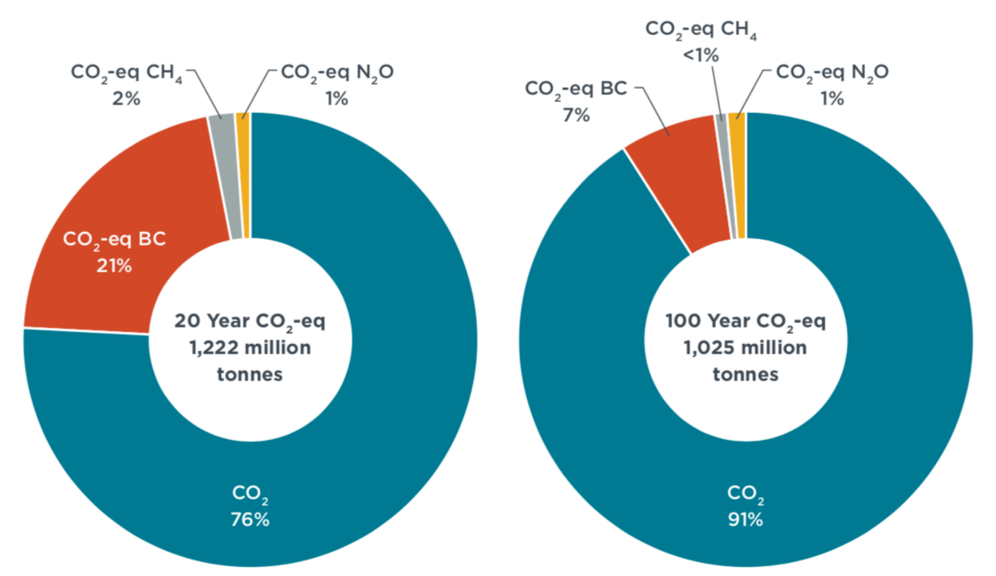


Figure ES-3. Total shipping CO_2-eq emissions, 20-year and 100-year GWP, 2015

BC warming impact over 20 vs. 100 years

(in CO_2 equivalents)

1) https://theicct.org/publications/GHG-emissions-global-shipping-2013-2015
2) https://www.ccacoalition.org/en/slcps/black-carbon

Science Behind How Energy is Spent in Moving Things

Science-based Models:

THEIR STRENGTHS:

We will soon move on to discussion of reducing real-world transport energies

And you will see that, not only are there many modes of transport,

but that for each mode there is a long list of would-be "solutions"

The resulting list of lists can be overwhelming

And even if the proposed "solutions" separately seem to make sense,

prioritizing them on the basis of their likely impact can be very, very difficult

But transport can be modeled based on high-school-level Sir Isaac Newton science

Specifically, based on his laws describing force, momentum and kinetic energy

The resulting models can identify WHERE each form of transport uses energy

Further, via relatively simple equations they can predict HOW energy use

varies based on the vehicle's size, weight, speed, altitude, etc.

Science-based Models:

THEIR WEAKNESSES:

Precison demands that Newton's Laws be applied to every moving object involved

That is possible for A car, or A truck, or A train, or A plane, or A ship

It's also possible if volumes of air or water are treated as single moving units

Moving vehicles DO cause blocks of air & water to move as units, but they also

stir up individual atoms & molecules within that air and water, producing **heat**

But applying Newton's Laws to $\sim 10^{23}$ atoms or molecules is nearly impossible

The following models thus treat air & water as ONLY single blocks/volumes for which,

if block's velocity changes by Δv, velocity of each atom/molecule also changes by Δv

By ignoring differences in the movement of individual atom & molecules

these models neglect the loss of energy to **heating** of air and water,

making these models useful, but optimistic, approximations of the real world

MODEL 1: Stop-and-Go Vehicles [1]

Assume vehicle moves a distance **L**, at velocity v_{max}, stops, then repeats this cycle

At the start of each cycle, fuel energy is transformed into vehicle kinetic energy of:

$$E_{vehicle\_kinetic} = \frac{1}{2} M_{vehicle} v_{max}^2$$

As in all of these models, energy put into air heating is neglected

But if vehicle never goes very fast, energy put into moving blocks of air is **also** small

Leaving the above vehicle kinetic energy as the major expenditure of energy

That energy (almost alone) carries the vehicle a distance L, yielding:

$$\textbf{Energy per distance}_{stop\_go} = M_{vehicle} v_{max}^2 / 2L$$

OR, rate of energy consumption while vehicle is moving = $\Delta E / \Delta time$ = Power

Over moving part of cycle: $\Delta E = \frac{1}{2} M_{vehicle} v_{max}^2$ $\Delta time = L / v_{max}$ yielding:

$$Power_{stop\_go} = M_{vehicle} v_{max}^3 / 2L$$

This model approximates **car city driving AND commuter rail travel**

1) This and models that follow build upon David J.C. McKay's chapters "Cars II" (link) & "Planes II" (link), *Ways of minimizing this energy of stop and go travel*

Based on: **Energy per distance$_{stop_go}$ = $M_{vehicle}\, v_{max}{}^2 / 2L$**

1) Decrease vehicle's weight (reduce $M_{vehicle}$):

Vehicle with **1/2** the weight gets you there with **1/2** the energy

2) Slow down (reduce v_{max}):

Vehicle traveling **1/2** as fast gets you there with **1/4** the energy

3) Find a route with fewer stop signs / stop lights / stations (increase L)

OR INSTEAD: RECLAIM most of vehicle's kinetic energy when it stops

Via "Regenerative Braking" / "Kinetic Energy Recovery Systems (KERS)"

which, instead of dumping kinetic energy into brake heating, converts it to electricity

A conversion that is particularly easy for electric vehicles because when

an **electric motor** is forced to turn, it becomes an **electric generator**

(for details, see my note set: **Magnetic Induction** (pptx / pdf / key))

MODEL 2: Steadily Moving Vehicles

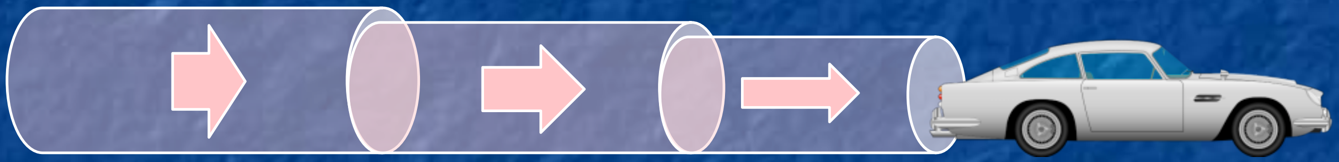
Which is mostly what is going on during long trips:

Then, the interval between accelerations is **vastly** stretched out

Diluting the kinetic energy investment during acceleration described by MODEL 1

The dominant energy loss then becomes the loss due to the "drag" of air

That is, the vehicle accelerates & drags along a volume of air at almost its own speed



That moving air thereby acquires its own kinetic energy (and gradually spreads out)

But while the energy going into moving those **blocks** of air is now accounted for,

energy going into **air friction / heating** is still neglected

which is again a better approximation for lower speeds of travel

This model will approximate **car highway driving AND long distance rail travel**

Car image from: www.clipartlord.com/category/transportation-clip-art/

The analysis:

Consider a cylinder of air that WAS stationary in front of the vehicle

but is now being dragged along behind it at a nearly the vehicle's speed

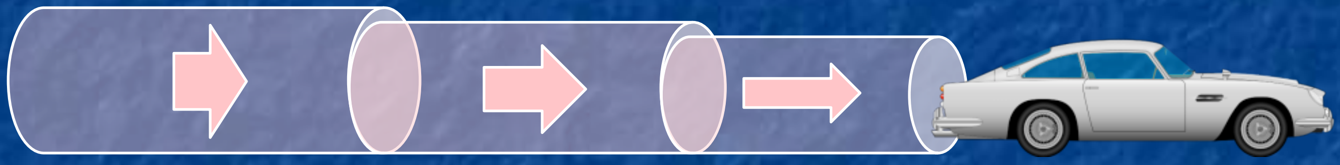
The cross-section of that air cylinder will depend upon the car's streamlining

Better streamlining => Less air accelerated => Smaller cylinder cross-section (A):

$$\text{Area}_{air} = c_{drag}\ \text{Area}_{vehicle}$$

That is, the air's cross section = c_{drag} x (vehicle's frontal cross-section area)

With c_{drag} likely being < 1 and decreasing with better and better streamlining



Then, over a time interval t, the volume of accelerated air = A_{air} x (v_{steady} x t)

with that accelerated volume now moving at ~ vehicle's velocity = v_{steady}

Energy gained by trailing cylinder of air:

For **air of mass density ρ_{air},** we can then calculate its gained kinetic energy:

$$E_{air\_kinetic} = E_{drag} = ½\ M_{air}\ v_{steady}^2 = ½\ (\ \rho_{air}\ x\ \text{volume of air}\ )\ v_{steady}^2$$

But from above, volume of air = A_{air} x (v_{steady} x t) = $c_{drag}\ A_{vehicle}\ v_{steady}\ t$ and thus:

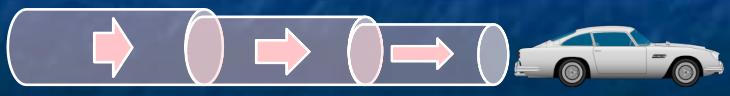
$$E_{drag} = ½\ \rho_{air}\ (A_{air}\ v_{steady}\ t\ )\ v_{steady}^{\ 2} \Rightarrow ½\ \rho_{air}\ c_{drag}\ A_{car}\ t\ \ v_{steady}^3$$

Dividing that by distance (v_{steady} x t) gives the energy expended per distance:

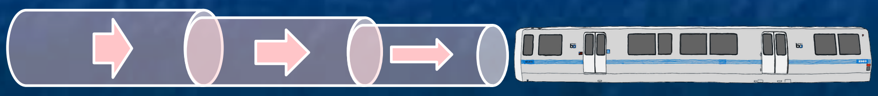
$$\textbf{Energy per distance}_{\ steady} = ½\ \rho_{air}\ c_{drag}\ A_{vehicle}\ \ v_{steady}^2$$

Or dividing it by time gives the power used while moving:

$$\textbf{Power}_{steady} = ½\ \rho_{air}\ c_{drag}\ A_{vehicle}\ v_{steady}^{\ 3}$$



OR



Ways of minimizing the energy of steadily moving travel?

Based on: **Energy per distance $_{steady}$ = $\frac{1}{2}\,\rho_{air}\,c_{drag}\,A_{car}\,v_{steady}^2$**

1) Slow down - as with earlier stop and go model:

Vehicle traveling **1/2** as fast gets you there with **1/4** the energy

2) Reduce drag: By reducing c_{drag} (a function of the vehicle's shape) OR

By reducing $A_{vehicle}$ (= vehicle's head-on cross sectional area)

NEITHER VEHICLE LENGTH NOR MASS APPEAR IN EQUATION ABOVE

Suggesting longer / heavier vehicles consume no more energy per distance

Yes, this model considers only how much energy is added to air as it is taken from being stationary ahead of a vehicle to being dragged at speed behind it

Real world vehicles moving **through** air **also** produce chaotic turbulence which, at finer and finer scales, ends up enhancing atom & molecular movement = **Heat**

NEVERTHELESS: LONGER rail & road trains DO make excellent energy sense!

The first way of reducing a vehicle's drag:

1) Reduce its Drag Coefficient (c_{drag}) via better streamlining:

	c_{drag}:
Honda Insight	0.25
Prius	0.26
Renault 25	0.28
Honda Civic	0.31
Volkswagen Polo	0.32
Peugeot 206	0.33
Ford Siesta	0.34
Audi TT	0.35
Honda Civic	0.36
Citroen 2CV	0.51

For modern cars (≠ Citroen 2CV):

Streamlining => diminishing returns

- Somewhat boxy Polo: c_{drag} = 0.32
- Teardrop shaped Insight: c_{drag} = 0.25
- Total range: **Ratio of 1.5 to 1**

So more severe streamlining is **not** likely to be an energy "silver bullet"

Especially as we are **already** cutting into usable head room & cargo space

After "Sustainable Energy without the Hot Air" (page 257)

The second way of reducing a vehicle's drag:

2) Reduce its Drag Area (c_{drag} $A_{vehicle}$) - numbers below are given in m^2:

	c_{drag} $A_{vehicle}$	
Honda Insight	0.47	
Volkswagen Polo	0.65	
Honda Civic	0.68	
"Typical Car"	0.8	
Volvo 740	0.81	
Land Rover Discovery	1.6	

For modern cars (≠ Citroen 2CV):

SIZE MATTERS A LOT!

- Small Honda Insight: 0.47

- "Typical Car:" 0.8

Sub-range: **Ratio of almost 2 to 1**

- Land Rover pushes ratio to almost 3:1

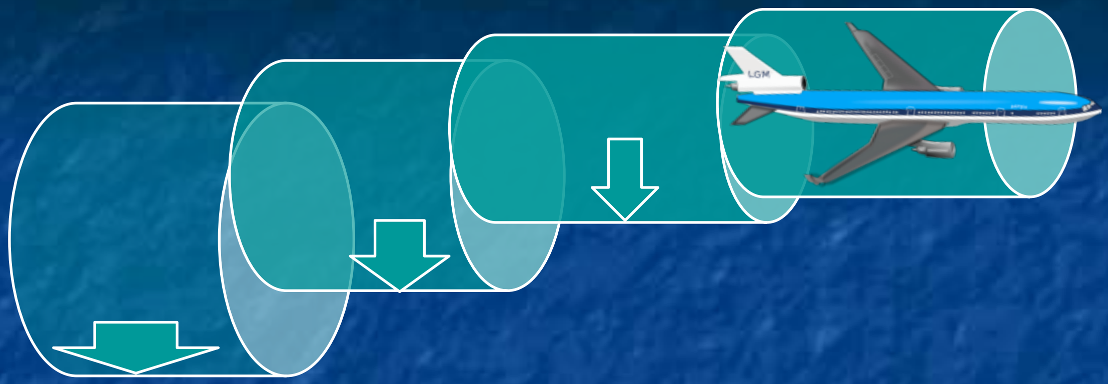
- As would **popular large U.S. SUV's**

Full range: **Ratio of 3 to 1**

("We have met the enemy, and he is us")

After "Sustainable Energy without the Hot Air" (page 257)

MODEL 3: Steadily Moving Planes



To offset the force of gravity, planes **must** exploit Newton's **Action = Reaction:**

An airplane's wings thus steadily push a LARGE volume of air downward

Neglecting air heating AND details such as wingtip vortices AND

approximating volumes of air pushed downward as simple cylinders:

$$\mathbf{Mass_{lift\_cylinder} = density\ x\ volume = \rho_{air}\ x\ (v_{plane}\ t\ \ Area_{lift\_cylinder})}$$

Where ρ is air density, A is cylinder's cross-sectional area

And (v_{plane} t) is the distance the plane flies in a time t

Jet image from: www.clipartlord.com/category/transportation-clip-art/

(continuing)

Over span of plane's wings, **air is forced downward at a velocity v_{air_down}**

Cylinder's downward momentum = $M_{lift\_cylinder}\ v_{air\_down} = (\rho_{air}\ v_{plane}\ t\ \ A_{lift})\ v_{air\_down}$

That momentum per time = Force imparted by plane's wings => Force lifting plane

Force = $\rho_{air}\ v_{plane}\ A_{lift}\ v_{air\_down}$

Which had better match the force of gravity pulling that plane downward = $M_{plane}\ g$

Equating those forces and solving for $v_{air\_down} = M_{plane}\ g\ /\ (\rho_{air}\ v_{plane}\ A_{lift})$

Using value of v_{air_down} to calculate kinetic energy lost to that downward moving air:

$$\tfrac{1}{2} M_{air}\ v_{air\_down}^2 = \tfrac{1}{2} (\rho_{air}\ v_{plane}\ t\ \ Area_{cylinder})\ (M_{plane}\ g\ /\ (\rho_{air}\ v_{plane}\ A_{lift}))^2$$

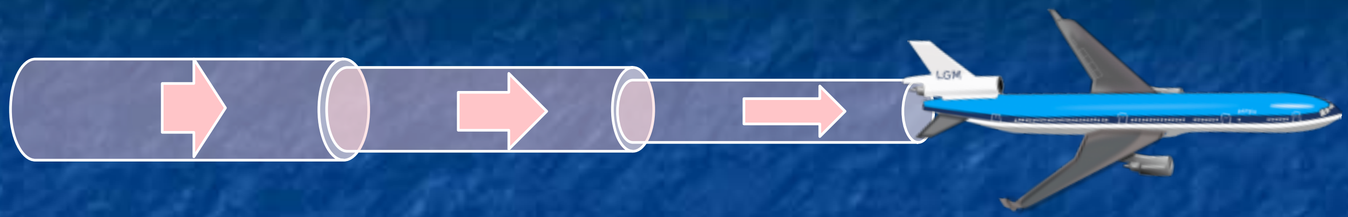
$$= t\ (M_{plane}\ g)^2\ /\ (2\ \rho_{air}\ v_{plane}\ A_{lift})$$

So the power (= energy / time) transferred to that lift air is:

$$\mathbf{Power_{lift} = (M_{plane}\ g)^2\ /\ (2\ \rho_{air}\ v_{plane}\ A_{lift})}$$

*But **additional** energy is expended on drag:*

For which the analysis is just like that for the earlier steadily moving car or train:



Meaning that we only have to update the subscripts in Model 2's formula,

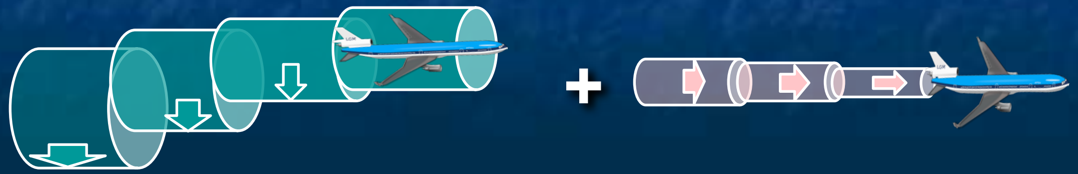
but noting that **dragged** air cylinder is only ~ width of plane's **fuselage** (not wings)

$$\mathbf{Power_{drag} = \tfrac{1}{2}\, \rho_{air}\, c_{drag}\, A_{fuselage}\, v_{plane}^3}$$

Then, adding the (now color coded) LIFT and DRAG power expenditures:

$$Power_{total} = Power_{lift} + Power_{drag}$$

$$= (M_{plane}\, g)^2 / (2\, \rho_{air}\, v_{plane}\, A_{lift}) + \tfrac{1}{2}\, c_{drag}\, \rho_{air}\, A_{fuselage}\, v_{plane}^3$$



Finally, converting energy per time to energy per distance:

Energy / distance = (Energy / time) (time / distance) = Power / velocity =>

$$\text{Energy\_per\_distance}_{flight} = (M_{plane}\, g)^2 / (2\, \rho_{air}\, v_{plane}^2\, A_{lift}) + \tfrac{1}{2}\, c_{drag}\, \rho_{air}\, A_{fuselage}\, v_{plane}^2$$

But to **minimize this,** airplanes try to travel at the most energy conserving speed

At such an optimum speed (from Calculus): $dE_{per\_distance} / dv_{plane} => 0$

Differentiating top equation for $E_{per\_distance}$, then setting result equal to zero:

$$\rho_{air}\, v_{plane\_optimum}^2 = M_{plane}\, g / (c_{drag}\, A_{fuselage}\, A_{lift})^{1/2} \quad \text{OR:}$$

$$v_{plane\_optimum}^2 = M_{plane}\, g / \rho_{air}\, (c_{drag}\, A_{fuselage}\, A_{lift})^{1/2}$$

Unlike both Models 1 & 2, slowing down is NOT better!

