Overview of Energy Storage Technologies for Excess Renewable Energy Production

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Abstract: This paper presents an overview of energy storage technologies for excess renewable energy production. In particular, wind and solar energy systems are investigated. A case study was conducted for a self-sustainable energy system configuration to realise the impact and the importance of a suitable energy storage system. The issues relating to such a system design is investigated using a specific application and the performance of the system under variable conditions are determined. From the results and analysis, it is clear that the batteries are still best option for self-sustainable renewable energy systems. However, large-scale systems may require alternative storage mechanism such as P2G methods.

Keywords: Energy storage, renewable energy, P2G method, super-capacitor, batteries

1. INTRODUCTION

Recently, there is a growing interest in renewable energy systems, storage and its infrastructure around the world [1 - 4]. Primarily because there is a significant amount of renewable energy production from several resources, through a number of sustainably technological routes [2]. The combination of renewable energy sources such as solar and wind with suitable energy storage systems may be able to resolve the growing energy demand [5]. Many sectors, including building and housing sector has increasing energy demand, yet it is mainly dependent on the grid system [5 - 6]. The key issue with using renewable energies to supply the grid, is the fluctuational production; due to dependency on environmental factors such as wind and solar radiation [7]. Nevertheless, the supply side cannot react flexibly to the demand; which may result in an overproduction and supply to the grid [8]. Decoupling the production from the demand side maybe a solution; by storing the overproduced energy and then utilising it when required during peak time or when an insufficient production of energies occurs. Therefore, it is important to have a suitable energy storage system to bring the power transition into successful future.

Power transition of small-scale system such as self-sustainable renewable energy system can be manage with the use of battery energy storage system (BEES) and supercapacitors are useful to provide short duration power requirements [9 - 12]. Large-scale systems maybe manage by using method such as Grid to Vehicle (G2V) and Power to Gas (P2G) [6, 13 -15]. In order implement these energy storage systems, a number of technical and economic challenges must be overcome [16]. These challenges are associated with the capital cost of components needed, operation with renewable energy sources, lifetime and reliability[17-18]. G2V method is targeted at to maximise energy supply (storage) to electric vehicles/ hybrid electric vehicles and to facilitate more renewable energy onto the grid [6]. P2G technology maybe a suitable solution to bring the power transition in large-scale system [18 - 22]. The underlying idea behind this method is the overproduced electricity reformed into chemical energy via electrolysis. The product is hydrogen as gas; which can be stored in many different ways [5]. For example, a simple hydrogen storage system was developed at the University of South Wales (USW) hydrogen centre [5] to demonstrate the P2G technology (see Fig.1). The USW hydrogen centre has a 20kWp PV array, 10Nm3/hr alkaline electrolyser, 10barg intermediate storage cylinder together with 200barg compressor and associated storage cylinder, 12kW PEM fuel cell with additional battery storage, along with a hydrogen/CNG vehicle refuelling station.

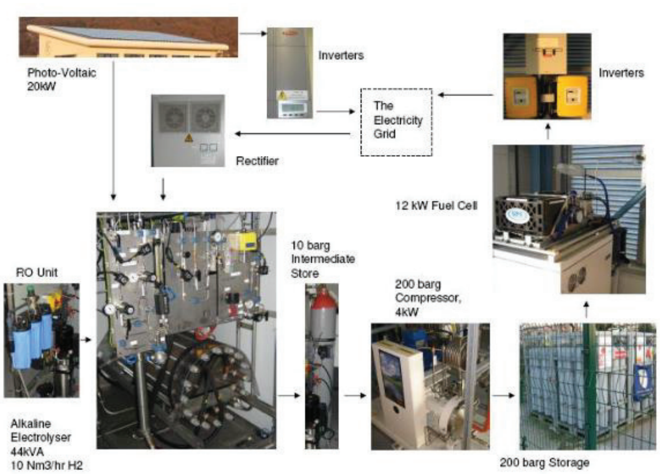

Fig.1. Hydrogen production and storage system installed in USW hydrogen center [5]

Hydrogen, or further developed SNG, in its gaseous state can be used for different sectors, like mobility, heating and electricity supply [23 - 25]. This will connect the renewable energies to almost any energy consuming sector and lead to a sector coupling in an integrated energy system (see Fig.2).

