Introduction to Smart Grids*

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CHAPTER 10:

Electric Vehicles and Hybrids

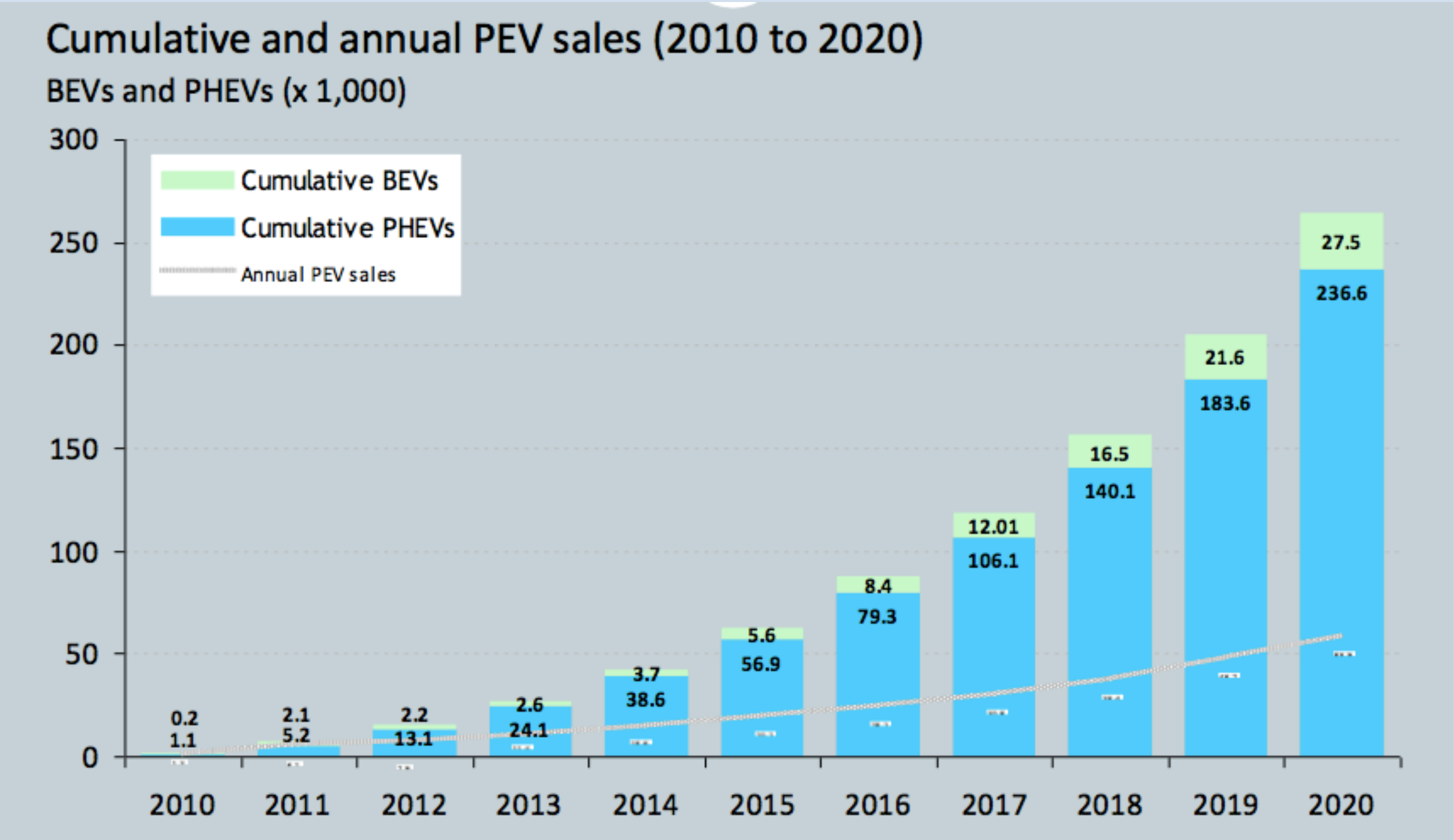
Benefits of Electric Vehicles

- Many more sensible reasons could be given: the following four are perhaps the most common and pressing:
- Reduce oil consumption – a finite resource
- Reduce oil imports to achieve increased energy security and improved balance of trade
- Reduce greenhouse gas emissions
- Reduce urban pollutant emissions

EV, HEV, and PHEV

- Electric Vehicle (EV) – Rely solely on electricity from (electric) grid
- Hybrid Electric Vehicle (HEV) – Rely solely on gas (oil) as energy source. (battery cannot be charged with el

Expected Increase in EVs



Technology Variants

EV vs Hybrids

Electric Vehicles (EVs)

- Large battery pack: Expensive
  Limited range
  Uncertain life
- Pure electric drivetrain
  + Excellent energy efficiency
  + Independent of oil

Hybrids

- Smaller battery pack
  + Cheaper
  + Longer range
  + Manageable lifetime
- ICE-based drivetrain
- Incremental efficiency gain
- Dependent on oil

Can we have the best of both worlds?

Hybridization

The vehicle is a….

If it…	Micro Hybrid	Mild Hybrid	Full Hybrid	Plug-in Hybrid
Automatically stops/starts the engine in stop-and-go traffic				
Uses regenerative braking and operates above 60 volts				
Uses an electric motor to assist a combustion engine				
Can drive at times using only the electric motor				
Recharges batteries from a wall outlet for extended all-electric range				


Citroën C3


Honda Insight

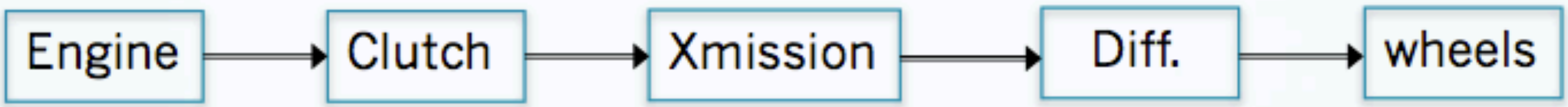

Toyota Prius


Chevy Volt

Vehicles Power Components

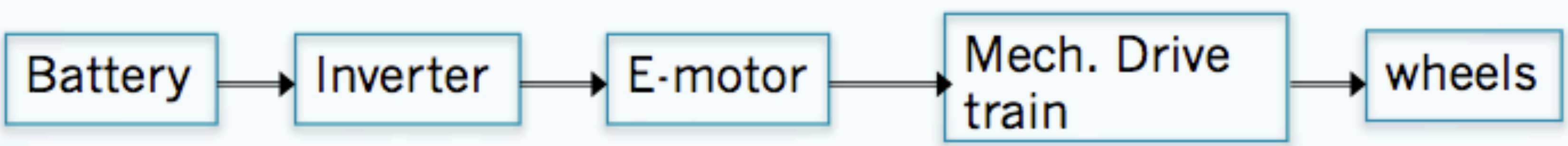
Vehicle Power Efficiency

- ICE drive train:



