System integration and grid simulation for ancillary services in V2X (Vehicle-to X: X=home, buildings and grid) applications

Yoo, Yeong; Liang, Qi; Tchagang, Alain

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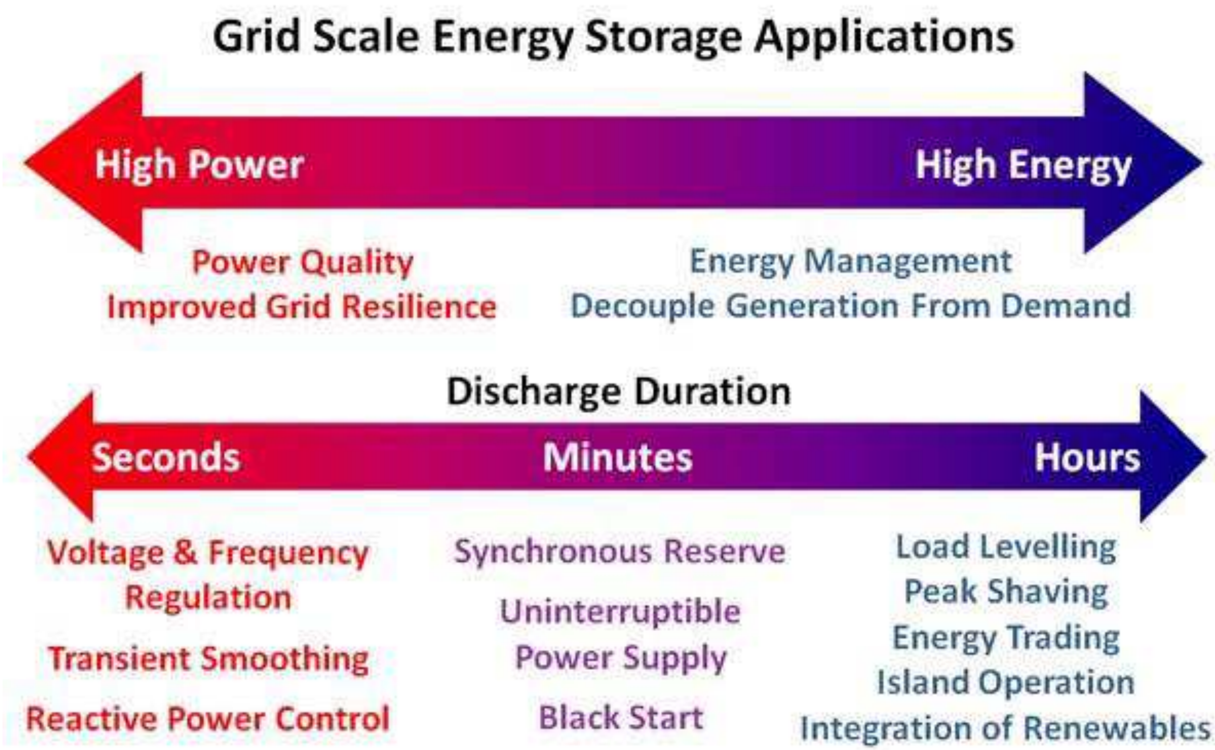
Contents

Introduction

- The Canadian Government has set a target of reducing Greenhouse Gas (GHG) emissions by 30% in 2030 compared to emission levels in 2005.
- The transportation sector is responsible for 23% of energy related GHG emissions.
- EVs can significantly reduce transportation emissions in Canada.
- The global EV market share is expected to be 54% of new car sales and 33% of the global car fleet by 2040.
- V2X (X=home, buildings and grid) may create an additional stream of revenue for EV owners, enabling much faster adoption of EVs and earlier realization of large environmental benefits in Canada.

Introduction:
Why is Energy Storage needed?



Ref.: Electropaedia, Battery and Energy Technologies

- Energy storage has been successfully deployed to improve the technical and economic performance and the flexibility and resilience of the electricity grid.

