Plug-In Vehicle to Home (V2H) Duration and Power Output Capability

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***Abstract*-This work analyzes the capability for Plug-in electric vehicles (PEVs) in Vehicle to Home (V2H) scenarios, for which the vehicle acts as a residential battery storage system and/or a backup generator during a grid outage or more frequent short duration distribution system fault. In this paper, we use residential energy data collected from a smart grid testbed in Austin, Texas with a custom PEV model to assess the performance (in terms of duration and power output) of a PEV used for backup power. Our results quantify the extent to which photovoltaic (PV) generation and the characteristics of a PEV (battery size, gasoline availability) affect the backup duration of a PEV based V2H system during an electric outage. We use the insight gained from our results to explore optimal engine-generator control for PV-enabled V2H, strategies to further increase backup duration, and non-continuous self-sustaining off-grid alternatives.**

I. INTRODUCTION

Vehicle to Home (V2H) capability describes a scenario in which a plug-in electric vehicle (PEV) not only receives charge from the grid to power the vehicle, but also provides backup power to an islanded load such as a home during an outage, similar to a stand-alone emergency generator [1][2]. V2H capability is a different concept than Vehicle to Grid (V2G), where the vehicle provides two-way power flow from/to a functioning electric power grid for peak shaving or grid ancillary services [3].

Because of the value that V2H can provide during sustained grid outages, interest in BEV V2H has increased greatly in Japan after the Fukushima disaster [4]. In other scenarios, a V2H capable vehicle may provide seamless backup power for more frequent but typically shorter duration grid distribution faults.

V2H systems with rooftop photovoltaic (PV) generation combined with electric vehicles have been explored to improve the utilization of PV generated electricity [5]. With today's conventional operational standards, a typical home with residential PV generation must shut down if the grid power is lost [6]. The requirement for a PV system to shutdown is to ensure that the PV system does not backfeed to the grid creating safety problems for lineman repairing the distribution system and to avoid microgrid stability problems given the lack of storage or a stiff grid to effectively regulate voltage, reactive power, and current surges. However, solar PV systems combined with local storage can remain operational even during an outage. Thus, a V2H capable vehicle connected to a PV equipped home could enable fully off-grid operation or the vehicle to power a home or other isolated load as a convenient, safe, and powerful backup generator.

PEVs are offered with and without an internal combustion gasoline/diesel engine range extender. A PEV without an internal combustion engine relies entirely on its battery to provide energy for its traction motor, and is referred to as a battery electric vehicle (BEV). A PEV with a range extending gasoline engine is typically called a Plug-in Hybrid Electric Vehicle (PHEV) or a particular type of PHEV named an extended range electric vehicle (eREV). In this study, both PHEVs and eREVs are functionally considered PHEVs. PHEVs inherently have the ability to generate considerable power from their on-board gasoline engine/motor-generator powertrains.

One advantage of PEV systems (in contrast with traditional generators), is that to achieve their typical 350+ mile range, these vehicles have a sufficiently large gasoline tank which could fuel the engine-generator for a meaningful period of time. Unlike a conventional stand-alone backup generator which may require an owner to inconveniently store gasoline containers in their garage for long periods of time, dispose of stored gasoline which as become stale during storage, or carry heavy hand-carted gasoline containers repeatedly from the gasoline station to the generator, a homeowner with a V2H capable PEV could simply unplug with a few gallons of gasoline remaining in the PHEV fuel tank, drive to a remote gas station, conveniently refill the vehicle gasoline tank, and then return to the stricken location to again power the home.

Additional advantages of a PHEV over a conventional backup generator include more efficient operation of the engine-generator given the large battery storage to buffer transient load conditions, and a lower emissions and higher efficiency engine given advanced automotive technology such as fuel injection and catalytic converters required to meet emissions or fuel economy requirements compared to a typically less efficient carbureted generators that are not required to meet the same standards. Residential backup generators also can be susceptible to clogged fuel systems from infrequent use. PHEVs may also exhibit quieter operation compared a standard backup generator.

