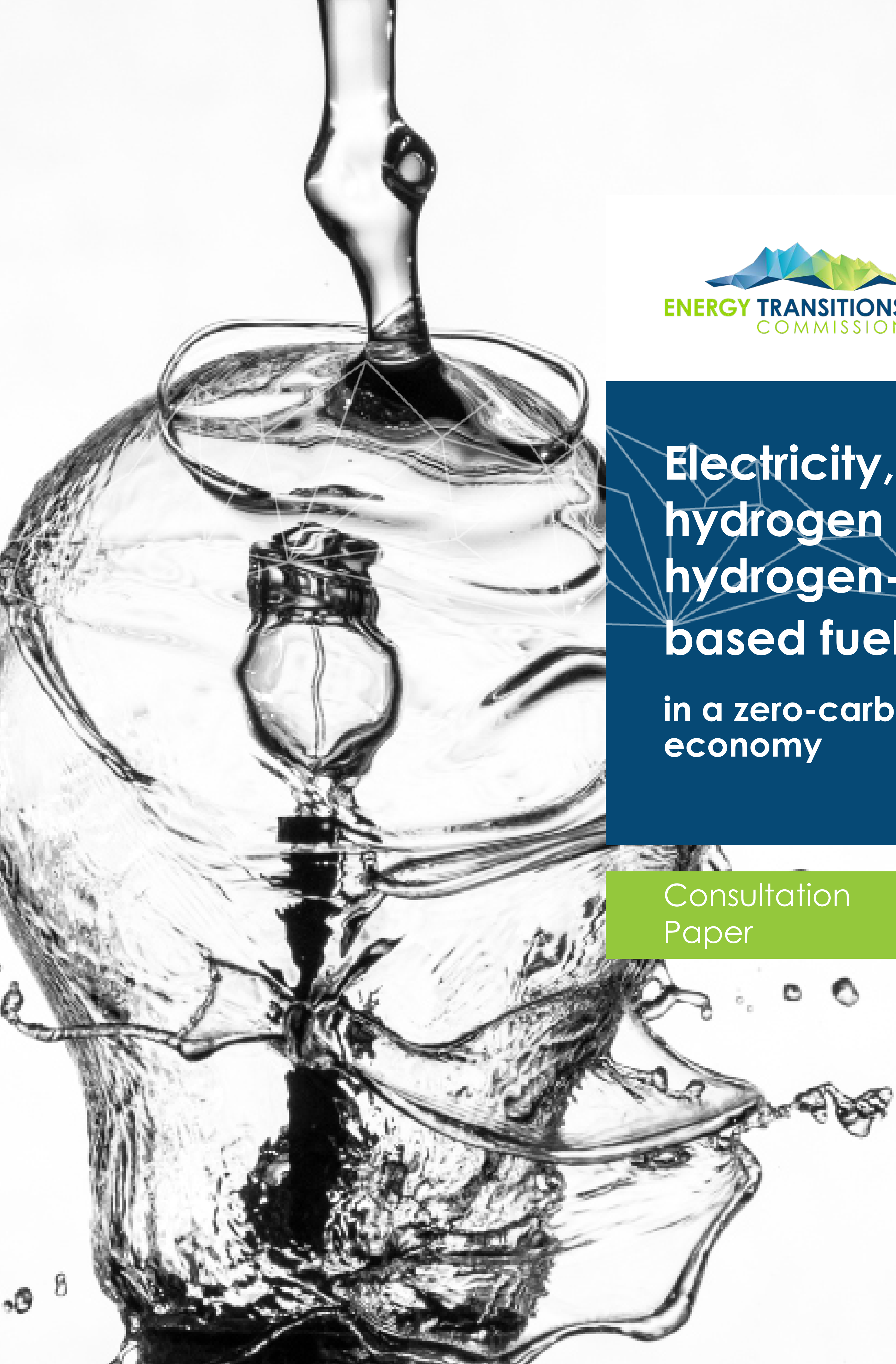


ENERGY TRANSITIONS
COMMISSION

Electricity, hydrogen & hydrogen-based fuels

in a zero-carbon economy

Consultation Paper

WHO ARE WE?

The Energy Transitions Commission (ETC) is **a global coalition of 30 leading executives from across the energy landscape** (energy companies, energy-intensive industries, investors, environmental NGOs and academics). Its mission is to define how to most effectively transition to low-carbon energy systems while also delivering the large increases in energy supply needed in many developing countries to enable economic prosperity, and to accelerate required action from public and private decision-makers.
In 2017, the ETC published Better Energy, Greater Prosperity, a report that outlines four strategies to cut carbon emissions by half by 2040. It argues in particular for an energy productivity revolution and a rapid decarbonization of electricity generation combined with the electrification of a wider range of economic activities.

OUR WORK ON "HARD-TO-ABATE" SECTORS

In 2018, the ETC is focusing its analytical and influencing efforts on **those sectors which are likely to be harder to decarbonize in heavy duty transport – trucking, shipping and aviation – and industry – steel, cement and plastics.** Together these sectors represent 40% of carbon emissions from the energy systems today, but this share will grow to 60% of remaining emissions by 2040 in a 2˚C scenario, as other high-emitting sectors are decarbonized and demand for mobility and materials grows in emerging economies. Our aim is to **assess whether and how these sectors can be fully decarbonized and to accelerate action** from key policy, industry and finance players.

WHAT IS THE PURPOSE OF THIS PAPER?

In June 2018, the ETC started releasing a series of **consultation papers** which lay out pathways to reach zero carbon emissions for these 6 different sectors. In addition, there are 3 consultation papers covering key cross-cutting technologies: electricity and hydrogen, biomass, and carbon capture, utilization and storage. These 9 consultation papers will form the basis of a series of targeted stakeholder engagement with industry players and civil society in order to refine our analysis and conclusions. This process will then **feed into an integrated report on the decarbonization of "hard-to-abate" sectors in industry and heavy-duty transport**, to be published in November 2018. The ETC also carries out actions to influence key decision-makers, which have begun with the ongoing consultation process and will intensify after the publication of the integrated report.

HOW WAS THIS PAPER DEVELOPED?

This consultation paper was **developed by the ETC Secretariat**, with the support of its members. It draws heavily on analysis from our research partners Material Economics, McKinsey and SYSTEMIQ, as well as on a review of the existing literature. It integrates feedback received through a **consultation workshop and bilateral exchanges with industry experts and representatives**, whom we would like to thank for their contributions.
Please note that the analysis and conclusions presented in this paper are still **being refined and should therefore be treated as being "work in progress"**. The members of the Commission and the institutions with which they are affiliated have not been asked to formally endorse this paper.

HOW CAN YOU PROVIDE FEEDBACK?

We warmly welcome feedback on this paper until 31st August 2018. Please send comments, questions and requests for follow-ups to pmo@energy-transitions.org. We are particularly interested in feedback on the feasibility and cost of different decarbonization options, and on the recommendations to policymakers, industries, businesses and investors. This feedback will be integrated in the final report to be published in November 2018.

TABLE OF CONTENTS

ELECTRICITY, HYDROGEN AND HYDROGEN-BASED FUELS IN A ZERO-CARBON ECONOMY

The Energy Transitions Commission's analysis of how to reach zero carbon emissions from "hard-to-abate" sectors in heavy industry and heavy-duty transport reveals that there are **three main routes to decarbonization**:

(i) The use of low/zero-carbon electricity, whether used directly or as a means to produce hydrogen and hydrogen-based fuels;

(ii) The application of carbon capture on carbon-emitting industrial processes, then combined with either carbon storage or carbon use;

(iii) The use of sustainable bioenergy and bio-based products.

This consultation paper assesses **the potential role of electricity-based technologies** to achieve a zero-carbon economy, and the resulting implications for industry and public policy. In its assessment of the role of hydrogen and hydrogen-based fuels, it considers both **hydrogen produced by electrolysis and hydrogen produced by steam methane reforming (SMR) combined with carbon capture**.

Separate consultation papers on *Carbon capture in a zero-carbon economy* and *Bioenergy and bio-based products in a zero-carbon economy* consider the role of those alternative decarbonization routes.

Our emerging conclusion is that **electricity, hydrogen and hydrogen-based fuels will play a major and, in the long term, possibly dominant role in achieving a zero-carbon economy**. Exhibit 1 summarizes how they could offer decarbonization solutions in each of the main hard-to-abate sectors in heavy industry and heavy-duty transport, as well as in other key sectors of the economy. But the role of electricity-based technologies **will vary by country/region**, given major differences in renewable power resources, and **the respective scopes of electricity, hydrogen and hydrogen-based fuels will depend on technology developments** which could alter their relative feasibility and cost-competitiveness in different sectors.

Exhibit 1 – Role of electrification and electricity-based fuels in the hard-to-abate sectors

Sectors		Direct electrification	Electricity-based fuels	Decarbonization alternatives
Industry	Cement	Electrification of kiln heat (process emissions remain)	Hydrogen fired kilns	CCS Timber substitution
	Iron and steel	Electric Arc Furnace production Direct iron electrolysis (possibly in long term)	Hydrogen as reduction agent and heat source	CCS Biomass as heat source and reduction agent
	Ammonia		Production from hydrogen from electrolysis	CCS Biogas as substitute for methane in SMR
	Ethylene	Electrification of furnace heat	Hydrogen as heat source and feedstock	CCS Biogas as fuel or feedstock Recycling/reuse of plastics
Transport	Trucking	Battery Electric Vehicles Catenary overhead wiring	Hydrogen in ICE or fuel cell	Biodiesel or bio-gasoline as fuel
	Aviation	Battery electric for short distance	Hydrogen fuel cells for short distance Synthetic jetfuel	Bio-jetfuel
	Shipping	Battery electric for short distance Cruise and RoPax ships	Hydrogen fuel cell or ICE Ammonia in ICE	Biodiesel Direct combustion of biomass/waste
Building heating		Through heat pumps or induction	Hydrogen as a substitute for natural gas Ammonia for transportation and seasonal storage	Biogas as substitute for methane Biomass and district heating

SOURCE: Energy Transitions Commission analysis

The ETC's indicative maximalist scenario indicates that **demand for hydrogen could grow up to 10 times by mid-to-late century, while electricity demand could be multiplied by 4 due to direct electrification and by 5 if all hydrogen is produced by electrolysis.** This trend has major implications for investment needs in power generation and grid strengthening. In particular**, it makes power decarbonization even more crucial** as major carbon emissions would result from electrification if it was powered by unabated coal and gas generation.

Top 3 actions to accelerate the transition for…		
… R&D	**… Industry/Businesses**	**… Public policy**
• Achieving breakthroughs in battery cost, weight density and charging rates • Driving down the cost of electrolysis, fuel cells, hydrogen tanks and refueling stations • Pilot electricity-based and hydrogen-based industrial processes	• Develop joint R&D projects between energy producers and energy-intensive sectors to pilot new technologies • Agree on an industry roadmap to shift to green hydrogen • Expand the EV100 campaign to 100% green trucking	• Develop an integrated power strategy combining electrification and power decarbonization • Ramp up investment in renewables and low-carbon electricity generation • Develop electric charging and hydrogen refueling infrastructure

1. POTENTIAL SCOPE AND KEY PRIORITIES FOR 3 ELECTRICITY-BASED DECARBONIZATION ROUTES

The ETC's first major report *Better Energy, Greater Prosperity*, published in April 2017, described the dramatic reductions that have occurred and will likely continue to occur in the cost of renewable electricity generation. **We suggested that, by 2035, it will be possible in almost all geographical locations to run electricity systems which are nearly completely (i.e. roughly 80%) dependent on variable renewable sources while providing electricity at a maximum all-in cost of below $70/MWh**, with $40/MWh for renewable power generation and $30/MWh for the provision of flexibility and back-up, using lithium ion batteries for daily storage and gas plants for additional peaking needs[1].

