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Multi-objective optimization of combined peak shaving and frequency regulation in Vehicle-to-Building/Grid (V2B/V2G)

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Canada

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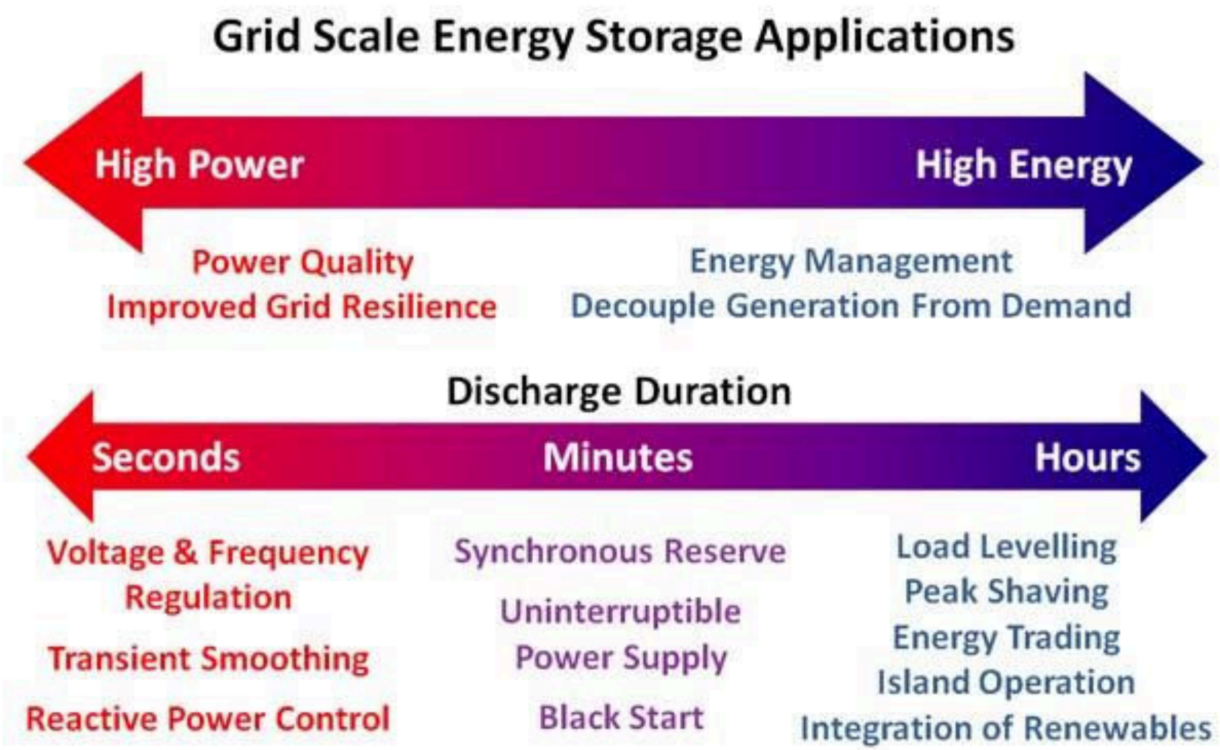
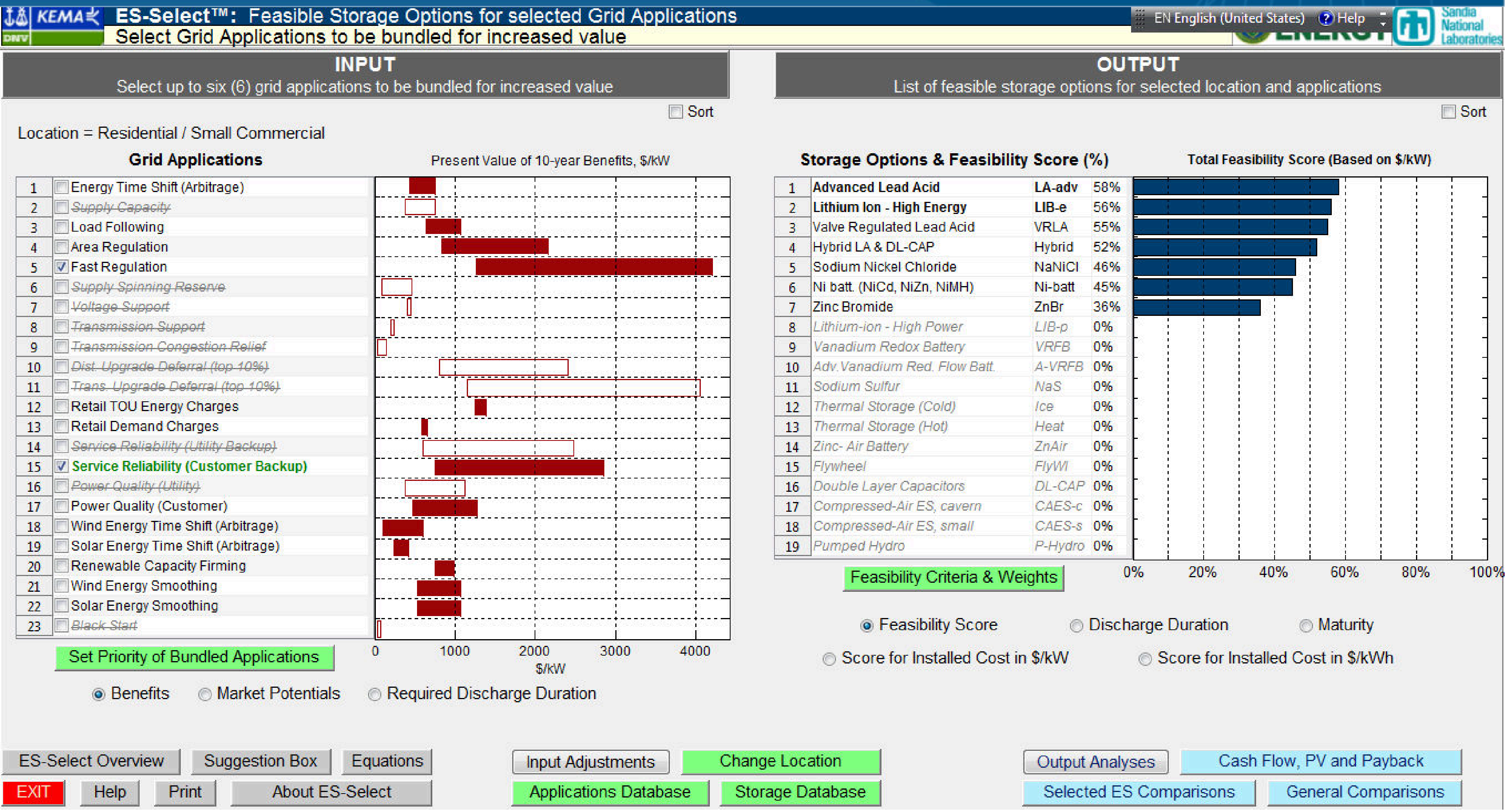
Introduction:
Why is Energy Storage needed?



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.

