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ESIG
ENERGY SYSTEMS INTEGRATION GROUP

Electrification and Industrial Sources of System Balancing Flexibility

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Outline

- Background and scope
- The team
- The role of energy intensive industries
- The role of hydrogen
- Conclusions

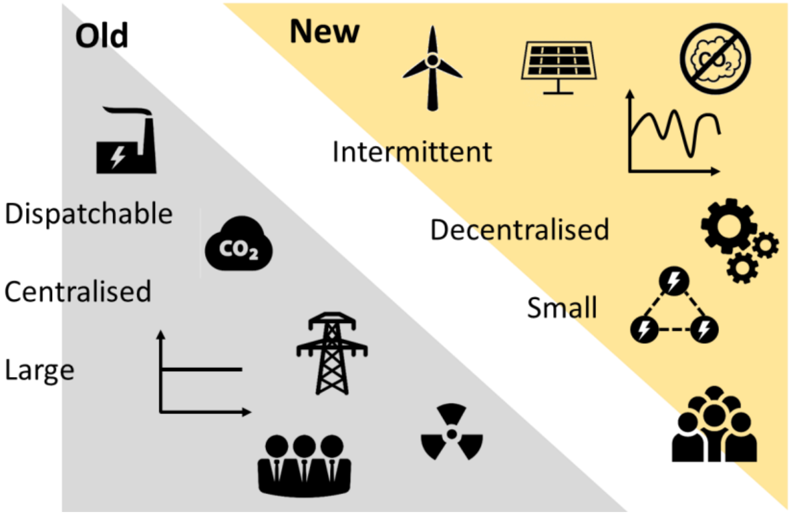
Background and scope

- Since the 2015 Paris Agreement, net zero commitments have become increasingly common from countries around the world.
- Similarly, individual US states and private corporations have made their own commitments to reduce CO_2 emissions via a range of approaches, including *via* the increasing use of sources of intermittent renewable energy, *i.e.*, wind and solar power.
- More generally, increasing the electrification of the broader economy, e.g., heating, mobility, and industry, is an important part of the decarbonisation effort.
- It is broadly accepted that, in this context, ensuring the flexibility and resilience of the electricity grid becomes increasingly important.

Background and scope

- There are a range of mechanisms for providing flexibility, including demand side response at the domestic, commercial, and industrial levels, increased deployment of energy storage options, and carbon capture and storage applied to thermal power plants.
- The role and value of each mechanism will vary as a function of the broader landscape.
- The context for this study is one with extensive deployment of intermittent renewable energy sources, where existing sources of flexibility, *e.g.*, batteries, *etc.*, may no longer be sufficient.
- We recognise that, in practice, this will be highly region specific, however, we have tried to remain agnostic to location in this study.
- The balance of this presentation focuses on the energy intensive industries and hydrogen as options for providing flexibilty

Grid priorities are evolving



The power system is changing…

“+” → “+++” = low → high value

*modelled as minimum stable generation point, up-/down time

Technology Feature	Value in future power systems
High Efficiency	+
High Flexibility*	++
Low CAPEX	+++
Dispatchability	+++
Firm capacity/ancillary service provision	+++
Low OPEX	+
High Rate of Deployment	++

M Schnellmann, *et al.*, Int J GHG Con, 2018

Background and scope: defining flexibility

Technology	Frequency				Voltage		System Restart	Reserve Capacity		
	Inertia	Primary Response	Secondary Response	Tertiary Response	System Strength	Reactive Power	Black start	Regulating Reserve	Contingency Reserve	Load Following Reserve
Nuclear	O			O	O	O	O		O	O
Bio	O	O	O	O	O	O	O	O	O	O
OCGT	O	O	O	O	O	O	O	O	O	O
CCGT	O	O	O	O	O	O	O	O	O	O
Coal-CCS	O	O	O	O	O	O	O	O	O	O
CCGT-CCS	O	O	O	O	O	O	O	O	O	O
BECCS	O	O	O	O	O	O	O	O	O	O
Wind turbine	O	O	O	O		O		O	O	O
Solar		O	O	O		O		O	O	O
Pumped Hydro Storage	O	O	O	O	O	O	O	O	O	O
Battery		O	O	O		O	O	O	O	O

O	The technology can provide the service
O	The technology can provide the service but might be limited by the energy availability and economic-environmental aspects
O	The technology can technically provide the service but providing this service may not be beneficial for the plant (*i.e.*, iRES and Nuclear tend to operate at full capacity or availability)

