Hydrogen
meets digital

New opportunities for the energy and mobility system

Hydrogen Council September 2018

Discussion paper

This report was prepared for the Global Climate Action Summit and published in September 2018 to open up a conversation between the hydrogen and technology sectors on the potential of hydrogen for digitization.

This report was developed with the Study Task Force of the Hydrogen Council, consisting of senior executives of 6 companies: Air Liquide S.A., Hyundai Motor Company, Cummins Inc., Plastic Omnium, Toyota Motor Corporation, and 3M.

McKinsey & Company provided analytical support.

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The Hydrogen Council is the largest industry-led effort seeking to develop the hydrogen economy. Launched in January 2017 at the World Economic Forum, its members include leading companies that invest along the hydrogen value chain, ranging from hydrogen production, infrastructure, and retail to end users in the residential, industrial, and transportation sectors.

As members of the Council, we are convinced that hydrogen can offer economically viable, financially attractive, and socially beneficial solutions. Furthermore, in certain sectors and regions it may represent the best way to enable the energy transition and improve urban air quality.

This report seeks to start investigating the impact of digitization on energy demand and establish a dialogue with the ICT sector on how digitization and hydrogen could complement each other's impact during the energy transition. We believe hydrogen offers strong benefits that could enable major digital trends and thus serve as an efficient, zero-emission energy vector.

Contents

By 2030, hydrogen could fuel ...

~1.0-1.5 m
autonomous taxis

~300-700k
autonomous shuttles

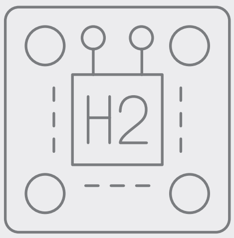
~3.0-4.0 m
delivery trucks and vans

~4-8k
vertical take-off and landing taxis (VTOL)

~1 TWh
of backup power in data centers

... amounting up to ...

~5-7 m tons
of annual hydrogen demand



~5.5-6.5 m
fuel cells in use

Executive summary

Vision: digitization drives new demand for versatile, clean energy

Digital technologies are transforming all sectors. They are changing how we work, live, and enjoy ourselves and how goods and services are created, transmitted, and consumed. Some of these technologies, such as autonomous driving, virtual reality, and artificial intelligence, will have both disruptive as well as cross-cutting effects on many parts of our economy.

Digitization creates massive new energy demands

While digitization can increase energy efficiency, e.g., by sharing of assets such as cars and improving energy efficiency in our daily lives through IoT, it also creates massive new energy demands. The information and communications technology (ICT) sector already consumes more than 50% of the US electricity consumption. In the coming years, energy demand for ICT is expected to grow further, doubling by 2050, and this forecast already considers the continuous improvement of ICT energy efficiency.

In order to limit global warming to two degrees Celsius, the world will need to make dramatic changes. With the clear imperative to reduce carbon emissions and improve air quality, these new energy demands must come from clean and renewable sources. This implies the need for an energy carrier that can take solar and wind power, channel it to its end use, and release the energy when needed.

Batteries and hydrogen technologies are complementary for different applications

Two main technologies – batteries and hydrogen – can provide the required storage for renewables. While often portrayed as competitors, they are, in fact, complementary for different applications.

Batteries are widely available, have low conversion losses, and have experienced rapid cost decreases in recent years. Their initial deployment does not require much infrastructure, easing adoption in the market.

Lower space requirements for hydrogen infrastructure allow for rapid and cost-effective scaling

The high energy density of on board hydrogen storage (about 10 times higher energy density compared to rechargeable batteries) makes hydrogen fuel cell systems ideally suited for powering large, heavy or “vertical” (e.g., flying) modes of transport.

Longer ranges go hand-in-hand with faster refueling, slashing wait times, increasing utilization, and reducing infrastructure requirements.

While initial incremental infrastructure investments might be higher, hydrogen infrastructure is less costly at scale and does not affect the electricity network, while direct charging infrastructure will require significant grid upgrades.

Use cases: four examples where hydrogen can enable new digital business models

Hydrogen is required for the energy transition. In addition to the applications we describe in our report Hydrogen – scalling up[1], hydrogen will also power new digital business models. In this report, we highlight four exemplary use cases that will contribute to cleaner, healthier, and more efficient cities over the next ten years.

Autonomous taxis and shuttles. Fully autonomous, driverless taxis and shuttles should hit the roads around 2020. Given their zero emissions requirements in many future urban centers and the need to drive long distances and remain always on, they can benefit from hydrogen's high energy density and fast refueling. Since they operate in cities, the lower space requirements for hydrogen infrastructure allow for rapid and cost-effective scaling. By 2030, approximately 1.0 million to 1.5 million autonomous taxis and roughly 300,000 to 700,000 autonomous shuttles could be powered by hydrogen fuel cells (out of a total of about 20.5 million autonomous taxis and shuttles on the roads in 2030).

Hydrogen provides an ideal energy vector to fuel the whole freight chain

Digitally enabled freight chains. Freight is fueled by the booming e-commerce sector and we foresee that all modes of commercial transport will eventually switch to autonomous technology. Hydrogen provides an ideal energy vector to fuel the whole freight chain – from forklifts, long-haul trucks, short-haul vans, and autonomous ships to last-mile parcel drones. By 2030, hydrogen and fuel cells could fuel approximately 3.0 million to 4.0 million delivery trucks and vans globally.

Vertical take-off and landing (VTOL) taxis are setting out to revolutionize urban transport

VTOL taxis. Vertical take-off and landing (VTOL) taxis are setting out to revolutionize urban transport, with companies planning to launch first operations already by 2020. VTOLs require a safe, clean, energy-dense, and fast-refueling energy storage to power their flights, and hydrogen could allow high aircraft uptime, long ranges, and an efficient buildup of the start and land infrastructure. With some 20 to 40 percent of electric VTOLs powered by fuel cells, between 4,000 and 8,000 hydrogen-powered VTOLs could fly in the skies by 2030.

Data centers. Data centers are the backbone of digitization, receiving, storing, and processing vast amounts of data. With more and more computing power and storage at a lower cost and

[1] This report focuses on new applications powered by digital technologies. For the application of hydrogen in all (existing) sectors, please see our global road map titled "Hydrogen – scaling up," available from the Hydrogen Council Website

digitization permeating all sectors, their energy demand is bound to continue to grow drastically. Data centers already account for an energy demand close to that of France and forecasts predict this will double by 2030. Data center operators are already building on-purpose renewable generation for their data centers and experimenting with fuel cells for power generation. Hydrogen could provide the power when solar and wind are not available, as well as efficient, responsive backup power.

Using hydrogen for these applications has the strong potential to unlock CO_2-neutral growth in transport, industry, and cities. In the four use cases described, the potential for hydrogen could amount to about 5 million to 7 million tons of annual hydrogen demand, for a total of some 5.5 million to 6.5 million fuel cells in use by 2030.