$\eta_{eng} < 0.4$; $\eta_{cl} < 0.98$; $\eta_{tr} < 0.9$; $\eta_{D} < 0.9$;

- EV drive train:



$\eta_{bat} < 0.95$; $\eta_{inv} < 0.98$; $\eta_{EM} \sim 0.99$; $\eta_{M} < 0.9$;

A Quick Comparison on Efficiency

- Internal combustion engine (ICE) vehicles
  - ❖ Engine efficiency η_{ic} typically ranges between $[0.1, 0.25]$.
  - ❖ In congested traffic, η_{ic} can even be as low as 0.1
  - ❖ Diesel engines are much more efficient, ~0.42
- EV: Electric power train efficiency, η_e ~ 0.8 (from battery to electric motor).
- HEV can be as high as EV.

Vehicle Force Components

- Rolling resistance force; $F_R = mgf_r$

  m = vehicle weight; g = gravity; fr=rolling resistance coeff.

- Air drag resistance force; $F_{Drag} = 0.5\rho C_d A v^2$

  ρ=air density; C_d=air drag coeff; A=cross section area;

  v=vehicle speed

- Acceleration; $F_{AC} = m\dot{v}(t)$

- Hill climbing – usually ignored if we only consider flat surface conditions.

Vehicle Power

- Power is the product of force and speed (if the force is constant).
- Total power balance = $(F_R + F_{Drag} + F_{AC})v(t)$

Electric Vehicle History

Early Electric Vehicle

- Electric vehicles are clean and easy to use.
- Low maintenance, available infrastructure.
- Electric motors were easy to control.
- Motors have high power-to-weight ratio.
- Limited range.

Electric Vehicle History

EV in the 19th Century

- 1832 Robert Anderson invented a non-rechargeable electric carriage.
- 1835 Thomas Davenport built the first practical electric vehicle and received a patent for the first electric motor in 1837.
- 1859 French physicist Gaston Planté invented the rechargeable lead-acid battery.
- 1891 William Morrison of Des Moines, Iowa built the first successful electric automobile in the United States.
- 1900 One-third of all cars found on the roads of New York City, Boston, and Chicago were electric.

Electric Vehicle History

EV in the 20th Century

- 1908 Henry Ford introduced the gasoline-powered Model T.
- 1912 Charles Kettering invented the electric automobile starter, eliminating the need for a hand crank starter on gasoline powered vehicles.
- 1972 Victor Wouk built the first full-size hybrid vehicle
- 1974 Vanguard-Sebring's CitiCar was introduced. It had a top speed of 30 mph and a 40 mile range.
- 1975 The U.S. Postal Service purchased 350 electric delivery jeeps from AM General.

Electric Vehicle History

The New Millennium EVs

- 1996 General Motors Saturn EV1 was released.
- 1997 Toyota introduced Prius, the first mass-produced hybrid.
- 2003 General Motors announced that it will not renew leases on EV1.
- 2007 General Motors unveiled the Chevrolet Volt concept car.
- 2008 Tesla Motors began production of Tesla Roadster
- 2009 President Obama announced a new gas-mileage policy that would require automakers to meet a minimum fuel-efficiency standard of 35.5 miles a gallon by 2016.
- 2010 Nissan Leaf delivered to North American and Japan markets.

