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Secondary Re-Use of Batteries From Electric Vehicles for Building Integrated Photo-Voltaic (BIPV) applications

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WP7: Integration of energy management and storage systems to improve BIPV

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1. Introduction

PV Crops is evaluating the use of battery technologies such as Vanadium Redox within Building Integrated Photovoltaic (BIPV) applications. However, their inclusion into BIPV systems will inevitably raise the overall costs of such systems. As a result, PV Crops is looking at other measures in parallel to help lower the costs associated with such systems. One particular area of interest is the potential secondary re-use of battery technology from Electric Vehicle (EV) market as a way of mitigating high costs of such systems as well as a means of encouraging battery recycling.

The global installed capacity for Photovoltaic's (PV) connected to the grid was 139 GW in 2013. This is expected to increase to an installed capacity of between 321 GW (low growth scenario) and 430 GW (high growth scenario) by 2018 [1]. Approximately two thirds of PV installations are connected to buildings, with the remainder accounting for large scale utility ground mounted systems. Like most renewable energies, BIPV generation suffers from intermittency and therefore when insufficient supply exits demand is met by importing electricity from the grid. Similarly, when supply exceeds demand surplus electricity is exported to the grid. The introduction of storage into BIPV systems negates the need for regular import/export of electricity from the grid which can lead to voltage and frequency disturbances. As a result, it allows for greater renewable energy penetration at the distribution grid by balancing supply and demand at a local level. Furthermore, integrating storage into BIPV systems can potentially assist the grid operator by facilitating demand response and frequency regulation which can help stabilise the network.

The secondary re-use of batteries within the automotive industry is also being considered as a mechanism to improve the affordability of purchasing such vehicles. Currently, the battery component within Plug-in Hybrid (PEV) and Battery Electric Vehicles (BEV) represents a significant proportion of the overall capital costs. However, batteries that reach the end of their useful lifespan within the automotive industry can still be considered for other applications as between 70-80% of their original capacity still remains. In extending the useful lifespan of EV batteries for secondary applications such as BIPV, the re-sale value could potentially make EV purchase more attractive from an economic standpoint.

1.1 Objectives and Scope

The objective of this study is to examine the feasibility of using recycled EV batteries from the automotive industry for use within BIPV applications. The study aims to inform both public and private parties as to the current state of the art and lead to better informed policy decisions at an EU and national level going forward. The study also acts as a source of information for the latest market developments and trends within the industry. The specific aims of the study are the following:

- Determine the current status of both the EV and BIPV markets worldwide
- Present growth for both EV and BIPV markets up to 2020 and beyond
- Determine the suitability of re-using EV batteries for use within BIPV applications
- Discuss the technical and economic barriers of re-using EV batteries for BIPV applications

2. EV market and battery availability

The EV market can be segmented into three technologies based on the manner with which electricity is used to power the vehicles. Three categories exist: Hybrid (HEV); Plug-in Hybrid (PHEV) and Battery (BEV) Electric Vehicles. HEV's use a combination of an Internal Combustion Engine (ICE) and electricity stored in an on-board battery to power the vehicle. Battery sizes for HEV's are typically small, less than 3kWh, and utilise electricity generated from the ICE as well as through regenerative breaking to charge the battery. As HEV battery sizes are small in comparison to PHEV's and BEV's, these will not be considered for secondary re-use within this study.

PHEV's are similar to HEV in that they also use a combination of an ICE and batteries to drive the vehicle. However, battery sizes are significantly larger (4-16kWh) and utilise power from the electricity grid to charge the battery. In contrast to HEV's and PHEV's, BEV's exclusively use electricity stored in a battery to drive the vehicle. As there is no other method to power the vehicle, battery sizes are typically large (20-85kWh) and also use electricity from the grid to charge the battery. A sub-category of this group, Extended Range Electric Vehicles (EREV), consist of similar battery capacities to BEV but also have an ICE for extended driving without charging.

The International Energy Agency (IEA) published a roadmap, which it aims to achieve 50% of all new light vehicle sales to come from EV's by the year 2050 [2]. Figure 1 shows indicative worldwide EV sales for BEV and PHEV up to 2050. The figure shows PHEV is expected to continue to outsell BEV and that from 2020 onwards there will be a significant rise in EV vehicle sales each year.

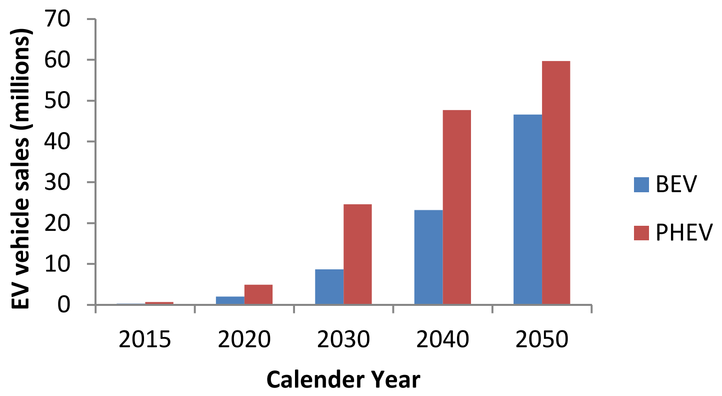


Figure 1: Global EV sales for BEV and PHEV [2]

Table 1 shows a selection of EV model types; their battery technology and capacity; and their market share based on 2013 sales. Lithium-Ion (Li-Ion) batteries are almost exclusively used in PHEV's and BEV's on account of their superior specific energy and power characteristics when compared to Nickel–Metal Hydride (NiMH) [3]. This is primarily because both PHEV's and BEV's are heavily reliant on the battery component of the vehicle to provide the necessary power to drive the vehicle. In contrast, HEV's take most of their power from the ICE, only occasionally relying on the battery to provide power. As a result, specific energy capacity is of less of a primary concern than it might be in PHEV's or BEV's.