In this paper we simulate a PEV used for backup power during an outage. We use residential energy data collected from a smart grid test bed in Austin, Texas to conduct the following analyses: 1) quantify the duration (in hours) of backup power that could be achieved with BEV or PHEV based V2H system and for a representative load, 2) determine how the time of an outage may affect the duration, 3) model the energy conversion efficiency of the PHEV

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generator, 4) identify more optimal engine-generator control for PV enabled V2H with a PHEV, and 5) identify strategies to further increase backup duration and non-continuous self-sustaining off-grid alternatives.

In Section II, we introduce the smart grid test bed from which the residential energy data utilized in this paper originates. Section III describes the PEV system model and the derivation of the PHEV gasoline generator energy conversion efficiency. Section IV briefly describes the interfaces with the vehicle to enable V2H capabilities. Section V discusses the results of backup duration simulations from the numerous PHEV and BEV configurations considered, as well as insights learned from this study. The final section includes the conclusions.

II. Representative Load and PV Data

To estimate the instantaneous load on a PEV used in a V2H application, we use data collected by Pecan Street Inc. [7] of Austin, Texas as part of their ongoing smart grid demonstration study. The overall Pecan Street study utilizes a test bed of 250 modern, green-built homes constructed after 2007, and 160 homes ranging from 10-92 years in age [8]. The homes are instrumented with various forms of energy metering equipment, which tracks electricity, natural gas, and water use. Of the homes in the study, 185 have rooftop PV panels. The power production from rooftop PV is metered separately from electric demand.

For the purposes of this paper, we utilize PV production and whole house electric demand data collected on a one-minute time interval from 20 homes over the year 2012. These homes were selected given their data availability for the entire year and installation of rooftop PV (which can be effectively turned-off in simulation to provide insights for scenarios with and without PV).

A small number of data dropouts were found (<1.5%) in the data. Because the majority of these dropouts appeared at common times, they were most likely caused by routine firmware updates carried out by the electricity monitoring equipment. Missing data points were patched with the prior day's data from the same home and time. Given typically low loads and no PV generation at these dropout times, patches from the prior day were assumed to be sufficiently representative of the originally lost data. The homes considered in this paper have PV systems ranging from 4 kW to 6.9 kW in rated capacity. The homes range in size from 1200 ft^2 to 2700 ft^2. We use PV production and electric demand data from these homes as the input to a PEV model, which is described in Section III.

III. System and Vehicle Models

A. System Model

Models to simulate V2H performance in response to an unplanned outage were constructed for both BEV and PHEV configurations using MATLAB. The model components consisted of the vehicle battery providing energy to the home load in conjunction with any PV energy provided and an engine-generator for a PHEV. Figure 1 shows the diagram for the V2H system model.

