Innovative energy storage solutions for future electromobility in smart cities

Kevin Green, New Technologies, QinetiQ ltd, United Kingdom

Salvador Rodríguez González, Green Power Technologies, Spain

Ruud Wijtvliet
Centrosolar Group AG
Germany

Abstract— **The stochastic nature of renewable energy sources will no doubt place strain upon the electrical distribution networks as power generation is converted to environmentally friendly methods. The use of energy storage technologies could significantly improve the usability of these energy sources. A domestic installation, based on a 4 kWh energy storage unit, is under development and modeling shows that the proposed unit would improve the energy autonomy of a household.**

Keywords—Battery energy storage, photo-voltaics, smart grid.

I. INTRODUCTION

The fundamental property of renewable power, such as wind and solar, is that it is intermittent. The use of energy storage technologies, such as batteries, compressed air (CAES) or thermal means is seen as route to increasing the effectiveness of renewable energy sources [1].

As Europe, which has a target of a 20% reduction in CO_2 emissions by 2020 compared to 1990, seeks to increase its use of renewable power, this will stress the electrical distribution network. The stochastic nature of renewable power for instance cannot be relied upon to provide peak power in the evening when motorists recharge their vehicles. The increased uptake of electric vehicles is a fundamental element in Europe's strategy for CO_2 reduction; it also promotes increased energy security by reducing the dependency on oil. In Europe it is expected that full battery electric vehicles (EV) will gain a higher market share than plug-in hybrid vehicles (PHEVs) and this will require the supporting infrastructure to be installed [2].

Recent developments in information technologies are supporting the development of the Smart Grid, which could enable increased efficiencies in both energy and power usage, for instance recharging the vehicle overnight rather than immediately upon connection [3]. The smart grid encompasses such developments as smart metering and e-billing as well as allowing real-time pricing data to be exchanged. In parallel, the use of photo-voltaic (PV) systems is being adopted across Europe not only to reduce CO_2 emissions, but also as a method of reducing household bills. The capability to store captured PV energy ensures a greater degree of energy independence, or autonomy, for a household. Domestic energy storage could dramatically alter the electrical demands of a household from the local electrical distribution grid [4]. There are several scenarios which encompass distributed energy storage devices as part of a future smart grid. Some of these scenarios use EVs to store the energy, but the presence of an EV to absorb excess power at the correct time is not guaranteed. Accordingly a dedicated domestic storage system could be utilised. A home energy storage device would support the emerging market for such systems leading to greater energy independence and flexibility within a future smart grid.

II. MODELLING

A. System design and key parameters

To determine the potential impact of an installed system, the combination of PV, inverter and battery pack can be modelled. In the model the key parameters were the increase in self-consumption fraction (part of produced PV energy that is consumed within the household) and the autonomy fraction (part of consumed energy that is produced by PV) attainable with a battery system.

To complete the model two scenarios are compared:

1. With battery system: surplus PV production is stored until the battery is full, surplus consumption is taken from the battery until fully discharged; boundary condition that (dis)charge power is less than or equal to the battery inverter maximum power.
2. Without battery system: only self-consumption of PV production that happens to occur simultaneously with consumption. This is called the base case.

In these, three quantities are important:

a. Grid-consumption: the amount of energy [kWh/annum] used for consumption, that is taken from the grid (and not from the PV installation);

b. Self-consumption: the amount of energy [kWh/annum] used for consumption, that is (ultimately, in case the energy is stored in batteries) taken from the PV installation;

c. Fed-in production: the amount of energy [kWh/annum] from the PV installation that is fed into the grid (and not consumed within the house).

The self-consumption and autonomy fractions are calculated in the following ways:

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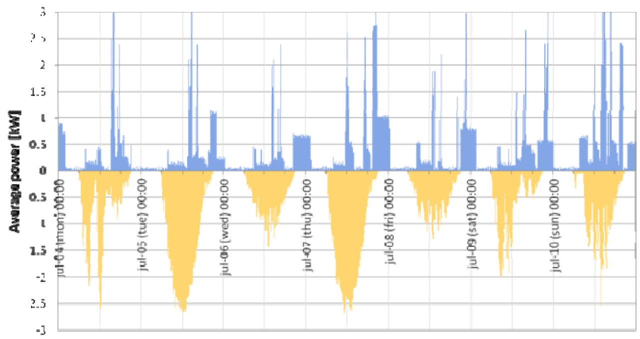

Fig. 1. Modelled power production and consumption for a UK household during July

$$self-consumption\ fraction = \frac{b}{(a+b)} \quad (1)$$

$$autonomy\ fraction = \frac{b}{(c+b)} \quad (2)$$

B. Modelling results

To calculate the power produced by the PV sub-system a south-facing, optimally-inclined, 4 kWp PV installation is taken in mid-UK, with an irradiance of 950 kWh/m^2/annum. The performance ratio is taken to be 80%, which is common for modern installations of this type. The simulation model included power production values with a time resolution of fifteen minutes.

