



Impact of Plug-in Hybrid Electric Vehicles with Vehicle-to-Grid Capabilities on Islanded Distribution Systems

Sid Suryanarayanan, Assistant Professor
Dept. of ECE, Colorado State University
<http://engr.colostate.edu/~ssuryana>

PSERC Webinar - September 27, 2011

Outline of presentation

- Introduction to PHEVs
 - Vehicle to grid (V2G)
- Islanded distribution system resources
 - Microgrids
- Impact of PHEVs with V2G on microgrids
 - Modeling PHEVs
 - Use of probabilistic simulation from Meliopoulos et al. [1]
 - A linear programming approach to vehicle charging
 - Comparing uncontrolled and controlled charging
- Concluding remarks and future work

[1]. S. Meliopoulos, J. Meisel and T. Overbye, —Power System Level Impacts of Plug-In Hybrid Vehicles (Final Project Report), PSERC Document 09-12, Oct. 2009.

Introduction

- Smart Grid Initiative (EISA07) encourages deployment of energy storage and peak-shaving technologies
 - Including PHEVs
- ARRA09 provides energy incentives for qualifying PHEVs purchased after 12/31/2009
- Under existing policies, 1 million PHEVs to hit the road by 2015



Motivation

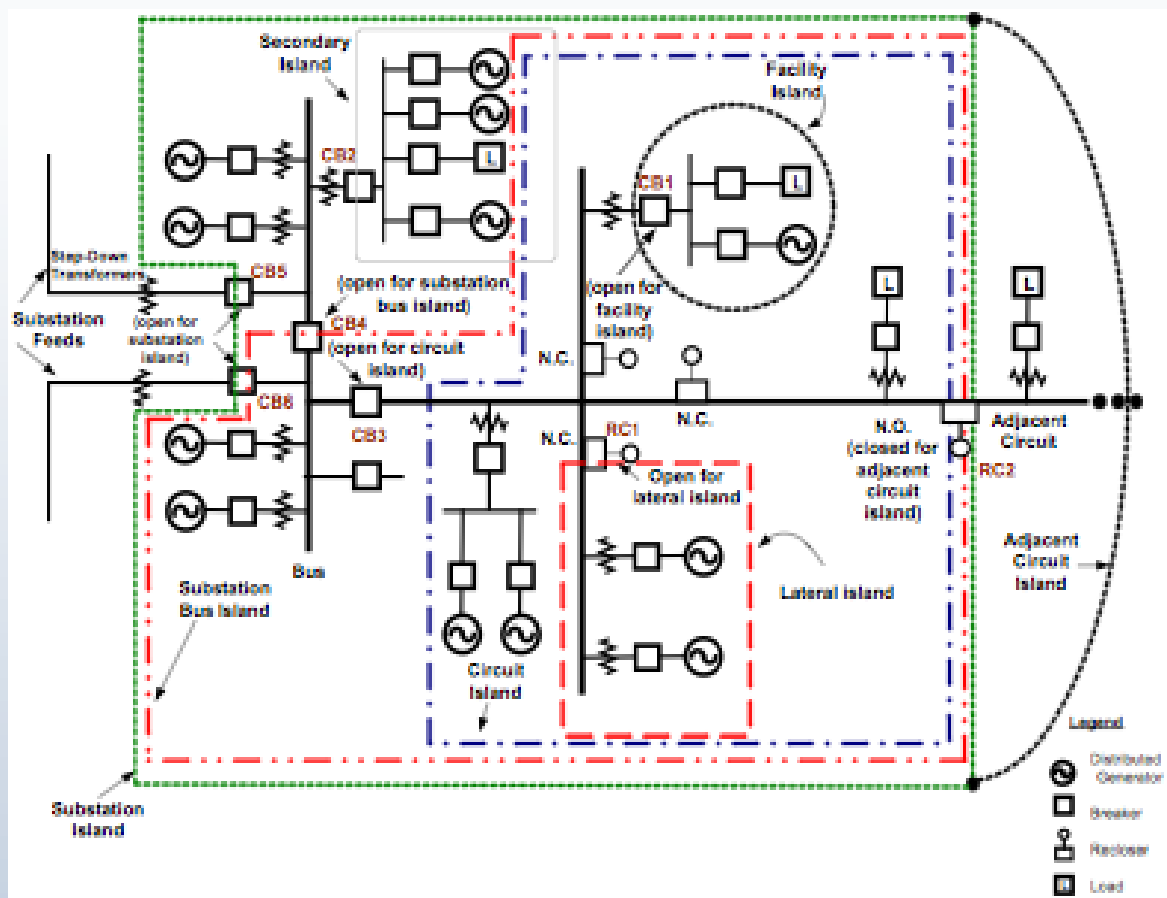
- PHEVs serve in 2 modes:
 - Power flows from grid to vehicle (G2V) during charging
 - Power flows from vehicle to grid (V2G) during discharging
- Utilities are expected to use PHEVs for peak-shaving and energy storage purposes
- Impact of PHEVs on distribution systems have been studied
 - Albeit, largely from cables and transformers perspective
- Electric distribution systems are transforming to include:
 - Intentionally islanded systems (microgrids with finite inertia)
 - Impact studies of PHEV penetration on microgrids will give best design solution
- Research on quantifying impact of V2G on microgrid reliability
 - Existing power system infrastructure may be inadequate to deal with increased demand and new patterns of energy consumption and power flows in the grid
 - Comparisons to controlled and uncontrolled charging
 - Peripherally, making the case for a new market entity (aggregator)

Introduction

- V2G concept provides electric energy back to grid when vehicle not engaged in transportation
- Most relevant vehicle type to V2G may be the 'hybrid'
- PHEV power train runs in 2 modes:
 - Charge depleting (CD) until battery reaches minimum SOC
 - Charge sustaining (CS) thereafter
 - Plays a crucial role in determining energy required per vehicle
- Research shows ancillary markets are most suited for V2G PHEVs

What is a microgrid?