Taking optimized $\boldsymbol{\rho_{air}\, v_{plane\_optimum}^2}$ and substituting it into **both** terms of top equation,

after a **whole lot of algebra**, you find that at energy minimizing speed:

$$\textbf{Energy per distance}_{flight\_at\_optimum\_speed} = (c_{drag}\, A_{fuselage} / A_{lift})^{1/2} \times M_{plane}\, g$$

Carefully analyzing that final optimized flight equation:

Energy per distance $_{flight\_at\_optimum\_speed} = (c_{drag} A_{fuselage} / A_{lift})^{1/2} \times M_{plane}\, g$

Airplane's ENERGY EFFICIENCY **is not improved** by:

Making plane bigger or smaller: Changes in A's cancel, negating effect

Changing altitude: Because air density dropped out of energy per distance equation

But to fix $v_{plane\_optimum}^2 = M_{plane}\, g / \rho_{air} (c_{drag} A_{fuselage} A_{lift})^{1/2}$ despite dropping M_{plane}

(due to fuel burn), **planes gradually climb over span of flight (=> smaller ρ_{air})**

Airplane's ENERGY EFFICIENCY **is improved** by:

Decreasing the plane's drag coefficient, i.e. by making plane more "streamlined"

Limited by the need to retain sufficient space for paying passengers & cargo

Making the plane lighter, which can be done in three ways:

By building it with lighter structural materials OR

Hauling less/fewer passengers, cargo, bags OR using lighter fuel

MODEL 4: Steadily Moving Ships?

There are three obvious ways in which moving ships expend energy:

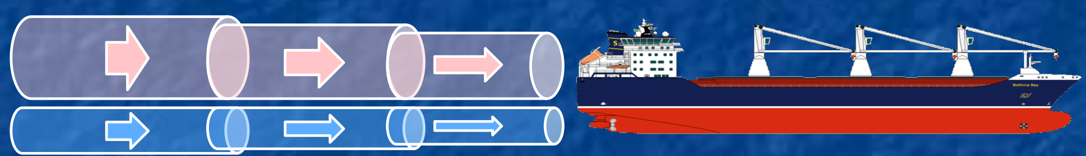
a) Above the waterline, the upper hull/superstructure drags air along behind it

b) Below the waterline, the submerged lower hull drags water along behind it

c) The submerged lower hull also pushes up waves => wake & turbulence

But a & b are just versions of the earlier "Steady Movement" of Model 2,

in which a "fluid" (now **either** air or water) is dragged behind a vehicle



Then, if $c_a A_a$ & $c_b A_b$ are the effective cross-sections above & below the water surface:

$$\text{Energy per distance}_{a+b} = \tfrac{1}{2} \rho_{air} c_a A_a v_{steady}^2 + \tfrac{1}{2} \rho_{water} c_b A_b v_{steady}^2$$

But while those effective cross-sections are similar in size,

the density of water (ρ_{water}) is 1000 times larger than that of air (ρ_{air}),

making the second term (b) hugely greater than the first term (a)

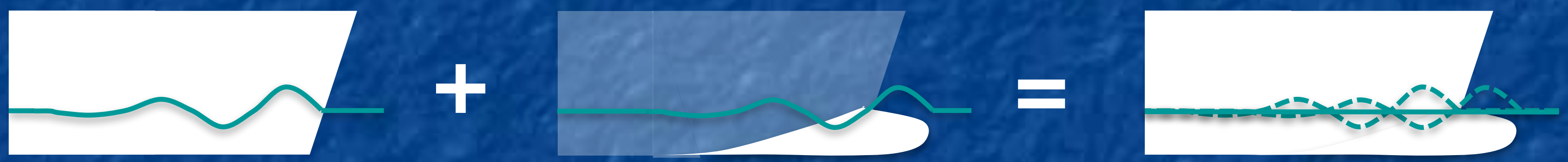
Might we similarly neglect energy lost to the wake (term c)?

Wakes are so complex that I found no mathematical model of their energy

But most large ships DO now have **bulbous bows** intended to **calm** (diminish) wakes

Wakes = Waves kicked up from the leading edge of shapes moving through water:

Wake of conventional bow: Wake of bulbous bow (alone): Wake of their combination:



Waves from the conventional + bulbous bow are offset, tending to cancel one another

But actual cancellation is imperfect & wake amplitudes diminish by perhaps only 1/2

Nevertheless, real-world bulbous bows cut ship propulsion power by ~ 15% [1]

That suggests completely **uncalmed wakes** siphon away about 1/3 of a ship's power

Which means that the wake term (c) is NOT << the dragged water term (b)

So we can't neglect either, and **there is NO simple Model 4 for ships**

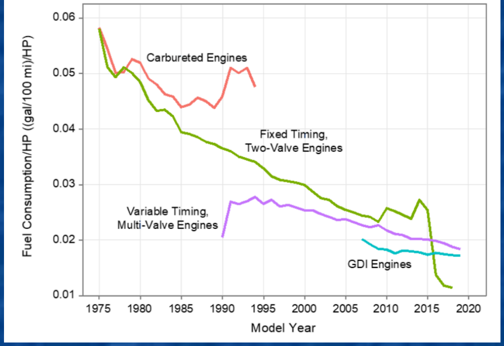
1) A value I found cited on Wikipedia's "Bulbous Bow" webpage, AND on multiple shipping industry webpages

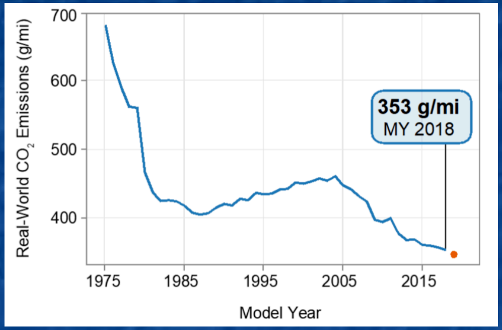
Energy Saving Technologies for Cars & Trucks:

Mitigation of air pollution has already driven car & truck technology for 50+ years

The resulting improvement in **fossil-fueled Internal Combustion Engines (ICE's)**

has been absolutely stunning, as seen in these earlier figures:





But looking forward, the sustained downward slopes seen in such plots,

plus the industry's easy acceptance of almost doubled mileage standards in 2012, [1]

indicate that the list of potential ICE vehicle improvements is far from depleted

To which we can add the potential benefits of a transition to all **electric vehicles**

At least when they are finally "fueled" by non-polluting electric power plants

Plus the benefits of **autonomous vehicles** - such energy-efficient convoying

At least if they don't **also** strongly suppress use of more efficient transport options

1) https://obamawhitehouse.archives.gov/the-press-office/2012/08/28/obama-administration-finalizes-historic-545-MPG-fuel-efficiency-standard

Adequately exploring the resulting options upon options

would have doubled the length of this note set

Which is why that exploration has instead become a separate note set entitled:

***Green(er) Cars & Trucks** (pptx / pdf / key)*

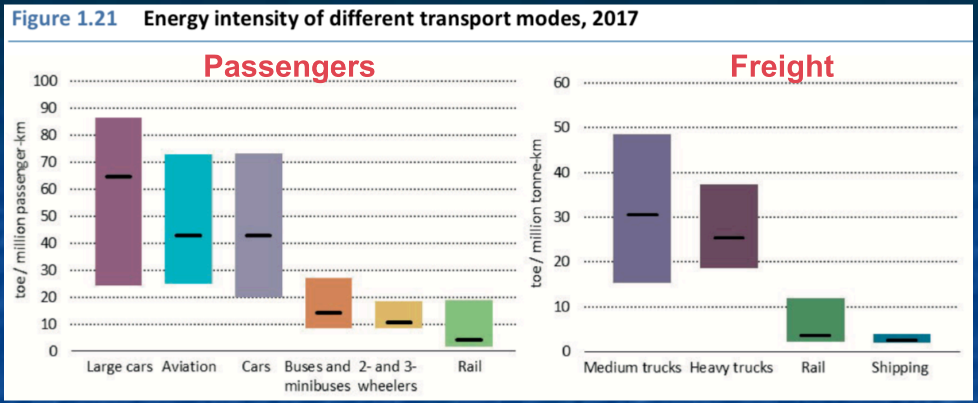
With "Greener" alluding to its discussion of nearer term ICE possibilities
and "Green" to its exploration of longer term electric and/or autonomous car & truck options

So, for now, I'll move on to:

Energy Saving Technologies for Trains:

Trains are already one of our most energy efficient transport options

As seen in this earlier IEA figure:



And according to Rail's science-based model there are few "knobs left to turn:"

$$\textbf{Energy per distance}_{\text{steady}} = \tfrac{1}{2}\, \rho_{air}\, c_{drag}\, A_{vehicle}\, v_{steady}^{2}$$

Decreasing ρ_{air} requires eliminating that air

Which IS the basis of Elon Musk's as yet untested "Hyperloop" proposal [1]

Decreasing c_{drag} requires better streamlining

Which Japan's Shinkansen has already pushed close to its practical limits [2]

Decreasing $A_{vehicle}$ would require smaller passengers or less cargo

While decreasing v_{steady} would undercut high speed rail's fundamental appeal

1) https://en.wikipedia.org/wiki/Hyperloop *2) https://en.wikipedia.org/wiki/Shinkansen*

But back in the non-idealized world:

A 2016 **International Railways Union** report spent almost 200 pages

listing "27 technologies and potential developments in rail systems"

none of which ultimately seemed to offer more than incremental improvement [1]

A 2019 **International Energy Agency** study of rail transport

also failed to identify opportunities for radical technology improvement [2]

Indeed, the common thread to both reports seemed to be that:

Passenger rail's main challenge is wider access to high speed trains

which will require extension of electrified high-speed rail routes

as supported by increased investment, stimulated by public policy

Freight rail's main challenge is competing with end-to-end truck transport

which will require much better integration of rail with short haul trucking

such that distance rail + local truck shipments can be completed more rapidly

1) https://uic.org/IMG/pdf/_27_technologies_and_potential_developments_for_energy_efficiency_and_co2_reductions_in_rail_systems._uic_in_colaboration.pdf

2) https://www.iea.org/reports/the-future-of-rail

Energy Saving Technologies for Planes:

1) A long delayed work in progress: Route Optimization

To minimize energy consumption, a plane should obviously follow the shortest route

Less obviously, it should fly at speed: $v_{plane\_optimum}^2 = M_{plane}\, g \,/\, \rho_{air}\, (c_{drag}\, A_{fuselage}\, A_{lift})^{1/2}$

Which, as the plane burns off fuel (thus loosing mass), says that it should

steadily climb (thereby compensating by rising into lower density air)

But planes can't adhere to such rules - because routes are NOW dictated by: [1, 2]

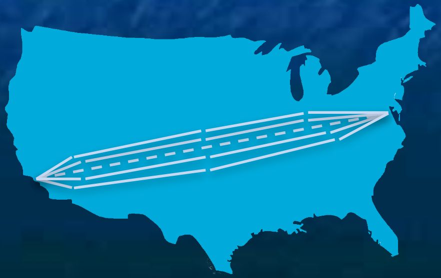
Overworked ground controllers, making decisions based on very limited information,

supplied by 50+ year old ground radar + altitude transponder technologies,

who then call to the planes via similarly antiquated limited-range voice radio

To compensate, controllers now try to maintain safety by **spreading planes far apart:**

Assigning them to different, generally straight, constant altitude, flight segments



1) https://en.wikipedia.org/wiki/Mitigation_of_aviation's_environmental_impact

2) https://en.wikipedia.org/wiki/Air_traffic_control

But technology has not been similarly stagnant ABOVE the ground:

A modern state-of-the-art passenger aircraft will likely have on board:

A plane-to-plane radar-based collision warning & avoidance system

A satellite signal based GPS system continuously calculating the plane's

3D position and speed, and doing so at accuracies **far greater** than ground radar

Global topography databases allowing the GPS to track & warn of ground obstacles

That real-time info is sent via un-congested two-way satellite data links which,

unlike ground control voice radio, maintain contact out over oceans and in bad weather

But this information is now shared with only the plane's operating company!

If a new automated flight routing system could tap into even a fraction of that information

airplanes could be much more closely spaced, and they could follow much more

direct / short routes, at continuously optimized altitude

The obstacle? Decades of failure at implementing a new computer-based control system

that can reliably outperform today's harried human controllers + antiquated technology

2) The ever-expanding use of Lightweight Composites

Which comes right out of our flight model's **other** equation:

$$\text{Energy per distance}_{\text{flight\_at optimum\_speed}} = (c_{drag}\, A_{fuselage} / A_{lift})^{1/2} \times M_{plane}\, g$$

Early planes maintained strength but reduced M_{plane} by substituting aluminum alloys

New planes reduce it by substituting even lighter & stronger **composite materials**

Composite materials consist of criss-crossed mats or stacked layers of parallel fibers

that bend easily but are extremely hard to pull apart (i.e., are very strong in tension)

These are then soaked in a resin that, once it solidifies, resists compression

Working together, this yields exceptionally light but flexible and strong material

- Very early composites (e.g., "Bakelite") used wood fibers
- "Fiberglass" was later strengthened by mats of glass fiber
- And now even stronger composites use carbon fibers:

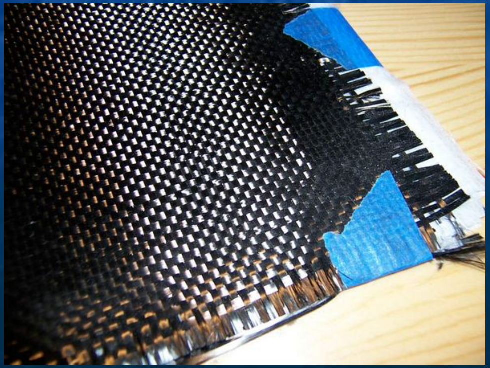
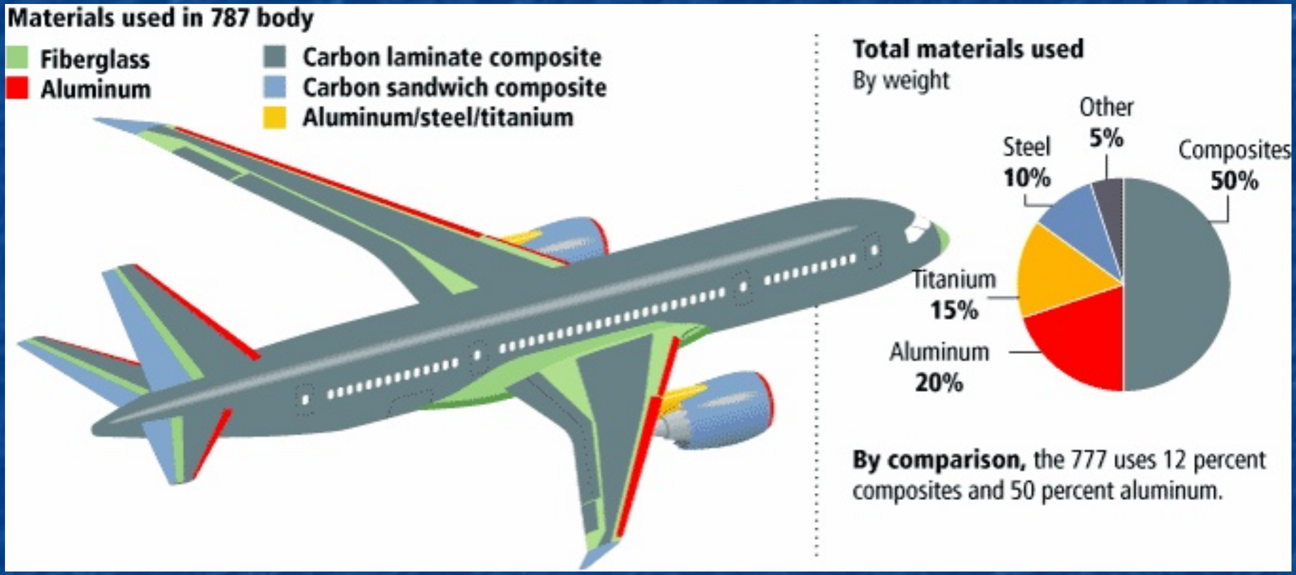


Figure: https://www.appropedia.org/Composites_in_the_Aircraft_Industry

Extent of lightweight composite use? Savings in fuel / CO_2?