- **This all-in cost could be further reduced – to $55-60/MWh – if using a broader range of flexibility options**, such as existing dispatchable hydro, interconnections and demand management[2].
- Since then, further evidence has demonstrated that progress is likely to be faster than anticipated, in particular that renewable power generation costs will be below $20/MWh in the most favorable locations in the 2030s. **Near-total-variable-renewable power systems delivering electricity at an all-in cost of $35-40/MWh would therefore be possible in these favorable locations** (see Section 4 for discussion of the regional variations in renewable resources and the implications for relative costs).

Even without a carbon price, **these cost levels would make a renewable-based power system cost-competitive – and possibly cheaper – than a gas-based power system**. Any energy strategy should therefore drive the deployment of renewable power as fast as possible. In this new energy landscape, **electrifying as much of the economy as is possible and cost-effective**, either directly or indirectly through electricity-based fuels, will also constitute a powerful driver of decarbonization.

A. DIRECT ELECTRIFICATION

Direct electrification is certain to play a major role in many transport and industry sectors [Exhibit 2].

- **In surface transport**, the inherent efficiency advantage of electric engines means that electric vehicles are certain to dominate in the passenger cars sector. Our analysis of the heavy road transport sector[3] suggests that they are also likely to play the dominant role there. Electric engines could be powered either by batteries or via hydrogen fuel cells. The relative importance of one versus the other will depend primarily on the weight and charging speed of batteries. Indeed, within the passenger car sector, batteries will likely dominate, whereas, in the trucking sector, there may be a major potential role for hydrogen fuel cells.
- **In aviation and shipping**, our analysis suggests that the potential for battery-based electrification will be limited to shorter-haul flights and voyages, unless and until there are major breakthroughs in battery energy density[4].

[1] ETC (2017), *Better Energy, Greater Prosperity* & Climate Policy Initiative for ETC (2017), *Low-cost, low-carbon power systems*
[2] Ibid
[3] ETC (2018), *Reaching zero carbon emissions from heavy road transport – Consultation paper*
[4] ETC (2018), *Reaching zero carbon emissions from shipping – Consultation paper* & *Reaching zero carbon emissions from aviation – Consultation paper*

- **In heavy industry**, analysis conducted by our knowledge partner McKinsey & Company[5] suggests that the electrification of heat input to several industrial processes, including cement kilns and ethylene production, is technically feasible and would become economic if electricity prices were very low [Exhibit 3]. The gradual shift of steel production from blast furnaces to direct iron reduction (with gas or hydrogen) and from primary production to secondary production will also generate significant electricity demand for electric arc furnaces (EAF)[6]. In the long-term, direct iron electrolysis may also become possible, but it is still at an early research stage of development.
- Outside the hard-to-abate sectors in heavy industry and heavy-duty transport, which the ETC has analyzed over the last year, the crucial open question relates to the best route to decarbonize **residential heat**. This may involve direct electrification made more efficient through use of heat pumps. Alternative routes include the use of hydrogen, biogas, or the direct distribution of heat (possibly generated from biomass).

Exhibit 2 – Direct electrification benefits and limitations

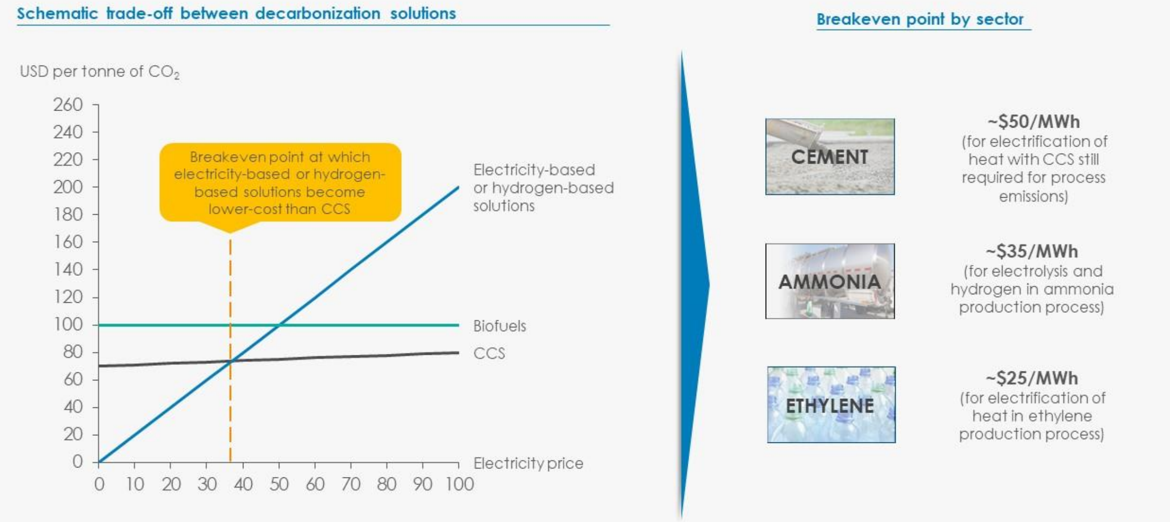
Sectors		Potential Role	Benefits and Limitations
Industry	Cement	Electrification of kiln heat (process emissions remain)	• Electric kilns still at development stage
	Iron and steel	Electric Arc Furnace production Direct iron electrolysis (possibly in long term)	• Will automatically grow with increased secondary steel volumes • Still at early research stage
	Ethylene	Electrification of furnace heat	• Electric furnaces still at early development stage
Transport	Trucking	Battery Electric Vehicles Catenary overhead wiring	• Fundamental efficiency advantage of electric engines (95% versus 35% for ICEs) mean BEVs or FCEVs likely to dominate long-term
	Aviation	Battery electric for short distance	• Efficiency advantage of electric engines offset by battery weight and volume related issues
	Shipping	Battery electric for short distance Cruise and RoPax ships	
Building heating		Through heat pumps or induction	• Heat pumps can deliver up to 300% efficiency (heat out to electricity in) in optimal conditions

SOURCE: Energy Transitions Commission analysis

It is inherently difficult to predict the exact role which electrification should and will play vis-a-vis other decarbonization routes. But all scenarios for achieving net zero carbon emissions from the energy sector assume that the use of electricity will increase dramatically to account for the majority of all energy use by the mid-to-late 21st century. The recently published Shell Sky Scenario, for instance, assumes that electricity use could rise from roughly 20% of total final energy demand today to more than 60% by 2070 [Exhibit 4][7].

[5] McKinsey & Company (2018), *Decarbonisation of the industrial sectors: the next frontier*
[6] ETC (2018), *Reaching zero carbon emissions from steel – Consultation paper*
[7] Shell (2018), *Shell Sky Scenario – meeting the goals of the Paris agreement*

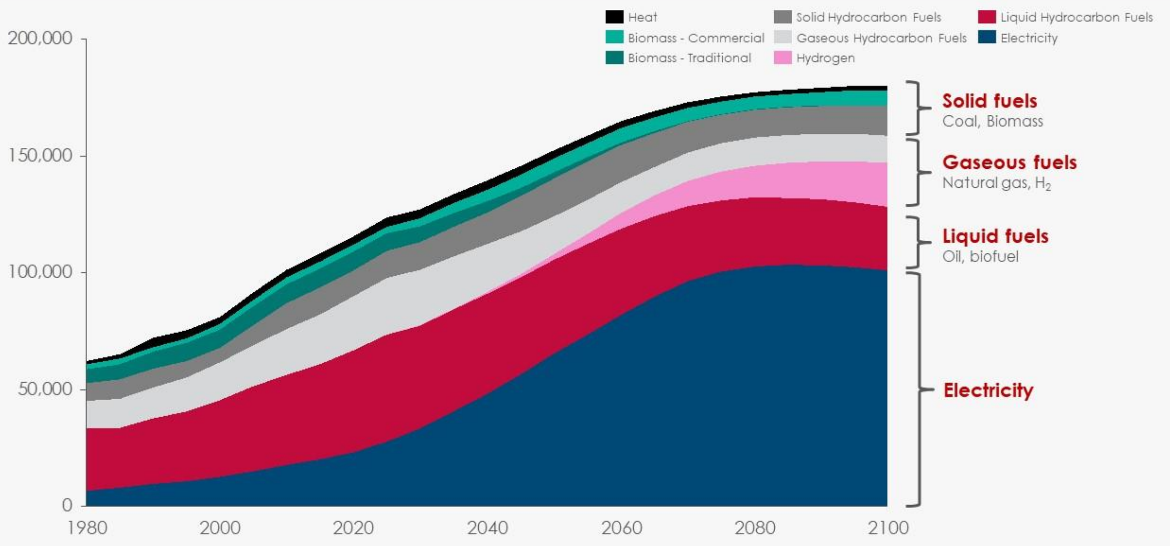
Exhibit 3 – In industry, the least-cost solution to decarbonize processes will vary from region to region depending on local resources, in particular local electricity prices



NOTE: Breakeven points are for greenfield plants
SOURCE: McKinsey & company, 2018, *Decarbonization industrial sectors: the next frontier*

Exhibit 4 – Global end-use energy consumption in Shell's Sky scenario

TWh per year (energy source)



SOURCE: Shell analysis, Sky scenario

Beyond renewable energy costs, key developments and policy actions which will determine the scale and crucially the pace of direct electrification include:

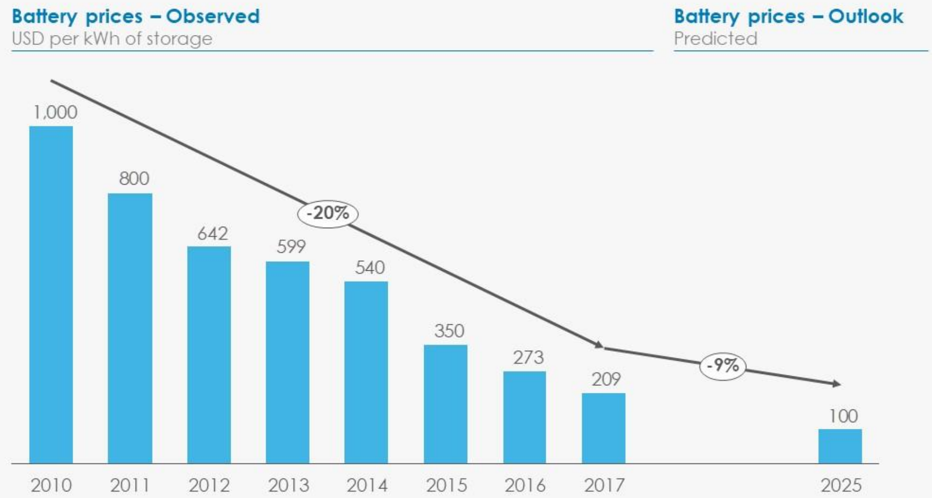
- **Improvements in battery cost:** The cost of lithium-ion battery packs for automotive applications has already fallen by 80% in the last six years, and is projected to fall below $100 per kWh by 2025, likely making electric cars cheaper than ICE vehicles [Exhibit 5]. The pace of cost reductions achieved will also be essential if batteries are to be used at scale as a flexibility mechanism in the power grid, versus other forms of storage (e.g. hydrogen, or heat) or backup (e.g. gas, biogas).
- **Improvements in charging rate:** Beyond cost, significant improvements in charging rate are still required for battery electric vehicles to play a major role in long-distance trucking. Very high-speed charging at 300-350 kW is currently under development and deployment, but much higher charging rates (in the 2000-3000kW range) would facilitate deployment of BEVs for long-distance road and would likely be required for shipping or aviation. [Exhibits 6 & 7]
- **Improvements in battery density:** Improvements in gravimetric (i.e. weight) density would also facilitate use of batteries on the longest-distance roads, while a six-fold improvement in gravimetric density would be needed to make battery flight feasible for international travel [Exhibits 6 & 7].
- **Widespread vehicle charging infrastructure:** The development of a widespread electric charging infrastructure with very high-speed charging points (e.g. at 350 kW or higher), in particular for passenger cars and trucks, will be essential to the deployment of battery electric vehicles on roads. Charging infrastructure for buses, short-haul electric ships and planes will likely be easier to deploy as it will be more concentrated.
- **Development of overhead (catenary) wiring infrastructure:** It would be possible to electrify very-long-distance trucking with smaller batteries, if governments were to drive the development of overhead (catenary) charging on major autoroutes/freight corridors. However, deployment costs and social acceptability of wiring infrastructure might play in favor hydrogen fuel cells as a "range extender" for trucking in place of overhead wiring.
- **Innovation in industrial electrification**: Most potential uses of electricity in heavy industry, in particular high-heat electrification in the cement or chemicals industries and direct iron reduction through electrolysis, are still at early stages of development and need to be further proven and piloted before a potential deployment.