- An autonomous self-sustainable subset of an area electric power system that can operate independent of the grid or in connection with the grid
- Applications in civilian and military milieus
- Microgrids may help achieve the SGI



Source: IEEE P1547.4 "Draft Guide for Design, Operation and Integration of Distributed Resource Island Systems with Electric Power Systems," Work Group web site <http://grouper.ieee.org/groups/scc21/1547.4/private/stdrafts.html>

Some characteristics of microgrids

- Designed to enhance reliability to loads
- Panoply of ancillary services
- Potential for economic incentives
- May incorporate renewable energy sources
 - Avenue for meeting RPS
- Types: remote, industrial, utility-owned
- New paradigm: customer-driven microgrids
- Caters to the Smart Grid Initiatives recommendations of evolving distribution systems

Key questions in study

KEY QUESTIONS TO STUDY THE IMPACT

- Modeling PHEVs in distribution systems
 - How many PHEVs?
 - What is the behavior of the driver?
 - For how long does a PHEV behave as a load?
 - For how long does a PHEV behave as distributed generator source?

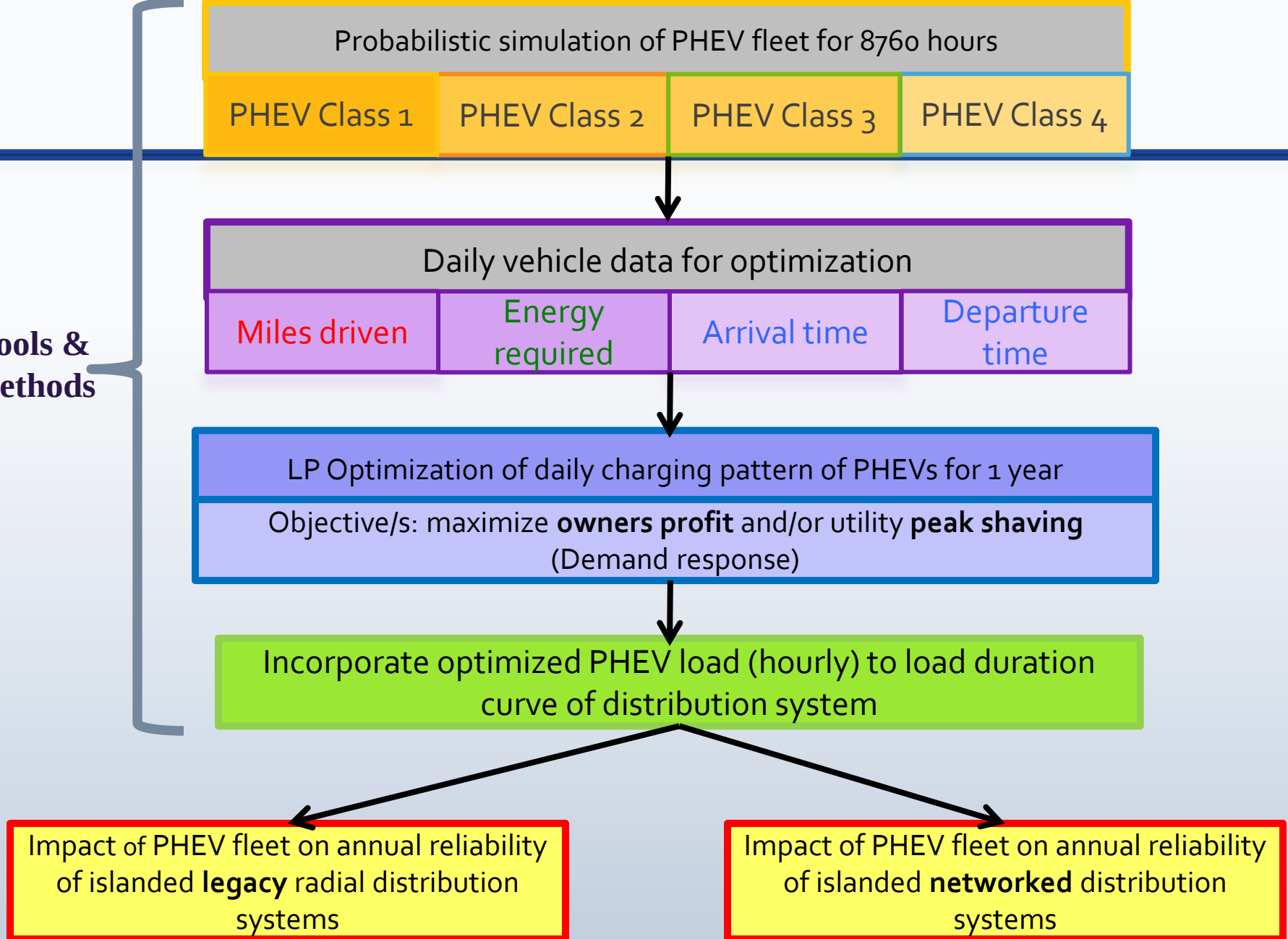
KEY ASSUMPTIONS TO STUDY THE IMPACT

- Unknowns and likely market penetrations and design characteristics must be assumed
- PHEV penetration level = 30% of transportation fleet
- Availability of charging stations
 - Vehicles charge at residence
 - Vehicles charge at commercial and office buildings
 - It is not considered if same vehicle charges at a residence or commercial building
- 50% of electric fleet charges at:
 - level 1 (120 V, 15 A, 1.8 kW charge rate per hour)
 - level 2 (240V, 30A, 7.2 kW charge rate per hour)