In the Boeing 787, indicated green wing areas are made of fiberglass composites while grey wing areas + major body areas are made of carbon fiber composites [1]



It's widely claimed that the resulting **aircraft weight reduction is typically about 20%**, and that **reduction in fuel use, and hence CO_2 emission, is about 10-12%**

The data trail I followed led to those final claims being pulled right out of thin air (!) [2, 3]

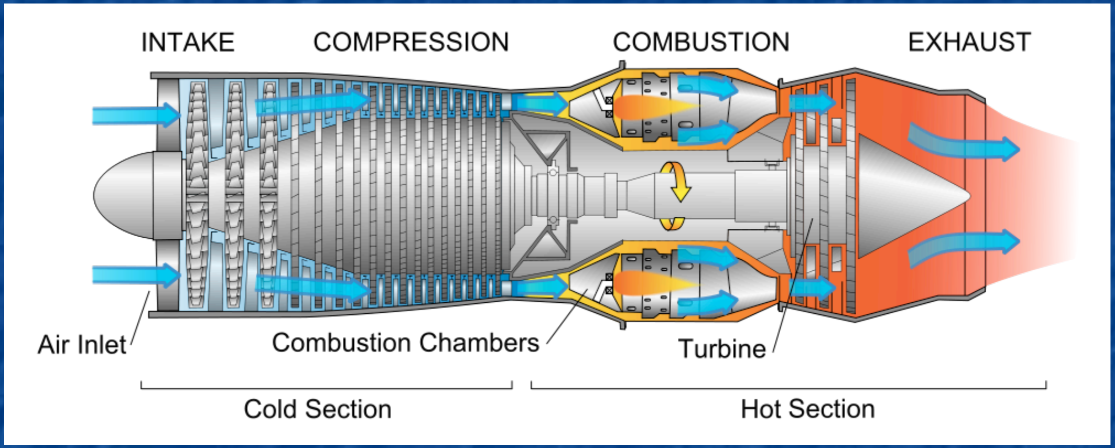
Nevertheless, expanding use of composites in aircraft clearly confirms their value

1) https://www.appropedia.org/Composites_in_the_Aircraft_Industry
2) https://www.sciencedirect.com/science/article/pii/S2212540X18300191
3) https://www.researchgate.net/publication/268814067_Advanced_Lightweight_Aircraft_Design_Configurations_for_Green_Operations

3) More energy efficient **Geared Turbofan Engines**

At the center of a **1950's jet engine**, compressed air entered a combustion chamber
where it was mixed with jet fuel vapor, and the mixture ignited

That now hot & expanding "exhaust gas" then passed thru a series of **turbine blades**,
and then "jetted" out the rear of the engine providing thrust for a Boeing 707 or DC-8



Those turbine blades were attached to shaft thereby spun by the exhaust gas

At the front of that spinning shaft a series of **compressor blades** were also attached,
which compressed thin incoming high-altitude air enough to maintain combustion

1) https://en.wikipedia.org/wiki/Jet_engine

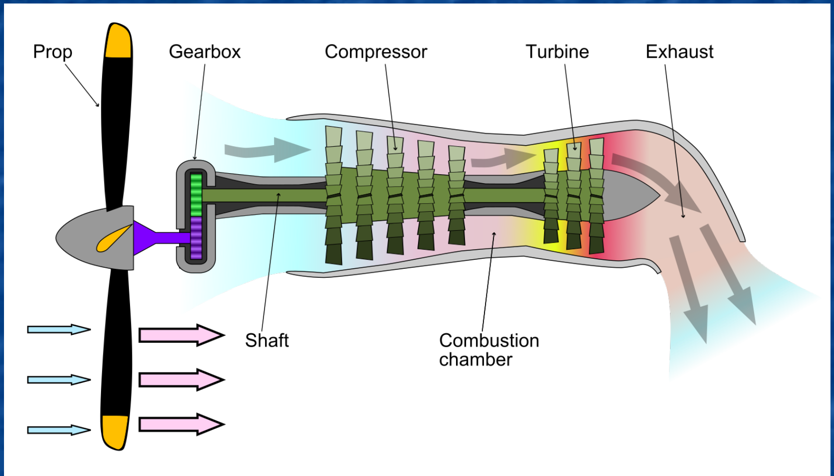
But then someone apparently wondered:

Why not also add a big propeller to the front end of that turbine's shaft?

But large conventional propellers must spin much more slowly than jet turbines

So a speed-reducing gearbox must also be added, which produced the

turboprop engine still powering many/most short-haul commuter aircraft: [1]



TURBINE rotating at: **35,000 RPM**

GEARBOX ratio: **18:1**

together driving

PROPELLER rotating at: **1,900 RPM** [2]

But by the late 1960's, a new smaller and specially designed high-speed "fan" was being attached **directly** to the front of rapidly spinning turbines, producing:

1) https://en.wikipedia.org/wiki/Turboprop 2) https://www.boldmethod.com/learn-to-fly/systems/this-is-how-a-turboprop-engine-works/

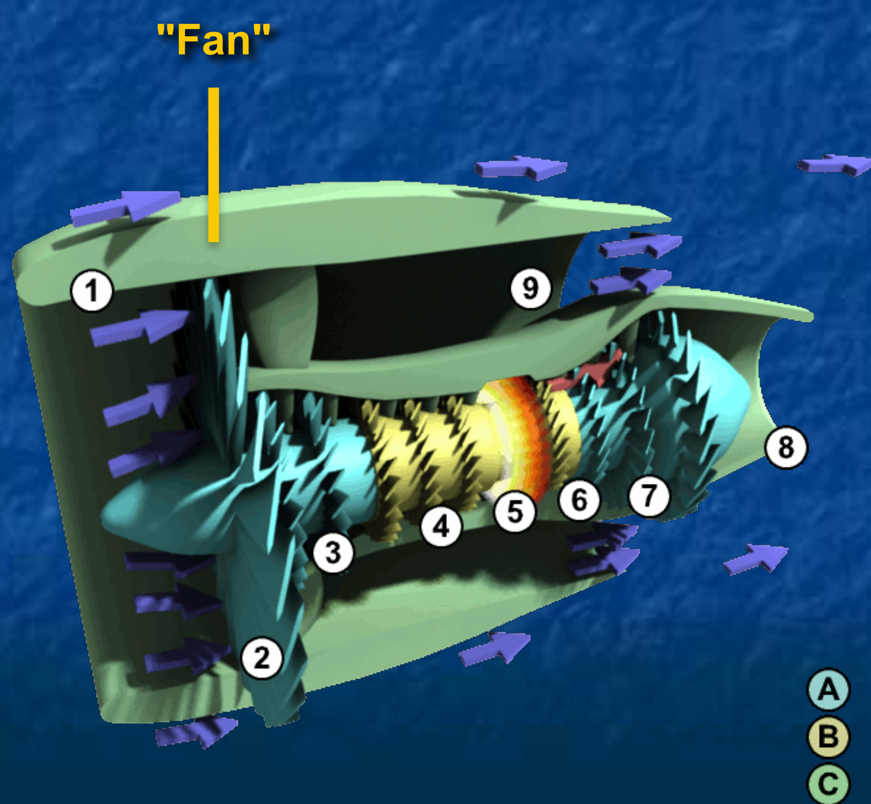
Today's jumbo-jet standard, the ***Turbofan Engine***

The front fan produces a much larger but slower and calmer flow of air

Most of which actually **bypasses** the turbine (passing around and along it)

This greatly enhances overall engine thrust and does so with less noise

(if necessary, **click** on this Wikipedia image to trigger its animation)



1) https://en.wikipedia.org/wiki/Turbofan

But that fan still rotates so fast that its blade tips go supersonic

And their resulting mini sonic booms waste energy because

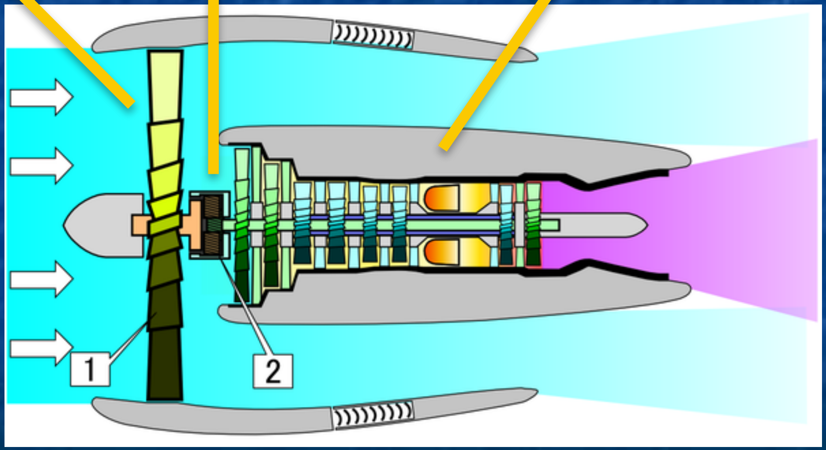
their noise must be muffled by adding layers to the engine's shell (increasing M_{plane})

and their turbulence also degrades the engine's fuel consumption / CO_2 emission

Leading to present day proposals that they be replaced by **Geared Turbofan Engines**

Which actually represent a half step back towards Turboprops:

Fan (non-supersonic) **Inline Gearbox** **Turbine**



GEARED TURBOFAN:

(Pratt & Whitney / United Technologies version) [1]

TURBINE rotating at:	**9,160 RPM**
GEARBOX ratio:	**3:1**
together driving	
FAN rotating at:	**3250 RPM**

VS. earlier turboprop's 35,000 RPM turbine => 18:1 Gearbox => 1900 RPM Propeller

1) https://en.wikipedia.org/wiki/Pratt_&_Whitney_PW1000G

But at 9160 RPM, inside a jet engine, that's got to be one heck of a gearbox!

Which Forbes Magazine thus christened "United Technology's Billion Dollar Bet" [1]

Technical drawing of the entire engine:

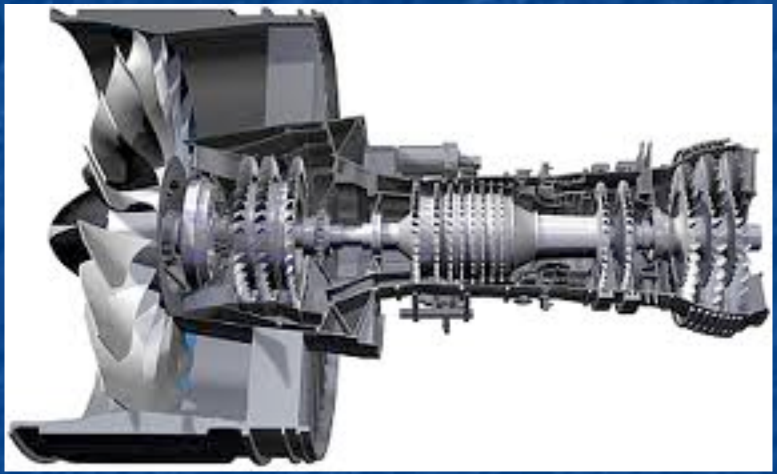


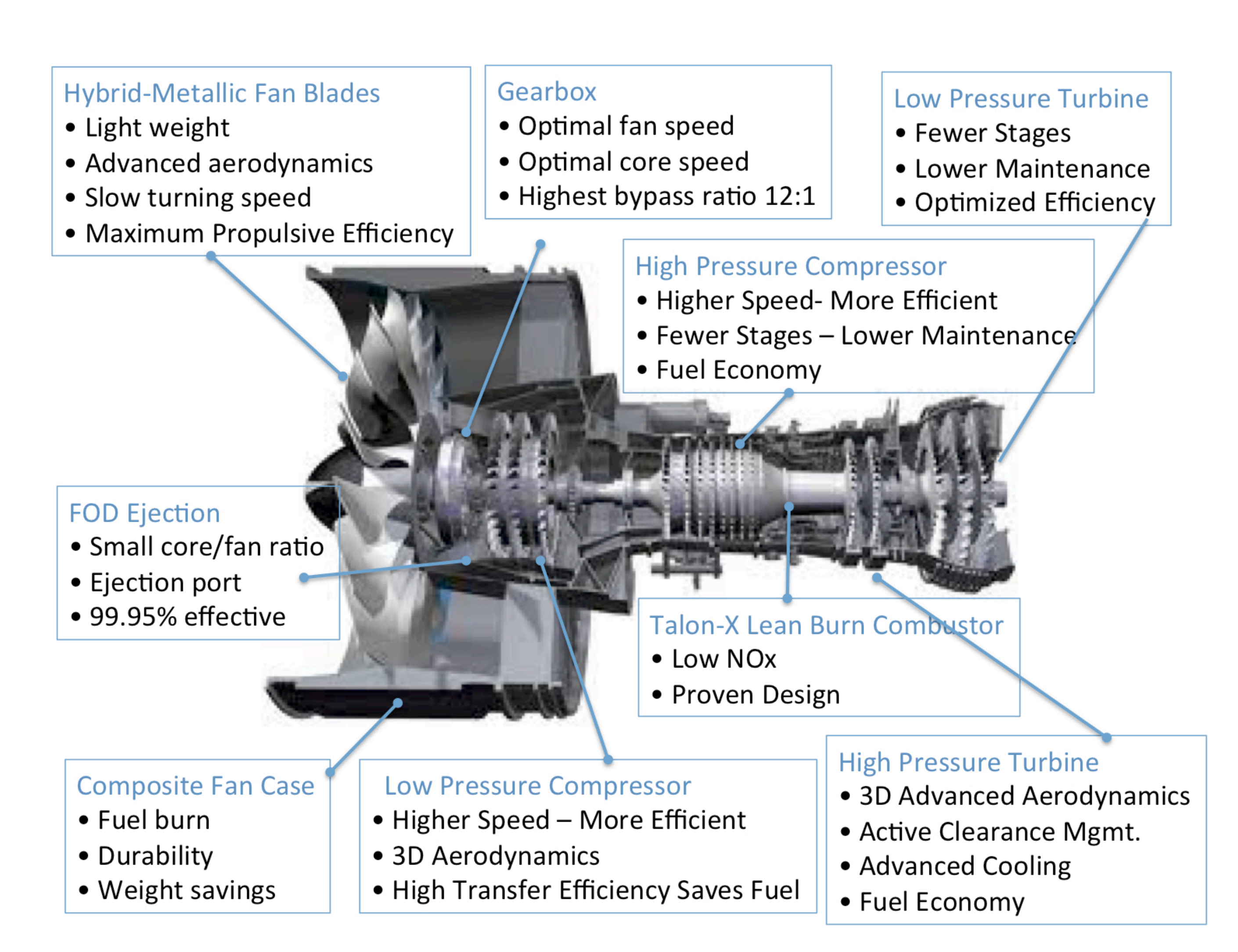
Photo of prototype inline gearbox: [2]

Their Geared Turbofan design goal:

"16% greater fuel efficiency while reducing the noise footprint by up to 75% [3]

1) http://www.forbes.com/sites/danielfisher/2013/01/23/the-billion-dollar-bet-on-jet-tech-thats-making-flying-more-efficient/
2) http://www.airplanegeeks.com/2012/01/24/episode-182-alan-epstein-and-the-geared-turbofan-engine/
3) According to United Technologies full page ads running in the Washington Post, February 2015

Or if you'd like even greater detail: [1]



1) https://aviation.stackexchange.com/questions/11586/what-is-a-high-bypass-geared-turbofan-and-why-is-it-so-much-more-efficient

But recent reports indicate that Geared Turbofans are now on hold

Wikipedia's webpage about Geared Turbofans lists six different industry projects

but closes abruptly by simply declaring that GE has abandoned its project

and that Pratt & Whitney was "postponing its use for a future application" [1]

Another webpage about Pratt & Whitney's geared turbofan says that in 2008

a prototype **was** ground tested and achieved its targeted 16% fuel savings,

and that other prototypes **successfully powered** 747 and A340 test aircraft

But ends with a confusing account of ongoing production & deployment difficulties [2]

A final webpage says Rolls Royce's two geared turbofans will be available only by the

"end of the 2020's" (Advance) or "could be ready for service from 2025" (Ultrafan) [3]

