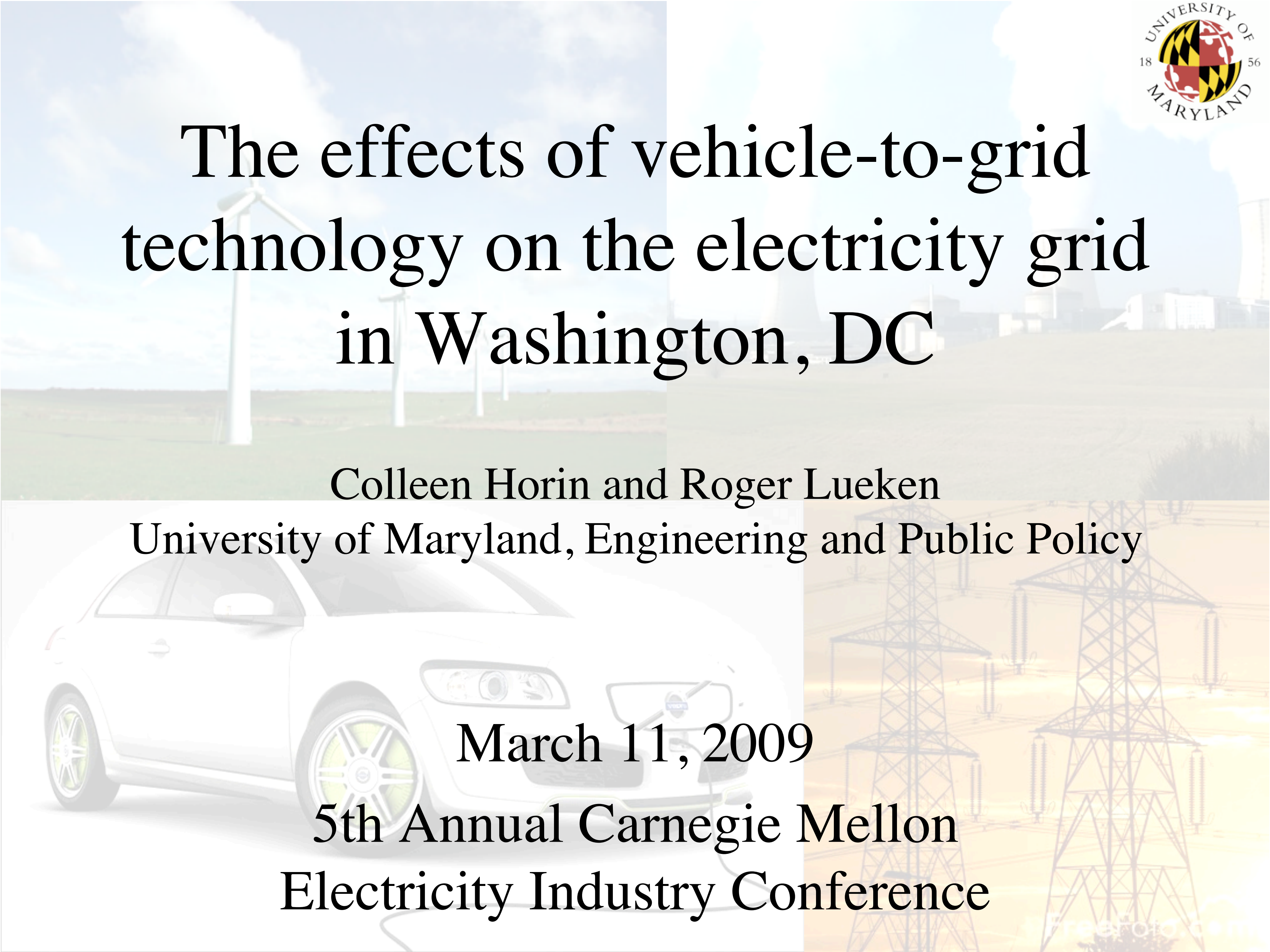

The effects of vehicle-to-grid technology on the electricity grid in Washington, DC

