The Payne Institute for Public Policy would like to thank you for joining us today for our webinar.

Please feel free to use the chat feature on the Zoom conference call to post questions for Dolf Gielen.

Questions will be answered at the end of the presentation.

Thank you!
The Issue

• Increasing calls for carbon neutrality by 2050
• The power sector is making progress
• Electromobility is emerging as a solution for light-duty vehicles
• This leaves “the other half”
  ➢ Energy-intensive industry
  ➢ Other transportation modes
• Solutions need to be tailored to sectoral needs
• Requirements:
  ➢ Affordable technology
  ➢ An enabling framework for sectors that are operating in an international and very competitive market (carbon leakage)
  ➢ Fear of carbon leakage and loss of competitiveness has resulted in a lack of policy action to date
Electrification paired with renewables is a major solution for decarbonisation

By 2050,
- Electricity becomes the central energy carrier
- 86% of electricity generation will come from renewables

A transformed energy system: Scaling up renewables not just for power, but also for heat and transport
Hard-to-decarbonise sectors (HTDS)

While the power sector is making progress, particular challenges remain in HTDS if carbon neutrality is to be achieved

- Energy-intensive industries:
  - Iron and steel making
  - Chemical and petrochemical production
  - Cement making
  - Aluminium making
- Transport except light vehicle fleets
  - Airplanes
  - Marine ships
  - Heavy long-distance freight trucks
## Global energy and climate relevance of hard-to-decarbonise sectors

<table>
<thead>
<tr>
<th>Sector</th>
<th>2017 Final energy use [EJ/yr]</th>
<th>2017 CO₂ emissions [Gt/yr] (Direct and indirect energy &amp; process)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road freight</td>
<td>24.0</td>
<td>1.75</td>
</tr>
<tr>
<td>Aviation</td>
<td>13.5</td>
<td>0.85</td>
</tr>
<tr>
<td>Shipping</td>
<td>9.1</td>
<td>0.68</td>
</tr>
<tr>
<td>Iron and steel</td>
<td>34</td>
<td>3.63</td>
</tr>
<tr>
<td>Aluminium</td>
<td>6.0</td>
<td>0.85</td>
</tr>
<tr>
<td>Chemical and petrochemical</td>
<td>46.8</td>
<td>2.72</td>
</tr>
<tr>
<td>Cement</td>
<td>10.7</td>
<td>2.48</td>
</tr>
<tr>
<td>Gas sector</td>
<td>130.0</td>
<td>7.28</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>274.1</strong></td>
<td><strong>20.24</strong></td>
</tr>
</tbody>
</table>

IRENA calculations
The other half of transportation emissions

Source: EIA (2016)
Renewable solutions are rising

- The cost of renewables have fallen dramatically
- This has opened up new opportunities for cost-effective renewable solutions in these sectors
- These can accelerate total renewables deployment
- IRENA has been active in analysing these sectors but the work is fragmented
  - Hydrogen studies
  - Decarbonising shipping
  - Advanced biofuels report and event
  - Country NDCs and energy transition plans
  - Industry sector roadmaps
  - Electrification of end use study with SGCC (ongoing)
  - Green gas and gas system stranded assets analysis

- Increasing international activity in this area (G20, HEM, WEF, etc.) – requests for IRENA engagement
Technology and economics are needed to create further policy room

- Decarbonise power and heat supply – a special role for renewable energy
- Electrify end uses as much as possible (electric cars, light duty trucks, heat pumps for space heating, hot water, industrial drying and mid-temperature heating processes)
- Develop new solutions for challenging sectors (30-40% CO₂ emissions)
  - Heavy duty long haul trucks (electricity, biogas, advanced biofuels, hydrogen)
  - Aviation (advanced biofuels, electricity for ground operations, hydrogen for auxiliary use)
  - Shipping (hydrogen, ammonia, electricity, biogas)
  - Iron and steel (hydrogen, RE electricity, biomass, relocation, CCS)
  - Cement (CCS, new cement types, materials substitution, alternative feedstocks, renewable energy)
  - Chemicals and petrochemicals (hydrogen, electricity, biochemicals, circular economy)
- Time is running out, transitions take decades
Hydrogen potential in end-use sectors by 2050

- **Technical potential is significant**
- **Economic potential** will depend on cost reductions and competition with other emerging options, with estimates on the order of 10-100 EJ
- Switching current feedstocks from fossil fuels to RE has a potential of 10 EJ

Note: Hydrogen from renewable electricity represents two-thirds of hydrogen supply under IRENA REmap scenario. Hydrogen Council roadmap does not specify renewables share in total hydrogen supply.
Hydrogen production costs

Presently accelerating investments in electrolysers worldwide

Key assumptions:
Electrolyser load factor: 4200 hours (48%), conversion efficiency 75%

Hydrogen from renewables is close to competitiveness at best solar and wind regions

Key assumptions: Electrolyser load factor: 4200 hours (48%), conversion efficiency 75%
AVIATION
Air transport – future demand growth

- Passenger aviation activity will more than triple even in a climate friendly scenario (REmap)

- Aviation as a country would be the eighth largest emitter of greenhouse gases in the world.