Outlook: developing new hydrogen applications

Many of the above-mentioned applications are currently in the development or demonstration phase. While they may seem futuristic and far off, their tremendous potential is fueling today's momentum and aggressive timelines. Companies are already testing autonomous vehicles (AVs) on the road in specific use cases today, and some service providers have announced the launch of full self-driving ride-hailing services in 2018. VTOL companies are planning for market demonstrations as soon as 2020 for goods and 2023 for passengers.

Given this strong momentum and the development cycles for these solutions, we believe that now is the time to develop and deploy hydrogen and fuel cell solutions. With comparatively limited infrastructure requirements compared to conventional mass-market technologies, these new applications also provide an ideal entry point for hydrogen and fuel cells.

> Now is the time to consider, develop, and deploy hydrogen and fuel cell solutions

We, the Hydrogen Council, are convinced that hydrogen can enable many of the new energy demands that will emerge over the coming decades from new digital applications. We stand ready to develop these applications jointly and scale the markets with the shapers of the new economy.

Methodology

This report describes several highly disruptive technologies and explores how hydrogen could help meet their specific energy demands. It focuses on four main applications: autonomous taxis and shuttles, digitally enabled freight chains, VTOL taxis, and data centers.

The descriptions that follow are based on discussions with several industry players in all four applications, ranging from specialized start-ups to established OEMs. To quantify the potential role of hydrogen in enabling these trends, we rely on external estimates regarding the magnitude of the digital trends (including, notably, the McKinsey Center for Future Mobility, or MCFM) and on hydrogen adoption rates estimates made by Hydrogen Council members (see, for instance, the report "Hydrogen – scaling up," launched by the Hydrogen Council during the COP23 (Conference of the Parties) meeting in Bonn in 2017).

Our vision

New opportunities for the energy and mobility system

Our vision: New opportunities for the energy and mobility system

Digitization and new technologies are disrupting our energy usage patterns, driving new demand for versatile, clean energy

The world we know today is undergoing dramatic changes. Notably, disruptive technologies and digitization are transforming everyday life, and they are just getting started. In this environment, new business models spring up as others decline, and it's happening so fast that the top 50 companies founded in the last decade are already worth almost USD 900 billion today.[2]

The top 50 companies founded in the last 10 years are already worth almost USD 900 billions today

Technologies like artificial intelligence, blockchain, and cloud computing are already available and will continue to grow. Applications and trends resulting from these technologies, such as vertical travel (e.g., "flying taxis"), digitally enabled freight chains, and autonomous driving, promise to resolve existing problems like congested roads, inner city emissions, and inefficient energy use. They will also change the networks that make modern life possible. Public services, travel, and seamless mobility will all evolve and improve as digitization takes hold.

Disruptive technologies will demand clean, green fuel

Successfully meeting the rising energy levels of these disruptive technologies will demand clean, green fuel and is key to the further success of digitized applications. Although new applications will enable more efficient energy use (e.g., in the form of ride sharing, which is more efficient than the individual use of private cars), digitization itself should cause per capita energy consumption to grow strongly. Specifically, the introduction of new digital services and applications will spark new energy demand, e.g., as the use of new mobility services increases relative to walking, cycling, or public transport.

Energy demand in the ICT sector today already exceeds 50% of the US electricity demand and is expected to double by 2050.[3] Further, by 2020, energy demand from data centers alone should surpass 500 TWh – more than twice the electricity demand in California.[4]

With the clear imperative to limit carbon emissions and improve air quality in cities, the energy required must come from clean and renewable sources. The need to limit the earths' temperature increase to 2 degrees Celsius, as ratified in the COP 23 agreement, requires countries and corporations to increase the share of renewable power massively. In addition, zero-emission policies in cities will add to the need to reduce local emissions and replace carbon-based, fuel-powered transport with electric mobility.[5]

[2] Pitchbook

[3] Andrae and Edler (2015); Enerdata; International Energy Agency

[4] Enerdata; expert interviews; Forbes; Gartner; International Energy Agency, U.S. Energy Infomation Administration

[5] E.g., plans to reduce local emissions and bans on diesel vehicles and internal combustion engines (ICE) announced in Brussels, Hamburg, London, Mexico City, Paris, Rome, Taipei. Source: press search

Increasing customer awareness of these goals will create additional market pull for efficient and emission-free products and services. Simultaneously, this green energy must be available at the right time in the right place. The key to achieving this involves finding ways to store fluctuating types of renewable energy like solar or wind – both characterized by intermittent supply – and to provide this zero-emission energy exactly when it is needed, e.g., powering homes in the evening or recharging battery vehicles at night.

Batteries and hydrogen can both store and provide green power

Currently, two main energy carriers can effectively store and provide clean power: batteries and hydrogen. While batteries enjoy high visibility, hydrogen is not as well-known. However, we believe hydrogen can provide unique benefits that complement those of batteries.

> Hydrogen can provide unique benefits that complement those of batteries

Batteries are highly efficient because battery storage generates only limited energy conversion losses. Widely available today, they have experienced rapid cost reduction in recent years, due in part to their growing volume. Also, their initial deployment does not require much infrastructure, easing adoption in the market.

Hydrogen's advantages include its high energy density (energy density of on board hydrogen storage is about 10 times higher energy density compared to rechargeable batteries)[6], which makes it the perfect energy vector for powering large and heavy vehicles or vertical transport (e.g., flying taxis). Hydrogen's high energy density makes long-range travel possible while keeping refueling times close to those for today's diesel or gasoline vehicles, which is many times faster than battery recharging, even if the latter is using a fast charger.[7] Further, hydrogen allows the long-term storage and transportation of large volumes of energy, such as from excess renewable energy generation, thus providing grid flexibility. Finally, while building a charging infrastructure for battery vehicles is currently cheaper than hydrogen refueling stations, studies project that required investments will be lower for the latter once the number of vehicles on the road is higher. The refueling infrastructure also requires less space than battery recharging if deployed at scale, which is another benefit of the quick refueling times, and will free up space for housing or green spaces in the city of the future.

Our vision: the city of the future

The interconnected city of the future will enable the highest quality of life possible. Convenient, shared forms of transportation will replace private cars. Autonomous taxis and shuttles will complement public rapid transit system trains and subways. With fewer

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6 0.2 kWh/ kilogram for rechargeable batteries used in battery electric vehicles (BEV) compared to 2.2 kWh/kilogram for onboard hydrogen storage for light-duty fuel cell vehicles (FCEV); Source: U.S. DOE Office of Energy Efficiency and Renewable Energy, MCFM

7 60 kWh battery (e.g., Chevrolet Bolt) at 500 minutes (7.2 kW regular charging) or 72 minutes (50 kW fast charging) compared to 3-5 minutes for an FCEV (e.g., Toyota Mirai)

private cars, buildings can grow taller and thereby provide a home for more people, and former parking spaces can become green public spaces. Because personal mobility and the movement of goods often go hand in hand, goods will move in largely digitized and autonomous logistics chains. Digital freight processes will enable consumers to decide when and where to receive home deliveries and whether a drone or autonomous van will make the last-mile delivery, all empowered by zero-emission energy.