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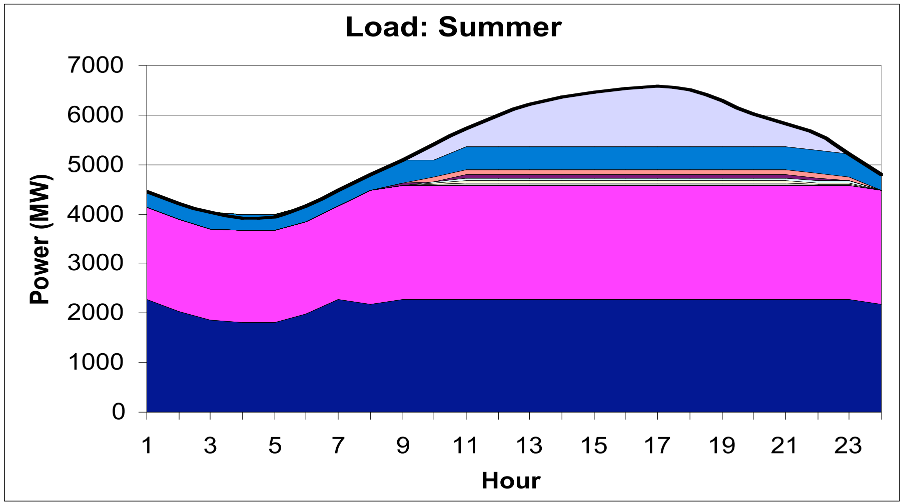
Outline

- Background and problem description
- Approach and methods
- Model construction
- Results
- Conclusions / future work

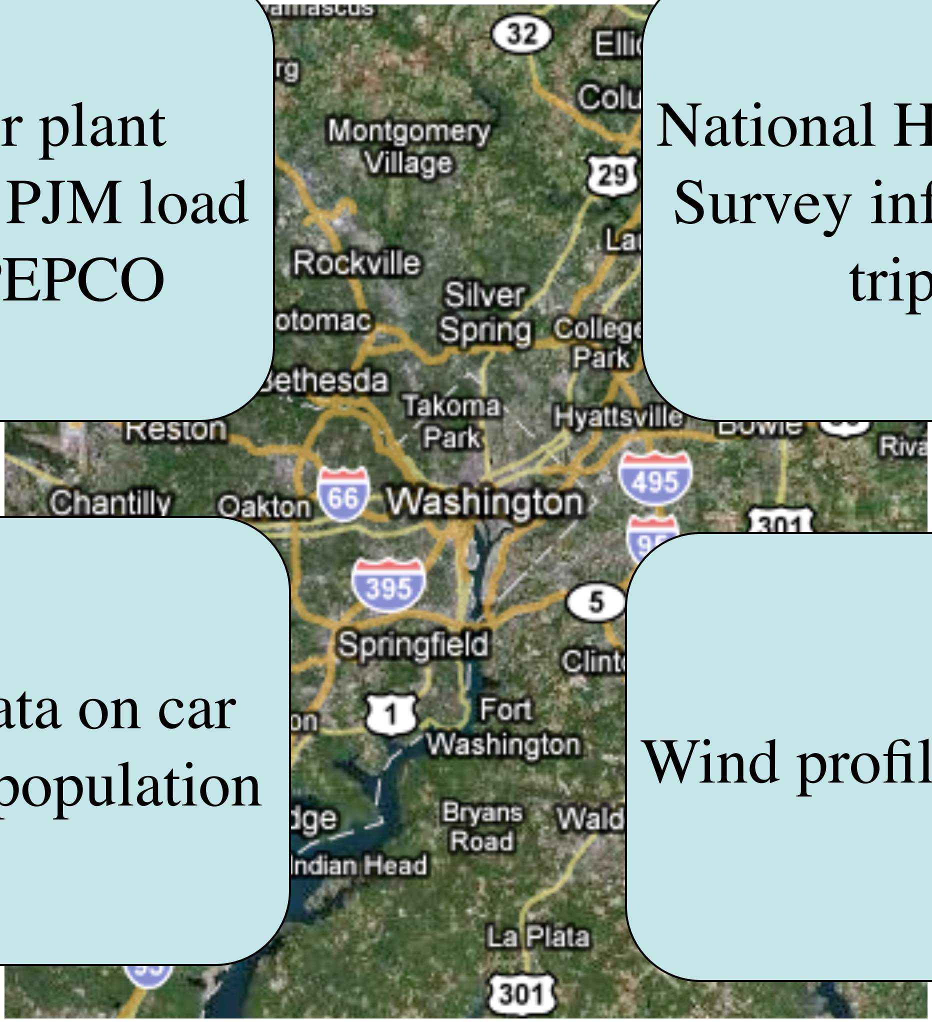
Background: The problem

- Storage is critical to integrating variable and clean sources of energy into the electricity grid
- The V2G storage option supposes that if electric vehicles become widespread, they could provide fast-response intermediate and peak load power to the grid while not on the road.
- Used stochastic programming to model PHEV and wind scenarios