Direct electrification of both transport and industry, in particular the need for widespread charging infrastructure for road transport, may require significant **reinforcement of local power distribution grids**. The extent of the investment required will be heavily influenced by the sophistication of demand management and pricing techniques. If car owners all tend to charge EVs at a similar time, significant investments in the "last 100 meters" distribution grids may be required. But if sophisticated time of day pricing, remotely controlled charging and smart management of shared car fleets (which are likely to grow in comparison to individual car ownership[8]) are developed, required grid strengthening may be minimal. We have yet to conduct quantitative analysis of this issue, but will include coverage of it in our final report on the decarbonization of hard-to-abate sectors which will be published in November 2018.

[8] Material Economics (2018), *The circular economy: a powerful force for climate mitigation*

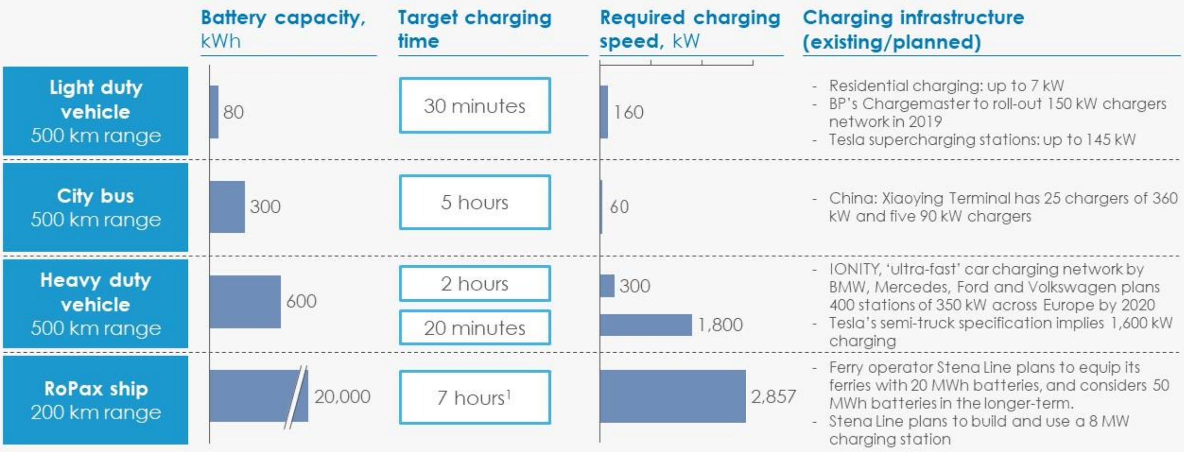
Exhibit 5 – Historical and forecast battery prices

USD per kWh of storage



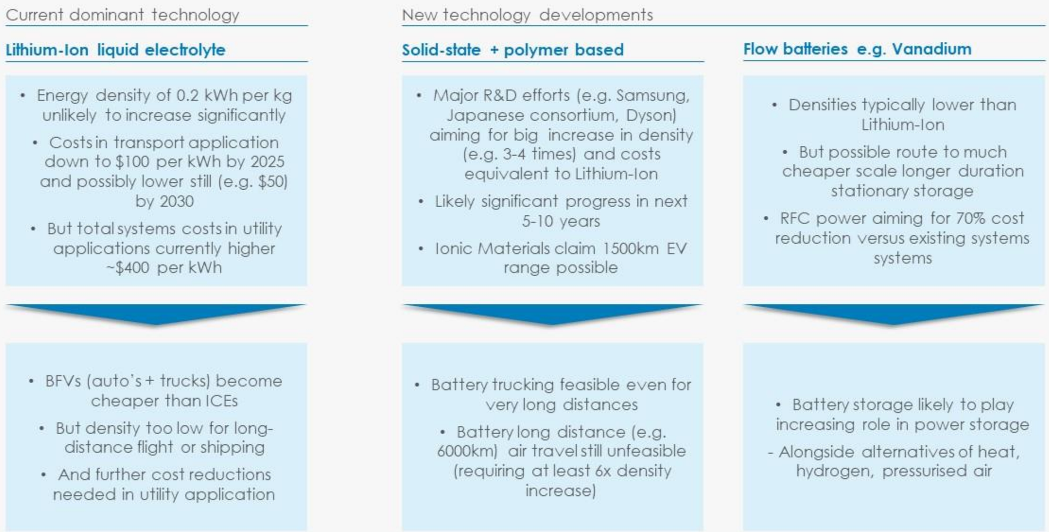
SOURCE: Bloomberg New Energy Finance, 2017

Exhibit 6 – Charging rate needs and planned



1: For MWh capacity batteries, modular charging might be considered (dividing into smaller batteries charged at the same time)
SOURCE: Energy Transitions Commission analysis

Exhibit 7 – Possible and required developments in battery technology



SOURCE: Energy Transitions Commission analysis; IVA's Electricity Crossroads project, 2016, Electricity storage technologies; IRENA, 2017, Electricity Storage and Renewables: Costs and markets to 2030; Schmidt et al., 2017, The future cost of electrical energy storage based on experience rate

B. HYDROGEN USE

While direct electrification is certain to be a major route to decarbonization in both the hard-to-abate and other sectors of the economy, **there are many applications where a "molecule-based" route to decarbonization is likely to be more cost-effective**, using either hydrogen/hydrogen-based fuels or biofuels/biogas to deliver low/zero carbon chemical energy [Exhibit 8].

- **In the heavy-duty transport sectors**, decarbonizing very long-distance trucking, shipping and aviation requires greater energy densities than batteries currently offer, but which hydrogen, ammonia, biofuels or synthetic hydrocarbon fuels may deliver.
- **In the steel sector**, blast furnace emissions arise from the iron reduction process as well as the energy input. Replacing coking coal with hydrogen as the reduction agent may be a key route to decarbonization, which has already been embraced by companies like SSAB and Salzgitter.
- **In other industrial processes** (e.g. cement and ethylene production), the use of a low-carbon heat source (hydrogen or biomass) may prove more cost-effective than direct electrification, where further development is still required before electric furnaces can be commercially deployed at large-scale.
- Finally, **in residential heating**, it is possible to use hydrogen, piped through converted gas networks, as an alternative to methane – as proposed by the Northern Gas Networks project being developed in the British city of Leeds[9]. But alternative routes to decarbonization, using electric heat pumps, biogas, or district heating systems may be more cost-effective.

[9] Northern Gas Networks, *Northern gas networks hydrogen project takes step forward as £25 million fund announced for hydrogen in homes*

In addition to this range of potential applications for hydrogen at final consumption level, hydrogen could also play a major role in **providing storage and flexibility backup within an electricity system** dependent primarily on intermittent renewables. Cheap, zero or even negative cost electricity might be used to generate hydrogen during periods when supply exceeds demand to subsequently be re-converted into electricity when demand exceeds supply.

Exhibit 8 – Potential role of electricity-based fuels

Sectors		Hydrogen	Ammonia	Synthetic hydrocarbon fuels
Industry	Cement	As kiln heat source		
	Iron and steel	As reduction agent and heat source		
	Ammonia	Input to Haber-Bosch process		
	Ethylene	Heat source for ethylene + other monomer production Potential role as plastics feedstock		
Transport	Aviation	Fuel cell electric planes for short distance		In conventional jet engine
	Trucking	FCEV or in ICE		In ICE
	Shipping	Fuel cell electric or burnt in ICE	Ammonia in ICE or fuel cell	
Building heating		As substitute for natural gas		
Electricity generation		Storage of energy from surplus electricity to cover peak needs	Storage device generated from surplus electricity to cover peak needs Used for transportation of hydrogen	

SOURCE: Energy Transitions Commission analysis

The balance between the use of hydrogen (or hydrogen-based fuels) and other routes to decarbonization (e.g. direct electrification, biomass or carbon capture) will be determined by **the relative costs of these different decarbonization routes**.

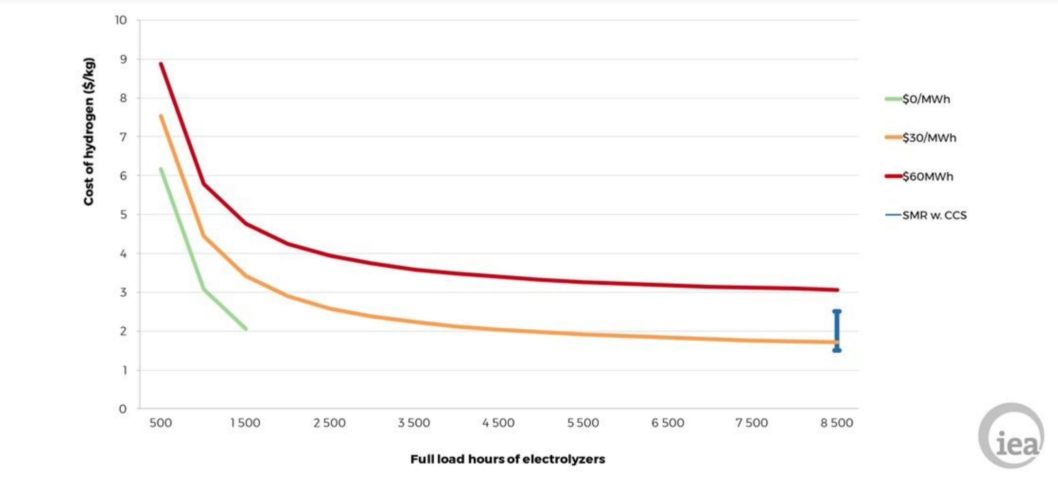
The cost of hydrogen itself will depend on the chosen production route. Today, more than 95% of hydrogen is produced through fossil fuel reforming, as this is currently the most economic pathway. In future, **zero-carbon hydrogen could be produced either by applying carbon capture to the existing steam methane reforming (SMR) process or via electrolysis.**

- Since SMR produces a close to pure CO_2 stream, the costs of capture from SMR are among the lowest across all CCS applications, at around $10 per tonne of CO_2 saved. This cost would, however, be higher if heat emissions, which are more diluted, had to also be captured[10]. **SMR plus CCS/U may be the most cost-effective way to produce zero-carbon hydrogen in some locations**, where underground carbon storage and/or a large carbon use market are available. But, as will be noted in Section 2 below, if all future hydrogen demand was met by SMR plus CCS/U, **the need for downstream carbon storage or use could reach 3 Gt per annum for hydrogen production only**[11].
- Given potential limits to the availability of carbon storage and to the size of the CO_2 market, there will therefore also be **a major role for hydrogen production via electrolysis**. The cost of producing hydrogen from electrolysis will be driven by the cost of electricity, and the capital cost and efficiency of electrolysis equipment. These costs are likely to fall significantly as renewable electricity gets cheaper and as deployment drives economy of scale and learning curve effects.