Which is consistent with promotional webpages I found on a Rolls Royce website

referring to "multi-shaft" (gearbox) engines as being only the "Future of Flight" [4, 5]

1) https://en.wikipedia.org/wiki/Geared_turbofan 2) https://en.wikipedia.org/wiki/Pratt_&_Whitney_PW1000G
3) https://en.wikipedia.org/wiki/Rolls-Royce_Trent#UltraFan
4) https://www.rolls-royce.com/media/our-stories/innovation/2016/advance-and-ultrafan.aspx#challenge#challenge
5) https://www.rolls-royce.com/media/our-stories/innovation/2016/advance-and-ultrafan.aspx#solution

Those improvements would be nice, but they're not game changers:

Composites claimed to produce 10-12% reductions in fossil fuel consumption

Geared Turbofans, in early tests, produced 16% reductions

Route Optimization, I'd guess, might someday produce ~ 10% reductions

Together raising the possibility of net ~ 1/3 reduction in aircraft fossil fuel use

Too little? Possibly **Too late? Almost certainly:**

Because the above cited wait for fully realized Geared Turbofans = 5-10 years

And the likely wait for full Route Optimization = Decades

Given that its required computer-controlled Air Traffic Management (ATM) system

has **already fallen multiple decades behind** its development schedule

Suggesting the need for much more timely & radical solutions, such as:

1) https://www.rolls-royce.com/media/our-stories/innovation/2016/advance-and-ultrafan.aspx#application

The Possibility of Electrically Powered Planes:

A major challenge in electrifying EITHER planes or ships

Which can be seen in a table from an earlier set of my web notes

Specifically, a table I compiled for my note set about **Fossil Fuels** (pptx / pdf / key)

in which I compared the energy stored per mass, and per volume

for just about every single energy storage technology

discussed anywhere on this WeCanFigureThisOut website

In addition to specific numbers for each technology,

in yellow highlighted columns and rows,

I compared each technology's energy storage to that of gasoline

Which yielded this rather sobering result:

Energy of various Materials & Storage Technologies: [1]

Increasing Energy per Mass →

Substance		Energy / Mass			Energy / Volume		
	Specifics:	MJ / kg	kW-h / kg	Ratio to Gasoline	MJ / liter	kW-h / liter	Ratio to Gasoline
Hydrogen (H_2) at 20°C	150 Atm. gas *	142	39.4	3.0	1.79	0.495	0.052
	1 Atm. gas				0.0119	0.0033	0.00035
Methane at -162°C	Liquefied	55.5	15.4	1.2	22.2	6.16	0.65
Diesel Fuel	Liquid	48	13.3	1.03	35.8	9.94	1.04
Propane / Butane LPG	Liquid	46.4	12.9	1	26	7.2	0.76
Gasoline	**Liquid**	**46.4**	**12.9**	**1**	**34.2**	**9.5**	**1**
Jet Fuel (Kerosene)	Liquid	42.8	11.9	0.92	37.4	10.4	1.09
Fat	Animal or Vegetable	37	10.3	0.79	34	9.4	0.99
Coal	Anthracite or Bituminous	~ 30	~ 8	0.65	~ 38	~ 11	1.1
Natural Gas at 15°C (70-80% CH_4)	150 Atm. gas *	26.9	7.45	0.58	5.19	1.43	0.15
	1 Atm. gas				0.0344	0.0001	0.0001
Protein		16.8	4.6	0.36			
Carbohydrates	Including Sugars	17	4.7	0.37			
Protein		16.8	4.6	0.36			
Wood		16.2	4.5	0.35	13	3.6	0.38
TNT		4.6		0.1			
Gun Powder		3	1.3	0.06			
Lithium Metal Battery		1.8	0.5	0.04	4.32	1.2	0.13
Lithium Ion Battery		0.36 - 0.875	0.1 - 0.24	0.007 - 0.02	0.9 - 2.63	0.25 - 0.0055	0.02 - 0.07
Flywheel		0.35 - 0.5	0.97 - 0.14	0.007 - 0.01			
Alkaline Battery		0.5	0.14	0.01	1.3	0.36	0.04
Nickel Metal Hydride Battery		0.288	0.08	0.006	0.504 - 1.08	0.14 - 0.3	0.01- 0.03
Lead Acid Battery		0.17	0.047	0.03	0.56	0.15	0.016
Super Capacitor		0.01 - 0.036	0.003 - 0.01	0.0002 - 0.0008	0.05 - 0.06	0.014 - 0.016	0.001 - 0.002
Capacitor		0.00001 - 0.0002	0.000003 - 0.0005	0.0000002 - 0.0000004	0.00001 - 0.001	0.000003 - 0.0003	0.0000003 - 0.00003

** Upper pressure range of common class 1 gas cylinders (capacity: 43-50 liters / weight: 50-85 kg)*

Table source: https://WeCanFigureThisOut.org/ENERGY/Energy_home.htm

1) Drawn from notesets: Fossil Fuels (pptx / pdf / key), Batteries & Fuel Cells (pptx / pdf / key), Hydrogen Economy (pptx / pdf / key)

Approximating those ratios to gasoline, and highlighting battery results:

	Energy / Mass	Energy / Volume
Hydrogen gas at 150 Atm. pressure	3	1/20
Gasoline / Diesel / Jet Fuel	1	1
Fat / Coal	3/4	1
Carbohydrates / Protein / Wood	1/3	1/2
High Explosives	1/12	-
Experimental Lithium Batteries	1/25	1/8
Lithium Batteries	1/75	1/20
Flywheels	1/100	-
Conventional Batteries	1/150	1/50
Super Capacitors	1/2000	1/600
Capacitors	1/200000	1/40000

BIG TAKEAWAY: Fossil Fuels pack 25X to 150X the energy of Batteries!

The impact of heavy batteries on ***Electric Planes:*** [1]

We think of planes expending most of their energy pushing air out of their way

Which suggests that the key to lower energy flight will be streamlining

But from the earlier science-based model of flight (**Model 3**)

Air MUST be ALSO be pushed downward to offset the pull of gravity on the plane

It's just another example of Newton's "Action equals Reaction"

Thus, heavier planes **must** push proportionally more air downward,

requiring proportionally greater expenditure of energy per mile traveled

So if future planes substitute heavy batteries for extraordinarily light fossil fuels,

they're going to use much more energy per distance traveled

But how MUCH more?

1) This discussion of Electric Planes is also part of my note set: ***Batteries and Fuel Cells*** *(pptx / pdf / key)*

To answer that, we need to know more about aircraft weight:

Assume we are talking about medium / large aircraft

carrying passengers and / or cargo,

over distances comparable to medium sized continents or oceans

The forces of physics & economics have driven a convergence of aircraft design

Which is why it's now difficult to tell one transport aircraft from another

A particularly successful / widely used / newer aircraft is Boeing's 777

Wikipedia's webpage on that aircraft included a massive data table

including entries for four different 777 models having different ranges [1]

On the following page I've edited together that table's entries pertaining to weight

For each model I then worked out the percentage of fully loaded aircraft weight

due to the **empty aircraft** itself, it's **fossil fuel**, and it cargo/passenger **load**

1) https://en.wikipedia.org/wiki/Boeing_777

From Wikipedia'a data table on the Boeing 777 [1]

Boeing 777 specifications

Variants	Initial[184]		Long-range[144]	
Model	**777-200/200ER**	**777-300**	**777-300ER**	**777-200LR/777F**
Range[175]	5,240 nmi / 9,700 km[d][171] 200ER: 7,065 nmi / 13,080 km[e]	6,030 nmi / 11,165 km[f][171]	7,370 nmi / 13,649 km[g]	8,555 nmi / 15,843 km[h] 777F: 4,970 nmi / 9,200 km[i]
Max Takeoff Weight	545,000 lb / 247,200 kg 200ER: 656,000 lb / 297,550 kg	660,000 lb / 299,370 kg	775,000 lb / 351,533 kg	766,000 lb / 347,452 kg 777F: 766,800 lb / 347,815 kg
Empty Weight	299,550 lb / 135,850 kg 200ER: 304,500 lb / 138,100 kg	353,800 lb / 160,530 kg	370,000 lb / 167,829 kg	320,000 lb / 145,150 kg 777F: 318,300 lb / 144,379 kg
Fuel capacity	31,000 US gal / 117,340 L / 207,700 lb / 94,240 kg 200ER/300: 45,220 US gal / 171,171 L / 302,270 lb / 137,460 kg		47,890 US gal / 181,283 L / 320,863 lb / 145,538 kg	

Load weight (Passengers + Cargo) = (Max. Takeoff weight) - (Empty weight) - (Max. Fuel weight):

Aircraft Model's Range:	10,000 km	11,000 km	13600 km	16,000 km
Max takeoff Wt (=100%):	247200 kg	299370 kg	351533 kg	347452 kg
Aircraft Empty Wt:	135850 kg **~ 55%**	160530 kg **~ 54%**	167829 kg **~ 48%**	145150 kg **~ 42%**
Max Full Fuel Load Wt:	94240 kg **~ 38%**	94240 kg **~ 32%**	145538 kg **~ 41%**	145538 kg **~ 42%**
→ Passenger + Cargo Wt =	17110 kg **~ 7%**	44600 kg **~15%**	38166 kg **~ 11%**	56764 kg **~ 16%**

Leading to the conclusion that **for a typical, fully loaded, trans-continental or oceanic flight:**

Load Weight is approximately ~ 3/4 Fuel versus 1/4 (Passengers + Cargo)

1) With two expanded acronyms, excerpted from main table at: https://en.wikipedia.org/wiki/Boeing_777

Consequences of those huge fuel loads:

Say typical super-sized passenger + carry-ons + checked luggage → 115 kg (250 lbs)

Requiring addition of ~ 3 x 115 kg = ~ 350 **kg** of fuel, which is mostly C (mass 12)

Which is then burned into ~ 350 kg x (44 / 12) = 1.3 tonnes of CO_2 (mass 44)

1 roundtrip long flight thus adds 2-3 tonnes to your personal carbon footprint [1]

Also based on load weight now being ~ 3/4 Fuel + 1/4 (Passengers + Cargo):

If aircraft replaced fossil fuel with batteries storing equivalent energy, but weighing just 1.33 times more, it could carry zero passengers on that long flight

But BEST of today's batteries weight / energy is ~ 25 times more than fossil-fuels

Meaning that to fly today's passenger + cargo loads, energy carried would be slashed by 25X, reducing aircraft's range down from 10,000-15,000 kilometers to a mere 400-600 kilometers

*1) For more about personal carbon footprints, see my note set entitled **Where Do We Go From Here?** (pptx / pdf / key)*

As "sanity check" I dug up articles with widely varying viewpoints & target audiences

Links to those articles, as well as cached copies

are provided on the Resource Webpage for this note set

In chronological order, the article titles and sources were:

Electric Aircraft - The Future of Aviation or Wishful Thinking? Phys Org, Aug 2015

The Age of Electric Aviation Is Just 30 Years Away, Wired, May 2017

Electric Flight is Coming, but the Batteries Aren't Ready, The Verge, Aug 2017

Preparing for Electric Flight, Royal Aeronautical Society, Aug 2017

The Long Road to an Electric Airplane Motor, ZDNet, Sept 2018

Short Hops, Clear Air and the Sweet Spot for Electric Aircraft, NewAtlas 2019

In that order, they stated or implied that today's batteries are overweight by a factor of:

43X, 50X, 43X, (?), 14X, 40-48X

Which, sadly, is entirely consistent with my above analysis

No article predicted near / mid term battery-powered air transports

The most enthusiastic articles instead dwelt on possible opportunities for

small short-hop aircraft and / or

immensely less cost-constrained corporate executive jets

With commercial passenger / cargo aircraft predicted to be ~ 30-50 years in the future,

based on their need for revolutionary & thus unpredictable battery breakthroughs

In fact, as described in my note set: **Biomass and Biofuels** (pptx / pdf / key):

A much more plausible near term path to green aviation

is the development of affordable biofuels

which, while their burning still releases greenhouse gases,

are net carbon neutral over their entire lifecycle [1]

1) https://www.greenbiz.com/article/heres-what-it-will-take-get-aviation-biofuels-ground

BREAKING NEWS:

World's Largest All-Electric Aircraft Ready for First Flight
The Guardian, 27 May 2020 [1]

"Can carry nine passengers . . . range of 100 miles"

Its commercial application is likely feeding rural passengers into main hub airports

But passengers within ~ 50 miles may just drive into the hub airport

Plane's success thus likely depends on transporting passengers from ~50-200 miles out

But to allow for air traffic delays & weather diversions, international regulations

require that aircraft be able to stay airborne for at least an extra 30-45 minutes [2]

To maintain such a reserve, **this plane** might be limited to routes **well under** 100 miles

Commercial viability thus likely requires at least doubling its range (**&** passenger load)

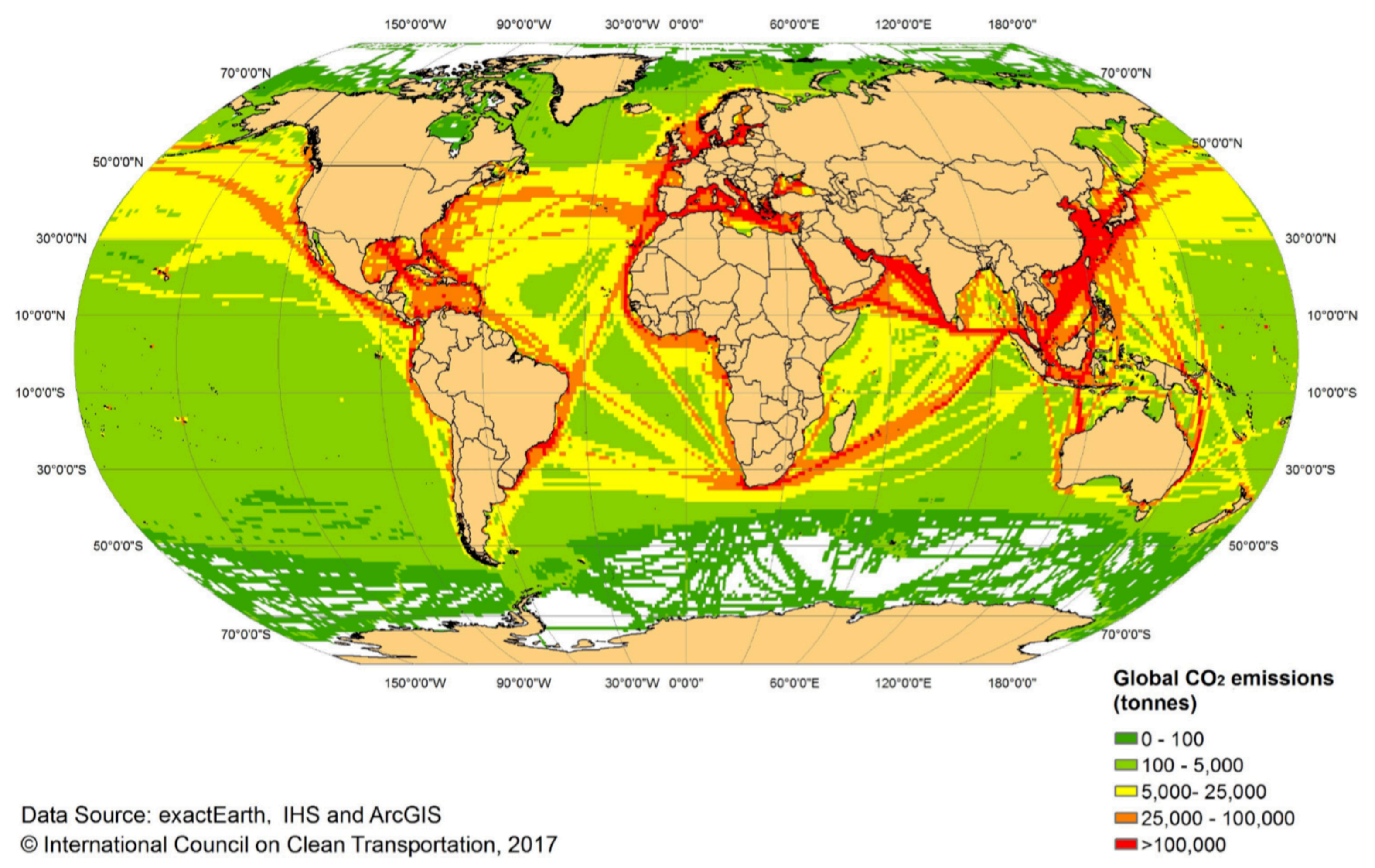
1) https://www.theguardian.com/world/2020/may/27/worlds-largest-all-electric-aircraft-set-for-first-flight?CMP=Share_iOSApp_Other
2) https://aviation.stackexchange.com/questions/3740/what-are-the-icao-fuel-reserve-requirements

Energy Saving Technologies for Ships:

Global CO_2 emissions from the ships facilitating international trade:

From the International Council on Clean Transport (ICCT)'s

"Greenhouse Gas Emissions from Global Shipping 2013-2015:" [1]



