Proliferation of Fuel Cell Electric Vehicles in Coordinated Operations of Hydrogen-Integrated Urban Transportation and Renewable Energy-based Power Distribution Networks

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Introduction

- The Apollo 11 mission, fifty years ago, relied on a hydrogen-powered fuel cell system, which supplied electricity and water for the mission, and on liquid hydrogen as fuel to propel the rockets.
- The industry has used hydrogen for decades by commercializing a wide range of technologies that produce, deliver, store, and utilize hydrogen across applications and sectors.
- Hydrogen is the lightest chemical element in the world. It is the most abundant element in the universe. It is a gaseous body that enters the composition of water.
- Hydrogen has been regarded as a promising energy for combating environmental pollution and climate change because of the advantage of low-carbon emission.
- It can be used to store energy over long periods of time and transport energy over large geographies.
- Hydrogen economy is an economy that relies on hydrogen as the commercial fuel that would deliver a substantial fraction of energy and services.

Distributed Solar PV Growth in California

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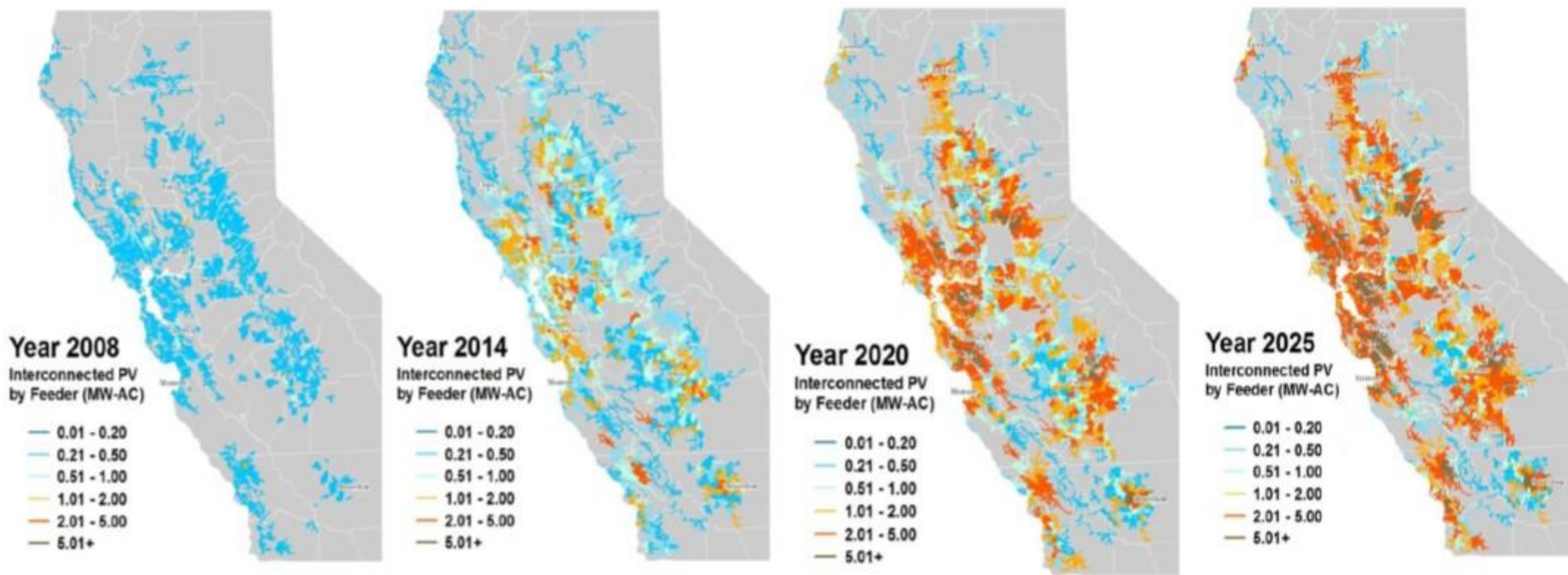
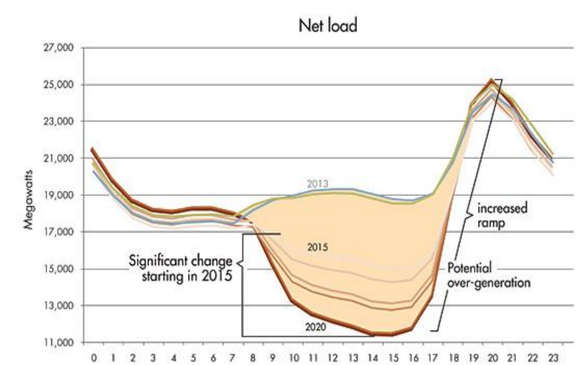
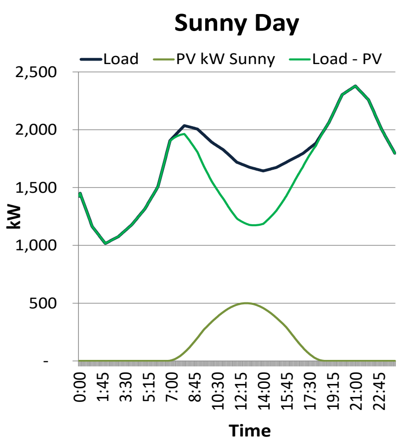
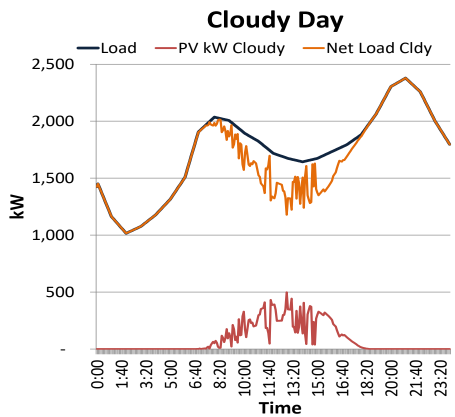