Modeling PHEVs in a distribution system

- How many vehicles?
 - Electric customer consumes 2 kW and has 1.5 vehicles for residential
 - 38 workers per office building and 17 workers per commercial and 1.5 vehicles per worker
- How many PHEVs in the system?
 - 30% penetration of the total transportation fleet
- What kind of PHEVs? What design and operational characteristics? What is the behavior of the driver?
 - Probabilistic simulation methodology from Meliopoulos et al.
- For how long does the PHEV behave as a load and as a generator?
 - Driving factors: peak-shaving; owner's benefit
 - LP algorithm for optimizing charging patterns

Tools & methods



Results

Impact of PHEVs in distributed resource islands

- Parameters for the Prob. Sim. Methodology [1]
- Four vehicle classes (types)
- Design characteristics (SOC):

<i>Vehicle class c</i>	<i>B_c [kWh]</i>	
	<i>Max</i>	<i>Min</i>
1	12	8
2	14	10
3	21	17
4	23	19

Battery size



Impact of PHEVs in distributed resource islands

- Parameters for the Prob. Sim. Methodology [1]
- Amount of driving supplied from electric battery? From fuel?
- $k_{phev}=0$ represents a charge sustaining (CS) mode in which on average all the drive energy comes from gasoline
- $k_{phev}=1$ represents a charge depleting (CD) mode, all of the drive energy comes from electricity
- Simulations run in Powerdrive Simulation Analysis Tool (PSAT)
- Performance parameter E_c : required energy per mile [kWh/mi]

$$E_c = a_c^E (k_{phev}_c)^{b_c^E}$$

Impact of PHEVs in distributed resource islands

- Parameters for the Prob. Sim. Methodology [1]
- Vehicle control strategy: drive in CD from battery while in SOC ranges and switch to CS to maintain SOC relying on gas
- Charge depleting distance M^D

$$M^D = \frac{B_c}{E_c}$$

$$M^D \approx 40 \text{ miles}$$

$$E_c = a_c^E (kphev_c)^{b_c^E}$$

Vehicle class c	$kphev_c$	
	Max	min
1	0.5976	0.2447
2	0.6151	0.2750
3	0.5428	0.3217
4	0.4800	0.3224

Impact of PHEVs in distributed resource islands

- Parameters for the Prob. Sim. Methodology [1]
- Four random parameters
 - k_{phev_c} and B_c
 - # Vehicles per class
 - Daily miles driven per vehicle
 - Driver's behavior ~ Time parameters

Impact of PHEVs in distributed resource islands

- Probabilistic simulation methodology [1]
- Vehicle design characteristics and usable battery capacity B_c are distributed according to a bivariate normal distribution with mean vector μ and covariance matrix Σ with 0.8 parameter correlation
- Performance parameter E_c is determined knowing $kphev_c$

<i>Vehicle class c</i>	<i>BC [kWh]</i>	<i>kphev_c</i>
1	14.3015	0.5976
2	14.1827	0.6151
3	19.1516	0.5428
4	21.3211	0.4800

Impact of PHEVs in distributed resource islands

- Probabilistic simulation methodology [1]
- Miles driven per vehicle per day $M_{d,c,v}$: log normal distribution with mean 3.37 and standard deviation of 0.5
- Daily energy required per vehicle from the grid [kWh]:

$$DE_{d,c,v} = \begin{cases} B_c & , \text{ if } M^D \leq M_{d,c,v} \\ M_{d,c,v} * E_c & , \text{ if } M_{d,c,v} > M^D \end{cases}$$

Impact of PHEVs in distributed resource islands

- Probabilistic simulation methodology [1]
- Driver's behavior ~ time parameters: Gaussian distribution

	Departure (am)		Arrival (pm)	
Parameter	Weekday	Weekend	Weekday	Weekend
μ_c	7	9	6	15
σ_c	1.73	2.45	1.73	2.45

- Only residential charging in [1], what about office and commercial loads?

$$Dep_{d,c,v}^{non-res} = Arr_{d,c,v}^{res} - \frac{M_{d,c,v}}{S}$$

$$Arr_{d,c,v}^{non-res} = Dep_{d,c,v}^{res} + \frac{M_{d,c,v}}{S}$$

average urban driving speed
25 mph

Impact of PHEVs in distributed resource islands

- By now we know:
 - ❖ **Size** and **design** characteristics of the PHEV fleet
 - ❖ **Daily energy** required per vehicle from the grid
 - ❖ Daily available **time** for charging per vehicle

DETERMINE DAILY CHARGING PATTERNS:
Utility peak shaving using LP algorithms

Impact of PHEVs in distributed resource islands

- Mathematical formulation of the LPs
 - Sets:

- ❖ I = set of **load types**, from $1 \dots N^I$
- ❖ C = set of **PHEV classes**, from $1 \dots N^C$
- ❖ V = set of **PHEVs** per class, from $1 \dots N^V$
- ❖ D = set of **days** in a year, from $1 \dots N^D$
- ❖ T = set of **hours** in a day, from $1 \dots N^T$

Impact of PHEVs in distributed resource islands

- Mathematical formulation of the LPs

- Parameters:

❖ B_c = **Battery size** per vehicle class c [kWh]

❖ $DE_{d,c,v}$ = **Daily energy** required per day d , vehicle class c and vehicle v [kWh]