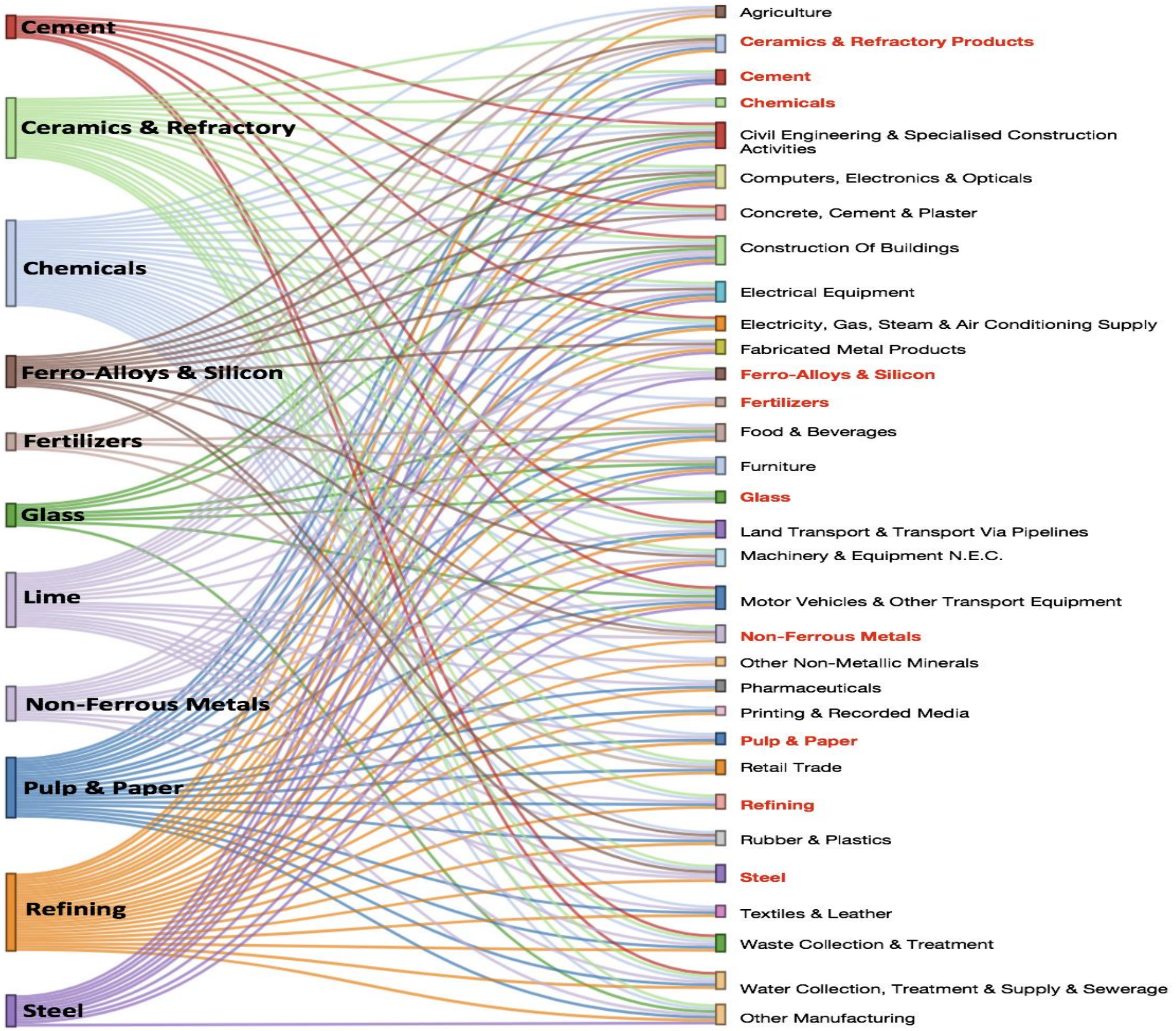
- The electricity requires a range of services in order to function reliably.
- Few, if any, technologies provide all services, and thus a portfolio solution is required.
- Additional services can include demand reduction via demand side response (DSR).
- The non-power sector can also provide some of these services.

Pratama and Mac Dowell, Beyond LCOE: Value of technologies in different generation and grid scenarios, IEA GHG, 2020

The team: a very diverse mix

- Aidan Tuhoy (EPRI)
- Niall Mac Dowell (Imperial College London)
- Elizabeth Endler (Shell)
- Julian Beere (Anglo American)
- Pierluigi Mancarella (University of Melbourne)
- Julia Matevosyan (ERCOT)
- Connor Anderson (ERCOT)
- Anthony Ku (NICE)
- Marta Yugo (CONCAWE)
- Ehsan Shafiei (CONCAWE)
- William D'haeseleer (KU Leuven)
- Toby Price (AEMO)

Energy intensive industries are enmeshed in the broader economy



- EII supply chains are intertwined
- Moreover, their products are, and will continue to be, required to enable the transition to a low carbon economy
- The EIIs were profoundly impacted by the economic crisis
- Most EIIs already see recycled materials as important elements of their supply chains

IES, Europe's Energy Intensive Industries contribution to the EU Strategy for long-term EU greenhouse gas emissions reductions, 2018