[10] ETC (2018), *Carbon capture in a zero-carbon economy – Consultation paper*
[11] SYSTEMIQ analysis for the Energy Transitions Commission

- An April 2017 IEA publication[12] sets out that **the cost of producing hydrogen from electrolysis may already be competitive with the traditional SMR route** (even without accounting for any CCS costs), if electricity prices are at $30/MWh or below and if high load factors can be achieved, even with electrolyzer capital costs of $850/kW [Exhibit 9]. In the 2030s, renewable electricity costs are likely to be at, and in many cases significantly below, this level in many favorable locations (see Section 4 below).
- **Lower capital costs for electrolysis equipment would significantly reduce hydrogen production costs** and would allow the production of low-cost hydrogen even in situations where cheap electricity was only available for a smaller number of hours per annum. As Exhibit 10 illustrates, moving from an electrolyzer capital cost of $850/kW to one of $250/kW makes little difference to the total cost of hydrogen if electricity costs are high and if electrolyzer utilization is also high. But if utilization rates are only 10% and electricity is available at $20/MWh, the same reduction in electrolyzer capital cost would halve the cost of hydrogen production.
- **Estimates of current and future potential electrolyzer costs vary greatly** and are hugely dependent on assumptions about the scale of production and future learning curve effects. Thus, while many literature studies assume that even 2030 capital costs for alkaline electrolyzer cells (AECs) will be close to $1000/kW[13], the Norwegian company NEL says that "for the time being, and for a large-scale plant of 200 to 400 MW, we estimate a capex level of $450/kW"[14]. This figure is in turn used for analysis in the IEA's report on *Renewable Energy for Industry*[15]. Some industry experts suggest that still lower electrolyzer costs, heading down towards the $250/KW, could be attainable if production scale were massively increased.

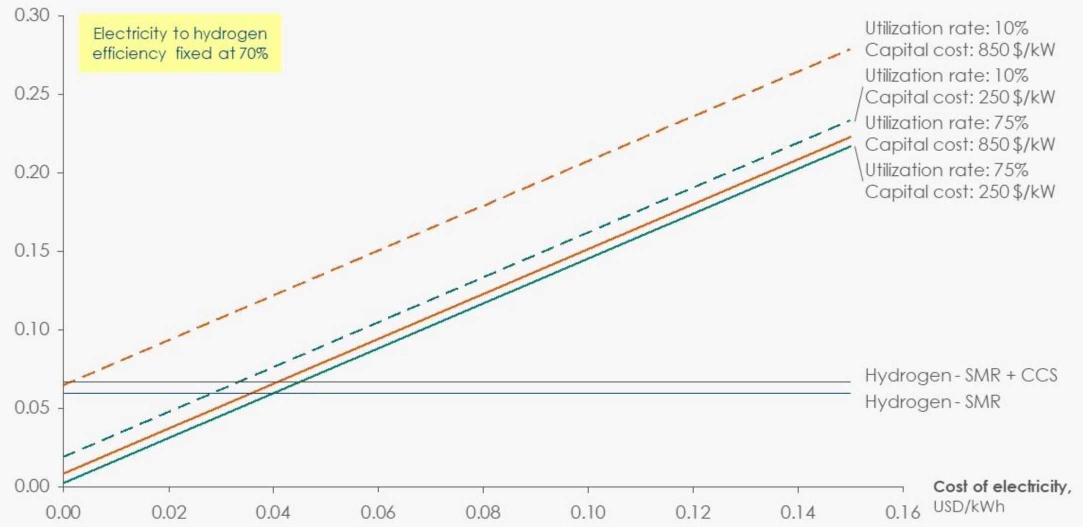
Exhibit 9 – Cost of hydrogen from electrolysis for different electricity costs and load factors
$ per kg



ASSUMPTIONS: Based on alkaline electrolyzer. CAPEX of electrolyzers USD 850/kW, WACC 7%, lifetime 30 years, efficiency 74%
Cost of hydrogen from SMR USD 1 to 3/kg, cost of CCS USD 0.75/kg H2 (~USD 75/tCO$_2$)
SOURCE: IEA, Commentary: Producing industrial hydrogen from renewable energy (April 2017).

[12] Cedric Philibert, IEA, 2017, *Producing industrial hydrogen from renewable energy*
[13] Schmidt et al. (2017), *Future cost and performance of water electrolysis: An expert elicitation study*
[14] Simonsen (2017), *Nel and high water: the ultra-efficient electrolyser*
[15] Philibert C., IEA (2017), *Renewable energy for industry*

Exhibit 10 – Cost of hydrogen from electrolysis for different electricity costs and load factors
$ per kWh



1: Assumptions: SMR costs are 1-3 $/kg, CCS cost is 30-40 $/ tons of CO_2, i.e. ~0.2-0.3 $/kg hydrogen
SOURCE: Energy Transitions Commission analysis, press research, International Energy Agency 10

In parallel, **a range of hydrogen-related technologies need to see their cost decrease** to enable widespread deployment of hydrogen-based solutions.

- In transport applications as well as in industry applications, **the cost of hydrogen storage** will be a key element of the overall cost-competitiveness of hydrogen-based solutions. Today's costs for pressurized tanks used in fuel cell electric vehicles are around $35/kWh, while the IEA Technology roadmap for Hydrogen and Fuel cells recommends reaching at least $15/kWh by 2025[16]. Other storage options like cryogenic storage, liquefaction or solid-state storage still required further research.
- In transport applications which use electric engines, **the cost of fuel cells** will be another crucial driver of relative costs[17]. Here too, the scale of production will be a key factor. The IEA roadmap, drawing on US Department of Energy analysis, suggest that while current costs for small scale production are around $280 per kW, with higher production volumes costs could fall to $50 per kW and eventually to significantly less [Exhibit 11][18].
- Finally, scaling up hydrogen for transport solutions would also require **major infrastructure investments**. The Hydrogen Council estimates the cost of a filling station at $1.25-1.5 million today. By 2030, this would represent $1,500-2,000 per FCEV, which is in the same order of magnitude as infrastructure cost for battery vehicles, considering a home charger costs $2,000 today. Hydrogen Council members aim to reduce charging infrastructure costs to $1000 per FCEV.[19]

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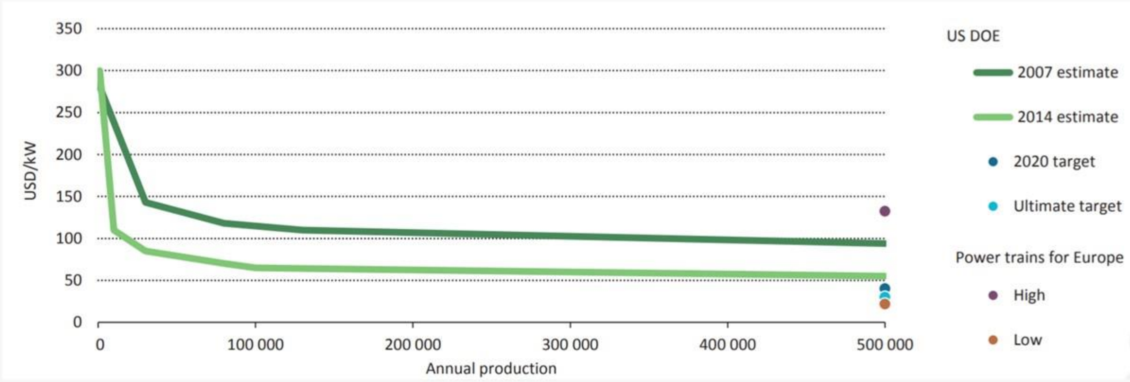
[16] IEA (2015), *Technology Roadmap: Hydrogen and Fuel Cells*
[17] In some transport applications – e.g. ships and aviation –, hydrogen may be burnt directly, or used in the form of ammonia or synthetic hydrocarbons which are in turn burnt.
[18] IEA (2015), *Technology Roadmap: Hydrogen and Fuel Cells*
[19] The Hydrogen Council (2017), *Hydrogen scaling up, a sustainable pathway for the global energy transition*

Exhibit 11 – Projection cost for PEMFCs for fuel cell electric vehicles as a function of annual production



SOURCE: IEA, 2015, *Technology Roadmap Hydrogen and Fuel Cells* (adapted from McKinsey and Co. (2011), A Portfolio of Powertrains for Europe: a Fact-Based Analysis, The Role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles; US DOE (2012), Fuel Cell Technologies Program Record; US DOE (2014d), DOE Fuel Cell Technologies Office Record – Fuel Cell System Costs)

The future cost path of hydrogen-related technologies will thus be strongly determined by the future scale of hydrogen production and use, which in turn will reflect these costs. Precise future developments are therefore impossible to predict. But we know from renewable power prices that **self-reinforcing economy of scale and learning curve effects can produce dramatic cost reductions** and that it is almost certain that the production volumes of hydrogen-related technologies will increase significantly by mid-century. In Section 2, we indeed present an indicative scenario in which **total global hydrogen production increases 10 times by the mid-to-late 21st century**. If half of this was produced via electrolysis and half via SMR plus CCS/U, **installed electrolyzer equipment would need to grow about 100 times**, given that electrolysis accounts for only about 5% of current hydrogen production[20].