Table 1: Top selling PHEV and BEV worldwide in 2013 [4]

Vehicle Make & Model	EV Type	Battery Technology	Battery Capacity	Market Share 2013 (%)
Nissan Leaf	BEV	Li-Ion	24 kWh	23%
Chevy Volt	PHEV	Li-Ion	16.5 kWh	13%
Toyota Prius	PHEV	Li-Ion	4.4 kWh	11%
Tesla Model S	BEV	Li-Ion	60/85 kWh	11%
Mitsubishi Outlander	PHEV	Li-Ion	12 kWh	9%
Renault Zoe	BEV	Li-Ion	22 kWh	4%
Volvo V60	PHEV	Li-Ion	12 kWh	4%
Ford C-Max Energi	PHEV	Li-Ion	7.6 kWh	3%
Ford Fusion Energi	PHEV	Li-Ion	7.6 kWh	3%
Renault Kangoo ZE	BEV	Li-Ion	22 kWh	3%

The expected lifespan of Li-Ion batteries for both PHEV and BEV is estimated to be between 5-15 years [5]. The reported wide deviation in longevity is related to the technology not reaching full maturity within the market. As a result, much uncertainty surrounds the long term performance of Li-Ion batteries within EV's. This has led to some of the larger manufactures such as Nissan and Tesla to guarantee their battery performance for eight years or 100,000 miles (160,000 km) in order to increase confidence in the market [6][7].

As a result of the predicted rise in EV sales, the rechargeable battery market is currently going through a period of significant growth. This is illustrated in Figure 2 where the automotive Li-Ion market size is predicted to grow from just over 10 billion USD in 2014 to over 30 billion in 2018 [8]. As part of this is Tesla motors planned "Gigafactory" in California which is due to start production from early 2017. The factory will have the capacity to produce battery packs for over 500,000 vehicles by 2020 and will have the capability to recycle Li-Ion batteries [9].

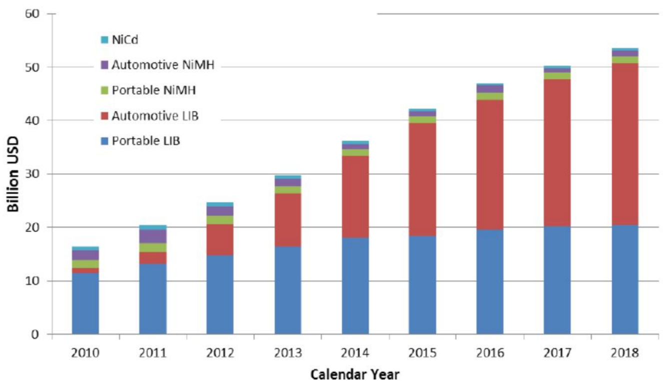


Figure 2: Worldwide market value for rechargeable batteries up to 2018 in billion USD [10]

However, the number of both PHEV and BEV only started being sold in significant numbers since 2010. As a result it is envisaged that reconditioned EV batteries will not become available in significant numbers until 2020. Figure 3 provides an estimate as to the potential battery storage capacity available assuming a ten year life-span prior to being reconditioned. The predicted capacity is based on estimated sales for BEV and PHEV from Figure 1 and assumes battery capacities of 24kWh and 16.5kWh respectively. It also assumes that only 50% of batteries are able to be reconditioned and at 70% of their original capacity. The graph shows that by 2025 nearly 7GWh of potential storage capacity could be available before steadily increasing to a total of over 700 GWh by 2060.

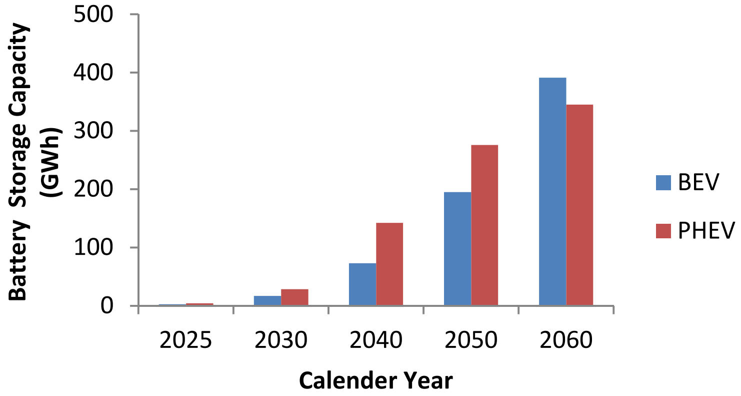


Figure 3: Potential availability of annual worldwide battery storage capacity available for BEV and PHEV

3. EV battery technology

Li-Ion technology has come to dominate both PHEV and BEV markets of late as was illustrated in Table 1. NiMH battery technology was popular among car manufactures Toyota, Honda and Ford in the early 2000's, however, more and more manufactures have now opted for Li-Ion on account of their higher energy and power capabilities. Therefore previous studies on the secondary re-use of EV batteries carried out in the early 2000's have tended to focus on NiMH as opposed to Li-Ion [12].

Figure 4 shows a comparison of specific energy and power capacities for a range of different battery technologies. Li-Ion has high specific energy characteristics, thus making them suitable for driving extended distances without having to recharge. Furthermore, Li-Ion also has high specific power which enables increased vehicle acceleration speeds. Similarly, NiMH also has the capacity for high specific power, however, its specific energy is much less when compared against Li-Ion. As a result, Li-Ion has become the technology of choice for both PHEV and BEV in order to meet the demand for increased driving ranges within the industry.

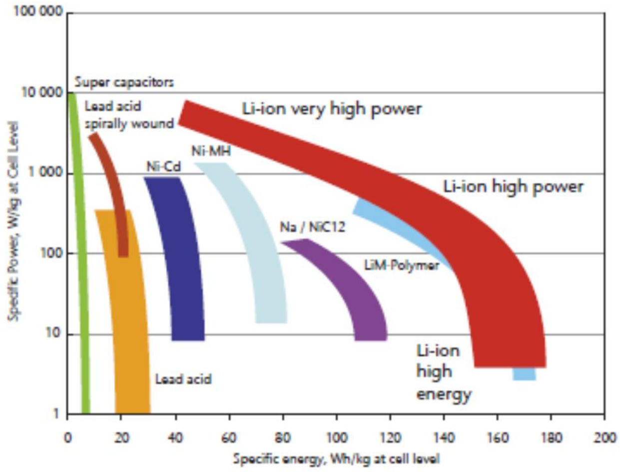


Figure 4: Specific power and energy by battery technology [2]

Technology costs have also been a factor in the move from NiMH to Li-Ion batteries for vehicle applications. In recent years Li-Ion batteries have become cheaper than NiMH both in terms of specific energy and power as is shown in Table 2 [13]. In terms of power, Li-Ion has considerably lower costs which make them more attractive to both the automotive industry and other secondary applications which will be discussed later. However, neither technology can compare to lead based batteries in terms of cost, which have been commercially available since the 1890's and still remain far cheaper than either NiMH or Li-Ion. Lead based batteries are unsuitable for PHEV and BEV on account of their low specific energy. Nevertheless, they provide an interesting comparison as to the possible future costs for Li-Ion once technological learning (i.e. reductions as technology manufacturers accumulate experience) matures within the sector. Therefore, for comparative purposes, both NiMH and lead based batteries are presented alongside Li-Ion in the following tables. It has been suggested that for Li-Ion to replace lead based batteries in stationary applications, technology costs will need to drop below that of €200/kWh [14].