- Air transport was responsible for 12% of global energy consumption in transport sector in 2016 – 920 Mt CO2 for all domestic & international flights
Ways to decarbonise aviation

• Improved efficiency through better aircraft design and operation to reduce fuel per person-km or tonne-km
  ▪ Well advanced, low in cost or even cost-reducing
  ▪ May be tough to reduce fuel use by more than half

• Sustainable Aviation Fuel (SAF) to reduce carbon emissions from fuel still used in more efficient aviation
  ▪ Substantial life cycle emissions reductions per litre
  ▪ If half as much fuel were needed and emissions were 80% less per liter, total emissions would decline 90%
  ▪ Hard to compete with fossil fuels: must work to reduce conversion costs, organise feedstock logistics
Options to introduce renewable energy and fuels in aviation

Sources: M. Hornung, Ce-Liner – Case Study for eMobility in Air Transportation, Aviation Technology, Integration and Operations Conference. Los Angeles. 12.8.2013
EU Project Centreline: www.centreline.eu ; F. Troeltsch - Concept for a hydrogen-powered long-haul aircraft, Bauhaus Luftfahrt Symposium, 8.5.2019

Source: Bauhaus Luftfahrt
Economics of E-Kerosene

Fischer-Tropsch SPK (synthesized Paraffine Kerosene) using syngas

(ASTM D7566)

- Produced from CO$_2$ and H$_2$ using the reverse water-gas-shift reaction

  \[ 8 \text{ CO}_2 + 25 \text{ H}_2 \rightarrow \text{C}_8\text{H}_{18} + 16\text{H}_2\text{O} \]

- 1 t fuel requires 3 t CO$_2$ and 0.44 t H$_2$

  - 0.44 t H$_2$/t synfuel $\times$ 1500 USD/t H$_2$ = 660 USD/t synfuel (2050, best case)
  - + 3 t CO$_2$/t synfuel $\times$ 100 USD/t CO$_2$ = 300 USD/t synfuel (biomass CO$_2$)
  - + capital cost, operating cost of conversion units
  - + process losses, energy needs ($\times$1.25)

- Realistically at best 1500 USD/t or 1.75 USD/litre by 2050

- Very cheap hydrogen is critical ($<1.5$ USD/kg) – remote locations

- Similar cost for methanol-to-fuel route
Modern bioenergy deployments should be more than four times larger than the current level

Data based on the Global Energy Transformation: A Roadmap to 2050 (IRENA 2019)
**Advanced biofuel - Where will we get our biojet?**

- **Feedstocks and technologies to consider:**
  - *Oilseed crops on restored land (upgrade biodiesel)*
    - Europe (rapeseed), China, Americas
    - FORBIO project – set aside land in EU
  - *Wood residues (thermochemical routes)*
    - Uncollected logging residue in Scandinavia
    - Unrealised forestry potential in SE Europe
  - *Sugar/Energy cane (1G+2G ethanol plus conversion)*
    - Brazil, Southern Africa, Caribbean
    - Economies from shared 1G/2G process steps
    - Future potential enhanced by high-yield energy cane
## Biojet conversion technology pathways

<table>
<thead>
<tr>
<th>Pathway</th>
<th>Certified technology pathways (end of 2018)</th>
<th>Technology Readiness Levels of Biojet Pathways</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oilseed crops (oleochemical routes)</strong></td>
<td>• HEFA: ASTM D-7566 Annex A2 (2011)</td>
<td>• HEFA: TRL = 6 – 9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Pyrolysis: TRL = 4 – 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Hydro-Thermal Liquefaction: TRL = 1/3 – 4)</td>
</tr>
<tr>
<td></td>
<td>• DSHC/SIP: Annex A3</td>
<td>• DSHC/SIP: TRL = 5 – 7</td>
</tr>
<tr>
<td></td>
<td>• Much more costly than ATJ</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Farnesene has alternative uses</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Brazil plant has shifted to higher-value products</td>
<td></td>
</tr>
</tbody>
</table>
Select biojet pilot projects