[20] Gandia et al., 2013, *Renewable hydrogen technologies*

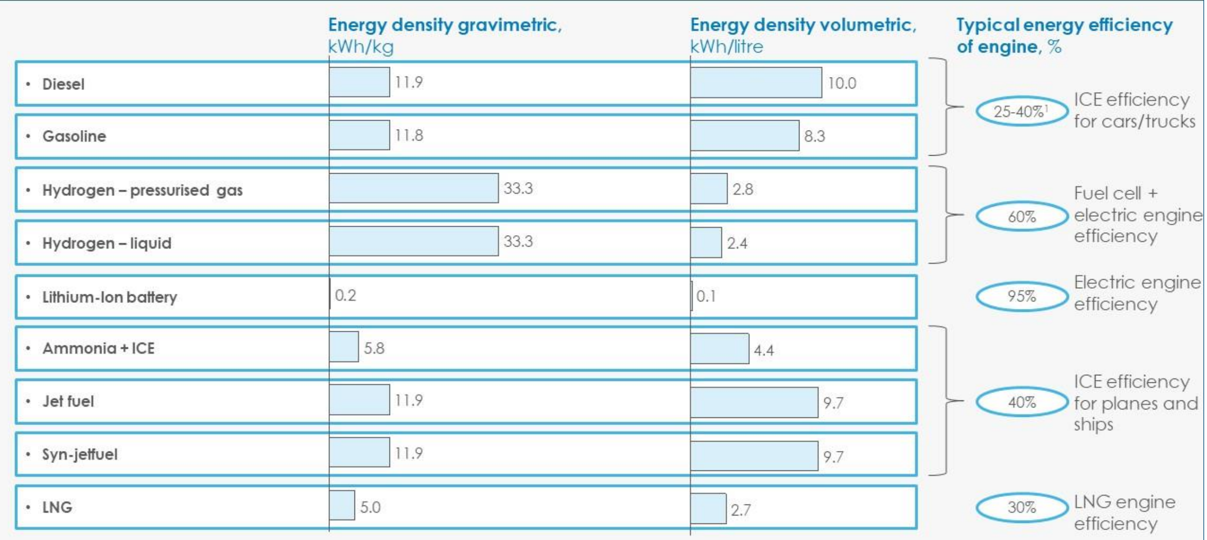
C.HYDROGEN-BASED FUELS: AMMONIA AND SYNTHETIC HYDROCARBONS

At 33 kWh per kg, hydrogen is, in gravimetric terms, far more energy dense than diesel and gasoline at around 12 kWh per kg; but, in volume terms, it is far less dense with 2.4-2.8 kWh per liter compared with 8.3 kWh for gasoline and 10 kWh per liter for diesel [Exhibit 12]. **This volume density disadvantage may limit direct use of hydrogen in transport applications** where its high gravimetric density should in principle be a major advantage.

For instance, in aviation, the volume requirements for hydrogen storage would make it impossible for very long-distance flights if hydrogen tanks were retrofitted within existing airframes[21]. Similarly, in shipping, lost cargo space which would result if hydrogen tanks were installed in existing ships would impose a significant cost penalty[22].

It is possible that these disadvantages could be overcome by radical new designs for ships and aircrafts. A major direct role for hydrogen in long-distance aviation and shipping cannot therefore be excluded. The alternative possibility is that **hydrogen could be used to make more energy-dense fuels such as either ammonia or synthetic liquid hydrocarbons.**

Exhibit 12 - Characteristics of the energy sources



Note: the values for hydrogen are the low heating values (LHV). ICE means Internal Combustion Engine
1: 25% for light-duty vehicles and 40% for heavy-duty vehicles
SOURCE: Energy Transitions Commission analysis

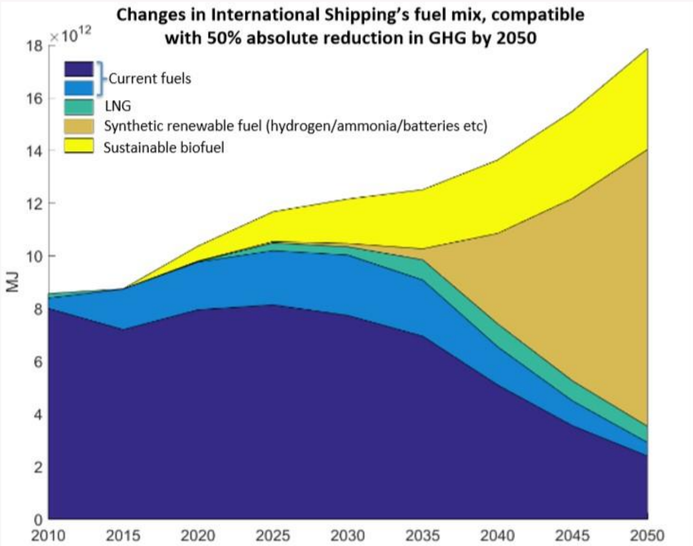
AMMONIA

If zero-carbon hydrogen is available (whether from electrolysis or from SMR plus CCS/U), zero-carbon ammonia can be produced via the standard Haber-Bosch process. The main advantage of ammonia is to have greater volumetric density than hydrogen (4 kWh/liter versus 2-3 kWh/liter) and far greater gravimetric density than batteries (5.8 kWh/kg versus 0.2 kWh/kg). It is also an easier fuel to store than hydrogen since liquid at the relatively workable temperature of -33.4°C (at 1 bar pressure) versus -253°C for hydrogen. **It is therefore likely to be easier to handle and transport than hydrogen.**

[21] ETC (2018), *Reaching zero carbon emissions from aviation – Consultation paper*
[22] ETC (2018), *Reaching zero carbon emissions from shipping – Consultation paper*

Ammonia may therefore be used in transport applications, where neither batteries nor hydrogen provide a satisfying solution due to their respective gravimetric and volumetric densities. Ammonia can either be passed through a reformer and a fuel cell to produce electricity and power an electric engine, or combusted directly in internal combustion engines. As we noted in our consultation paper on shipping**, ammonia may therefore be a very attractive route towards decarbonization of shipping**, enabling the retrofit and continued use of existing engines within the ship fleet – a major advantage in an industry with very long asset lifetimes[23]. Scenarios developed by UMAS/Lloyds Register suggest ammonia combustion within ship engines currently using HFO – which are sturdy engines that can adapt to a range of fuels – may be the most important route towards zero-carbon shipping [Exhibit 13].

Exhibit 13 – International shipping's fuel mix compatible with 50% absolute GHG reduction by 2050, MJ



SOURCE: Smith, T., Raucci, C., Haji Hosseinloo S., Rojon I., Calleya J., De La Fuente. S., Wu P., Palmer K, October 2016, CO_2 *emissions from international shipping. Possible reduction targets and their associated pathways.* Prepared by UMAS.

In addition, **it is possible that a major role for ammonia may emerge as an intermediate energy carrier**, with hydrogen converted to ammonia for transport, and subsequently turned back to hydrogen before end use. This could facilitate international trade of cheap hydrogen produced in favorable locations, especially in case the practicalities and cost of hydrogen storage do not improve significantly. However, the technology to extract hydrogen from the ammonia at end of export has been missing until recently. CSIRO have established a pilot plant to refine hydrogen from gasified ammonia hoping to prove the concept[24], which would allow them to export renewable energy to countries like Japan, which face geographical constraints to deploying enough renewable energy domestically to meet energy demand.

SYNTHETIC LIQUID HYDROCARBONS

An alternative way forward is to **use hydrogen to produce synthetic fuels which are the precise chemical equivalent of existing fuels**. Like biofuels, synthetic fuels can be used directly within existing engines and require no change to existing fuel distribution or handling systems.

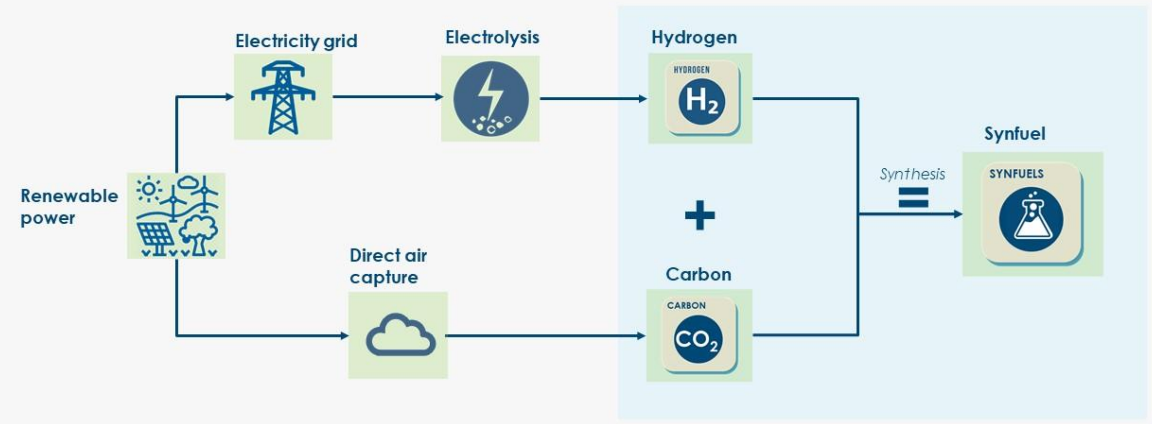
- **Synthetic fuels and biofuels may therefore be a key route to aviation decarbonization**, where there is limited alternative to using a low-carbon liquid hydrocarbon, especially for long-haul flights, in the absence of technology breakthroughs in batteries and hydrogen tanks[25].

[23] ETC (2018), *Reaching zero carbon emissions from shipping – Consultation paper*
[24] CSRIO, 2017, *Membrane to fill gap in hydrogen export market*
[25] ETC (2018), *Reaching zero carbon emissions from aviation – Consultation paper*

- **They might also play a role in shipping decarbonization**, although the range of alternative solutions for shipping is broader, including direct use of hydrogen and ammonia either in fuel cells or in internal combustion engines[26].

Synthetic hydrocarbons – including aviation jet fuel – can be produced from the synthesis of CO_2 and H_2, with the latter in turn produced by electrolysis using renewable electricity [Exhibit 14]. The CO_2 could be sourced from either direct air capture (DAC) or from carbon capture at the end of industrial processes or power plants. In the latter case, the fact that "the same molecule is used twice" delivers a net CO_2 reduction during the transition to a zero-carbon economy, but only the former (DAC) provides a route to a truly zero-carbon system.

Exhibit 14 – Overview of synfuels production process



Source: German Energy Agency, 2017, *The potential of electricity-based fuels for low-emission transport in the EU*

The balance between synthetic fuels versus biofuels in aviation decarbonization will be determined by relative costs, and in particular by the cost of DAC and the cost of hydrogen.

- Recent analysis of the technology developed by the Canadian company Carbon Engineering suggests that **DAC costs of below \$100 per tonne of CO_2** are possible[27]. As a comparison, researchers from the Center for Negative Emission of Arizona State University estimate the capture cost of the technology they develop (ion exchange resin) to be between \$30 and \$200 per tonne of CO_2[28].
- The ETC's discussions and analysis suggest that with capture costs around this level, it could be **possible to produce synthetic jet fuel at a price premium of 100% over conventional jet fuel[29]**, and that this price premium is likely to decline significantly over time. At this stage this price premium would be in the same order of magnitude than available bio jet fuel[30].

As the ETC's consultation paper *Reaching zero carbon emissions from aviation* argues, **higher fuel costs would add between \$40 and \$120 to the price of a 6500km journey for an economy passenger.** While significant, this additional cost appears to be an acceptable and manageable cost of emissions reduction for the end consumer.

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[26] ETC (2018), *Reaching zero carbon emissions from shipping – Consultation paper*
[27] Keith D. W. et al (2018), *A process for capturing CO_2 from the atmosphere* & Tollefson, J., 2018, *Sucking Carbon Dioxide from the air is cheaper than scientists thought*
[28] Ishimoto Y. et al (2017), *Putting costs of direct air capture in context*
[29] SYSTEMIQ analysis for the Energy Transitions Commission
[30] ETC (2018), *Reaching zero carbon emissions from aviation – Consultation paper*

Hydrogen-based fuels are thus likely to play a role in an eventual zero-carbon economy. But their impact on CO_2 emissions depends crucially on whether hydrogen production itself is low-carbon, and therefore, in the case of electricity-based hydrogen, on how far power generation has been decarbonized. Issues relating to the carbon intensity of hydrogen-based fuels, relative to conventional fuels and to direct electrification, are considered in Section 3 below.