Introduction: Grid Applications



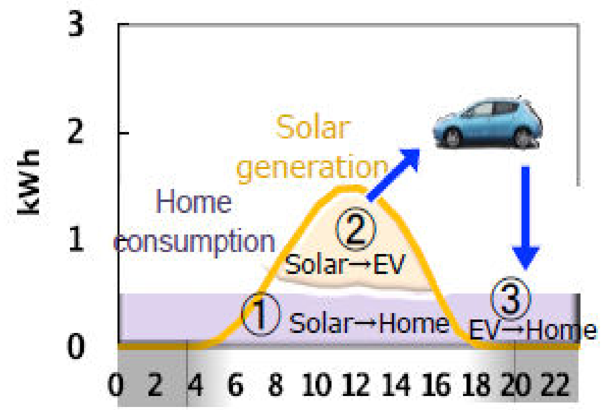
Ref.: ES-Select, DNV KEMA

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

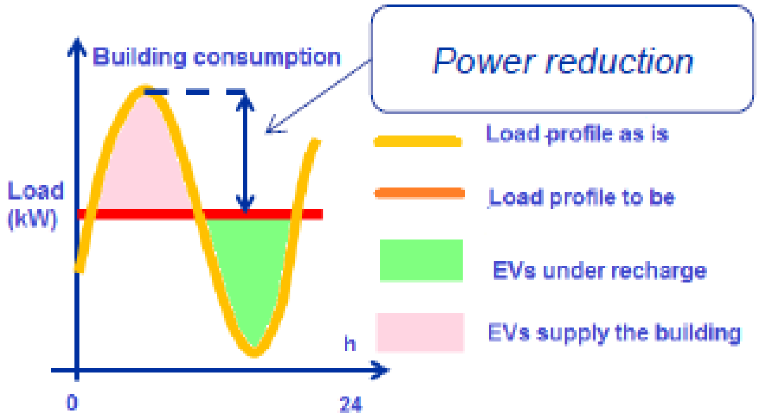
Source: Nissan Motor Company

V2H



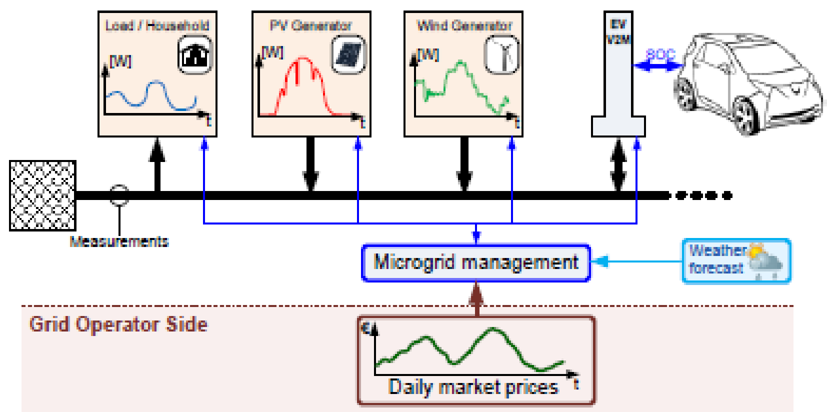
Source: Nissan Motor Company

V2B



Source: Enel

V2G

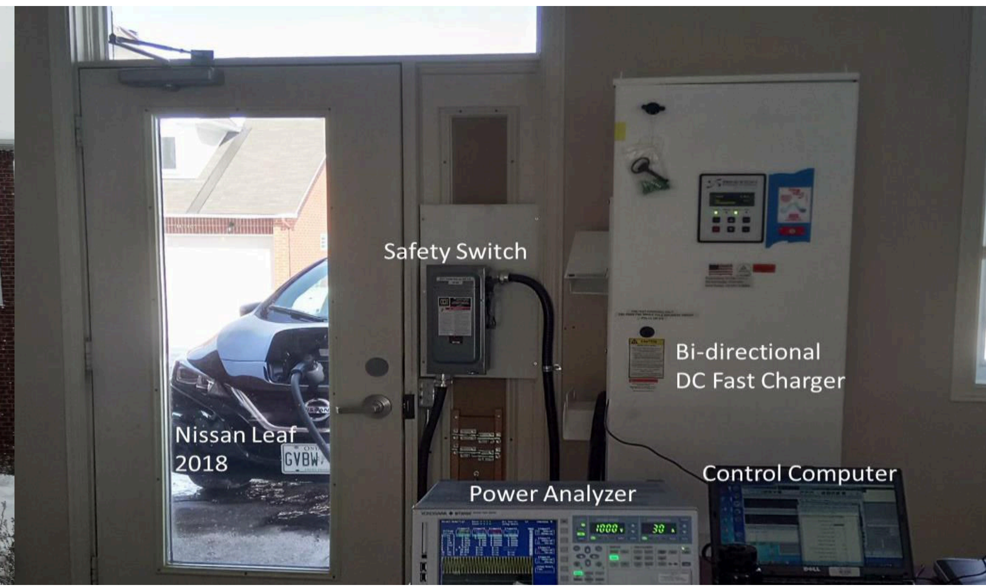


Source: IREC

Vehicle-to-X (X= Home, Buildings and Grid): Field Trial at CCHT Flexhouse

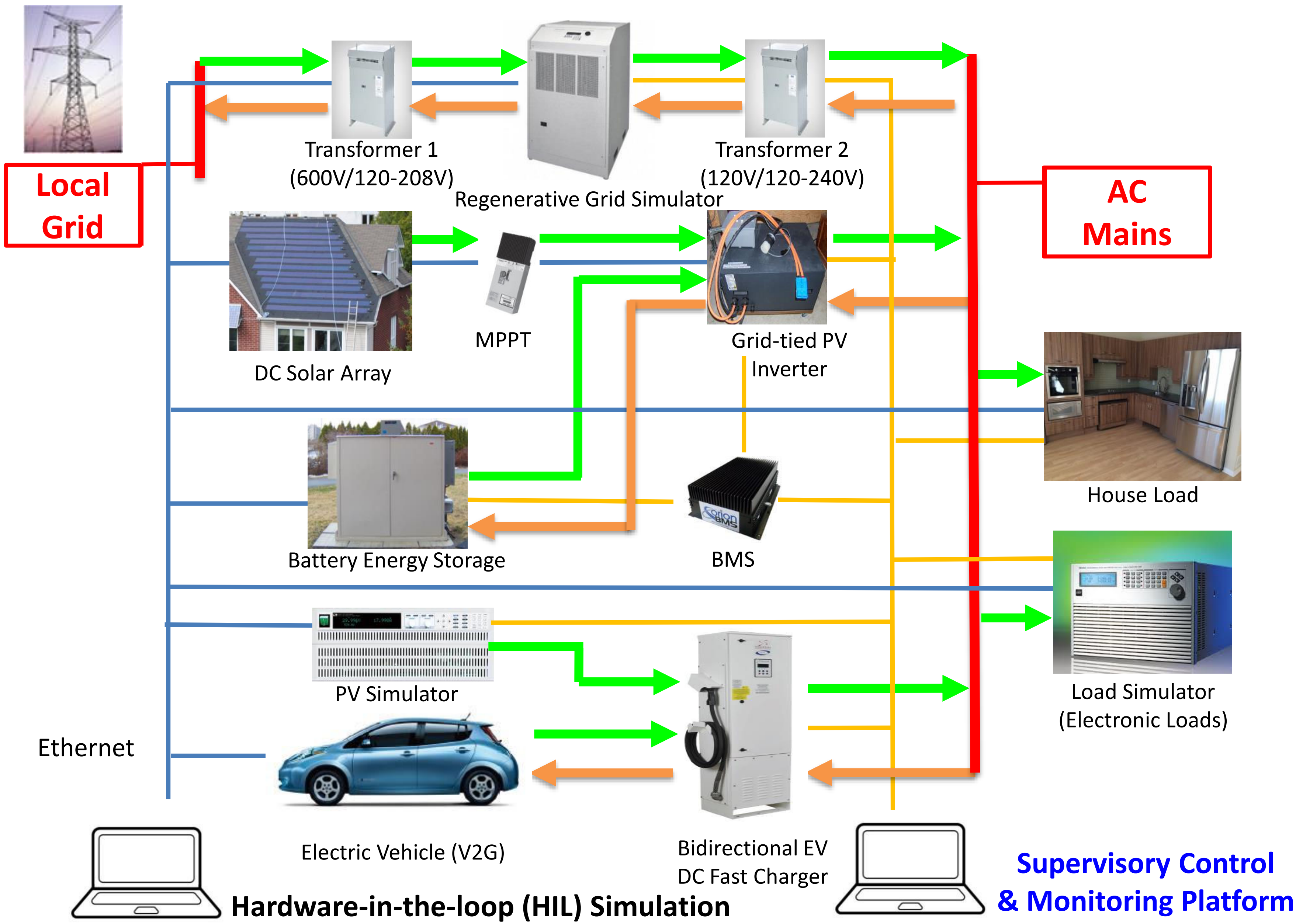
✓The Canadian Centre for Housing Technology features twin research houses to evaluate the whole-house performance of new technologies in side-by-side testing.