Two load profiles are taken, each for a typical four-person family – parents and two children. The profiles are each for a total yearly consumption of 4500 kWh/annum, but one has "daytime use", meaning that there is always someone at home during the daytime, and the other has "no daytime use", meaning that it is assumed no one is at home during working days, 9:00-17:00. This distinction has to be made, as it has a large impact on the outcomes. In the model the consumption curves are available with a time resolution of fifteen minutes.

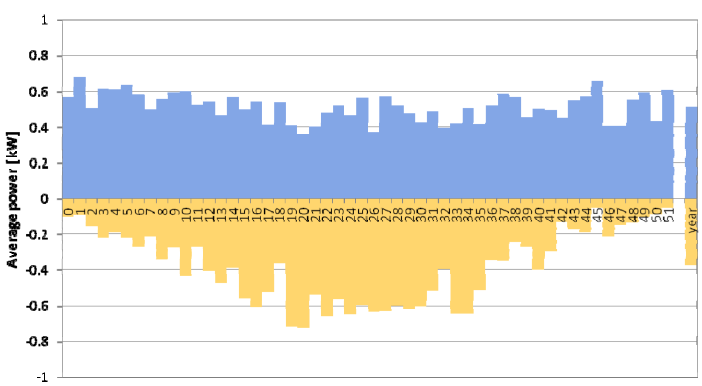

Fig. 2. Modelled power production and consumption for a UK household during a typical year

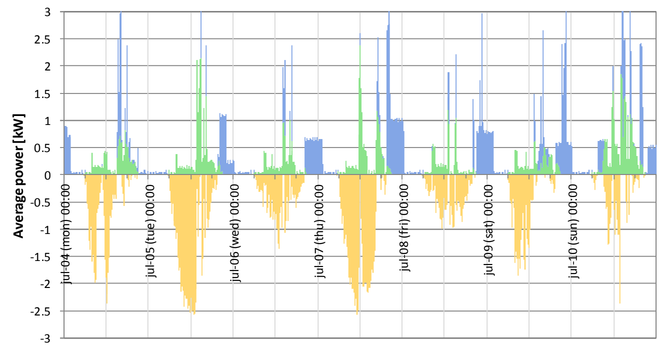

Fig. 3. Modelled power production and consumption for a UK household during a typical week of July

In Fig. 1 the consumption (positive, blue) and production (negative, yellow) power are shown for each 15 minutes interval during a July week, and Fig. 2 shows the PV power generation and household power consumption modelled over an entire year.

When it is analysed which part of the PV production is used towards covering the consumption, the July week above changes to become Fig. 3. In it, the consumption is now split into consumption from PV (green) and consumption from the grid (blue). The surplus PV production, which is fed into the grid, is shown in yellow.

By adding the green, blue and yellow areas for the entire year, the values for the self-consumption and autonomy fraction can be calculated. For each of the two consumption cases, these are given in Table 1.

TABLE I. MODELED VALUES FOR BASE CASE SCENARIO (NO ENERGY STORAGE)

Usage	Calculated efficiencies	
	Self-consumption Fraction	***Autonomy Fraction***
No Daytime Use	18%	13%
Daytime Use	39%	29%

When an energy storage device is included in the system the energy transferred between the distributed electrical network and the household is dramatically reduced. For the model, the battery energy storage capacity is assumed to be 4 kWh, with a maximum (dis)charge rate of 2 kW and a "round-trip" efficiency of 91%.

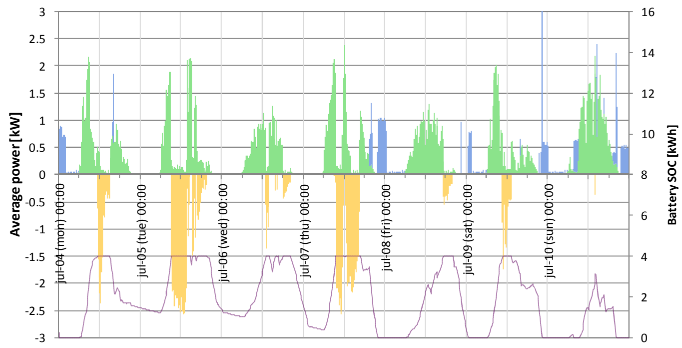

Fig. 4. Modelled power production and consumption for a household PV system including an energy storage element

C. *Modelling results*

The key indicators of the use of a battery system are the increases in self-consumption and autonomy it achieves, compared to the values one would have achieved without it.