❖ $A_{d,c,v}$ = **Daily arrival time** per day d , vehicle class c and vehicle v [h]

❖ $D_{d,c,v}$ = **Daily departure time** per day d , vehicle class c and vehicle v [h]



From the Probabilistic Simulation Methodology

Impact of PHEVs in distributed resource islands

- Mathematical formulation of the LPs

- Parameters:

❖ C_c^{max} = Maximum hourly **charge rate** per vehicle class c [kW]

❖ $L_{d,i,t}^{base}$ = **Base load** (without PHEVs) on day d , load type i and hour t [kW]

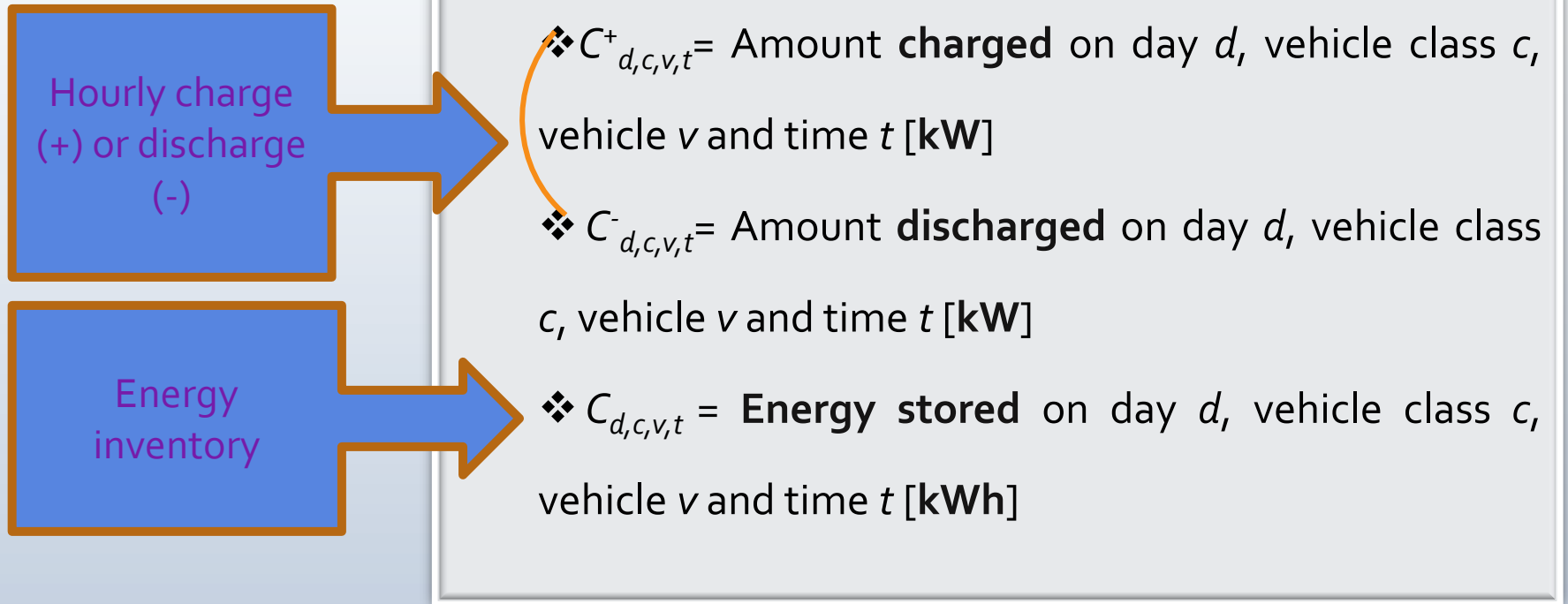
❖ $L_{d,i}^{av}$ = **Average base load** (without PHEVs) on day d and load type i [kW]

❖ $P_{d,t}$ = **Price of energy** on day d and hour t [\$/kWh]

Impact of PHEVs in distributed resource islands

- Mathematical formulation of the LPs

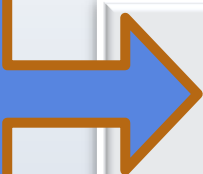
- Variables:



Impact of PHEVs in distributed resource islands

- Mathematical formulation of the LPs
- Variables:

If positive, a change in the direction of power in the battery



❖ $W_{d,c,v,t}^+$ = Absolute value of the difference between $C_{d,c,v,t}^+$ and $C_{d,c,v,t+1}^+$ [kW]

❖ $L_{d,i,t}$ = New load on day d , load type i and hour t [kW]

❖ $Z_{d,i,t}$ = Absolute value of the difference between $L_{d,i,t}$ and $L_{d,i}^{av}$ [kW]

Impact of PHEVs in distributed resource islands

- Mathematical formulation of the LPs
- Battery constraints:

Limit the charge/discharge to the available connection

$$\begin{aligned} C_{d,c,v,t}^+ &\leq C_c^{\max} \text{ for every } d, c, v, t \\ C_{d,c,v,t}^- &\leq C_c^{\max} \text{ for every } d, c, v, t \end{aligned}$$

Energy in the battery when the PHEV arrives home

$$C_{d,c,v,t} = B_c - DE_{d,c,v} \text{ for } t = A_{d,c,v} - 1 \text{ and every } d, c, v$$

Inventory balance

$$C_{d,c,v,t} = C_{d,c,v,t-1} + C_{d,c,v,t}^+ - C_{d,c,v,t}^- \text{ for } A_{d,c,v} \leq t \leq D_{d,c,v} \text{ and every } d, c, v$$

