Guest Forum

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The Merging of Two Environmentally-Driven Paradigm Shifts in Energy

環境対策として進められているエネルギー分野のふたつのパラダイムシフトの統合について

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The environmental challenges of Climate Change and degraded Urban Air Quality are driving paradigm shifts in two major energy sectors, the generation of electricity (electric power) and the powering of vehicles (vehicle power). In the electric power sector, the paradigm shift is from fossil fuel to the sun as the source of energy. In the vehicle power sector, the paradigm shift is from fossil fuel to the sun as the source of energy. These parallel changes result in a zero emission of greenhouse gases to the atmosphere, and a zero emission of urban air quality degrading pollutants to the atmosphere. A major side effect is fuel independence, removing the reliance on internationally sourced fossil fuels and associated geo-politics and conflicts. Fortuitously, the paradigm shifts are resulting in a merging of the two sectors.

気候変動と都市の大気環境の悪化に対する環境対策が，電力エネルギー供給とクルマの動力というふたつの分野についてパラダイムシフトをもたらしつつある。電力供給分野では，エネルギー源が化石燃料から太陽光に移るというパラダイムシフトがある。クルマの動力の分野では，エネルギー源が化石燃料から太陽光に移るというパラダイムシフトがある。同時進行しているこれらの変化が大気中への温室効果ガスの排出をゼロにし，大気中への環境汚染物質の放出をゼロにするのである。この副次的効果として，エネルギー自給率が向上し，海外からの化石燃料調達に伴う地政学的対応や紛争のへの関与から解放されることになる点は重要である。これらのパラダイムシフトの結果，幸いにもふたつの分野が統合されつつある。

Introduction

The combustion of fossil fuels has served society for centuries as the driving force for economic growth and the quality of life. Whether generating electricity, propelling aircraft, powering automobiles, trucks, and buses, cooking, heating water, space heating, or drying clothes and dishes, combustion is the technology used to liberate and transform the energy bound in the fossil fuel to high-temperature gases in an engine or appliance burner to produce the useful product which we take for granted. Simply itemize the number of your activities in one day that are rooted in combustion. The hot shower, the egg omelet, the commute to work, the call on the cell phone, the news on the television, the Internet, your computer, the light in the room, the air conditioning in your office, the food on your table.

As remarkable combustion has been in serving society, certain ramifications are causing a shift to alternatives. One ramification is the dependence of combustion on fossil fuels. A second ramification is the emission of contaminants (CO_2, CH_4, N_2O as examples) that drive climate change. A third is the emission of criteria pollutants (CO, NO_X, HC, as examples) that degrade urban air quality[*1].

These ramification are leading to changes across the energy spectrum, especially the two sectors (electric power and vehicle power) that collectively have the largest energy demand and collective CO_2 emission worldwide. As a result of the growing evidence of the environmental and resource impacts over the past six decades, both sectors are experiencing paradigm shifts from a classic "combustion-dominant construct" to a "renewable-

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*1: Climate Change Gases: CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide) as examples.
Criteria Pollutants: CO (carbon monoxide), NO_X (oxides of nitrogen), HC (partially oxidized hydrocarbons) as examples

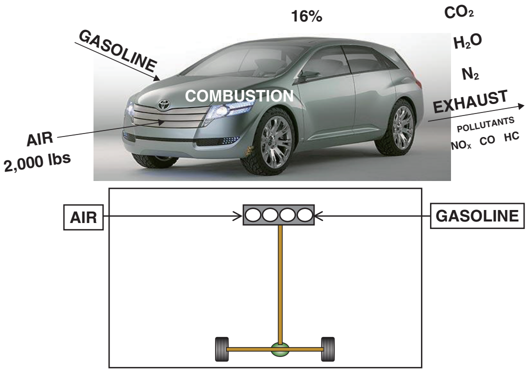
dominant construct" with the goal to mitigate climate change and provide a quality of air for future generations.