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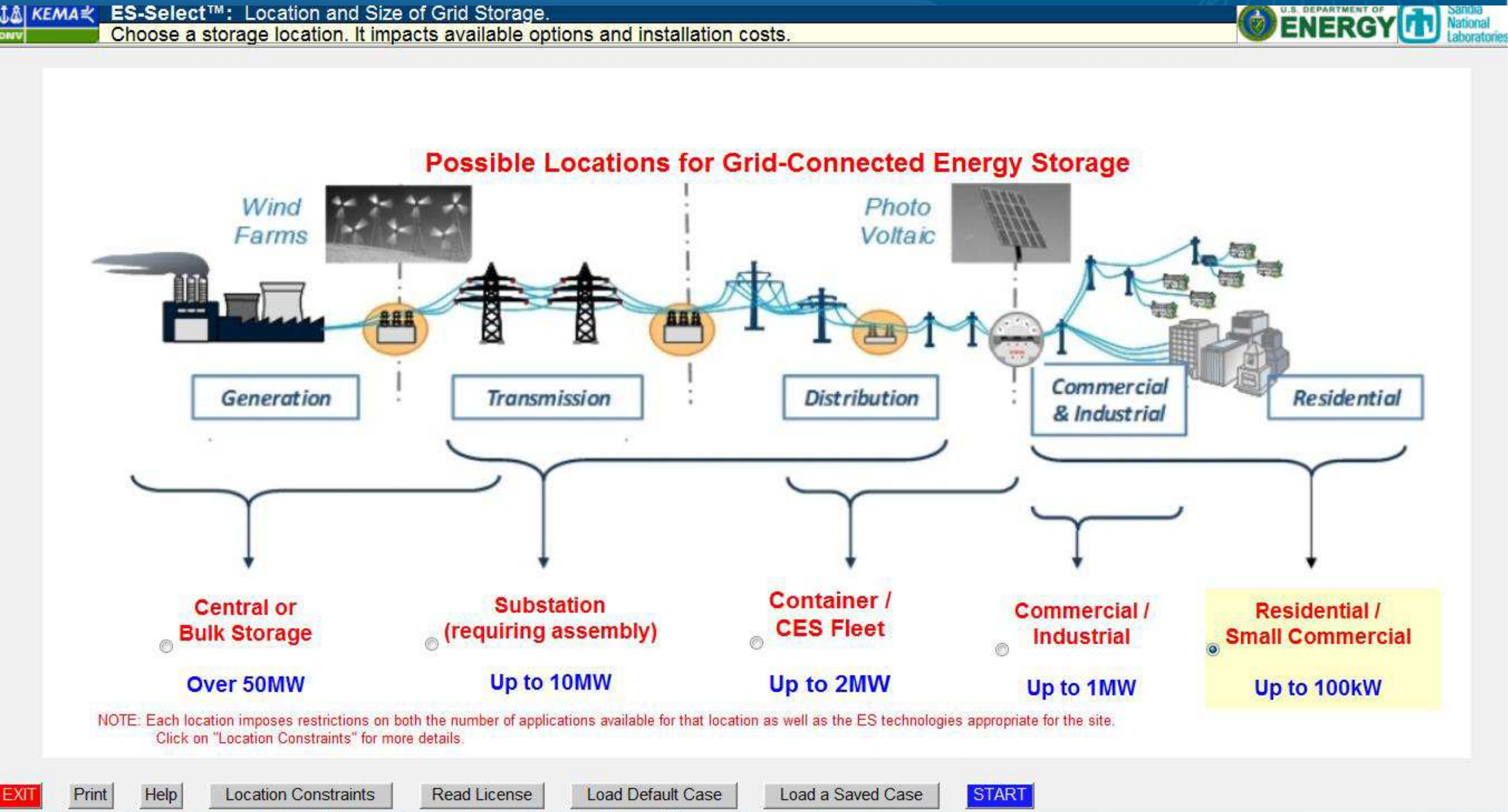
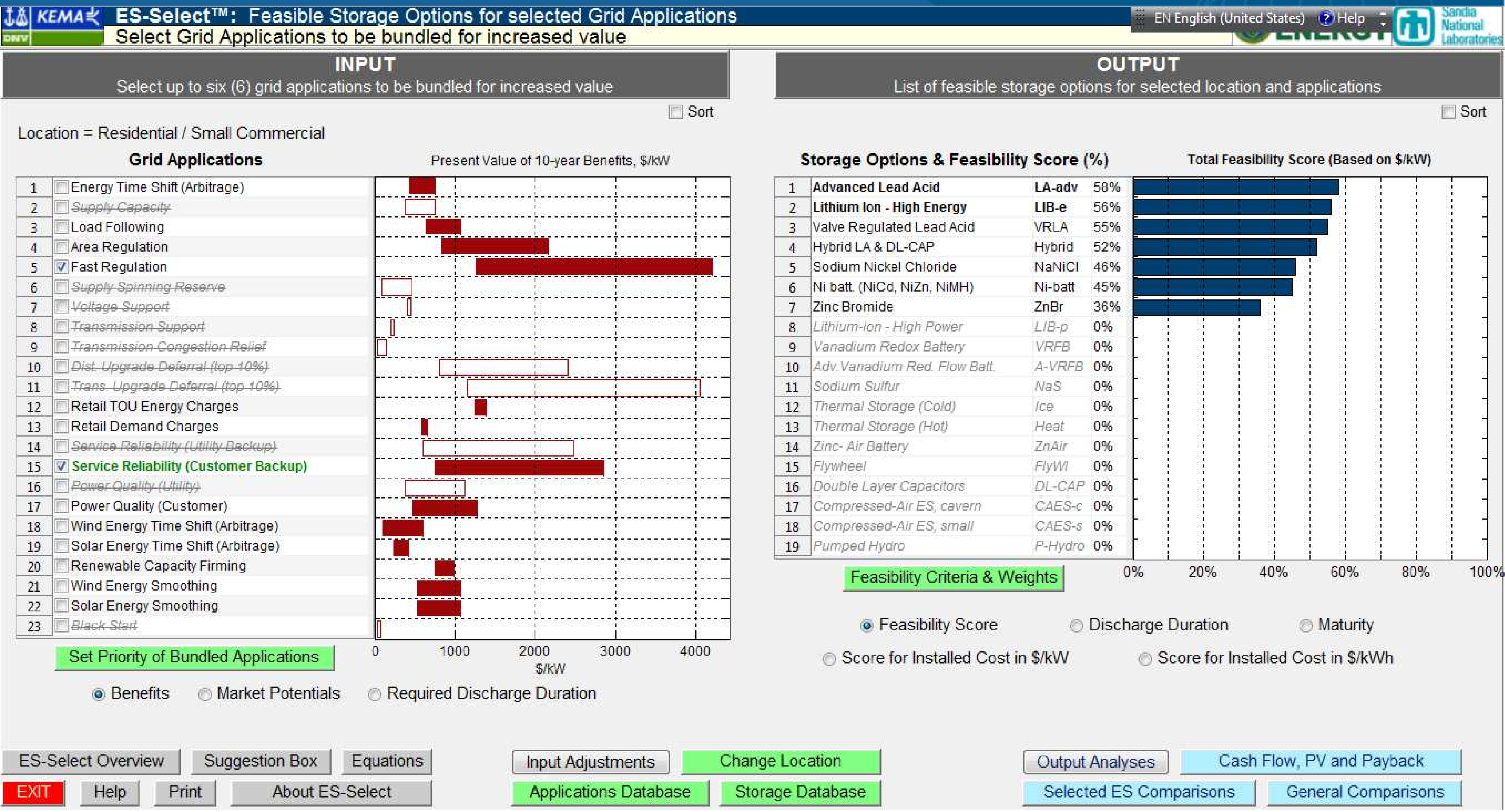
Introduction:
Grid-Connected Energy Storage



Ref.: ES-Select, DNV KEMA

Introduction: Grid Applications



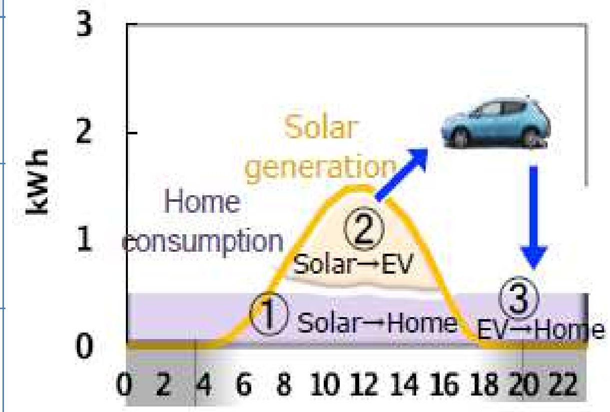
Ref.: ES-Select, DNV KEMA

Introduction:
Vehicle-to-X (X= Home, Buildings and Grid)

EVSE	Power Flow	kW	Operation	Purpose
Electric Vehicle Supply Equipment: **Bi-directional**	⟷	5-10	Vehicle to Home (V2H)	• Emergency power • RE storage • TOU rate arbitrage
	⟷	10-15	Vehicle to Building (V2B)	• Demand charge avoidance • Emergency power
	⟷	15-30	Vehicle to Grid (V2G)	• Wholesale power market participation

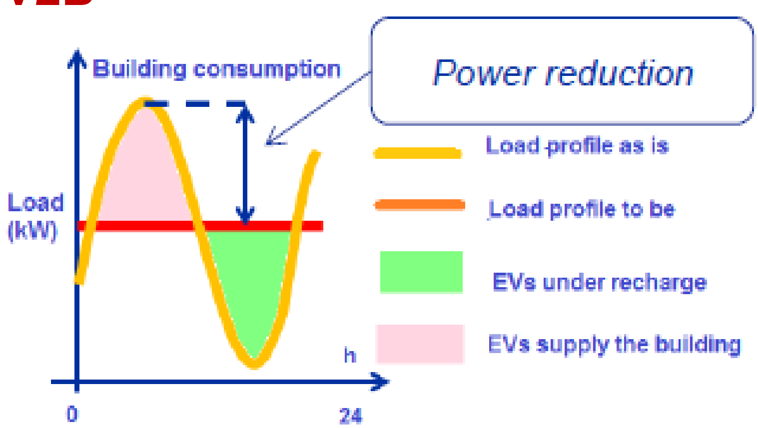
Source: Nissan Motor Company

V2H



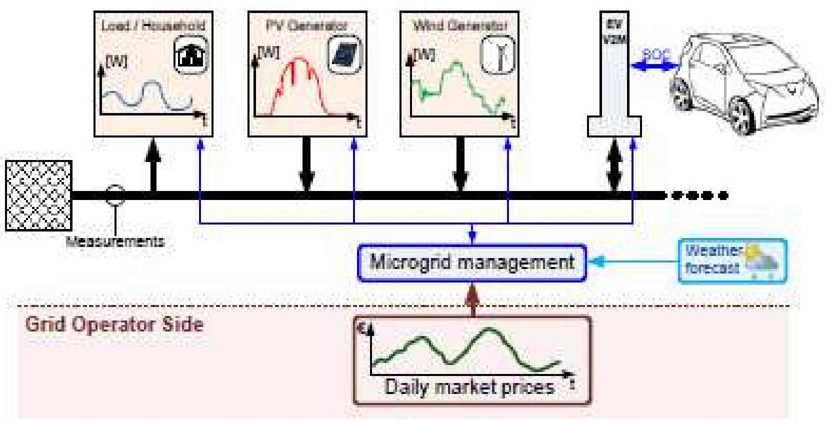
Source: Nissan Motor Company

V2B



Source: Enel

V2G



Source: IREC

System Integration: Field Trial at CCHT facilities

- ✓ The Canadian Centre for Housing Technology features twin research houses to evaluate the whole-house performance of new technologies in side-by-side testing
- ✓ New leading-edge low-rise multi-unit residential building to be *smart-homes* to respond to client needs for R&D services and testing in the following areas: mechanical equipment, renewable energy & control systems, and intelligent building and smart grid integration technologies