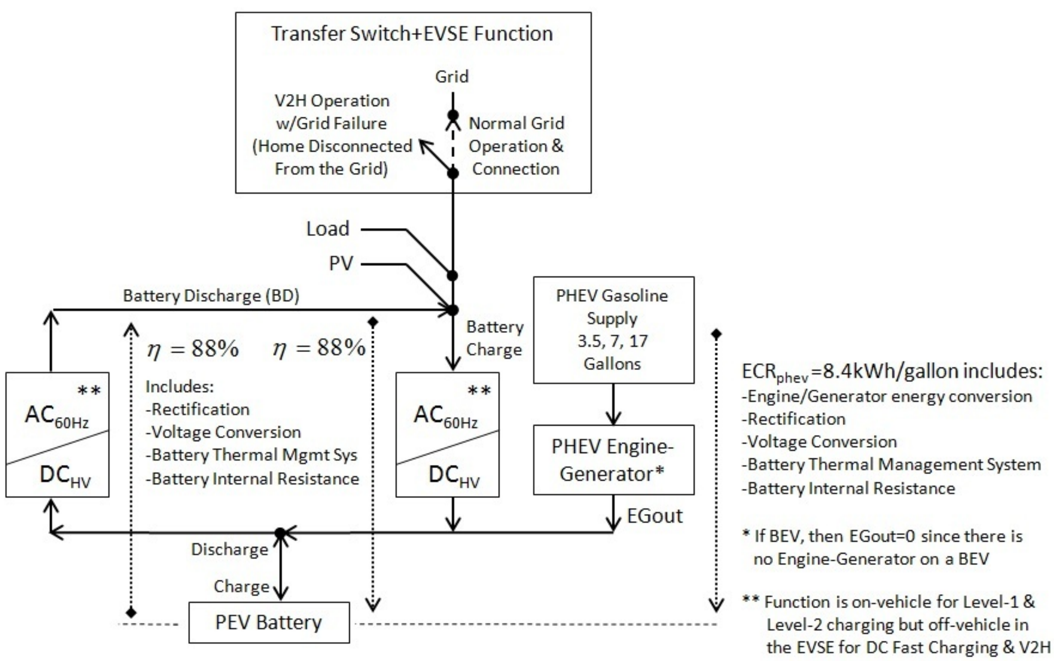

Fig. 1: V2H System Model. Note that for the BEV model, the Generator output is forced to zero.
BEV battery sizes are 19.2kWh and 32kWh, PHEV battery sizes are 3kWh and 10.5kWh.

If the PV output was greater than home load demands, the battery was assumed to be charged until it reached full state-of-charge (SoC). In this analysis, the home is assumed to have lost grid power and had thus begun using its electric vehicle based V2H system. Any excess PV energy that could not be stored in its fully charged PEV battery was assumed to be "spilled" and lost. When there was no PV output, energy from the battery was used to power the home load. For the PHEV model, PV energy is consumed first, then battery energy is used to power the home, and then finally the engine-generator is deployed to power the load and recharge the battery until the gasoline supply is exhausted. The backup duration was calculated as the time duration when the battery was terminally exhausted and could no longer support the home's load.

Using specifications of battery size, usable battery SoC window [9], and measurements of input energy from the grid the overall charging efficiencies (η) were calculated during varied temperature conditions for a Chevrolet Volt PHEV according to equation (1).

$$\textit{Battery Size} \bullet \textit{SoC Window} \bullet 1/(\textit{Input Grid Energy}) = \eta \quad (1)$$

With:

Battery Size = 16kWh [9]
SoC Window = 65% [9]
Input Grid Energy = 11.2kWh (temperate weather)
Input Grid Energy = 11.8kWh (hot weather)

An author measured this input energy using an eGauge energy monitoring system measuring the dedicated 240V circuit for an AC Level-2 charger for his Chevrolet Volt. This 1-way conversion efficiency includes rectification, step-up to the traction battery voltage of over 370V DC, battery internal resistance, and energy for the battery thermal management system. This measurement and calculation was useful as an estimate for the V2H off-grid configuration which would also deploy similar (but off-vehicle) stages of circuitry, utilize the same battery thermal management system, and exhibit the same battery internal resistance.

A conservative 88% conversion efficiency is assumed from measurement of charging during hot weather (with regional weather station data indicating 92 to 96 degrees Fahrenheit during the charging period) on the Volt. During more moderate temperatures (weather station data indicating 67 to 71 degrees) the efficiency is observed to reach a calculated 93%. The 5% efficiency loss appears to be consumed by the battery thermal management system to cool the battery during hot weather. Given this efficiency parameter is set conservatively in the model, the backup duration times could be somewhat longer in moderate temperature conditions. The same 88% efficiency factor is used for both BEV and PHEV models since the battery technology, battery thermal management, and power electronics are assumed to be similar. The 1-way charging and 1-way discharging efficiencies are assumed to be equal.