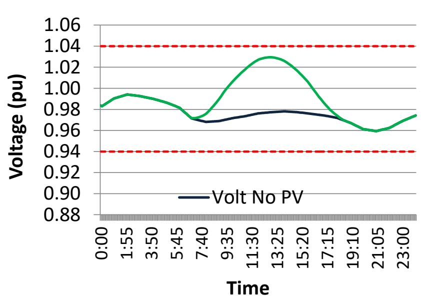


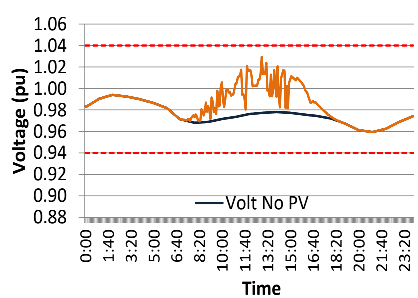
Solar PV in Distribution Grid

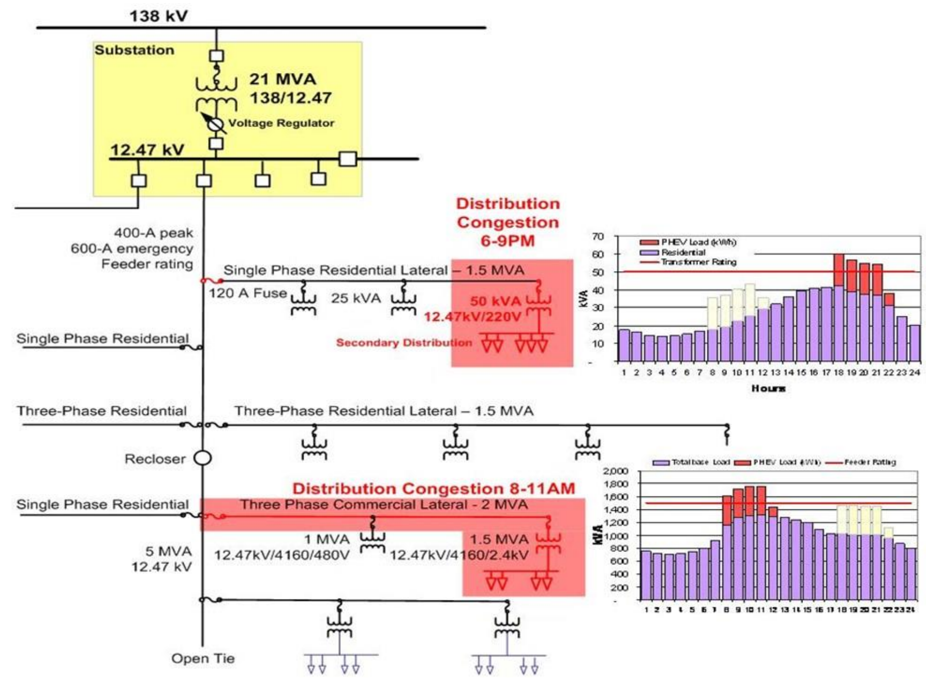


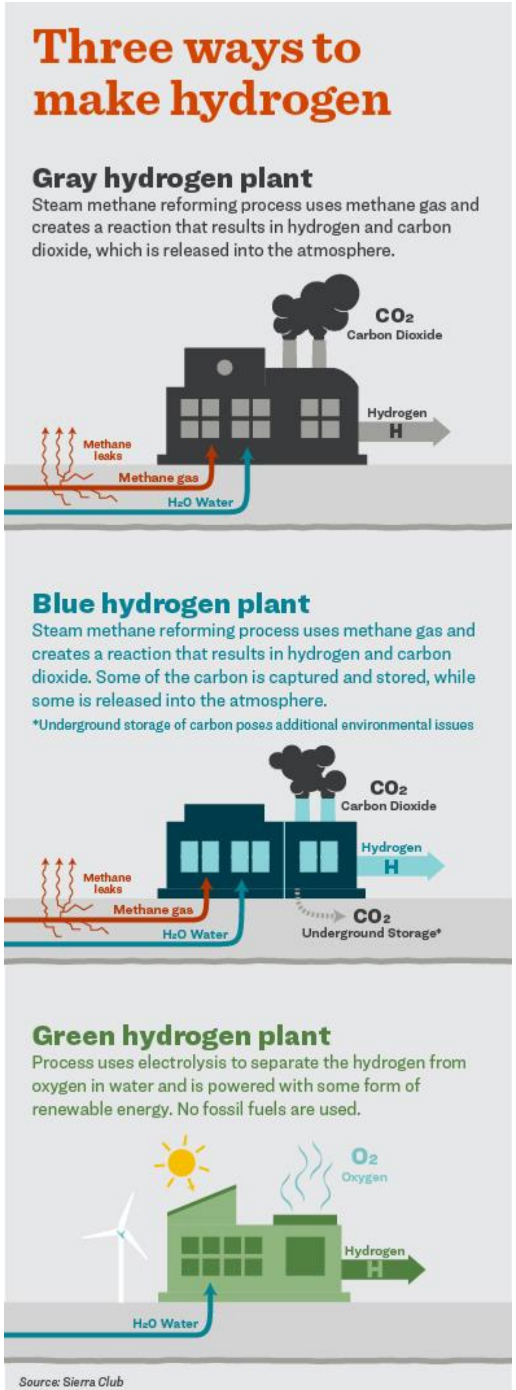


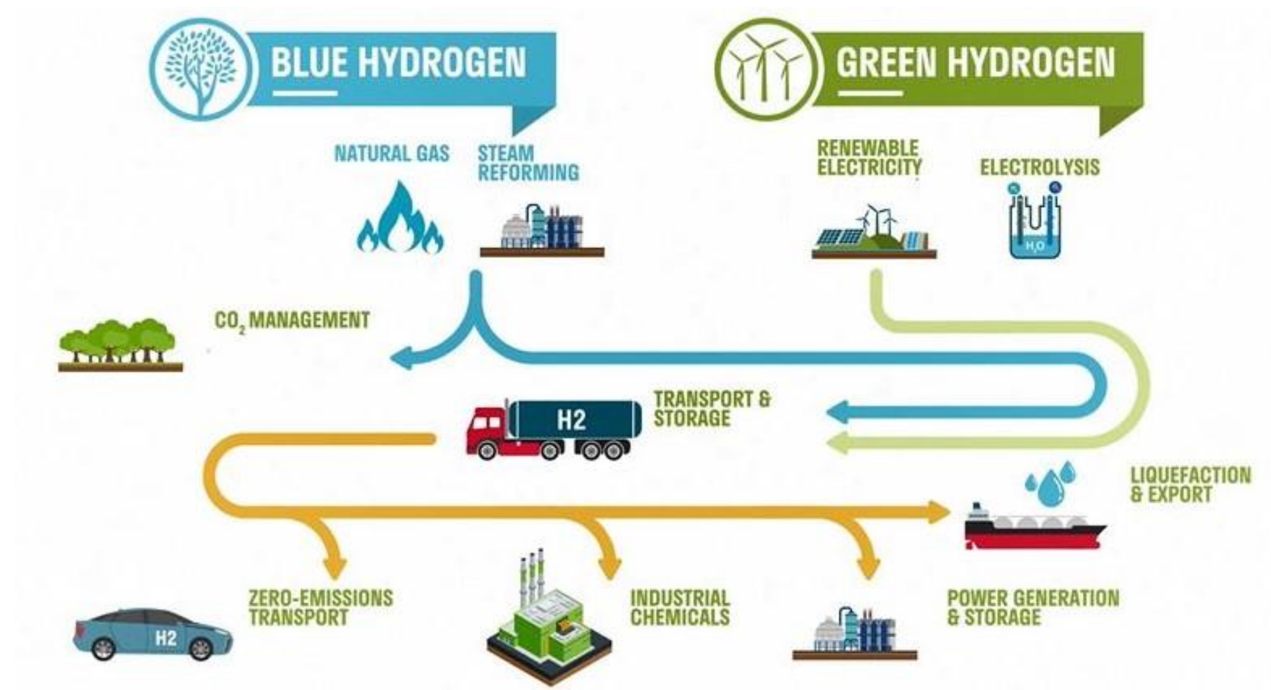
Voltage








Three ways to make hydrogen
Gray hydrogen plant
Steam methane reforming process uses methane gas and creates a reaction that results in hydrogen and carbon dioxide, which is released into the atmosphere.
CO_2
Carbon Dioxide
Hydrogen
H
Methane leaks
Methane gas
H_2O Water
Blue hydrogen plant
Steam methane reforming process uses methane gas and creates a reaction that results in hydrogen and carbon dioxide. Some of the carbon is captured and stored, while some is released into the atmosphere.
*Underground storage of carbon poses additional environmental issues
CO_2
Carbon Dioxide
Hydrogen
H
Methane leaks
Methane gas
H_2O Water
CO_2
Underground Storage*
Green hydrogen plant
Process uses electrolysis to separate the hydrogen from oxygen in water and is powered with some form of renewable energy. No fossil fuels are used.
O_2
Oxygen
Hydrogen
H
H_2O Water
Source: Sierra Club


BLUE HYDROGEN
GREEN HYDROGEN
NATURAL GAS
STEAM REFORMING
RENEWABLE ELECTRICITY
ELECTROLYSIS
H_2O
CO_2 MANAGEMENT
H2
TRANSPORT & STORAGE
LIQUEFACTION & EXPORT
ZERO-EMISSIONS TRANSPORT
INDUSTRIAL CHEMICALS
POWER GENERATION & STORAGE
H2


breeze


FCV
ZERO EMISSION

Blue Hydrogen

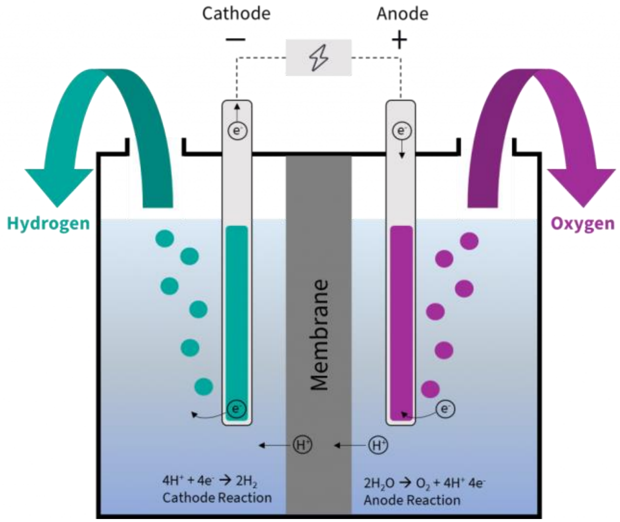
- Steam methane reforming (SMR) is a method of producing hydrogen from natural gas, which is mostly methane (CH_4). It is currently the cheapest source of industrial hydrogen.
- The process consists of heating the gas to between 700–1,100 °C (1,292–2,012 °F) in the presence of steam and a nickel catalyst.
- For this process, high temperature steam (H_2O) reacts with methane (CH_4) in an endothermic reaction to yield syngas. $CH_4 + H_2O \rightarrow CO + 3\ H_2$
- In a second stage, additional hydrogen is generated through the lower-temperature, exothermic, water-gas shift reaction: $CO + H_2O \rightarrow CO_2 + H_2$
- Essentially, the oxygen (O) atom is stripped from the additional water (steam) to oxidize CO to CO_2. This oxidation also provides energy to maintain the reaction. Additional heat required to drive the process is generally supplied by burning some portion of the methane.