Battery fully charged by dep. time

$$C_{d,c,v,t} = B_c \text{ for } t = D_{d,c,v} \text{ and every } d, c, v$$

Impact of PHEVs in distributed resource islands

- Mathematical formulation of the LPs
- Battery constraints:

$$-W^+_{d,c,v,t} \leq C^+_{d,c,v,t} - C^+_{d,c,v,t+1} \leq W^+_{d,c,v,t} \text{ for every } d, c, v$$

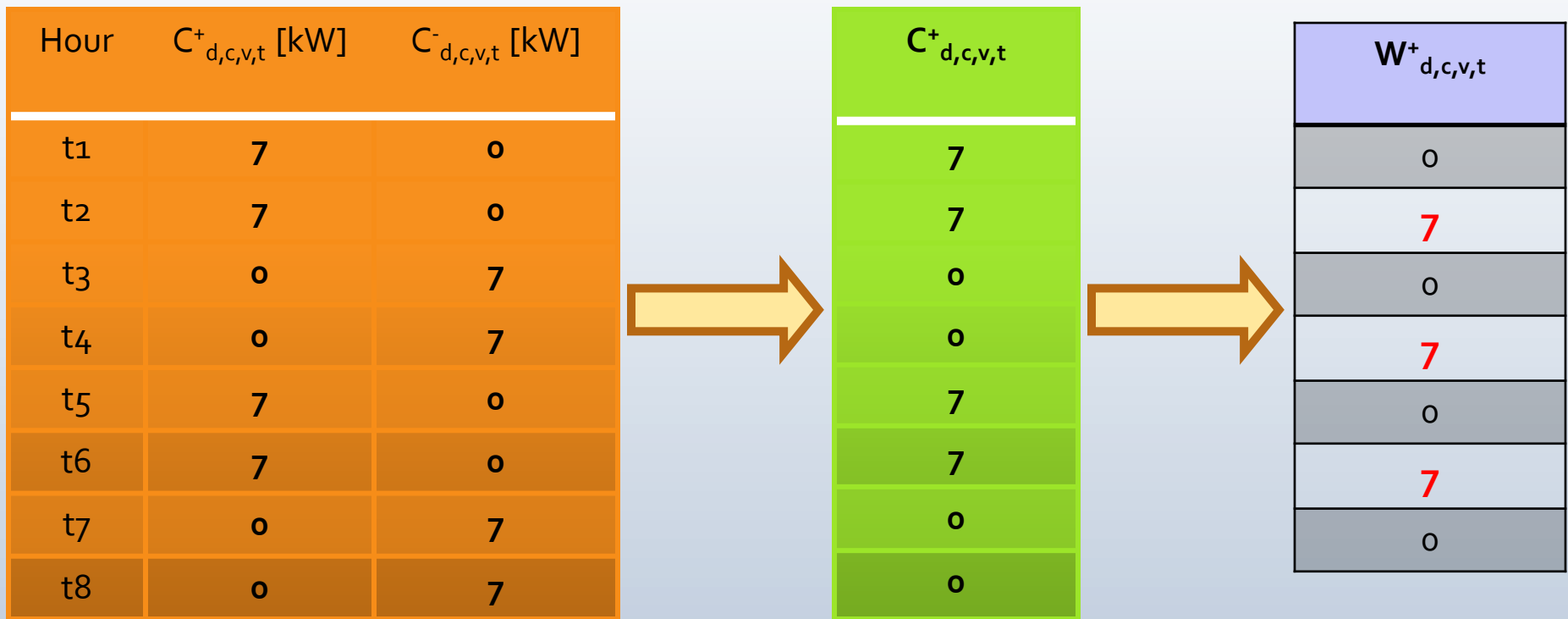
$$A_{d,c,v} \leq t \leq D_{d,c,v} - 1$$

$$\sum W^+_{d,c,v,t} \leq 3 * C^{max}_c \text{ for every } d, c, v$$

$$A_{d,c,v} \leq t \leq D_{d,c,v} - 1$$

Impact of PHEVs in distributed resource islands

$$W^+_{d,c,v,t}?$$



Impact of PHEVs in distributed resource islands

- Mathematical formulation of the LPs
- Load constraints:

New load
with PHEVs

$$L_{d,i,t} = L_{d,i,t}^{Base} - \left(\sum_{v=1}^{N^V} C_{d,c,v,t}^- + C_{d,c,v,t}^+ \right) \text{ for every } d, i, t$$

Peak-
shaving
measure

$$-Z_{d,i,t} \leq L_{d,i,t} - L_{d,i}^{av} \leq Z_{d,i,t} \text{ for every } d, i, t$$