Goal: Model implications of V2G on Washington DC electric grid

Background:
The Washington, DC Region



eGRID power plant information and PJM load Profiles for PEPCO

National Household Travel Survey information about trip patterns

U.S. Census data on car ownership and population

Wind profiles from NOAA

Method: Stochastic Modeling and Electric Power

- Stochastic modeling accounts for uncertainties in system variables
- One method of stochastic modeling, chance constrained programming, solves problems of the basic form: $\mathbf{P(A(x) > b) > \alpha}$
  - Where **A**(**x**) and/or **b** is a random variable
- In electric power, **A**(**x**) represents generation, **b** represents load, and $\boldsymbol{\alpha}$ is the probability with which the generation at any given time is greater than the load

Model Assumptions

- There is already a PHEV charging infrastructure in place (so that cars may charge whenever they are not in use)
- All PHEV's are the Chevy Volt (16 kWh battery)
- There are no transaction costs or inefficiencies involved in charging and discharging batteries
- Consumers are willing to sell-back as long as utility meets the minimum charge constraint for the hour
- Wind has no variable costs

Model Construction

- Chance-constrained program

  Minimize **system cost**

  s.t. at each time period,

  P(Power Gen +PHEV discharge> Load + PHEV charge) > reliability

- Deterministic equivalent

  Minimize **system cost**

  s.t. at each time period,

  Power Gen > μLoad + net changePHEV charge +z * σLoad

- Where the objective function (system cost) is:

  System Cost = $\Sigma_{time}\Sigma_{plants}$(Operation costs + Fuel costs + Fixed costs + Startup costs)

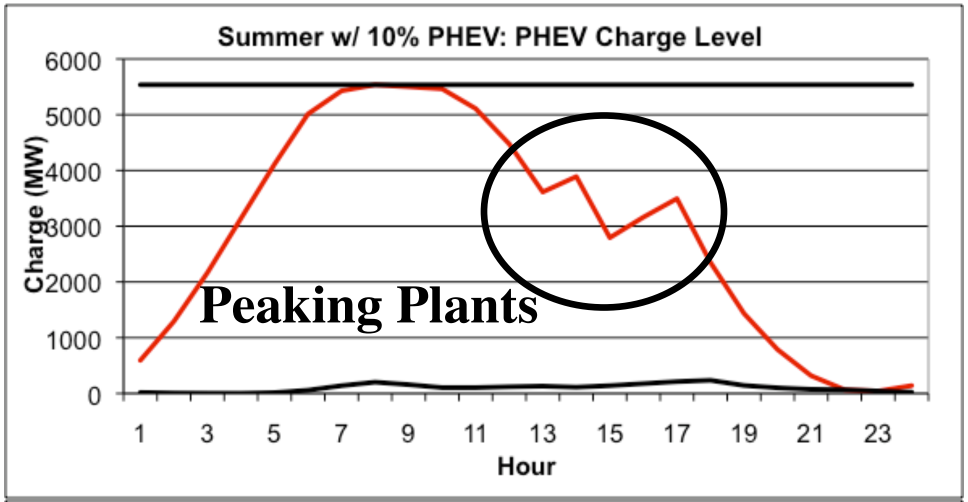
- Other constraints:
  - Any change in collective PHEV charge cannot exceed total charge of all PHEV’s connected to the charging infrastructure at a given time, nor can it go below the projected demand for charge from PHEV’s in the next hour
  - Plants must pay a start up cost when turning on (but not required for plants operating continuous baseload)

Results

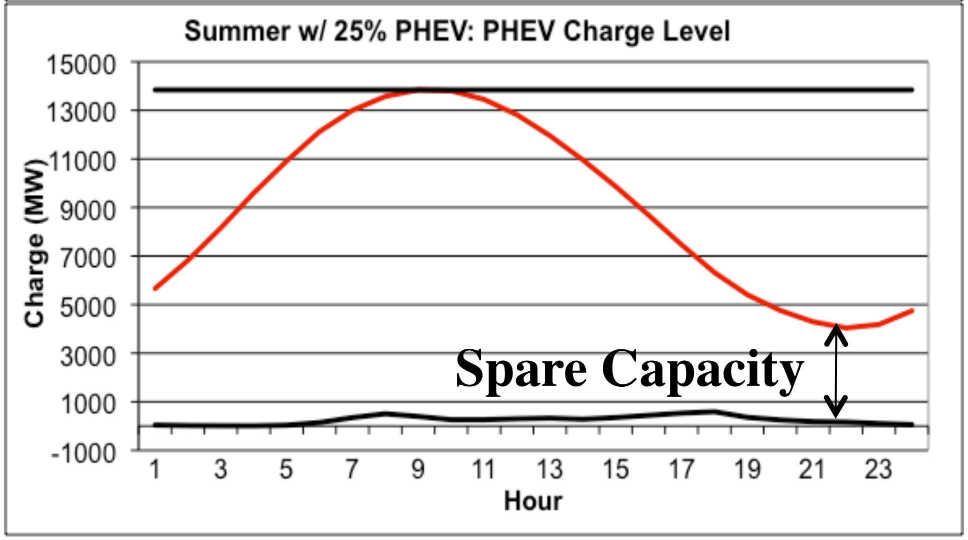
1. **PHEV market penetration**: How does PHEV market penetration affect the electric grid?
2. **Wind**: How might V2G help intermittent renewable resources penetrate the market?
3. **Carbon pricing**: How would a price on carbon affect the types of power plants the utility uses?