TABLE II. MODELED VALUES FOR BASE CASE SCENARIO WITH 4 KWH ENERGY STORAGE

Usage	Calculated efficiencies	
	Self-consumption Fraction	***Autonomy Fraction***
No Daytime Use	57%	40%
Daytime Use	74%	53%

D. *Effect of energy storage capacity on modelled results*

The effect of size of the energy storage module on the results was also modelled. This can also be seen from Fig. 5, where the two parameters are shown in dependence of the battery size, for sizes between 1 kWh and 14 kWh.

The model highlights the fact that each additional kWh of battery capacity is increasingly less used, as evidenced by the reduction in gradient of the curves. The slope of the curve shows that for small battery systems, a self-consumption increase of about 10.0%/kWh is reachable.

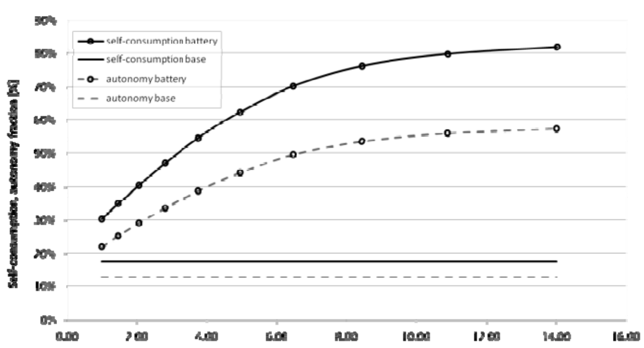

Fig. 5. Effect of energy storage capacity on system performance (no daytime use)

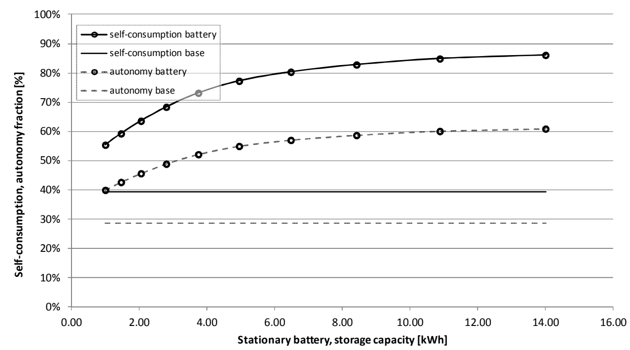

Fig. 6. Effect of energy storage capacity on system performance (daytime use)

For the case where there is someone at home during working days, the obtained increases for the 4 kWh pack are shown below, as well as the dependence on other battery pack sizes in the graph.

Although there is a large difference between the base values for the 2 household types, the increases are very similar; the increases for this household type being a slightly lower. This can be explained by the fact that the presence of a lot of daytime consumption reduces the availability of surplus PV production to store and use later.

III. PRACTICAL DEVELOPMENT

In order to realise the benefits of a smarter energy storage option, QinetiQ is developing a 4 kWh energy storage module, Fig. 7, in line with the above model. Large community energy storage systems (25 kWh) are already becoming available but a smaller unit could be installed as part of a household PV system. Although a larger system would enable greater autonomy, this would be at a higher price. According to the model, beyond 4 kWh there is a decreasing benefit by increasing the energy storage.

The module is based on lithium-ion batteries. Battery-based systems are perhaps the most familiar energy storage device and have been used for many large and small scale applications. Using the module design, larger systems could be simply constructed by connecting the 4 kWh units in parallel.

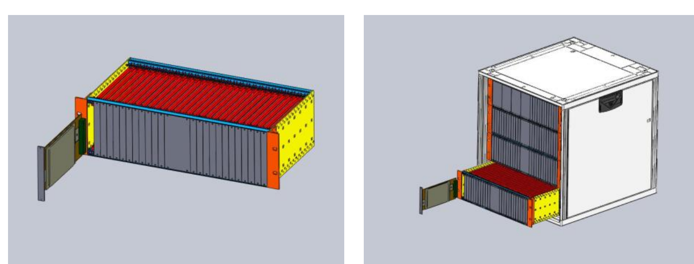

Fig. 7. Drawings of the 4 kWh energy storage module, showing individual ‘tray’ (left) and assembled unit (right)

The cells are being designed and built by QinetiQ using the latest in high performance materials. The lithium-ion cell offers a high energy density, but at a cost higher than its competitors, such as lead-acid. The lithium cells are 13 Ah with an energy density of 205 Wh/kg, which is superior to many commercially available pouch cells. The pouch cell construction uses a plastic-aluminium laminate packaging to prevent moisture ingress into the cells. Lithium-ion cells are very sensitive to water contamination and are assembled in low humidity conditions.