CCHT Twin-House

CCHT Renewal

System Integration:
Nissan Leaf 2018 for V2X at CCHT Flexhouse

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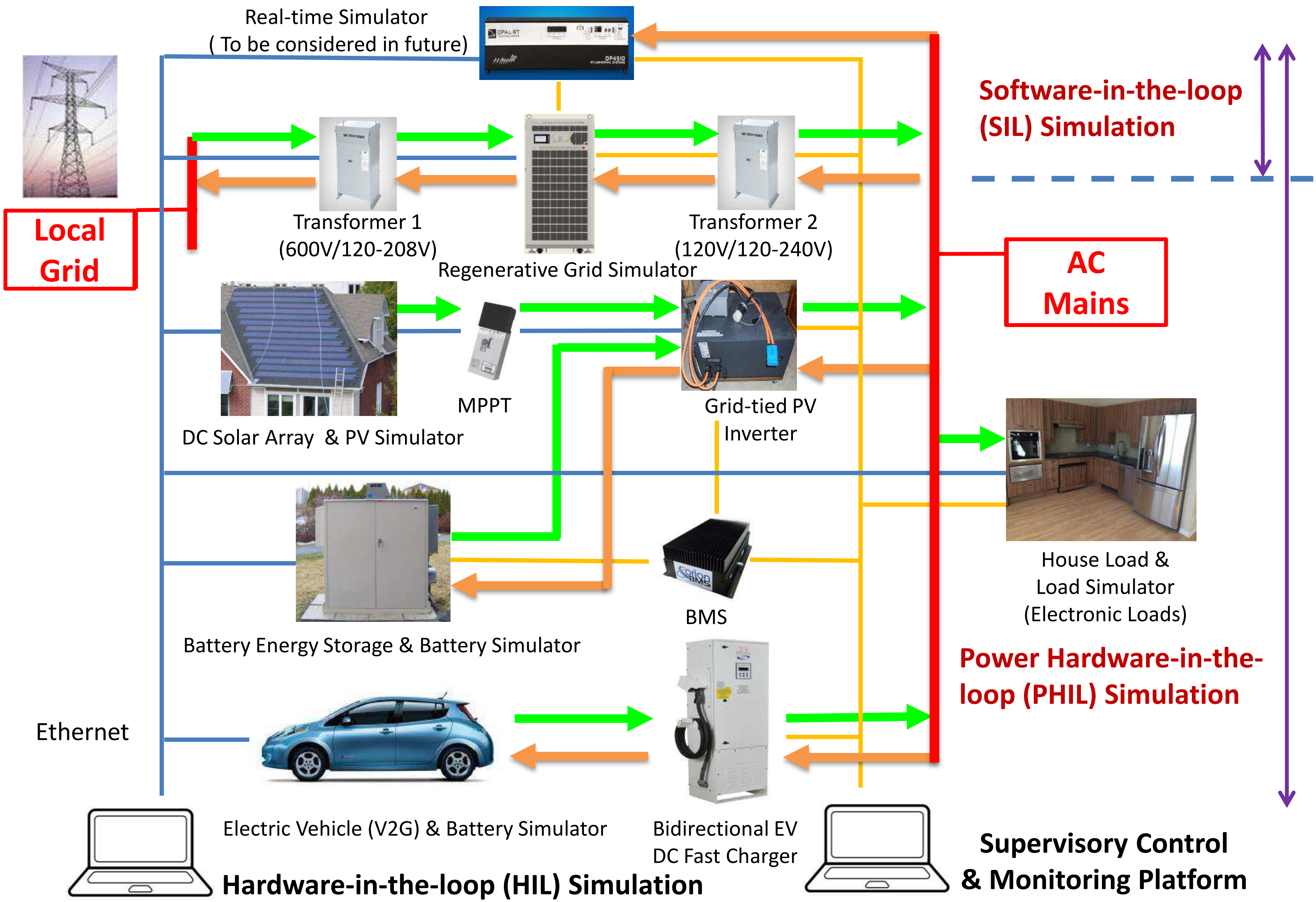
Conceptual design of a validation system based on PHIL simulation for V2X



System Integration: V2X Testing Protocols

1. Grid interconnection tests

- Unintentional islanding and Harmonics etc.

2. Grid support or function tests

- Frequency regulation and Volt-VAR regulation etc.

3. V2G performance tests

- Conversion efficiency (roundtrip efficiency) and available energy capacity etc.

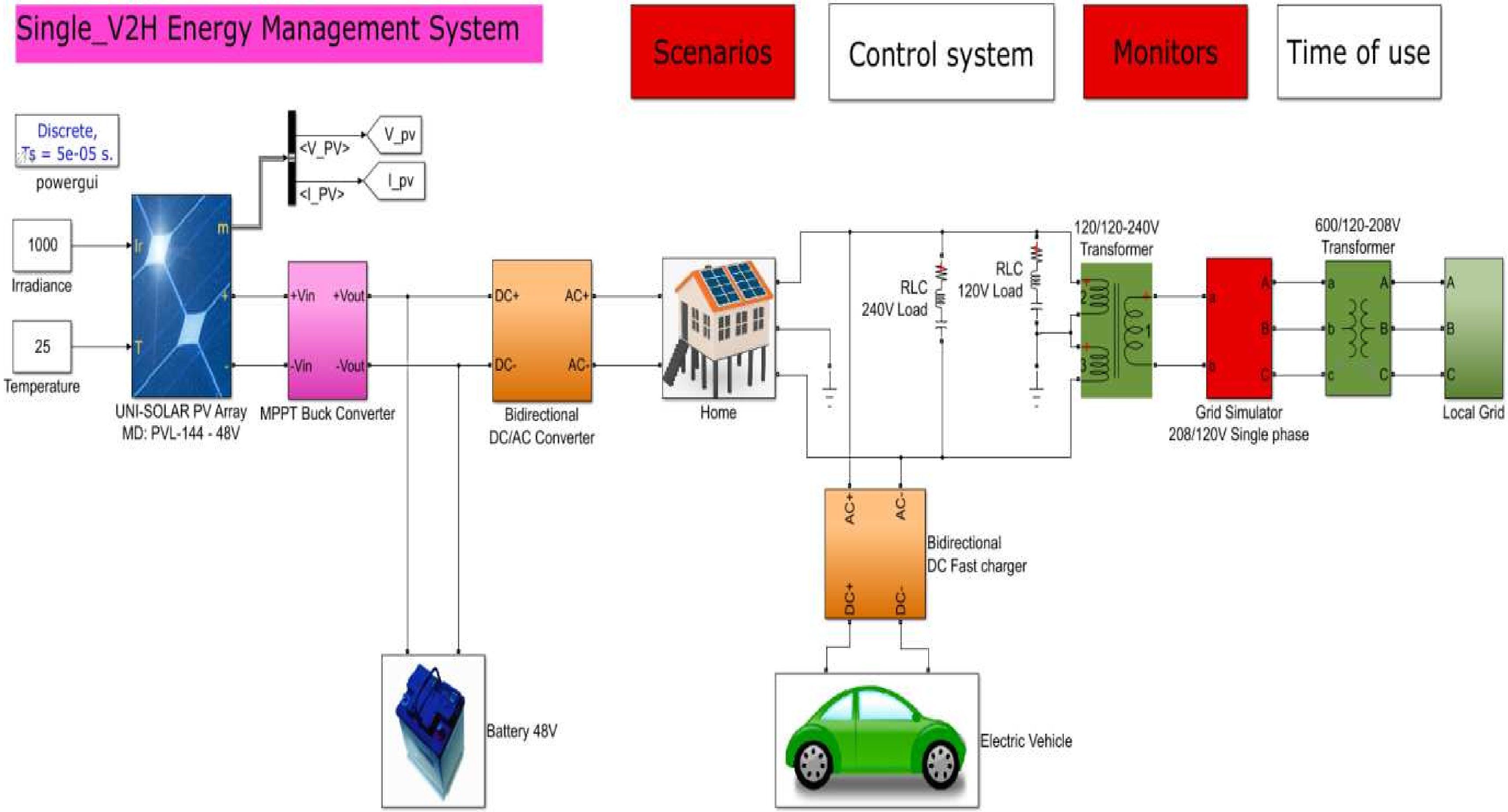
4. V2H/V2B tests

- Load back-up (DCFC) and PV charging test etc.