Vehicle Power

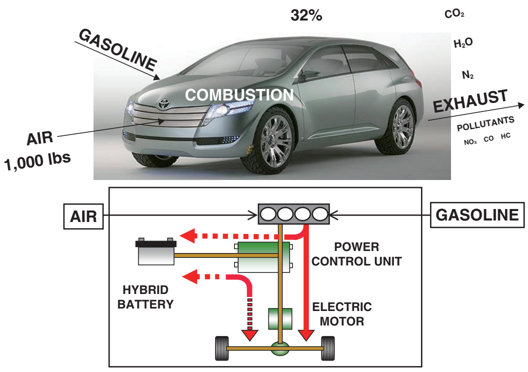
Conventional combustion vehicle drivetrains and exhaust emissions are illustrated in Figure 1. The classic combustion vehicle (Figure 1a) has a mechanical drive train and emissions of both major products of combustion (CO_2, H_2O, N_2) and criteria pollutants.[*2] The efficiency of the classic combustion vehicle (CCV) is 16% and processes 2,000 pounds of air and removes 400 pounds of oxygen from the atmosphere per tankful (20 gallons) of gasoline.

*2: H_20: Water
N_2: Nitrogen

The introduction of the Prius by Toyota in 1997 was the first major step in the paradigm shift of vehicle power (Figure 1b). In the hybrid combustion vehicle (HCV), the drive train is transitioned from mechanical to electric, and a large battery (along with power electronics and an electric motor) are added to the mix. The net result is a doubling of the efficiency, the reduction by 50% of the amount of oxygen consumed per tankful of gasoline, and a proportional decrease in the emission of CO_2 and criterial pollutants.



(a) Classic Combustion Vehicle (CCV)



(b) Hybrid Combustion Vehicle (HCV)

Figure 1 Conventional Combustion Vehicles

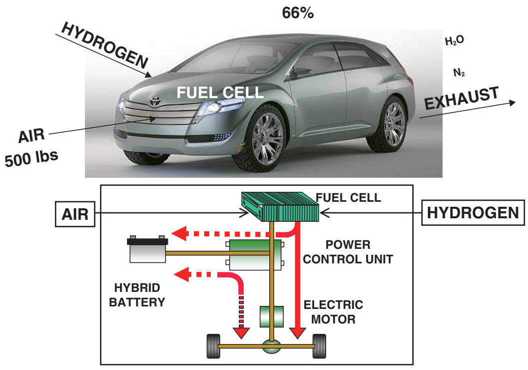
In Figure 2, the next-generation of zero-emission vehicles are illustrated. The fuel cell electric vehicle (FCEV) utilizes the hybrid electric drive train platform with two notable changes (Figure 2a). The combustion engine is replaced by a fuel cell engine, and the fuel is changed from gasoline to hydrogen, both in their own right paradigm shifts. The efficiency again doubles, the amount of oxygen consumed is reduced by 50%, and neither greenhouse gases (GHGs) or criteria pollutants are emitted. The FCEV is virtually the replacement to the CCV and HEV, providing the accustomed range (300 to 400 miles), fueling time (under 5 minutes), and an engine block (fuel cell engine) that can scale to power the largest vehicles (e.g., class 8 heavy-duty long-haul trucks, locomotives, ships).

For short range use and applications where the time to charge is not an issue, the battery electric vehicle (BEV) provides the convenience of fueling at home (Figure 2b), at a hub for a fleet of autonomous vehicles, or at a hub for medium duty vehicles such as buses and delivery trucks.

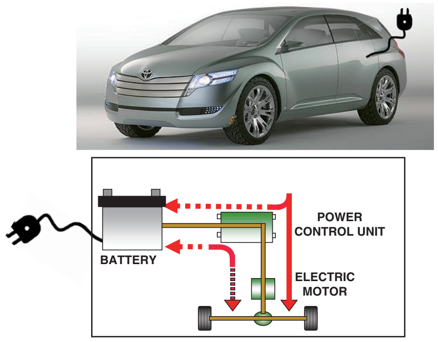
Combining the features of the FCEV with the BEV results in a compelling product for both customer satisfaction and efficiency (Figure 2c). The plug-in fuel cell electric vehicle (PFCEV) has the advantage of charging at home with an all battery electric range (BER) of 40 miles or more, and an overall range of 300 to 400 miles when desired.[1] (Notable, in most urban areas, over 80% of trips are 40 miles or less.)