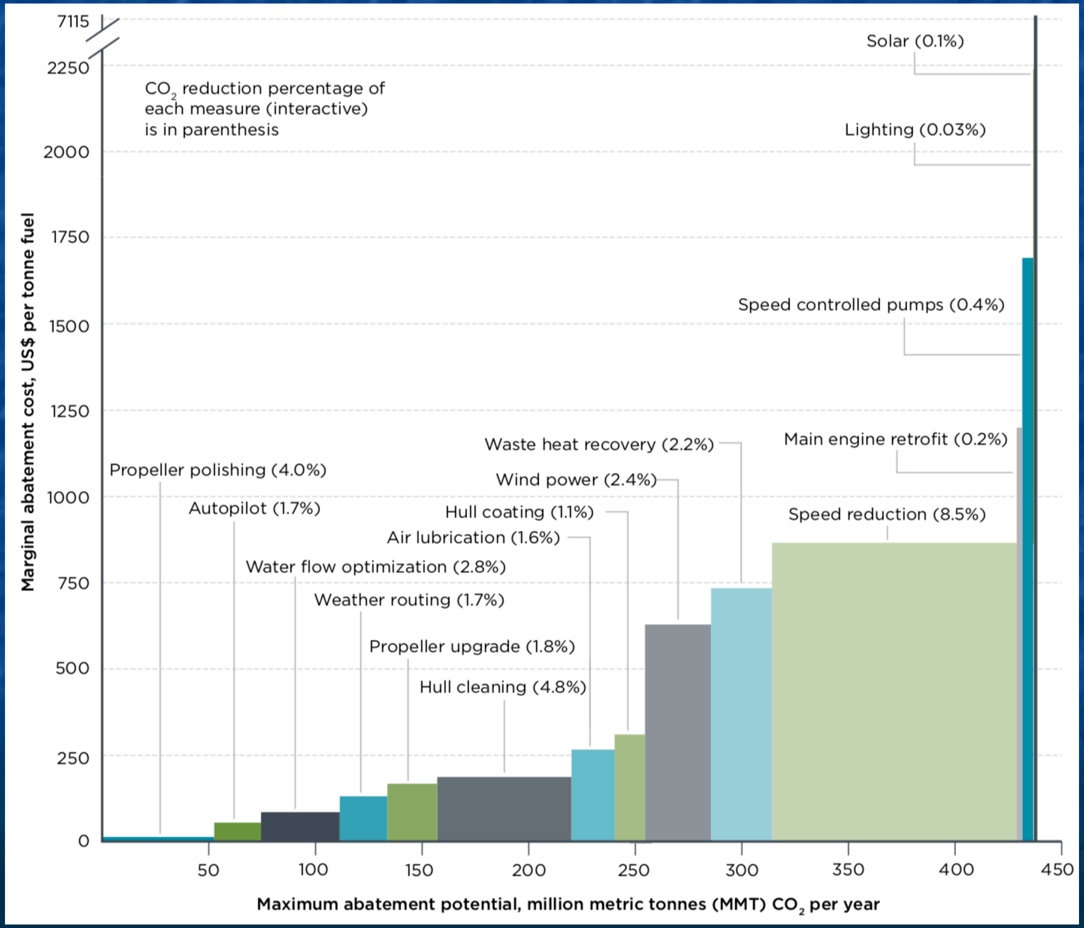
1) Page 13 in: https://theicct.org/publications/GHG-emissions-global-shipping-2013-2015

Effectiveness & cost of shipping's CO_2 abatement options:

From the International Council on Clean Transportation (ICCT)'s 2011 report:

"Reducing the Greenhouse Gas Emissions from Ships - Cost Effectiveness of Available Options" [1]

CO_2 Emission Abatement Potential & Cost of Fuel Saving:



CO_2 Reduction Percentage:

Speed Reduction	8.5%
Hull Cleaning	4.8%
Propeller Polishing	4%
Water Flow Optimization	2.8%
Wind Power	2.4%
Waste Heat Reduction	2.2%
Propeller upgrade	1.8%
Weather Routing	1.7%
Air Lubrication	1.6%
Autopilot	1.7%
Hull Coating	1.1%
Speed Controlled Pumps	0.4%
Engine Retrofit:	0.2%
Solar Power	0.1%
Lighting	0.03%

1) Page 10 : https://theicct.org/sites/default/files/publications/ICCT_GHGfromships_jun2011.pdf

Some quick observations about some of those rank-ordered options:

Speed Reduction: Comes from earlier discussion about drag's role in ship energy loss:

$$\text{Energy per distance water drag} = \tfrac{1}{2}\, \rho_{water}\, c_b\, A_b\, v_{steady}^2$$

Thus ship moving at **1/2** the speed puts **1/4** the energy into dragging along water

Hull Cleaning: Partly what it sounds like: Scrapping off drag inducing barnacles . . .

But also about possibility of special paints inhibiting **initial attachment** of barnacles . . .

Wind Power: Only a possible SUPPLEMENT to main fossil-fuel engines that requires

SIGNIFICANT additional equipment producing only MINOR added propulsive power

Air Lubrication: Air jets creating foamy water layer against hull => Viscosity / drag reduction

Solar Power: Only a possible SUPPLEMENT to main fossil-fuel engines that requires

MAJOR additional equipment producing only MINUSCULE added propulsive power

These follow from papers linked to this note set's Resources Webpage, including:

Study on Energy Efficiency Technologies for Ships
Basic Principles of Ship Propulsion
How to Design a More Efficient Ship (Parts I & II)
Ship Energy Efficiency Measures - Status and Guidance
Reducing Fuel Consumption In Shipping Via Propulsion Efficiency

Versus the OECD's suggestions about decarbonizing the seas:

From "Decarbonizing Marine Transport - Pathways to Zero Carbon Shipping by 2035" [1]

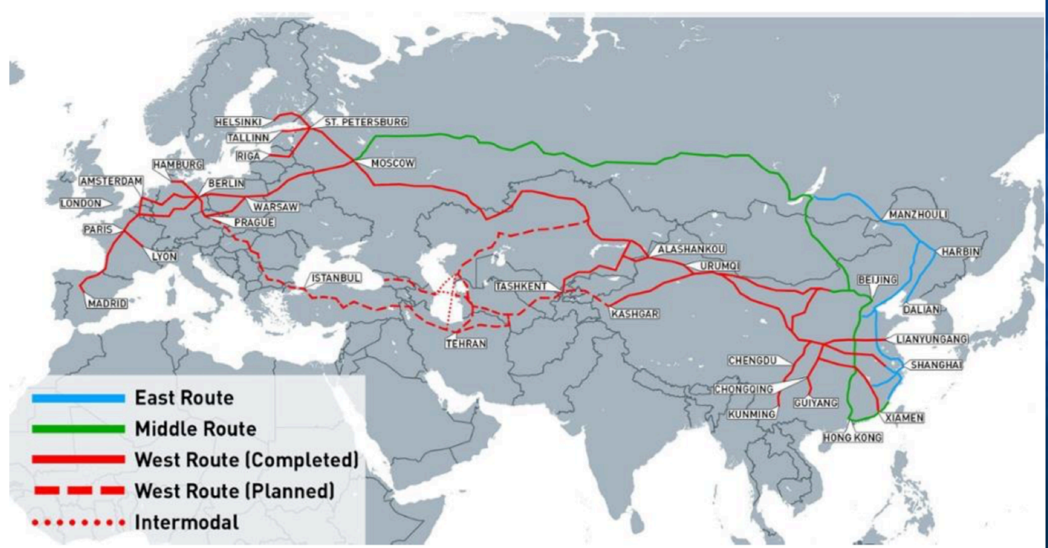
First, where possible, **move freight transport off the seas and onto clean trains**:

"(Rail is) attractive for highly time-sensitive goods, such as fashion, electronics, car parts and perishable goods, such as food.

Compared to air transport, rail transport has a cost advantage (2 times cheaper) with longer transport time (6 times longer)

Compared to sea transport, it has a time advantage (1.7 times quicker) with higher transportation costs (5 times more expensive).

Figure 7. **Existing and planned Trans-Eurasian railways connecting China and Europe**



1) Pages 22-23 in: https://www.itf-oecd.org/decarbonising-maritime-transport

And for the ships that remain, the OECD suggests: [1]

Change ship DESIGN:

Measures	Potential fuel savings
Light materials	0-10%
Slender design	10-15%
Propulsion improvement devices	1-25%
Bulbous bow	2-7%
Air lubrication and hull surface	2-9%
Heat recovery	0-4%

Change ship OPERATION:

Measures	CO_2 emissions reduction potential
Speed	0-60%
Ship size	0-30%
Ship-port interface	1%
Onshore power	0-3%

Change ship POWER SOURCE:

Measures	CO_2 emission reductions
Advanced biofuels	25-100%
LNG	0-20%
Hydrogen	0-100%
Ammonia	0-100%
Fuel cells	2-20%
Electricity	0-100%
Wind	1-32%
Solar	0-12%
Nuclear	0-100%

1) Pages 26, 28 and 32 in: https://www.itf-oecd.org/decarbonising-maritime-transport

The OECD & ICCT pretty much agree on ship design & operational changes

But the OECD introduces the possibility of completely new ship fuels:

Measures	CO_2 emission reductions
Advanced biofuels	25-100%
LNG	0-20%
Hydrogen	0-100%
Ammonia	0-100%
Fuel cells	2-20%
Electricity	0-100%
Wind	1-32%
Solar	0-12%
Nuclear	0-100%

The fuels with maximum GHG reduction / minimum controversy or downside risk are:

Biofuels, Hydrogen, Ammonia, and Electricity

Biofuels are discussed in my note set: **Biomass and Biofuels** (pptx / pdf / key)

Hydrogen fuel is covered in my note set: **A Hydrogen Economy?** (pptx / pdf / key)

So here I'd like to instead explore the remaining options of:

Electric Powered Ships [1]

Ammonia Powered Ships

1) This discussion of Electric Ships is also part of my note set: ***Batteries and Fuel Cells*** *(pptx / pdf / key)*

The Possibility of Electrically Powered Ships:

What do these large modern ships have in common?

Having crammed on top ever more stateroom decks or layers of cargo containers:

These ships are incredibly top heavy, and to prevent capsizing

they NEED low offsetting weight

Below their waterlines, beneath that income-producing upper deck space:

Batteries might supply that weight while powering such ships

But in contrast to aircraft, **you wouldn't need light batteries**, such as Li-Ion's

You'd instead want normal or even exceptionally heavy batteries

But below those waterlines, is there enough space for enough batteries?

Left: https://www.limos4.com/blog/european-cruising-largest-cruise-ships-in-2016
Right: http://www.shipspotting.com/gallery/photo.php?lid=2536561

To answer that question, we need to figure out two things:

The typical below waterline volume of such modern megaships

The energy needed to power such ships through the long legs of their voyage

Despite ship diversity, below waterline volume is often limited by a single consideration:

Retaining the option of someday using the **Panama Canal**

Figures and data from) https://en.wikipedia.org/wiki/Panamax

The Canal's older locks accommodate hulls with length x width x draft of:

290m x 32m x 12m which defines the so-called **Panamax** class of ship

The Canal's new (2016) locks accommodate hulls with length x width x draft of:

366m x 51m x 15m, which is called the **New Panamax or Neopanamax** class [1]

Crudely approximating those below deck spaces as simple rectangular boxes:

Panamax => 111,360 m^3 **Neopanamax => 279,990 m^3**

Next: Energy to move such a ship from China to the U.S. or Europe?

I found two sources giving the peak power of megaship diesel engines:

An exceptionally large 2004 engine produced up to 110 khp => 86 MW [1]

A broad 2007 study cited container ship engine powers of 22 - 54 MW [2]

Container and cruise ships have since grown very significantly in size,

but during most of their voyage engines may operate at more like 50% power,

so let's estimate a new ship's trip-average power as **~ 50 MW = 50,000 kW**

Which must then be multiplied by the duration of the trip:

Sources give trip length China to US as 20-35 days vs. ~ 30 days to Europe [3, 4]

Using 30 days, energy required = 50,000 kW x 30 x 24 hours = **36,000,000 kW-hr**

From the Energy Storage Cross Comparison table shown a dozen or so slides above:

Today's BEST experimental batteries store ~ 0.5 kW-h / kg or ~1.2 kW-h / liter

1) https://newatlas.com/most-powerful-diesel-engine-in-the-world/3263/

2) http://www.dieselduck.info/machine/01%20prime%20movers/2007%20Wartsila%20engines%20for%20panamax%20containerships.pdf

3) https://www.chinaimportal.com/blog/how-long-does-it-take-to-ship-from-china/

4) https://www.theodmgroup.com/calculating-container-shipping-time/

From those data, to provide voyage-long power:

Such a ship would have to carry: **72,000 tonnes of batteries**

Which would occupy: **30,000 cubic meters**

But you would also need massive shelves on which to secure those batteries

Plus intervening passages and / or overhead space to accommodate

servicing, cooling, and wiring between those batteries

Suggesting that overall battery space might be more like **60,000 cubic meters**

But looking back at our estimated below-waterline hull volumes:

Panamax: 111,360 m^3 **Neopanamax => 279,990 m^3**

So this scheme **could work in a Panamax ship, and work easily in a Neopanamax ship**

especially as electric motors are much more compact than diesel engines

and should thus fit easily in the remaining below-waterline space

Unlike battery-powered long-distance flight (calculated to now be wildly impractical),

battery-powered long-distance shipping survives back-of-the-envelope analysis

Then what's holding up electric shipping?

The most likely answer is, of course, economics

Bloomberg New Energy Finance put 2018 Li-Ion battery cost at $175 / kW-h [1]

So our hypothetical megaship, requiring a voyage long **36,000,000 kW-hr,**

might need as much as **6.3 billion dollars in batteries**

(Which might need replacement every 5, 10, 15 years?)

For today's fossil-fueled megaships I found sources giving total construction costs of:

- **105 million dollars** for a 12,000 container-capacity container ship [2]

  (today's container ships range up to 23,000 containers)

- Up to **1.5 billion dollars** for cruise ships (e.g., Royal Caribbean's Allure of the Seas) [3]

So it sounds like cost is indeed the problem:

Battery-powered container ships could cost as much as ~ 60X more to build

Battery-powered cruise ships could cost as much as ~ 5X more to build

1) https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/ *2) https://en.wikipedia.org/wiki/Container_ship*
3) https://www.cheatsheet.com/culture/how-much-do-cruise-ships-cost.html/

Which explains why:

The claimed "World's Largest All Electric Cargo Ship" is this: [1]

Instead of carrying **12-20,000 containers, over 30 days, at 16-25 knots** (18-29 mph) [2]

this ship, launched by China in 2017, will carry "2,200 tons of cargo"

for a total of "**50 miles** at a top speed of **8 miles per hour**"

before needing a two hour battery recharge [2]

From the photo, assuming the total container stack is 4 high x 4 wide x pictured 6 long,

this ship's full container load looks to be no more than **100 containers**

1) https://oilprice.com/Alternative-Energy/Renewable-Energy/China-Launches-Worlds-First-All-Electric-Cargo-Ship.html
2) https://en.wikipedia.org/wiki/Container_ship

I can think of an additional BIG challenge for battery powered ships:

Economics compels captains to absolutely minimize unproductive time in port

Container ships now unload, reload, and leave port within 24-48 hours

My postulated mega container ship needed **36,000,000 kW-hr** of battery capacity

Which, in port, it would want to recharge within that same 24-48 hours

Assuming that its batteries could cope with such rapid recharging,

it would require incoming electrical power of 36000 MW-hr / (24-48 hr)

= **750 - 1500 MW**

If that harbor served just ten such docked and recharging ships at any point in time:

The total necessary harbor electrical power would be 7.5 - 15 GW,

REQUIRING AT LEAST 5 TWO-REACTOR NUCLEAR POWER PLANTS

(or a larger, to hugely larger, number of non-nuclear plants)

Why not just add solar roofs to the top layer of containers?

They could then power the ship & charge batteries during day, with that smaller number of batteries continuing to power the ship overnight

Calculating deck sizes:

Panamax: 290m x 32m = 9280 m^2

Neopanamax: 366m x 51m = 18,666 m^2

Drawing on calculations given in my note set: **Today's Solar Cells** (pptx / pdf / key):

Averaged around the clock, for 20% efficient Si PV-solar cells, in different weather:

Output Power = 25 - 50 Watts / m^2 = 0.025 - 0.05 kW / m^2

A full deck or container top solar array would thus produce average output power of:

Panamax: 9280 m^2 x (25-50 W/m^2) = **232 - 464 kW**

Neopanamax: 18,666 m^2 x (25-50 W/m^2) = **464 - 933 kW**

Comparing that to power now used moving such ships (estimated earlier at **50,000 kW),**

SOLAR PV + BATTERIES => LESS THAN 1/50th POWER NEEDED FOR SHIPPING

Figure: https://www.industryabout.com/industrial-news/801-news-transportation/48073-historic-un-deal-for-shipping-industry-could-lead-to-solar-powered-ships

The Possibility of Ammonia Powered Ships:

Figure from: "Safe and effective application of ammonia as a marine fuel" Niels de Vries - Thesis - University of Delft - 2019.pdf
https://repository.tudelft.nl/islandora/object/uuid:be8cbe0a-28ec-4bd9-8ad0-648de04649b8?collection=education

Why even consider smelly & irritating Ammonia as a shipping fuel?