(a) Nissan Leaf 2018

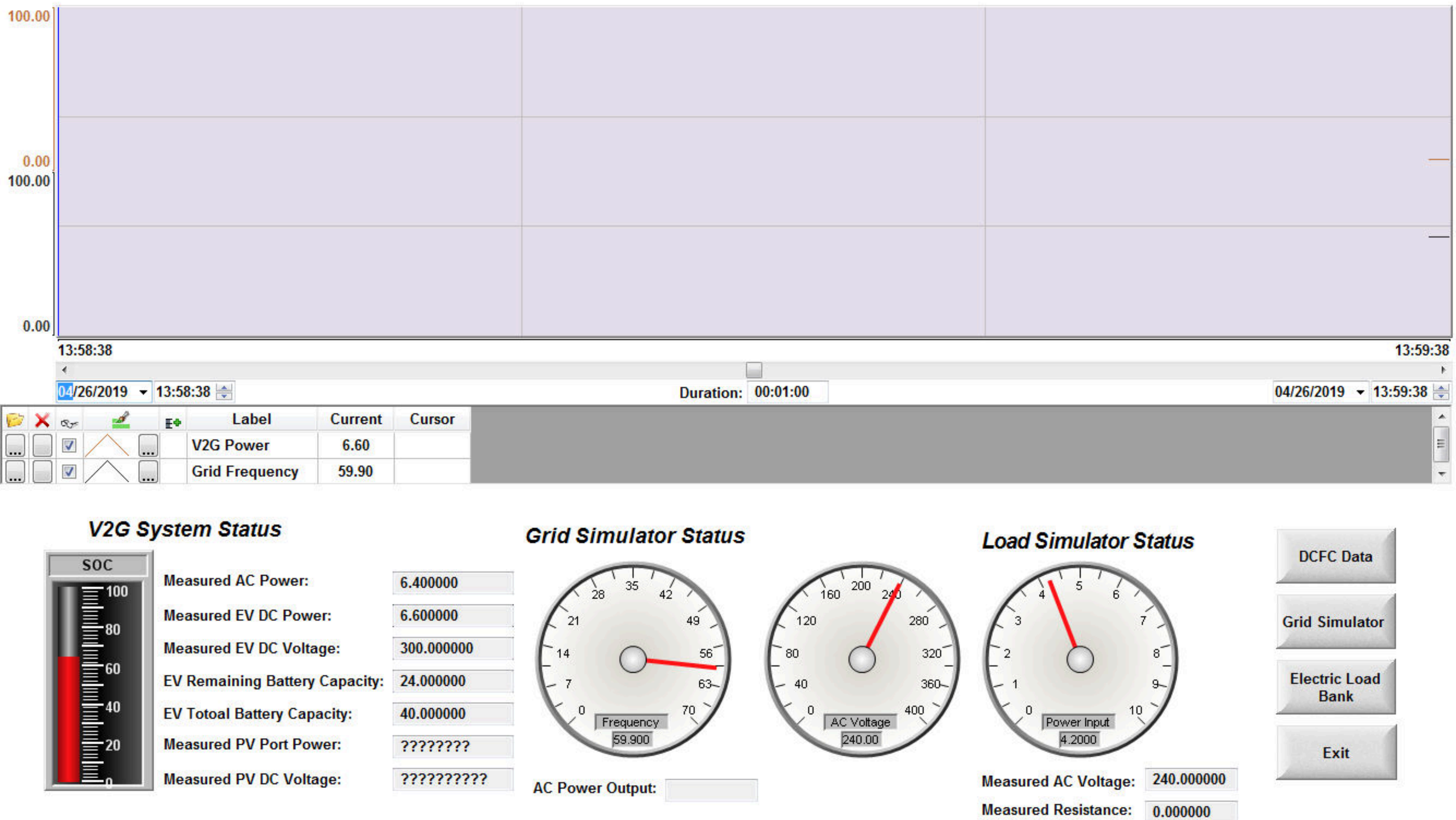


(b) CCHT-V2X testing facility

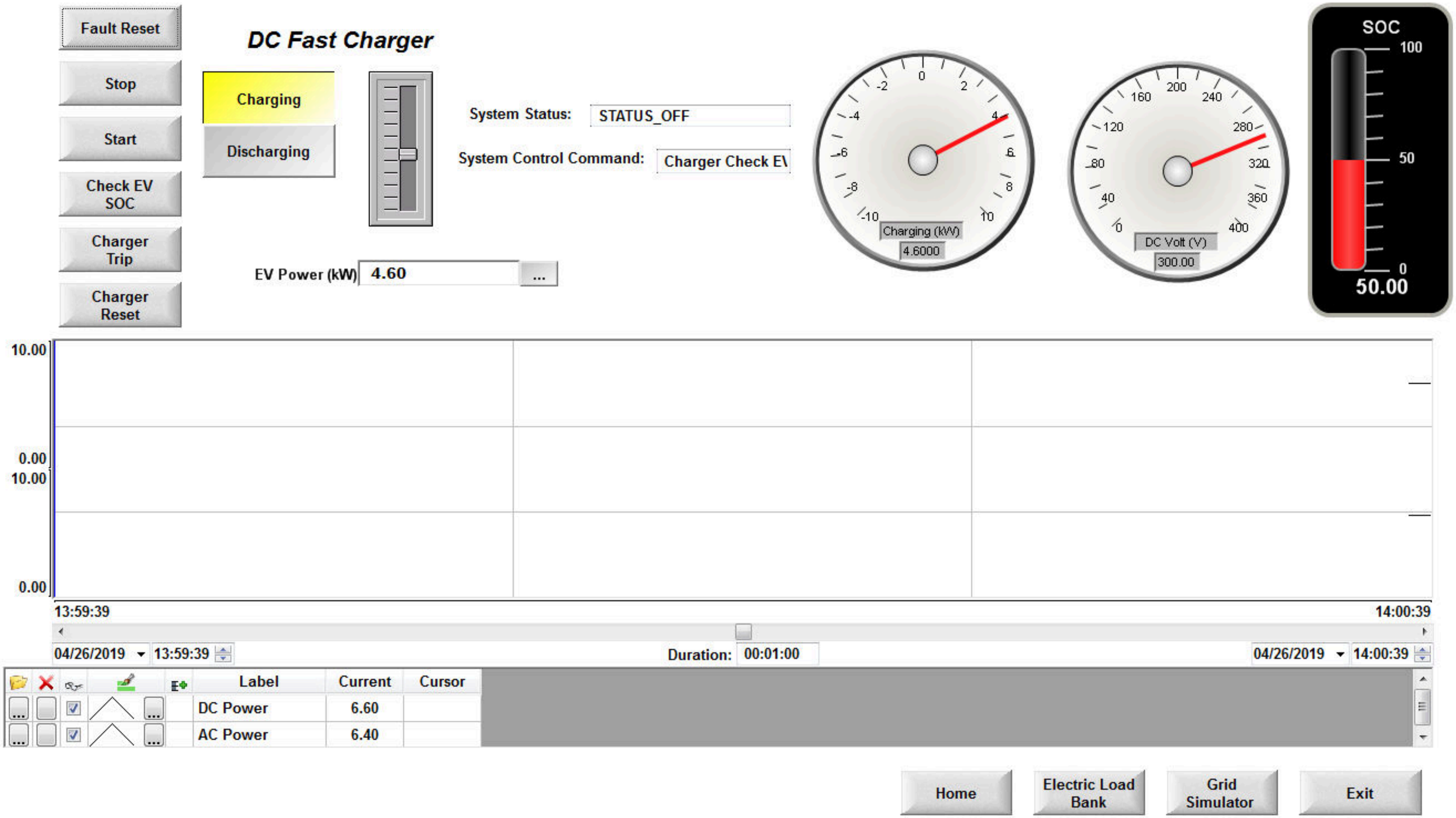
Conceptual design of a validation system based on HIL simulation for V2X