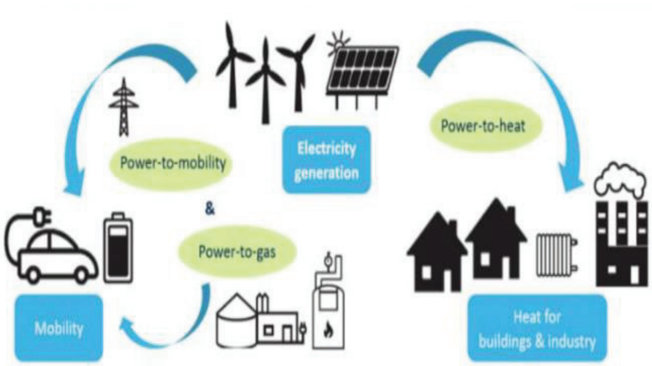

Fig. 2. Sector coupling – an integrated energy system based on renewable electricity [25].

Therefore the possibility to integrate and use it for different applications will result in a more efficient energy sector [25].

Among all different kind of renewable energy sources, solar and wind energies are the most popular ones mainly because it is free and in abundant supply for many regions [5]. Therefore, in this work energy storage issues with solar and wind energies are investigated.

2. ENERGY STORAGE OPTIONS

There are three distinct options of energy storage solutions to be considered and researched, whilst developing a sustainable grid connected energy system. In order to maximise the use of renewable energies detailed analysis must be carried out to maximise opportunities in the capture, storage and management of energy.

a) Supercapacitor

Supercapacitors, work on a principle that is, storing energy in an electric field that is created when charges of opposites sign are held separated from each other [26]. Supercapacitors have the ability to withstand a high volume of charge and discharge cycles without losing energy storage capability. However, the main problem of supercapacitors is their low energy density, therefore the storage capacity is limited, i.e., the amount of energy supercapacitors can store per unit weight is low compared to batteries [27]. Nevertheless, life expectancy of supercapacitors is longer than the batteries, but the cost is still restrictive [28]. Due to its high rate charge and discharge capability, it is useful for providing short duration power requirements [26, 30].

b) Batteries

In relation to energy storage for stand-alone and self-sustainable renewable energy systems, Lead acid batteries are still ahead of the game in terms of energy storage / cost comparison, Lithium Ion batteries are continues to reduce in price, and now the market is approaching a position where Lithium-Ion batteries are able to compete on price [2].

Battery energy storage system are mainly used for household or smaller industrial applications, to store excess renewable energy and good for self-sustainable renewable energy systems, since they can be used independently as possible from the grid [30]. This is because there are only small periods, where it has to act as a buffer and the peak demand is low, compared to the grid. However, on the long run energy lost in batteries are unavoidable. Moreover, large batteries are heavy, take up a lot of space, and therefore not useful for many large scale applications. Nevertheless, in order to cope with the larger scale storage issues, industry is begin to develop large battery packs [30]. For example, Tesla in Australia, built a 1000 MW Li-ion battery pack with a storage capacity of 120MWh and it is connected to a nearby wind farm (Fig.3) which is operated by Neoen [31]. The key issue with the use of batteries in large-scale systems is the finite availability of the (rare) materials.

Fig.3. Large-scale battery storage system [31]

c) Power to Gas Methods.

Concerning the large-scale storage management, it is important to discuss the development of a new system, tailored for large-scale storage [13, 15, 30]. P2G energy storage method is a process of converting excess renewable energy supply into (hydrogen) gas by rapid response electrolysis and its subsequent injection into the gas distribution network [15].