The air above cities will become busier due to VTOL taxis and goods being transported via drones, which, powered by electricity, will also operate without emissions and at very low noise levels.

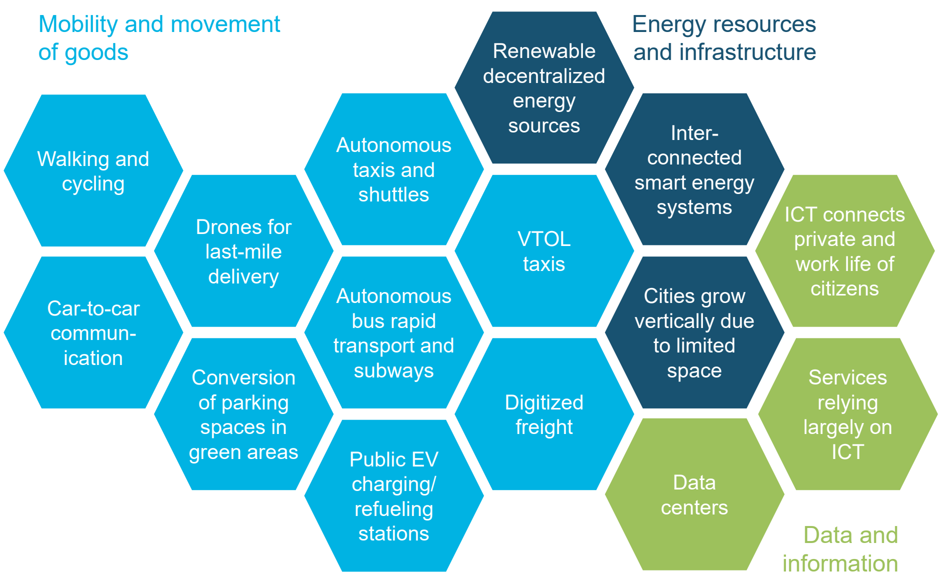
Meeting the ever-growing energy demand needed to turn the city of the future from dream into reality will require new ways to connect decentralized renewable energy sources and smart energy systems. Because cities will increasingly rely on wind parks and solar farms, which come from decentralized sources, they will require an interconnected, smart distribution system along with appliances capable of responding to fluctuations in supply and demand.

The processing of all data and seamless integration of all ICT devices and applications will occur in data centers not far from the point of usage. Short latency times will result from geographical flexibility and data centers will be powered by green energy.

Bearing all these developments in mind, we believe hydrogen's ability to act as an energy vector for all these applications could significantly improve the future lives of city dwellers everywhere (Exhibit 1).

EXHIBIT 1

Our lives in the city of the future will become cleaner, healthier, and more efficient due to hydrogen-powered digital technologies



Deep dives

Potential and impact assessment for hydrogen within selected digital applications

Deep dives: Potential and impact assessment for hydrogen within selected digital applications

This section demonstrates the enabling role hydrogen can play in four digital applications that will significantly contribute to making the city of the future a reality:

1. Autonomous taxis and shuttles (shuttles are pooled taxis with five or more passengers)
2. Digitally enabled freight chains (which range from material handling in warehouse and long-distance trucking to last-mile delivery via vans or drones)
3. VTOL taxis (flying taxis)
4. Data centers.

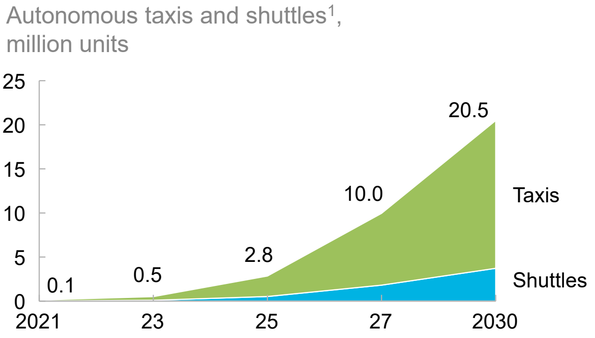
The following deep dives on the selected digital applications present a market assessment of each individual technology and demonstrate the potential impact of hydrogen when applied to these technologies compared with batteries or fossil fuels.

Application 1: autonomous taxis and shuttles

AVs no longer only inhabit science fiction movies: they will probably operate on a street near you very soon. Investments in autonomous driving in the past 5 years have exceeded 15 billion USD. As of today, level 4 autonomous cars have driven over 16 million test kilometers on the road, and the technology has undergone many more millions of test kilometers in simulators. Over 10 automakers are planning to launch level 4 autonomous cars by 2020, and level 5 cars by 2025. By 2030, we believe more than 20 million autonomous taxis and shuttles could be on the road, transporting passengers in the city of the future (Exhibit 2).[8]

EXHIBIT 2

Autonomous taxis are becoming a reality



~USD 15-20 bn
investments in the past 5 years

16+ m test kilometers
in level 4 autonomous cars

10+ OEMs
planning for level 5 autonomous cars by 2025

1 Shuttles = shared robotaxis with pooled demand

SOURCE: Bloomberg; expert interviews; GM; IHS Automotive; press reports; Uber; Waymo

Despite all these developments, however, AV technology must still meet several important prerequisites to achieve full market potential. For instance, autonomous taxis and shuttles require high uptime. With no driver breaks (or drivers) and routing optimized via artificial intelligence, autonomous cars need an energy vector that ensures the highest utilization and enables 24/7 operations that pay for the high initial capital investment.

[8] Expert interviews; Forbes; IHS Automotive; press search; Waymo; MCFM

Fast refueling is another critical factor, undermining the applicability of batteries. Limited parking availability in dense urban areas cannot handle large numbers of taxis refueling for 30 minutes or more, and driving to dedicated refueling/recharging areas outside of cities would limit uptime.

Finally, AVs need a high energy density fuel that provides enough power for the onboard computing technology for level 5 autonomy. Estimates point to a power demand of up to 1 to 2 kilowatts (kW) from level 5 technology. Taking into consideration low average speeds in cities, this could increase energy consumption by over one-third.[9] The energy source must also enable shuttle operations with larger and heavier vehicles, which will increasingly replace urban buses.