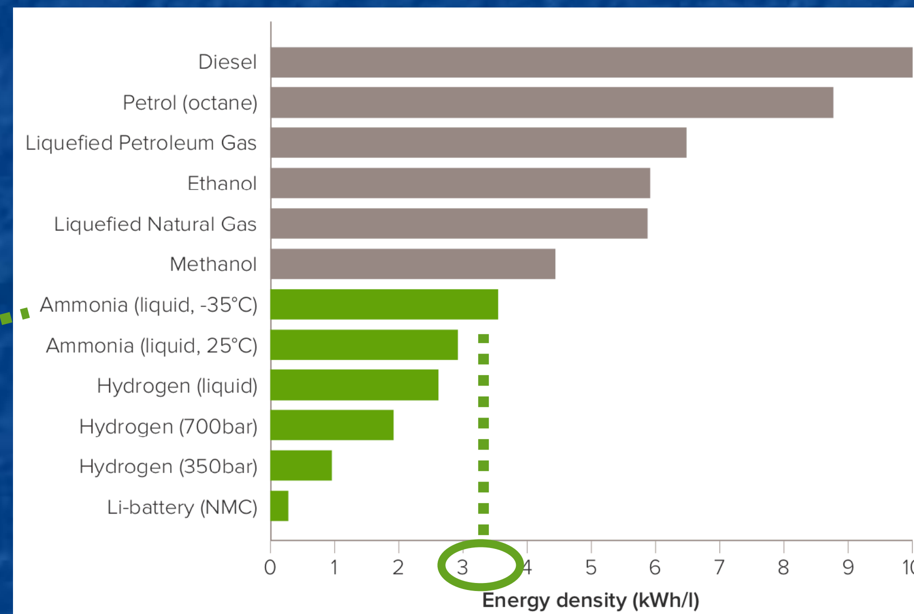
It goes right back to my earlier table about Energy Storage Densities:

Liquid Ammonia has an **energy density ~ 1/3 that of fossil fuels,**

allowing ships to carry **enough of it** to complete full transoceanic voyages

Substance		Energy / Mass			Energy / Volume		
	Specifics:	MJ / kg	kW-h / kg	Ratio to Gasoline	MJ / liter	kW-h / liter	Ratio to Gasoline
Hydrogen (H_2) at 20°C	150 Atm. gas *	142	39.4	3.0	1.79	0.495	0.052
	1 Atm. gas				0.0119	0.0033	0.00035
Methane at -162°C	Liquefied	55.5	15.4	1.2	22.2	6.16	0.65
Diesel Fuel	Liquid	48	13.3	1.03	35.8	9.94	1.04
Propane / Butane LPG	Liquid	46.4	12.9	1	26	7.2	0.76
Gasoline	**Liquid**	**46.4**	**12.9**	**1**	**34.2**	**9.5**	**1**
Jet Fuel (Kerosene)	Liquid	42.8	11.9	0.92	37.4	10.4	1.09
Fat	Animal or Vegetable	37	10.3	0.79	34	9.4	0.99
Coal	Anthracite or Bituminous	~ 30	~ 8	0.65	~ 38	~ 11	1.1
Natural Gas at 15°C (70-80% CH_4)	150 Atm. gas *	26.9	7.45	0.58	5.19	1.43	0.15
	1 Atm. gas				0.0344	0.0001	0.0001
Protein		16.8	4.6	0.36			
Carbohydrates	Including Sugars	17	4.7	0.37			
Protein		16.8	4.6	0.36			
Wood		16.2	4.5	0.35	13	3.6	0.38
TNT		4.6		0.1			
Gun Powder		3	1.3	0.06			
Lithium Metal Battery		1.8	0.5	0.04	4.32	1.2	0.13
Lithium Ion Battery		0.36 - 0.875	0.1 - 0.24	0.007 - 0.02	0.9 - 2.63	0.25 - 0.0055	0.02 - 0.07
Flywheel		0.35 - 0.5	0.97 - 0.14	0.007 - 0.01			
Alkaline Battery		0.5	0.14	0.01	1.3	0.36	0.04
Nickel Metal Hydride Battery		0.288	0.08	0.006	0.504 - 1.08	0.14 - 0.3	0.01- 0.03
Lead Acid Battery		0.17	0.047	0.03	0.56	0.15	0.016
Super Capacitor		0.01 - 0.036	0.003 - 0.01	0.0002 - 0.0008	0.05 - 0.06	0.014 - 0.016	0.001 - 0.002
Capacitor		0.00001 - 0.0002	0.000003 - 0.0005	0.0000002 - 0.0000004	0.00001 - 0.001	0.000003 - 0.0003	0.0000003 - 0.00003

** Upper pressure range of common class 1 gas cylinders (capacity: 43-50 liters / weight: 50-85 kg)*   *Table source: https://WeCanFigureThisOut.org/ENERGY/Energy_home.htm*



NOTE HOWEVER (per my earlier "Model 3" / aircraft weight discussion):

Ammonia's tripled weight alone would prevent an **airplane** from ever taking off,

made even worse by Ammonia's need for more complex / heavier fuel tanks:

1) Figure at right from page 7 in: https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/

*Hydrogen's energy density numbers are **almost** as good*

And it is neither irritating (in low concentrations) nor toxic (in higher concentrations)

But this is where consideration of pressure & fuel tanks comes strongly into play: [1, 2]

Hydrogen boils at minus 253.9 ºC = **Hugely** below room temperature

Thus, to concentrate it up to the energy densities cited in those charts

it must be pressurized at up to ~ **700 atmospheres**

That intense pressurization requires use of high-energy-consumption compressors,

And once pressurized, H_2 must be it held within either massive heavy-walled tanks

OR by diffusing it into exotic (and hence expensive) H_2 absorbing materials

In comparison, pure **Ammonia boils at minus 33.3 ºC** and thus at room temperature

it liquifies at only ~ **9 atmospheres** [1] requiring fairly simple compressors & tanks

Ones comparable to those used in our homes by carpenters and DIY'ers

Further, if tanks are cooled toward -33.3 ºC, pressures fall toward 1 atmosphere

Addition of refrigeration thereby facilitates use of even more lightly built tanks

1) https://www.engineeringtoolbox.com/ammonia-pressure-temperature-d_361.html   2) https://www.mdpi.com/2077-1312/8/3/183/htm

Generating Ammonia - Today's Process:

1) Nitrogen gas is separated from air via either: [1]

Refrigeration to condense N_2 into a separable liquid at 77.4 ºK (-350 ºC) OR

Repeated pressurization to condense molecular N_2 layers onto zeolite surfaces

2) Hydrogen gas is produced from methane (natural gas) via steam reforming: [2]

$CH_4 + H_2O$ (steam) => $CO + 3\ H_2$ $\Delta H = -206$ kJ / mole

$CO + H_2O$ (steam) => $CO_2 + H_2$ $\Delta H = -41$ kJ / mole

Combined: **$CH_4 + 2\ H_2O$ (steam) => $CO_2 + 4H_2$** $\Delta H = -247$ kJ / mole

3) N_2 and H_2 are then combined via the Haber-Bosch Process to form Ammonia: [3]

At ~ 100 atmospheres pressure and 400-500ºC, in the presence of metal catalyst:

$N_2 + 3\ H_2$ => $2\ NH_3$ $\Delta H = -91.8$ kJ / mole

But a single pass converts only about 15% of the reactants, so the process is repeated over and over until ~ 97% reactant conversion is achieved

1) https://en.wikipedia.org/wiki/Air_separation 2) https://en.wikipedia.org/wiki/Steam_reforming 3) https://en.wikipedia.org/wiki/Haber_process

The very serious shortcomings of today's process:

Both methods of separating N_2 from air consume energy to provide

either the extremely cold temperatures or repeated pressurization cycles required

H_2 liberation via methane steam reforming requires

major heat **energy input** of which only 65-75% goes into bond breaking & making [1]

Further, the central chemical reaction liberates the **greenhouse gas CO_2**

Haber synthesis of NH_3 involves repeated cycles of high pressure & temperature

Both require massive direct and indirect **energy inputs**

of which only 60% goes into bond breaking & making [2]

Putting all of that together, it is estimated that: [2]

"Ammonia production (alone!) consumes about 2% of the world's energy and generates 1% of its CO_2"

1) https://en.wikipedia.org/wiki/Steam_reforming
2) https://www.sciencemag.org/news/2018/07/ammonia-renewable-fuel-made-sun-air-and-water-could-power-globe-without-carbon

*But low-GHG Ammonia will require **much more** low-GHG electrical energy:*

The **N_2 separation step** requires electrically-driven refrigerators or pumps

Which, to be low-GHG, would have to be powered by low-GHG grid electricity

The existing **H_2 generation step** must be eliminated (based on its CO_2 emission)

And, as detailed below, alternate sources of H_2 require low-GHG grid electricity

The **Haber synthesis step** requires pressurization via electrically driven pumps,

and heat from fossil-fuel heaters that would have be supplanted by electric heaters

ALL of which would then require low-GHG grid electricity

Thus, as with so many seemingly simple "green innovations" (such as electric cars),

low-GHG Ammonia requires a low-GHG electrical grid which,

in most of the industrialized world, is still more dream than reality

Possible exceptions:

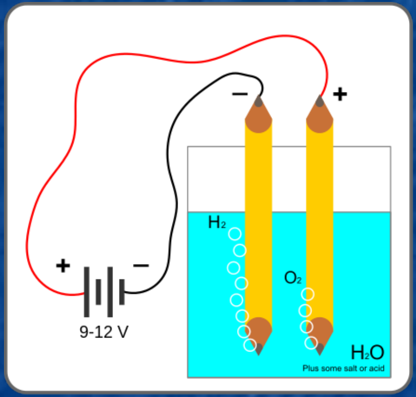
Nuclear-powered France? Hydro-powered Quebec or Washington State?

Alternate sources of H_2:

There are a number of possibilities, but the most obvious and well-developed is:

Electrolysis of Water

Which in its simplest form requires only electrical power + two inert metal electrodes: [1]



At the left negatively charged cathode:

$$4\ H^+\ (aq) + 4\ e^- \Rightarrow 2\ H_2\ (g)$$

While at the right positively charged anode:

$$2\ H_2O\ (l) \Rightarrow O_2\ (g) + 4\ H^+\ (aq) + 4\ e^-$$

Industrial scale electrolysis boosts reaction rates by adding an **alkaline electrolyte** [2]

Then labeled "ALK electrolysis" it has an energy efficiency of ~ 65-68%

Much higher gas pressures can be generated via **proton exchange membranes** [2]

This newer "PEM electrolysis" achieves comparable efficiencies of 57-64%

While emerging **solid oxide electrolysers** offer the possibility of higher efficiencies [2]

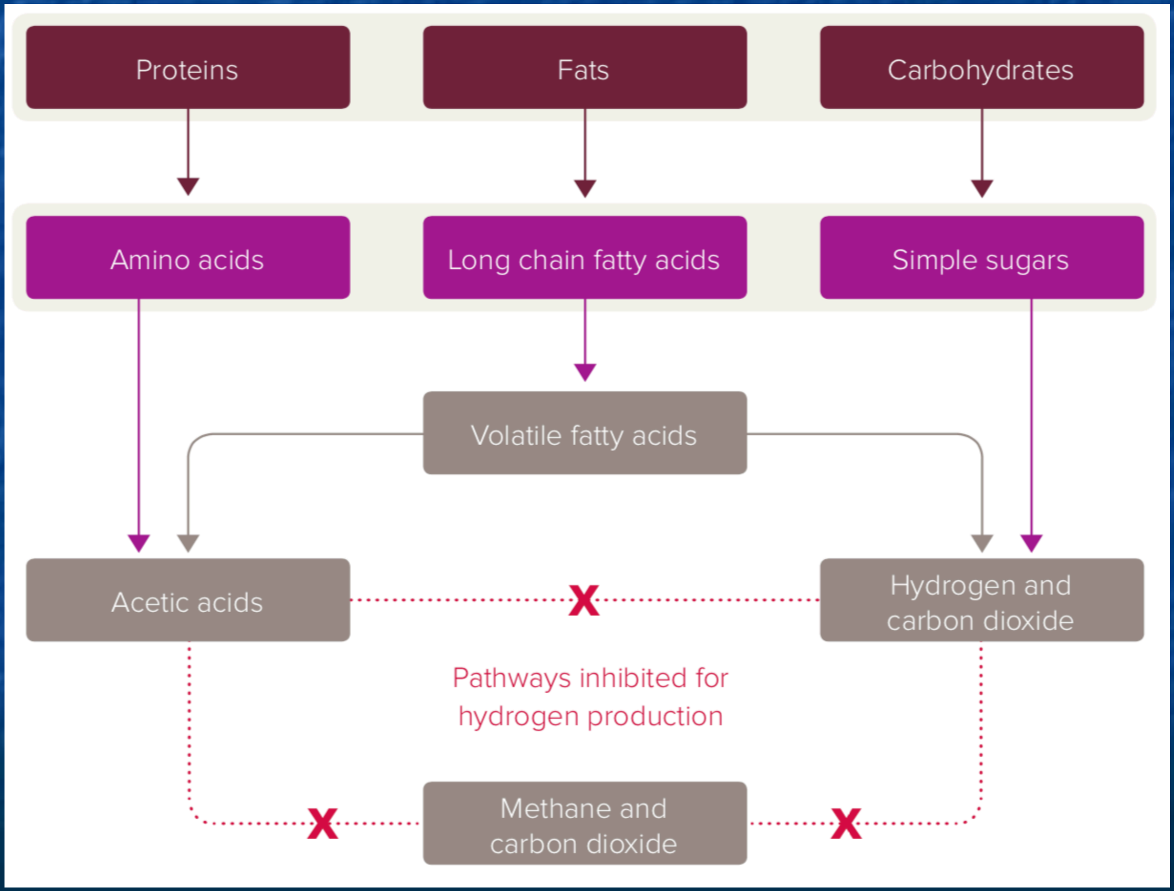
1) and figure: https://en.wikipedia.org/wiki/Electrolysis_of_water
2) https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf

The Royal Society suggests two more futuristic possibilities: [1]

The first is low temperature production of H_2 via biological processes

based on the anaerobic digestion of biomass by microbes,

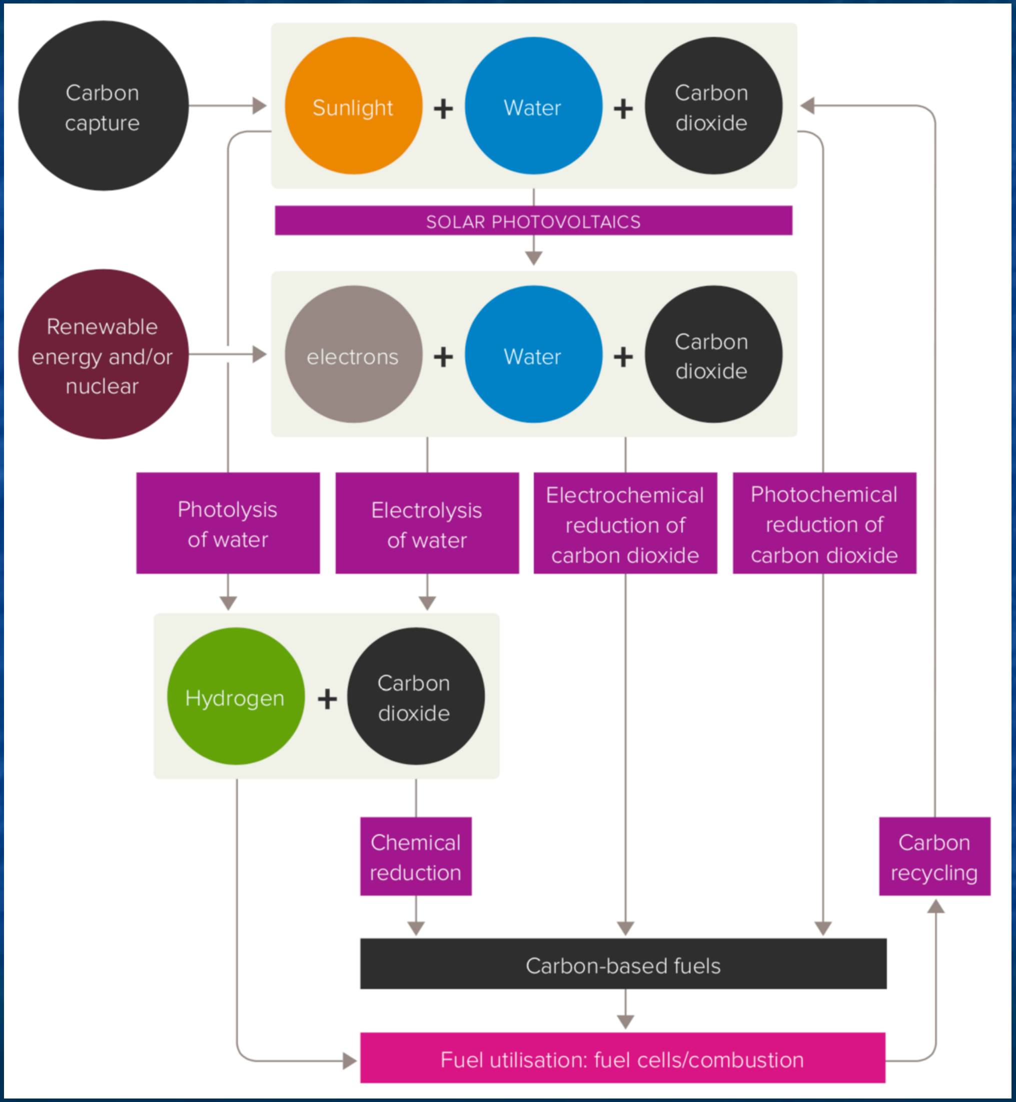
but altered to block normal CH_4 & CO_2 generation in favor of H_2 liberation:



1) https://royalsociety.org/~/media/policy/projects/hydrogen-production/energy-briefing-green-hydrogen.pdf

Royal Society suggestions (cont'd):

A second suggestion is using sunlight in ways inspired by photosynthesis that would split water into H_2 and O_2 while capturing atmospheric CO_2 (possibly in the form of useful biofuels)



NOTE that while this Royal Society [1] report included many enticing concepts, it omitted any detail on how these might some day be realized!