Broader considerations in the decarbonisation of EIIs

- It is important to note that, in a European context, the EIIs have already played an important role in emission reductions – in the period 1990 – 2015, EIIs reduced greenhouse gas (GHG) emissions by 36%, representing approximately 28% of economy wide reductions, *despite* the fact that EIIs were only responsible for 15% of total EU GHGs in 2015.
- To date, EII emission reduction has come about via a combination of improvements in energy efficiency, fuel switching, and, unfortunately, plant closures or reduced output, largely as a result of the 2008 financial crisis.
- There are a range of pathways further emission reduction, including
  - Further energy efficiency improvements
  - Process integration
  - Electrification of heat and processes
  - Use of blue and green H_2
  - The use of CO_2 capture, utilisation, and storage technologies

Electrification is useful, but not a silver bullet

	Electrification (heat and mechanical)	Electrification (processes: electrolysis/ Electrochemistry excl. H2)	Hydrogen (heat and/or process)	CCU	Biomass (heat and feedstock)/ biofuels	CCS	Other (including process integration)
Steel	**xxx**	xx	xxx	xxx	x	xxx	Avoidance of intermediate process steps and recycling of process gases: xxx Recycling high quality steel: xxx
Chemicals fertilizers	xxx	xxx	xxx	xxx	xxx	xxx(*)	Use of waste streams (chemical recycling): xxx
Cement Lime	xx (cement) x (lime)	o (cement) o (lime)	x (cement) x (lime)	xxx (cement and lime)	**xxx** (cement) x (lime)	xxx (cement and lime)	Alternative binders (cement): xxx Efficient use of cement in concrete by improving concrete mix design: xxx Use of waste streams (cement): **xxx**
Refining	xx	o	xxx	xxx	xxx	xxx	Efficiency: **xxx**
Ceramics	xxx	o	xx	x	x	o	Efficiency: **xxx**
Paper	xx	o	o	o	**xxx**	o	Efficiency: **xxx**
Glass	xxx	o	x	o	xxx	o	Higher glass recycling: xx
Non-ferrous metals/alloys	**xxx**	**xxx**	x	x	xxx	x	Efficiency: **xxx** Recycling high quality non-ferrous: xxx Inert anodes: xxx

o: Limited or no significant application foreseen
x: Possible application but not main route or wide scale application
xx: medium potential
xxx: high potential
***xxx**: Sector already applies technology on large scale (can be expanded in some cases)*
(*) in particular for ammonia and ethylene oxide

- There are a range of approaches for decarbonising the EIIs
- They are not all mutually compatible
- Electrification is already quite widely applied in e.g., secondary steelmaking, with electrification of heat a possible solution in some sectors, e.g., ceramics.
- However, in others, e.g., cement, or refining, it is at best a partial solution and will have to be used in combination with other options.

IES, Europe's Energy Intensive Industries contribution to the EU Strategy for long-term EU greenhouse gas emissions reductions, 2018

Some challenges to electrifying EIIs

- Whilst heat may be readily provided *via* electrification, the quality of that heat is a key consideration.
- Low temperature heat (T < 300C) can be relatively easily provided *via, e.g.*, electric arcs, induction, microwaves, and electron beam heating.
- However, higher temperatures (T > 1,000C), as are required in the production of cement and glass, are more challenging. Electric furnace technology exists, but is at a relatively small scale, and would require adaptation for deployment in these contexts.
- Moreover, owing to the deeply integrated nature of these industrial processes, altering any process element will have knock-on implications to the rest of the process, and will have capital cost implications.