B. Energy Conversion Efficiency of PHEV Generator

An advanced automotive diagnostic tool (the Autoenginuity Enhanced Interface for GM Family EI02 which can read the battery state of charge in real time through the OBDII diagnostic port) allowed estimation of the gasoline to electricity kWh output energy conversion ratio. Two Chevrolet Volts (2011 and 2013 models) were used for data observation and acquisition. The Volts were driven until the battery was depleted (confirmed by the range extending engine generator turning on and the SoC status measurement), and then the vehicle was immediately parked with all accessory loads turned off and placed into "Mountain Mode" [10]. Mountain Mode is a special setting which forces the engine generator to charge the battery well above the typical operating threashold to enable the vehicle to maintain speed while climbing a very long mountain. Measurements were made of time, fuel used, and SoC in Mountain Mode until the engine generator turned off (Figure 2).

With knowledge of the battery size, the change in SoC, and the fuel used at the observed Mountain Mode steady state 1700RPM engine operating speed, the energy conversion ratio (ECR_{phev}) of approximately 8.4kWh/gallon was calculated according to equation (2).

$$\textit{Battery Size} \bullet \Delta\, \textit{SoC} \bullet 1/(\textit{Gas Consumed}) = ECR_{phev}\ (\textit{kWh/Gal}) \quad (2)$$

With:

Battery Size = 16kWh
Final SoC = 40%
Initial SoC = 19%
Gas Consumed = 0.40 gallons

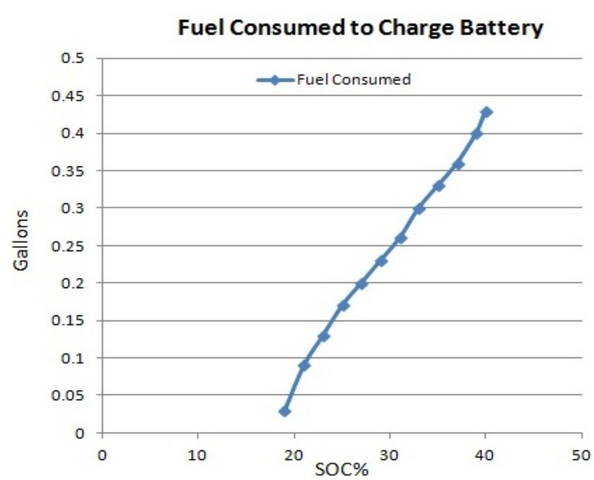

Fig. 2. PHEV Fuel Consumed versus SoC (2011 Volt)

The average power output at the steady state engine operating speed of 1700rpm was calculated to be approximately 12.4kW according to equation (3).

$$Energy\ (kWh)\ /Elapsed\ \ Time(h)=\ Average\ Power\ (kW) \quad (3)$$

With:
Energy = 3.36kWh
Elapsed Time = 0.27h

The engine output maximum is stated as 63kW SAE Net power, well above the observed 12.4kW output level even with conversion to equivalent metrics. The Volt's traction motor is quoted at over 110 kW maximum [10]. Hence, the battery output is assumed to be capable of providing 110kW power output, well beyond the needs of a residential load.

For a rough comparison, an additional calculation was made to estimate the gasoline to electrical kWh output conversion ratio of a large, commercial-scale backup generator using heat rate data [11] for a diesel electric generator and the heating value of gasoline[12]. For these commercial grade large scale generators, a conversion ratio (ECR_{lsg}) of 10.7kWh/gallon was calculated according to equation (4).

$$1/HR\ (kWh/Btu) \bullet HV\ (Btu/Gallon)= ECR_{lsg}\ (kWh/Gal) \quad (4)$$

With:
HR=Large Scale Generator Heat Rate = 10,800 Btu/kWh
HV=Gasoline Heating Value (Lower) = 116,090 Btu/gallon

This ECR_{lsg} includes only the conversion of energy fed into the grid in real time, not into a battery storage system. For a more accurate comparison, this 10.7kWh/gallon must be further derated to include equivalent rectification, voltage conversion, and battery internal resistance. Using the same 88% (η) grid-to-battery conversion efficiency from equation (1), the large-scale generator would produce 9.4kWh/gallon. This approximately 12% better efficiency over the PHEV engine-generator is plausible given the large-scale generator is a purpose built design, assumed to have scale economies in overall efficiency. Furthermore, there may be more efficient operating points for the engine generator than the particular 1700rpm level observed during the experimental measurement. Therefore, the 8.4kWh/gallon PHEV energy conversion ratio is assumed to be reasonable.