The P2G system is a connection of multiple technologies; it includes feed-in, storage and supply technologies for different usage [25]. Storage of the energy carrier in gaseous state is the key part of P2G method. The P2G method can use the existing infrastructure and may be able to substituting conventional fuel or natural gas in the mobility and other sectors [15]. In P2G applications, hydrogen and methane are the producible gases [30]. Methanation is one process step behind the hydrogen, which reduces its effectiveness; however, it increases the usability for different sectors [25]. The more process steps involved, the more losses will appear during the chain of applications. This may be the key issue to be resolve for the future; to increase the efficiency and reduce the costs - particularly for methanation.

3. SYSTEM ANALYSIS

It is clear from the above analysis, for small-scale systems, that the battery technology systems are preferable for continuous energy storage and usage. The supercapcitor is another storage device, it has a very quick charge/discharge times but due to its lower specific energy capabilities than batteries, it is not preferable.

A case study of a solar powered sustainable energy system was carried out, in-order to determine the best possible energy storage option for such systems. Two different type of battery systems, such as Lead-acid and Li-ion batteries were investigated. The reliance that the world's consumer markets have placed on battery technologies can be seen in the vast amount of applications required today. Typically used in portable electronic devices such as mobile phones and small items of equipment [32], lithium battery technologies are now becoming more common in many sectors. However, a less obvious application is their integration into many stationary applications. The industrial applications include backup power systems for industry and energy storage for renewable energy systems. There are several large battery technologies being used in today's industry. The following advantages are gained through using lithium technologies over other cell chemistries: (i) a higher cell voltage, which is key to the high energy density; (ii) greatly improved cycle count, with typical figures of 300 – 400 cycles; (iii) a more consistent manufacturing process between cells of the same type, resulting in more balanced battery modules and (iv) an improved specific energy and energy density. However, the benefits of lithium batteries are counterbalanced by several drawbacks: (i) high initial cost – although prices are reducing with increased high volume production; (ii) costly electronics for the battery management system (BMS) to protect the cells; (iii) increased risk of overheating and fire due to the high energy, albeit this is mitigated by the use of a BMS or the consequences of error can results in overheating, fire or explosion [2]. Although there have been many battery chemistry implementations, to meet the specific needs listed above, the oldest battery chemistries still command a large market share. The lead acid battery may not have the high energy density or fast cycle rates that the Li-ion technologies possess, but they are unparalleled in their tolerance for abusive conditions and are low cost [28]. This is most notable in uninterruptible power supply (UPS) systems where a battery bank can be stored in a remote area, usually an attic or a basement, where temperatures can vary significantly on a daily basis and have little effect of the ability of lead acid to perform. The preferred use of lead acid batteries in UPS systems also reflects their low price, with lead acid batteries on average 8.5 times cheaper than lithium technologies (£/kWh) [28, 32]. In a system where the batteries are going to be used only in an emergency, low purchase price is essential. As the batteries are only required in case of an emergency, it is of the utmost importance to ensure that, when called upon, the batteries are in an operational state. Therefore, for the PV based sustainable energy system in buildings, it is obvious that the best option for energy storage is the use of lead-acid battery pack [32]. Lead acid batteries also have the advantage of being over 99% recyclable [33], with the recycled lead as chemically pure as the original virgin material.

Case study – Solar PV systems combined with a home energy management system, capable of minimising the cost to consumers. A structural block diagram for the solar energy system is shown in Fig.4. The system will have the following elements; PV modules, battery pack, energy management system and load [2].