TABLE III. KEY PARAMETERS OF ENERGY STORAGE STATION

Parameter	Value
Capacity	4 kWh
Voltage range	226.8 - 352.8 V
Charging	External charging, max current 20 A
Std. discharge current	13 A
Max discharge current	40 A
Operating temperature range	10 to + 45°C

The energy storage module consists of 84 13 Ah lithium-ion cells connected in series. The cells are arranged in seven banks of twelve cells, providing a 84S1P configuration. The voltage range of 235 – 352 V has been specifically chosen as it corresponds to the operating voltage of the GPT charger/inverter.

The energy storage module will initially be integrated with a charger/inverter supplied by Green Power Technologies (GPT), Spain, Fig. 8. The charger/inverter automatically controls the power between the electrical grid and the energy store. The communications between the two devices is based upon the common MODBus protocol.

Fig. 8. Green Power Technologies solar inverter system

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To reduce price and development time the units will be assembled on a standard 19" rack mount chassis. Six of the modules will be arranged in three banks of two, whilst the seventh module will be in a separate layer with the microprocessor which provides the monitoring and communications functions. Each separate module of twelve cells is monitored by a battery management system (BMS) processor which communicates to the master microprocessor through a CAN interface. The temperature and voltage of each cell voltage is monitored to ensure safe operation, and alerts if over/under voltage conditions are present. Monitoring is accomplished by a range of off-the-shelf integrated circuits. Further secondary protection is provided by another sub-system in case of failure of the monitoring system.

Cooling is provided through a tray of fans located at the bottom of the unit forcing air up through the rack. The fans automatically turn on when a pre-set temperature limit is reached.

The current is measured to ensure it sits within the pre-set values. For standard operations, there will be no user interaction as all of the functions are automatic. Solid-state switches are controlled by the master microprocessor and the secondary safety layer, so that in the event of a pre-set condition being met the unit switches off and is electrically isolated.

A. Modes of operation

The sub-system will ultimately be linked to the building energy manager (BEM) which will be linked to the internet gateway by a local WiFi network. The BEM will provide real-time pricing information and ultimately could control whether the unit is charging or discharging.

Although the 4 kWh energy capacity is large compared to mobile consumer devices it is small compared to electric vehicles (typically 30 kWh or more) and daily domestic power consumption. The modules themselves have a cycle life that is dependent upon the depth of discharge, amongst other factors, and complete discharges reduce the cycle life of the battery. Shallow or low discharges do not age a battery so much. As a result of the gradual degradation of the battery through cycling, every Joule extracted from the module has a corresponding value that varies according to the cycle life of the battery (defined as the number of charge/discharge cycles completed) and the depth of discharge of that cycle. The BEM will need to interact with the module to determine the benefits of charging or discharging the battery against a given market rate for the electricity. For instance it might make economic sense for the battery to be discharged during peak times (such as the early evening when the occupants return to the house) when electricity prices are likely to be at a premium and recharge overnight when electricity prices are lower.

It seems evident that the BEM will also need to calculate whether it is economically sensible to charge the energy storage device during the day with excess power or to sell this to the local Distributed Network Operator (DNO).

These modes of operation can be viewed as significant discharges. In addition, the increasing fraction of renewable sources within the power generation network might mean that the quality of generated/ received energy is poorer or suffers from transient fluctuations. In which case, the local energy store could be used to ensure voltage and frequency regulation for the household.

As the concept of the Smart Grid develops it is anticipated that the functionality of the energy storage module will be extended.

IV. CONCLUSIONS

The model for a PV-energy storage system shows that increases in energy independence can be achieved with the addition of an energy storage device. Larger energy storage units do not necessarily benefit of an energy storage system as have has been modelled.

A 4 kWh system is being developed with interfacing to a commercial charger/inverter. The small module will enable greater autonomy for households to be realised.

The smart grid will enable real-time pricing to control the charge/discharge of the sub-system to maximise the economic benefits of the energy storage device that should also reduce the associated CO_2 emissions.

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