The introduction of alternative fuels requires infrastructure for the charging of plug-in vehicles and dispensing of hydrogen for fuel cell vehicles. The principal strategy for PEVs is home charging with both work places and commercial centers deploying chargers for convenience and to mitigate range anxiety.

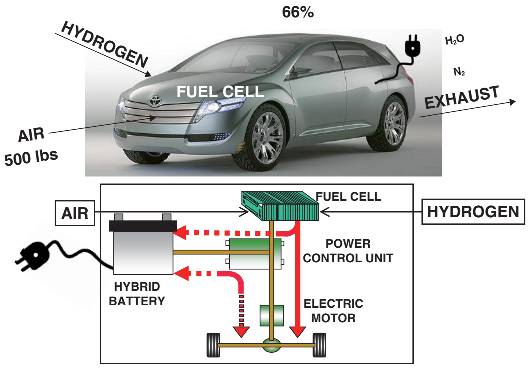
The hydrogen fueling infrastructure is being deployed at existing gasoline stations. The initial deployment in California, for example, followed a plan established by the University of California Irvine (UCI) Advanced Power and Energy Program under contract to the California Energy Commission (Figure 3a).[2, 3] Twenty-two stations were identified in two northern California focus areas (the San Francisco Peninsula, and the East Bay) and forty stations in three southern California focus areas (Irvine/Newport Beach, Torrance, and Santa Monica). In addition, a few "weekend destination" locations were proposed (e.g., Santa Barbara, San Diego, and Lake Tahoe) as well as a "connector" station at Harris Ranch between southern and northern California. In total, 68 stations were identified as the minimum to enable the early market for FCEVs. Shown in Figure 3b is the UCI hydrogen station that, in 2019, regularly daily dispensed



(a) Fuel Cell Electric Vehicle (FCEV)



(b) Battery Electric Vehicle (BEV)



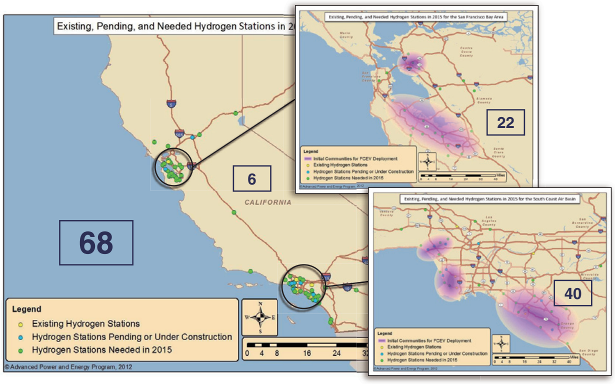
(c) Plug-In Fuel Cell Electric Vehicle (PFCEV)

Figure 2 Zero-Emission Vehicles

in excess of 350 kg and served over 100 FCEVs with one fueling position. Also shown is a FirstElement Fuel station as an example of hydrogen dispensing at an established gasoline station in Long Beach. California has a target for 100 stations in 2020.

Currently, the state has 9,800 gasoline stations. Were all the vehicles PFCEVs in the state, it is estimated that 1,600 hydrogen stations would be needed to satisfy access. For FCEVs, the number of stations would likely double to meet the capacity required.[4] The higher the percentage of PFCEVs, the fewer the number of stations over and above 1,600 that will be required.

While zero-emission vehicles themselves emit zero GHGs and zero criteria pollutants, the supply chains for



(a) Infrastructure Planning

(b) Hydrogen Stations

Figure 3 Hydrogen Fueling Infrastructure

electricity and hydrogen can be major sources of GHGs and criteria pollutants if not carefully planned. In Figure 4, various supply train scenarios are illustrated for the emission of CO_2.[5] In addition to tailpipe emissions, CO_2 can also be emitted by the extraction of the fuel feedstock, the fuel production, the distribution of the fuel, and the manufacturing of the vehicle itself. Shown in the Figure at the top is the CO_2 signature associated with the CCV (25 miles per gallon ave) along with an arrow that conveys the overall goal to reduce the signature to zero. Yellow highlighted are the following scenarios worthy of note:

- **FCEV-H_2 from NG, Liquid**. While resulting in a reduction in CO_2 emission, the decrease is modest from what is required, demonstrating the need to harvest hydrogen from a renewable, zero-emission resource rather than from the historical dependence on natural gas (NG) as the source of hydrogen.
- **BEV-100% RE**. This scenario represents the epitome of clean transportation with both a zero-emission of CO_2 from the tailpipe and a 100% renewable

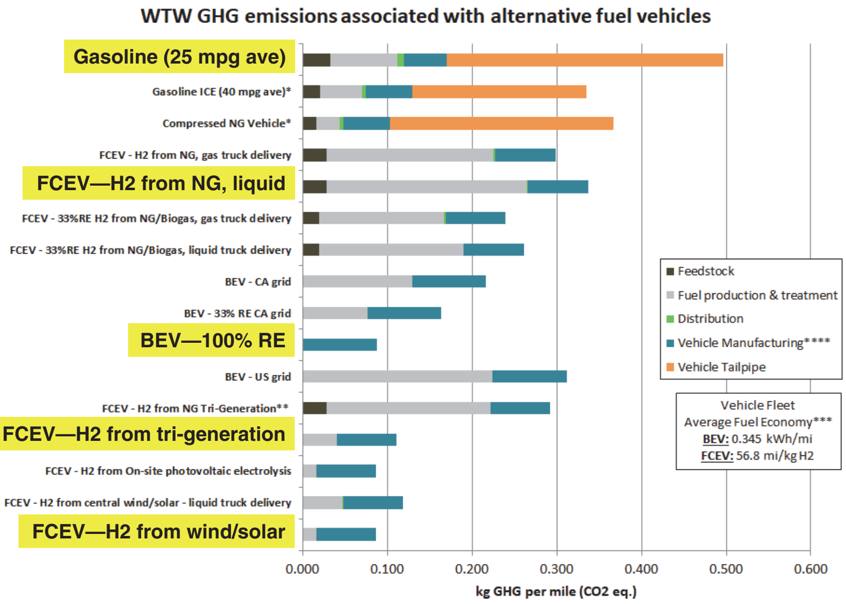


Figure 4 Life Cycle CO_2 Emission of Automobiles.[5]

energy (RE) fuel (electricity) supply train. The focus for the residual CO_2 is directed to the manufacturing of the vehicle which is a challenge given the international sourcing of parts and assembly, and conveyance to the point of sale.

- **FCEV-- H_2 from Tri-Generation**. In this scenario, the hydrogen is sourced from human sewer waste using a technology described in the following section.
- **FCEV-- H_2 from 100% RE**. This scenario also represents the epitome of clean transportation with both a zero-emission of CO_2 from the tailpipe and a 100% RE fuel (hydrogen) supply train. In this scenario, the hydrogen is sourced from otherwise curtailed solar and wind, described in the following section. The remaining focus for CO_2 reduction is on manufacturing as well as fuel production.

With zero emission from the vehicle tailpipe, attention must be next directed to the fuel supply train for both electricity and hydrogen. While electricity will be clearly sourced from the electric grid, hydrogen will as well.

Electric Power

Historically, electric power is centrally generated at large, combustion powered plants in the general range of 100 to 1,000 MW. While hydro and nuclear contribute to varying degrees, combustion fueled by fossil fuels (natural gas, oil, or coal) has been the dominant strategy for the generation of electricity in the classic grid. The **first stage** in the paradigm shift from the classic form to a new configuration is shown in Figure 5a. Examples of the paradigm shift shown in Figure 5a include:

- **Renewable Power Generation**. At both the central and distribution levels, solar and wind generation resources are being deployed to generate renewable electricity. In California, for example, the penetration of renewable solar and wind resources has increased dramatically and is on course to meet a target of 60% in 2030.[6]

- **Distributed Generation**. Distributed generation (DG) encompasses the generation of power at or in the vicinity of the customer on the distribution side of the utility, and is emerging as a strategy to improve the efficiency of power utilization, increase the reliability and resiliency of the power supply to the customer, and reduce the cost of energy to the consumer.