Green Hydrogen

Grid-connected hydrogen production can manage the deployment of variable renewables.

The potential of solar energy with the total available surface power of 85,000 TW (85,000 × 10^{12} W) , which is currently around 15 TW, is far more than enough to meet human needs.

The use of hydrogen makes renewable energy even more valuable for energy production.



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Hydrogen for Microgrids

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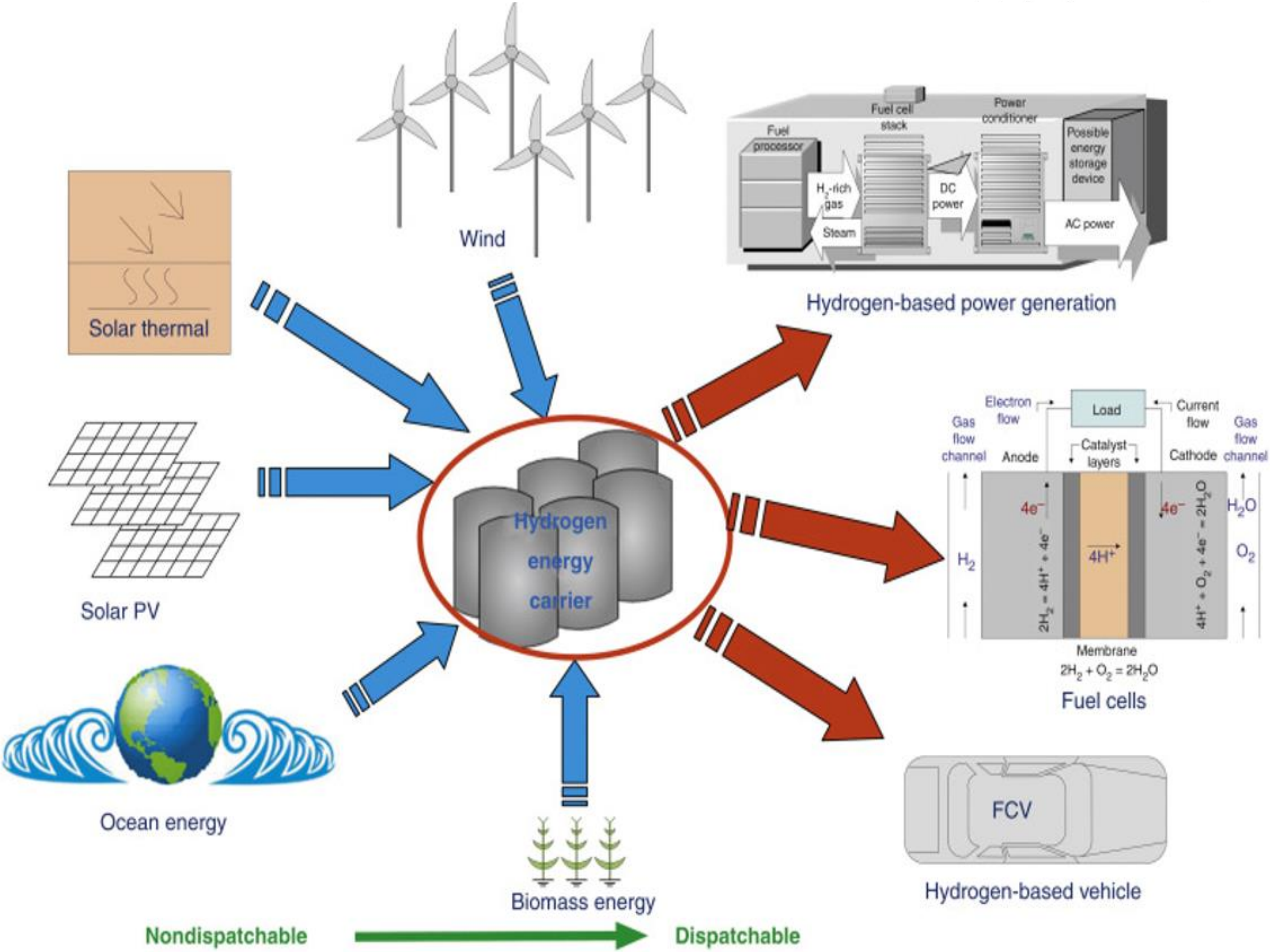
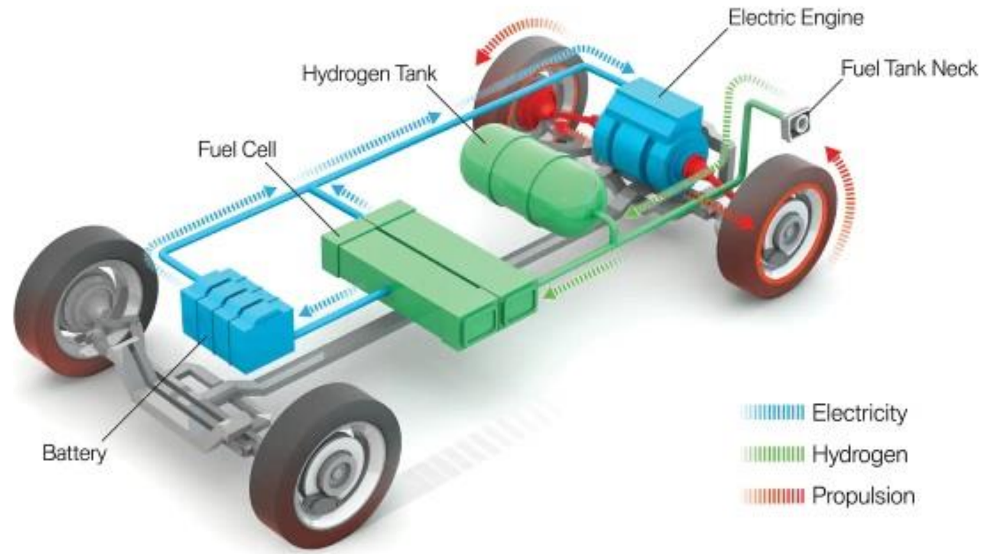
- As backup power or off-grid power. Through stationary fuel cells, hydrogen provides clean, noiseless, and odorless power.
- Hydrogen can be used in buildings (an estimated 47 percent of US homes currently have natural gas space heating, and another 3 to 8 percent use liquified petroleum gas (LPG) heating).
- Replacing or blending some natural gas with low-carbon hydrogen would lower GHG emissions of residential, commercial, and industrial heating, without new infrastructure deployment.
- It provides backup power for data centers, hospitals, and other critical infrastructure, as well as off-grid power on military bases and in other remote facilities with fast ramp-up or ramp-down capabilities.
- The use of hydrogen fuel cells instead of diesel generators in data centers will achieve cost parity in three to five years and has additional advantages, such as reduced clean-air permit constraints and increased operational flexibility.



Wind
Fuel processor
Fuel cell stack
Power conditioner
Possible energy storage device
H_2-rich gas
DC power
Steam
AC power
Hydrogen-based power generation
Solar thermal
Solar PV
Hydrogen energy carrier
Electron flow
Load
Current flow
Gas flow channel
Anode
Catalyst layers
Cathode
Gas flow channel
$4e^-$
$4e^-$
H_2O
H_2
$4H^+$
O_2
$2H_2 = 4H^+ + 4e^-$
$4H^+ + O_2 + 4e^- = 2H_2O$
Membrane
$2H_2 + O_2 = 2H_2O$
Fuel cells
Ocean energy
FCV
Biomass energy
Hydrogen-based vehicle
Nondispatchable
Dispatchable