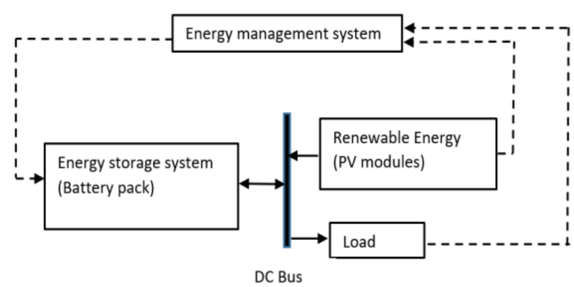

Fig.4. Solar PV energy and storage system [2]

This case study is intends to prove a more cost effective system other than grid connected systems that are available and provide cost effective solutions to consumers. This work investigates typical sustainable energy system configuration with energy management controller (EMC). The potential benefits of such a system design is investigated using data collected at three specific location within the UK and the performance of the system under variable conditions are determined. The solid arrows represent the electricity flow and the dotted arrow represent the control/sensor signals. A photovoltaic array is considered as the main power source to the system, which enables it to meet the load demand. Due to the inherent intermittency of solar irradiation, Battery Energy Storage System (BESS) is included, not only to smooth the fluctuation of the solar energy generated, when such smoothing is necessary, but when excess energy is available it will be stored in BESS. However, when there is a shortage of direct solar energy, the stored energy will be used. The load characteristics selected for the energy management system (EMS) applied to a solar based renewable energy system were based on data collected from three distinct areas, Plymouth on the South West Coast of England, St Athans in the Vale of Glamorgan in South Wales and Nottingham in the North Midlands of England. The choice of location was to give a broad geographic spread to the sizing algorithms whilst validating the calculations. Authors, previous work [2] shows that, if the consumer stores the excess energy, and bills are calculated over a 12 month period, the cost of domestic energy bill can be significantly reduced. It has been shown that using a 4kW PV system in the South of England under idealised conditions consumption and generation can be balanced to almost achieve a break even point. In the South Wales region, the bills can be reduced around £48/year and in the North Midlands of England, the annual bill may be reduced to around £115/year (see Fig.5). It should be noted that adding more panels to the system, may continue to reduce the overall cost to the consumer. It also highlights regional variations in the UK, primarily due to geographic changes in irradiance. It can be seen that with a 4kW panel system, almost breaks-even on an annual basis in the South West of England, saving the consumer over £500/year in electricity. Whilst in Nottingham a 4kW system has an annual cost of around £150, but only produces around £35 from FIT. However, this is still a significant saving over the approximate £630 of energy consumed every year. The overall payback periods can be constructed by considering the initial investment of the BESS. It is interesting to note that due to the regional variations in both solar irradiance, the amount of daylight per region and the electricity demand due to climate conditions, the payback period for the three regions chosen is similar (See Fig.6).

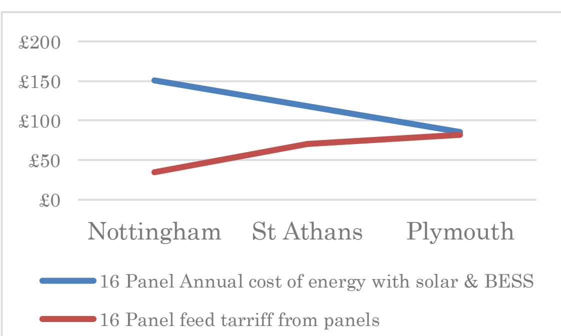

Fig.5. Cost analysis and break even indicator

The payback period of a current solar powered system alone can be shown to be in the region of 21 years, this is primarily due to over production being fed in the grid, but with a BESS and Solar PV system, this can be reduced to 15 years. However, the key issue is that the development of a demand side management system (DSMS), that will be form a crucial part of the energy management system.