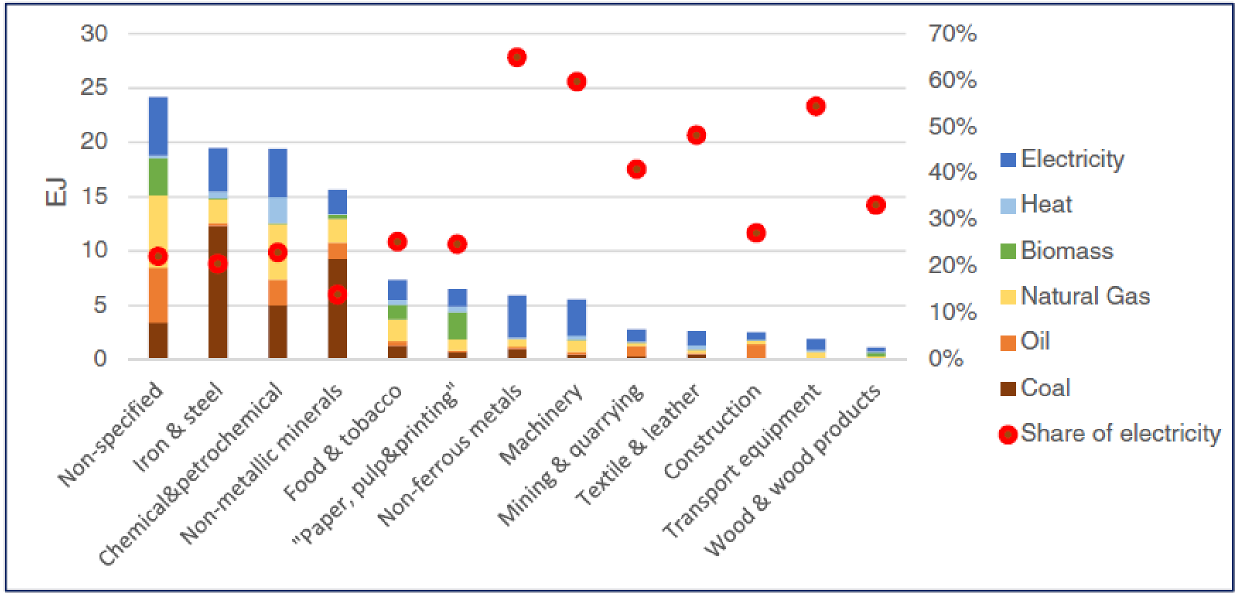
Some challenges to electrifying EIIs

- Key to progressing this area will be the progression of technologies to TRL > 7 and the further decarbonisation of the electricity grid.
- The electricity grid needs to be deeply decarbonised for electrification to be a plausible route to decarbonisation relative to credible counterfactuals for the near-to-medium term.
- Regardless of timing, electrification of EIIs will require require large amounts of power to operate. In a European context, EIIs may become the largest electricity consumer, consuming between 2,980 – 4,430 TWh/yr.
- Moreover, this power must be made available in a reliable, affordable, and decarbonised manner.

Some challenges to electrifying EIIs

- Thus, EIIs and the electricity sector may well co-evolve, and thus quantifying and qualifying the role and value of EII's "flexibility service" will be key.
- As noted, EIIs have the potential to substantially increase power consumption. This demand is typically baseload.
- Concurrently, it is understood that power supply becomes inherently less reliable with greater integration of intermittent renewable energy sources – wind and solar power do not, themselves, provide baseload power.
- It is therefore important to consider how EIIs can contribute to the resilience of such a system.

Electrifying the EIIs



- The share of electricity in the incumbent EII sector varies widely, between ~ 14% in non-metallic minerals, *i.e.*, cement, glass, and ceramics, to approximately 65% in the case of non-ferrous metals, *i.e.*, primary aluminium production
- In general, electricity is used for machine drives, process control, and the direct provision of heat.
- With increasing demand for renewable energy technology, requiring increased production and refining of rare earth elements, and increasing recycling of metals, a general shift towards increased electricity use in the industrial sector may be expected in the near to medium term.

IES, Europe's Energy Intensive Industries contribution to the EU Strategy for long-term EU greenhouse gas emissions reductions, 2018

Barriers to industrial electrification

- Incumbent fuels are relatively cheap. Natural gas costs are particularly hard to overcome with direct electrification often having higher operating costs. Similarly, so-called “own-use” fuel, *I.e.,* fuel that is produced during an industrial process and subsequently used as a fuel or as a feedstock tend to be very cheap. Examples include blast furnace gas produced during the combustion of coke in the iron and steel industry, is typically recovered and used as a fuel within the plant, or refinery fuel gas is produced from a refinery catalytic cracker unit and can be used for refinery own-use.
- Capital costs of fuel-switching
- Existing regulations and policies that may favor one fuel over another
- Electric delivery infrastructure costs and constraints
- Risk aversion in industry

Barriers to industrial electrification

- Availability of electric process equipment in industry and lack of engineering knowledge or capacity to redesign manufacturing process lines and/or process integration
- Heterogeneity of industrial sectors
- High temperature processes due to their higher energy costs relative to industries with lower process temperatures and are often found in low-margin sectors (e.g., cement, iron and steel, and glass)
- If intermittent renewable electricity is used, then low-cost power may only be available for some hours of the year during times of overproduction or very low overall demand, and process equipment capacity factors will be low, or additional investment in energy storage will be required. This will drive up the cost of production and require more flexible modes of operation and potentially modified equipment designs.

The role of EIIs in providing flexibility

- Shoreh *et al*. and Dorreen *et al.* observed that EIIs could provide a range of grid services, including frequency regulation services from variable frequency drives, and non-spinning reserve from electrolytic processes, and electric arc furnaces.
- However, the ability of industry to implement and benefit from a "smart" interaction with the grid is inherently limited by its production processes and their tolerance for interruption.
- EPRI have evaluated the impact of industrial electrification on the electricity grid. Their most aggressive scenario shows the electricity share of industry final energy demand increasing to about 45% in 2050 from the reference scenario of about 27%.

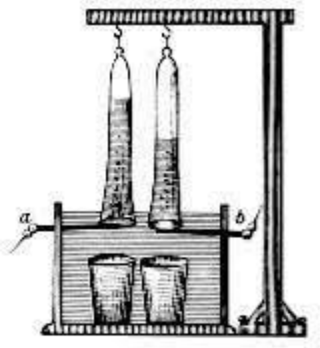
Shoreh, et al., A survey of industrial applications of demand response. Electr Power Syst Res, 2016
Dorreen, et al., Transforming the way electricity is consumed during the aluminium smelting process. In: Zhang et al., editors. Energy Technol: Springer International Publishing, 2017
Electric Power Research Institute (EPRI). U.S. national electrification assessment, 2018.