Results: PHEV Market Penetration

Scenario	System savings (%)
BAU	N/A
10% PHEVs	4%
25% PHEVs	9.6%
50% PHEVs	9.6%


Summer w/ 10% PHEV: PHEV Charge Level

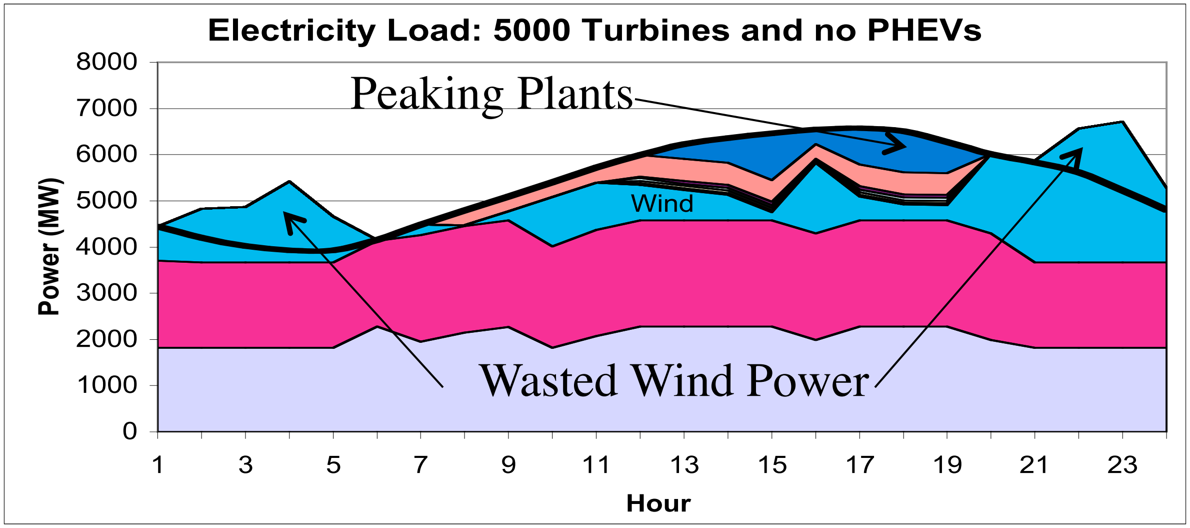
Peaking Plants


Summer w/ 25% PHEV: PHEV Charge Level

Spare Capacity

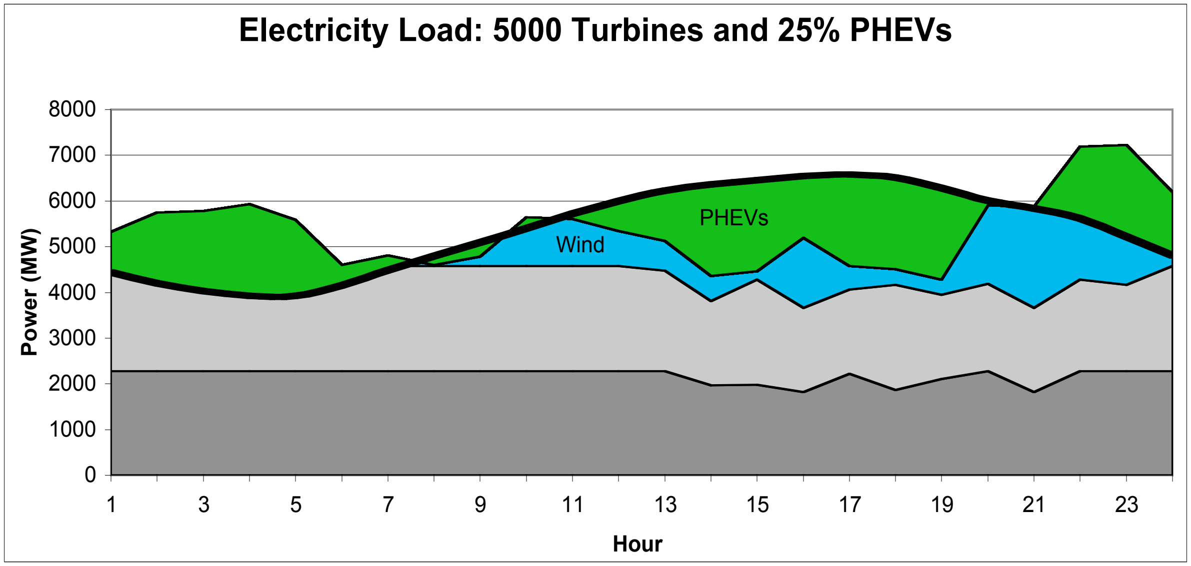
- ***Increasing V2G penetration eliminates need for peaking plants.***
- ***Benefits from V2G max out after 25% PHEV penetration***

Results: Wind Power Integration



Electricity Load: 5000 Turbines and no PHEVs

- Typical wind profile from Appalachian wind farm
- ~10% of total capacity



Electricity Load: 5000 Turbines and 25% PHEVs

- **Savings: 16%**
- **Reduces required generating units from 9 to 2**

With **20,000 turbines** (~40% of total capacity) and **50% PHEVs,** savings increase to **36%**

V2G allows more efficient integration of wind power

Results: Carbon Pricing

Scenario: (Summer)	System Cost (0% PHEVs)	System Cost (25% PHEVs)	Savings (Percentage)
No carbon price	$1,898,000 Active Generators: 10	$1,716,000 Active Generators: 9	$182,000 (9.6%)
$25/tonCO$_2$ price	$2,127,000 Active Generators: 11	$1,716,000 Active Generators: 9	$411,000 (19%)
$100/tonCO$_2$ carbon price	$2,530,000 Active Generators: 12	$1,716,000 Active Generators: 9	$813,000 (32%)

V2G makes high carbon prices more affordable by allowing greater dispatch flexibility.

Conclusions

- To maximize social benefit from V2G system
  - PHEV purchases must be encouraged
  - Charging infrastructure must be created
  - Optimal charging patterns must be encouraged
- V2G *reduces costs* of operating the electricity grid
  - However, storage savings to variable costs are MINIMAL ($40/car/year)
  - Regulation services savings may be higher (>$2,000/car/year)[1]
- V2G *enables* large deployment of variable renewables, efficient adaptation to carbon prices, and adoption of PHEVs.
- V2G *improves utilization* of existing assets, reducing need for additional generating and transmission capital expenditures.