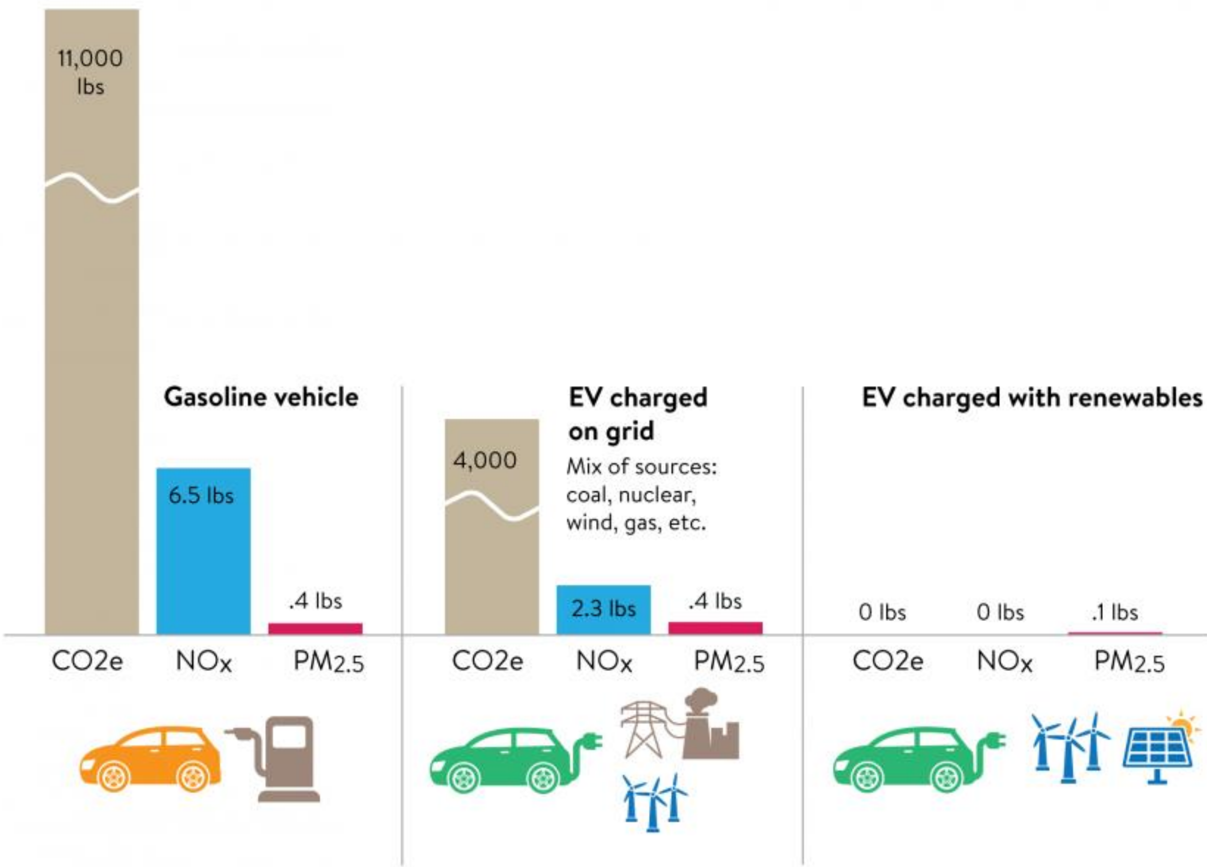
Hydrogen for Mobility

- Transport accounts for a third of US carbon emission and directly affects air quality in cities.
- 1 kg battery can store 0.1 kWh of energy whereas 1 kg of hydrogen has a usable energy content of 33 kWh.
- Hydrogen Fuel Cell electric vehicles (HFCEV) is 2-3 times more efficient than an internal-combustion engine.
- Hydrogen used as vehicle fuel completely eliminates emissions of tailpipe particulates, nitrogen oxides (NOx), and sulfur oxides (SOx), improving regional air quality while reducing greenhouse gas emissions (GHG) emissions.



Benefits of HFCEVs

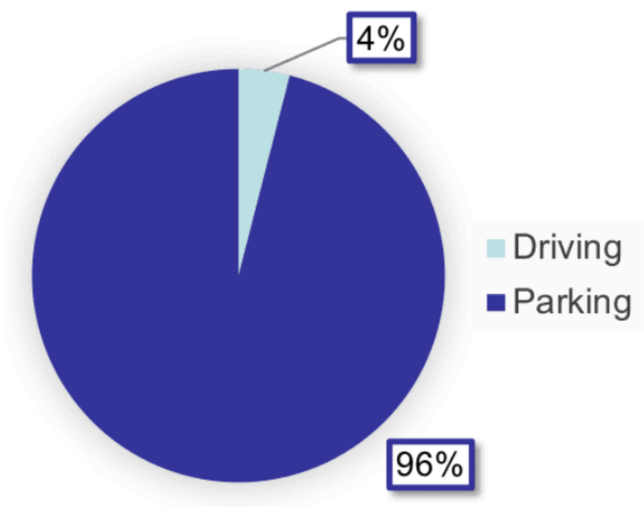
- HFCEVs will significantly reduce carbon emission and other harmful air pollutions.
- HFCEVs charged with renewable energy will not produce any carbon emission when the car is operating.



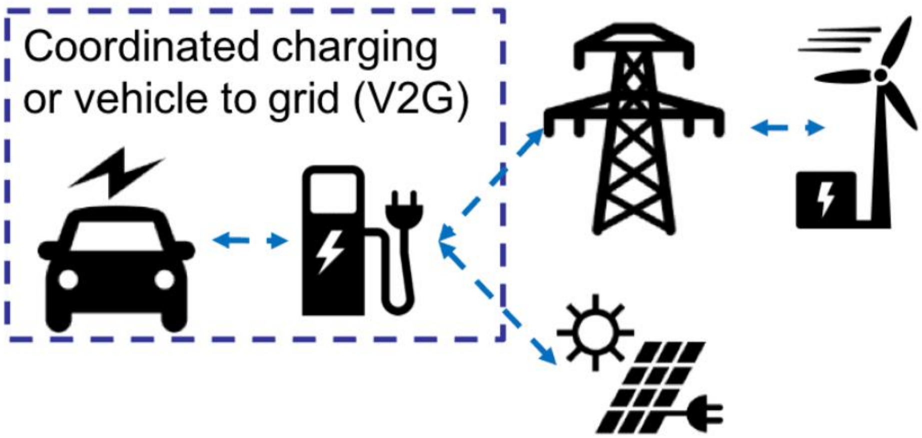
Annual car emission by fuel type

Benefits of HFCEV Utilization

- An HFCEV is parked for over 90% of its life time and its necessary charging duration is much shorter than its parking duration. Hence, an HFCEV's charging profile is quite flexible.
- Utilizing vehicle-to-grid (V2G) technology, the HFCEV fleet can behave like a storage system for arbitraging in the energy market by providing ancillary services and promoting the integration of renewable resources.



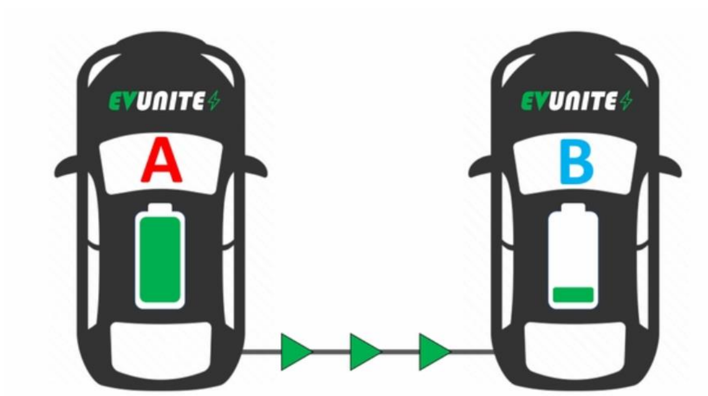
Common parking time and driving time of HFCEV

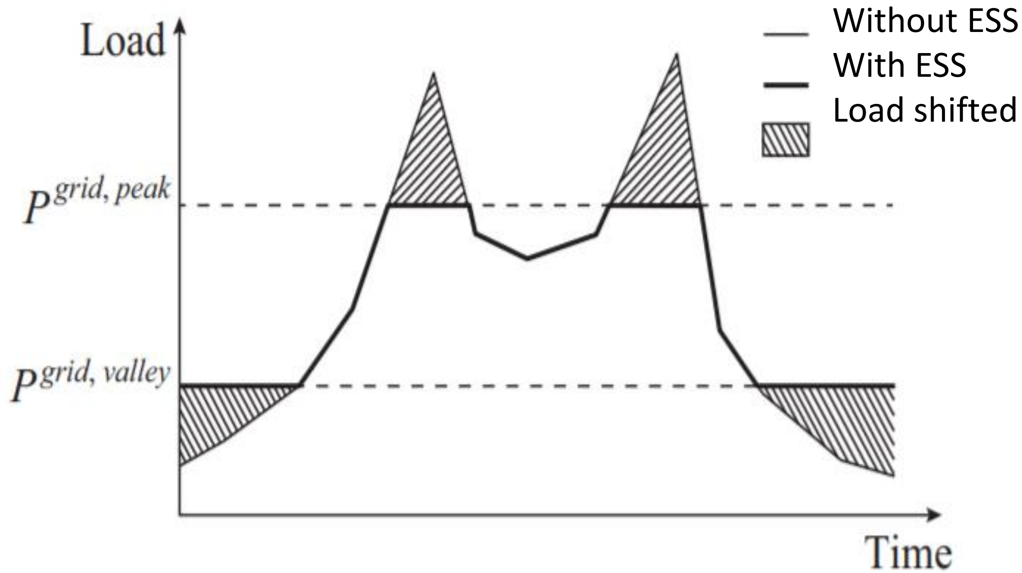


V2G scheme

Benefits of HFCEV Utilization

- V2V (Vehicle-to-Vehicle) charging is the ability for one electric vehicle to charge another.
- V2V charging has the potential to provide more flexibility to EV charging, reduce the need for the additional charging station infrastructure, and provide an opportunity to shift peak time utility load to off-peak times.