Supervisory Control Platform: Frequency Control



Supervisory Control Platform: Bidirectional DCFC



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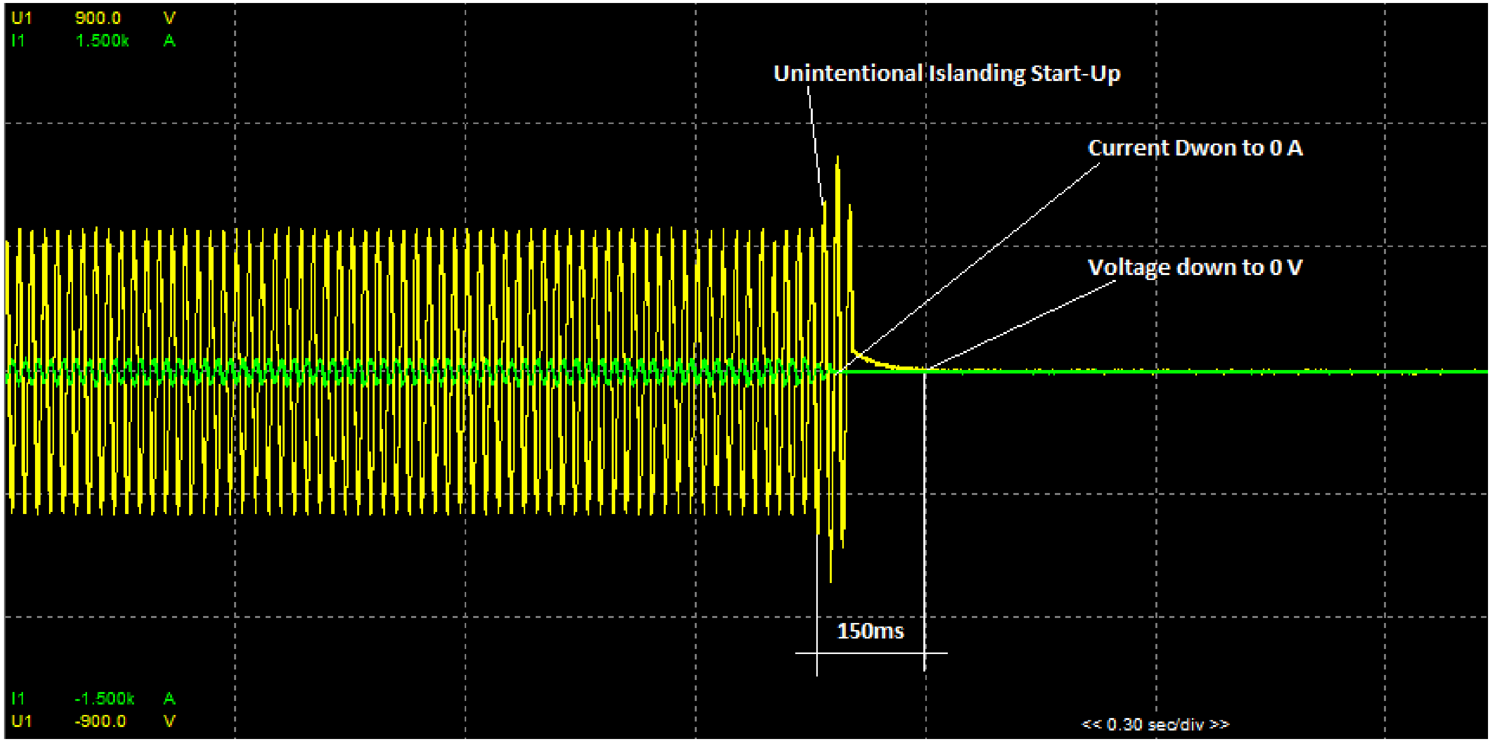
Grid Interconnection Tests: Unintentional Islanding

- IEEE1547 requirements: Clearing time shall be within 2 seconds (2,000ms) when grid loses power.
- Unintentional islanding test results:

  Test rounds: 4, Trip time: min.150-max.160ms



Example of Unintentional Islanding Test, Trip Time=150ms

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

$$H = H^{elec} + H^{peak} = \alpha_{elec}\int_{T_0}^{T} r(t)dt + \alpha_{peak}\max_{t=T_0...T}[r(t)] = \alpha_{elec}\int_{T_0}^{T} r(t)dt + \alpha_{peak} r_{peak}$$

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

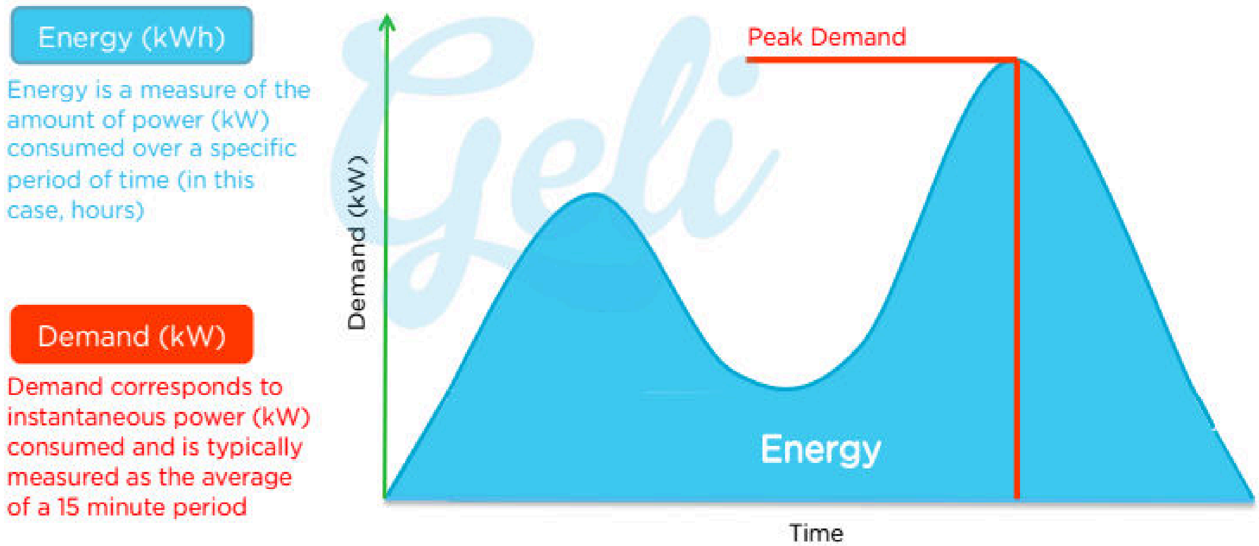


Image courtesy of Geli.