2. AN INDICATIVE SCENARIO FOR TOTAL ELECTRICITY AND HYDROGEN DEMAND

While the exact role of both direct electrification and of hydrogen-based fuels in the decarbonization of any one sector is uncertain – and likely to vary by country/region depending on local resources availability –, it is clear that, in aggregate terms, **any credible path to a zero-carbon economy in the second half of the 21st century will require a massive expansion of power generation, and almost certainly a huge increase in hydrogen production.**

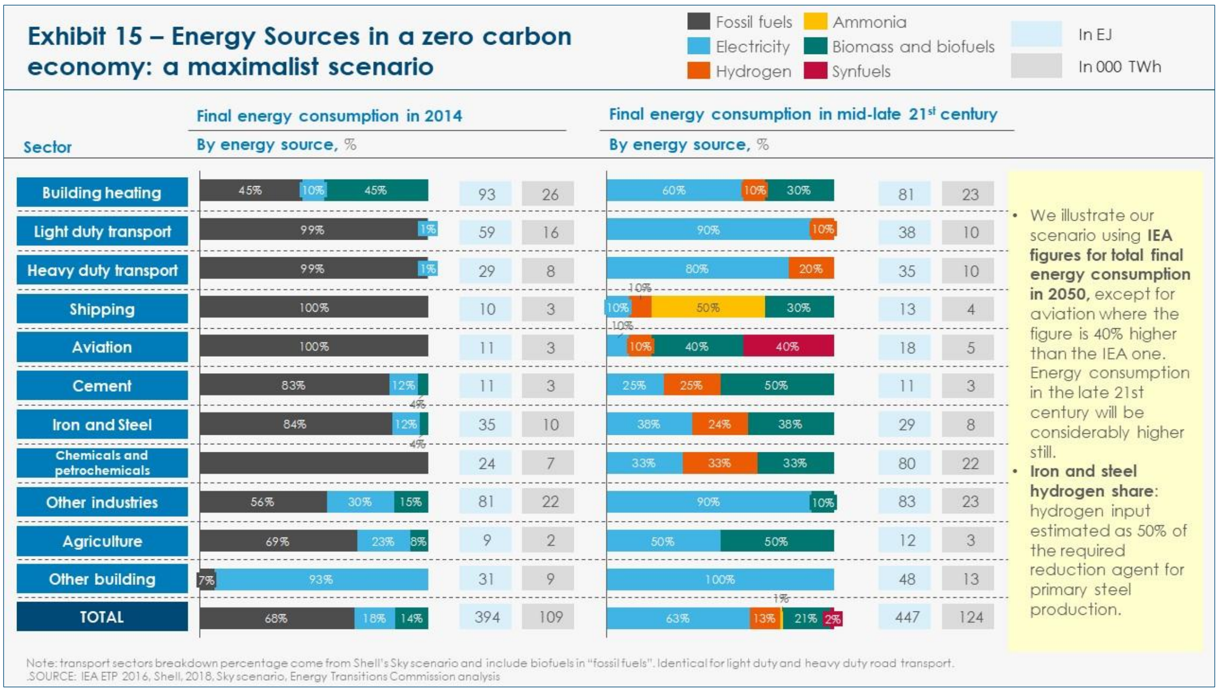
Exhibit 15 sets out **an indicative zero-carbon scenario** in which final fossil fuels consumption has been phased out and all sectors of the economy have been decarbonized primarily by electricity or electricity-based fuels, with a more limited role for bioenergy and no carbon capture (except for the use of carbon capture in hydrogen production via SMR)[31]. This scenario does not constitute a forecast, but rather a thought experiment to appreciate **how big electricity and hydrogen demand could grow by mid-to-late century in a "maximalist direct and indirect electrification" scenario**. In that scenario:

- **Electricity demand grows in line with global economic growth and rising energy use** in emerging economies, **but is also swollen by a dominant role for direct electrification** in road transport, a major role in residential and commercial heating, a significant role in heavy industry, plus a more limited role in aviation and shipping. These changes take final energy consumption of electricity **from 20,000 TWh today to around 80,000 TWh** by mid-to-late century – before accounting for additional electricity demand for hydrogen production.
- **Hydrogen demand grows from the current 60 million tonnes to over 600 million tonnes** by mid-to-late century[32], as hydrogen plays a significant role (i) in trucking, shipping (whether as hydrogen itself or as ammonia), and aviation (whether as hydrogen or as synthetic jet fuel); (ii) in steel and several other industries; and (iii) in residential and commercial heating (although other routes like direct electrification via heat pumps and biogas may play larger roles still).
    - **If this hydrogen was produced from electricity** (rather than from SMR plus CCS/U), **it would create an additional 23,000 TWh of electricity demand** [Exhibit 16][33].
    - **If, by contrast, this hydrogen was produced entirely via SMR plus CCS/U, the total CO_2 produced**, which would need to be stored or used, **would amount to 3.3 Gt**[34].
    - In practice the balance between electrolysis and SMR plus CCS/U is likely to vary by geographical location given variations in natural resource reserves (see Section 4 below).

[31] Biomass and carbon capture are likely to play a more important role in a zero-carbon economy that what is assumed in this indicative "maximal direct and indirect electrification" scenario. See the ETC's consultation papers on *Bioenergy and bio-based products in a zero-carbon economy* and *Carbon capture in a zero-carbon economy* for more details.
[32] In this simplified version, assuming an almost complete phase out of fossil fuels use, hydrogen production for refineries is considered as nil and hydrogen production for ammonia used as an input to fertilizers is also disregarded at this stage.
[33] Using a 70% electrolyser (electricity-to-hydrogen) efficiency.
[34] Given the chemical formula $CH_4 + 2H_2O >> CO_2 + 4H_2$, 8 atoms of hydrogen produced result in 1 molecule of CO_2, and thus one tonne of hydrogen results in 5.5 tonnes of CO_2.

- In addition, it is possible that hydrogen will play a role as a **storage device within the electricity generation system.** In a near-total-variable-renewable power system, roughly 80% of power demand could be met by electricity produced in the same hour, with a need to either store energy or use peaking capacity to meet the remaining 20%[35]. In a world delivering 100,000 TWh of final power consumption, **if 15% of electricity supply had to be delivered from stored energy and if one third of this storage was provided by hydrogen, this would require the production of an additional 210 million tonnes of hydrogen per annum**, and the input of 10,000 TWh of electricity. While this additional hydrogen demand might not show up in future forecasts of total hydrogen demand (since it would be produced and used internally by electricity generators), it would still contribute to an increased market demand for electrolysis and fuel cell equipment, and thus be a powerful further driver of economy of scale and learning curve effects.

Exhibit 15 – Energy Sources in a zero carbon economy: a maximalist scenario



Note: transport sectors breakdown percentage come from Shell's Sky scenario and include biofuels in "fossil fuels". Identical for light duty and heavy duty road transport.
.SOURCE: IEA ETP 2016, Shell, 2018, Sky scenario, Energy Transitions Commission analysis

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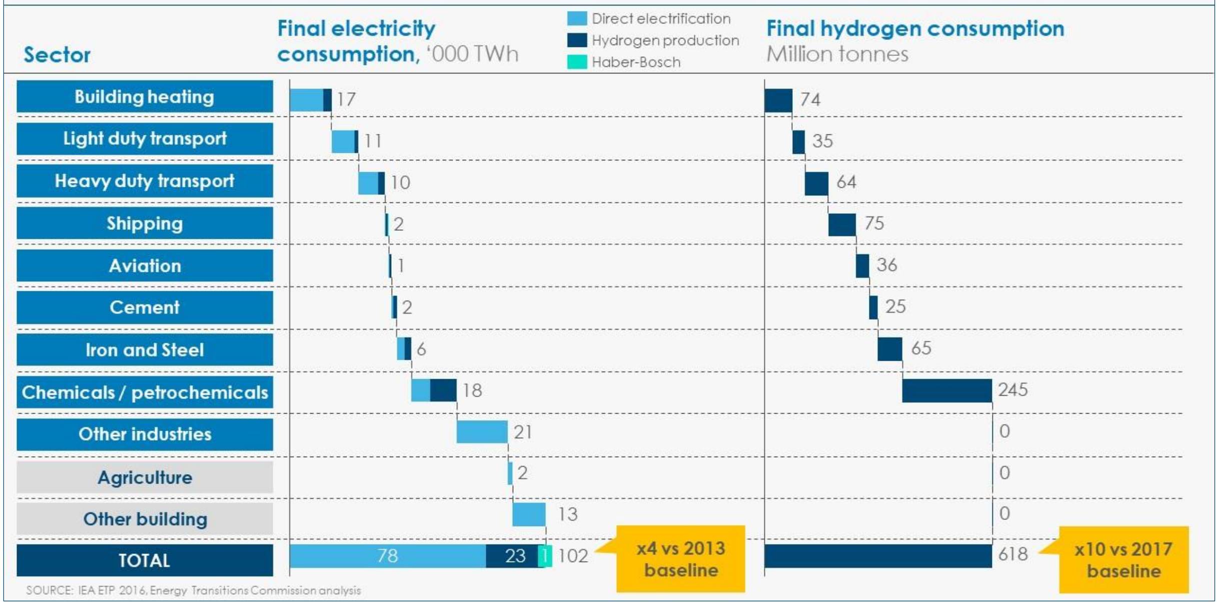
35 SYSTEMIQ analysis for the Energy Transitions Commission, based on Climate Policy Initiative for ETC (2017), *Low-cost, low-carbon power systems*

Exhibit 16 – Electricity and hydrogen demand in an indicative mid-late century scenario



In a "maximalist direct and indirect electrification" scenario, **global power demand could therefore be multiplied by 5, to reach 100,000 TWh by mid-to-late century**. The figures shown in our scenario are simply illustrative: any one of the assumptions may well turn out very differently. But other scenarios which achieve net zero emissions by 2070 assume similarly huge increases in electricity demand and, usually, very large increases in hydrogen production.

- The **Shell Sky Scenario** for instance envisages a total final hydrogen consumption reaching 325 million tonnes by 2070 and 580 million tonnes by end century (vs. 600 million tonnes in our scenario), with total direct electricity consumption reaching about 100,000 TWh by 2070[36].
- Our assumptions are also aligned with the ones from **the Hydrogen Council**, whose latest scenario envisions a 18% share of hydrogen in the final energy demand (vs. 13% in our scenario), plus 3% for the hydrogen-based ammonia and synfuels (vs. 2% in our scenario)[37].

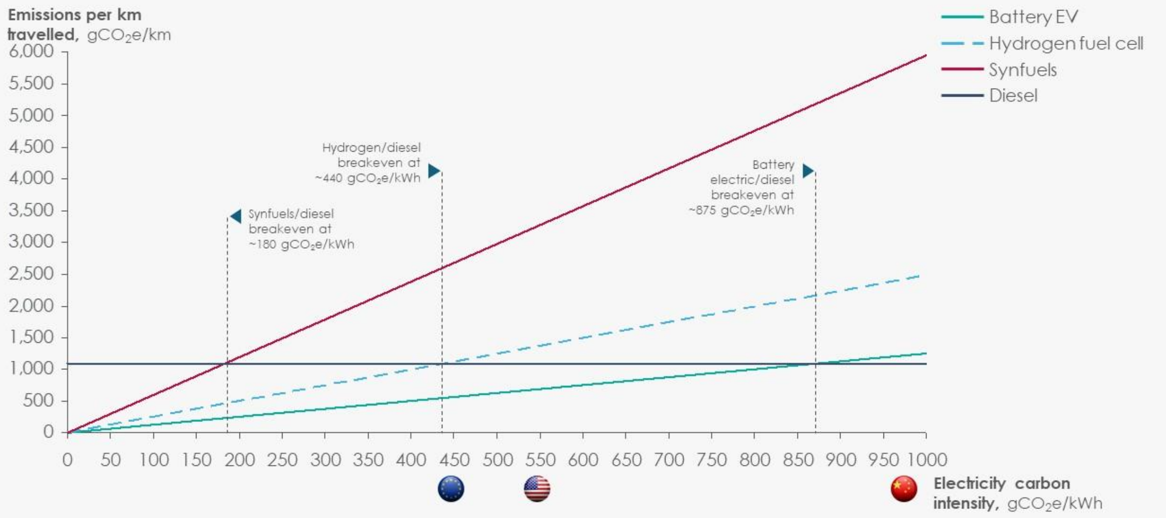
Issues relating to availability of natural resources to meet these massive increases in electricity demand are considered in section 4.