Up to 35 percent higher consumption from autonomous systems (1 to 2 kW)

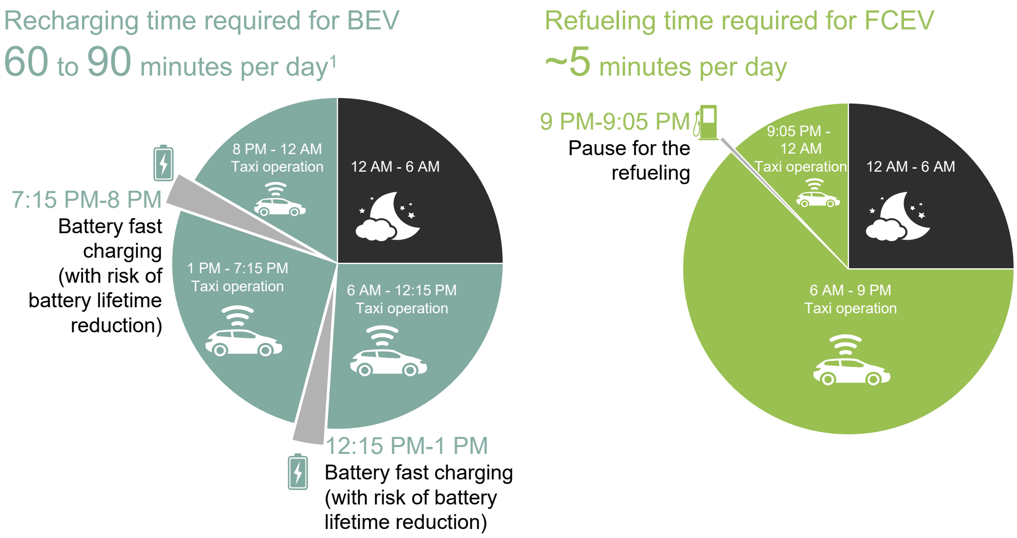
Hydrogen offers three distinct benefits that make it the ideal energy vector to power autonomous taxis and shuttles. First, its high energy density helps when powering larger and heavier shuttles and meeting the computing requirements for level 5 autonomy without any compromises on payload or range. Second, hydrogen ensures high uptime by offering long ranges and fast refueling times. And third, the refueling infrastructure needs little space in dense urban areas.

Exhibit 3 provides an example of an airport shuttle operating between a city center and the airport between 6:00 and 00:00.

EXHIBIT 3

Hydrogen as energy vector for autonomous taxis enables zero emission operation without long stops for battery charging

Example: airport shuttle



1 Depending on availability of fast charging infrastructure

[9] BEV with 18 kWh/100 km consumption and average speed of 30 km/h, equaling a consumption of 5.4 kWh per hour; 2 kW additional consumption from level 5 technology would increase the consumption by 35 percent. Source: Bloomberg; expert interviews; Wired

The battery-powered shuttle would have to refuel twice during those 18 hours of operation, resulting in **a downtime of 60 to 90 minutes** for this period. During the downtime interval, it would not be able to generate revenue from passenger transport. This calculation also assumes fast charging, which will negatively impact the lifetime of batteries.

The hydrogen shuttle, on the other hand, would reach a utilization rate of 99 percent. It would require only one quick refueling cycle during the evening (or earlier, if routing allows), lasting a maximum of ten minutes. It would require only one quick refueling **stop of 5 minutes** during the evening. Furthermore, this quick refueling process does not inflict any lifetime durability issues or expenses.[10]

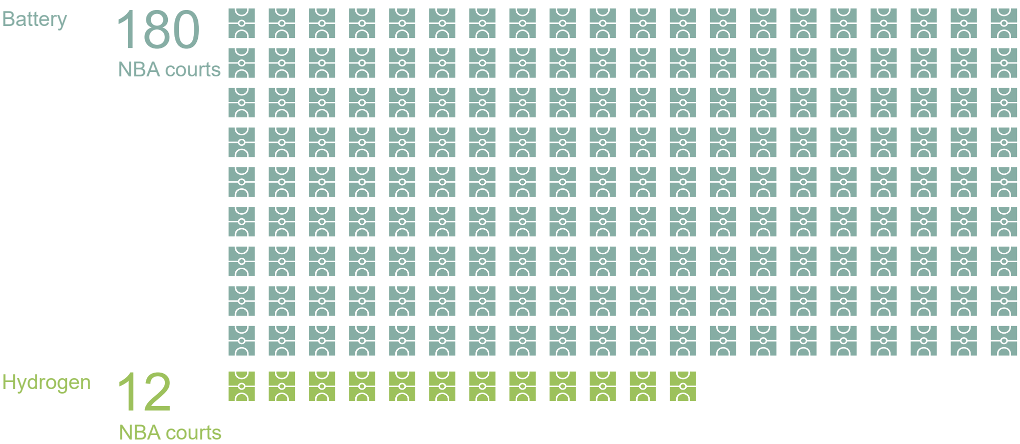
When comparing the space requirements of a battery and a hydrogen refueling station, there are again significant advantages for hydrogen (see Exhibit 4).

EXHIBIT 4

Hydrogen as an energy vector for autonomous taxis and shuttles requires less space for refueling infrastructure

Example: New York City cabs[1]

Charging stations for all NYC cabs would take up space equal to …



1 Number of taxis and cabs: ~74,000; annual mileage per taxi 70,000 miles; refueling times FCEVs 0.02 minutes/mile, BEVs 0.26 minutes/mile; area for one fueling station 30 m²; size of NBA court (436 m²; 28.7 x 15.2 m)

SOURCE: EPA; Curbed New York; NBA; New York City Taxi and Limousine Commission; Tesla

Due to faster refueling times, comparable hydrogen stations would occupy about 15 times less the space than battery chargers, which need more charging points due to the extended charging time.[11] Exhibit 4 illustrates this using taxis in New York City. Taking into consideration all current taxis in New York City, 180 NBA courts would be required for charging stations if they all ran on batteries. In comparison, hydrogen taxis would only need the space of 12 NBA courts for refueling stations.

[10] Curbed; EPA; NBA; New York City Taxi and Limousine Commission; Tesla; MCFM

[11] Nationale Plattform Elektromobilität (NPE)

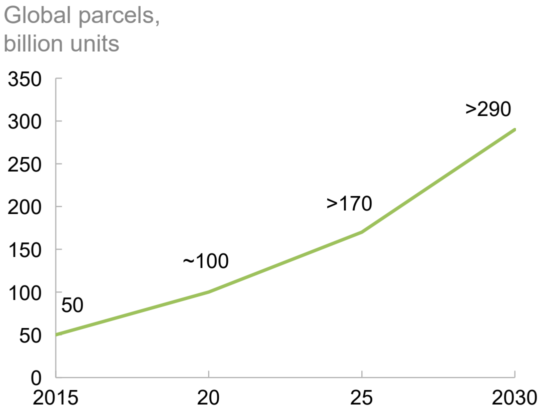
By 2030, hydrogen and fuel cells could power significant percentages of the vehicles sold. About 16.8 million autonomous taxis could be on the road at that point in time, serving as a baseline. These vehicles could see a potential hydrogen adoption rate of roughly 10 to 15 percent of sales in 2030, which would lead to a hydrogen fleet of about 1.0 million to 1.5 million vehicles by 2030. Likewise, the baseline for autonomous shuttles could be about 3.8 million vehicles. Applying the same adoption rates for autonomous taxis would yield a total fleet of about 0.3 million to 0.7 million vehicles by 2030.[12]

Application 2: digitally enabled freight chains

The current boom in e-commerce and growing demand for home deliveries indicate that consumers want to have their purchases delivered as frequently and quickly as possible, e.g., keeping items like food fresh and of high quality. In 2015, services delivered about 50 billion parcels globally; a number expected to rise to almost 300 billion in 2030 (see Exhibit 5).