1) https://royalsociety.org/~/media/policy/projects/hydrogen-production/energy-briefing-green-hydrogen.pdf

But others suggest completely trashing the existing NH_3 process

And replacing it with "reverse" fuel cell synthesis of Ammonia, using electricity

to drive the intake of **H_2O + N_2 directly from the air**,

pushing **Ammonia's normal fuel cell oxidation reaction backward:**

$$4\ NH_3 + 3\ O_2 \Leftarrow 2\ N_2 + 6\ H_2O$$

But while this possibility is widely noted in both government and NGO studies,

I could only track down only a handful research efforts *actually* pursuing this goal

One was featured in the 2018 Science Magazine article which introduced this figure:

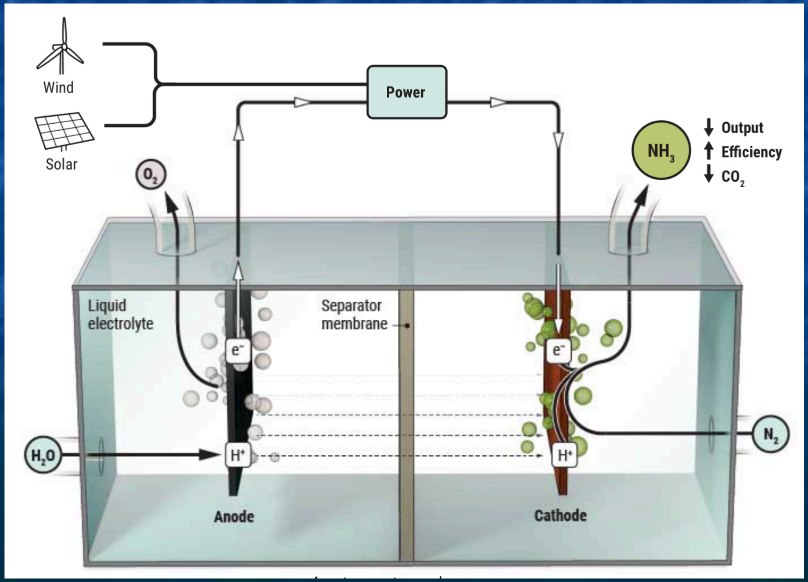
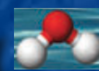


Figure: https://www.sciencemag.org/news/2018/07/ammonia-renewable-fuel-made-sun-air-and-water-could-power-globe-without-carbon

But that figure was inspired by a single 3.5 page "paywalled" journal article

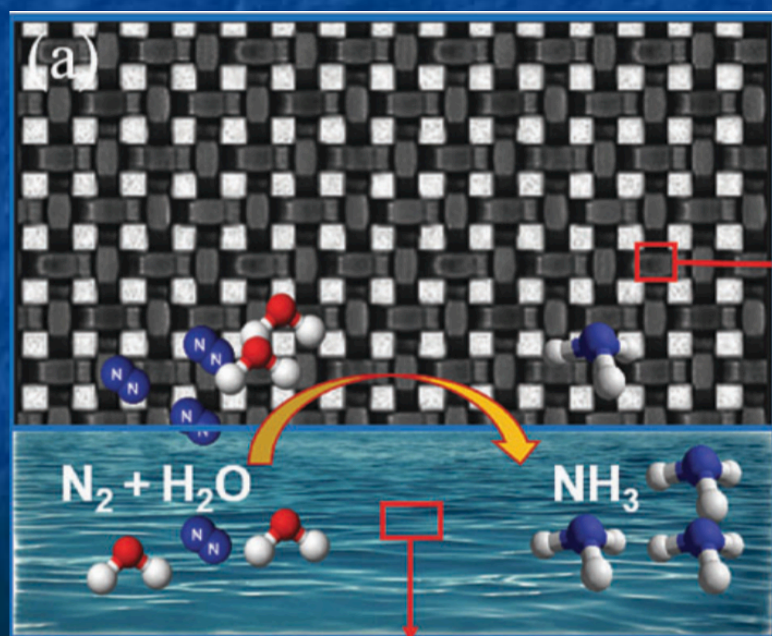
Which I was only able to access via my connections as a former professor

The article claimed two innovations, one of which was a "nano-patterned" iron catalyst

that would draw H_2O molecules () and dissolved N_2 molecules ()

onto adjacent sites where they could then react to form Ammonia (),

That process was depicted schematically in this pane of the article's first figure:

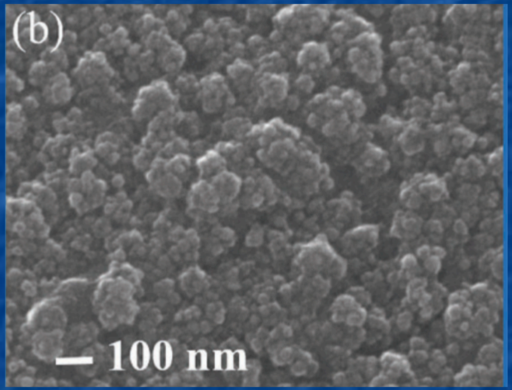


1) https://pubs.rsc.org/en/content/articlelanding/2017/ee/c7ee02716h#!divAbstract

Versus an SEM micrograph of the actual "nano-patterned" iron catalyst:

Which was not directly nano-patterned (a very difficult & time-consuming process),

but spontaneously patterned via the natural growth of adjacent Fe nanocrystals:



The other claimed innovation was the use of "non-aqueous Ionic Liquid" electrolytes

to enhance dissolved N_2 concentration, thereby enhancing NH_3 synthesis

Which would have made sense if a **truly non-aqueous** electrolyte would not

also block NH_3 synthesis by eliminating the other necessary reactant, H_2O

But using what I assume must really have been a **low-aqueous** electrolyte,

the researchers reported a ten-fold enhancement in the cell's "Faradaic Efficiency"

Figure pane from: https://pubs.rsc.org/en/content/articlelanding/2017/ee/c7ee02716h#!divAbstract

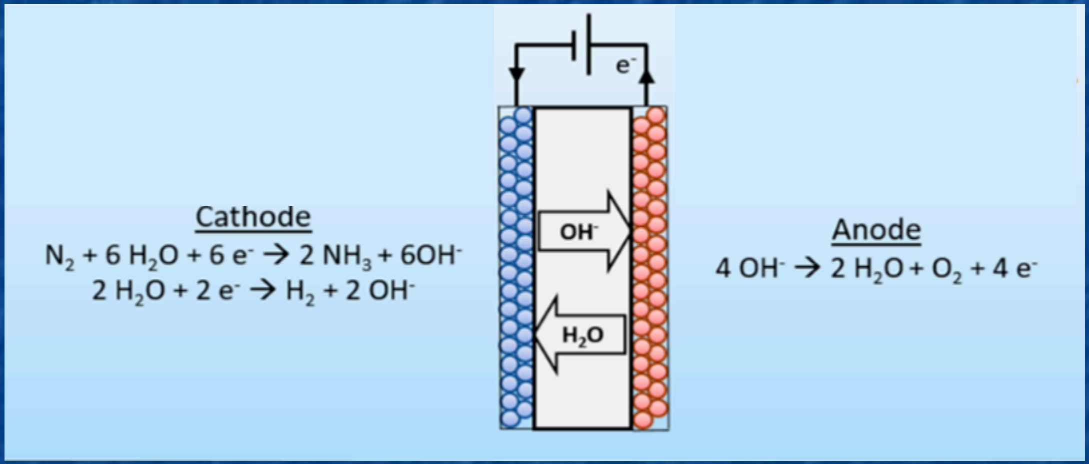
*A second study only **proposed** a new NH_3 synthesis **scheme**:*

It would expose a fuel cell's cathode surface to almost pure **H_2 + N_2 gas + H_2O vapor,**

which would electrolytically react forming NH_3 & H_2 on that cathode side of the cell,

while sending OH^- ions across to cell to the anode where they would react

forming O_2 gas then exhausted from that anode side of the cell



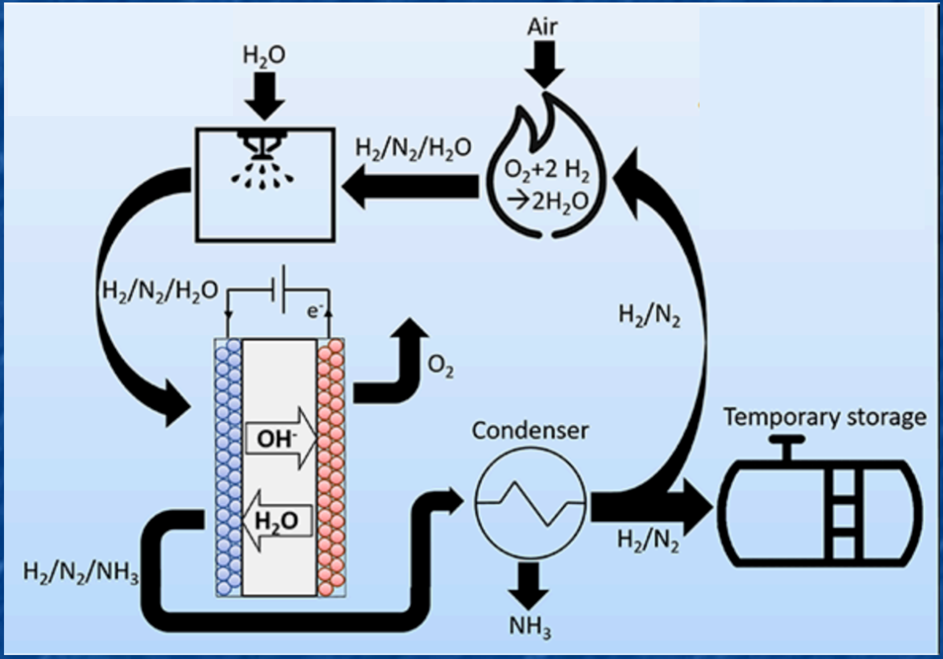
But what would generate that almost pure H_2 + N_2 + H_2O? Some outlying equipment:

Figure is slightly modified from: https://pubs.acs.org/doi/pdf/10.1021/acsenergylett.0c00455

Circling clockwise from the below:

3) Water is sprayed into that mixture of $H_2 + N_2 + H_2O$ to increase its H_2O content and this is then piped back to the cathode

2) A small amount of air ($N_2 + O_2$) is mixed with the piped in $H_2 + N_2$ and then ignited producing an almost pure mixture of $H_2 + N_2 + H_2O$



1) From the cathode (blue), H_2, N_2 & NH_3 are piped to a condenser that separates out the NH_3 product while piping onward the remaining $H_2 + N_2$

Figure is slightly modified from: https://pubs.acs.org/doi/pdf/10.1021/acsenergylett.0c00455

Those are clever and promising NH_3 reverse fuel cell ideas

But the first study amounts to what can be considered only a **proof of concept**

While the second study is no more than an **announcement** of concept

The Royal Society reached similar conclusions about fuel cell synthesis of Ammonia: [1]

"Electrochemical production is a technology for producing green ammonia directly from water and nitrogen using electricity. Importantly there is no separate hydrogen production process step . . .

However, to date, only low rates of ammonia production have been demonstrated in laboratory studies. New electrocatalysts, electrolytes and systems must be developed that can produce ammonia in preference to hydrogen and achieve competitive production"

Science Magazine's 2018 survey of NH_3 reverse fuel cell projects also concluded

that then existing fuel cell synthesis needed to be improved by "orders of magnitude" [2]

Meaning that, for now, "greening" of Ammonia will likely be limited to switching

the synthesis of reactant H_2 from methane steam-reforming to electrolysis

Moving on to how green (or at least greener) Ammonia might then be used:

1) https://royalsociety.org/~/media/policy/projects/hydrogen-production/energy-briefing-green-hydrogen.pdf
2) https://www.sciencemag.org/news/2018/07/ammonia-renewable-fuel-made-sun-air-and-water-could-power-globe-without-carbon

The many ways in which Ammonia might power ships: [1, 2]

Ammonia could be burned inside a

Diesel OR Spark-Ignition Internal Combustion Engine (ICE)

which could then drive EITHER the ship's propellers

OR electric generators, powering electric motors, driving the propellers

OR

Ammonia could be used as only an **easily-stored energy-dense medium**

then decomposed onboard as needed into **H_2** for use in combustion or fuel cells

(effectively using H_2 as the ship's fuel but avoiding complications & cost of H_2 storage)

OR

Ammonia could be used as one of the **inputs to some type of fuel cell**

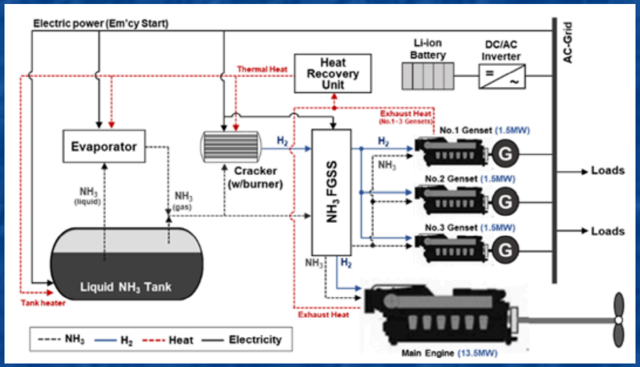
generating electricity, powering electric motors, driving the propellers

1) https://www.mdpi.com/2077-1312/8/3/183/htm
2) https://www.transportenvironment.org/sites/te/files/publications/2018_11_Roadmap_decarbonising_European_shipping.pdf

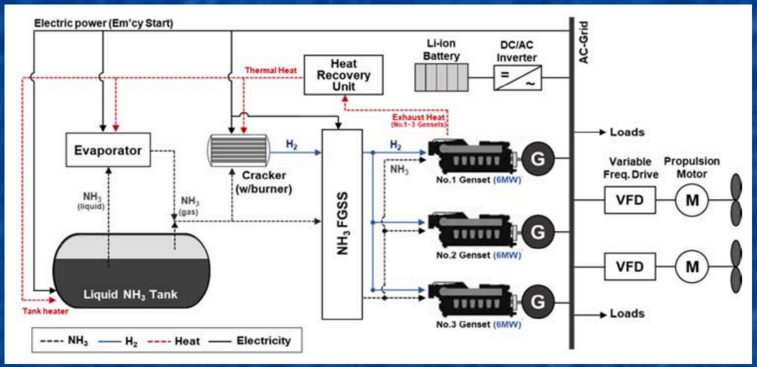
That resulting complex range of options was explored in a 2020 study on

"Alternative Ship Propulsion System(s) Fueled by Ammonia" - which included: [1]

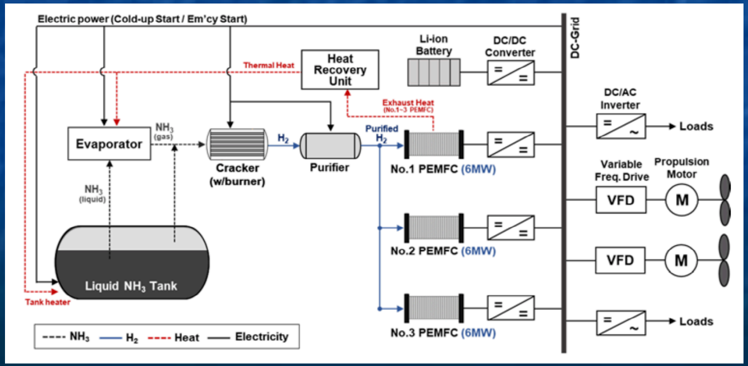
Mixture of NH_3 + H_2 (from NH_3) burned in ICE driving ship's propeller



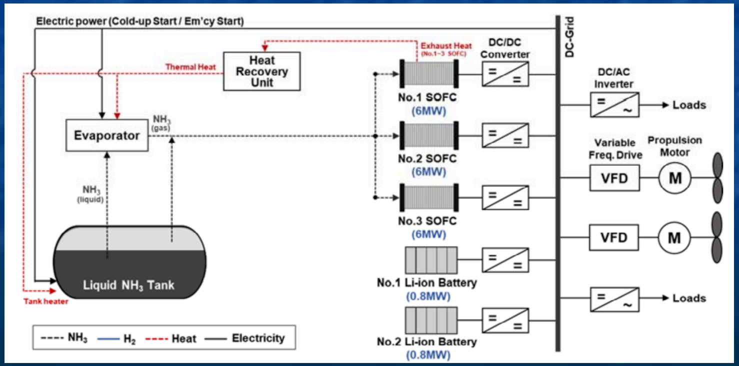
H_2 (from NH_3) burned in ICE driving electric generators powering propellers' electric motors



H_2 (from NH_3) feeding fuel cells producing electricity powering propellers' electric motors