C. Scenarios

The homes selected have rooftop PV, PV output data, and whole home load data on a per minute basis for 2012. The simulation models were constructed to enable analysis without and with PV output extending the backup duration. BEV useable net battery capacities were assumed to be 19.2kWh and 32kWh, representative of two commercially available BEVs: a Nissan Leaf [13] and entry-level Tesla Model S [14], respectively. The PHEV usable net battery capacities were assumed to be 3kWh and 10.5 kWh, representative of a Toyota Prius PHEV [15] and a Chevrolet Volt PHEV [16] (slightly larger than a 2011 Volt, slightly smaller than a 2013 Volt), respectively. The PHEV gasoline quantities available were assumed to be 3.5, 7 and 17 gallons. The 3.5 gallon quantity represents the minimal amount of fuel that a PHEV owner may have in their tank under many circumstances. The 7 gallon quantity reflects the amount of gasoline a representative PHEV owner would have in a full tank with a few gallons remaining to drive the PHEV to a distant gas station for refueling (e.g. 2.3 gallons remaining in a 9.3 gallon Chevrolet Volt fuel tank). The 17 gallon quantity represents a PHEV with a considerably large on-board fuel tank or a Volt-sized fuel tank plus additional gasoline stored in two common 5-gallon containers.

IV. KEY INTERFACES WITH THE VEHICLE

The common vehicle power interface for PEVs in the U.S. is the SAE J1772 [17]. This standard provides for both AC and DC interface capabilities with various power capacities. The AC interface standard supports grid-common 120V or 240V 60Hz AC power with the vehicle incorporating on-board rectification, voltage step up to the appropriate DC battery charging voltage (typically above 300V DC), and all battery related control functions. The AC Level-2 interface defined supports up to 19.2kW.

The DC interface provides a more direct connection to the vehicle's high-voltage/high-capacity traction battery. The DC Level-1 specification supports up to 40kW and the DC Level-2 interface supports 100kW, well above any typical residential home load (typically less than 20kW). Other regions around the world have functionally similar but typically different physical vehicle connectors [18][19]. It is likely that PEV manufacturers will prefer to provide V2H support through a DC interface [20] to provide sufficient power capacity, avoid the complexity of dealing with a large number of regional variations in electrical code and equipment, limit adding additional weight and cost to the vehicle, and a variety of other reasons. The DC interface could be provided by either a ChaDEmo or SAE J1772 connector. Utilizing the universal U.S. SAE AC Level-2 connector for V2H with DC power flow may be possible using the SAE DC Level-1 configuration or for a greater power transfer capability, a SAE DC Level-2 "Combo" connector can be deployed [21]. Associated communication, use case, and interoperability standards that enable control of the V2H session are also under development [22][23][24].

Home AC power could be provided by standard electrical recepticle outlets mounted on the vehicle, electrical recepticle outlets mounted in a weatherproof enclosure mounted on a pole or bollard, or through an Electric Vehicle Supply Equipment (EVSE) plus transfer switch function mounted in the residence. An EVSE is a device that interfaces the grid (or in the case of V2H a single home residential microgrid) to the vehicle for charging. Transfer switches are common devices used in conjunction with backup generators to isolate the home from the grid, switch the desired circuits to be fed by the backup generator, and then switch back once power is restored by the grid. The EVSE+Transfer switch function would provide the most seamless integration to the home for an off-grid backup power V2H scenario.

V. RESULTS

Simulation models used Pecan Street home load and PV data, calculated energy conversion ratios, power output levels, conventional PHEV control algorithms, and a variety of battery (BEV: 19.2kWh and 32kWh, PHEV: 3kWh and 10.5kWh) and gas supply sizes (3.5, 7, and 17 gallons). The simulations showed that the PHEVs and BEVs can provide considerable backup capability, particularly during seasons with modest load, for homes with PV installed and with strong PV output. Figure 3 shows the backup duration of a BEV V2H system with and without PV and the substantial benefit of rooftop PV for a V2H system. It is interesting to note that the 32kWh battery (67% larger than the 19.2kWh BEV battery) did not provide commensurately greater backup duration in non-PV BEV V2H system, mostly from spillage. By reducing spillage, intelligent load control, curtailment, or shifting may be much more valuable than a considerably more expensive battery under some circumstances.