Electric Vehicle History

EV for Your Perusal

1902 Woods Electric Phaeton

1911 Baker Electric

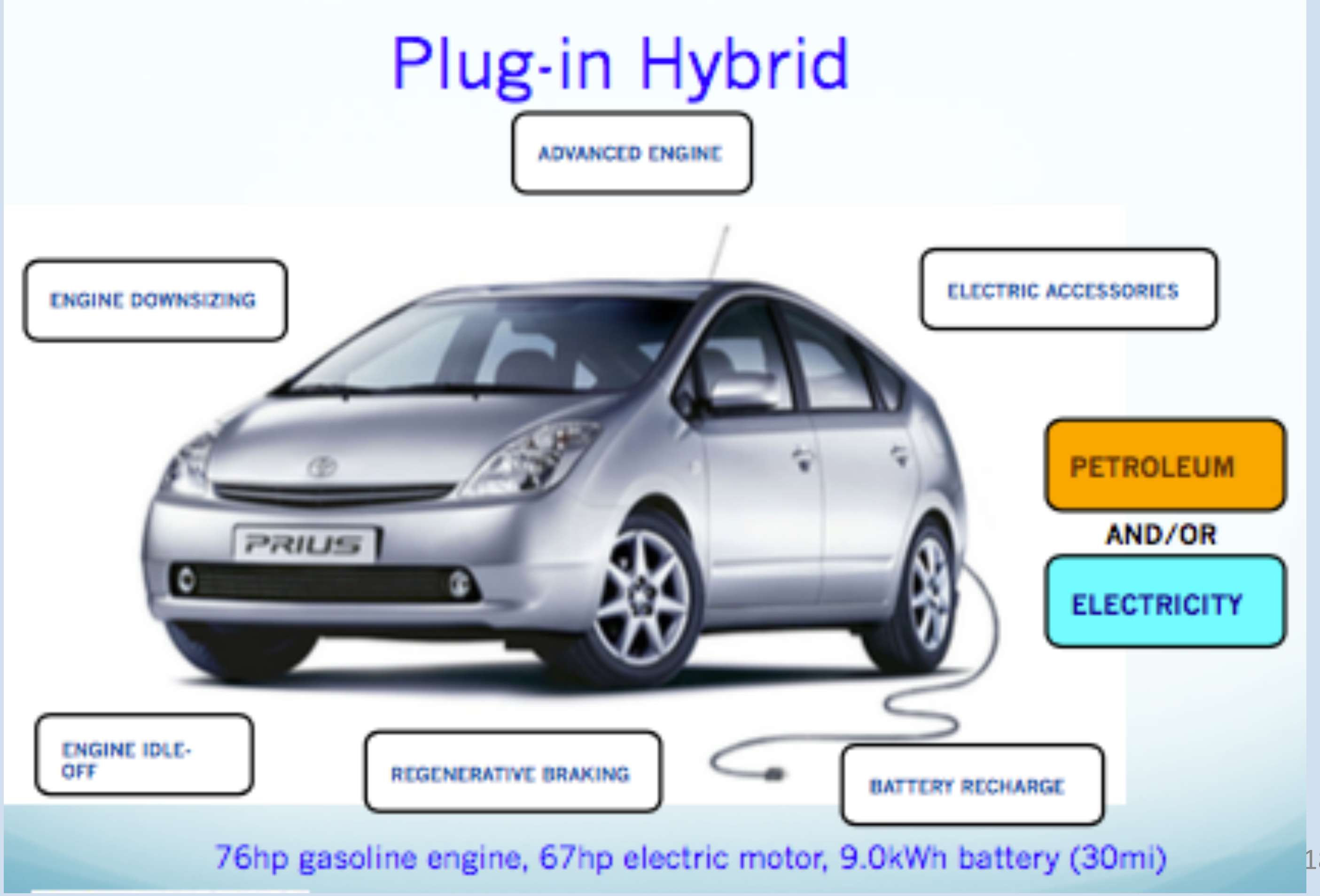
1975 Sebring-Vanguard-CitiCar

1996 Saturn EV1

Electric Vehicle History

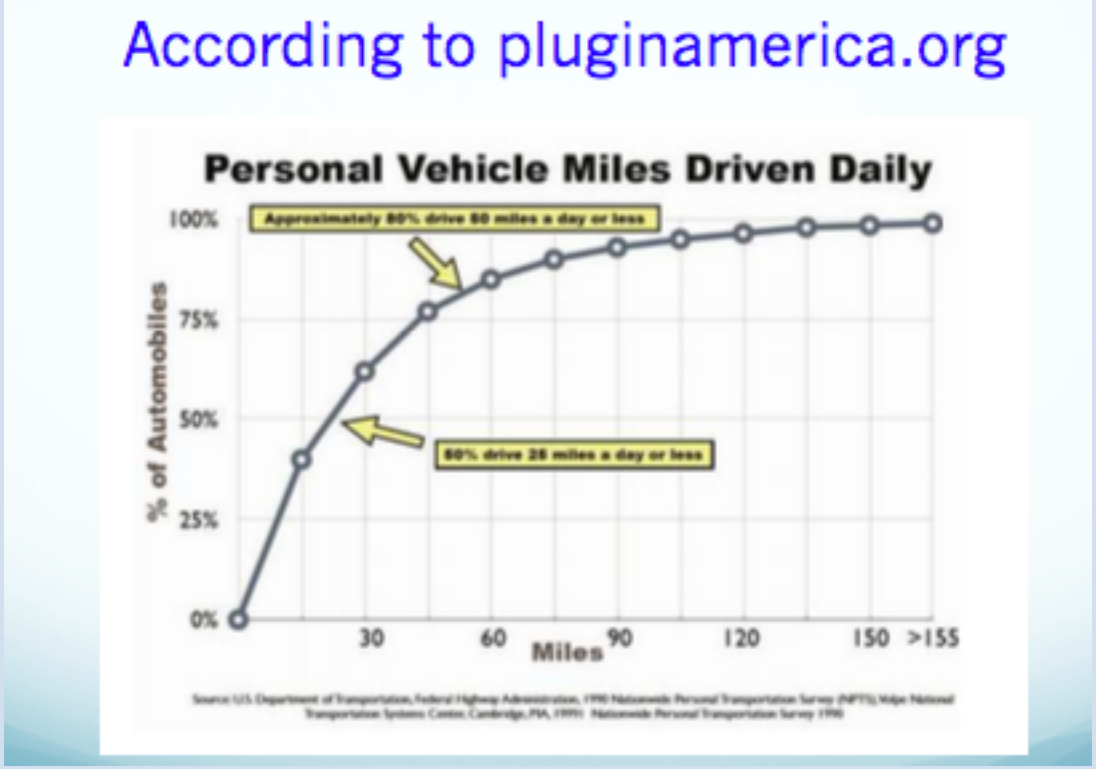
Plug-In Electric Vehicles

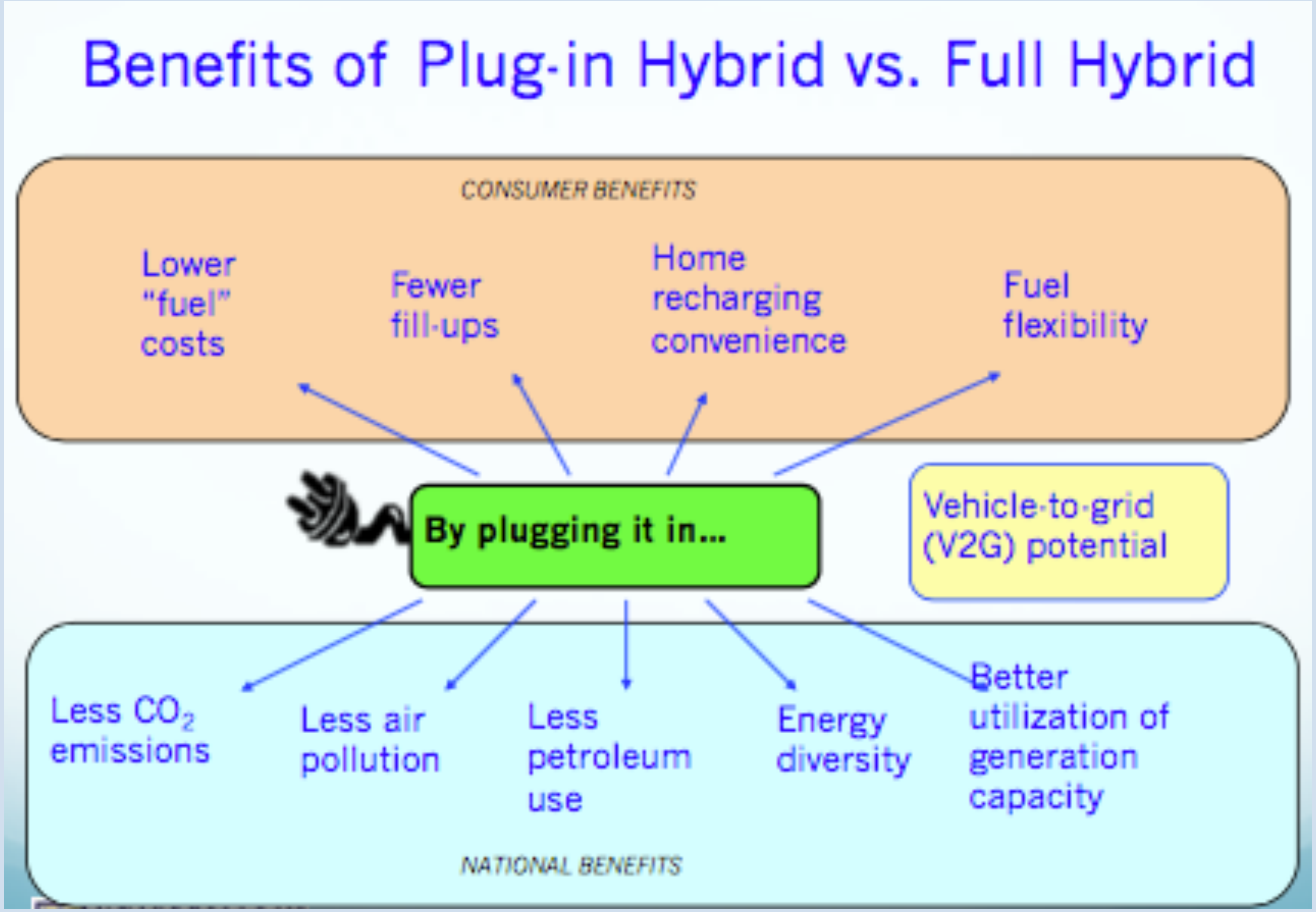
Why PHEV



Plug-In Electric Vehicles

Why PHEV





Benefits of Plug-in Hybrid vs. Full Hybrid
CONSUMER BENEFITS
Lower "fuel" costs
Fewer fill-ups
Home recharging convenience
Fuel flexibility
By plugging it in...
Vehicle-to-grid (V2G) potential
Less CO_2 emissions
Less air pollution
Less petroleum use
Energy diversity
Better utilization of generation capacity
NATIONAL BENEFITS

Plug-in Hybrid Fuel Economy

Predicted fuel economy and operating costs for midsize sedan[1]

Vehicle Type	Gasoline Fuel Economy	Electricity Use	Annual Energy Use	Annual Energy Cost	Recharge Time[3]
Conventional	27 mpg	---	564 gal.	$2,030	---
Hybrid-Electric	36 mpg	---	416 gal.	$1,498	---
Plug-In Hybrid 20mi range	51 mpg	0.09 kWh/mi	297 gal. and 1394 kWh[2]	$1,069 + $125	< 4 hrs
Plug-In Hybrid 40mi range	69 mpg	0.16 kWh/mi	218 gal. and 2342 kWh[2]	$785 + $211	< 8 hrs

1) Assumes 15,000 miles annually, gasoline price of $3.6 per gallon, electricity price of 9c/kWh
2) Note that an average US household consumes 11,500 kWh of electricity each year
3) Using 110V, 20A household outlet

EV’s and the Grid

Grid Energy Resources Issues

- Wind and solar resources are highly variable and have considerable randomness.
- Instantaneity in the power grid: *Energy delivered must match energy used, second by second.*
- Integration of random resources requires extra conventional capacity to achieve the match.
- Energy flexibility: an electric or plug-in hybrid can run on nuclear, solar, wind, or other carbon-free resources.

Where to Charge PHEV?

Home charging

- ❖ Most people in the U.S. recharge overnight in their own garage, carport or even on the driveway.

Public charging

- ❖ There are public chargers for electric cars as well in parking garages and shopping centers.
- ❖ Federal, state and local governments and Air Quality Management Districts are funding installation of thousands of charging stations beginning in late 2010.

PHEV Charging Example

120V (1.2 kW) charging

- Plugs into standard household outlet
- Full charge in about eight hours (temperature dependent
- No additional equipment or installation

120V Cordset

240V (3.3 kW) charging

- Full charge in about three hours
- Efficient and enables more opportunity to drive electrically
- Will usually require a one-time investment to upgrade garage with dedicated 240V circuit