Impact of PHEVs in distributed resource islands

28

Mathematical formulation of the LPs

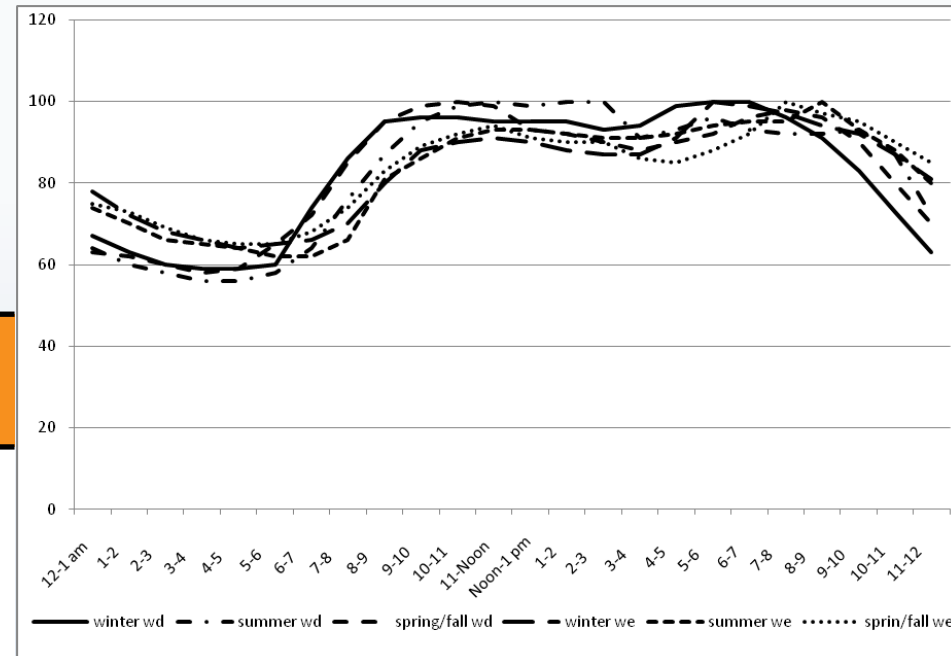
- Objective function: Utility peak-shaving

$$\textit{Peak - shaving} = \textit{Minimize} \left\{ \sum_{d,i,t} Z_{d,i,t} \right\}$$

Measure of deviation
of daily peak load
from average load

Application to a test system - RBTS

Customer Type	Load points i	Average Load, [MW]	Max. Peak Load, [MW]
Residential	1, 4-7, 20-24, 32-36	0.4684	0.8367
Residential	11, 12, 13, 18, 25	0.4758	0.8500
Residential	2, 15, 26, 30	0.4339	0.7750
Small Industrial	8, 9, 10	0.8472	1.0167
Commercial	3, 16, 17, 19, 28, 29, 31, 37, 38	0.2886	0.5222
Office Buildings	14, 27	0.5680	0.9250



Application to the RBTS test system

Day	% Annual Peak Load
Monday	93
Tuesday	100
Wednesday	98
Thursday	96
Friday	94
Saturday	77
Sunday	75

Week	Peak Load	Week	Peak Load	Week	Peak Load	Week	Peak Load
1	82.2	14	75	27	75.5	40	72.4
2	90	15	72.1	28	81.6	41	74.3
3	87.8	16	80	29	80.1	42	74.4
4	83.4	17	75.4	30	88	43	80
5	88	18	83.7	31	72.2	44	88.1
6	84.1	19	87	32	77.6	45	88.5
7	83.2	20	88	33	80	46	90.9
8	80.6	21	85.6	34	72.9	47	94
9	74	22	81.1	35	72.6	48	89
10	73.7	23	90	36	70.5	49	94.2
11	71.5	24	88.9	37	78	50	97
12	72.7	25	89.6	38	69.5	51	100
13	70.4	26	86.1	39	72.4	52	95.2

Impact of PHEV fleet penetration on islanded distribution systems

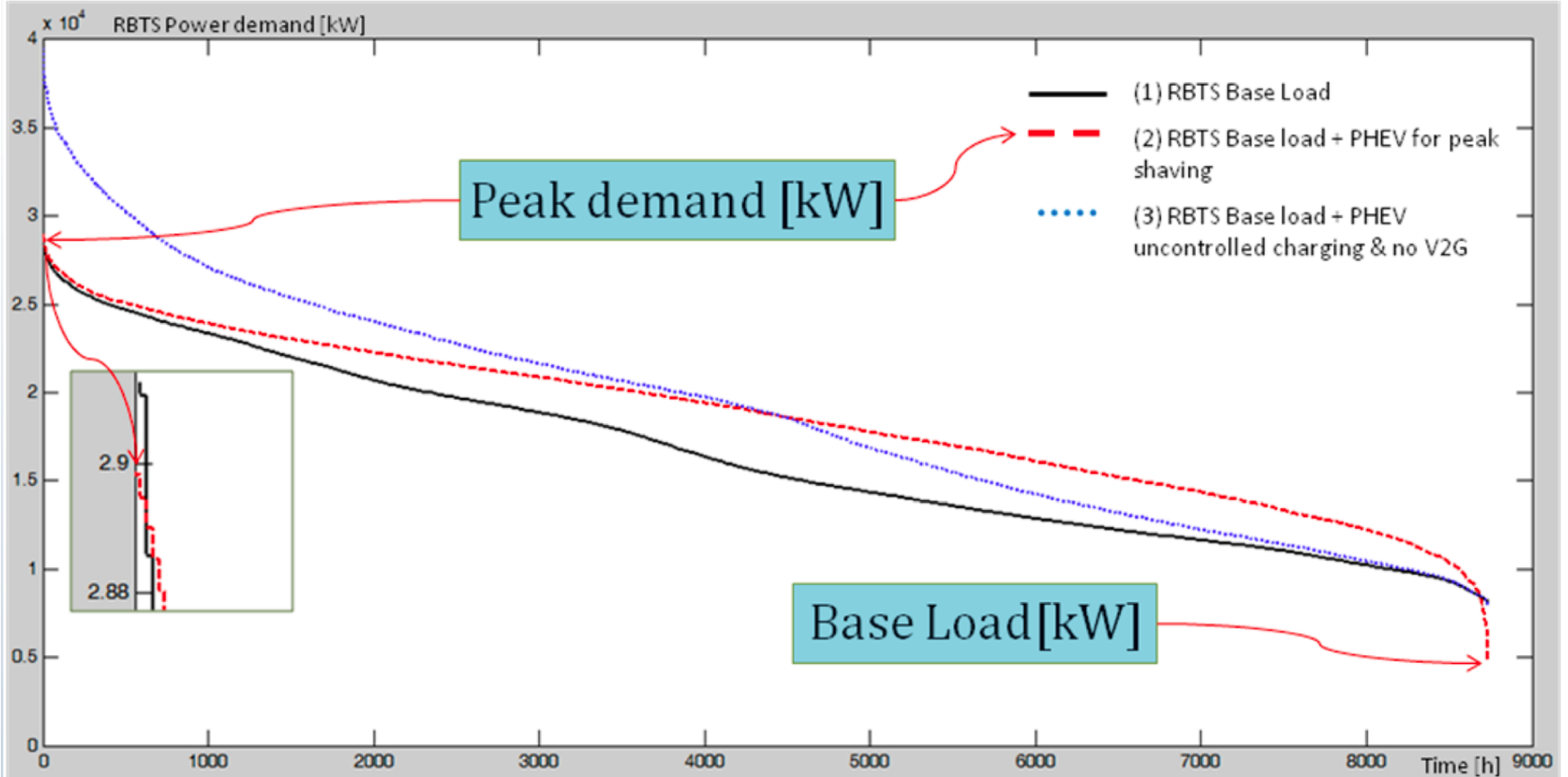
Probabilistic Sim. Meth. applied to the RBTS test system – From Meliopoulos, et al.