Electricity Bill Calculation: Peak Shaving

❑ Peak shaving

$$H^a = \alpha_{elec} \int_{T_0}^{T} [r(t) - \sum_{n=1}^{N} b_n(t)]dt + \alpha_{peak} \max_{t=T_0 \ldots T} [r(t) - \sum_{n=1}^{N} \bar{b}_n(t)] + \sum_{n=1}^{N} f(b_n)$$

where, H^a: total adjusted electricity bill,

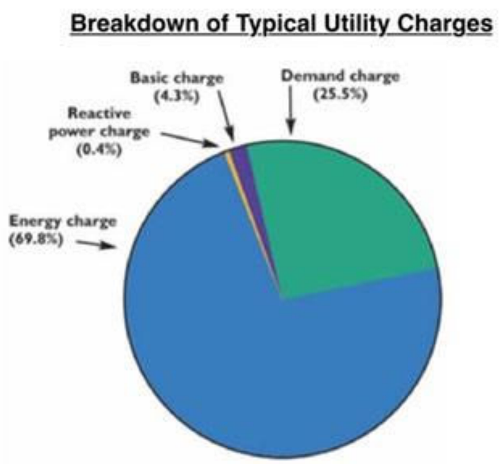
$b_n(t)$: power injected by n^{th} MBESS at a given time t, $b_n(t) > 0$ for discharging, $b_n(t) < 0$ for charging,

$r(t)$: power meter reading at time t,

$r_a(t) = r(t) - \sum_{n=1}^{N} b(t)$: actual power meter reading when N EVs are connected to the grid,

$\bar{b}_n(t)$: average 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

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Electricity Bill Calculation: Frequency Regulation

- Frequency regulation

$$S = \alpha_c CT - \alpha_{mis} \int_{T_0}^{T} \left| \sum_{n=1}^{N} b_n(t) - Cs(t) \right| dt - \sum_{n=1}^{N} f(b_n)$$

where, S: revenue to provide frequency regulation service over time T (in PJM market),

s(t): normalized frequency regulation signal,

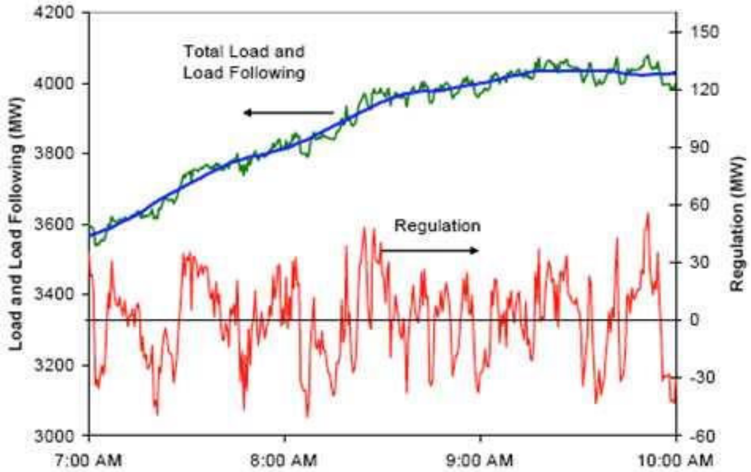
α_c: benefit from frequency regulation in \$/MW,

α_{mis}: mismatch 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.

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Electricity Bill Calculation: Battery Degradation

- Battery degradation cost

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

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

λ_{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

$$H^{multi} = \min_{c_n, b_n^{ch}(t), b_n^{dc}(t), y(t), N} H^a - \lambda_c T \sum_{n=1}^{N} c_n + \lambda_{mis} \int_{t=T_0}^{T} |-r(t) + \sum_{n=1}^{N} b_n(t) + y(t) - \sum_{n=1}^{N} c_n s(t)| dt$$

$$\text{s.t.} \quad b_n(t) = b_n^{dc}(t) - b_n^{ch}(t)$$

$$\sum_{n=1}^{N} c_n \geq 0$$

$$SoC_{min}^n \leq \frac{SoC_{ini}^n + \int_{\tau}^{t} [b_n^{ch}(\tau)\eta_c - \frac{b_n^{dc}}{\eta_d}] d\tau}{E} \leq SoC_{max}^n$$

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

$$0 \leq b_n^{dc}(t) \leq P_{max}^n$$

➔ Cn: frequency regulation capacity of each EV,

$b_n^{dc}(t), b_n^{ch}(t)$: battery charging/discharging power of each EV

y(t): frequency regulation load baseline

λc: benefit from frequency regulation in $/MW

λmis: mismatch penalty cost for frequency regulation in $/MWh

Simulation for V2B/V2G: Problem Formulation

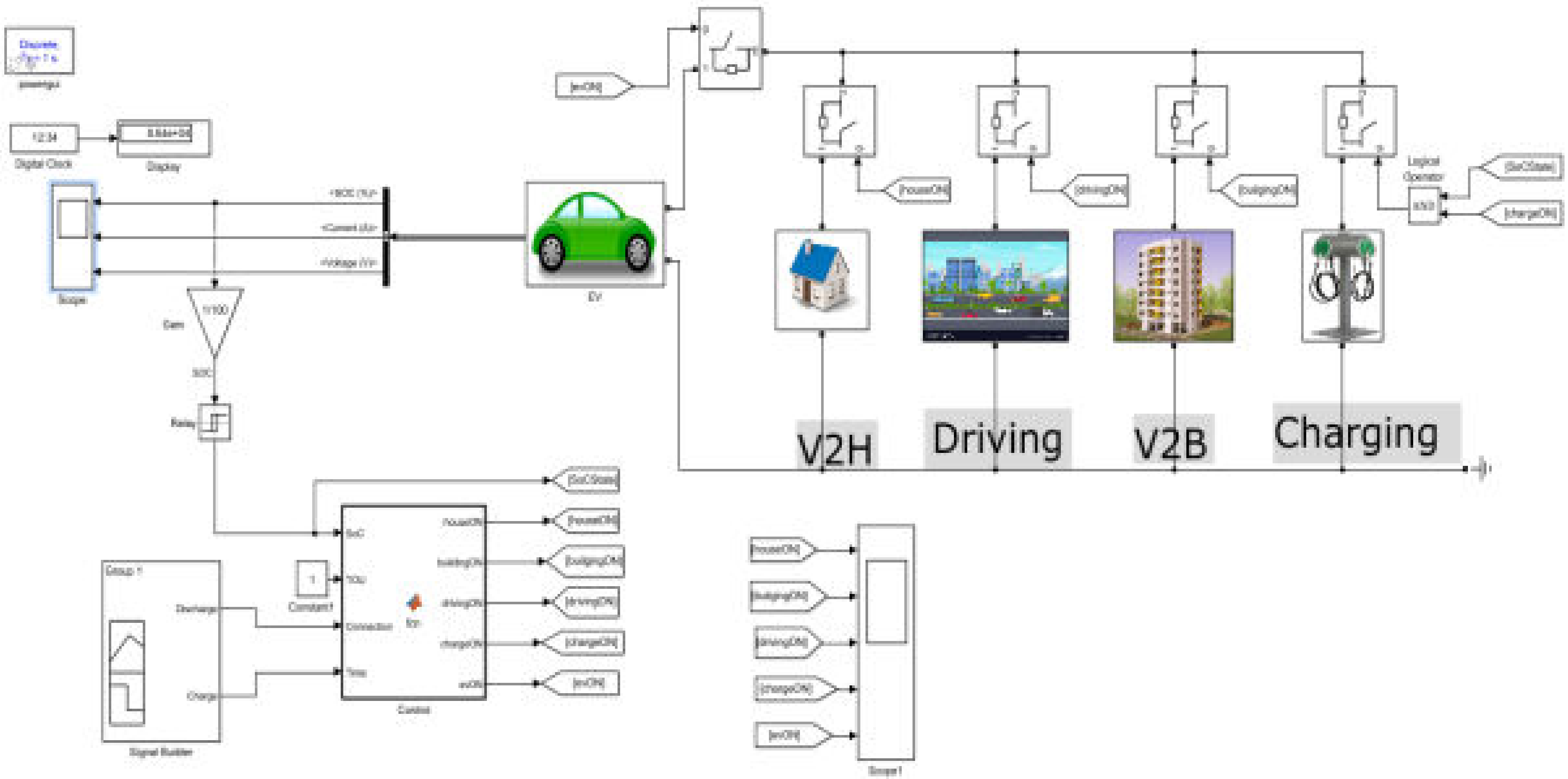
- Assumption: A small residential building or commercial unit with an electricity consumption of 70 kWh/day and 5 EVs having a battery storage capacity of 24 kWh per EV
- Simulation: Battery degradation and electricity bill estimation
- Objectives of this work:
  1) To reduce the total energy cost H,
  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, Driving, V2B/V2G and Charging