The role of EIIs in providing flexibility

- Electrifying the industrial sector will require a very significant amount of new electricity generation capacity.
- Assuming electro-thermal technologies for heating and electrolysis for material separations replace all energy requirements of eight energy intensive industries in the European Union, Lechtenböhmer et al. estimate a 4-fold increase in electricity demand by 2050.
- Replacement of petroleum-derived fuels and feedstocks with H_2, CO_2, and syngas involves nearly ten times more electricity by 2050.
- Palm et al. considered the implications of the electrolytic production of EU plastics would require 1,400 – 1,900 TWh and could lead to a 300% increase in production costs.

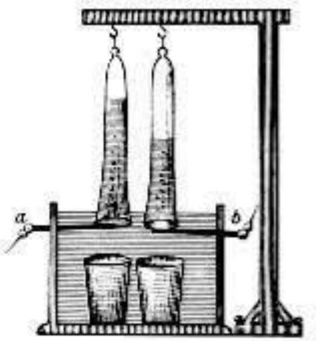
Lechtenböhmer et al, Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand. Energy. 2016
Palm et al., Electricity-based plastics and their potential demand for electricity and carbon dioxide. J Clean Prod. 2016

Origins of green H_2

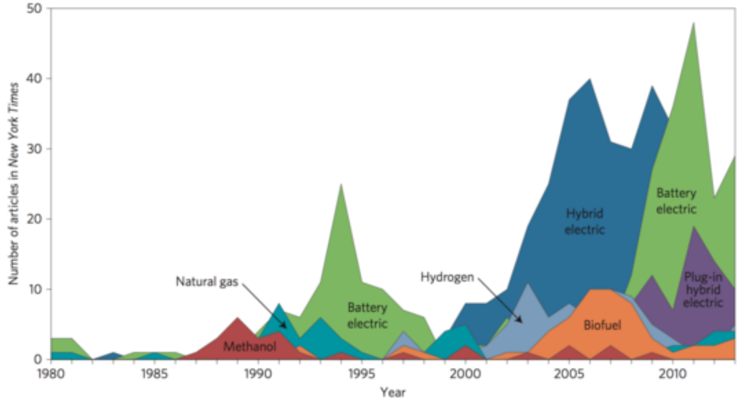


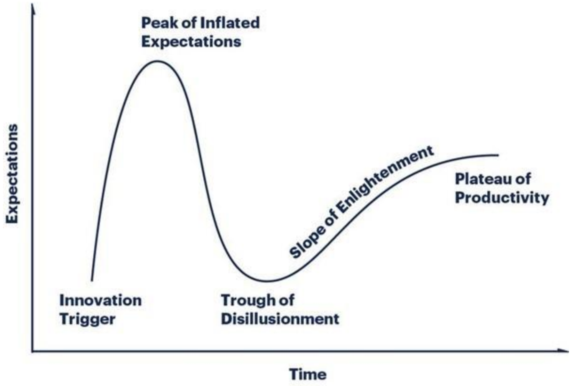
- The concept of electrolytic H_2 has its origins in the 18th century – the phenomenon of water electrolysis was first demonstrated in 1789 by the Dutch merchants Jan Rudolph Deiman and Adriaan Paets van Troostwijk using an electrostatic generator to produce an electrostatic discharge between two gold electrodes immersed in water
- It wasn't until 1888 – almost a century later – for electrolytic H_2 to make it out of the lab and be demonstrated in industry - Dmitry Lachinov was the first to demonstrate this.
- By 1902, more than 400 alkaline water electrolysis units were in operation, and by 1920, this technology had been brought to the 100 MW scale, primarily for the production of ammonia fertiliser in Canada and Norway using low-cost hydroelectricity.

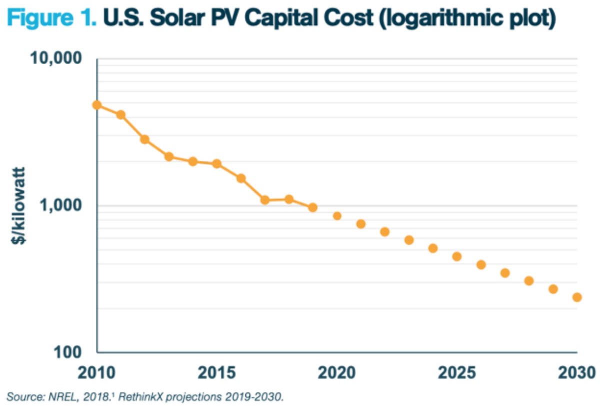
Origins of green H_2



- Over the course of the last century (1920 – 2021), hydrogen hype cycles have come and gone, usually fuelled by promises of “too cheap to meter” electricity.
- This “free power” was originally to come from nuclear power (see Lewis Strauss, 1954), and now, potentially, renewable energy.