For example, DG provides the opportunity to capture and use heat that would otherwise be exhausted and fulfill additional customer needs such as hot water, space heating, steam, or chilled water. This capture and use of heat in this manner displaces the electricity and natural gas that would otherwise be required.

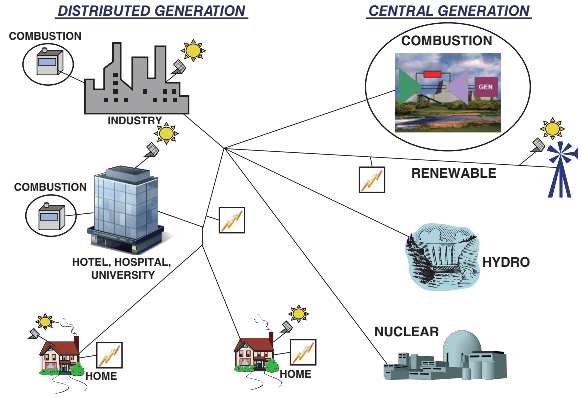
A second example utilizes a fortuitous attribute of the emerging DG technologies such as fuel cells, photovoltaic panels, and microturbine generators. Each produce direct current (DC). To serve the alternating current (AC) loads at the customer site, the DC is inverted to AC with an expense of energy of approximately 5-10%. In the new area of electronics, many major loads in buildings are DC powered loads such as computers, monitors, cable boxes, modems, servers, and LED lighting. These DC loads are served historically by rectifying AC to DC with up to 50% lost in energy as heat, resulting in not only an inefficiency but an increased energy-intensive air conditioning load as well.

To support reliability and resiliency, DG allows the customer to remain in operation should the utility grid serving the customer experience an outage. While the customer might need to shed ("turn-off" or "drop") some non-critical loads to balance the load with the operating DG, the breaker to the utility can be opened and thereby island the customer's electricity operations. When the utility grid returns, the breaker can be closed. While easier said than done, islanding is a wave of the future and already implemented in many facilities around the world with the benefit of on-site DG.

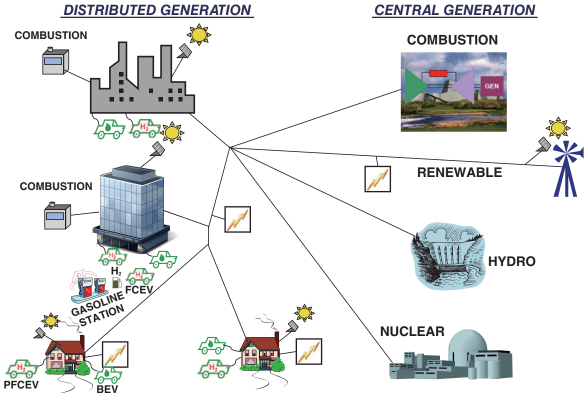
- **Battery Storage**. Unfortunately, solar and wind do not produce electric power continuously. Both vary diurnally and produce varying amounts of electricity each day based on the meteorology (e.g.., wind conditions and solar insolation). Solar and wind also experience intermittency, namely an abrupt reduction (e.g., a cloud passing over a solar panel, or a momentary decrease in wind) or over generation (e.g., a burst of wind). To manage the diurnal variation and intermittencies, the base load power plants (e.g., combustion power plants) must respond faster in the future than they do today, and electric battery storage must be deployed as shown in Figure 5a at both the central and distributed generation levels.

A **second stage** in the paradigm shift to a new configuration is the emerging load from plug-in BEVs and PFCEVs (Figure 5b). A challenge to electric utilities is the development of control strategies that can manage the charging to protect utility assets (e.g., transformers) and balance the vehicle charging load with the available generation. Efforts worldwide are addressing this challenge as well as evaluating the potential of the large batteries installed in plug-in vehicles to serve as a potential source of stored energy available to the grid upon command.