[1] Kempton, W., California Air Resources Board & California EPA, June 2001

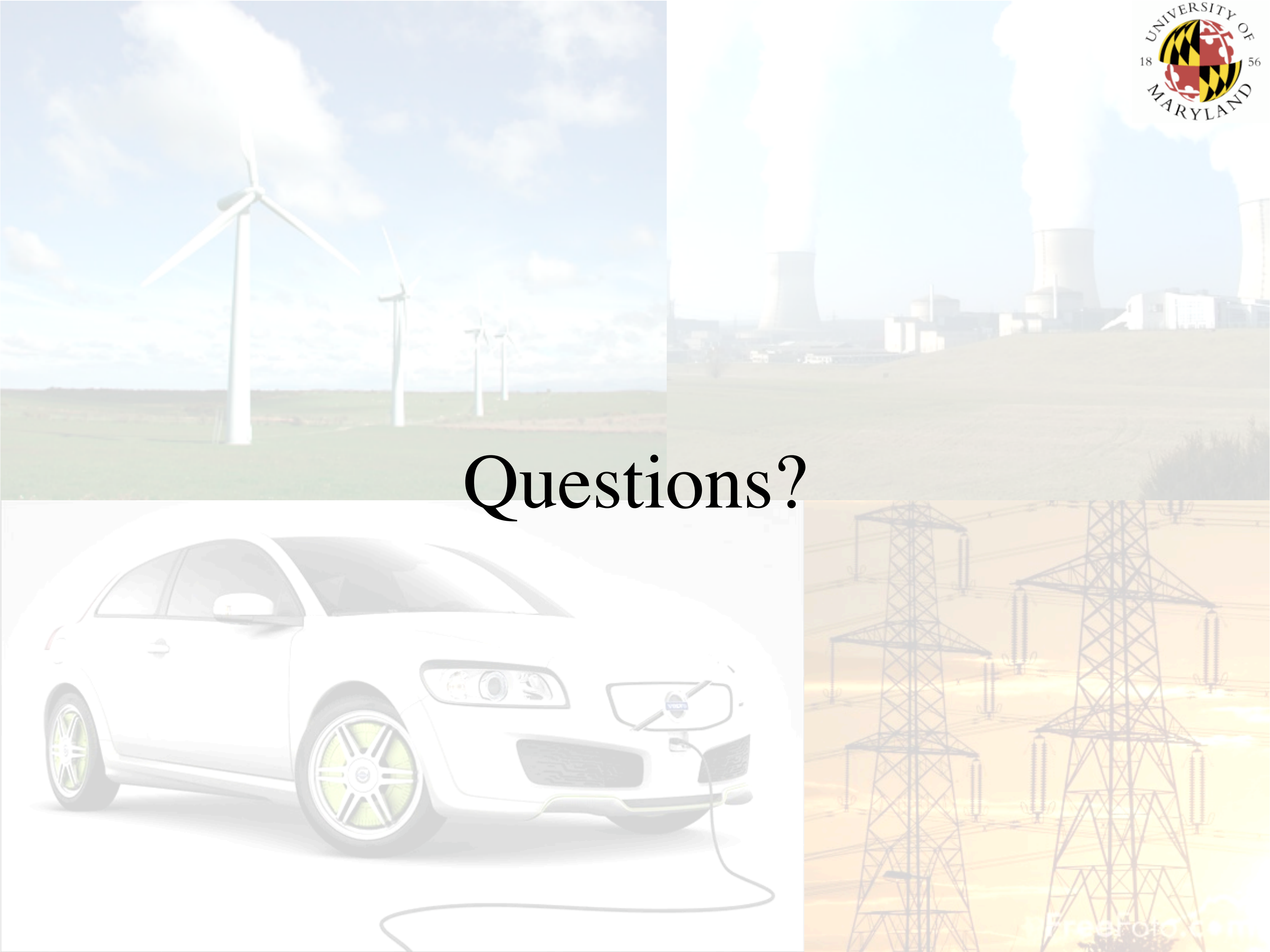
Future Work

Model Improvements

- Include transient effects & ramping speeds
- Battery degradation
- Include value of provided regulation services

Policy/Economic Modeling

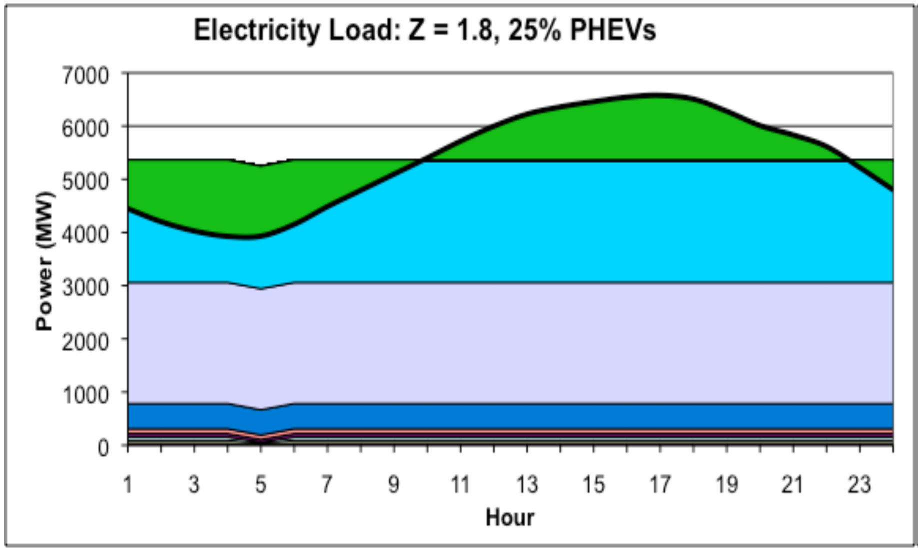
- Understand most effective distribution of V2G benefits amongst utilities and consumers
    - Funds required to develop charging infrastructure
    - Appropriate subsidy levels to encourage PHEV adoption
    - Hourly price signals necessary to ensure desired consumers charge in an optimal fashion
- Quantify effects of V2G on electricity prices