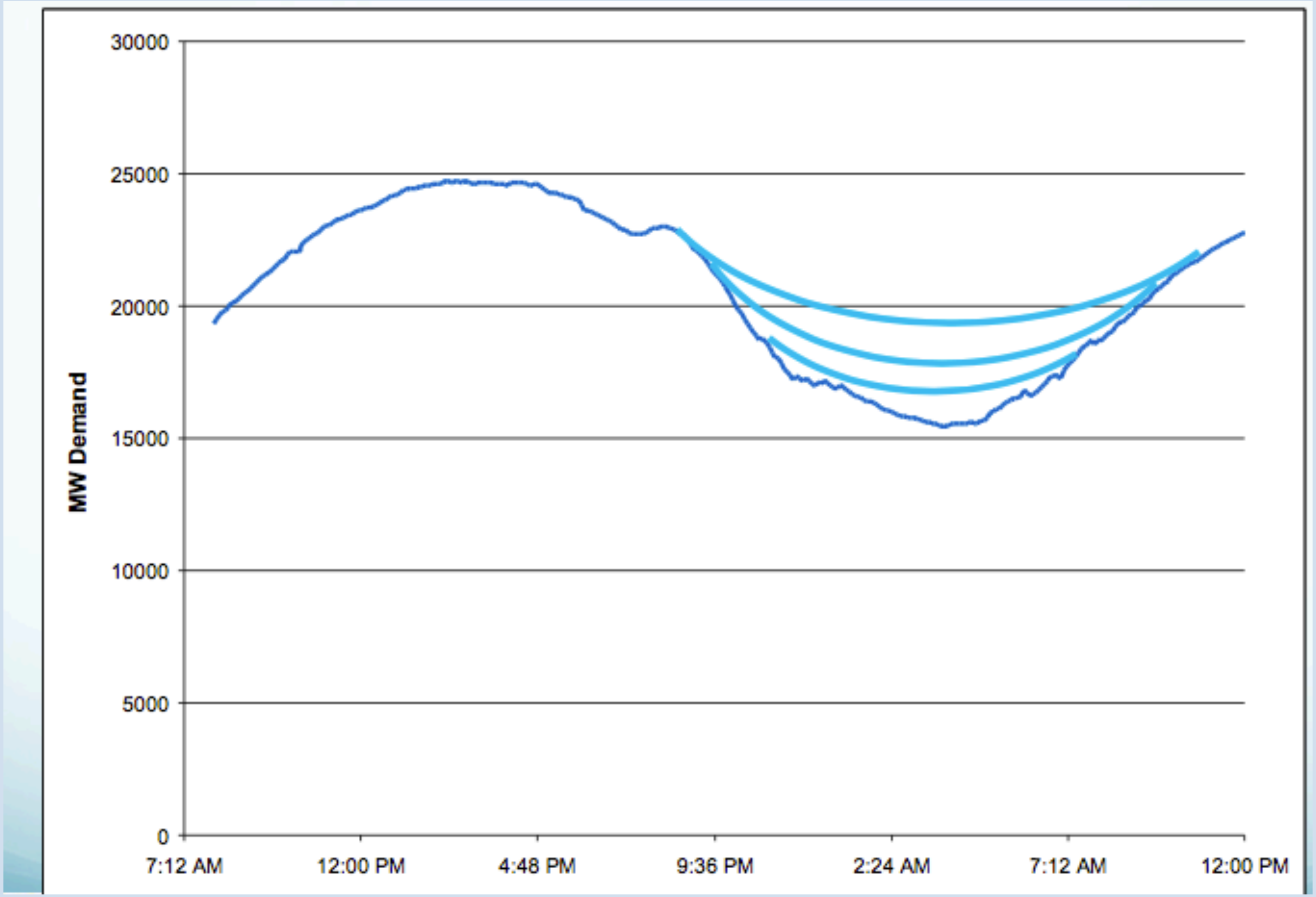
240V Charge Station

PHEV Charging Example

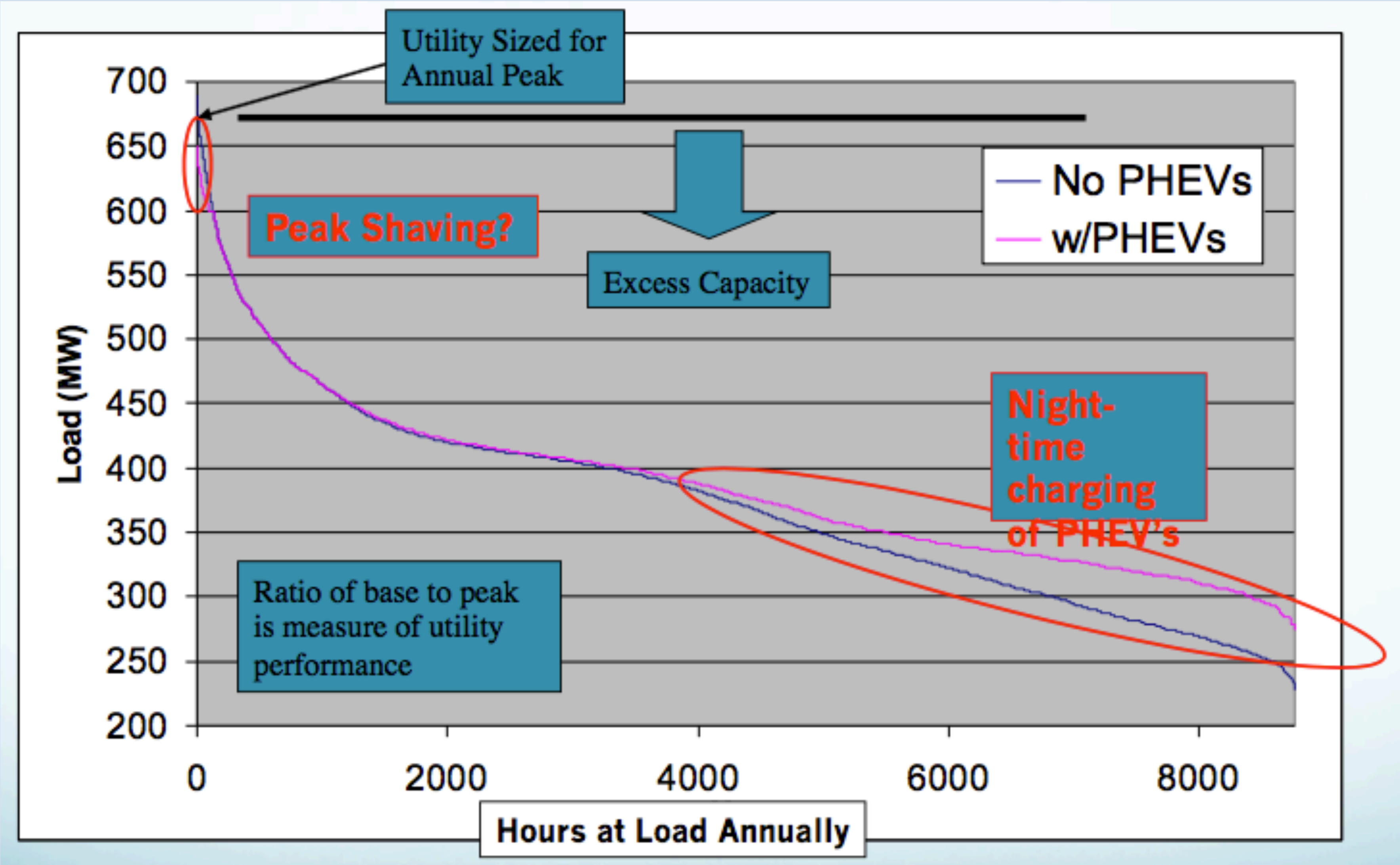
To remove the need to connect a vehicle to a charging station – Wireless Charging

- ❖ For example, a wireless power transmission system called Inductive Power Transfer (IPT) has been developed.
- ❖ A transmitter pad needs to be no more than 400mm away from the vehicle's receiver pad, which in turn is connected to the vehicle's battery.
- ❖ Such a system is desirable not only because it is simple for the driver to use, but has less that can go wrong due to no cables or connectors needing to be attached to the car repeatedly.