- **Oilseed crops (oleochemical routes)**
  - SkyNRG (HEFA)
  - Neste (vegetable oils, jatropha, camelina, animal fats)

- **Wood residues (thermochemical routes)**
  - Red Rock (wood residues)
  - Fulcrum (municipal solid waste)

- **Sugar to Alcohol to Jet (biochemical routes)**
  - Raizen (Sugarcane 1G/2G to ethanol)
  - Gevo (Maize to butanol)
  - Poet (Maize to ethanol)
  - Clariant (Maize 1G and stover 2G to ethanol)
  - Lanzatech (waste to ethanol)
  - Biogy (catalytic synthesis of alcohols to biojet)
  - PNNL – dehydration/oligomerization/hydrogenation
How do total costs for biojet compare?

**Feedstock price will rise with demand**

![Bar chart showing unit total cost, 10% discount rate for different feedstocks (vegetable oils, corn and sugarcane, wood residues). The chart indicates varying costs at different crude oil prices ($50-100 per barrel).](image-url)

- **LO** and **HI** represent low and high scenarios for feedstock costs, capital costs, and O&M costs.
- The chart highlights the impact of feedstock prices on total costs, with vegetable oils, corn and sugarcane, and wood residues shown in separate bars.
Global biofuel investments are on a declining trend

The industry has reached and even exceeded the USD 20 billion level in the past, which is needed for biofuels in the low-carbon transport sector pathway.

- To achieve the 5-fold increase goal, more than 100 refineries should be developed annually at an investment cost of USD 20+ billion.
- More than 10% of bioliquids should be allocated for aviation but the buildout of biojet refineries is slow.
Advanced Biofuels – what holds them back?

Objective of the study

✓ Clarify the factors explaining the stagnating investment activity in advanced biofuels

(Method of analysis)

✓ A review of past literature + survey by questionnaire with industry executives in companies that have invested in 2G biofuel productions (14 respondents)

✓ Statements evaluated on a five-point agreement scale (the Likert Scale) under the five following groups
  • feedstock (8 statements)
  • technology and financing (7 statements)
  • markets through mandates and targets (16 statements)
  • trends in consumer demand (12 statements)
  • environmental and social concerns (11 statements)

✓ A ranking question about the level of various possible barriers (rank a minimum of three of the most important areas of risk or barriers from among 14 categories)
  • highest scored barrier = value of 3
  • second scored barrier = value of 2
  • third scored barrier = value of 1
What really matters? - **Ranking the barriers**

<table>
<thead>
<tr>
<th>Stability of regulation</th>
<th>Level of blending mandates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology risk &amp; process reliability</td>
<td>Availability &amp; cost of financing</td>
</tr>
<tr>
<td>Feedstock availability</td>
<td>Feedstock price</td>
</tr>
<tr>
<td>Conversion efficiency &amp; CAPEX</td>
<td>Level of subsidies</td>
</tr>
<tr>
<td>Public perceptions</td>
<td></td>
</tr>
</tbody>
</table>

- **Stability of regulation** is clearly the most important barrier to investments followed by the cost and availability of **financing** and level of **conversion efficiency & capex**.

- The three issues of **policy stability**, **mandates** and **subsidies** (46%) are all dependent on regulation and thus subject to societal preferences and political control.

- The second largest ”block” relates to **cost competitiveness** of advanced biofuels production, formed jointly by ”conversion efficiency & CAPEX” and ”feedstock price”.

Source: IRENA survey
SHIPPING
• Annual CO₂ emissions associated with international shipping

• International shipping accounts for around 9% of global transport sector emissions

The current energy needs of the shipping sector are mostly met by heavy fuel oil (82%), marine gas and diesel oil (18%).

Global trade volume is estimated to grow at 3.8% per year over the next five years.

Between 2000 and 2017, the CO₂ emissions associated with the shipping sector grew at an average annual rate of 1.87%.
82% of global cargo by weight is linked to very large ships and 85% of CO₂ emissions in the sector come from large ships i.e. mainly oil tankers, bulk and container carriers.

A shift toward a cleaner sector will require changes to port terminal infrastructure and operational equipment.