EXHIBIT 5

Quickly growing home deliveries require energy that is zero-carbon and emission-free



Growing e-commerce and clean cities

- Booming **e-commerce** and growing demand for delivery speed
- Cities take action against **local emissions**
- **Freight operations** along the entire value chain need to be green

Autonomous forklifts, trucks, or drones could help provide 24/7 freight delivery and fulfill customer needs for quick yet cost-efficient delivery. At the same time, cities are also taking steps to reduce local emissions and improve air quality by restricting the entry of heavy-emission vehicles or announcing bans on diesel and internal combustion engine (ICE) cars, vans, and trucks in the future.[13]

> More than 20 cities worldwide announced that they will ban diesel vehicles and ICEs in the future

[12] Baseline from MCFM; taxi and shuttle adoption rates from “Hydrogen – scaling up”, factor 1.5 to 2.0 for autonomous taxis since we assume they will only consist of BEVs and FCEVs as zero-emission powertrains

[13] E.g., plans to reduce local emissions and bans on diesel vehicles and ICEs announced in Brussels, Hamburg, London, Mexico City, Paris, Rome, Taipei. Source: press search

For example, more than 20 cities worldwide announced that they will ban diesel vehicles and ICEs in the future.

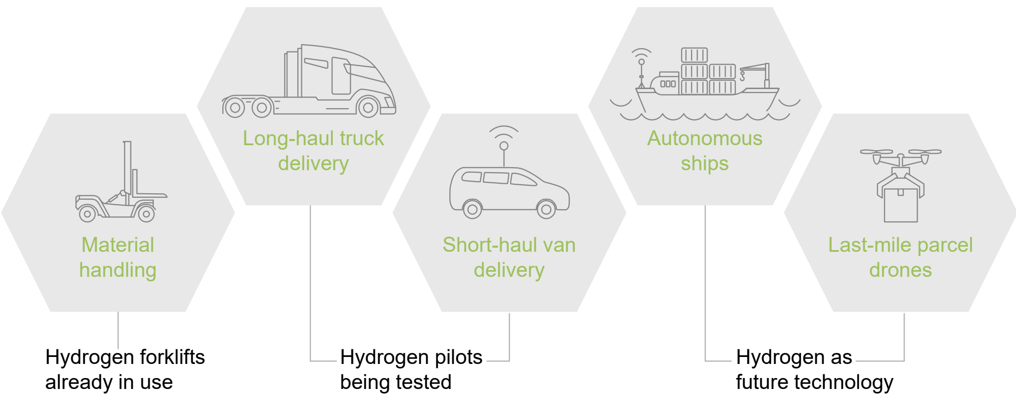
Making zero-emission, digitized delivery work requires four prerequisites. First, to meet the increasingly strict requirements of many cities, delivery vehicles need to increasingly be free of local emissions. Second, high uptime and fast refueling cycles will be a key advantage, since autonomous trucks can run 24/7 and their owners will seek to recuperate high capital investments as quickly as possible. Third, vehicles will require range autonomy for distances up to 800 kilometers to enable extensive regional deliveries and long-haul applications. And fourth, to achieve the greatest revenue-generating payload and minimize costly drive-train weight, vehicles will require the highest fuel energy density possible.

Hydrogen can meet these requirements throughout the freight value chain, which runs from the warehouse to the customer's door – or window, in the case of last-mile delivery by drone (see Exhibit 6).

EXHIBIT 6

Hydrogen can efficiently move goods from the warehouse to the door

Hydrogen technology status



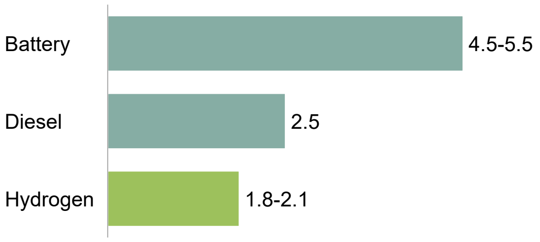
Hydrogen already powers material-handling vehicles such as forklifts, and both long- and short-haul delivery vehicles could benefit from it as an energy vector. In fact, several pilot stage initiatives already exist. Freight vectors of the future – such as autonomous ships and last-mile parcel drones – will also provide additional opportunities for the deployment of hydrogen.

Throughout the value chain, hydrogen's high gravimetric energy density offers measurable benefits to logistics providers. E.g., Exhibit 7 compares the powertrain weight for an 18-ton tractor unit of a semitruck. Using a diesel truck as a reference, its powertrain weighs about 2.5 tons. Powering the same truck via battery would lead to about twice the weight, at 4.5 to 5.5 tons. On the contrary, the powertrain of a hydrogen-powered truck would only weigh about 1.8 to 2.1 tons. This weight benefit of the hydrogen truck would enable it to carry more and heavier loads or reduce the consumption needed to run the truck. To achieve the same payload efficiency as hydrogen- or diesel-powered trucks, the energy density of current batteries would need to improve tenfold.[14]

EXHIBIT 7

Hydrogen as an energy vector for long-haul trucks requires less weight for the powertrain

Powertrain weight comparison,
in tons (18-ton tractor unit of a semitruck)



Hydrogen tanks have
10 times
the energy density (by weight) than batteries[1]

1 0.2 kWh/ kilogram for rechargeable batteries used in battery electric vehicles (BEV) compared to 2.2 kWh/kilogram for onboard hydrogen storage for light-duty fuel cell vehicles (FCEV); Source: U.S. DOE Office of Energy Efficiency and Renewable Energy, MCFM

SOURCE: DOE; Nikola Motors; Bloomberg; Manager Magazin; Sustainable Transportation Lab

Apart from energy density, hydrogen offers system cost advantages for long-haul trucks, as displayed in Exhibit 8. Battery-powered trucks have lower initial system costs, but higher costs per driven kilometer, measured as energy capacity in kW converted to the potential range of a long-haul truck.

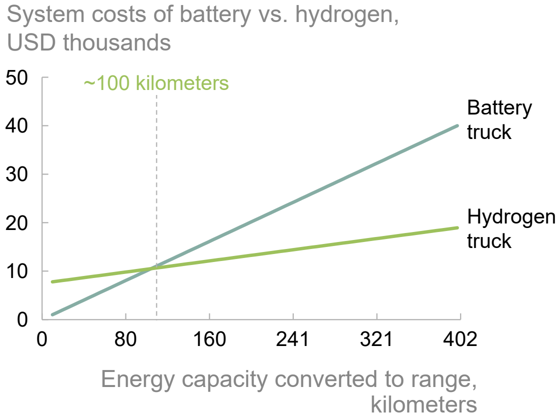
Fuel cells, on the other hand, are more expensive in terms of initial investment, but become more cost efficient than batteries as soon as the energy capacity exceeds around 210 kW or converted to range, about 105 kilometers.[15] For applications focused on enabling intra- and inter-country cargo transport, long-haul trucks must be able to travel long ranges; thus, the cost advantages of hydrogen grow as the range and power requirement of trucks increase. Switching to autonomous trucks even further increases the need for high ranges to enable long uptime and high utilization.