Table 2: Technology battery costs for specific energy and power [13]

	Cost	
	€/kWh	€/kW
Lead based	100 - 250	10 - 25
NiMH	400 - 500	910 - 1,140
Li-Ion	300 - 450	100 - 200

There is much uncertainty as to the long term performance of Li-Ion batteries in EV's for a number of different reasons. Firstly, PHEV's and BEV's have really only become commercially available in significant numbers since 2010. Therefore there has not been sufficient time to collect data relating to the long term performance of the batteries within these vehicles. Secondly, few studies exist on the actual performance of the batteries in PHEV's and BEV's. Literature to date has focussed on testing batteries in laboratory environments rather than on real life studies where many factors combined may contribute to a shortening of their lifespan. Table 3 shows an approximation as to the lifetime for each battery technology with Li-Ion expected to last ten years before a replacement is required [13]. It must be noted that battery operating conditions such as: temperature, depth of discharge and re-charge rate can all have a significant bearing on battery longevity and also need to be considered.

Table 3: Expected battery lifetime [13]

	Lifetime (years)
Lead based	5 - 7
NiMH	8 - 10
Li-Ion	10+

High ambient temperatures, especially during charging and discharging accelerate chemical or electrochemical processes within the battery. This has a damaging affect on its chemistry and reduces its performance thus shortening its lifespan. Similarly, recharging at low temperatures should also be avoided particularly in the case of Li-Ion as metal plating can occur resulting in early deterioration for the battery. Contrary to that stated above, high temperatures can also have a positive effect on batteries by lowering their internal resistance, thus increasing efficiency. However, the occurrence of accelerated chemical reactions within the battery has a far greater damaging effect on performance and therefore temperatures for batteries are recommended to be kept within specified operational ranges. Table 4 illustrates optimal temperature ranges for each battery technology [13]. Although Li-Ion can tolerate higher ambient temperature ranges, active cooling is usually used to maintain temperatures below 25˚C thereby minimising any accelerated temperature reactions that may lead to a reduction in battery life.

Table 4: Battery technology optimal operating temperature ranges [13]

	Temperature Range (°C)
Lead based	0 to 40
NiMH	-10 to +45
Li-Ion	-10 to +25

The longevity of a battery is often represented as a function of the number of cycles it sustains over its lifetime before its capacity is reduced to an unacceptable limit. A battery within an EV is deemed to have reached its “end of life” when the vehicle can no longer sustain a minimum travel distance (when the battery is fully charged) or when a certain acceleration is no longer attainable. These points are generally accepted to occur within the EV industry when the storage capacity is reduced by 20% or when the available peak power has decreased by 25% of its maximum [5]. This can be seen to occur in region C in Figure 5 (a) [15]. Unfortunately manufactures tend not to publish data for region D when the battery is nearing its end of life, making it difficult to determine the longevity of the battery during this period.

Capacity fade is the gradual reduction in capability of the battery over its lifetime. Figure 5 shows capacity fade as a function of number of cycles, voltage and time. A cycle refers to the charging and discharging of the battery and this can have an impact on longevity. Therefore battery life is also influenced by how often the vehicle is used. This is illustrated in Figure 5 (b) below where performance decreases for increasing number of cycles. Moreover, even if a battery is not continually in use its capacity still decreases as shown in Figure 5 (c) due to self discharge. Table 5 shows typical daily discharge rates for each battery technology [13].

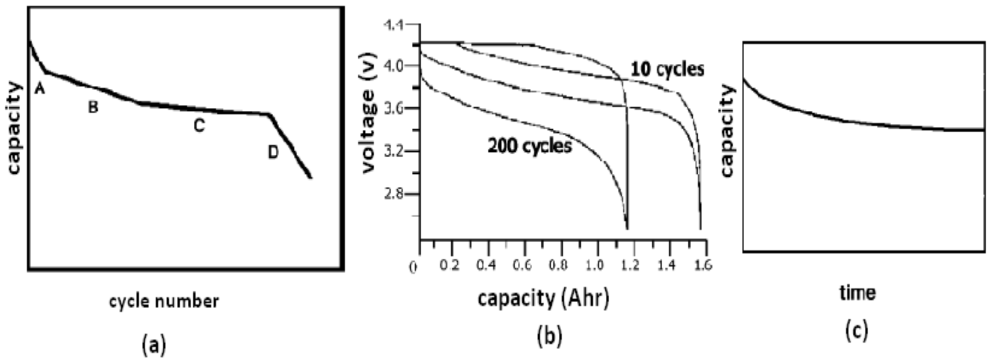


Figure 5: Capacity fade as a function of (a) cycle number, (b) voltage and (c) time [15]

Table 5: Battery technology by daily self-discharge rate [13]

	Discharge rate (%)
Lead based	~ 3%
NiMH	~ 15% to 20%
Li-Ion	~ 5%

The Depth of Discharge (DoD) with which a battery is subjected to over its lifetime can also have a bearing on its longevity. If a battery is routinely cycled through a high degree of DoD it will eventually cause permanent damage to the electrodes and experience a reduced lifespan overall. For this reason EV batteries are normally oversized so as to avoid damaging the battery when subjected to high DoD's. Similarly overcharging also causes premature battery degradation, however, this is usually resolved by using control circuitry to limit battery charging in such instances. Table 6 shows battery longevity as a function of cycles for high and low DoD [13]. Li-Ion and NiMH have a significant advantage over lead based batteries (historically the dominant technology in stationary applications) in terms of their ability to achieve high DoD without battery damage. In addition they do not suffer from any sulfation problems (occurs in lead based batteries when the electrolyte starts to break down) when not fully charged. Li-Ion can sustain a significantly larger amount of cycles when compared to NiMH for both high and low DoD's making then well suited to stationary applications.