5. Measurements

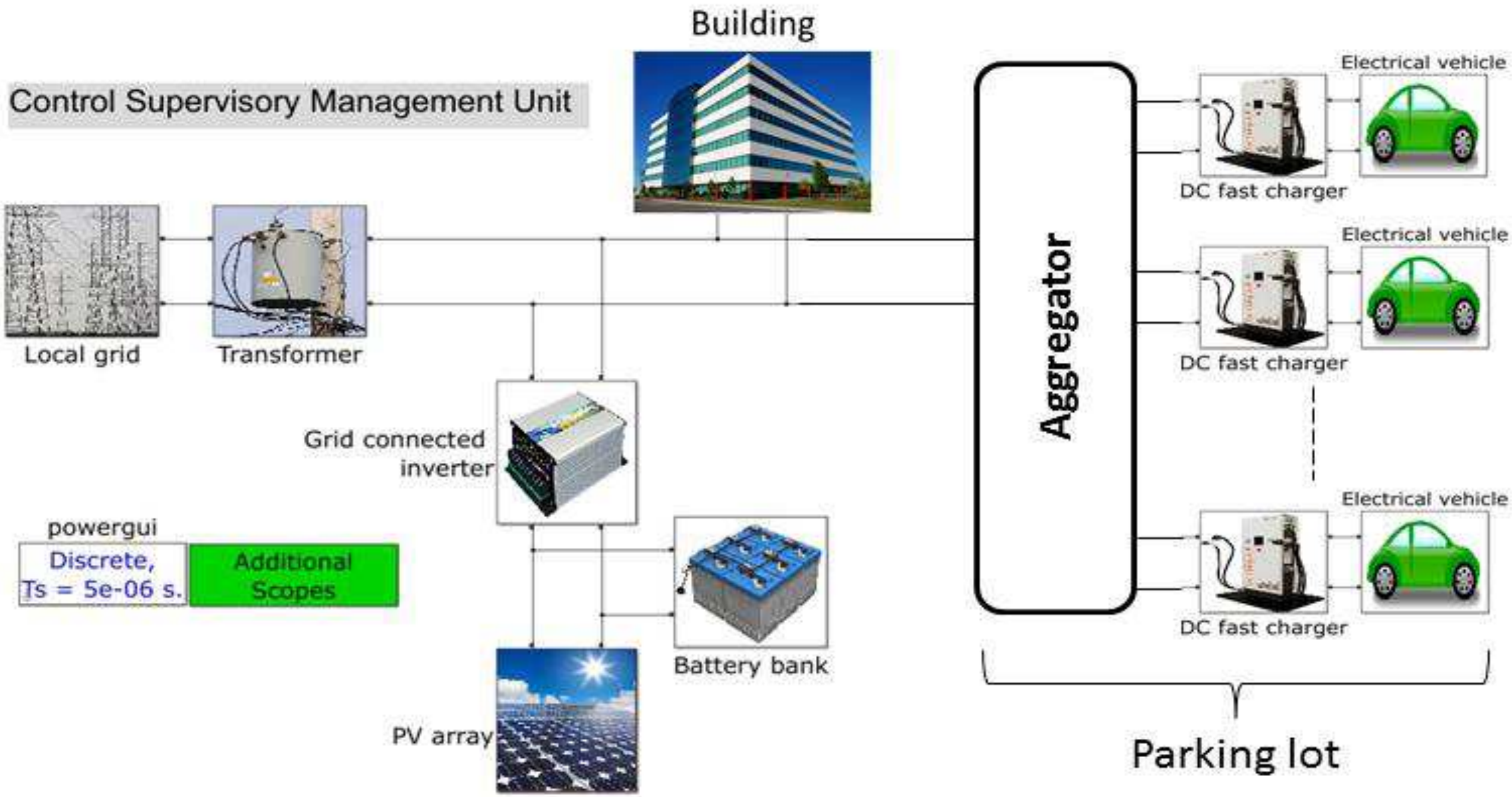
- Power analyzer, grid simulator, load simulator, and DCFC

Modeling and Simulation for V2H



Simulink model for V2H simulation

Modeling and Simulation for V2B/V2G



Simulink model for V2B/V2G simulation

Vehicle-to-building/Grid (V2B/V2G)

- Proactively manage energy consumption and costs of buildings using the energy stored in EVs
- Potential benefits to both vehicle and building owners by offsetting some of the higher cost of EVs, lowering buildings' energy costs, and providing reliable emergency backup services
- Part of microgrid and smart grid technologies
- Being integrated with renewable energy generation, smart buildings, EV bidirectional charging, and in some cases, stationary backup storage
- Market opportunities including demand charge avoidance, peak shaving, time-of-use pricing, ancillary services, and other utility energy pricing schemes, reducing the cost of building operations and providing emergency backup power

Simulation for V2B/V2G with ancillary services: Objectives and Methodologies

- Goal: To use electrical energies from EV batteries for peak shaving and frequency regulation in a vehicle-to-building/grid (V2B/V2G) technology
- Proposed Approach: Multi-objective optimization framework for EV batteries to perform 1) load management (building load and driving), 2) peak shaving, and 3) frequency regulation services
- This framework accounts for 1) battery degradation, 2) operational constraints, and 3) uncertainties in customer loads, driving profiles and regulation signals.

Simulation for V2B/V2G with ancillary services: Objectives and Methodologies

❖ Utilization of published models on stationary battery storage for V2B/V2G simulation application:

➔ Y. Shi, B. Xu, D. Wang, B. Zhang, "*Using battery storage for peak shaving and frequency regulation: joint optimization for super linear gains*" arXiv: 1702.08065v3, 2017.