[14] Reference: 18-ton tractor unit, maximum weight of 40 tons including trailer, including trailer; diesel powertrain includes ICE system (1,000 kilograms), fuel system (1,050 kilograms), transmission (200 kilograms), and exhaust (200 kilograms); battery powertrain includes electric motors with reduction gears (180 kilograms), power electronics (320 kilograms), and battery (5,000 kilograms in 2018; 4,000 kilograms in 2030); hydrogen powertrain includes electric motors with reduction gears (180 kilograms), power electronics (320 kilograms), battery (500 kilograms in 2018; 400 kilograms in 2030), hydrogen tank (~670 kilograms in 2018; ~450 kilograms in 2030), and fuel cell (~460 kilograms). Source: DOE; Nikola Motors; Bloomberg; Manager Magazin; Sustainable Transportation Lab; MCFM

[15] Fuel cell with 250 kW performance; battery costs at USD 50/kWh; fuel cell costs USD 30/kW, hydrogen tank at USD 10/kWh; fuel cell efficiency: 70 percent; consumption 5 kWh/kilometer. Source: DOE

EXHIBIT 8

Hydrogen as an energy vector for long-haul trucks enables storage of large amounts of energy at lower costs than batteries



~100 kilometers: the threshold range for hydrogen trucks to become cheaper than battery trucks

SOURCE: DOE; Hydrogen – scaling up

By 2030, approximately 3.0 million to 4.0 million short- and long-haul hydrogen delivery trucks could be on the road. These include medium- and heavy-duty trucks for long-haul deliveries, with a baseline of about 22 million vehicles globally in 2030. Assuming a hydrogen adoption rate of about 1 percent of sales in 2030, it could lead to an estimated 80,000 medium- and heavy-duty hydrogen-fueled trucks. Another potential segment involves short-haul delivery vans for last-mile trucking. In 2030, the global fleet baseline for these vehicles could number roughly 155 million units. A hydrogen adoption rate of about 6 percent of sales would lead to a total of about 3.5 million vans similarly equipped in 2030.[16]

Moreover, there could be around 350,000 hydrogen forklifts by 2030, derived from a total fleet of approximately 8.5 million vehicles and a hydrogen adoption rate of about 4 percent of sales.[17] Hydrogen fuel cells could also power some 130,000 to 260,000 delivery drones for last-mile deliveries. This estimate takes into account an estimated 290 billion packages in 2030, with about 10 percent express parcels, of which 10 percent are drone deliveries. The hydrogen-powered drone estimate is a result of our scenario, which assumes a total of roughly 3,000 annual deliveries per drone and a hydrogen adoption rate of about 20 to 40 percent.

Application 3: VTOL taxis

VTOL taxis support on-demand aviation services, which offer rapid, zero-emission passenger transport. The economic value of this technology is particularly high in congested urban areas like Los Angeles, where residents spend over 100 hours per year stuck in traffic jams.[18] These residents could benefit from a significant reduction in travel time.

[16] Baselines from IHS Markit; adoption rates from "Hydrogen – scaling up"

[17] Baseline from IHS Markit; adoption rate from "Hydrogen – scaling up"

[18] INRIX

Furthermore, VTOLs can make commuting to major cities from the suburbs more convenient, reducing the need to live close to the city center. While still in the pilot phase, estimates claim over 20,000 VTOLs will be flying by 2030.[19]

More than 20,000 VTOLs are estimated to be flying by 2030

More than 80 companies are currently working on the technology. While most are start-ups, major mobility companies are also investing research efforts into VTOL technology. For instance, Uber plans to launch its Uber Elevate service in three cities in 2023 (see Box 1).

Hydrogen has four distinct benefits when used as an energy vector to power VTOL taxis. One, its high energy density helps in powering vertical transport and computing requirements as future generations of VTOLs become autonomous. As a side note, it seems clear that the computing requirements for autonomous air transport will likely exceed those for cars. Two, due to its high energy density, hydrogen provides high uptime, which can maximize flying times and thus offset the high initial investment needed for developing and setting up an entirely new industry. High uptime also converts to longer-range capabilities, opening additional routes not servable with battery VTOLs. Three, it allows for quick refueling without the risk of powertrain lifetime reductions as seen for batteries.

[19] MCFM

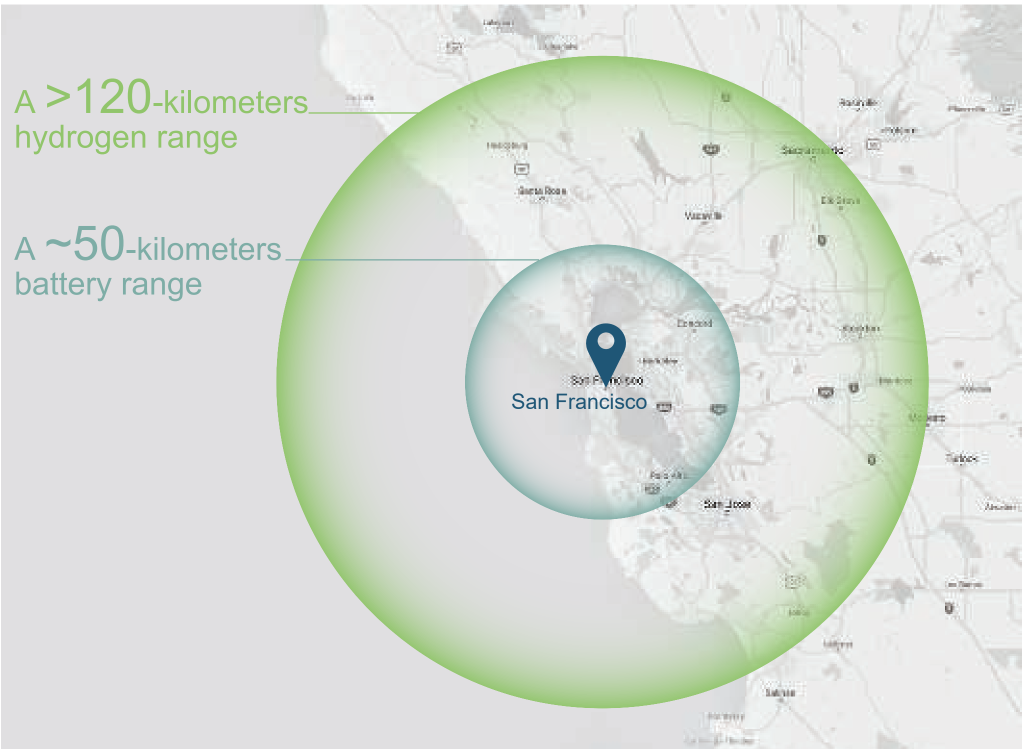
Box 1: Selected companies

Finally, VTOLs will require the setup of an entirely new take-off and landing infrastructure, so-called vertiports. Because vertiports will likely make use of rooftops in cities, they will have limited amounts of available space. Using hydrogen as an energy vector will allow vertiports to use this space efficiently. It can easily refuel VTOLs from multiple OEMs and the space dedicated to refueling stations is smaller due to quick refueling times. In contrast, setting up a vertiport infrastructure for battery VTOLs would necessitate either more space due to longer recharging times or the need for special battery storage rooms for each OEM's multiple spare batteries, thus requiring higher investment.