Vehicles per class: normal distribution with mean $\#PHEVs * Probability \text{ vehicle class}$ and 1% standard deviation

- **Total # vehicles (light transportation fleet):** 15, 269 = 14,925 res + 230 com+ 114 off
- **Uniform distribution of the #PHEVs throughout the load points of the RBTS per demand type~ daily parameters generated only for the #PHEVs in one load type~**
- **Vehicle population size per class:**

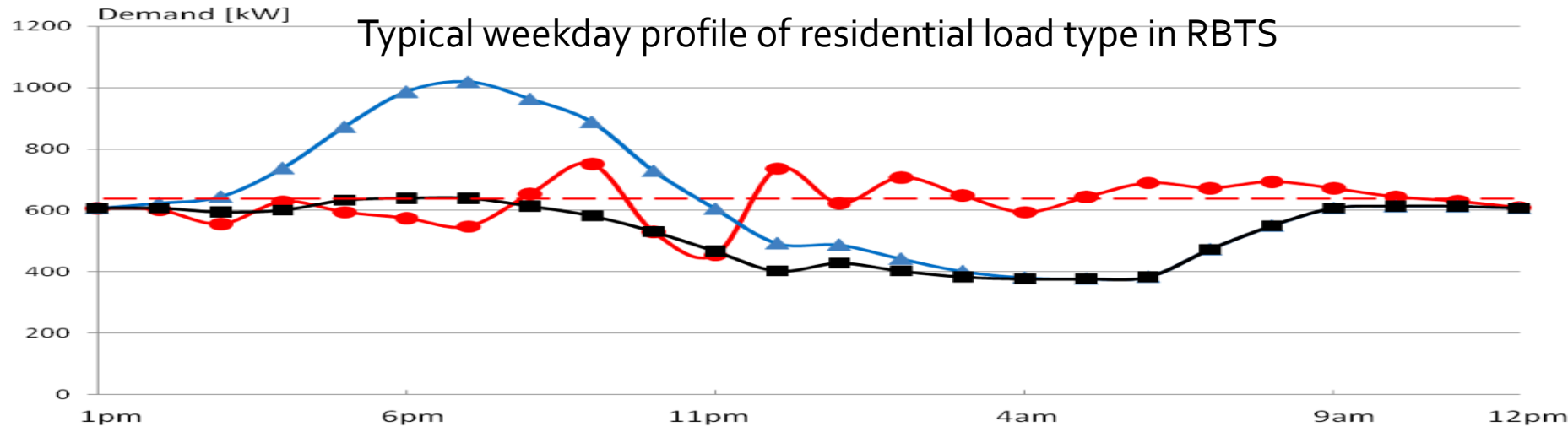
Vehicle class <i>c</i>	Vehicles per load point type		
	Residential	Commercial	Office building
1	44	15	7
2	48	18	9
3	45	14	6
4	49	19	8