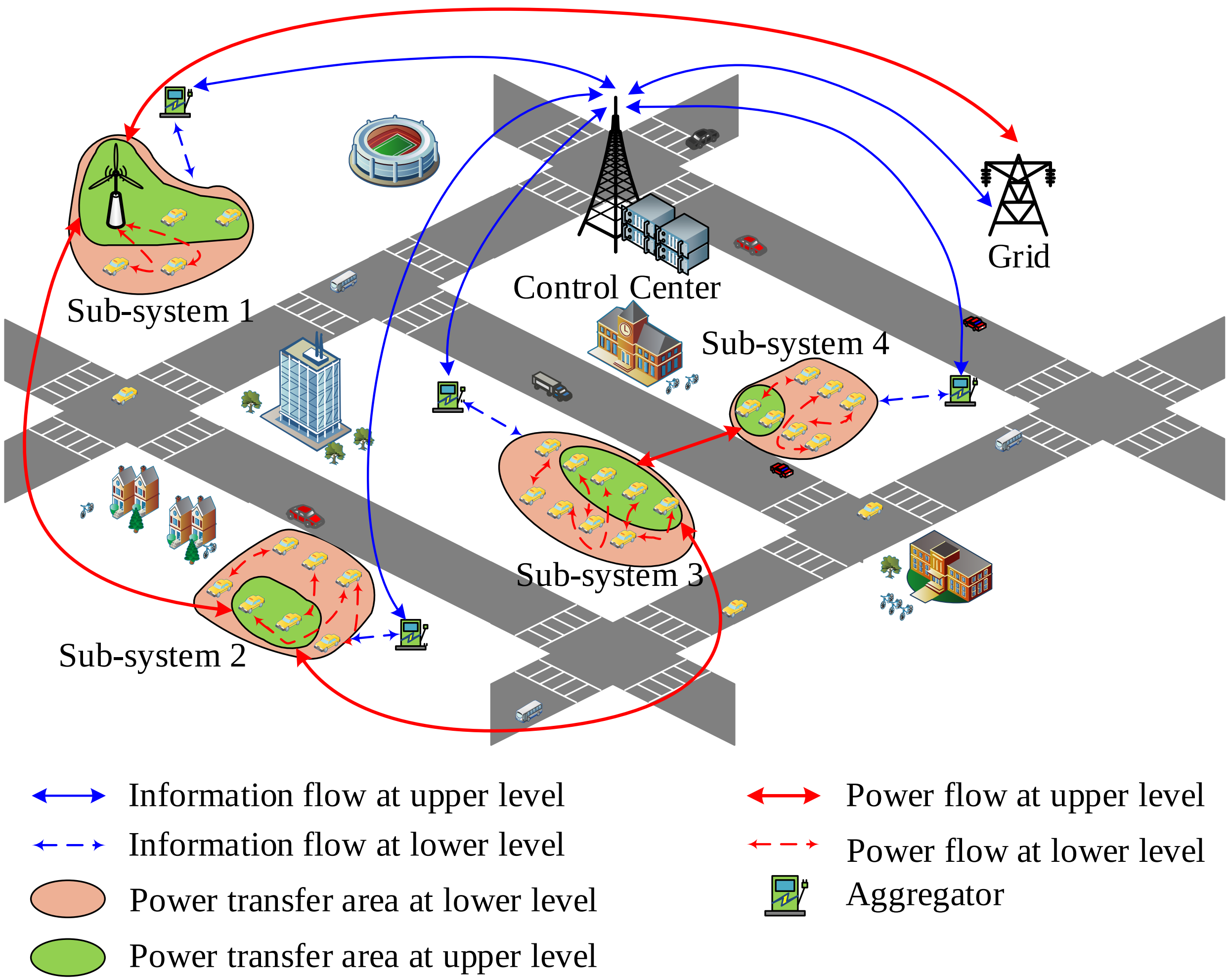


Hydrogen Refueling Station (HRS)

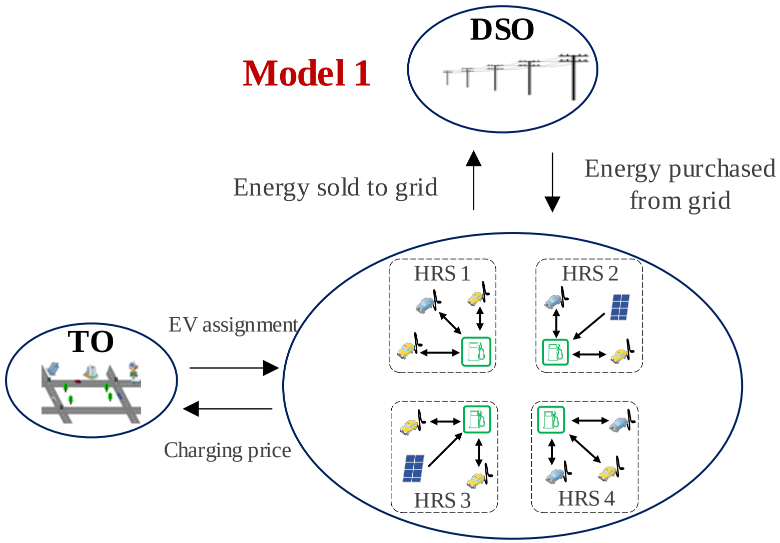
- The existing HRSs can be roughly classified into outsourcing HRSs and on-site HRSs according to the source of hydrogen.
- The hydrogen can be transported from large central production plants to outsourcing HRSs or directly generated at distributed on-site HRSs with power-to-hydrogen technology.
- There are three major hydrogen transportation methods, compressed hydrogen in tube trailers, liquid hydrogen in supercold tanker trucks, and hydrogen pipelines network.
- Compared to outsourcing HRSs, on-site hydrogen production contributes to reducing hydrogen delivery cost, and responds flexibly to time-varying hydrogen demand of HFCEVs and nodal electricity prices of PDN buses connected to HRSs.

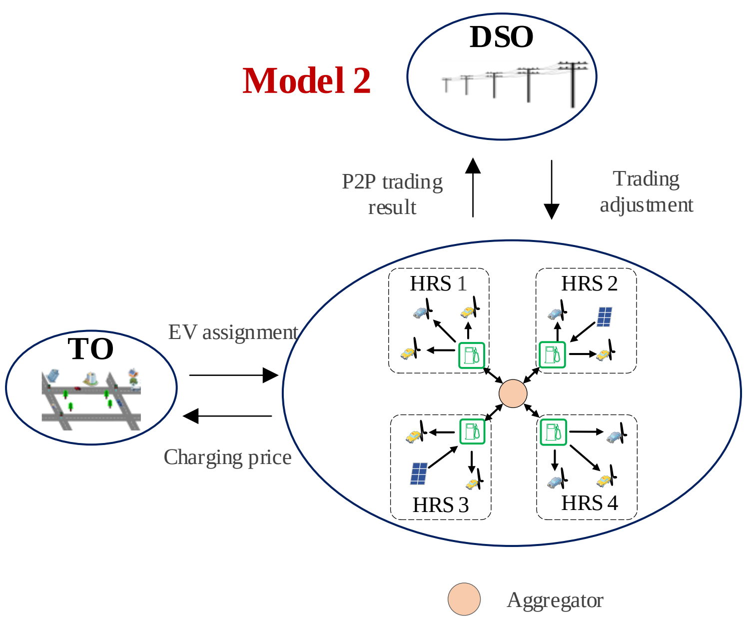
Transactive Energy for V2V Trading among HRSs

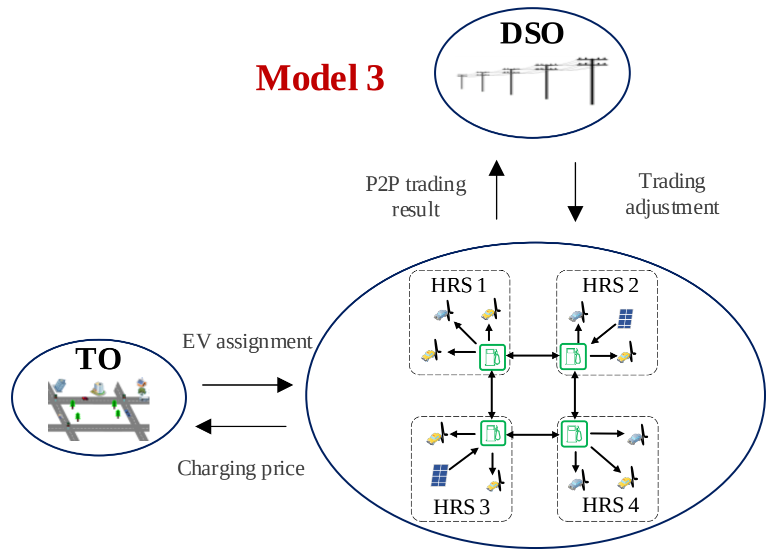
- EVs can trade energy (i.e., V2V and V2G alternatives) during the day to help utilities manage the duck curve.