Table 6: Battery technology by Depth of Discharge (DoD) [13]

	Depth of Discharge (DoD)	
	Low (≤80%)	High (>80%)
Lead based	600 - 800	--
NiMH	15,000	2,500
Li-Ion	20,000	3,000

The rate at which batteries are charged and discharged can also have an influence on its lifetime. This is called the C-rate and reflects the charging rate relative to its maximum capacity. For example a rate of 2C means that a complete battery discharge can occur within half an hour. Table 7 illustrates that Li-Ion can be charged at a rate of up to 2C (with active cooling) which means it can be fully re-charged within thirty minutes [13]. The ability to charge and discharge Li-Ion batteries quickly has clear advantages in stationary applications over other battery technologies. This is particularly the case for grid applications where short intervals of power may be required in order to provide stability services to the network.

Table 7: Battery technology by C-rates [13]

	C-rate (kW/kWh)
Lead based	0.35
NiMH	1[ab]
Li-Ion	0.5 - 2[a]

[a]Charge must be managed by an active cooling system
[b]Charge must be managed by an adequate electronic and electric control system

C-rates are also highly related to battery operational temperatures. As a battery's internal resistance generates waste heat, the faster the rate of charge the greater amount of heat generated. This has important limitations for EV applications and as a result, active cooling systems are often used to minimise temperature increases. Similarly, waste heat generated from BIPV may be of a concern, particularly when batteries are located close to PV panels. This is often the case in order to minimise electrical losses between BIPV systems and batteries. Therefore, it may be the case that similar to EV applications active cooling may be required to keep batteries operating within temperature limits presented earlier in Table 4.

The battery characteristics presented above indicate Li-Ion technology has become the dominant technology within the automotive industry for both PHEV and BEV due to their high specific energy and power properties, deep cycle DoD capabilities and high achievable C-rates when compared to any other battery technologies. Similarly, as discussed these same characteristics also make Li-Ion batteries well suited to stationary applications.

Finally, Table 8 below presents a breakdown of the total refurbishment costs associated with Li-Ion batteries [16]. It is interesting to note that the refurbishment of the batteries makes up the smallest component while battery and transportation costs make up the largest. Low and high values are used to reflect price uncertainty and the figures are applied later to estimate the total end-use costs for residential, commercial and industrial applications.

Table 8: Costs for reconditioned Li-Ion batteries [16]

	Cost of used batteries ($/kWh)	Balance of system cost ($/kW)	Refurbishment cost ($/kWh)	Transportation cost ($/kWh)	O&M cost ($/kW)
Cost (Low)	220	50	3	126	50
Cost (High)	75	8	2	63	25

4. BIPV Applications with Reconditioned EV Battery Storage

The IEA forecast a significant rise in the quantity of installed PV generation capacity as illustrated in Figure 6 [17]. Currently an estimated 135GW of PV generation capacity exists worldwide. This is expected to rise to 1,721GW by 2030 and 4,674GW by 2050.

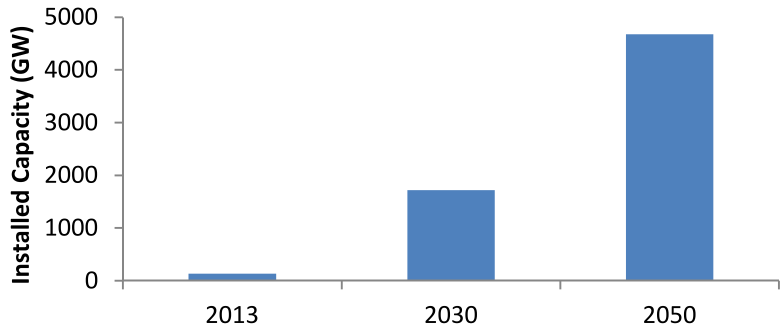


Figure 6: Global predicted installed PV capacity [17]

Global installed PV capacity is shown to be segmented into four different categories as illustrated in Figure 7 [1]. Ground connected systems are the largest sector with 34% of the market. The commercial sector accounted for 27% with residential and industrial making up the remainder at 22% and 17%. The figures presented are European average values for 2013 and therefore the size of the segments may vary between countries and in terms of cumulative installed capacities.

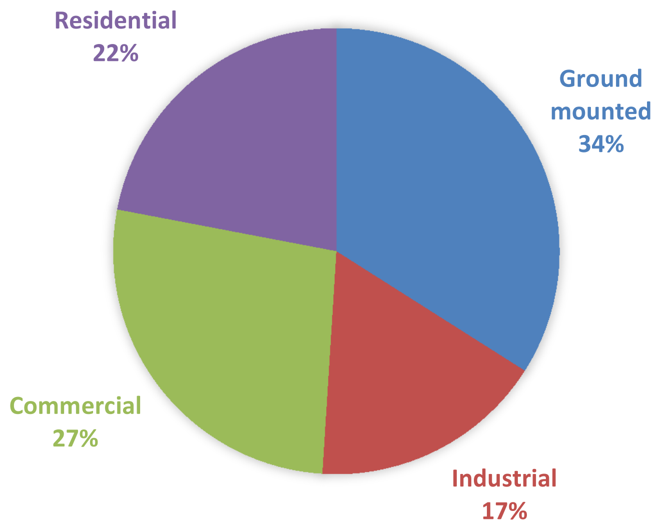
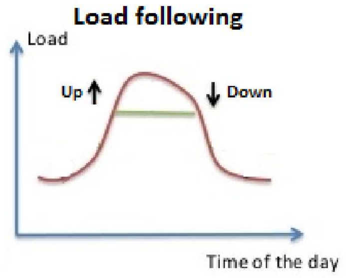


Figure 7: European PV market segmentation based on 2013 figures [1]

A series of potential applications exist for BIPV with battery storage which can be described below.

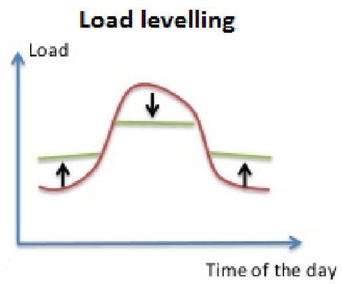
Load following

Load following allows for the provision of network electricity capacity to cater for a gradual increase or decrease in demand over a period of time. It is used to balance the difference between demand and supply over a period ranging from minutes to a few hours.