The volume of gasoline available for PHEVs is the most important determinant of overall backup duration given the considerable energy storage provided by each gallon of gasoline, effectively 8.4kWh per gallon. The battery size is the most important factor for the BEV system throughout the year. During off-peak months, the PV output complements the PHEV generator to substantially extend backup durations from a few days to nearly 25 days (Figure 4).

Prior studies of community level storage [25] have shown that the time at which an outage begins for homes with PV can be a large determinant of the backup duration. The storage must have enough energy to maintain the load until the PV can start producing.

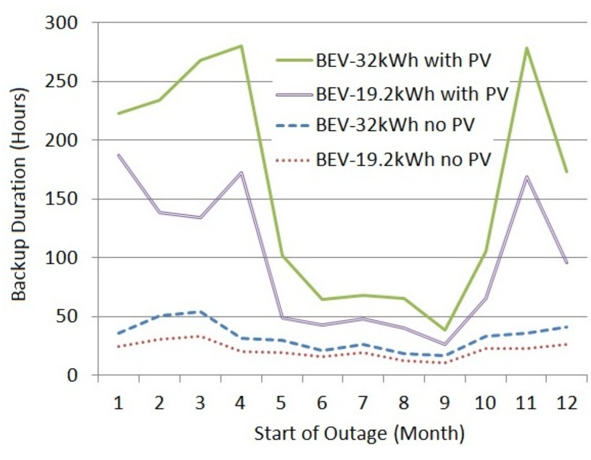

Fig. 3. BEV Backup Durations (20 home average) with and without PV for outages starting the 1st day of each month with 32kWh & 19.2kWh battery sizes

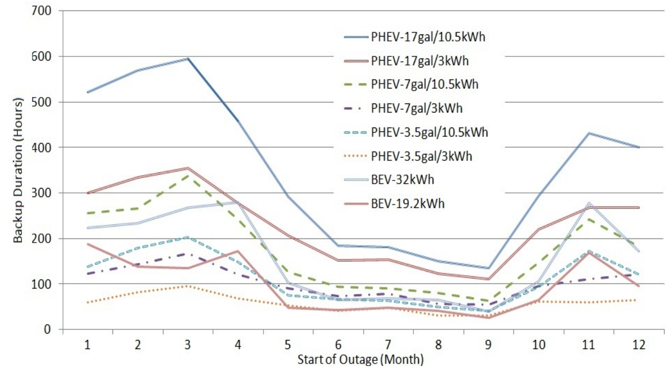

Fig. 4. PHEV and BEV Backup Durations (20 home average) with PV for outages starting the 1st day of each month with varied battery and gasoline tank sizes

The initial charge understandably would have the greatest effect on a BEV-V2H system without PV. However, given PV needs a working storage system to not shut down, if the initial SoC is low, a BEV with PV system backup duration could be meaningfully shortened if the battery is exhausted before the PV production can ramp up.

Given the relatively large energy potential of storage gasoline, PHEV based V2H is relatively insensitive to the initial battery charge, with only modest amounts of gasoline available. This analysis assumed initial state of charge was 100% given lower initial levels can be approximated as smaller BEV battery sizes, initial SoC having negligible impact on PHEVs, and the need to reduce the complexity of the analysis.

For advanced systems, it is conceivable that a home energy management system (HEMS) and PEV could coordinate using weather service information to modify the charge rate of the PEV (i.e., if a storm is approaching, then charge the vehicle as rapidly as possible to increase the possibility of reaching 100% SoC before a grid outage).