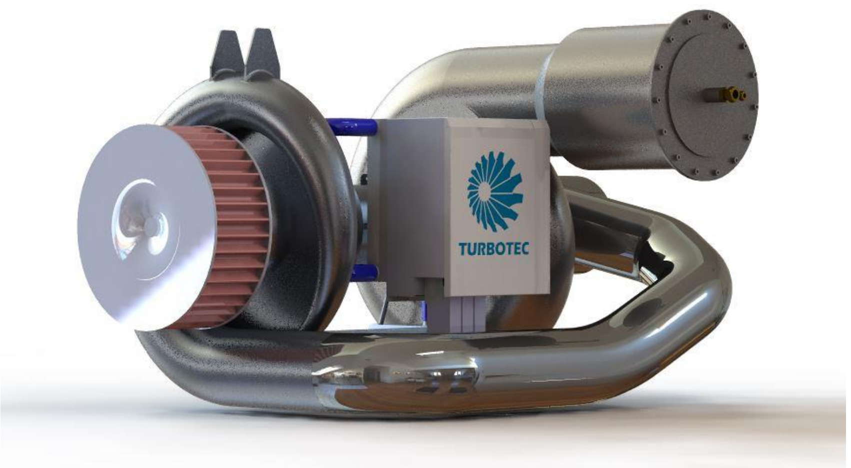




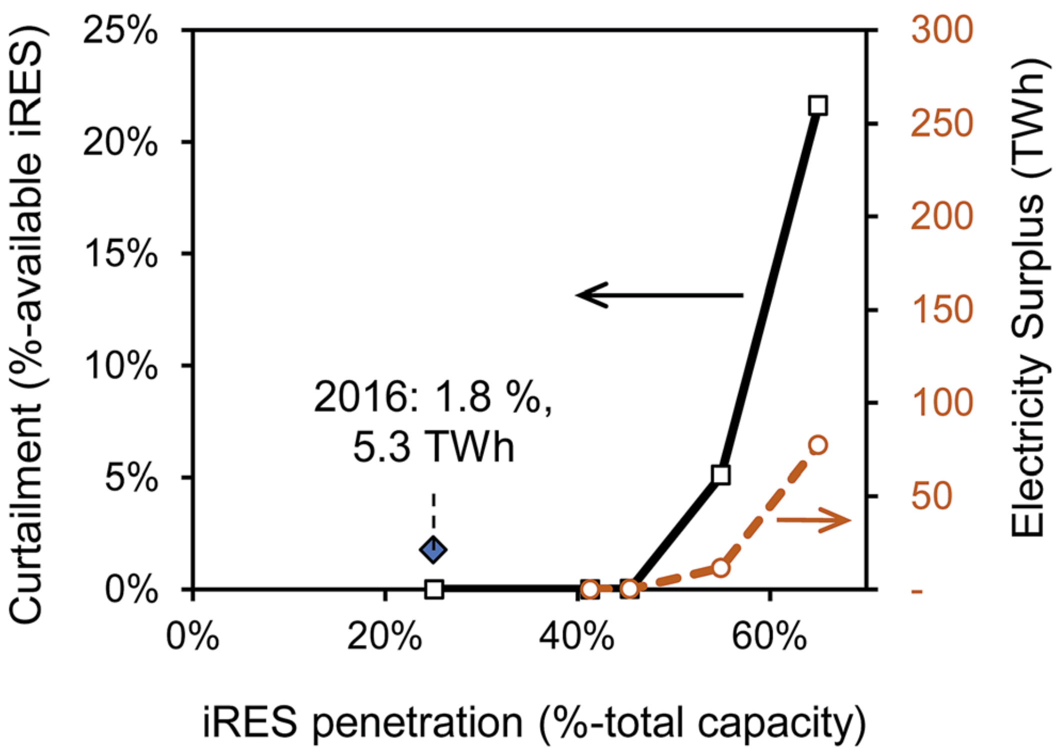
https://www.greencarcongress.com/2016/03/20160302-sperling.html https://theconversation.com/sun-and-wind-could-finally-make-electricity-too-cheap-to-meter-34166

Origins of green H_2

- H_2 as an energy carrier is beguiling – it can, in theory, provide all the energy services we need – heat, power, and mobility – and with technologies that are available today
- Key challenge – demand for energy services has limited elasticity, and is highly time sensitive – the value of lost load (VoLL) is too great.