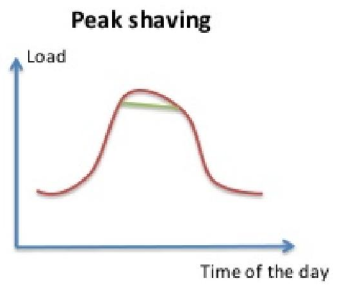
Load levelling

Load levelling involves the storage of power at periods when demand is low to be used at times when demand is high. Overall, it allows the production of power to become flatter and thus cheaper baseload generation can be increased.



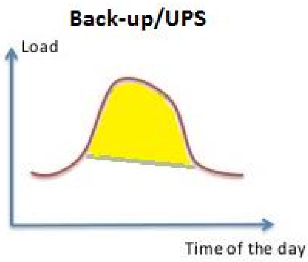
Peak shaving

Peak shaving allows for the deferral of power away from peak time use. It is similar to load levelling except it is mainly used for the purposes of reducing demand at peak times thus avoiding having to operate expensive generating capacity at these times.



Back-up systems or Uninterruptable Power Systems (UPS)

Back-up systems provide storage capacity for intermittent generators such as solar or wind. UPS systems provide storage for critical systems such as telecommunications masts, hospitals etc.



Transmission quality/stabilisation

Transmission quality services help stabilise the network after a fault occurs. These services are numerous and can relate to such functions as voltage support, reactive power services and frequency regulation.

Spinning reserve/area regulation

Spinning reserve (or area regulation) is the provision of capacity which can respond to compensate for generation or transmission outages. The capacity is needed at short notice and therefore it is kept online but unloaded.

Renewables firming

Renewables firming provides capacity for smoothing output fluctuations from renewable energy generators such as BIPV. It is important as currently dispatchable plant is used to service demand when output drops. It needs to be available at short notice for example when solar generation decreases suddenly due to cloud cover.

Table 9 shows estimated power and energy requirement for each end-use application [12]. In particular load following and back-up system applications appear the most feasible due to their lower power and energy requirements.

Table 9: Energy storage applications for the electricity grid [12]

Application	Power	Energy	Frequency
Load following residential	1kW	3-4kWh	Daily
Load following light commercial	25kW	75-100kWh	Daily
Load levelling	10MW	50MWh	100-200 days/year
Peak shaving	1MW	3-4MWh	Daily to 6 times a year
Back-up systems	<5kW	25-50kWh	2 times a year
Transmission quality/stabilisation	100MW	100MWh	once a month
Spinning reserve/area regulation	20MW	7.5MWh	once a month
Renewable firming	1MW	1-10MWh	10-20 days/month

Each application is now discussed in terms of each BIPV sector: residential, commercial and industrial.

4.1 Residential Applications

In 2013 22% of installed PV capacity was used in residential buildings. Assuming sectorial breakdowns do not change significantly between periods a predicted capacity of 379GW and 1,028GW is expected to be installed in 2030 and 2050 respectively. The estimated storage capacity from the secondary re-use of EV batteries was presented earlier in Figure 3 and is also shown alongside PV capacity in Table 10. The table shows that a single hour's storage could be provided for 12% of residential installed PV capacity in 2030 and 46% by 2050.

Table 10: Estimated residential PV and battery storage capacity

	2013	2030	2050
PV installed capacity (GW)	29.7	378.6	1,028.30
Estimated storage (GWh)	--	45.1	470.3

Electricity is mostly used within the home to power electrical appliances and for space and water heating. Patterns of electricity use vary greatly by region especially between hot and cold climates due to electric cooling and heating respectively. Figure 8 shows a typical load profile for the residential sector in Ireland where neither electric heating nor cooling is prevalent. As most of the demand occurs in the evening, at times when little or no PV generation occurs, residential dwellings are well suited to battery storage applications. This enables PV generation throughout the day to be stored for use later in the evening thereby increasing self consumption within the building.

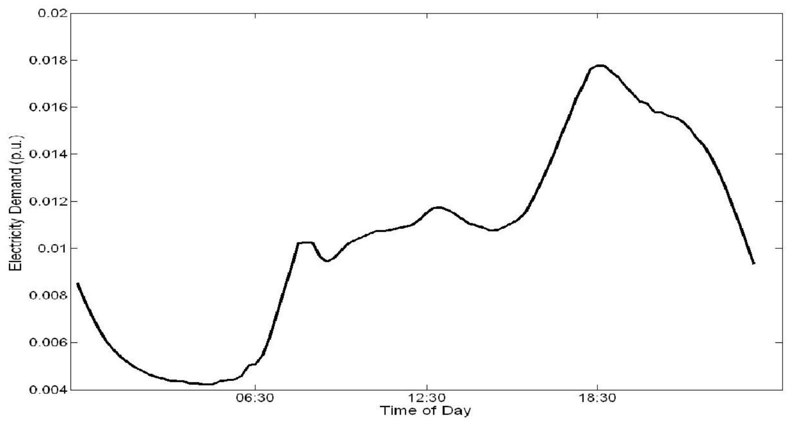


Figure 8: Typical residential demand load profile (LP1 - Urban Domestic 24 Hour) [18]

Residential opportunities for storage are presented in Table 11. These were compiled as part of a North American study investigating the potential for energy storage on the electricity grid [19]. The table shows that up to 25 kWh of storage capacity is typically required for renewable energy systems. Assuming a reconditioned battery has 70% of its original capacity available this would be equivalent to two Nissan Leaf BEV's batteries connected together. In contrast, load following applications require much less storage capacity (between 3-4 kWh) equivalent to a reconditioned PHEV battery such as a Ford Fusion Energi. Therefore a potential 3 million homes could be supplied with reconditioned Li-Ion batteries for renewable energy backup applications by 2030 and 31 million by 2050. Similarly up to 13 million homes could be serviced with reconditioned PHEV batteries for load following applications by 2030 or 134 million by 2050.

Table 11: Residential opportunities for battery secondary re-use [20]

Residential Storage Applications
Load following
- 3 to 4 kWh
- One deep discharge and several shallow discharges per day
- C/3 discharge rate typical
Back-up systems
- up to 25kWh for off-grid
- Daily, moderately deep discharges (>50% DoD)

Table 12 shows estimated costs for reconditioned Li-Ion batteries for residential applications presented above. The associated costs for backup battery storage for home renewable energy installations are more than six times greater than that for load following applications. Considering that the supply of PHEV's is likely to be much greater than BEV's in the short to medium term (as indicated in Figure 3) any battery reconditioning EV policies should initially favoured towards PHEV's.