To illustrate the benefits of higher energy density, let us consider its implications on the range of a VTOL. This would be sufficient for one flight between San Francisco and Palo Alto, yet would require recharging or battery swapping after one flight. Due to the better energy density, hydrogen-powered VTOLs are expected to reach a range two to three times higher than battery VTOLs. Ranges above 120 kilometers would enable hydrogen VTOLs to offer complementary routes, e.g., San Francisco to Sacramento, or fly several routes without the need to recharge, e.g., enabling construction of small vertiports without a refueling infrastructure.[20]

EXHIBIT 9

Hydrogen as an energy vector for VTOLs allows for longer routes without recharging



[20] Assessment of ranges from expert interviews from VTOL companies.

Higher energy density also decreases the weight of onboard energy storage. Calculating the weight requirements for a battery powertrain capable of completing five flights between San Francisco and Palo Alto, which corresponds to a total of 240 kilometers, leads to an estimated power-train weight above 800 kilograms, even when factoring in recharging during vertiport transfers. The hydrogen powertrain, benefitting from its higher gravimetric density, would need to weigh around 500 kilograms. Hence, savings from the powertrain could reach several hundred kilo-grams, which could be used to either achieve higher uptime and longer ranges or transport more passengers, leading to increased revenue.[21]

Hydrogen enables lighter powertrains for higher uptime, longer ranges, and more passengers

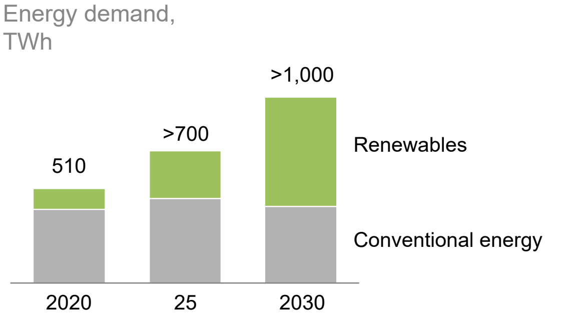
With some 20,000 VTOLs comprising the global fleet in 2030, a hydrogen share of 20 to 40 percent based on our scenario assumptions would mean that some 4,000 to 8,000 VTOLs could be powered by hydrogen in 2030.[22]

Application 4: data centers

Data centers represent the backbone of virtually all digital trends and require large amounts of energy. Exhibit 10 reveals the trend in overall energy consumption of data centers. By 2020, data centers are expected to require a total of around 500 TWh, with most of the energy supply coming from conventional energy sources. Within the next decade, this demand could double, equaling the energy needs of two Germanys.[23]

EXHIBIT 10

Data centers, as the backbone of all digital trends, require large amounts of green energy



35%
annual growth of data center storage from 2016 to 2021

30-50%
of data center costs are attributed to energy, mostly for cooling

SOURCE: Bloomberg; Cisco; Digital Realty; Enerdata; expert interviews; Forbes; Gartner; IEA; Intellect UK; zdnet

[21] Assumptions: energy density at 400 Wh/kilogram for battery VTOL, 700 Wh/kilogram for hydrogen VTOL; San Francisco to Paolo Alto: 50 kilometers; cruise speed 100 kilometers per hour; minimum battery safety reserve 30 minutes; take-off/landing power 650 kW for 1.5 minutes each; in-flight consumption 2.25 kilometers per kWh; transfer time between flights 10 minutes with 5 minutes recharging at 350 kW. Higher energy density of battery assumed than for land transport due to more efficient battery. Source: Airbus; Bartini; DOE; Elevate; expert interviews; Porsche Consulting; Uber; MCFM

[22] Expert interviews

[23] Enerdata; expert interviews; Forbes; Gartner; International Energy Agency.

Due to the high costs of energy in total operational expenditures (30 to 50 percent of total operating costs), data centers are increasingly producing their electricity on-site. However, geographical placement limits constrain this energy, such as the need for proximity to end users (to reduce latency times) and to country borders (to avoid political conflicts). While a data center may have good access to wind power, for instance, it might not have access to pumped hydro storage to balance the fluctuations in supply.

Hydrogen as an energy source would provide several benefits when used as energy vector for data centers

Hydrogen would provide several benefits when used as energy vector for data centers. Data centers could benefit from hydrogen being responsive and versatile and can use it irrespective of their location. Furthermore, it provides a way to balance and store fluctuating renewable power sources and use this green energy for the data centers when it is required. Third, it allows the effective long-term storage of excess energy from renewable sources to balance the grid. Beyond serving as energy source for electricity generation, hydrogen can also be used for cooling of servers in data center. Stored liquefied hydrogen could be used to cool down servers before it's used as a fuel. Also heat emissions from H_2 fuel cells or H_2 gas turbines could be used for cooling via absorption type chillers.

Users could deploy hydrogen as an energy vector for data centers. It is an ideal and versatile backup energy source for powering data centers in case of outages. It would allow a fuel cell to power up if the grid were down, e.g., just as a diesel generator would today, while providing the added advantage of being a green fuel. Our research indicates that hydrogen could provide about 1 TWh of backup energy (i.e., at a 20 percent market share of backup power, or about two days p.a.) in 2030.

Ultimately, hydrogen could serve as the primary energy source for data centers. For instance, Microsoft is currently testing 20 x 10 kW fuel cell systems as the prime power for one of their servers. While fuel cells in data centers currently use natural gas as feedstock, they could switch to hydrogen in the future.

Summary

Hydrogen has strong potential to foster CO_2-neutral growth in transport, industry, and cities by bringing clean energy to a range of applications.

Taking four technologies of the city of the future as an example, this report shows how hydrogen can complement batteries to enable new technologies and make our city living cleaner, healthier, and more efficient. For these four applications – autonomous taxis and shuttles, digitally enabled freight chains, VTOL taxis, and data centers – hydrogen can meet an energy demand of an estimated 5 to 7 million tons of hydrogen per year, powering approximately 5.5 million to 6.5 million fuel cell applications (see Exhibit 11).