Home Charging-Night Charging

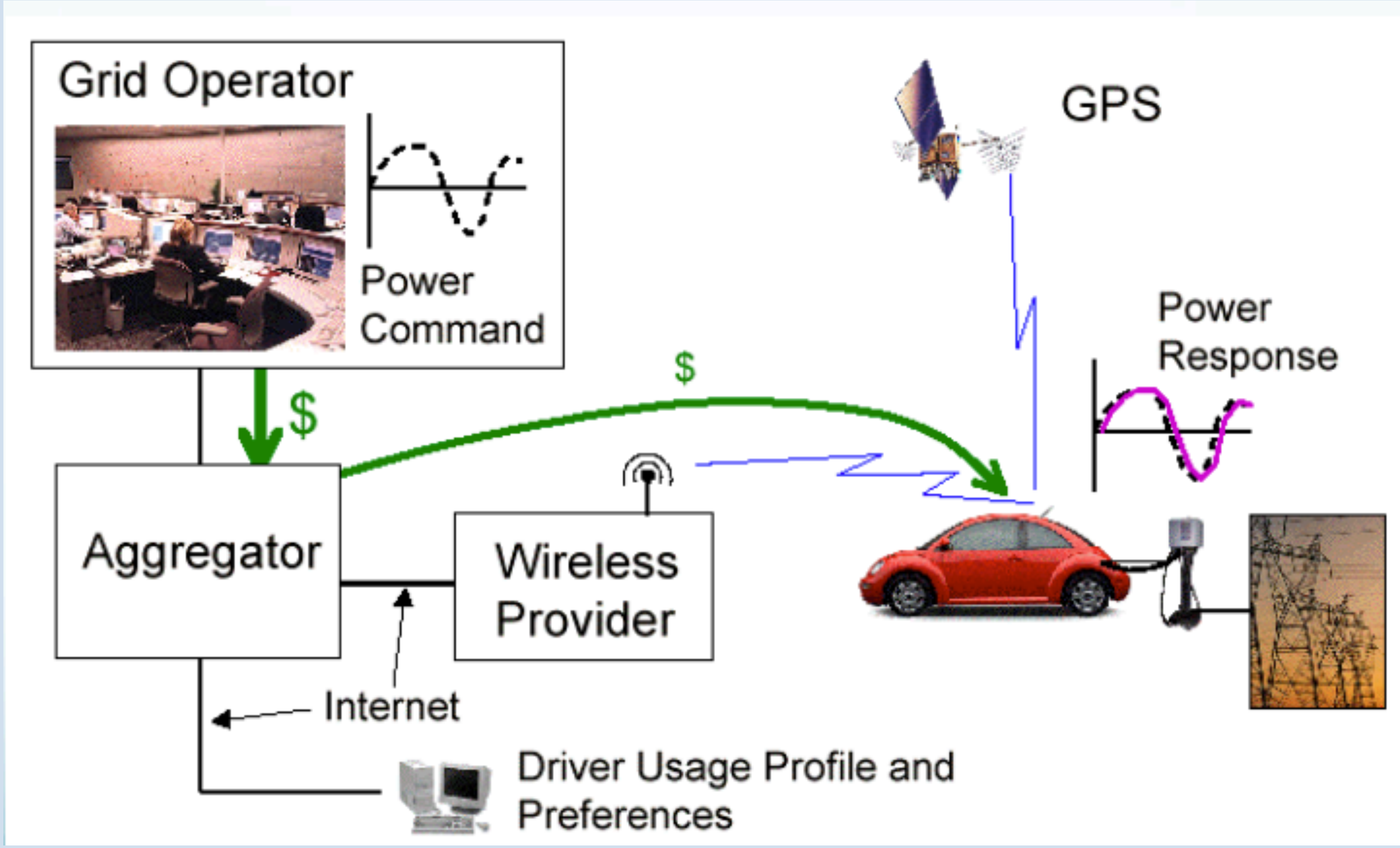


Impact on Grid – Night Charging



Assumes utility controlled night-time charging for 50% of the vehicles in this utility district

Vehicle to Grid (V2G)



V2G Technology

- Allows communication between utility and vehicle.
- Integration of more renewables like wind.
- Used EV batteries could be used as stationary batteries for utilities.
- With so much focus on energy efficiency reducing electricity sales and expensive renewable energy generation mandated, EVs could be a welcome new segment for utilities
    - They could still be a nightmare
- Batteries could provide ancillary services.

PHEV Challenges

- Limited Range
  - Large battery weight/size
- Long charge times
- High initial cost
- Battery life
- Consumer acceptance
- Grid integration

Battery

- Lithium sources
  - We're not Lithium constrained
  - Abundant
  - Recyclable
- Recycling – 90% recoverable
- Extending battery life
- Battery management systems
- Weight/Volume reductions
- Alternative chemistries

Battery

- **Li-ion** batteries are capable of storing up to three times more energy per unit weight and volume than the conventional **lead sulfate** (or Pb-acid) and **nickel–metal hydride** battery (NiMH) batteries.
- Because of the high-energy characteristics, Li-ion batteries find wide-spread applications including aerospace, EV, and hybrid EV designs.
- The self-discharge rate of the solid-state Li- ion battery is fairly low—5% of the capacity per month, compared to the 15% for the VRLA battery and 25% for NiMH battery.

PHEV Charging Infrastructure

Charging Stations

- A charging station is an element in an infrastructure that supplies electric energy for the recharging of PHEV.
- Charging stations for electric vehicles may not need much new infrastructure in developed countries, less than delivering a new alternative fuel over a new network
- The stations can leverage the existing ubiquitous electrical grid and home recharging is an option
- Also most driving is local over short distances which reduces the need for charging mid-trip

Various Charging Rates

- Normal and fast charging have been developed.

Charging time	Power supply	Voltage	Max current
6-8 hours	Single phase - 3.3kW	230 VAC	16 A
2-3 hours	Three phase - 10kW	400 VAC	16 A
3-4 hours	Single phase - 7kW	230 VAC	32 A
1-2 hours	Three phase - 24kW	400 VAC	32 A
20-30 minutes	Three phase - 43kW	400 VAC	63 A
20-30 minutes	Direct current - 50kW	400 - 500 VDC	100 -- 125 A

Public Charging

current

EV only, maximum stay – with/without parking charge

Proposed

- display of permits required
- parking whilst charging only
- free parking or concessions common
- standards and charges vary across locations

Renewable Charging Stations

- Charging stations are usually connected to the electrical grid, which means that their electricity originates from fossil-fuel power stations or nuclear power plants.
- Renewable power (solar or wind) is also suitable for electric vehicles.