➔ Published models: Electricity bill calculation, peak shaving, frequency regulation, and battery degradation

Simulation for V2B/V2G: Electricity Bill Calculation

- Bill calculation for an industrial building or a commercial unit

$$H = H^{elec} + H^{peak} = \alpha_{elec} \sum_{t=1}^{T} r(t) + \alpha_{peak} r_{Peak}(t)$$

where, α_{elec} (\$/MWh): energy price, r(t): power consumed at t,

α_{peak} (\$/MW): peak demand price, $r_{peak}(t)$: power consumed at t over 15 or 30 minutes

➔Electricity Bill: Summation of **energy charge** and **peak demand charge**

- Energy vs. Power Demand

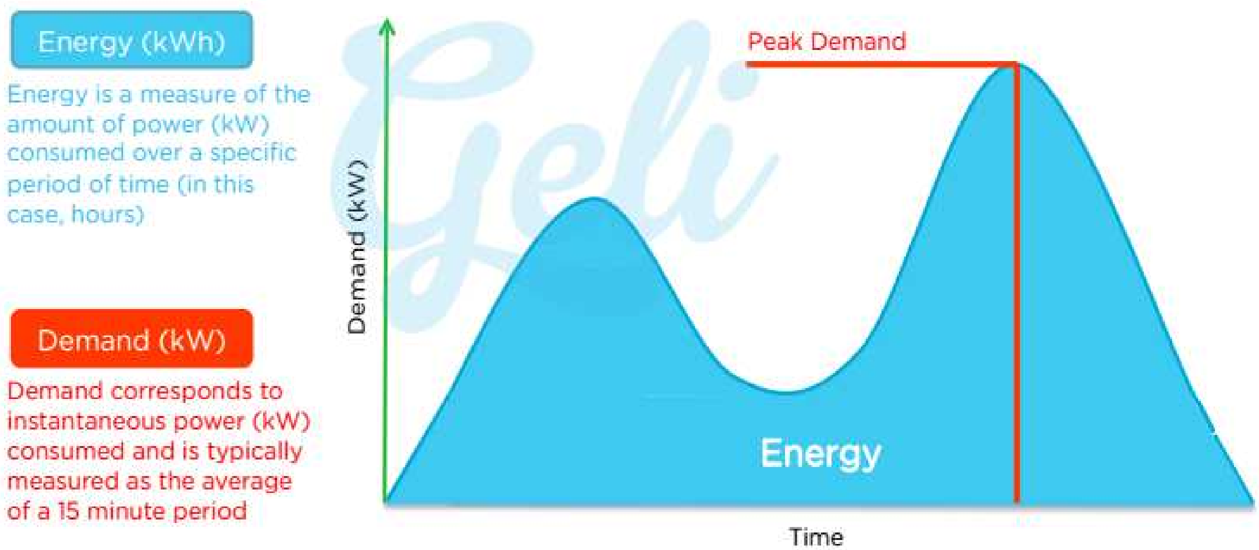


Image courtesy of Geli.

Electricity Bill Calculation: Peak Shaving

- Peak shaving

$$H = H^{elec} + H^{peak} = \alpha_{elec} \sum_{t=1}^{T} r_a(t) + \alpha_{peak} r_{peak}^{a}(t) + \sum_{n=0}^{N} f(\mathbf{b_n})$$

$$r_a(t) = r(t) - \sum_{n=0}^{N} b_n(t) \qquad r_{peak}^{a}(t) = r_{peak}(t) - \sum_{n=0}^{N} \bar{b}_n(t)$$

where, $b_n(t)$: power injected by n^{th} MBESS (i.e. batteries of the n^{th} EV; stationary batteries power in case of n=0),

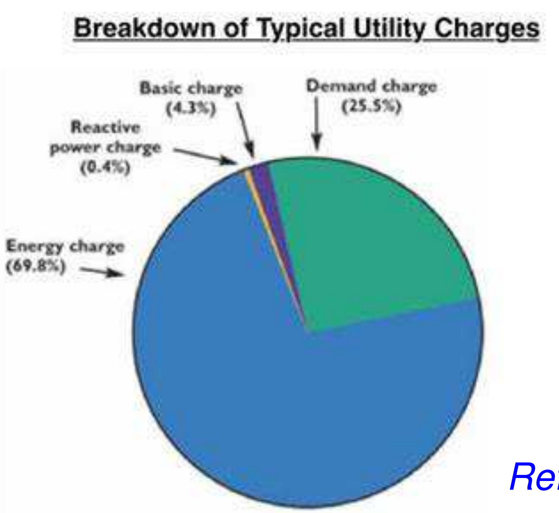
$b_n(t) > 0$ for discharging, $b_n(t) < 0$ for charging,

$r_a(t)$: actual power drawn from the grid at a given time t,

$r_{peak}^{a}(t)$: residual peak demand power

$\bar{b}_n(t)$: averaged power injected by n^{th} MBESS,

$f(\mathbf{b_n})$: operating cost of n^{th} MBESS.



➔ **Demand charges** make up a significant portion of commercial and industrial customers' total electricity costs, typically between **20** and **70 percent**.

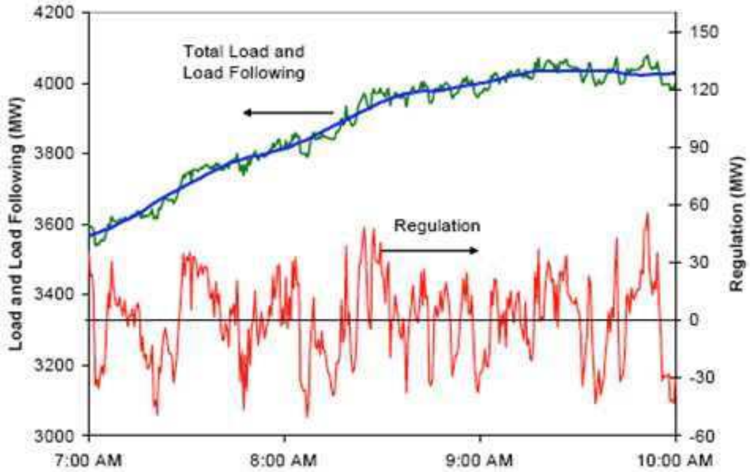
Ref.: SunnyCal Solar

Electricity Bill Calculation: Frequency Regulation

- Frequency regulation

$$S = \alpha_c C.T - \alpha_{\min} \sum_{t=1}^{T} \left| \sum_{n=0}^{N} b_n(t) - Cs(t) \right| - \sum_{n=0}^{N} f(\mathbf{b}_n),$$

where, S: revenue to provide frequency regulation service over time T (in PJM market),
s(t): normalized frequency regulation signal,
α_c: benefit from frequency regulation in $/MW,
α_{min}: penalty cost for frequency regulation in $/MWh,
C: total battery power capacity,
Cs(t): demand frequency regulation energy
$f(\mathbf{b}_n)$: operating cost of n^{th} MBESS.



Ref.: "[Frequency Regulation Basics and Trends]" (December 2004), Oak Ridge National Laboratory

- Smooth blue line: Load ramp up from 3,600 MW to 4,000 MW over a three-hour period from 7 to 10 a.m.
- Jagged green line: Actual demand during the same time period
- Very jagged red line at the bottom: Scaled up representation of the minute-to-minute differences between the blue supply line and the green demand line

➔ The 60 MW slice of highly variable demand is the domain of frequency regulation.

Electricity Bill Calculation: Battery Degradation

- Battery degradation/cost

$$f(\text{[redacted]}) = \frac{\alpha_{cell}^{n}.10^{6}}{2K_{n}.(SoC_{\max}^{n} - SoC_{\min}^{n})} |b_{n}(t)|$$

where, f($\mathbf{b_n}$): operating cost of n^{th} MBESS mainly resulting from battery degradation,

α_{cell}^{n} : n^{th} MBESS cell price ($/Wh),

K_n: number of cycles of n^{th} MBESS,

$SoC_{\max}^{n}$: max. state of charge of n^{th} MBESS,

$SoC_{\min}^{n}$: min. state of charge of n^{th} MBESS.