Table 12: Estimated reconditioned Li-Ion battery costs for residential applications

Residential Applications	Power (kW)	Energy (kWh)	Cost - Low ($)	Cost - High ($)
Load following	1	4	592	1,495
Back-up systems	4	25	3,626	9,117

The re-use of batteries from both BEV and PHEV vehicles could potentially be well suited to residential applications. In particular, capacities are suitable with one or two batteries being more than adequate to service demands for load following and energy back-up system applications. Furthermore, DoD and C-rates for BEV and PHEV Li-Ion batteries are more than adequate to meet the demands for both load following and renewable energy system backup applications. However, active temperature cooling may be required in a domestic setting in order to ensure maximum temperatures are not exceeded and result in a further reduction in battery life. Finally estimated costs for the residential sector are relatively low particularly for load following applications.

4.2 Commercial Applications

The commercial sector is the largest of the three categories (excluding ground mounted systems) as illustrated in Figure 7 and had an installed PV capacity of approximately 37 GW in 2013. Table 13 shows predicted installed PV capacity for the commercial sector which is expected to increase to 465GW and 1,262GW by 2030 and 2050 respectively.

Table 13: Estimated commercial PV and battery storage capacity

	2013	2030	2050
PV installed capacity (GW)	36.5	464.7	1,262.00
Estimated storage (GWh)	--	45.1	470.3

Figure 9 illustrates a typical load profile for commercial premises which comprise of offices, supermarkets, bakeries, etc. In contrast to the residential sector, peak demand occurs closer to midday when generation from BIPV is at its greatest. As a result, shifting demand away from the evening peak time is less of a concern as demand is already greatest when generation is most likely to occur. This is of course not always the case, especially in environments where cloud is prevalent, thus reinforcing the need for storage. Furthermore, as commercial loads are on average much greater than residential dwellings other applications such as peak shaving and load following may be more appropriate.

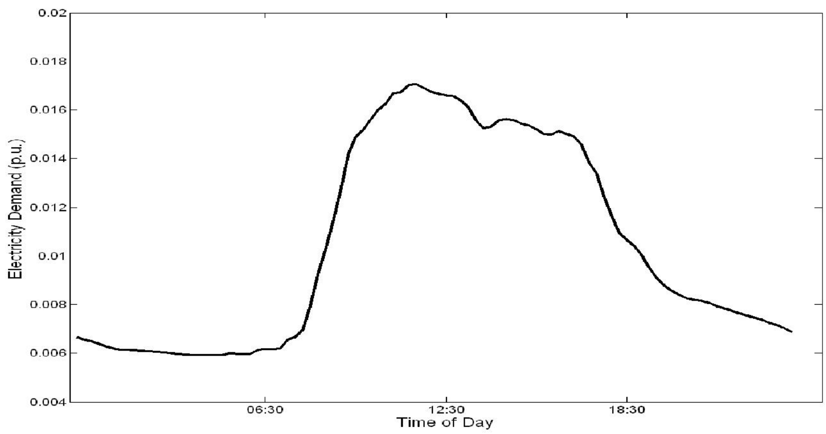


Figure 9: Typical commercial demand load profile (LP5 - Non Maximum Demand Non domestic 24hour) [18]

Commercial opportunities for secondary re-use of EV batteries are presented in Table 14. Peak shaving requires a significant amount of storage capacity and therefore multiple reconditioned batteries would need to be combined together. For example: a reconditioned Nissan Leaf battery at 70% capacity would require between 178 – 238 batteries to be connected to enable peak shaving as described in Table 14. Therefore it is unlikely that reconditioned batteries could be used for peak shaving applications. However, batteries could provide a form of distributed peak shaving, by engaging in Demand Side Management (DSM) schemes. This would enable multiple smaller sites to be connected together to assist in peak reduction through DSM but would require a third party aggregator to become involved.

Table 14 highlights opportunities for battery secondary re-use in the commercial sector. Similar to that described for residential sector, a well suited application is load following. This would involve between 4 – 6 reconditioned batteries to be combined which may be a more practical application when compared to peak shaving. As the battery is expected to receive one deep and several shallow discharges per day this application would only be suitable in climates that receive good daily solar irradiance so as to avoid excessive DoD's. C-rates for Li-Ion batteries would also be more than adequate to meet the demands for load following. Battery back-up applications (such as telecommunications masts) in remote areas would also be well suited due to their relatively small power requirements. An estimated 902,000 commercial premises could potentially be supplied with storage for renewable energy back-up systems by 2030 and 941,000 by 2050. Similarly up to 451,000 commercial premises could be serviced with reconditioned batteries for load following applications by 2030 or 4.7 million by 2050.

Table 14: Commercial opportunities for battery secondary re-use [20]

Commercial Storage Applications
Load following
- 75 to 100 kWh
- C/3 discharge rate typical
- One deep discharge and several shallow discharges per day
Back-up systems
- Standby power
- C/5 discharge, infrequent
Peak shaving
- 3,000 to 4,000 kWh
- C/2 to C discharge, daily

Table 15 presents estimated costs for commercial applications discussed above. Peak shaving has the largest costs due to the high power and energy requirement for such applications. Load following on the other hand requires significant less capital costs. The costs associated with battery back-up applications would be approximately five times greater than that for load following. Considering the number of commercial premises that could potentially use reconditioned Li-Ion batteries for load following applications it is recommended that any battery reconditioning EV policies should initially be focussed in this area.

Table 15: Estimated reconditioned Li-Ion battery costs for commercial applications

Commercial Applications	Power (kW)	Energy (kWh)	Cost - Low ($)	Cost - High ($)
Load following	25	100	14,801	37,369
Back-up systems	50	500	71,530	179,345
Peak shaving	1,000	4,000	592,040	1,494,760

4.3 Industrial Applications

The industrial sector accounted for 17% of installed PV capacity representing 23 GW in 2013. Table 16 illustrates the predicted installed PV capacity for the industrial sector which is expected to increase to 293 GW and 795 GW by 2030 and 2050 respectively. The industrial sector has declined in size in comparison to 2012 figures and this may be related to the increase in the amount of utility scale PV systems being installed [21]. Table 16 illustrates that one hour's storage could potentially be provided for 15% and 59% of installed industrial PV capacity in 2030 and 2050 respectively.