A possible optimal control strategy for cases where the initial BEV state of charge is low may be to shut off load support during the remaining portion of the night and later use the remaining BEV battery charge to support the single home residential microgrid equivalent of blackstart [26] once the rooftop PV production has increased sufficiently to recommence supporting the load and begin charging the battery.

When the battery is fully charged and the PV is fully serving the load, the opportunity to capture any additional PV energy is lost. This loss is named "spillage" in this paper.
Small battery PHEV configurations suffered disproportionate PV spillage compared to their overall backup duration. A Home Energy Management System (HEMS) to shift load would be particularly useful for this circumstance to maximally extend the backup duration.

The simulation model developed for this analysis used a conventional algorithm for PHEV engine-generator control. This algorithm typically allows the battery SoC to drop to a lower control bound with the engine off, then deploys the engine-generator until the battery is charged at a higher control bound to achieve efficient operation and low emissions. In this model, 0% SoC of the net usable battery capacity was the lower control bound and 100% SoC of the net usable battery capacity was the upper control bound. For a PHEV V2H system without PV, this control algorithm was a good fit. However, it was discovered from the simulation data that for a residential PHEV V2H system with PV, there are periods where this control system is a poor fit. In certain cases the battery becomes fully depleted early in the morning immediately before the sun rises and PV begins production. When the engine-generator commences operation using the conventional control algorithm it will then fully charge the battery. If the PV generation is strong and/or the load is low, the battery then has limited capacity to capture this PV energy, and the energy is spilled, as shown in Figure 5. A more optimal engine-generator control strategy may be to charge the battery to some lesser upper SoC control bound for PV-V2H systems to save gasoline, provide just enough spare capacity in the battery to capture the excess PV energy, and extend overall backup duration. Ideally, this engine-generator algorithm could be fully optimized with time of day, PV production history and projections, load projections/HEMS coordination, and weather forecasts.

With additional optimization of the generator control and intelligent load shifting, the amount of PV energy spilled could be reduced and the overall backup duration could be extended. Table 1 illustrates the amount of PV energy lost to spillage. In a number of cases the potential to extend backup duration is considerable.

Another possible optimal control strategy might provide blocks of usable PV enabled backup. This algorithm would cease supporting load by the battery before the battery is fully depleted. By doing so, the remaining battery charge would be available to restart the ability to power the home load (or provide single home residential microgrid blackstart) the PV system once PV production resumes. While this method would not provide continuous uninterrupted power, it has the potential to indefinitely provide sustainable power for blocks of time every day that the PV is providing output.

TABLE I
PHEV PV SPILLAGE (KWH OF ENERGY LOST)

	Fuel Tank Size/Battery Size					
Outage Start	17gal/ 10.5kWh	7gal/ 10.5kWh	3.5gal/ 10.5kWh	17gal/ 3kWh	7gal/ 3kWh	3.5gal/ 3kWh
Jan	147.9kWh	89.0	50.6	127.5	63.4	34.6
Feb	153.0	56.7	37.0	110.9	34.8	20.0
Mar	194.0	111.5	62.2	150.1	81.3	50.9
Apr	161.0	93.3	51.4	139.0	64.1	36.1
May	68.4	25.2	16.4	71.3	29.8	18.8
Jun	30.2	18.2	15.0	40.3	24	17.1
Jul	25.9	14.1	10.4	34.7	20.4	12.4
Aug	26.9	16.4	10.5	36.3	18.7	11.0
Sep	24.0	9.5	4.9	28.5	12.8	7.3
Oct	66.2	40.8	30.7	79.4	47.9	34.6
Nov	127.4	78.7	57.1	120.3	54.8	31.7
Dec	91.0	32.7	21.6	82.8	36.4	16.9

Large BEV batteries can provide considerable backup duration combined with PV. The simulation results show the batteries became fully depleted once a period of poor PV production and/or large load occurred (Figure 6), terminally exhausting the battery.