Optimization Scheme and Control Algorithm: Multi-Objective Optimization Model

$$H^{multi} = \min_{C,b^{ch}(t),b^{dc}(t),y(t)} \alpha_{elec} \sum_{t=1}^{T} E_s[r(t) - \sum_{n=0}^{N} b_n(t)]$$

$$+\alpha_{peak} \max_{t=1...T} E_s[\overline{r}(t) - \sum_{n=0}^{N} \overline{b}_n(t)] + \sum_{t=1}^{T}\sum_{n=0}^{N} f(b_n(t))$$

$$-E_{rs}[\lambda_c T.C - \lambda_{\min} \sum_{t=1}^{T} | -r(t) + \sum_{n=0}^{N} b_n(t) + y(t) - Cs(t) |]$$

s.t. $b_n(t) = b_n^{dc}(t) - b_n^{ch}(t)$,

$C \geq 0$,

$$SoC_{\min}^{n} \leq \frac{SoC_{ini}^{n} + \sum_{\tau=1}^{t}[b_n^{ch}(\tau)\eta_c - \frac{b_n^{dc}(\tau)}{\eta_d}]t_s}{E} \leq SoC_{\max}^{n} \quad ,$$

$0 \leq b_n^{ch}(t) \leq P_{\max}$,

$0 \leq b_n^{dc}(t) \leq P_{\max}$, for n = 0 to N,

$f($[redacted]$) = \frac{\alpha_{cell}^{n} .10^6}{2K_n.(SoC_{\max}^{n} - SoC_{\min}^{n})} |b_n(t)|$

➔ C: frequency regulation capacity; y(t): frequency regulation load baseline

Simulation for V2B/V2G: Problem Formulation

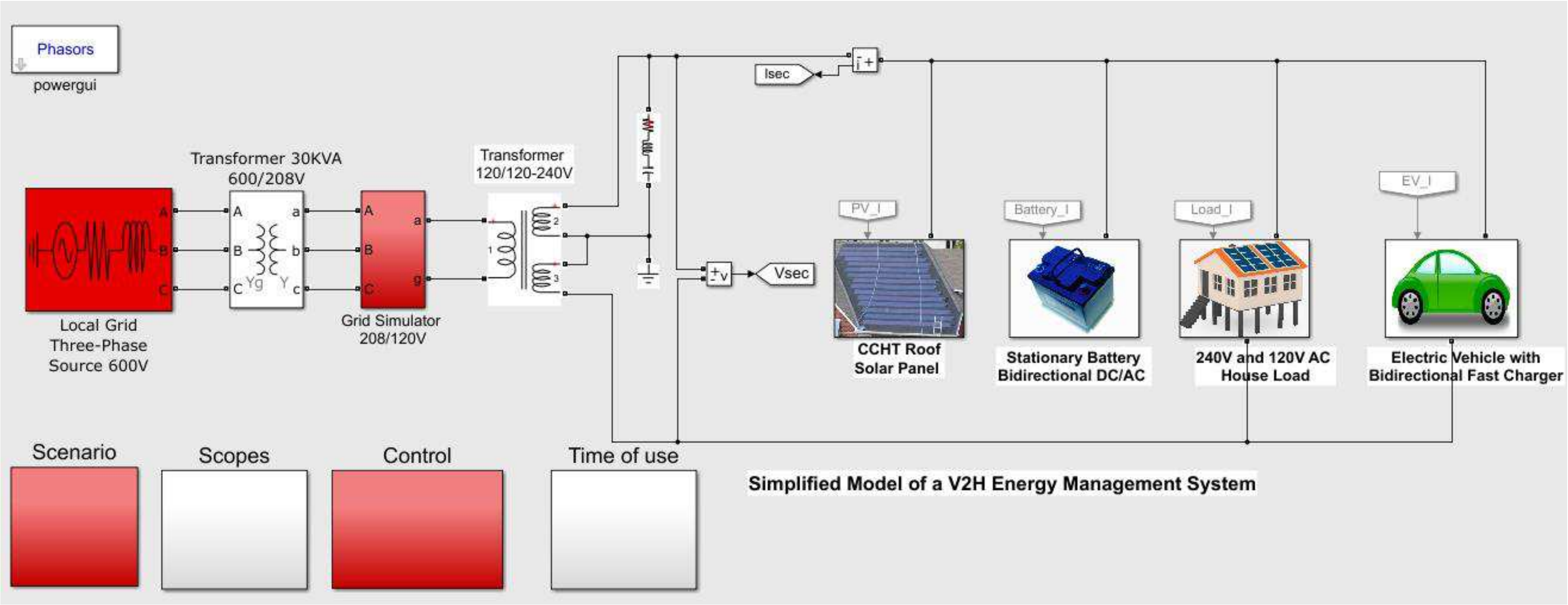
- Assumption: A small residential building or commercial unit with an electricity consumption of 70 kWh/day and 5 EVs having a battery storage capacity of 24 kWh per EV
- Simulation: Battery degradation and electricity bill estimation
- Objectives of this work:
  1) To reduce the total energy cost H,
  2) To find the SoC optimal range to reduce battery degradation rate,
  3) To provide building load supply when necessary,
  4) To utilize EV batteries for EV powertrain, peak shaving and frequency regulation simultaneously.

Optimization Scheme and Control Algorithm: Multi-Objective Optimization

- Goals → use EV battery to provide
  - Peak Shaving for building owner
  - Frequency regulation as an ancillary service for building owner
  - Load management (house load and driving) for EV owner
- While
  - Minimizing the electricity bill of building owner
  - Minimizing the electricity bill of EV owner
  - Minimizing the degradation of EV battery for EV owner

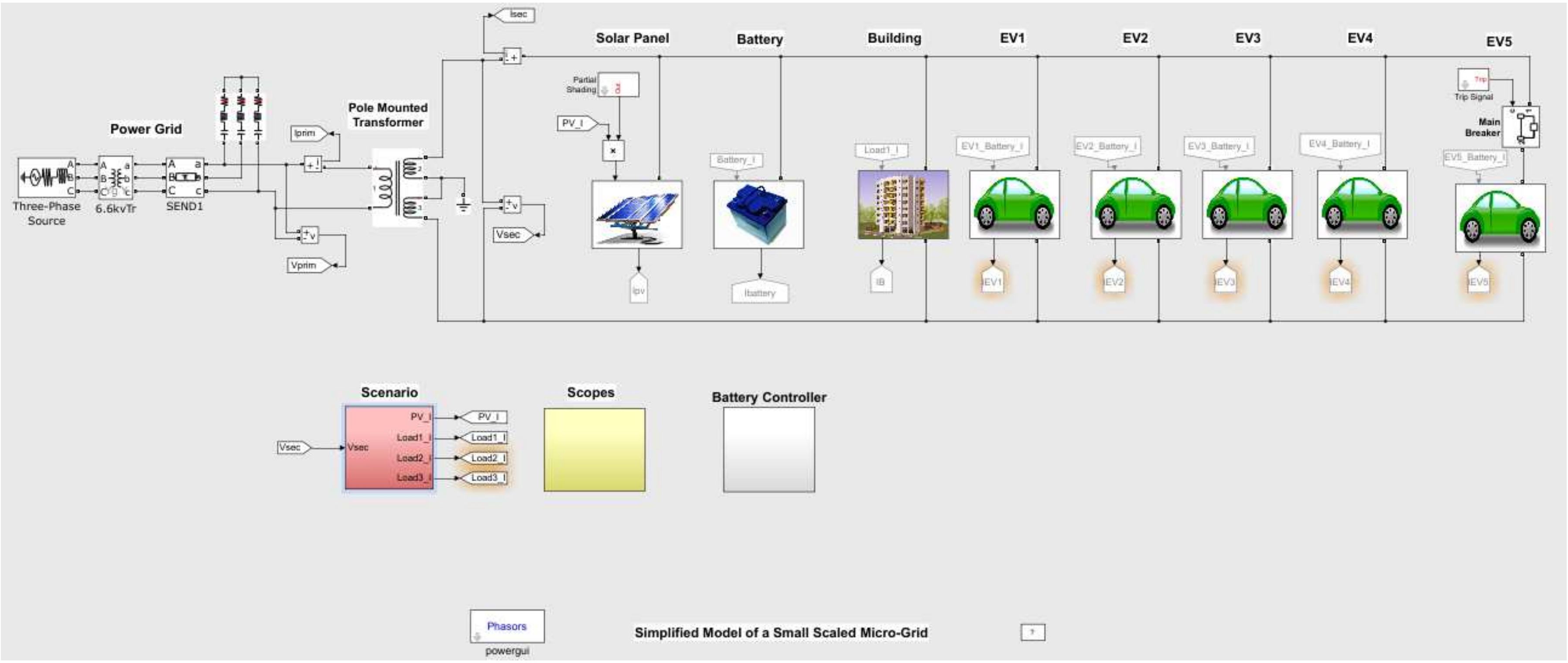
→ *Minimizing* ***total electricity cost****, including energy cost, peak demand charge, EV battery degradation cost and frequency regulation service revenue*