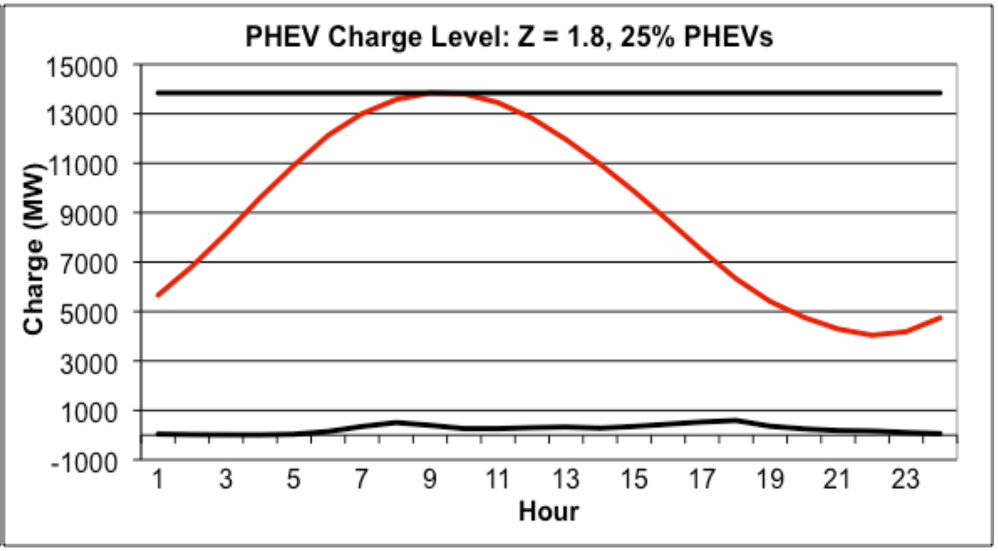


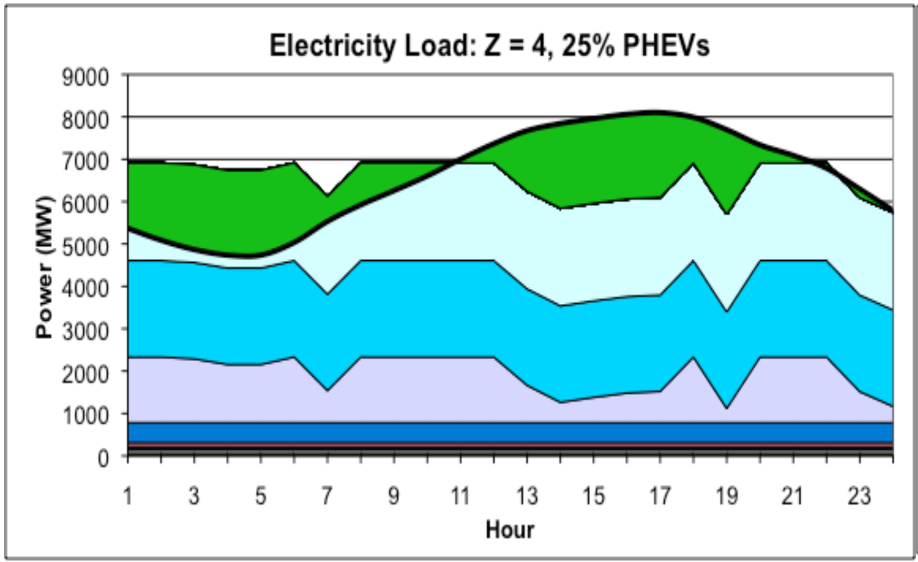
Questions?