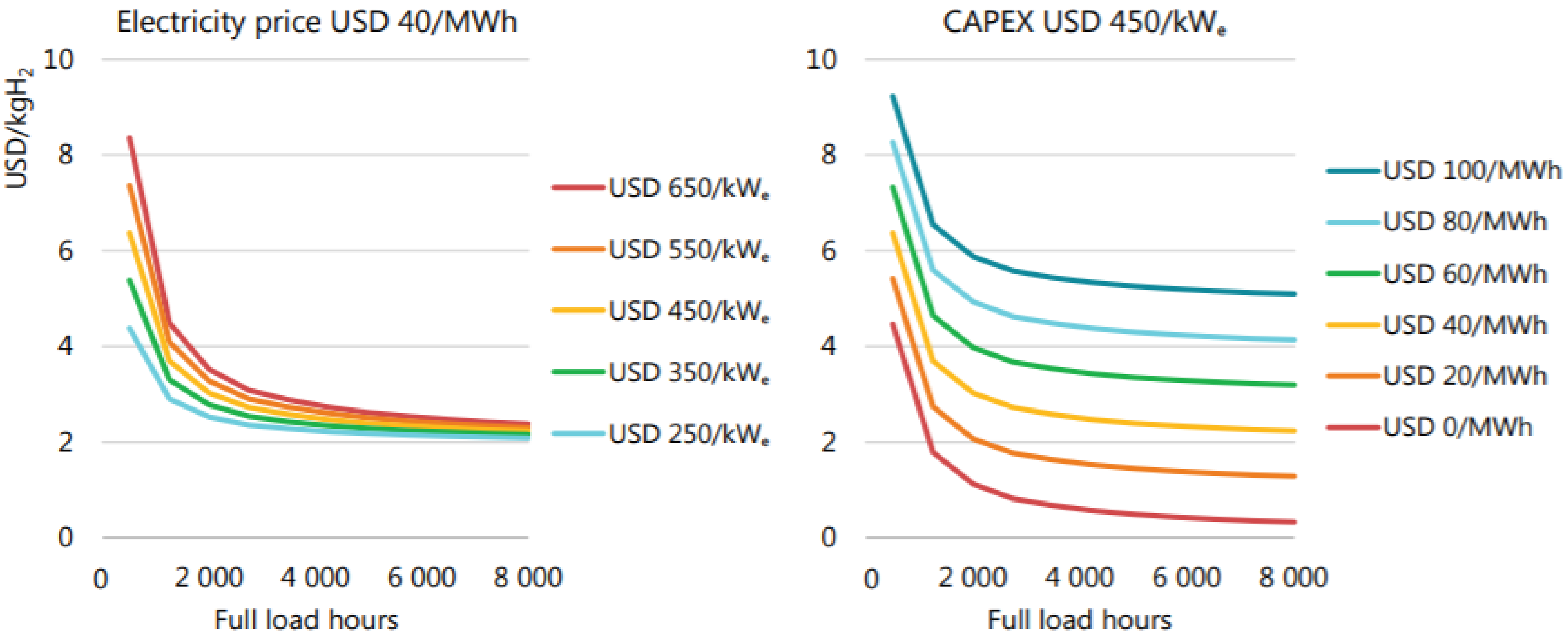
Production of Hydrogen – the “curtailed renewables” story



- The availability of “otherwise curtailed” renewable energy will be very much location specific in terms of wind speeds and solar irradiance, and will moreover be a function of policy incentives.
- iRESs penetration needs to be a significant fraction of total installed capacity before a meaningful amount of curtailment is likely to occur.
- Key point: using “curtailed electricity” will result in a very low capacity factor

Daggash, et al., Sustainable Energy Fuels, 2018

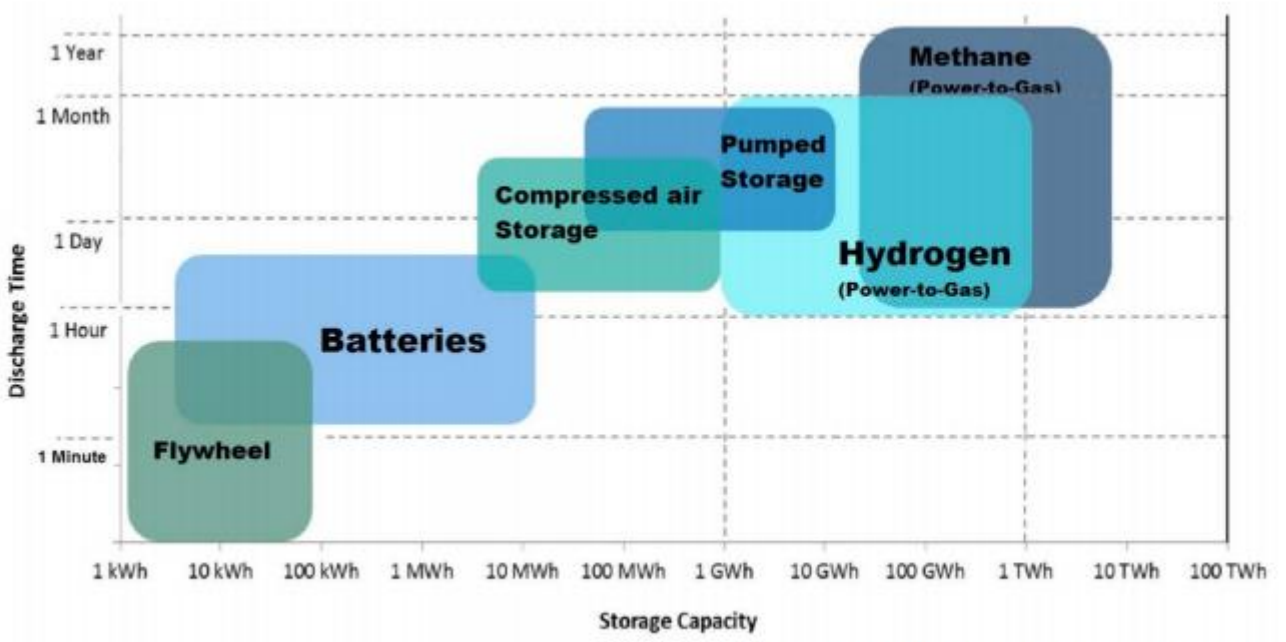
The impact of capacity factor on H_2 costs