[36] Shell (2018), *Shell Sky Scenario – meeting the goals of the Paris agreement*
[37] The Hydrogen Council (2017), *Hydrogen scaling up, a sustainable pathway for the energy transition*

3. IMPLICATIONS OF THE CARBON INTENSITY OF POWER

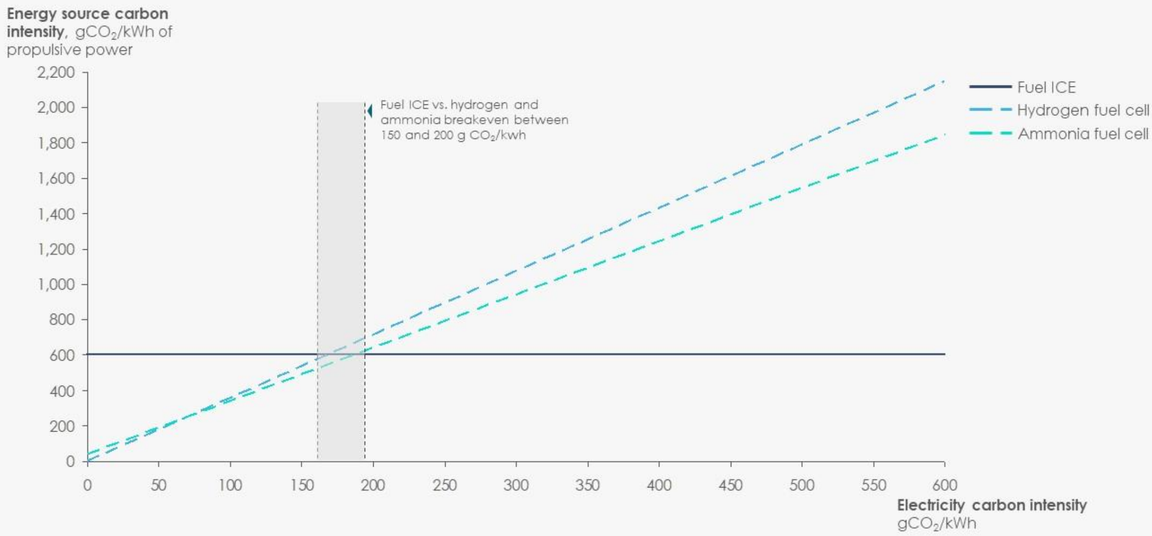
In the long run, **electrification and the use of hydrogen-based fuels offer a route to a completely zero-carbon economy, but only if electricity itself comes from zero-carbon sources.** Whether moving from conventional fuels to direct use of electricity or to hydrogen-based fuels reduces carbon emissions therefore depends on the carbon intensity of electricity generation. **The breakeven carbon intensity level below which switching reduces emissions varies by fuel.** Exhibit 17 illustrates breakeven points for alternative truck engines/fuels while Exhibit 18 illustrates them for alternative ship engine systems.

Exhibit 17 – Carbon intensity breakeven points in heavy-duty road transport



SOURCES: Energy Transitions Commission analysis , press research, International Energy Agency

Exhibit 18 – Carbon intensity breakeven points in shipping



SOURCE: Lloyd's Register & UMAS, 2017. Zero-Emission vessels 2030, Energy Transitions Commission analysis

Direct electrification (e.g. switching from gasoline/diesel to battery electric vehicles) **will start reducing emissions if the carbon intensity of electricity is below about 850 gCO_2 per kWh**, and is very significantly carbon reducing once grids reach the carbon intensity seen, for instance, in the UK (around 250 gCO_2 per kWh and falling fast) or France (80 gCO_2 per kWh).

But the energy losses involved in producing hydrogen and hydrogen-based fuels – which increase as we progress from hydrogen, to ammonia, to synthetic fuels – mean that **the breakeven points for electricity-based fuels are much lower**. Hydrogen fuel cell trucks only produce less emissions than diesel if the carbon intensity of electricity is less than about 440 gCO_2 per kWh, and for synthetic liquid hydrocarbon fuels, the breakeven point is below 180 gCO_2 per kWh. In ships, moving from HFO to hydrogen or ammonia as the ICE fuel, will only reduce emissions if electricity with a carbon intensity below 150 to 200 gCO_2 per kWh is used.

Implications are twofold:

- Firstly, it is vital to **decarbonize electricity generation** as rapidly as possible.
- Secondly, **premature switches to fuels with low breakeven points** (e.g. synthetic liquid hydrocarbons) should be avoided in countries where the carbon intensity of electricity is still well above the breakeven point and likely to remain so for many years.

This does not mean, however, that switching should never occur until the breakeven point has been reached: the carbon intensity which determines whether buying an electric car reduces emissions, for instance, does not depend just on the carbon intensity of the vehicle at the time of purchase, but on the average carbon intensity across the whole operational life of the vehicle. But it does imply **the need for national emissions reductions plans to take an integrated approach to electricity decarbonization and electrification**.

4. IMPLICATIONS OF NATURAL RESOURCES VARIATIONS BY REGION

Section 2 sets out an indicative scenario in which total electricity demand grows from 20,000 TWh today to over 100,000 TWh by mid-to-late-century, in line with the Shell Sky Scenario[38]. The implication of this for the land area that needs to be devoted to solar or wind power are manageable. **Delivering 100,000 TWh of electricity entirely with solar power would**, with typical solar panel yields, **require a land area of about 1-2 million km²** to be devoted to solar panels[39]. This is about 1-2% of the total global land area and 0.2-0.4% of the total earth surface which would be available if it were possible to deploy floating solar panels above the sea. In theory, sufficient global resources to support massive electrification of the global economy are therefore clearly available.

However, this scale of renewables expansion could face obstacles:

- **There are huge variations in wind and solar resources between countries and regions**, with for instance, China, the US, Australia, the Middle East and the Sahara particularly well placed [Exhibit 19].
- **Large differences in population density have important implications for the likely costs of solar electricity and for the feasibility of massive solar deployment.** China would only need to use about 0.8-1.1% of the land area of its five under-populated western provinces (Tibet, Qinhai, Xinxiang, Inner Mongolia and Gansu) to meet its entire current electricity demand from solar power. But, for Bangladesh to support equivalent electricity use per capita with solar energy alone would require 6-11% of its entire land area to be devoted to solar panels, in a country where almost all land is already intensively used for agriculture[40].
- **In the medium term, the feasible pace of deployment of renewables might also be too slow to both substitute existing fossil fuel capacity and meet fast-growing power demand**, especially in emerging economies, creating a risk of increased reliance on fossil fuels, in the absence of alternative low-carbon power generation source.

Three implications follow:

- Firstly, while electrification and hydrogen-based fuels will undoubtedly play a major role in global decarbonization, **the optimal balance between the electrification, bioenergy and CCS/U routes will vary between locations** in light of different wind and solar resources, biomass availability per capita and the availability of potential storage for captured CO_2 [Exhibit 20].
- Secondly, **an optimal low/zero-carbon global economy would almost certainly entail significant international trade in clean energy**, whether in the form of electricity carried over long distance transmission lines, or in the form of hydrogen, ammonia, or biomass freighted across the world. National energy security considerations might, however, constitute a barrier to such international trade, leaving resource-constrained countries in search of alternative low-carbon power generation options.

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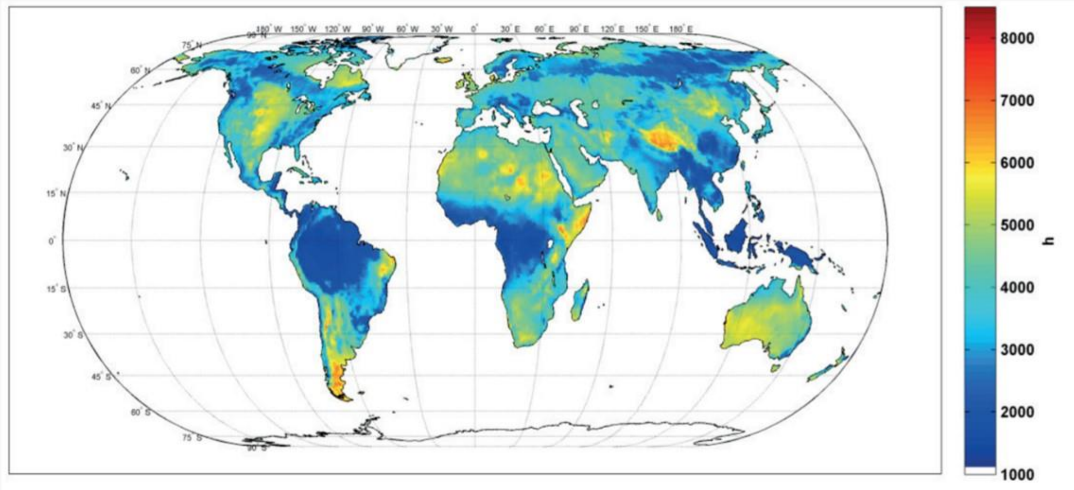
[38] Shell (2018), *Shell Sky Scenario – meeting the goals of the Paris agreement*

[39] SYSTEMIQ analysis for the Energy Transitions Commission. Using the generation-weighted average land use from NREL (2013), *Land-Use Requirements for Solar Power Plants in the United-States*: 3.1 to 5.5 acres/GWh/year, i.e. 0.013-0.022 km²/GWh/year

[40] SYSTEMIQ analysis for the Energy Transitions Commission based on NREL (2013), *Land-Use Requirements for Solar Power Plants in the United-States* for land requirements and IEA (2016), *Energy Technology Perspectives* for current electricity demand – ~6000 TWh/year today in China.

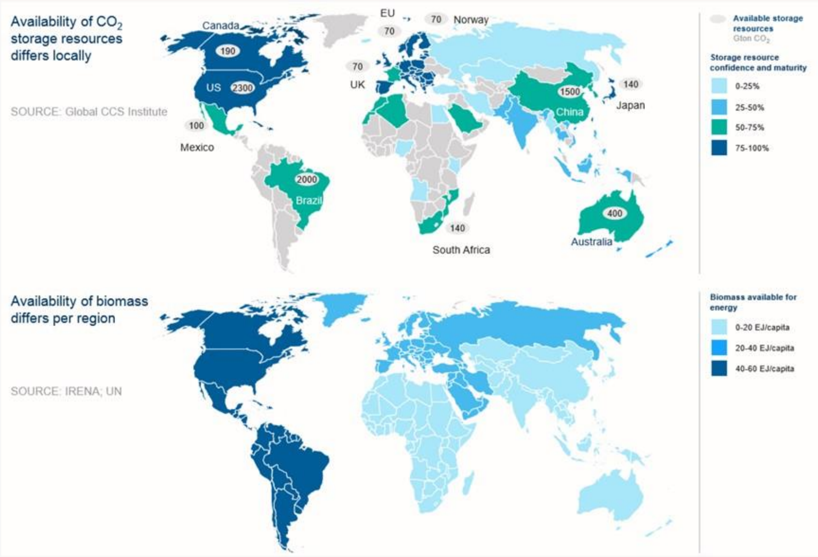
- Finally, the fact that some countries are naturally endowed with plentiful, and potentially very cheap, renewable electricity resources may also carry **implications for the optimal long-term location of energy intensive industries**.