Control of HFCEV Infrastructure







Coordinated HFCEV and Power Grid Infrastructures

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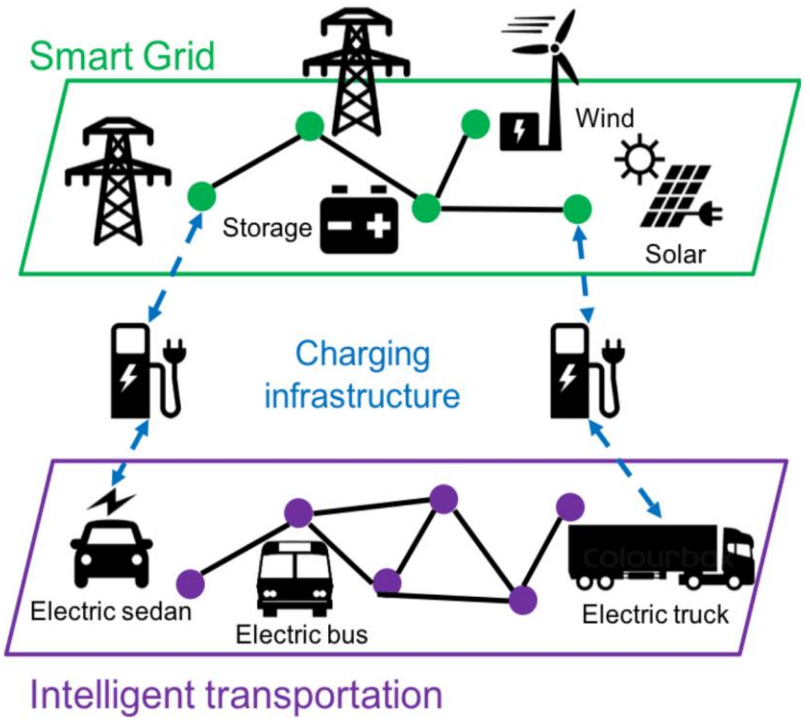
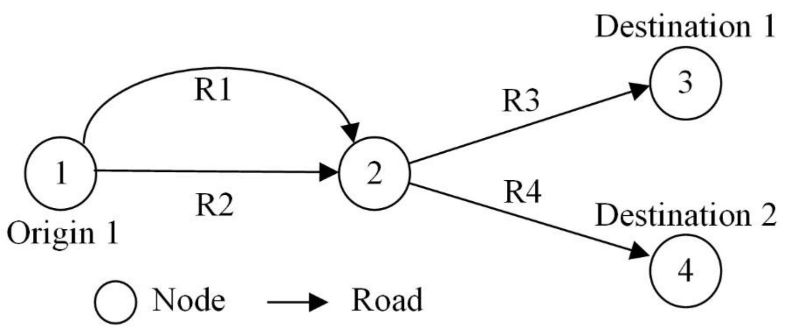
- Since HFCEV refueling stations couple transportation and power networks, their locations and sizes will significantly impact transportation and power network operation.
- The planning of refueling stations should take both transportation and power system constraints into consideration.
- The locations and sizes of HFCEV refueling stations in a transportation network should satisfy HFCEV driving demands, while simultaneously ensuring the security operation constraints of power systems, e.g., voltage limits.
- The transportation road capacities are expanded subject to the available budget, while refueling stations, stationary storage (ESS), and electric power lines are subject to investment on electric power systems.



Traffic Operator

- The proposed TN is represented by a directed graph composed of a set of nodes (i.e., road intersections) connected through links (i.e., roads).

- The vehicles' mobility in the directed graph is modeled as trips carried out from a set O of origin nodes to a set D of destination nodes with multiple choices of paths, where each path is composed of several roads.



Transportation network topology

Hydrogen-integrated UTN and PDN

- At present, UTN and PDN are operated independently for historical reasons, hydrogen refueling prices of HRS are typically determined by electricity prices of PDN which remain fixed irrespective of traffic congestion states in UTN.
- However, unguided traveling and uncoordinated refueling behaviors of massive HFCEVs will also deteriorate the holistic efficiency of both UTN and PDN.
- On the one hand, the uneven traffic flow distribution of HFCEVs may cause the unbalanced spatial distribution of hydrogen demand in UTN, which will influence the power demand of HRSs for hydrogen production.
- Hydrogen refueling service fees will influence the HRSs selection of HFCEVs and may lead to traffic congestion in UTN. It means that the traffic flow assignment in UTN and power flow distribution in PDN are coupled and intertwined.
- Coordinated operation of hydrogen-integrated UTN and PDN from a holistic perspective with efficient control measures is extremely imperative.

ADMM Framework for the Proposed Model

- The HRSF based coordinated operation model is formulated as a mixed-integer nonlinear program with a large number of variables and constraints, which enormously increases the computational complexity of optimization.

- Alternative direction method of multipliers (ADMM) as a distributed algorithm, is well suited to large-scale convex optimization problems and has been successfully applied in power system OPF.

- It relies on the augmented Lagrangian function to improve convergence rate and takes the form of a decomposition-coordination procedure, by which the small local sub-problems are solved in a predetermined order to find a solution of the large global problem.

- The proposed model is decoupled and solved in a decentralized framework based on the ADMM and verified on the hydrogen-integrated UTN and PDN in Sioux Falls.

Coordinated Operation of Hydrogen-Integrated UTN and PDN

- With the popularization of HFCEVs, hydrogen-integrated UTN and PDN were coupled tightly. The traveling and refueling behaviors of massive HFCEVs will influence the traffic flow of arcs and the hydrogen demand of HRSs in UTN.
- The hydrogen sold to HFCEVs is produced by water electrolysis in the on-site HRSs at the current or previous time intervals, which need to purchase electricity from PDN.
- A hydrogen refueling service fees (HRSF) based control strategy is proposed to guide HFCEVs in selecting HRSs for reducing traffic congestion and promoting a more balanced distribution of traffic and power flow.

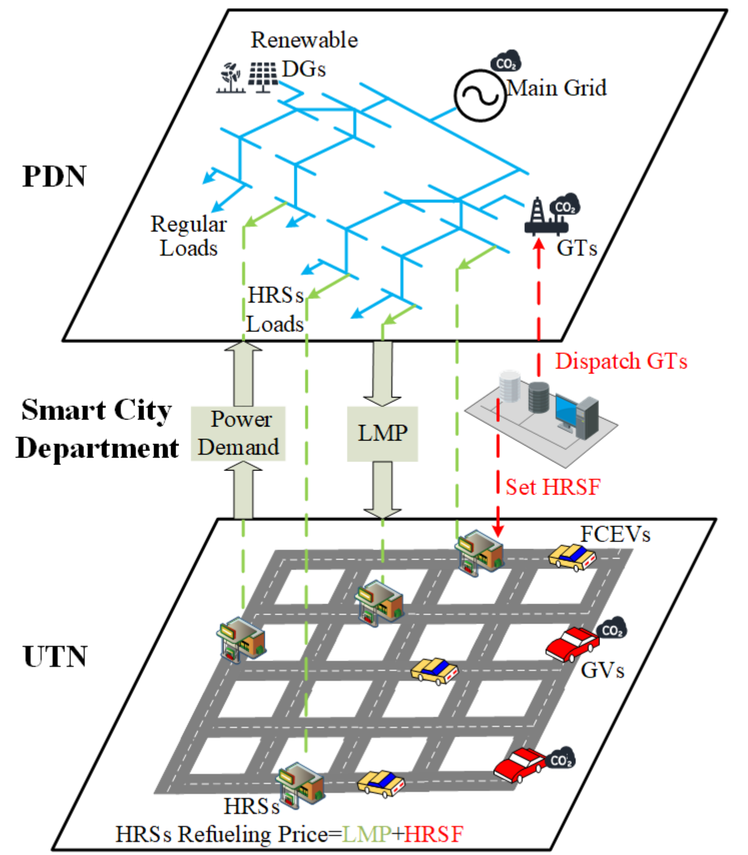


Fig. 1. HRSF based coordinated operation framework of hydrogen-integrated UTN and PDN.