Results

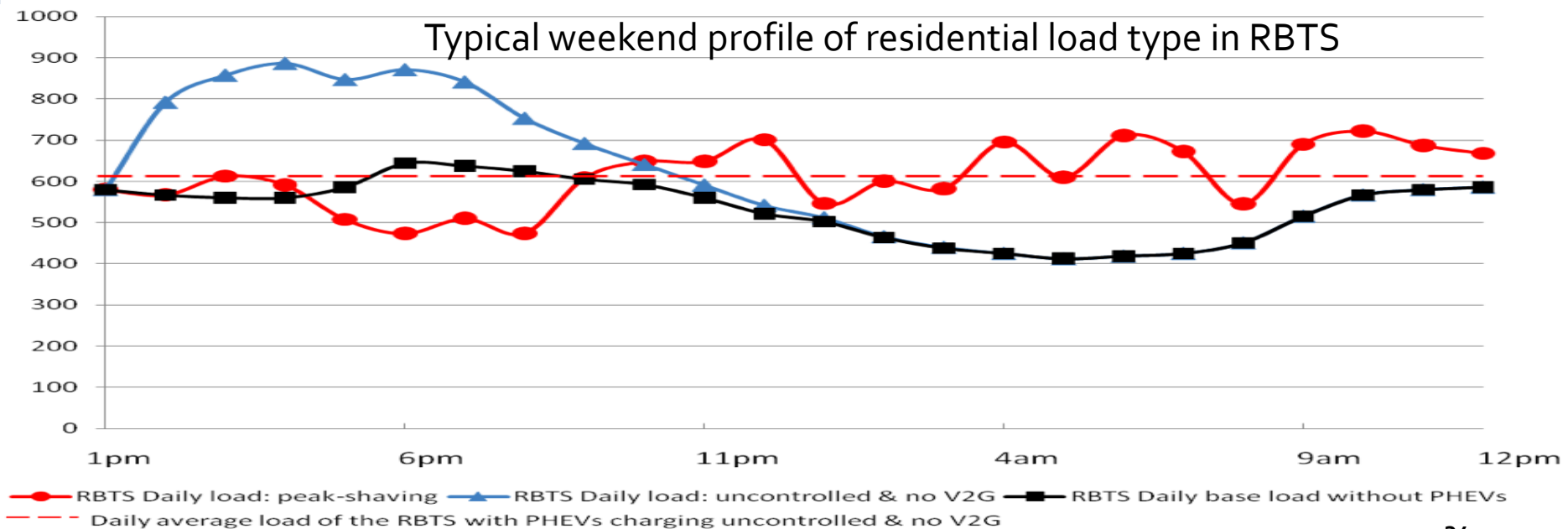


Results

Typical weekday profile of residential load type in RBTS

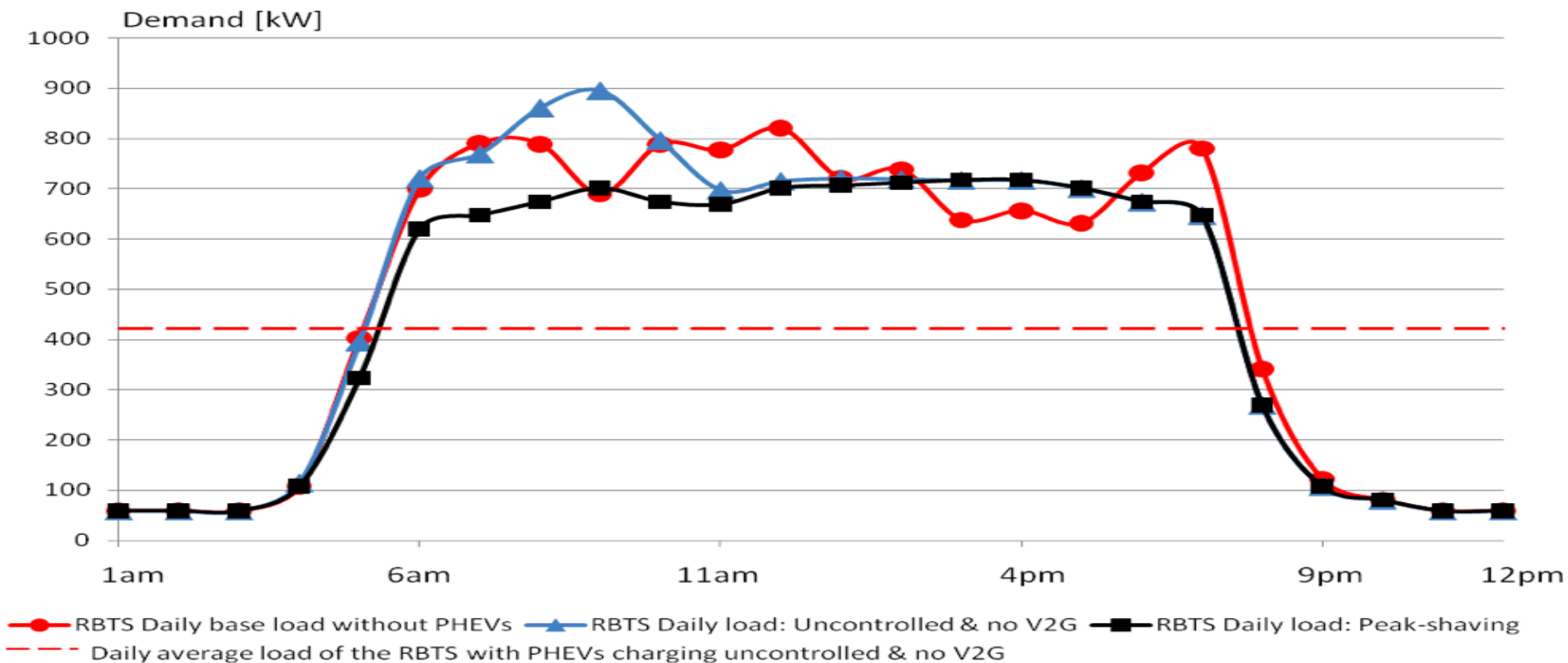


Typical weekend profile of residential load type in RBTS



Results

Typical weekday profile of non-residential load type in RBTS



Concluding remarks

- A linear programming based charging algorithm for PHEVs with V2G is examined
- Impact on distributed resource island is quantified for peak-shaving purposes
- Initial results on a test system indicate increased energy consumption (expected) but corresponds to valley-filling (peak is conserved)
- Impact based on owner benefit using ToU pricing is to be investigated
 - Nash equilibrium?
- Comprehensive study of PHEV penetration may include:
 - Economic impact of high fuel efficiency
 - Rate structure for utility and aggregators

Acknowledgments

- Graduate student
 - Ms. Julieta Giráldez (CSM, NREL)
- Funding sources
 - PSERC T-41
 - Project wiki: <http://pserc-smart-dsys.pbworks.com/w/page/19551292/FrontPage>