Modeling and Simulation for V2H



- ❑ Connection: EV owner side

Modeling and Simulation for V2B/V2G



❑ Connection: Building owner side

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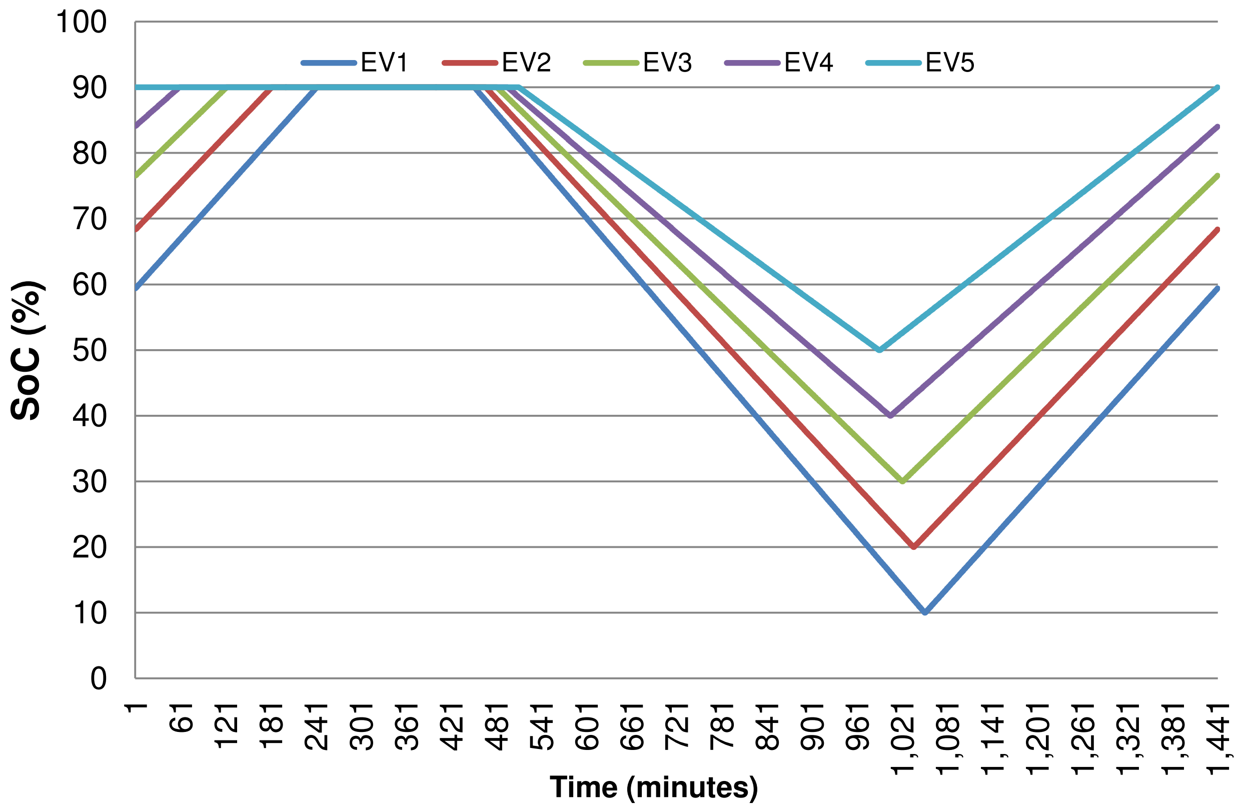
Simulation for V2B/V2G: SoC usage per EV for a Commercial Unit with 70kWh/day

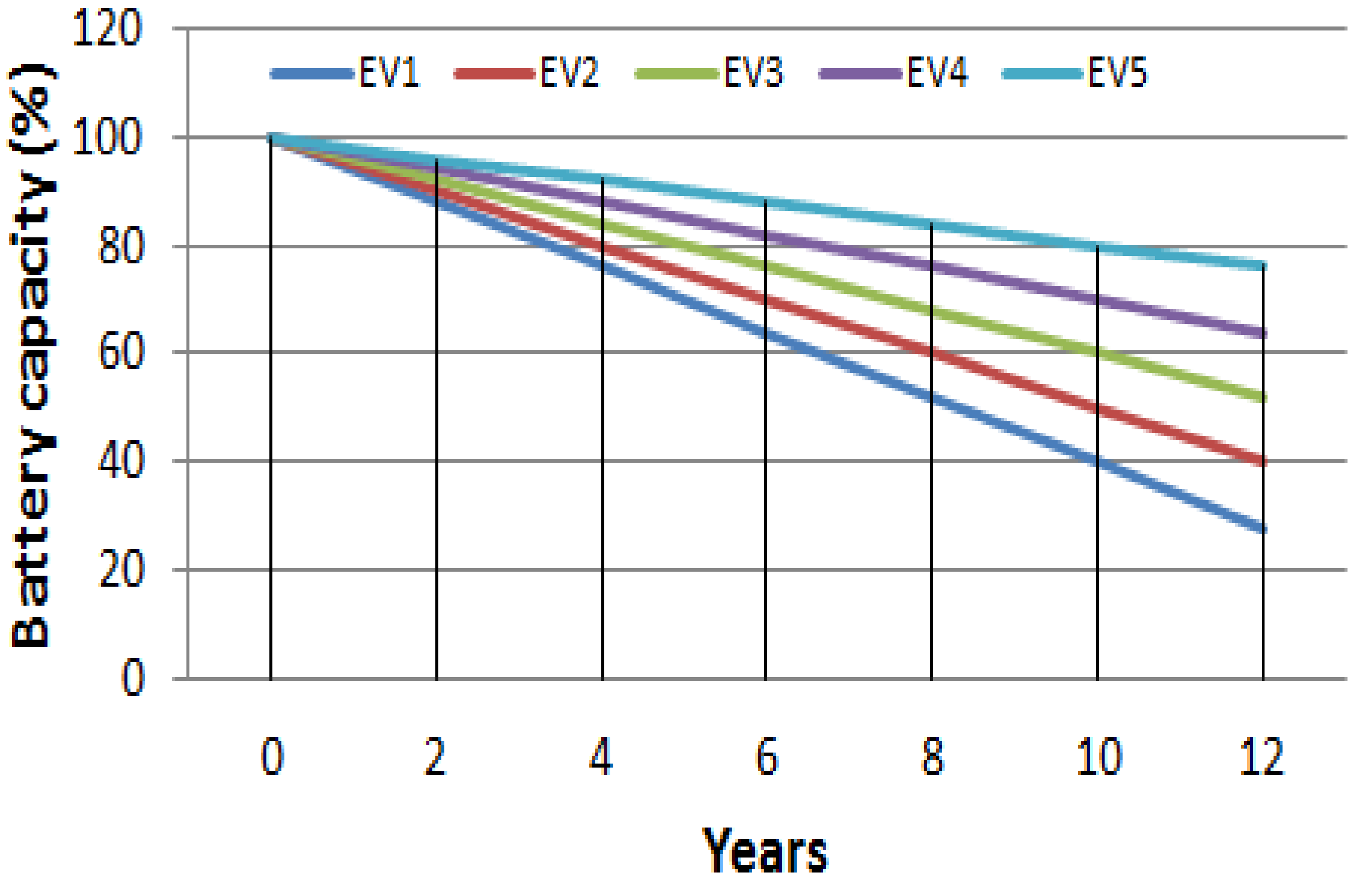
	SoC (%)				
	EV1	EV2	EV3	EV4	EV5
Min SoC	10	20	30	40	50
Max SoC	90	90	90	90	90
Available daily SoC range	**80**	**70**	**60**	**50**	**40**
Driving to work and errands	25	20	15	10	5
Driving home and errands	25	20	15	10	5
Peak Shaving (work)	15	15	15	15	15
Frequency regulation (work)	15	15	15	15	15