Case Studies: Basic Settings

- The validity and rationality of the proposed HRSF based coordinated operation model, is established on a hydrogen-integrated UTN and PDN in Sioux Falls, South Dakota, USA.

- The topology of the hydrogen-integrated UTN and PDN in Sioux Falls city is shown on the right, which is composed of 24-node UTN and 33-node PDN.

- For PDN, HRSs are connected to buses 7, 9, 13, 18 and 29. Distributed GTs are connected to buses 13 and 29

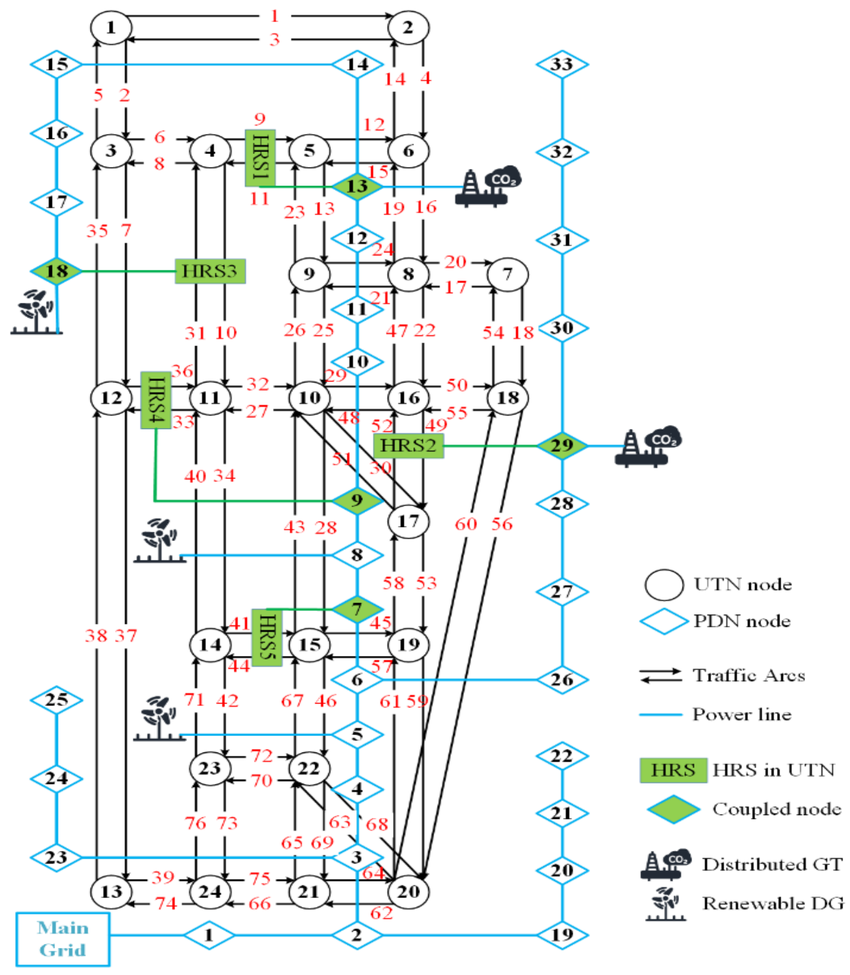


Fig. 2. Topology of the hydrogen-integrated UTN and PDN in Sioux Falls city.

Case Studies: Cases Overview

- Three cases are considered.

	Vehicle Type	Operation mode of UTN and PDN
Case 1	100% GVs	Independent operation
Case 2	80% HFCEVs, 20% GVs	Independent operation
Case 3	80% HFCEVs, 20% GVs	Coordinated operation

- The contrast between Case 1 and Case 2 is designed to show the contribution of popularizing HFCEVs to carbon emission reduction, and the comparison of Case 2 and Case 3 is designed to study the effect of the HRSF based coordinated operation strategy on carbon emission, renewable energy accommodation, traffic and power flow distribution, and the total cost of UTN and PDN.

- Case 1 is considered as a base case, and Case 2 is designed to explore the effect of emission reduction through introducing HFCEVs. Compared with Case 2, the coordination between UTN and PDN, and HRSF control strategy are considered in Case 3.

Case Studies: Carbon Emission Results

- The carbon emissions of the coupled system in three cases are shown in Fig. 3, where the emission of HFCEVs has been excluded from GTs and substation emission in PDN.

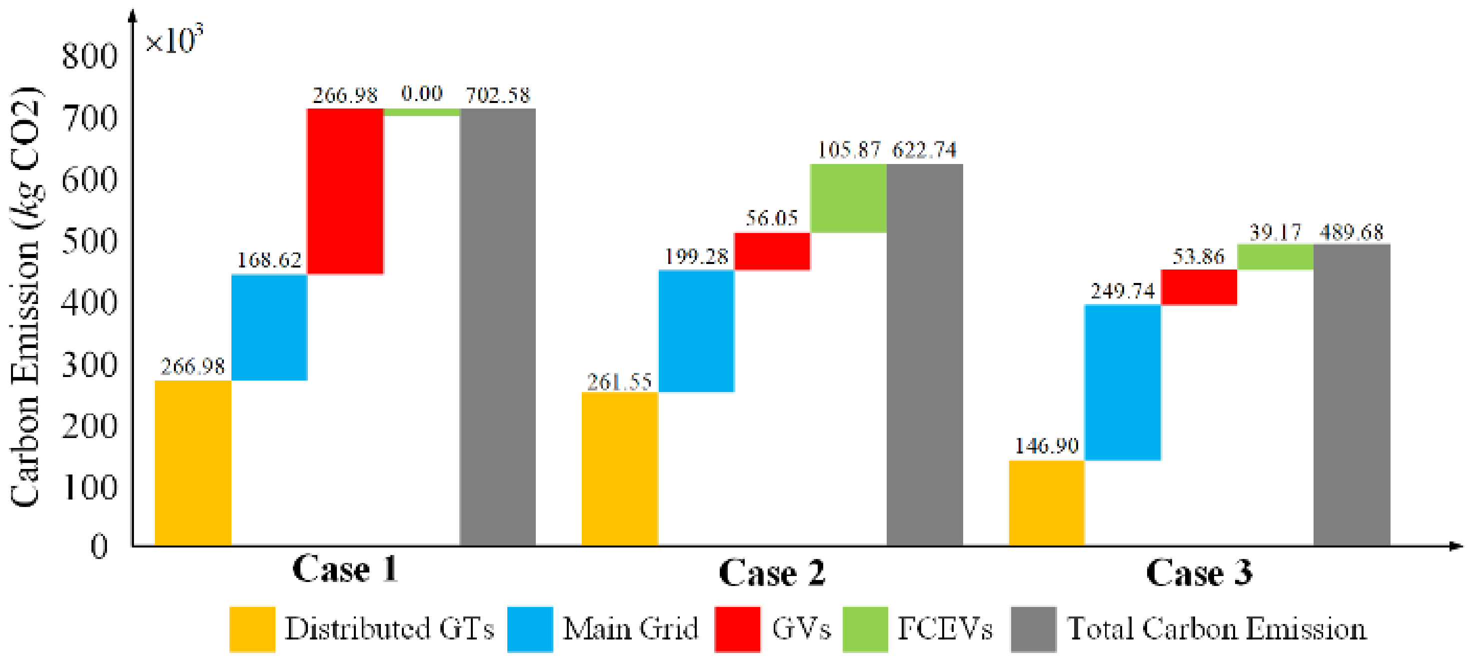


Fig. 3. Carbon emissions of the coupled system in three cases.

- The total carbon emission of Case 2 is less than Case 1, which means it is feasible to reduce emissions by popularizing HFCEVs.

Power Demand and HRSF Results

- For convenient presentation, the power demand and HRSF at the time interval (t=2) in cases 2 and 3 are illustrated in Fig. 4.