- It is understood that electrolytic H_2 needs to be available at less than $\$1/kg_{H2}$ to be viable for the production of fuels
- Assuming this is deliverable via "curtailed renewables" is a brave assumption…

Mazloum, MSc Thesis, Imperial College London, 2020

The role of H_2 in providing energy storage



Source: School of Engineering, RMIT University (2015)

Figure 3. Available storage technologies, their capacity and discharge time.

- There are a range of options for providing grid flexibility *via* energy storage
- H_2 can play an important role via so-called power-to-gas-to-power
- The prevailing assumption is that you would have a two-way coupling of the H_2 infrastructure via, *e.g.,* an electrolyser, H_2 storage facility, and a H_2 fuel cell.

https://commons.wikimedia.org/wiki/File:Available_storage_technologies,_their_capacity_and_discharge_time.jpg

One-way vs two-way grid coupling of H_2

- Conceptually, a two-way coupling in which water electrolysis is used to generate H_2 during peak generation periods and H_2-derived power (via fuel cells or H_2 turbines) is contributed during trough generation periods is appealing.
- While this may represent the optimal, long-term role of H_2 in supporting flexibility (remains to be proven), there are two reasons to believe that the path to this end state may evolve in an uneven manner.

One-way vs two-way grid coupling of H_2

- First, cost structures for each direction are not the same.
  - The capital cost of electrolyser systems and fuel cell systems are currently high, but the potential for cost reductions is uneven.
  - US DOE estimates the capital costs of PEM electrolysers (100 MW) to currently be in the $1353-1653/kW range (2018) with 2030 cost targets for economic competitiveness at $393-481/kW.
  - US DOE estimates for stationary fuel cell systems (100 MW) to currently be in the $1188-1452/kW range (2018) and 2030 cost targets for economic competitiveness to be $854-1044/kW.
  - Corresponding ranges for an all-in two-way system (100 MW, 10 hr) comprising a PEM electrolyzer, H_2 storage, and fuel cell are therefore $2793-3488/kW in 2018 and thus $1440-1824/kW by 2030. On a storage basis, the numbers are $279-349/kWh in 2018, and $144-182/kWh by 2030.
  - In a bidirectional energy storage system, the fuel cell contribution to the cost roll-up accounts for about 40% of the total capex of a current 2-way system (2018) but would grow to 60% of the total capex due to smaller expected levels of improvement.
  - In contrast, a unidirectional system that only withdraws electricity from the grid during peak production periods could see cost reductions of 70%, rather than 50% for a bidirectional system. While this ignores some of the downstream integration costs for the use of unidirectional H_2 production, the point is clear. If cost reductions follow qualitative expectations, the attractiveness of withdrawing power during peak production periods could see faster improvements relative to returning power during trough production.

One-way vs two-way grid coupling of H_2

- The use of H_2 to provide flexibility does not have to be bidirectional immediately.
- An alternative to the integrated H2 energy storage solution (e.g., electrolyzer, storage, and generation) is a dynamic arrangement where pockets of unidirectional flexibility develop as separate localized operations that coordinate via market signals:
  - electrolysis during peak production (i.e., to reduce curtailment)
  - system-level demand response options
- This might provide a more achievable path towards use of H_2 for flexibility services, rather than an integrated solution with expensive parts.

Some conclusions so far

- Flexibility is anticipated to become increasingly important as decarbonisation efforts progress.
- However, the role of EIIs and PtGtP H_2 in providing this service are far from straightforward.
- EIIs are deeply enmeshed in the economy, so any change here will have implications elsewhere.
- Further electrification of EIIs is possible, but not everywhere, and will result in very substantial increases in demand for power.
- It is not obvious that the electrification of EIIs will be even close to cost-neutral.
- There is some evidence for the extent to which EIIs can provide grid services, but this could result in profound and significant changes in the way in which EIIs operate – not obviously practicable at large scale.

Some (more) conclusions so far

- Electrolytic H_2 has a long and storied history, going back to the 18th century!
- The concept of storing "otherwise curtailed power" in electrolytic H_2 is a pervasive concept – especially in the inorganic chemistry literature.
- However, very substantial deployment of iRES is required before material amounts of curtailment emerge.
- Owing to very low capacity factors, this implies a very costly process, notwithstanding the fact that now the power is no longer "curtailed", and hence no longer "free".
- It is not obvious that two way coupling of H_2 production is optimal – given the amount of sector coupling anticipated, a one way connection might be more cost-effective.
- In all this, there is ample space for future work.