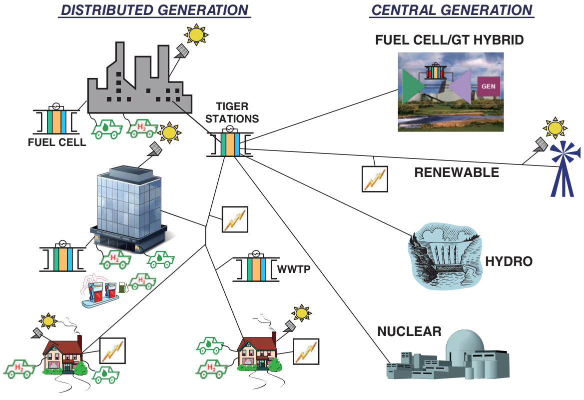
A **third stage** in the paradigm shift to a new configuration is the emerging deployment of stationary fuel cells as an alternative to combustion based generators for the 24/7 production of electricity (Figure 5c). With the deployment if diurnally varying and intermittent renewable solar and wind generation, the 24/7 plants must be operated more dynamically, namely ramping up and down in response to the varying renewable resources. Because combustion emits carbon dioxide and criteria pollutants as unavoidable byproducts, an alternative to combustion that can operate (1) more efficiently than combustion (thereby reducing CO_2 per megawatt-hour), (2) operate on a zero-carbon fuel (thereby emitting no CO_2), and (3) without the emission of criteria pollutants would be preferred. In parallel with vehicle power, stationary fuel cell technology is emerging as an alternative to combustion for the generation of electrical grid power. Like their vehicle counterpart, stationary fuel cells operate on hydrogen. Although thousands of miles of dedicated hydrogen pipelines are installed worldwide, hydrogen infrastructure is not today ubiquitous. As a result,



(a) Classic Grid with First Stages of Transition



(b) Plug-in Vehicles



(c) Stationary Fuel Cells

Figure 5 Electric Grid Evolution

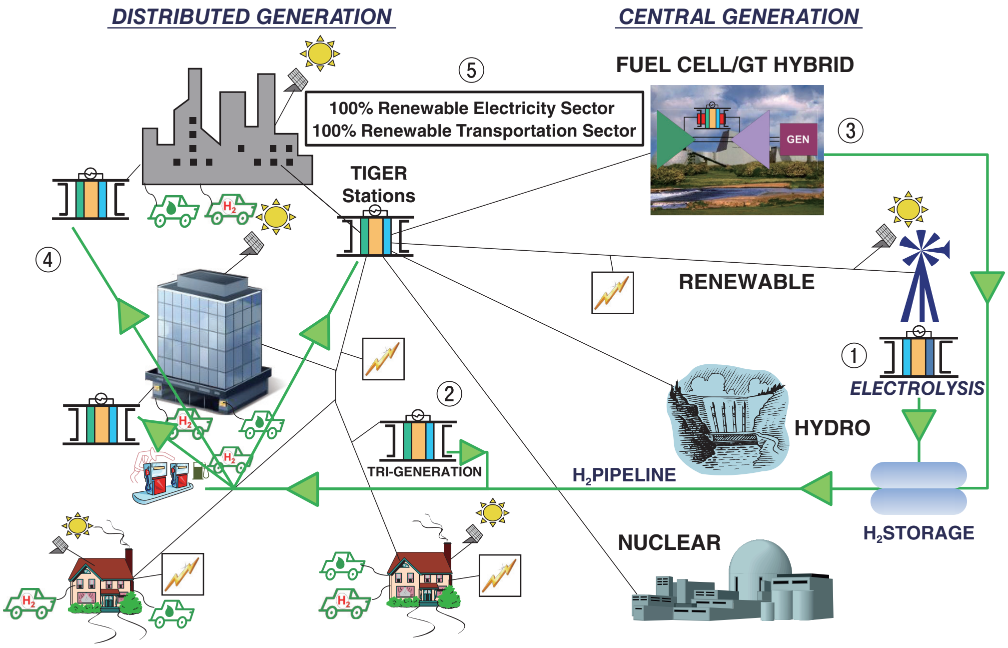


Figure 6 100% Renewable Energy Grid

stationary fuel cells today operate on natural gas or biogas, both rich in methane. Within the fuel cell system, the hydrogen is extracted from the methane using steam methane reformation. The fuel flexibility of stationary fuel cells is a major attribute, providing the flexibility to operate today on natural gas and bio gas, tomorrow on blends of natural gas and renewable hydrogen (described in the "fourth stage"), and eventually solely on renewable hydrogen.