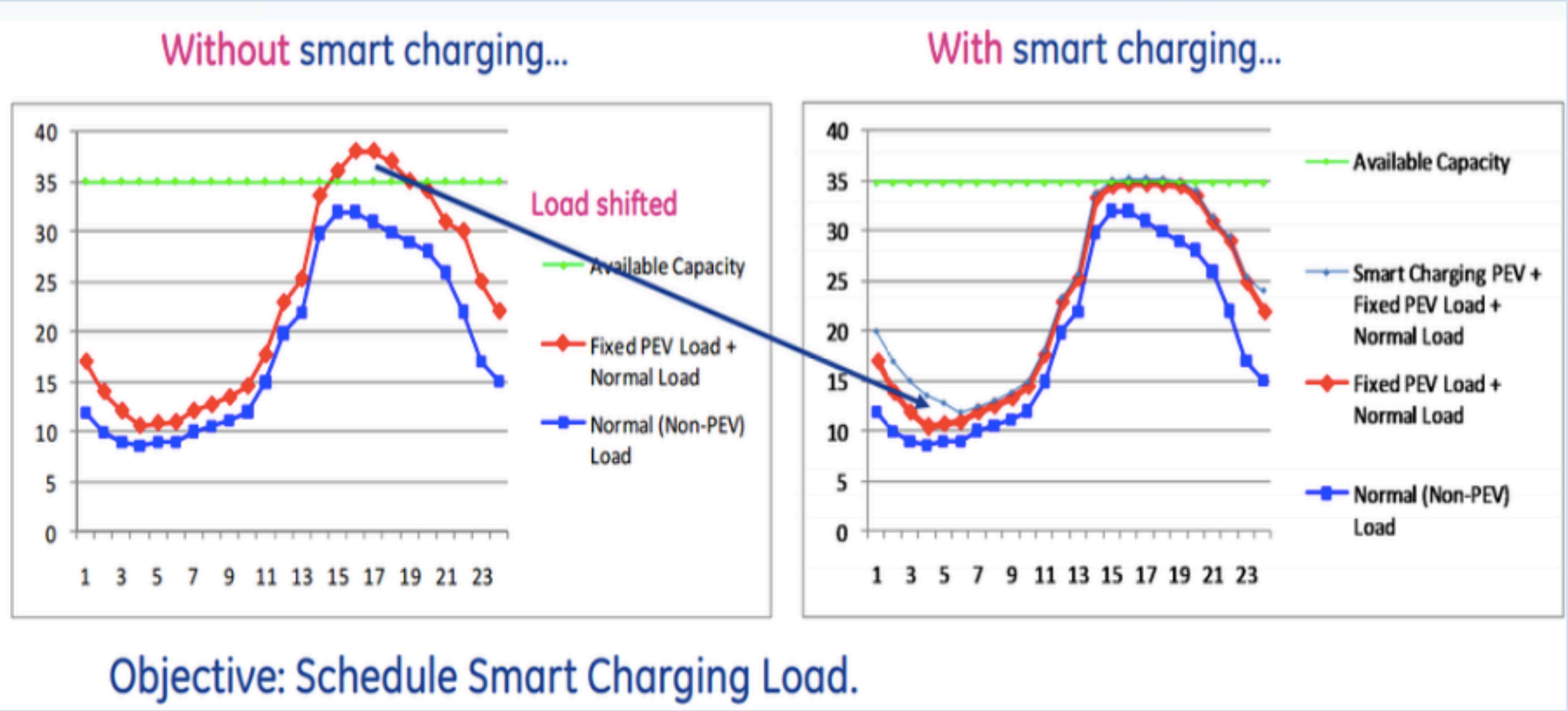
Challenges in PHEV Charging

- Congestion on the power grid: Uncoordinated charging may cause congestion to the power grid as many PHEVs may clustered into the same area
- Level of demand: an isolated station along a busy highway may see hundreds of customers per hour if every passing PHEV has to stop there to complete the trip
- Location and number of charging stations: It is difficult to *optimize* location and number of charging stations

Smart Vehicle = Smart Charging

- Vehicles connect to smart metering infrastructure.
- Utility and vehicle exchange information:
  - Price of electricity;
  - Billing information;
  - Energy needed.
- Charging managed according to user preference.
- Vehicle can respond to utility requests or electricity price information.

Smart Charging Illustration



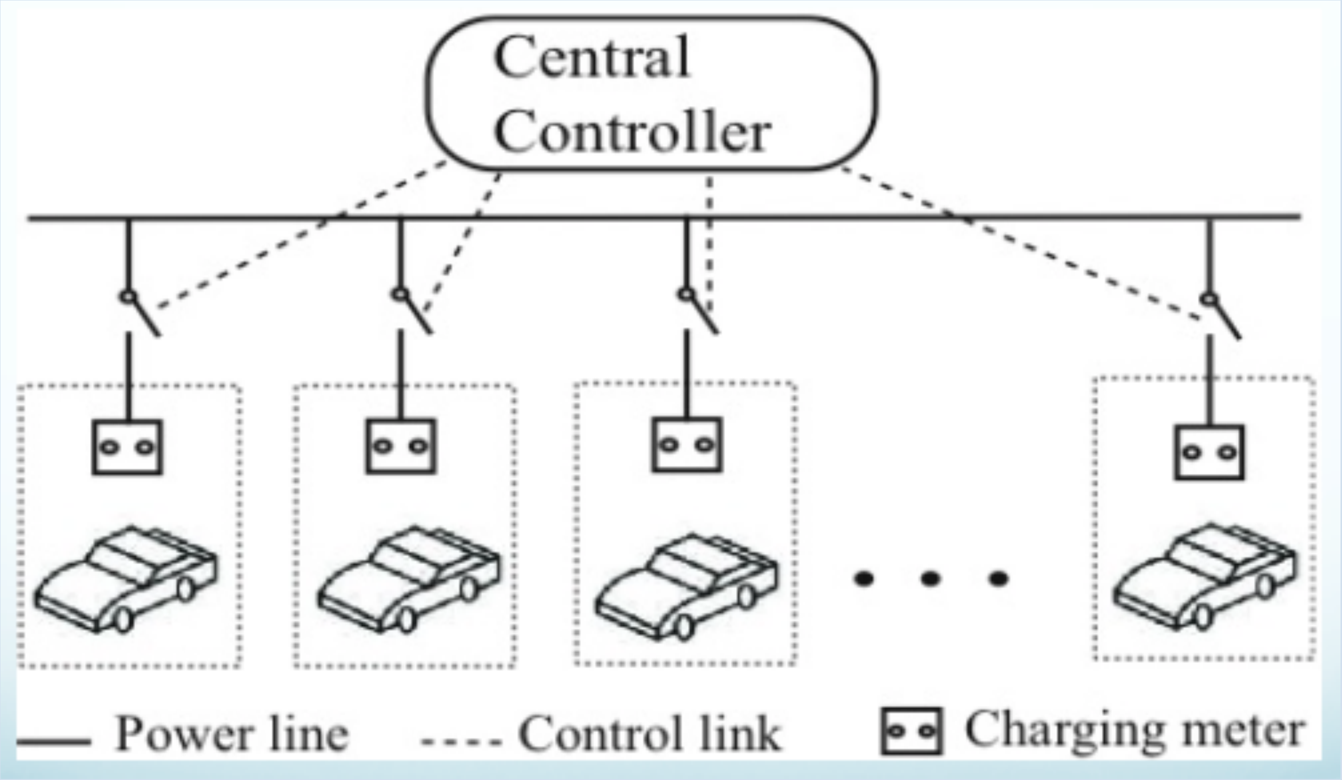
Smart Charging Needs Smart Pricing

- **Time-of-use pricing (TOU pricing):**

  Prices paid for energy consumed during any particular period are pre-established and known to consumers in advance.
- **Critical peak pricing:** TOU prices are in effect except for certain peak days, when prices may reflect the costs of generating and/or purchasing electricity at the wholesale level
- **Dynamic pricing:** prices may change as often as hourly. Price signal is provided to the user on an advanced or forward basis, reflecting the utility's cost of generating and/or purchasing electricity at the wholesale level

PHEV Charging Schedules

Centralized Scheduling



PHEV Charging Schedules

- Common public charging infrastructures:
  - Work places – university campus or business/
  - industry buildings
  - Malls
- Public parking plazas, e.g., in the city center
- Common-sense approach: Consumers input departure deadline, desired charging amount, rate etc.