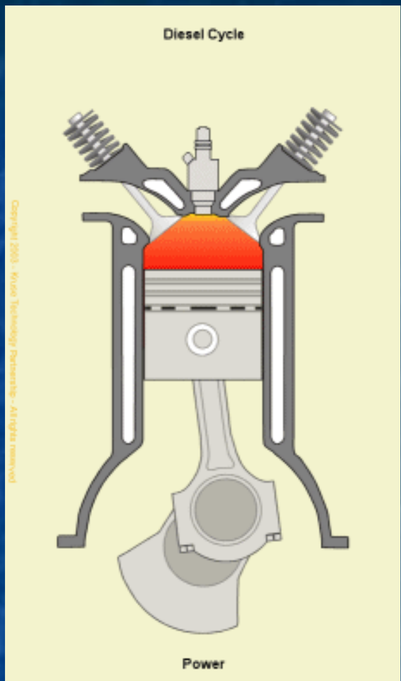


NH_3 feeding fuel cells producing electricity powering propellers' electric motors



1) https://www.mdpi.com/2077-1312/8/3/183/htm

The first group using ***Ammonia Internal Combustion Engines (ICE's):***



PgDn to start animation

http://www.kruse-ltc.com/Diesel/diesel_animation.html

The shipping industry now relies upon **Diesel ICEs** in which

compression heats the fuel to its "auto-ignition temperature"

However, while normal diesel fuels auto-ignite at 210-225 ºC

Ammonia requires an impractically high 651 ºC [1]

But **Ammonia + fossil-fuel mixtures** do diesel auto-ignite

which could reduce, but not eliminate diesel GHG emission

This is seen as a near term way of reducing ship pollution

A cleaner approach would be to first decompose some of the NH_3

producing **H_2 then mixed with the remaining NH_3**

yielding diesel auto-ignition with zero GHG emission [1]

Or future ships might be built with new car-like **spark-ignition ICE engines**

But this would do nothing for existing ships living out their decades long lifetimes

Further, spark-ignition may not produce complete (and thus clean) NH_3 combustion [2]

1) https://www.transportenvironment.org/sites/te/files/publications/2018_11_Roadmap_decarbonising_European_shipping.pdf
2) See page 11 in: https://www.mdpi.com/2077-1312/8/3/183/htm

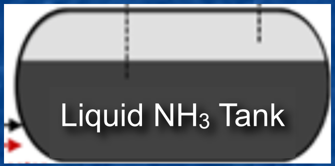
The second group using ***Ammonia as a Hydrogen Storage Medium:***

These exploit what is effectively just a cheaper H_2 gas tank - Cheaper because:

Cooled to -33.3 ºC, NH_3 tanks are not pressurized and do not require thicker walls

While room temperature tanks need withstand only 9 atmospheres of NH_3 pressure

Versus the massive construction required for 700 atmosphere H_2 tanks



But H_2 is then easily produced via thermal decomposition of NH_3 ("**cracking**")

And from that point onward, ships could fully exploit the mainstream H_2 technology

described in my note set: **A Hydrogen Economy?** (pptx / pdf / key)

The only unique challenge concerns the **completeness** of NH_3 => H_2 conversion,

because some fuel cells using H_2 to produce electricity can be poisoned Ammonia

In fact, as little as 1ppm of Ammonia is said to poison non-alkaline H_2 fuel cells [1]

Use of H_2 from NH_3 might thus require intense onboard purification

1) https://www.transportenvironment.org/sites/te/files/publications/2018_11_Roadmap_decarbonising_European_shipping.pdf

*The third group using **Electricity from Ammonia Fuel Cells:***

Here, for shipping, current attention focuses on **Solid Oxide Fuel Cells (SOFCs)**

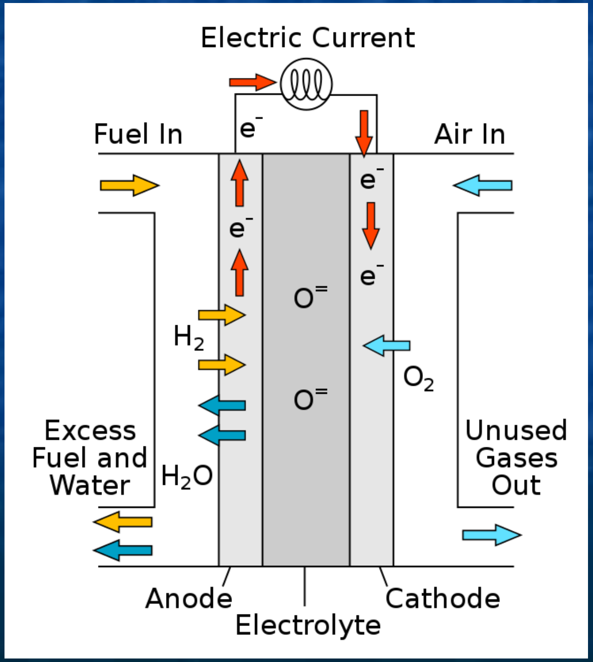
The SOFC Cathode (right) would decompose the O_2 in air passing by its outer surface:

$$3/2\ O_2\ (g) + 3\ e- \Rightarrow 3\ O^-\ (aq)$$

Moving across the cell, at the Anode arriving O^- ions would react with passing NH_3:

$$2\ NH_3\ (g) + 3\ O^-\ (aq) \Rightarrow N_2\ (g) + 3\ H_2O\ (g) + 3\ e^-$$

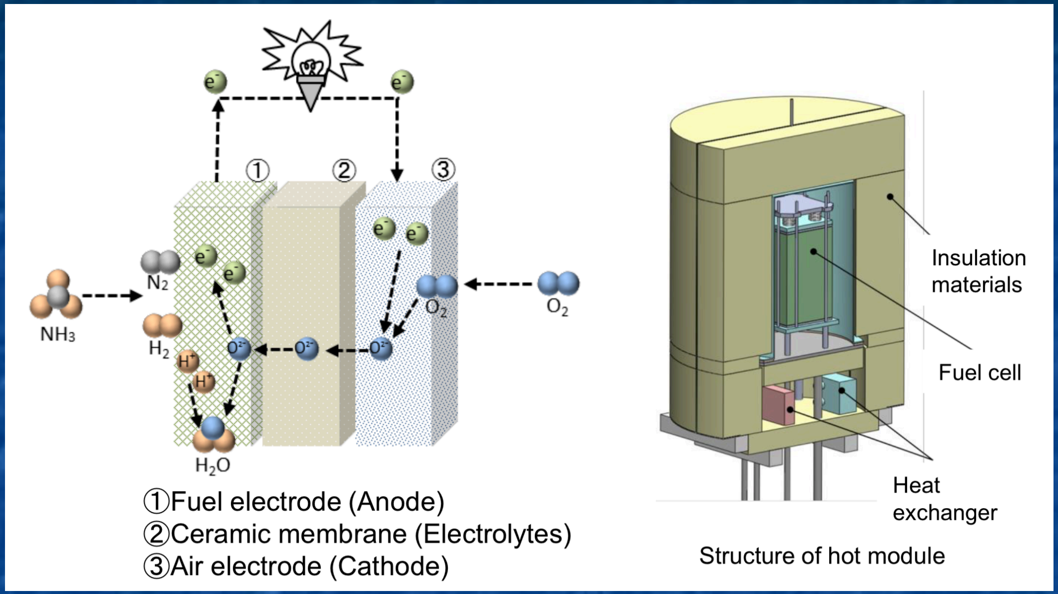
Thereby producing 3 e^- of electricity via: $2\ NH_3\ (g) + 3/2\ O_2\ (g) \Rightarrow N_2\ (g) + 3\ H_2O\ (g)$



1) https://en.wikipedia.org/wiki/Solid_oxide_fuel_cell

The most commonly cited work on NH_3 Solid Oxide Fuel Cells?

At a 2018 conference, Japan's IHI Corporation described this NH_3 SOFC prototype



Reporting 56% efficient output above 1kW, with stable thermally independent operation

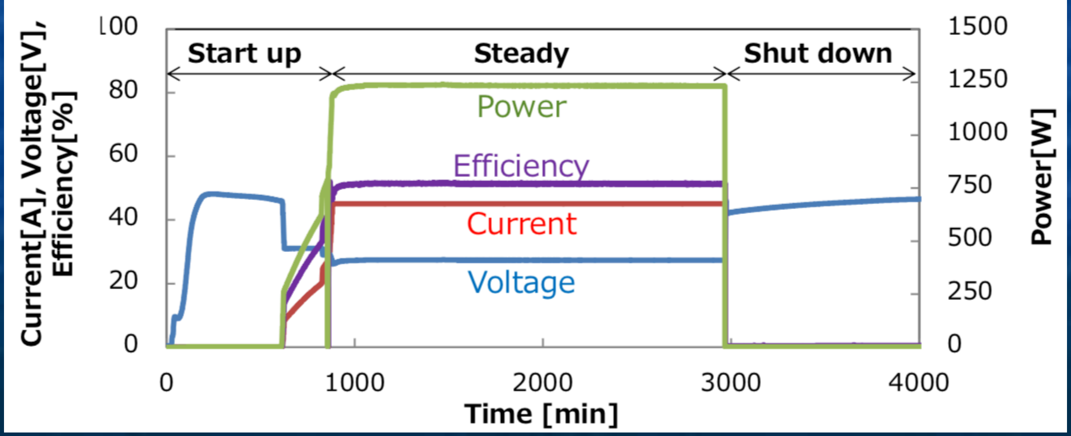


Figure: https://nh3fuelassociation.org/wp-content/uploads/2018/11/AEA-Imp-Con-01Nov18-Toshiyuki-Suda-Session-2.pdf

The first ever high-power NH_3 SOFC will be installed on the "Viking Energy"

As funded by the **European Union's fourteen nation ShipFC project,** [1]

which in 2020 signed a contract for SOFCs with Norway's Prototech corporation [2]

Their fuel cells are slated to produce 2 MW of electricity (~ 2700 horsepower)

With installation on the Viking Energy test vessel scheduled for late 2023:

1) https://www.prototech.no/news/2020/01/23/prototech-awarded-contract-to-supply-2mw-zero-emission-ammonia-fuel-cell-module/
2) https://www.prototech.no

Bottom lines regarding Ammonia powered ships?

The cited 2020 review of "Alternative Ship Propulsion System(s) Fueled by Ammonia" [1]

concluded that Ammonia powered alternatives to fossil-fueled diesel ships would:

Require 1.6 - 2.3 times the volume

Be 1.4 - 1.6 times heavier

Have a total life cycle cost 3.5 - 5.2 times larger

But could reduce GHG emissions by 83.7 - 92.1%

Going beyond that study, based on the long list of barely 50-75% efficient technologies (including multiple sets of fuel cells, compressors, heaters, coolers, purifiers . . .),

NH_3 shipping seems to need far more net energy input than today's shipping

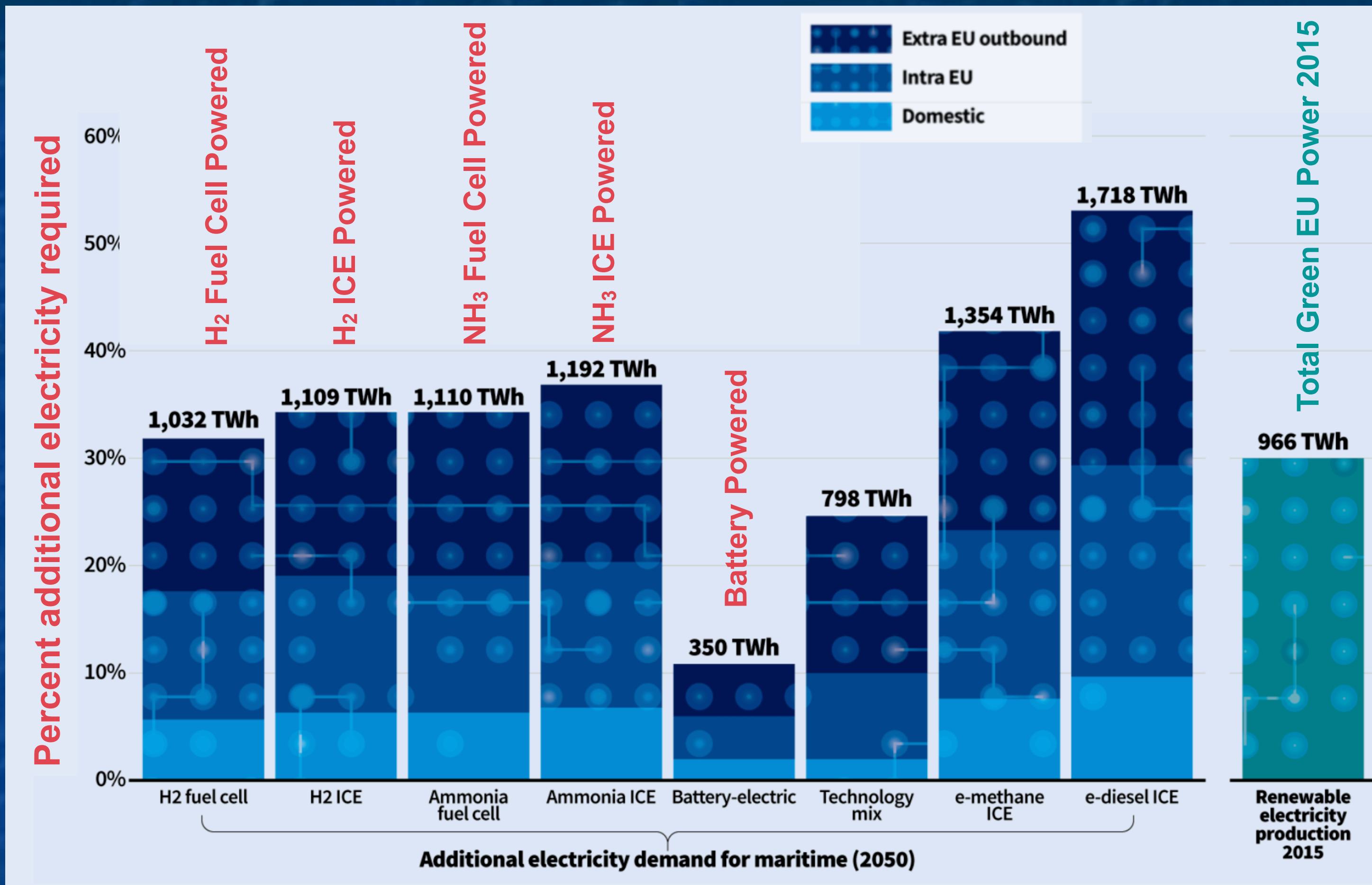
all supposedly coming from a new low-to-no-GHG electrical grid

Bringing to mind my earlier calculation that to recharge **battery-driven Electric Ships**, a single port might need the full electricity output of multiple nuclear power plants

1) https://www.mdpi.com/2077-1312/8/3/183/htm

Enter these estimates of new grid energy required for all-green EU shipping:

From a "Roadmap to Decarbonising European Shipping" - TransportEnvironment.org: [1]



Confirming my prediction of massive grid energy required for battery-powered shipping, but indicating that **H_2 and NH_3 alternatives would require several times MORE**

1) Page 15 (my labels added): https://www.transportenvironment.org/sites/te/files/publications/2018_11_Roadmap_decarbonising_European_shipping.pdf

Conclusions about Transportation Energy:

The good news:

I have identified **many** ways of decreasing transportation's energy consumption

And **many** ways in which we can mitigate transportation's environmental impact

(even if some forms of mitigation require **increased** energy expenditure)

Similarly abundant & plausible options are identified in my note sets about:

Energy Consumption in Housing (pptx / pdf / key)

Green(er) Cars & Trucks (pptx / pdf / key)

So we're NOT up against a wall: There are MANY IMPACTFUL THINGS WE CAN DO!

Conclusions - Part II:

The ~~bad~~ cautionary news:
Identifying the best solutions requires Wisdom

Because few if any of of these solutions are magical "silver bullets"

(the closest might be buying no vehicle having more than 20X your own weight)

And the more appealing & easily understood solutions are seldom the best ones

Prime examples: The simple & romantic ideas of wind or solar powered ships

as widely promoted online and in the popular press: [1, 2]

Despite **Wisdom** (in the form of only a little investigation) indicating GHG reductions

of as little as 2.4% for added wind power, and far less than 1% for solar power [3]

1) https://www.theguardian.com/environment/2018/may/03/future-sailors-what-will-ships-look-like-in-30-years
2) https://www.industryabout.com/industrial-news/801-news-transportation/48073-historic-un-deal-for-shipping-industry-could-lead-to-solar-powered-ships
3) https://theicct.org/sites/default/files/publications/ICCT_GHGfromships_jun2011.pdf

Conclusions - Part III:

More ~~bad~~ cautionary news:
Implementing those solutions requires Willpower

The best example from this note set may be the contrast between aviation & shipping:

Greener Ammonia powered shipping is now being actively promoted via academic & industry projects,[1] government initiatives [2] and industry associations [3]

Versus aviation, which now produces 5X greater GHG emissions, but is nevertheless specially exempted from international climate control agreements [4]

And for which the most plausible solution, biofuel development, is receiving little more than token industry involvement

The **best** example of which is United Airline's annual use of 1 **million** gallons of biofuel versus their continuing annual use of 1 **billion** gallons of fossil-fuel [4]

1) *https://www.ammoniaenergy.org/articles/development-of-direct-ammonia-fuel-cells/*
2) *https://vpoglobal.com/2020/01/24/major-project-to-convert-offshore-vessel-to-run-on-ammonia-powered-fuel-cell/*
3) *https://www.ammoniaenergy.org/*
4) *https://www.greenbiz.com/article/heres-what-it-will-take-get-aviation-biofuels-ground*

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This set of notes was authored by John C. Bean who also created all figures not explicitly credited above.