Considering the characteristics of the current infrastructure, the use of suitably produced biofuels appear as the immediate option.
Key options for zero-emission shipping

- Alternative fuels
  - Ammonia
  - Methanol – 15 ships on the water, more to come
  - Biomethane
  - E-fuels

- Clean sourcing and certification is key
- Economics and upscaling need attention
- Bunkering logistics and ship design considerations needed

- The Getting to Zero Coalition aims to develop zero-emission vessels and make them commercially available by 2030
**Ammonia vessels**

- Ammonia works out 32% cheaper than hydrogen and 15% cheaper than methanol (KR research, 2020)
- Ammonia is toxic but ammonia transportation vessels operate safely
- Fuel tank for liquid ammonia is 4x size of bunker fuel tank
- MAN Energy Solutions developing ammonia fuel engines. There are more than 3,000 existing MAN B&W engines, which can be modified into ammonia fuel engines
- MISC along with Samsung Heavy Industries, Lloyd’s Register and MAN Energy Solutions set about building an ammonia-fuelled tanker
- Eidesvik’s 2003-built LNG-fuelled platform supply vessel Viking Energy will have a high-power ammonia fuel-cell installed
- Various ammonia ship designs under development
Given that ammonia has no special storage needs, the overall capital cost is likely to be more attractive than the direct use of hydrogen

- Apart from the cost of adapting infrastructure, ammonia is toxic to both humans and aquatic life. Considerable safety measures must therefore be taken.
- While renewable electricity costs continue to drop, ammonia technologies could become more competitive in the long term.
Action focused on the reduction of GHGs by cutting liquid fossil fuel use must consider total life cycle emissions of alternative RE options

Total life cycle GHG emissions per kWh of engine output for different fuels

- The use of LNG would support the reduction of SOx emissions but to achieve IMO targets, the shipping sector will need to fully shift to renewable fuels and alternative propulsion means.

- The characteristics of the clean fuels play an important role on the techno economic feasibility e.g. energy density, storage temperature and pressure.
Some concluding thoughts on transport

• Transport sector decarbonisation calls for accepting several fuel alternatives simultaneously rather than resorting to a single, all-encompassing solution

• E-fuels and advanced biojet fuel will be essential to the RE transition and full decarbonisation of energy supply since aviation cannot be completely electrified and efficiency improvements can only go so far

• To date, grey and blue hydrogen are cheaper, but green hydrogen is on a solid path to become the most economic choice in the future, coupled with low-cost renewable power.

• Dedicated renewable plants seem more economic in the long term. Grid-connected electrolysers tend to pay higher prices for electricity, although they can maximise operating hours and be located closer to demand, thereby saving significant logistics costs.

• Intercontinental hydrogen trade can enable economic access to remote RE resources while decarbonising centres of high demand elsewhere. This enables increased energy security and air quality benefits.

• E-fuels can complement electricity, hydrogen and biofuels in the coming decades. However the prospects are still uncertain as prospects for cost reduction are uncertain.
IRON AND STEEL
Global energy use for iron and steel making, 2015

<table>
<thead>
<tr>
<th>Energy use</th>
<th>[EJ/yr]</th>
<th>[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coking coal and coke</td>
<td>24.1</td>
<td>70.0</td>
</tr>
<tr>
<td>Other coal</td>
<td>6.1</td>
<td>17.6</td>
</tr>
<tr>
<td>Blast furnace gas and coke oven</td>
<td>-3.3</td>
<td>-9.6</td>
</tr>
<tr>
<td>gas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural gas</td>
<td>2.3</td>
<td>6.7</td>
</tr>
<tr>
<td>Oil</td>
<td>0.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Biomass</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Electricity</td>
<td>4.0</td>
<td>11.8</td>
</tr>
<tr>
<td>Heat</td>
<td>0.6</td>
<td>1.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>34.4</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Source: OECD/IEA (2018)
Note: Includes BF and coke ovens
Example: Carbon-free steelmaking

- The bulk of direct CO₂ emissions is related to ironmaking processes.
- Today’s ironmaking is coke and coal based.
- Interesting opportunities to use hydrogen (from renewable energy).
- Hydrogen-based direct reduced iron (DRI) production is technically feasible – many ongoing development projects.
- DRI is a bulk commodity.
- Solution: replace iron ore imports with imports of DRI produced at the mining site.
- Consider import of DRI that is produced with renewable H₂ from countries such as Australia and Brazil.
Material flows in the global iron and steel sector, 2015 (millions of tons per year)

**Fuels and utilities**
- Coal, coke and other products: 823
- Gas: 45
- Oil: 9
- Biomass: 11
- Hydrogen: 0
- Limestone/dolomite: 224