Control Strategy for V2B/V2G simulation: 5 different EV Driving and SoC Profiles for a Commercial Unit with 70kWh/day



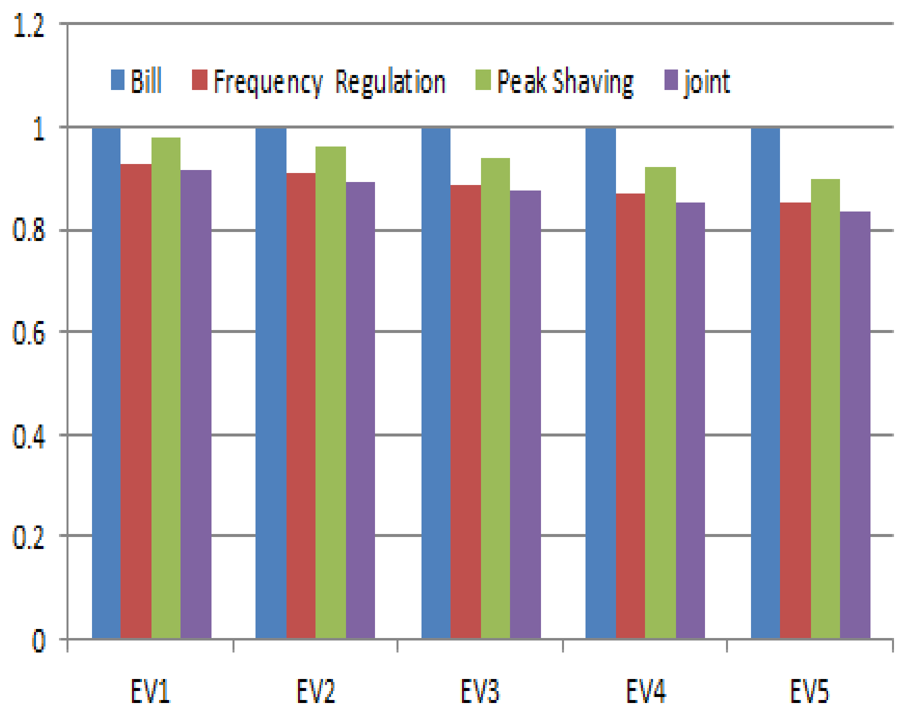
EV1 = [10% - 90%],
EV2 = [20% - 90%],
EV3 = [30% - 90%],
EV4 = [40% - 90%],
EV5 = [50% - 90%].

Simulation for V2B/V2G: Battery degradation and electricity bill estimation for V2B/V2G (Commercial Unit with 70kWh/day)

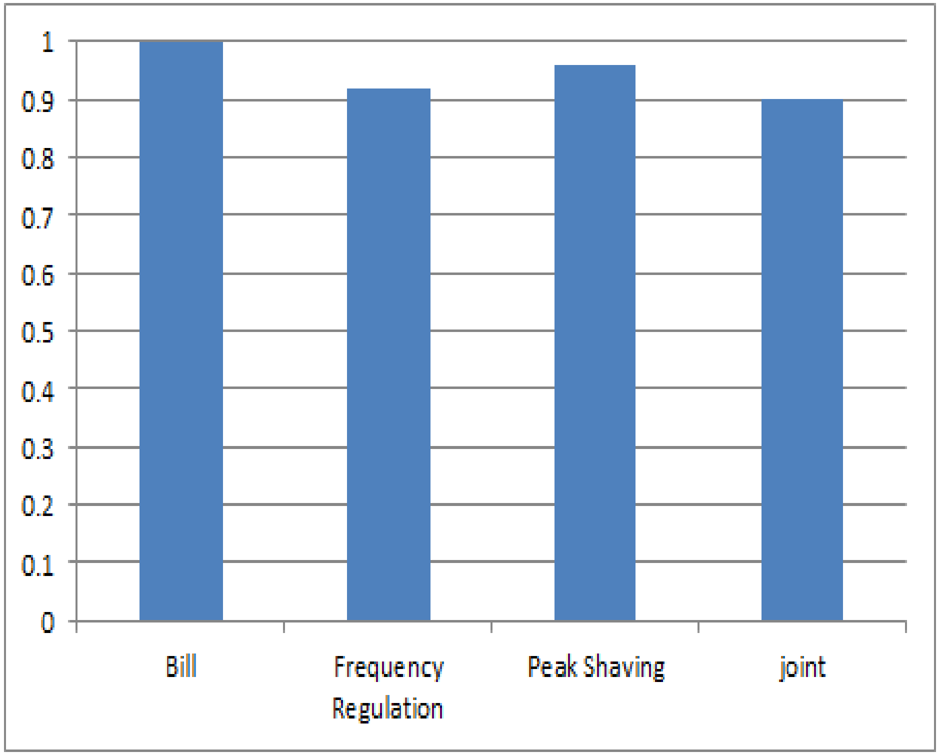


Battery degradation depending on SoC limits: EV1 = [10% - 90 %], EV2 = [20% - 90%], EV3 = [30% - 90%], EV4 = [40% - 90%], and EV5 = [50% - 90%].

Simulation for V2B/V2G: Battery degradation and electricity bill estimation for V2B/V2G (Commercial Unit with 70kWh/day)



Electricity bills to be paid by **EV owners** after reflecting reimbursement for ancillary service



Electricity bill for **building owner**

Comparative analysis of the original bill normalized to 1 with bills after peak shaving, frequency regulation, and combination of peak shaving and frequency regulation, under different SoC limits

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Conclusions

1. V2X validation testing facility has been built at CCHT Flexhouse at NRC Montreal Rd. campus in Ottawa ON, including grid simulation, renewable power generation, load simulator and bi-directional DC fast charger.
2. This V2X test facility will be utilized for determining the effect of bidirectional charging on V2X-capable EVs and performing the simulation and validation of energy management and control strategies to verify potential benefits of V2X.
3. NRC's V2X testing protocols include V2X interconnection tests, grid support tests, and V2G performance tests.
4. In order to verify the proposed control algorithm for V2B/V2G application, a small residential building or commercial unit with an electricity consumption of 70kWh/day and 5 EVs having a battery storage capacity of 24 kWh per EV has been utilized for simulation on **battery degradation** and **electricity bill estimation**.

Conclusions

5. A multi-objective strategy using EV batteries was presented not only for V2B (building load and powertrain) application, but also for reducing the peak demand charge and gaining revenue from participating in frequency regulation market as V2G.
6. The results can be applicable to any larger buildings with a fleet of EVs by multiplication and additional detailed adjustment.
7. The **deeper** the depth of battery discharge is used, the **higher** the battery degradation is pronounced. Among five EVs with short and different commute driving profiles, 5th EV with SoC within [50% - 90%] showed the **lowest** battery degradation.
8. Comparative analysis with previous works that used battery storage systems for either peak shaving or frequency regulation showed that EV batteries for V2B/V2G can achieve superior economic benefits under controlled SOC limits.

Acknowledgments

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Thank you

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