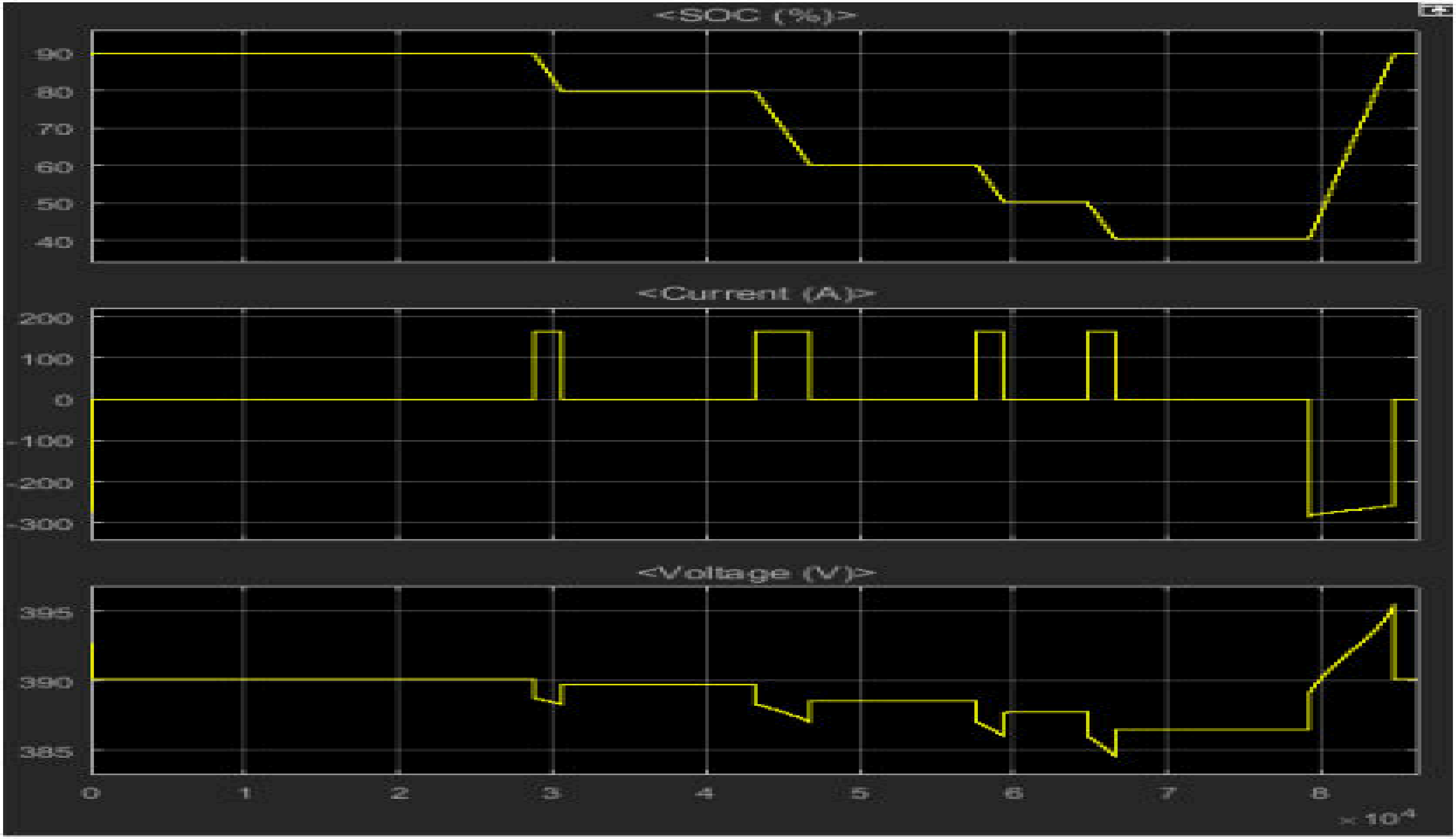


- Connection: EV owner side

5 different EV Driving and SoC Profiles

	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
V2B/V2G	20	20	20	20	20
Driving home and errands	25	20	15	10	5
V2H	10	10	10	10	10

Daily SoC simulation profile of EV4 = [40%-90%] with SoC usage for Driving to work, V2B/V2G, Driving to home, V2H and Charging in chronological order