22% CO
5% H₂
20% CO₂
53% N₂
0.92 Gt CO₂ eq

*Source: Gielen et al. (2020)*

**Abbreviations**
- BF = blast furnace
- BOF = basic oxygen furnace
- DRI = direct reduced iron
- EAF = electric arc furnace
- Mt = million tonnes

*Note: In this figure, it is assumed that the DRI process' energy efficiency would improve by 25% between 2015 and 2050.*

*Source: Gielen et al. (2020)*
## Unit costs of different iron and steel production technologies in Europe (net of taxes)

<table>
<thead>
<tr>
<th>Techno-economic specification</th>
<th>Conventional</th>
<th>Hydrogen High-cost</th>
<th>Hydrogen Low-cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity price [USD/kWh]</td>
<td>-</td>
<td>0.057</td>
<td>0.034</td>
</tr>
<tr>
<td>Technology [USD/t steel]</td>
<td>BF-BOF</td>
<td>DRI-H2-EAF</td>
<td>PDSP</td>
</tr>
<tr>
<td>Coke</td>
<td>94.9</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.0</td>
<td>247.5</td>
<td>148.0</td>
</tr>
<tr>
<td>Iron pellets*</td>
<td>0.0</td>
<td>94.9</td>
<td>0.0</td>
</tr>
<tr>
<td>Iron ore</td>
<td>213.6</td>
<td>213.6</td>
<td>213.6</td>
</tr>
<tr>
<td>Services</td>
<td>50.9</td>
<td>45.2</td>
<td>45.2</td>
</tr>
<tr>
<td>Labor</td>
<td>55.4</td>
<td>49.7</td>
<td>49.7</td>
</tr>
<tr>
<td>Capital (wear and tear)</td>
<td>54.2</td>
<td>54.2</td>
<td>54.2</td>
</tr>
<tr>
<td>OPEX [USD/t steel]</td>
<td>469.0</td>
<td>705.1</td>
<td>510.8</td>
</tr>
<tr>
<td>Difference with BF-BOF [USD/t steel]</td>
<td>236.2</td>
<td>41.8</td>
<td></td>
</tr>
<tr>
<td>Process emissions [tCO₂/t steel]</td>
<td>1.7</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Break-even CO₂ price [USD/t CO₂]</td>
<td>157.1</td>
<td>28.3</td>
<td></td>
</tr>
<tr>
<td>Investment costs [USD/t steel]</td>
<td>1258</td>
<td>1179</td>
<td></td>
</tr>
<tr>
<td>CAPEX** [USD/t steel]</td>
<td>118.7</td>
<td>111.9</td>
<td></td>
</tr>
</tbody>
</table>

Notes: * Additional costs due to the intermediate stage of producing iron pellets out of iron ore. **Greenfield' facility assumptions: 2% interest rate, 12 years lifetime and investment phase. The low interest rate is balanced by a low economic lifetime, technical lifetime is several decades.

Source: Mayer et al. (2019)
Industry relocation: Iron case study

- Today half of global iron ore is mined in Australia
- Australia is also the largest supplier of coking coal
- Australia has significant renewable energy potential
- Value proposal: convert iron ore with VRE in Australia to DRI (sponge iron)
- Ship DRI to the consumer markets
- Downstream processing of DRI into steel

- 400 Mt DRI would require 600 GW renewable power
- 10-fold increase power generation capacity in Australia needed
- Approx. 10 000 km² needed for solar & wind – 0.1% of the total Australia land area
Material flows in the global iron and steel sector, 2050 (millions of tons per year) – 1.5 degrees case

<table>
<thead>
<tr>
<th>Fuels and utilities</th>
<th>Amount (millions of tons per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal, coke and other products</td>
<td>630</td>
</tr>
<tr>
<td>Gas</td>
<td>30</td>
</tr>
<tr>
<td>Oil</td>
<td>7</td>
</tr>
<tr>
<td>Biomass</td>
<td>114</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>35</td>
</tr>
<tr>
<td>Limestone/dolomite</td>
<td>229</td>
</tr>
</tbody>
</table>

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- BF = blast furnace
- BOF = basic oxygen furnace
- DRI = direct reduced iron
- EAF = electric arc furnace
- Mt = million tonnes

**Note:** In this figure, it is assumed that the DRI process' energy efficiency would improve by 25% between 2015 and 2050.

Source: Gielen et al. (2020)
Thank you!

Upcoming 2020

Released 2019

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