Some Scheduling Strategies – A Queuing Theoretic Approach

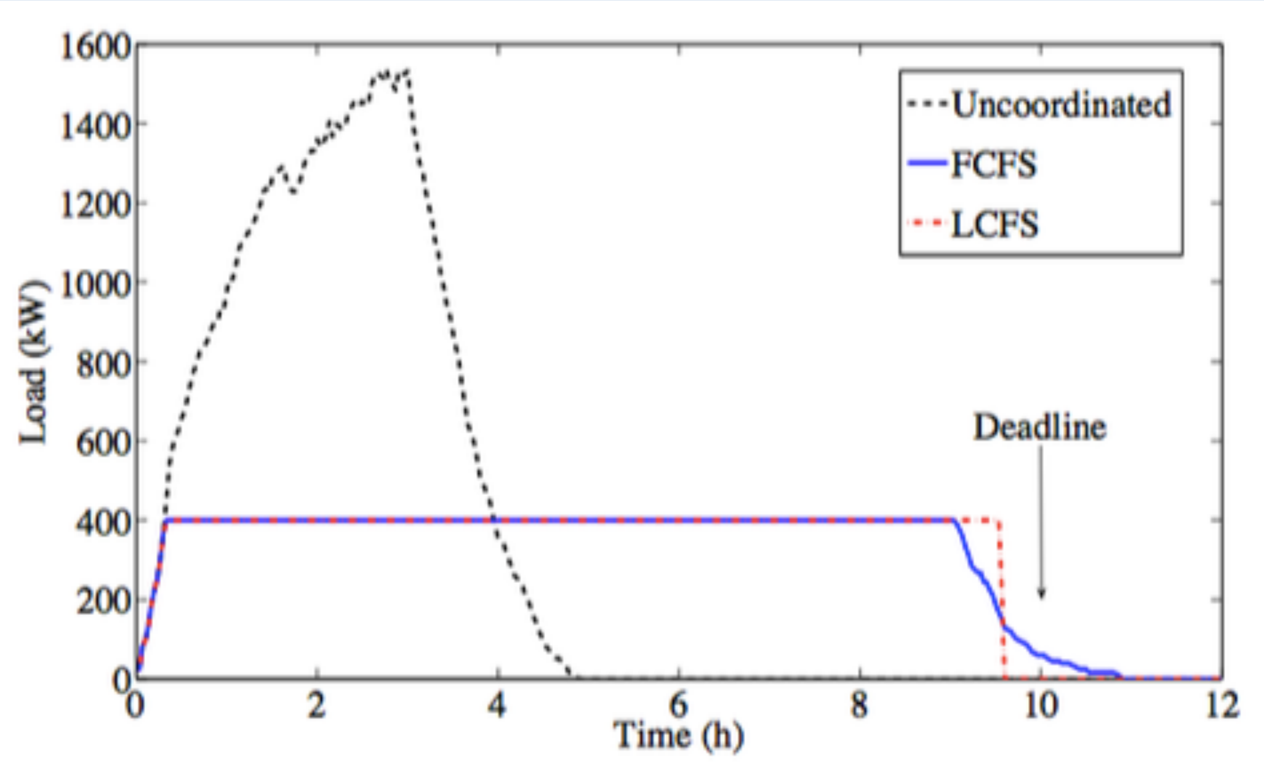
- First Come First Serve (FCFS): simple "first in first out" queue.
- Shortest Charging-time First Serve (SCFS): customer that needs the shortest service time is served first.
- Longest Charging-time First Serve (LCFS): customer that needs the longest service time is served first.
- McNaughtan (McN): Minimize completion time when all jobs are simultaneously present at time 0
- Earliest Deadline First (EDF): the earliest deadline to get served first.

Implementation –
Preemptive or not preemptive

- **Preemptive:** The charging of any PEV can be split into any number of nonconsecutive time slots (time scale is quantized).
- **Non-preemptive:** The charging of any PEV must happen in a continuous time window.

Multiple Charging Stations

Benefits of Scheduling – simulation



Future Directions

- Consider additional types of charging stations, e.g., event-specific types, office/business for employees, or for fleets.
- Variable charging rates - soft constraints on charging levels/ rates.
- Other factors to consider in defining objective functions: battery charging profile (e.g., first 90% fast, last 10% slow); value of partial v/s full charge.
- Consider multi-attribute optimization, or projection onto economic dimension (i.e. business models with utility companies).

Charging Station Location

- Different constituents demand different optimization viewpoints–
  - The station owner;
  - Utility companies;
  - EPA (Environmental Protection Agency);
  - Municipalities;
  - The consumers, i.e., vehicle owners;
  - Minimization of congestion, etc.
- Modeling energy use for driving: home to work.
- An important measure: total energy consumption.
- Comparison with the solution of the optimal placement choice of the station owner.
- Analysis of differences and recommendations.

Addressing Consumer Perception

- Accepting limited range
  - Most people drive less than 40 mi/day
  - Most cars are parked 23 hours of the day anyway
- Smaller vehicles & reduced performance

  In the last 30 years, nearly 100% of efficiency improvements have gone to increasing vehicle size and performance, not reducing consumption.
- How do you get people to charge at the right time?

PHEV Summary

- PHEVs are a key technology in the portfolio of options to reduce US oil use.
- They also provide significant other consumer and national benefits.
- Pre-commercial PHEV prototypes are on the road today.
- There has been a surge in community, industry and political support for PHEVs
- The key remaining barriers to commercial PHEVs are battery life, packaging, cost, and charging infrastructure.

Some References

1. Gan, Lingwen, Ufuk Topcu, and Steven Low. "Optimal decentralized protocol for electric vehicle charging." Decision and Control and European Control Conference (CDC-ECC), 2011 50th IEEE Conference on. IEEE, 2011.
2. D. Ban, G. Michailidis, and M. Devetsikiotis. "Demand response control for PHEV charging stations by dynamic price adjustments." Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES.
3. Morrow, Kevin, Donald Karner, and James Francfort. "Plug-in hybrid electric vehicle charging infrastructure review." US Departent of Energy-Vehicle Technologies Program (2008).