EXHIBIT 11

For the four selected use cases, hydrogen demand could grow to 5-7 m tons by 2030

In 2030, hydrogen could power …

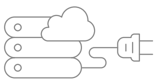
~1.0-1.5 m
autonomous taxis

~300-700k
autonomous shuttles

~3.0-4.0 m
delivery trucks and vans

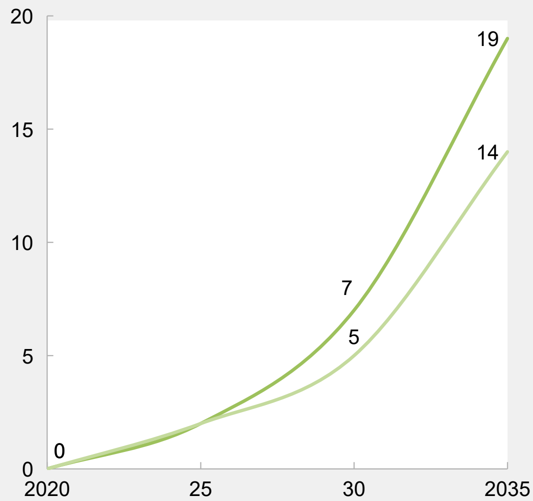
130-260k
drones for express parcel delivery

~4-8k
vertical take-off and landing taxis (VTOL)



~1 TWh
of backup power in data centers

Hydrogen demand of the four selected use cases, million tons



While the technologies described here may seem futuristic and beyond current agendas, their tremendous potential is fueling momentum in the market. In fact, all of these technologies are currently in development and demonstration phases. Thereby, they all share the need for versatile and carbon-free energy sources.

In many cases, the first projects are using battery power rather than hydrogen fuel cells because batteries are more readily available and companies are racing to bring their technologies to the market. However, hydrogen technology exists and is ready for deployment. Given the strong benefits these hydrogen-based solutions offer when it comes to bringing new technologies to scale, we believe now is the time to become involved – while players are shaping markets and standards are being set.

In some of the more conventional fuel cell applications such as passenger cars or residential energy uses, infrastructure represents a major barrier to deployment. For new technologies such as AVs or VTOLs, however, initial infrastructure requirements are more limited, and a small number of hydrogen stations can power large autonomous fleets.

The Hydrogen Council is convinced that clear, green hydrogen can meet many of the new energy demands that will emerge over the next decades. We stand ready to jointly develop these applications today with the shapers of the new economy.

Glossary

AV	autonomous vehicle
BEV	battery-electric vehicle
FCEV	fuel cell electric vehicle
ICT	information and communication technology
IEA	International Energy Agency
kWh	kilowatt hour
MCFM	the McKinsey Center for Future Mobility
MJ	megajoules
MW	megawatt
OEM	original equipment manufacturer
PEMFC	proton exchange membrane fuel cell
SOFC	solid oxide fuel cell
ton	metric ton (1,000 kilograms)
TWh	terawatt hour
VTOL	vertical take-off and landing taxis

Bibliography

Airbus, "CityAirbus Demonstrator Passes Major Propulsion Testing Milestone," October 2017

Andrae and Edler, "On Global Electricity Usage of Communication Technology: Trends to 2030," Challenges, Vol. 6 (1), pp. 117-157, 2015

Bartini, "Technical Specifications," 2018

Bloomberg, "Driverless Cars Are Giving Engineers a Fuel Economy Headache," October 2017

Bloomberg, "Microsoft is Getting Hungry for Fuel Cells," October 2017

Bloomberg, "Tesla's Newest Promises Break the Laws of Batteries," November 2017

Cisco, "Cisco Global Cloud Index: Forecast and Methodology, 2016–2021," February 2018

Curbed, "Uber and Lyft Cars Now Outnumber Yellow Cabs in NYC 4 to 1," January 2017

Data Center Knowledge, "How Microsoft is Keeping its Cloud More Efficient Than Your Data Center," May 2018

Digital Realty, "Cost of Data Centre Operation/Ownership," March 2013

DOE (U.S. Department of Energy), "DOE Technical Targets for Onboard Hydrogen Storage for Light-Duty Vehicles," 2018

DOE (U.S. Department of Energy), "DOE Technical Targets for Fuel Cell Systems and Stacks for Transportation Applications," 2018

Enerdata, "Electricity Domestic Consumption," June 2018

Enerdata, "World Energy Statistics," June 2018

EPA, "Fuel Economy," July 2018

Forbes, "Waymo is Millions of Miles Ahead in Robot Car Tests; Does it Need a Billion More?" March 2018

Forbes, "Why Energy is a Big and Rapidly Growing Problem for Data Centers," December 2017

Gartner, "Forecast: Data Centers, Worldwide, 2015-2022, 2018 Update," May 2018

Greater London Authority, "Mayor Sets Out Bold Strategy to Make London the Greenest Global City," May 2018

Hydrogen Council, "Hydrogen Scaling Up – A Sustainable Pathway for the Global Energy Transition," November 2017

Hyundai, "E-Mobil 2.0: Der Hyundai Nexo mit Brennstoffzellenantrieb," June 2018

IHS Automotive, "IHS Automotive Light Vehicle Sales," June 2018

IHS Markit, "Commercial Vehicle Market Performance," June 2018

INRIX, "INRIX Global Traffic Scorecard," 2018

Intellect UK, "Data Centres and Power: Fact or Fiction?" 2012

International Energy Agency, "Energy Technology Perspectives," 2017

International Energy Agency, "World Energy Outlook," 2017

Manager Magazin, "Was Wir Bereits über Teslas Elektro-Truck Wissen," November 2017

McKinsey Center for Future Mobility (MCFM), "How Battery Storage Can Help Charge the Electric-Vehicle Market," February 2018

McKinsey Center for Future Mobility (MCFM), "Perspective on Autonomous Driving," May 2018

Nationale Plattform Elektromobilität (NPE)

Navigant Research, "Microsoft Deploys Fuel Cells into the Core of World's First Gas Data Center," October 2017

NBA, "The Game Court," September 2002

New York City Taxi and Limousine Commission, "Taxicab Factbook," 2014

New York City Taxi and Limousine Commission, "TLC Factbook," 2016

Nikola Motor, "Nikola Motor FAQs," 2018

PitchBook Data Inc., "Financing Valuations," July 2018

Porsche Consulting, "The Future of Vertical Mobility," 2018

Sustainable Transportation Lab, University of Washington, "Does the Tesla Semi Defy the Laws of Physics?" February 2018

Tesla, "Model S," July 2018

The Vertical Flight Society, "The eVtol News," 2018

Uber Elevate, "Fast-Forwarding to a Future of On-Demand Urban Air Transportation," October 2016

Waymo, "On the Road," July 2018

Wired, "Self-driving Cars Use Crazy Amounts of Power, and it's Becoming a Problem," June 2018

zdnet, "Energy Costs Mean Tough Decisions for Datacentre Owners," April 2013