In addition to high efficiency and zero-emission of criteria pollutants, fuel cells are quiet – a welcomed attribute for deployment as distributed generators in the midst of where the public resides and works.

Applications of stationary fuel cells on the customer side of the electric meter include industry, hotels, hospitals, university campuses, and waste water treatment plants (WWTP). Examples on the utility side of the meter are comprised of "Transmission Integrated Grid Energy Resource (TIGER) Stations" to provide local grid support.[*3] [7] While concepts are under development for the deployment of hybrid fuel cell/gas turbine technology at 100 to 1,000 MW central generation power plants, pervasive deployment remains decades away.[8] (The largest fuel cell plant deployed in 2019 was a 59 MW facility in Korea.)

Early markets adopting the stationary fuel cell power generation technology in the distribution generation regime include California, Korean, Japan, and the northeast of the United States operating on a combination of natural gas and biogas. In 2019, over 500 MW of stationary fuel cell product was deployed in the United States, and over 300 MW in Korea.[9]

Notable in Figure 5c is the absence of combustion as a source of both grid electric power and vehicle power, representing the culmination of the paradigm shift from combustion-dominant electric grid and transportation sectors with the associated limited efficiencies and emission of criteria pollutants, to electrochemical-dominant electric grid with and transportation sectors with high efficiencies and virtually zero emission of local air pollutants such as nitrogen oxides. While notable, it is important to recognize that this paradigm, while zero in the emission of criteria air pollutants, may not be zero in the emission of carbon. If the fuel cells are operating on natural gas, biogas, or syngas, carbon dioxide will be generated in the reformation process and liberated in the exhaust. If the fuel cells instead are operated on renewable hydrogen (from otherwise curtailed solar and wind, for example), zero carbon will be emitted from the electric grid sector. In addition to the electric sector, a zero carbon source is required for hydrogen generated for the transportation sector. Hydrogen generated from steam reformation plants operating on natural gas will result in the emission of carbon dioxide. The hydrogen must instead by provided from a carbon-free source to result in truly 100% renewable electric grid and transportation sectors. This leads us to the fourth stage.

*3: Side of the Meter. The customer side of the electric utility meter encompasses the circuits owned and managed by the customer. The utility side of the electric meter encompasses the circuits and electrical resources owned and managed by the utility.

The **fourth stage** in the paradigm shift to a new configuration is the emerging role of renewable hydrogen (Figure 6). Solar and wind generation cannot load follow, generating instead whenever the "fuel" (sun or wind) is available. As a result, renewable wind and solar generators are "must take" resources. If the load is less than the renewable generation being produced, the solar and wind resources must be curtailed.[*4] An option is to not curtail but rather continue to generate and store the renewable electricity for use at a later time when the demand calls.

*4: Curtailment is the action of reducing (in the extreme, turning off) the renewable wind or solar generation resource when load on the grid is insufficient to utilize the electricity that would otherwise be produced.

While electric battery and pumped hydro will play a role, a massive storage technology is needed to capture the massive energy projected from otherwise curtailed solar and wind, and overcome the limitations of pumped hydro (capacity) and electric batteries (degradation, cost, self-discharging, and inability to accommodate seasonal shifts in energy demand). Systems analyses consistently demonstrate that the generation of renewable hydrogen through electrolysis powered by otherwise curtailed solar and wind (① in Figure 5c) may fortuitously be the means to fill this need, providing the necessary capacity and seasonal shift capability in support of a 100% renewable grid.[10] Once generated, the electrolytic renewable hydrogen can be stored by injection into the natural gas infrastructure or a dedicated hydrogen pipeline, and conveniently conveyed to the points of use such as fueling the new paradigm of fuel cell vehicles with carbon-free fuel, powering fuel flexible stationary fuel cells, and serving industry demands for hydrogen.