During a grid outage, a V2H system, particularly with PV, has the ability to have considerable backup power duration extension with selective load level changes. In a simulation using one of the home load/PV profiles, the worst case backup time period (September start month, a PHEV with a 3kWh battery and only 3.5 gallons of gas was extended from to 18.7 hours to 26.7 hours with a crude 50% reduction in load. It is interesting to note that with a 50% reduction in load, the duration was increased less than 2x from the non-advantageous timing between PV and this particular load, which resulted in considerable spillage of PV energy. Load shifting by the HEMS or behavior changes by the residents (e.g. washing clothes during PV production periods where PV would otherwise be spilled) could extend the backup duration.

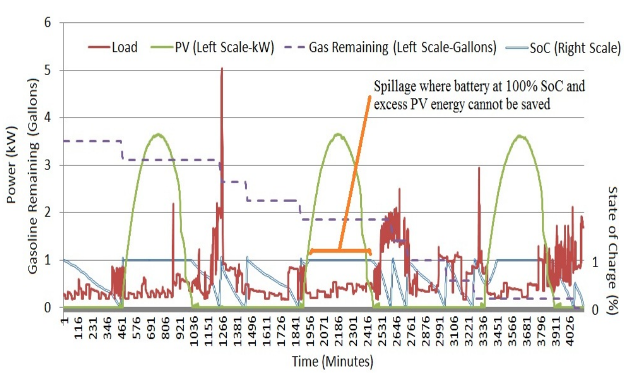

Fig. 5. PHEV SoC, Load, PV output, and remaining gasoline over a backup event (Note spillage during high PV output where SoC is at the maximum 100%).

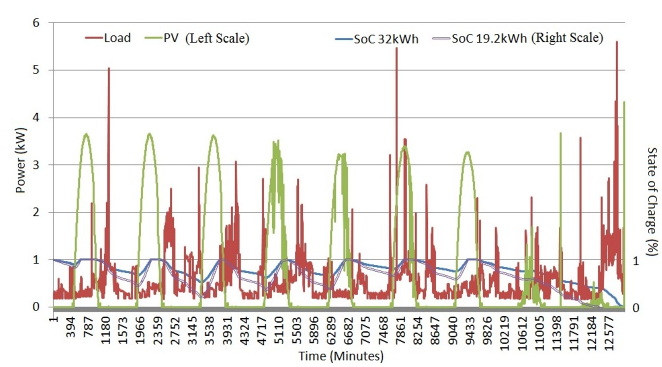

Fig. 6. BEV SoC, Load, PV Output over a Backup Event (note the longer duration with the larger 32kWh battery).

Various optimal control stategies could be devised for different outage scenarios. If an outage occurs from a localized distribution fault with a modest outage duration, the HEMS could decide to simply use the PEV for seamless backup without any load modifications. If a large storm creates an outage and weather alerts have been issued, the system could be programmed to significantly limit loads to essential functions only (e.g. refrigerator, lights, pumps, communications) to maximize backup duration until the home occupant overrides the system or indicates an estimated restoration of grid electrical service. With this estimate of restored service, the HEMS could then optimize the load automatically in the case of intelligent devices or provide guidance to the occupant on optimal times to deploy particular loads (e.g.: HVAC, clothes washing, electric hot water heating)

VI. CONCLUSIONS

Combining a BEV or particularly a PHEV with a PV system provides the opportunity to create a single home microgrid with considerable capabilities to provide backup power. PV systems typically must turn off their inverter output if the grid power is lost (or if there is no energy storage to create an off-grid microgrid). With an electric vehicle based storage node, the V2H system can create an off-grid microgrid that has the sufficient voltage regulation, energy storage, and safety disconnects. Our results indicate that a residential V2H system coupled with rooftop PV could provide backup power for approximately 19-600 hours, depending on the time of year and the precise vehicle configuration. Particularly with curtailed or shifted load during a grid emergency situation, an electric vehicle based V2H-PV microgrid system could provide considerable backup duration capability supporting the conventional home load. More intelligent microgrid control systems, better optimized PHEV engine generator control algorithms, and selective load curtailment could further extend backup duration. Furthermore, sophisticated V2H control systems could save a modest portion of remaining battery power to blackstart the PV system to enable self-sustaining non-continuous power indefinitely.

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