Table 16: Estimated industrial PV and battery storage capacity

	2013	2030	2050
PV installed capacity (GW)	23	292.6	794.60
Estimated storage (GWh)	--	45.1	470.3

Figure 10 presents a typical load profile for the industrial sector which shows a large peak either side of mid-day. As PV generation is usually greatest at this time, storage can provide backup capacity when solar irradiance is low. The profile also shows a large difference between maximum and minimum electricity use between early morning and mid-day. Utility load levelling uses storage such as batteries to shift demand away from the peak to other times of the day. As industrial customers tend to be heavy users of electricity, load levelling requires a significant amount of storage capacity. For example, a typical industrial customer might require approximately 6,000 reconditioned batteries of similar size to the Nissan Leaf to be combined in order to engage in load levelling. Therefore, for practical reasons it is unlikely that reconditioned batteries will be used in such applications.

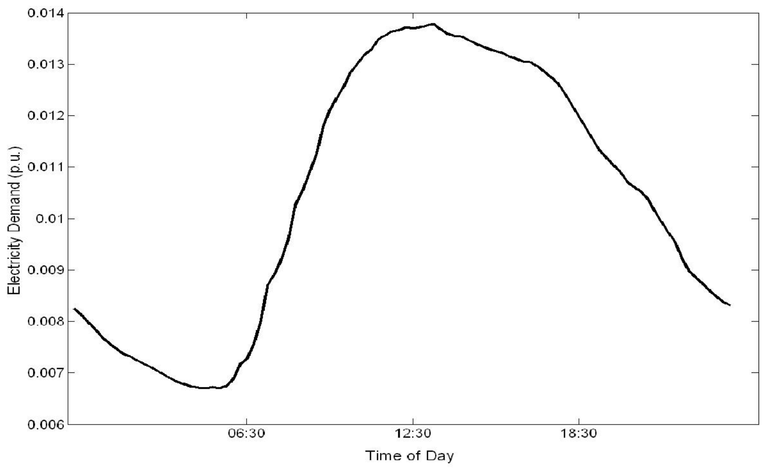


Figure 10: Typical industrial demand load profile (LP8 - MD Load Factor >30 to 50%) [18]

Table 17: Industrial opportunities for battery secondary re-use [20]

Industrial Storage Applications
Load levelling
- 100,000 kWh
Renewables firming
- 1,000 to 10,000 kWh
- C/5 discharge, frequent
Spinning reserve/area regulation
- 5,000 to 7,500 kWh
- C/2 to C discharge, infrequent
Peak shaving
- 3,000 to 4,000 kWh
- C/2 to C discharge, daily
Transmission stabilisation
- 140 kWh, 500,000 kW
- 5 to 10 pulses per second, once/month

Renewable firming for industrial applications would require significantly less storage capacity (between 1,000kWh and 10,000kWh) when compared to load levelling. However, between 60 and 595 reconditioned Nissan Leaf batteries would still be required to provide the necessary back-up capacity to strengthen the network in areas with high renewable energy penetration is prevalent. Similar to the commercial sector discussed earlier, peak shaving would require a similar amount of capacity for the industrial sector. Finally, transmission stabilisation requires very short bursts of power to be available in order to stabilise voltage and frequency variations on the network. It is unlikely that reconditioned EV batteries could provide this function as it would greatly exceed Li-Ion C-rate capabilities.

Table 18 presents estimated costs for industrial sector applications. As discussed, load levelling requires a large amount of power and energy capacity and therefore costs are extremely high. Similarly, transmission stabilisation services would equally be expensive, costing in the region of between $16 – $50 million. Peak shaving is possibly the most feasible option for industrial customers, however, costs are still quite excessive in the region of $600,000 – $1,500,000.

Table 18: Estimated reconditioned Li-Ion battery costs for industrial applications

Industrial Applications	Power (MW)	Energy (MWh)	Cost - Low ($million)	Cost - High ($million)
Load levelling	20	100	14.6	36.9
Renewables firming	2	10	1.5	3.7
Spinning reserve	4	8	1.2	3.0
Peak shaving	1	4	0.6	1.5
Transmission stabilisation	500	0.1	16.5	50.0

5. Management and Control

The use of batteries in off-grid applications where no connection to the grid exists is used to provide storage capacity for intermittent renewable energy technologies such as solar or wind. Historically lead based batteries have been the dominant technology in such applications; however, this is likely to change if Li-Ion costs continue to decrease. The use of batteries in on-grid applications such as: load following; peak shaving; and energy back-up systems are less prevalent but can assist in facilitating a greater amount of renewable energy technologies onto the network. Figure 11 demonstrates the application of battery storage at a building level where excess electricity is generated from PV during the day and is stored for use later that evening. This facilitates the generation of electricity for self-consumption by maximising use of locally generated BIPV thereby minimising power flows to and from the network. As a result battery storage can assist countries in meeting EU 20-20-20 targets by:

- improving energy efficiency within buildings by maximising self-consumption;
- providing firming capacity for the network thus facilitating the integration of a greater amount of renewable energy technologies onto the network; and
- displacing traditional fossil fuel generators thereby minimising Greenhouse Gas (GHG) emissions.

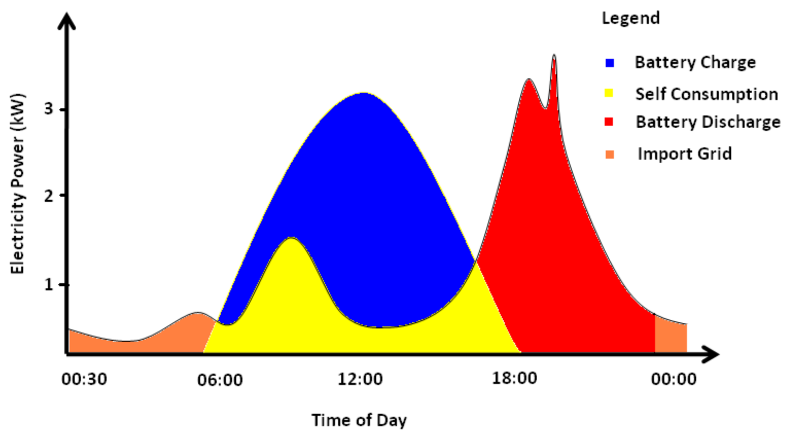


Figure 11: Typical residential building electricity load profile optimised for self-consumption

Furthermore, in areas of high renewable energy penetration, problems often arise in relation to voltage rise, harmonics on the network and issues surrounding frequency regulation. These issues can be mitigated by managing supply and demand within a building more effectively. In such instances, voltage rise on the network can potentially be minimised by diverting excess generation to a battery. Similarly, frequency regulation can also be achieved by choosing to either export or store excess capacity to and from the network. Therefore, battery storage can facilitate resolving some of the network issues thereby allowing for increased penetration of renewable energies onto the network.