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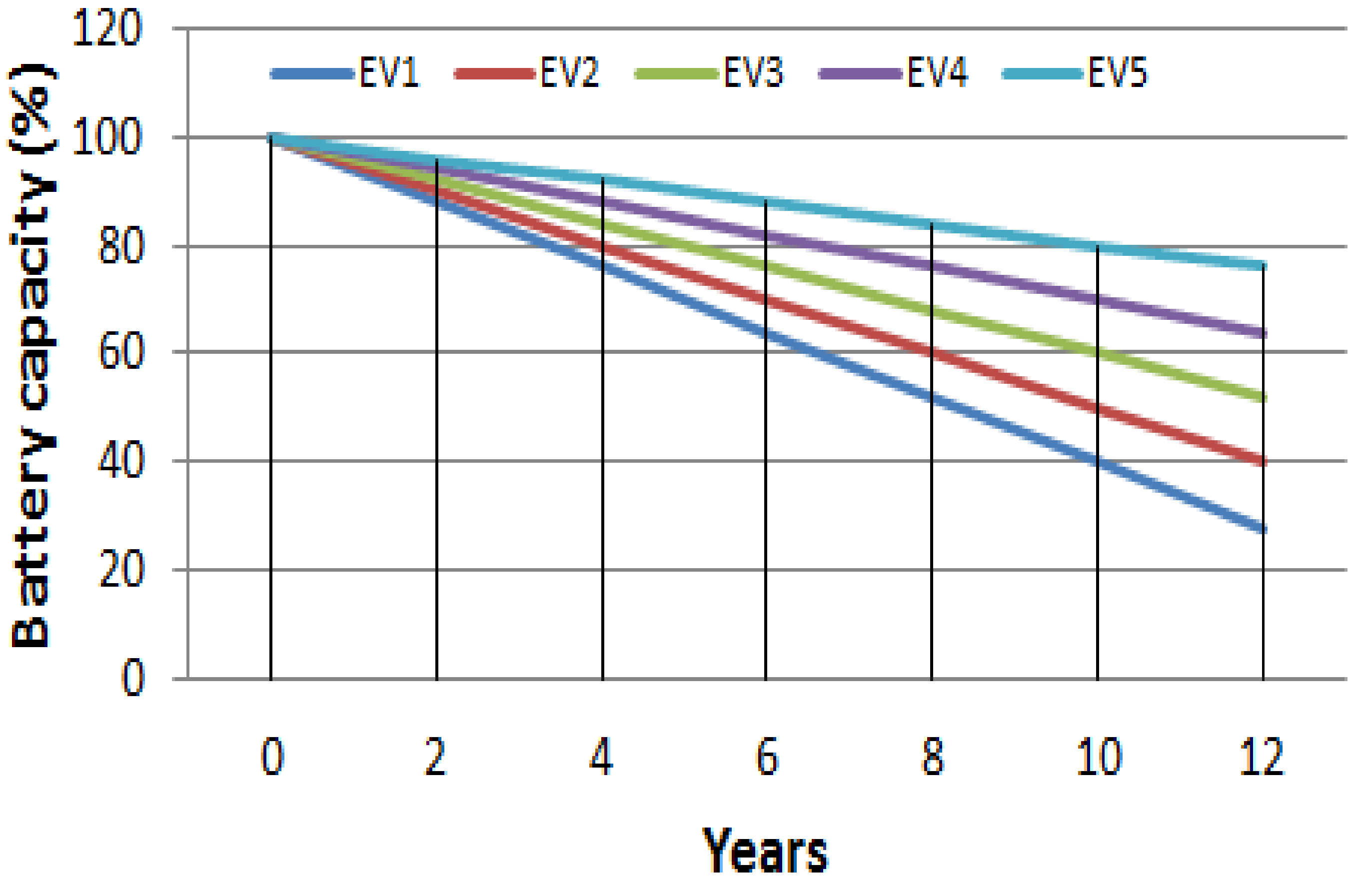
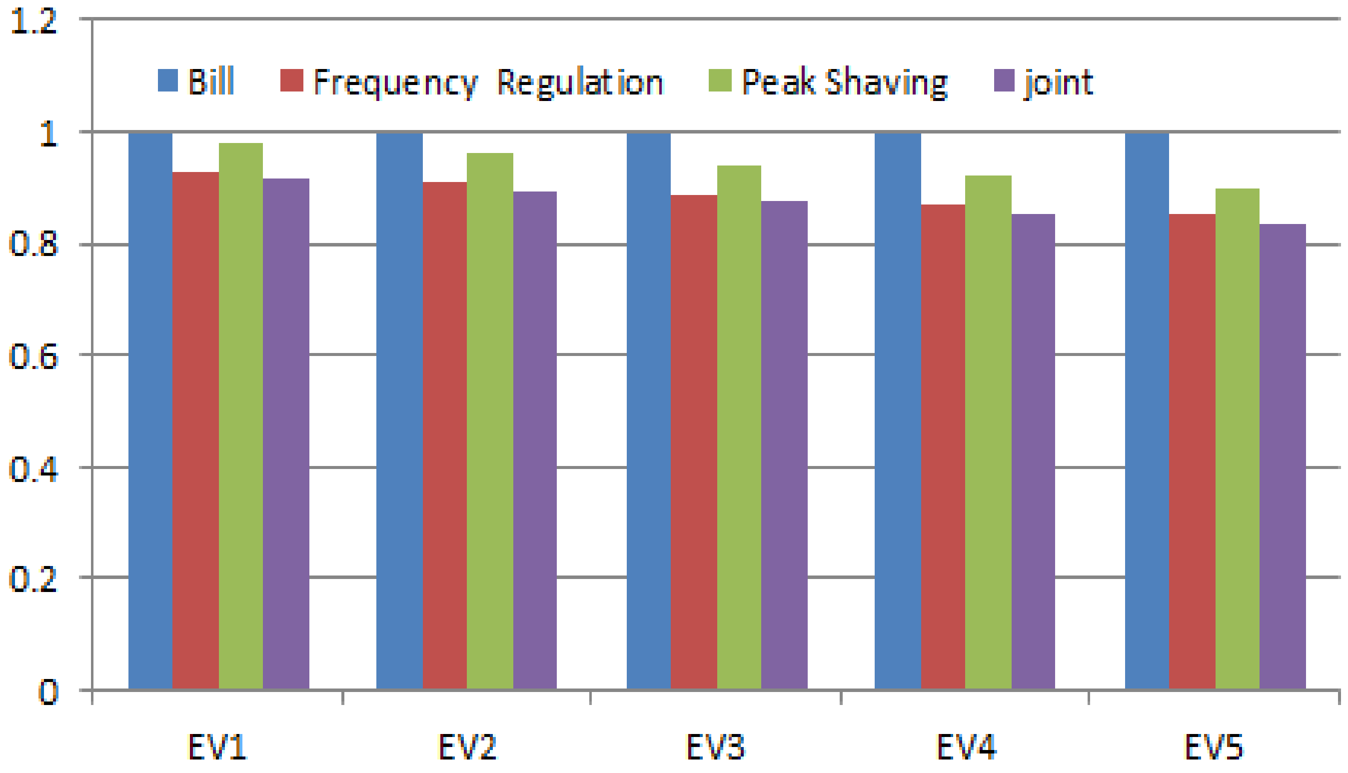
Battery degradation for various driving patterns and SoC limits