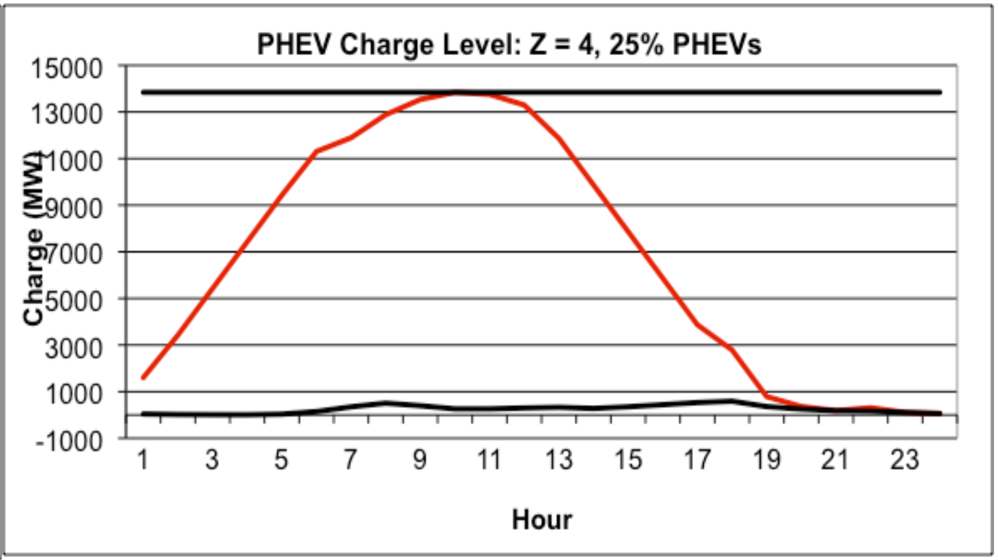
Backup Slides

Results: Increasing Reliability (Z)


Electricity Load: Z = 1.8, 25% PHEVs


PHEV Charge Level: Z = 1.8, 25% PHEVs


Electricity Load: Z = 4, 25% PHEVs


PHEV Charge Level: Z = 4, 25% PHEVs

Higher Z raises average demand; PHEVs at charge storage limits

Model Construction: GAMS code

```
Obj_Fn ..              Sys_Cost =e= sum(k, sum(t, P(k,t)*(G(k,'OC') + G(k,'FC') + G(k,'fuel') + CTax*G(k,'CO2')) +
      SCVar(k,t)));

Const1(k,t) ..         P(k,t) =l= BigM*V(k,t);
Const2a(k,t) ..        SCVar(k,t) =l= G(k,'Pmin')*G(k,'SC') * (V(k,t) - V(k,t--1)) + BigM * V(k,t--1);
Const2b(k,t) ..        SCVar(k,t) =g= G(k,'Pmin')*G(k,'SC') * (V(k,t) - V(k,t--1));
Const3a(k,t)  ..       P(k,t) =l= G(k,'Pmax') + BigM * (1 - V(k,t));
Const3b(k,t)  ..       P(k,t) =g= G(k,'Pmin') - BigM * (1 - V(k,t));

Const5(t) ..           Lmean(t) =e= H(t,'LavgSum');
Const6(t) ..           Lstddev(t) =e= H(t,'LstdvSum');

PHEV1(t)..             PHEVcharge(t) =e= PHEVcharge(t--1) + deltaPHEV(t);
PHEV2(t)..             PHEVcharge(t) =g= PHEVmktpen*H(t,'PHEVmin');
PHEV3(t)..             PHEVcharge(t) =l= PHEVmax*POVtot*PHEVmktpen;

Prob_Const(t)..        sum(k,P(k,t)) =g= Lmean(t) + z * Lstddev(t) - WindFract*(H(t,'WindAvg') + z*H(t,'WindStd')) +
      deltaPHEV(t);

Output1(t) ..          WindPwr(t) =e= WindFract*(H(t,'WindAvg'));
Output2 ..             NumPHEVs =e= POVtot*PHEVmktpen;
Output3(t) ..            MinPHEV(t) =e= H(t,'PHEVmin');
Model test /all/;
Solve test using mip minimizing Sys_Cost;
```

Data Sources

Data Source	**Data**
EPA	PEPCO power plant capacities, operating costs, CO2 emissions
PJM	PEPCO electricity load profiles
NOAA	Wind profiles (Borden Mountain, MA)
NHTS (National Household Travel Survey)	Number of vehicles in DC metropolitan area making trips during each hour
U.S. Census	Number of vehicles in DC metropolitan area
Wikipedia	PHEV specifications (charge capacity, charge rate)
Abrell, Kunz, Weigt*	Start up cost estimates for plants
Ozturk**	Chance-constrained to deterministic equivalent

Model Construction

- Objective Function: Minimize system costs

$Sys\_Cost = \Sigma_{time}\Sigma_{plants}\ (Op\_costs + Fuel\_costs + Fixed\_costs + Startup\_Cost)$

- Each plant's generation is within capacity limits

$Pmin < Power\_level < Pmax$

- Plant must pay startup cost when turning on

If $P(t) > 0$ *and* $P(t-1) = 0$, *then* $SC = startup\ cost$, *else* $SC=0$

- Battery levels are within capacity limits

$MinCharge < Charge < MaxCharge$

- Generation meets load with set reliability

$\Sigma_{plants}\ (Pwr\_level) + Wind > Load\_mean + z{*}Load\_stddev + PHEVcharge$