Li-Ion also has a number of distinct advantages over other battery types which have traditionally been used in stationary applications, particularly in terms of increased cycle rate (battery longevity), DoD and C-rate. The increased nominal cell voltage for Li-Ion as well as their ability to sustain deeper charge cycles means that a smaller number of batteries are required when compared against other battery types. Similarly, due to a higher specific energy and power, Li-Ion batteries tend to be smaller and lighter and therefore do not demand as much space. They also require less ventilation and significantly less maintenance than their lead based counterparts. However, Li-Ion batteries are susceptible to thermal runaway which occurs at elevated temperatures and therefore management controls are required to be put in place in order to ensure this does not occur particularly during charging and discharging.

Increased charge and discharge rates for Li-Ion can potentially facilitate applications such as renewable energy firming, load following and peak shaving as Li-Ion technology matures. However, load following applications would need to be carefully sized so as to avoid excessive C-rates being exceeded (currently at 2C) for Li-Ion batteries. In particular, load following for commercial applications require one deep cycle once a month which may cause a reduction in the reconditioned batteries life. As it stands Li-Ion would not be able to provide transmission stabilisation services due to the high bursts of energy required.

Finally, as the intended use for the batteries will have changed from mobile to stationary there are a number of aspects that need to be taken into consideration. Firstly the usage profile for the battery will be significantly different (in terms of DoD and C-rate and cycle no.). These have already been discussed, however, further research is required to ascertain whether this will have any damaging effect on battery performance. For example it is probable that a battery may receive less frequent cycle use when compared to an EV which may impact on its longevity. Secondly the operational environmental conditions (e.g. temperature, humidity etc) are likely to be significantly different between stationary and mobile applications. This may be compensated for by using an active cooling system, however, whether these conditions may impact on the battery life may need to be ascertained. Lastly the capacity required for a number of the applications discussed above is likely to require a series of reconditioned batteries to be connected together. This is common practice for new batteries, however, little research has been conducted into combining reconditioned batteries and therefore there may be operational and performance issues associated with this.

6. Refurbishment Considerations

The refurbishment of batteries from EV's into stationary applications such as BIPV involves a number of stages. The first stage of the process involves visually inspecting individual batteries for signs of physical damage or defects such as leaks. This removes batteries that are too severely damaged to be reconditioned. Damaged batteries can then be recycled by other measures such as smelting or direct recovery processes to extract the remaining valuable materials. Batteries that do not show signs of physical damage can then be inspected for labels, barcodes etc in order to identify: type; capacity; and age. Batteries that are close to their end of life (i.e. ≥15 years) can be excluded from any refurbishment processing and recycled by other measures mentioned above.

The next stage of the refurbishment process involves testing individual batteries for signs of degradation. It is envisaged that three different types of cell degradation may have occurred during their previous life. Firstly, some battery modules may have extensive cell damage and therefore will need to be recycled by direct recovery methods mentioned earlier. Secondly, batteries where some modules exhibit cell damage can be reconditioned by cleaning or re-generating the electrodes. Finally, batteries that show no cell damage (apart from expected degradation due to age) require no refurbishment of the module at all. A simple voltage and resistance test will indicate the health of each module of the battery and as a result the extent of any refurbishment works. Short circuits and dried out separators within the battery are some of the common problems that can be easily identified with such tests [12].

After such tests have been completed the battery can then be subjected to a test cycle to determine the remaining capacity and power. A series of charge and discharge cycles at different C-rates and DoD enables both capacity and power to be estimated. The modules can then be sorted by capacity, power and age for assembly into different battery packs. Battery packs can vary in size depending on the application but could range anywhere from 3-4kWh for a small domestic systems to 100MW for large commercial systems.

The Battery Management System (BMS) performs a number of core functions within an EV. In particular it provides: current and voltage protection; thermal management and State of Charge (SoC) protection. These functions are also vital when considering the re-use of batteries in stationary applications. However, as the refurbishment process involves breaking the battery down at a cell level for reconditioning it is likely that either a new BMS system will be required or an existing one will need to be reprogrammed. Furthermore, the BMS system will need to be redesigned to consider its new stationary environment with particular emphasis on duty cycle and thermal management.

7. Conclusions & Recommendations

This study examined the technical and economic feasibility of re-using Li-Ion batteries from EV's for use in BIPV. Little information is available as to the long-term performance of Li-Ion batteries; a consequence of their relative short existence in PHEV's and BEV's; with vehicles only staring to be sold in significant numbers since 2010. The study looked at key characteristics surrounding the battery technology and what impact this may have on their transfer of use over to BIPV applications.

The study also highlighted the combined growing markets of BIPV and EV's, with good potential to combine the two sectors together. A series of applications were presented for using reconditioned batteries in the residential, commercial and industrial sectors. In particular energy back-up systems and load following for both residential and commercial sectors appear technically feasible. Li-Ion as a technology is suited to such applications on account of its superior cycle rate (battery longevity), DoD and C-rate when compared to other battery types such as NiMH and lead based batteries. Conversely, there did not appear to be a technically feasible solution for the industrial sector due to the larger loads used within the sector.

The main refurbishment considerations were also discussed with economic data presented for: battery cost; balance of system; refurbishment; transportation and O&M. In particular the transportation costs were high when compared against the rest of the system. Each end-use application was costed with similar results to the technical study. Energy back-up systems and load following showed to be the most economic on account of the smaller capacities required.

Energy management and control was discussed in terms of contributing to achieve EU 20-20-20 targets. In particular, maximising BIPV for self-consumption could be aided with the availability of reconditioned batteries from EV's. Similarly, firming capacity could also be assisted with the availability of reconditioned batteries thus enabling a larger amount of renewable energy to be connected to the grid.

However, certain challenges still remain if reconditioned batteries are to be integrated into BIPV applications. In particular, little research has been carried out as to whether the usage profile of the battery, which is very different from an EV (in terms of DoD, C-rate and cycle no.), will have any effect upon its longevity within its secondary use. Also, the practically of combining multiple batteries, which may come from different manufacturers, but have similar ratings may be problematic.

Finally, recommendation made within this study are if reconditioned batteries from EV's are to be considered for use within BIPV applications, residential and light commercial sectors should be targeted first to provide energy storage capacity for load following and back-up systems.

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