In addition to carbon-free electrolytic renewable hydrogen, the following sources are emerging to provide carbon-neutral renewable hydrogen:

- **Tri-Generation of Renewable Hydrogen**. Tri-Generation is a technology capable of generating carbon-neutral hydrogen using a stationary fuel cell operating on biogas produced at a WWTP②, a landfill that stores biodegrading human waste, or a diary with large volumes of cow manure. The biogas powers a stationary fuel cell to produce carbon-neutral electricity and heat. By operating the fuel cell with more biogas than required for the electricity and heat alone, excess hydrogen is produced at the stack. This excess hydrogen can be extracted as a third product to serve a FCEV and PFCEV dispenser, or be stored in a natural gas or dedicated renewable hydrogen pipeline for later use. At a WWTP or diary, the renewable heat in the exhaust stream can be captured and used to provide the thermal energy required by digesters and thereby displace fossil-fuel boilers, further reducing CO_2 emissions. Tri-Generation is the epitome of sustainability, namely recovering and converting the energy from human and animal waste to renewable electricity, renewable heat, and renewable hydrogen.

- **Central Power Plant Generation of Renewable Hydrogen**. Fuel cell 100 to 1,000MW central generation power plants, operating on a mixtures of fossil fuels and biomass or entirely biomass as supply is available, are being designed to capture and utilize the exhaust heat for the co-production of hydrogen and capture the emission of carbon for sequestration③.[11] While development of these integrated fuel cell/gas turbine hybrid systems are a least a decade in the future, the principle, technology, and economic viability are compelling.

The **fifth stage** in the paradigm shift to a new configuration is utilization of the stored renewable hydrogen. In addition to fueling fuel cell vehicles and fulfilling industrial needs, renewable hydrogen can be employed to power the deployed fleet of stationary fuel cells, giving rise to the ultimate clean (zero emission of both carbon and criteria pollutants), firm (24/7, load following) generator of renewable electricity as a complement to, and answer to diurnal varying and intermittent renewable solar and wind④.

Notable, Figure 6 represents the ultimate goal of both a **100% renewable electricity sector**, and a **100% renewable transportation sector**, merged into one cohesive paradigm⑤.

Summary

To address both climate change and the degradation in urban air quality, paradigm shifts in the electric and transportation sectors began in earnest at the turn of the 21st century, and will evolve over decades before settling into the new paradigm of both a 100% renewable electricity sector, and a 100% renewable transportation sector. The principal attributes of the new paradigms are:

- Electric drive-train vehicles powered by electric batteries alone, or electric batteries in combination with fuel cell engines, powered by locally sourced renewable electricity, renewable hydrogen, or a combination of both.
- The generation of renewable electricity from diur-

nally varying and intermittent wind and solar,

- The generation of renewable electrolytic hydrogen from otherwise curtailed wind and solar,
- The complementary generation of renewable electricity from zero-carbon hydrogen powered stationary fuel cells with key attributes such as (1) zero emission of carbon and criteria pollutants, (2) provision of electricity 24/7, and (3) load following,
- Energy storage (e.g., electric battery, pumped hydro, renewable hydrogen) to capture and later (from hours, to days, to weeks, to months, to seasons) utilize energy from otherwise curtailed renewable resources,
- The electrification of transportation as a challenging grid load (on the one hand) and a potential source for the grid to tap for stored energy (on the other hand),
- The integration of the (1) electric sector, (2) the transportation sector, and (3) a new paradigm of the hydrogen "battery," namely:
    - ○ The generation of renewable hydrogen from otherwise curtailed renewable solar and wind resources,
    - ○ The storing and conveying of the renewable hydrogen by injection into existing natural gas infrastructure or through existing and new dedicated compressed hydrogen pipelines, and
    - ○ The utilization of the renewable hydrogen for fueling fuel cell vehicles, powering clean, firm stationary fuel cells for the generation of renewable electricity to balance diurnal varying and intermittent wind and solar, and serving the hydrogen requirements for industry.
- Fuel independence, removing the reliance on internationally sourced fossil fuels and associated geopolitics and conflicts.

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