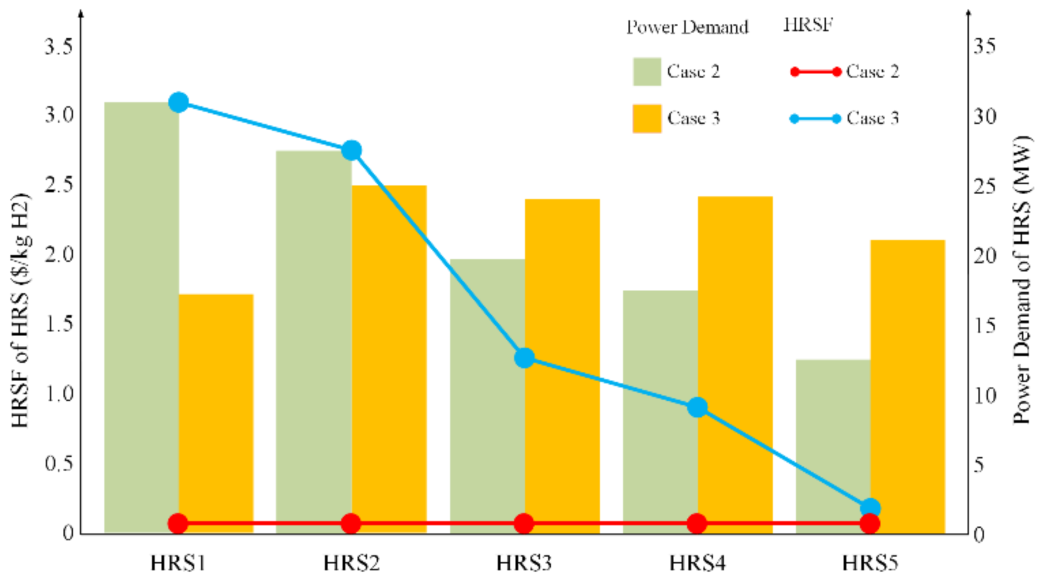


Fig. 4. Power demand and HRSF of HRSs at *t*=2 in Case 2 and Case 3.

- The average power demands of HRS1 and HRS2 in Case 2 is greater than Case 3, and the value of HRS 3, HRS4, and HRS5 have the opposite situation. This is because the traffic flow distribution of HFCEVs can be adjusted by setting different HRSF. The relatively higher HRSF of HRS1 and HRS2 increase the travel cost of individual HFCEV, then the HFCEV will change the traveling path and select other HRSs (like HRS3, 4, or 5) for hydrogen refueling.

Case Studies: Impact on PDN

- The voltage magnitude distribution of all buses is used to represent the PDN congestion.

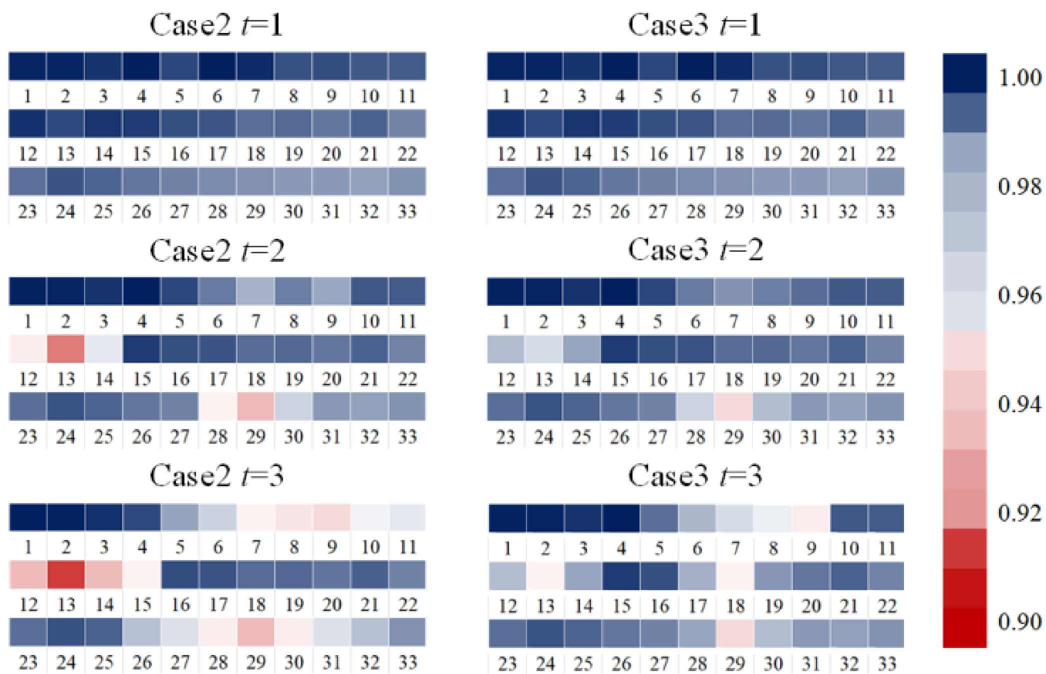


Fig. 5. The voltage magnitude distribution of all buses in PDN.

- We can observe that Case 2 and Case 3 share the same voltage magnitude distribution in the first interval. This is because the UTN has a light traffic demand when t=1, no congestion occurs in both UTN and PDN. Thus, the voltage magnitudes are maintained within the normal range, and the HRSF is equal to 0 in Case 3 at t=1.

Coupled PDN and UTN Efficiency

- The arc saturation is introduced to represent the congestion of UTN, which is defined as the ratio of traffic flow and capacity on this arc. The saturations of all arcs in Sioux Falls UTN at t=2 are shown in Fig. 6.

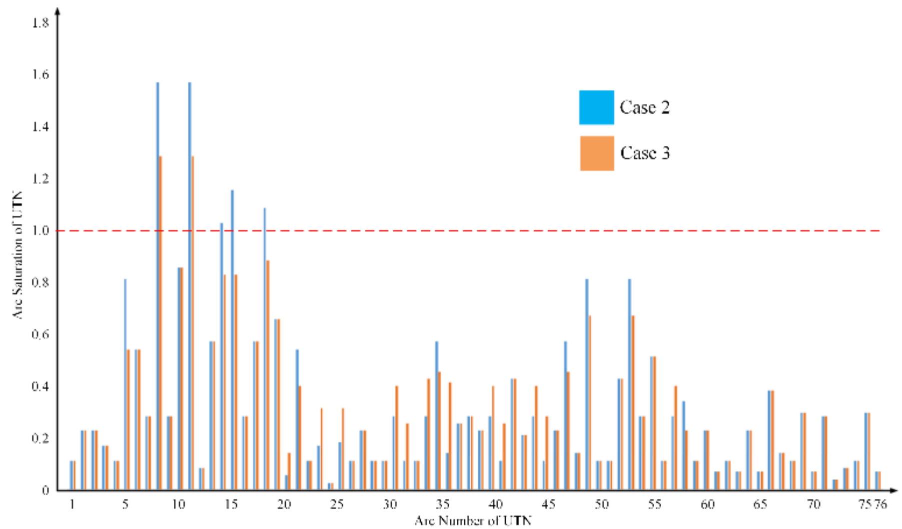


Fig. 6. The saturation of all arcs in Sioux Falls UTN at *t*=2.

- In Case 2, the saturation of arc 9, 12, 15, 16 and 19 exceed 1.0 before HRSF is charged. And now, the congestion of UTN is reduced evidently, where the traffic flow of arc 15, 16, and 19 is less than the arc capacity.

- The saturation of arc 9 and 12 decreases from 1.57 to 1.29 because their traffic flow is converted to other arcs by charging HRSF and guiding the HFCEVs in selecting HRSs.

Conclusion

- Considering environmental crisis and climate change mandates, additional international organizations and governments are paying attention to carbon emission reduction.
- It is of great significance to establish the coordinated operation model of hydrogen-integrated UTN and PDN considering carbon emission restrictions HFCEVs and HRSs are proliferated.
- In the proposed model, the overall carbon emission, the uncertainties of renewable DGs output and O-D traffic demand are considered simultaneously, and the HRSF based control strategy is proposed to guide HFCEVs in selecting HRSs.
- Simulation results indicate that popularizing HFCEVs contributes to emission reduction and the HRSF based coordinated operation method can further reduce carbon emission by promoting renewable energy integration.
- Besides, the HRSF-based coordinated operation can reduce congestion and improve efficiency for both UTN and PDN operations.
- With the proliferation of HFCEVs, if control measures would not be enough to alleviate congestion in the existing infrastructure, new construction of generators, transmission lines, roads, and HRSs should be planned.

Thanks

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