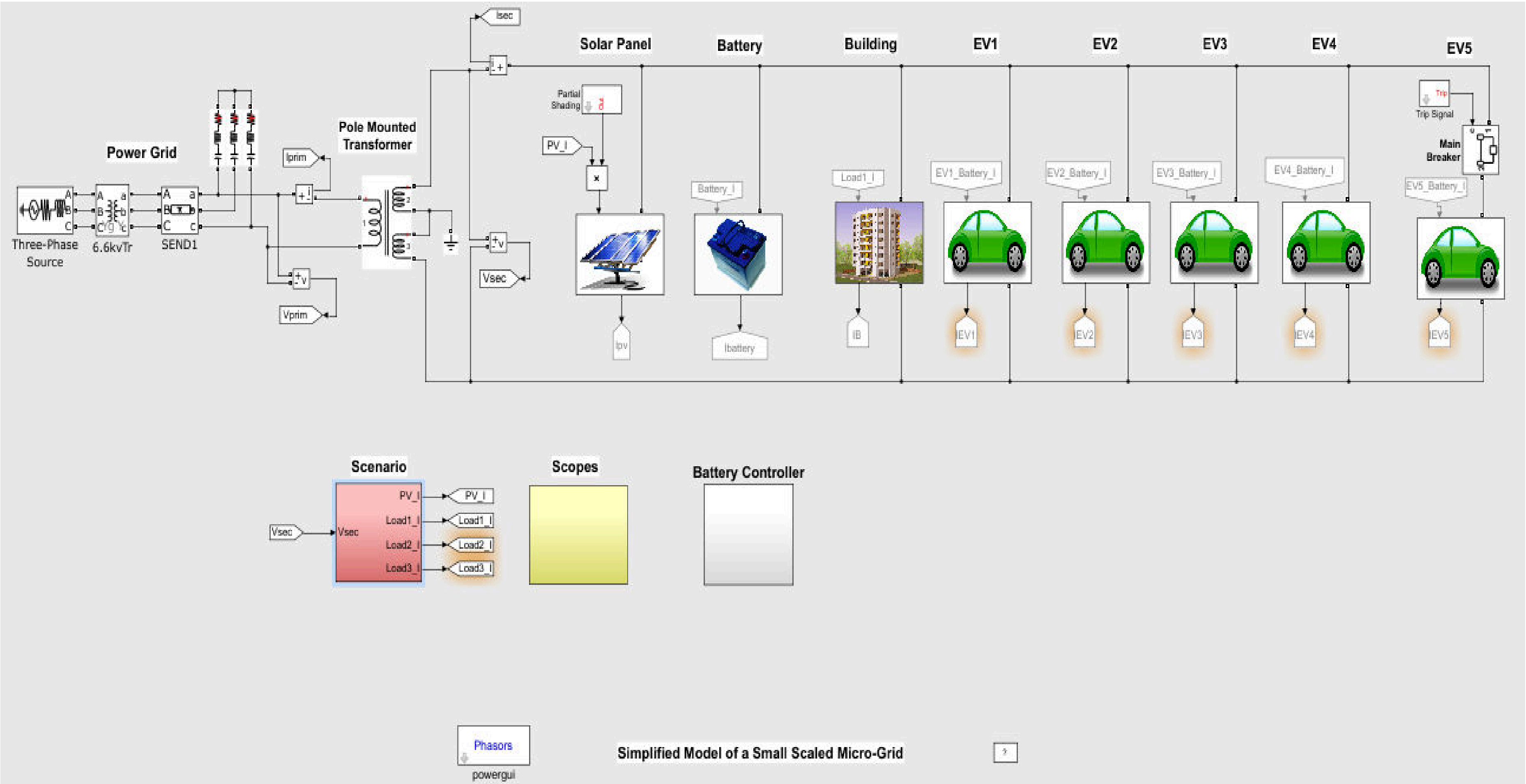
Battery degradation depending on SoC limits: EV1 = [10% - 90 %], EV2 = [20% - 90%], EV3 = [30% - 90%], EV4 = [40% - 90%], and EV5 = [50% - 90%].

Comparative analysis of the original bill normalized to 1 with bills to be paid by EV owners after ancillary services



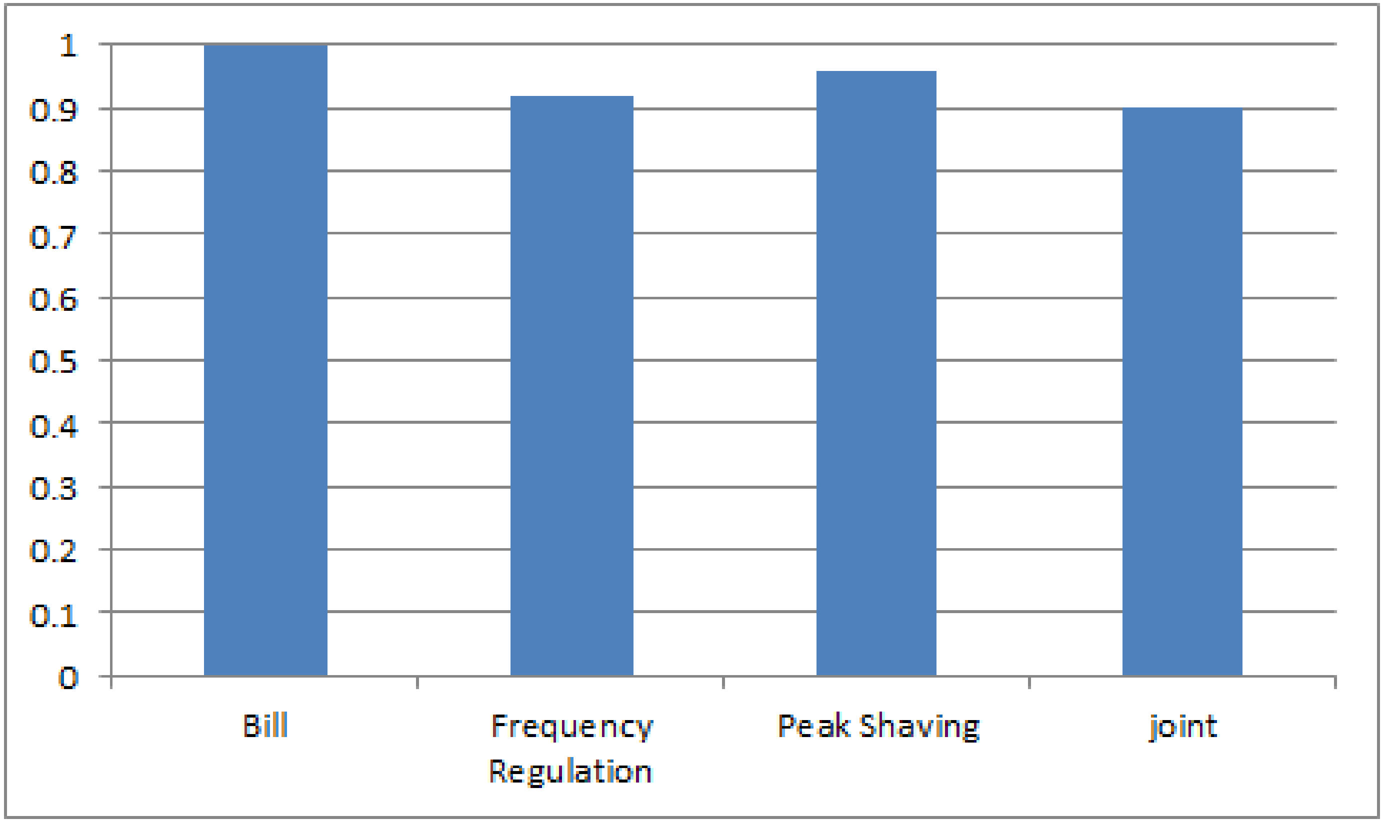
Electricity bills to be paid by EV owners after reflecting reimbursement for ancillary services of frequency regulation, peak shaving and a combination of frequency regulation and peak shaving under different SoC limits

Modeling and Simulation for V2B/V2G



- Connection: Building owner side

Comparative analysis of the original bill normalized to 1 with bills to be paid by a building owner for a commercial unit with 70kWh/day after ancillary services



Electricity bills to be paid by Building owner after reflecting reimbursement for ancillary services of frequency regulation, peak shaving and a combination of frequency regulation and peak shaving

Conclusions

1. V2X validation testing facility has been built at CCHT Flexhouse at NRC Montreal Rd. campus in Ottawa ON 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.
2. 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**.
3. 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.

Conclusions

4. The results can be applicable to any larger buildings with a fleet of EVs by multiplication and additional detailed adjustment.
5. 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, 5^{th} EV with SoC within [50% - 90%] showed the **lowest** battery degradation.
6. 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.

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Thank you

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