Exhibit 19 – Availability of wind and solar resources for energy by region



Disclaimer: The boundaries and names shown and the designations used on maps included in this publication do not imply official endorsement or acceptance by the IEA.
SOURCE: IEA, 2017, *Renewable Energy for Industry* (Adapted and based on Fasihi, Bogdanov and Breyer (2016), "Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants")

Exhibit 20 – Availability of CO_2 and biomass for energy by region



SOURCE: McKinsey & Company, 2018, *Energy Technology Perspectives*, based on IRENA and UN sources

5. EMERGING CONCLUSIONS AND IMPLICATIONS

While it is neither possible nor necessary to predict the precise role which electrification will play in the path to a zero-carbon economy (relative to biomass or CCS/U), it is certain that electrification will play a hugely important role and highly likely that hydrogen will also be very significant across multiple sectors. It is also clear that there is, in theory, no long-term land area constraint to renewable electricity and renewable-electricity-based fuels providing the majority of global final energy consumption. But there are major differences in renewable power resources (e.g. wind and solar) by country, implying that:

- The cost-effective route to a zero-carbon economy must also entail **a significant role for biomass and CCS/U**, and that
- Domestic renewable power generation will have to be complemented in many countries either by **international trade in electricity or electricity-based fuels**, or by **alternative low-carbon power generation sources** like nuclear.

Emerging policy implications for the next two decades, which are relevant whatever the precise long-term balance of different decarbonization routes, include the following:

- It is vitally important to **decarbonize power generation as rapidly as possible**, and to **plan for a scale of low-carbon electricity generation which can support widespread electrification**. Since there are limits to the feasible annual pace at which renewable (or nuclear) power generation can be grown (given the constraints of supply chain development), early progress in the expansion of low-carbon power generation capacity is essential to make it possible to achieve near total power decarbonization by mid-century, and to then meet higher power demand with low-carbon power.
- **Equally, shifting hydrogen production to low-carbon production routes is a key priority.** Analysis suggests that hydrogen is highly likely to play a major role in overall decarbonization even if its role in the passenger car sector is much less than some companies and policymakers assumed until recently. Driving down the cost of electrolysis, via R&D expenditures and initial deployment, is therefore essential, as is the development of carbon capture infrastructure for SMR plants and effective management of upstream methane leakages from gas used in SMR.
- **Countries should develop integrated strategies for power decarbonization and electrification which reflect the breakeven points for the carbon intensity of electricity** in different sectors illustrated on Exhibit 17 and 18 – i.e. the point below which electrification (or a shift to electricity-based fuels) will generate a reduction in CO_2 emissions. These strategies should be described in future versions of the Nationally Determined Contributions reported under the Paris Agreement. They need to allow for the likely timing of future developments:
    - If the carbon intensity of electricity is currently above the breakeven point, that does not necessarily mean that initial steps towards electrification should be postponed, as the carbon impact of shifting to, for instance, electric vehicles will be determined by the carbon intensity of electricity used over the entire vehicle life. Policies to stimulate the initial take-up of electricity-based technologies may be needed today to make it possible to achieve significant market penetration in 15 years' time. **But these electrification policies need to be coupled with policies to drive rapid decreases in the carbon intensity of electricity.**

- An integrated approach may reveal that **some "transitional" fuels have no valid role in an optimal decarbonization strategy**. For instance, if synthetic fuels for passenger cars and trucks will only generate carbon reductions once electricity carbon intensity is below 150 g/kWh, if in some countries this breakeven point will only be reached after 2030, and if by then it is likely that battery cost and density developments will make BEVs the most cost-effective solution for road transport (alongside FCEVs for very long distances), synthetic fuel deployment in the auto and trucking fleet may not be appropriate. Synthetic fuels are likely however to play a major role in aviation.

- While electrification and electricity-based fuels will likely play the dominant role in long-term decarbonization, it is also almost certain that **bioenergy and CCS/U also need to be deployed on significant scale**, in particular given the very different supply of renewable resources, biomass per capita and CCS storage capacity in different countries. **Support for electrification should therefore not exclude support for these alternative routes.** Effective carbon pricing has a vital role to play in achieving the optimal balance between the different paths.

In parallel, new developments in electricity-related and hydrogen-related technologies will be crucial to accelerate direct and indirect electrification:

- **Improved performance and reduced cost of batteries**, driven by continued R&D investment in this area, would be a key driver of extended direct electrification in transport, facilitating the decarbonization of trucking, as well as short-distance shipping and aviation. **Increased R&D expenditure in other electrification technologies**, such as high heat electrification for cement and chemicals, will also be crucial to broaden the scope of the solution space for heavy industry decarbonization.

- **Reducing the cost of hydrogen production and use is also a key priority**. Industry investment and public policy must support the combination of R&D expenditures and initial deployment which will drive down the cost of electrolysis, fuel cell equipment, hydrogen storage and refueling infrastructure. Driving the development of synthetic fuel technology (in particular of direct air capture) is also important.

6. RECOMMENDATIONS

Dramatically increasing the use of electricity, hydrogen and hydrogen-based fuels by mid-century presents a number of challenges, both in terms of scale of low-carbon electricity and hydrogen production and transportation, and in terms of market readiness and cost of electricity-using and hydrogen-using technologies across multiple application sectors. Key industry and policy actions recommended to enable this highly effective decarbonization route therefore include:

A. RESEARCH AND DEVELOPMENT

Public and private R&D spending should focus on enabling and driving scale of a range of electricity- and hydrogen-related technologies to unleash cost reductions and learning curve effects.

At energy production level, key priorities are to:

- Drive down the cost of electrolysis equipment and improve electrolysis efficiency, which are the two key cost determinants of electricity-based hydrogen beyond electricity prices;
- Develop and pilot different hydrogen transportation technologies (either in liquified form or through an intermediate energy carrier like ammonia);
- Continue investing in renewable electricity generation to prolong downward cost trends and improve yields;
- Drive down the cost of alternative low-carbon electricity generation, such as nuclear fission, and bring to market possible new low-carbon generation technologies, such as nuclear fusion;
- Support and pilot carbon capture technologies, in particular for direct air capture (DAC), in order to driven down the cost of synthetic fuels.

At energy use level, key priorities are to:

- Accelerate improvement of battery cost, weight density and charging rates to enable electrification of a wider range of transport modes;
- Develop demand management, remotely controlled charging and pricing techniques (e.g. day pricing) that can help mitigate the scale of investment required in reinforcement of local distribution grids to support electric mobility of passenger and freight;
- Drive down the cost of fuel cells, hydrogen tanks and refueling stations;
- Developing radical new designs for ships and aircrafts to accommodate hydrogen as a fuel;
- Develop and pilot a range of electricity-based and hydrogen-based technologies in industry, such as hydrogen-based direct iron reduction or electrification of heat for chemical processes.

B. INDUSTRY COLLABORATIONS AND COMMITMENTS

Several industry initiatives working on electrification and hydrogen already exist, such as the Hydrogen Council (which aims to develop the hydrogen economy) on the supply-side, or the EV100 campaign led by The Climate Group (through which a range of companies have committed to electrifying their light duty vehicle fleet) on the demand-side.

Meanwhile, joint R&D projects like the HYBRIT zero-carbon steel project – which just started building a first pilot plant for hydrogen-based direct iron reduction and involves an iron ore producer, a steel producer and a power company – demonstrate the value of partnerships between energy producers and energy users to develop new technologies.

Building on existing initiatives, energy companies and energy-intensive sectors could:

- **Accelerate take up of the RE100 commitment** – i.e. commitment to 100% renewable electricity purchase – in energy-intensive industries that currently have high electricity consumption or are likely to electrify in the next decades;
- **Clarify the Hydrogen Council's roadmap to shift to clean hydrogen production** over the next 10-15 years (either through electrolysis or through SMR plus CCS/U), possibly combining this roadmap with commitments from Council members;
- **Develop joint R&D projects between energy producers and energy users in key transport and industry sectors** to accelerate the development and piloting of new electricity-based and hydrogen-based technologies, including cross-border partnerships to pilot electricity or electricity-based fuel international trade;
- **Develop new voluntary commitments that would drive demand for and deployment of BEVs and FCEVs**, for instance by expanding the EV100 campaign to 100% green trucking (for both in-house fleets and subcontracted logistics services).

C.PUBLIC POLICY

Public R&D and deployment support, combined with **tighter regulations on carbon intensity** of transport, industrial processes and consumer products will be useful policy tools to accelerate the decarbonization of all hard-to-abate sectors. **Carbon pricing** also has a vital role to play in achieving an optimal balance between different decarbonization routes, across industries and geographies.

Beyond these generic recommendations, which are relevant across all decarbonization technologies and sectors, specific policy action should be taken to accelerate direct and indirect electrifiction, while ensuring that this increased electricity demand is met by low-carbon power and does not translate into increased carbon emissions:

- **Governents should develop integrated power strategies** as part of their next Nationally Determined Contributions to the Paris Agreement, **combining an electrification strategy and a power decarbonization strategy**, in particular to:
    - Plan for the necessary expansion in renewables power generation to meet increased power demand;
    - Anticipate domestic renewable resources constraints, by developing infrastructure required for renewable electricity imports (in the form of electricity or electricity-based fuel) and/or building alternative low-carbon power generation capacity, such as nuclear or fossil fuels with CCS/U;
    - Avoid premature switches to electricity-based fuels with low carbon-intensity breakeven points where the carbon intensity of electricity is still well above the breakeven point and likely to remain so for many years; and

- Plan for the strengthening of local distribution grids to support electric mobility for passenger and freight, while developing mitigation strategies to level peak demand through demand management.

- **Governments should also plan and support investment in the infrastructure required** to grow electricity and hydrogen use:
  - A widespread high-speed charging infrastructure for electric vehicles, possibly combined with overhead (catenary) wiring infrastructure along the main motorways, which would enable expanded ranges for BEVs in freight;
  - A widespread hydrogen transport (including possibly pipelines between main production and consumption areas) and refuelling infrastructure for road transport;
  - High-speed charging and/or hydrogen refuelling infrastructure in major ports and airports, if short-haul segments of the fleet are to switch to these alternative sources of energy;
  - Retrofitting of gas heating networks for hydrogen;
  - Carbon transport and storage infrastructure enabling hydrogen production from SMR plus CCS.

- **Finally, regulators in different sectors, especially in transport, will play a crucial role in homologating new technologies**, in particular to guarantee their safety for passengers.

The Energy Transitions Commission welcomes feedback on this consultation paper until 31st August 2018 at pmo@energy-transitions.org. We are particularly interested in feedback on the feasibility and cost of different decarbonization options, and on the recommendations to policymakers, industries, businesses and investors. This feedback will be integrated in the ETC's final report to be published in November 2018.

For more information, please visit www.energy-transitions.org or contact pmo@energy-transitions.org.