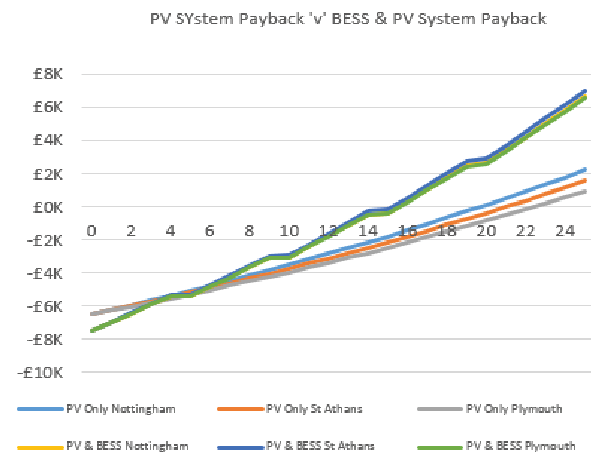

Fig.6. Payback periods

From the above analysis, it is evident that the battery technologies are more efficient compared to P2G systems; especially because battery storage systems store electric energy without reforming it. The start-up and response time to buffer peak times is good and results in a flexible system. A disadvantage of batteries is the long-term storage property; the loss over time is high, which makes it difficult to buffer fluctuation over an extended period. This problem may be tackled with P2G technology. P2G is useful for long-term electricity storage, heating and mobility. Other storage technologies, like pumped hydro-energy storage may still be used, but it has a limited area of use, because it requires geological formations to be implemented which limits its large-scale use. When using P2G method, the storage capacity can be increased almost indefinitely and the infrastructure for natural gas may be used to distribute hydrogen. However, for practical expansion the possible volumetric percentage limit need to be increased, which will take more research and further investigation. P2G application may be considered as a holistic solution for decentralised applications, like office buildings or domestic homes, to supply electricity, heat and fuel for cars. However, the main drawback is the low efficiency and high investment costs for complete installation including electrolyser, storage system and fuel cell. However, it is important to note that, P2G technology has potential to fill some aspects of the power transition for large-scale systems. Further research and development is required to determine how best to implement it into the energy supply system.

4. CONCLUDING REMARKS

From the results and analysis presented in the paper, it is clear that the batteries are still best option for stand-alone and self-sustainable renewable energy systems. Super-capacitors maybe considered as an intermediate storage solution for small-scale system. However, large-scale systems may require alternative storage mechanism such as P2G methods.

REFERENCES

[1] P.Rodatz., G.Paganelli., A.Sciarretta., L.Guzzella. Optimal power management of an experimental fuel cell/supercapacitorpowered hybrid vehicle. Control Engineering Practice, vol.13, pp.41-53, 2005

[2] E. Constant, K. Thanapalan, M. Bowkett. Optimal energy storage evaluation of a solar powered sustainable energy system. SICE-ISCS 2018 IEEE Int Conf, 193 – 198, 2018.

[3] M. Eroglu, E. Dursun, S. Sevencan, J. Song, S. Yazici, O. Kilic. A mobile renewable house using PV/wind/fuel cell hybrid power system. Int J of Hydrogen Energy, 32: 7985 – 7992, 2011.

[4] C. Ziogou, D. Ipsakis, C. Elmasides, F. Stergiopoulos, S. Papadopoulou, P. Seferlis, S. Voutetakis. Automation infrastructure and operation control strategy in a stand-alone power system based on renewable energy sources. J of Power Sources, 196:9488 – 9499, 2011.

[5] K. Thanapalan, S. carr, F. Zhang, G. Premier, A. Guwy. Renewable hydrogen vehicles and infrastructure developmnet in the UK. Int J of Energy Engineering, 3(1), 27 – 32, 2013.

[6] S. J. W. Carr et al., Integration of wind power and hydrogen hybrid electric vehicles into electric grids. In: Hakansson A., Höjer M., Howlett R., Jain L. (eds) Sustainability in Energy and Buildings. Smart Innovation, Systems and Technologies. Springer, Berlin, Heidelberg., vol.22, pp. 261- 270, 2013

[7] Evans A, Strezov V, Evans TJ (2012) Assessment of utility energy storage options for increased renewable energy penetration. Renew Sustain Energy Rev 16:4141–4147.

[8] Yekini Suberu M, Wazir Mustafa M, Bashir N (2014) Energy storage systems for renewable energy power sector integration and mitigation of intermittency. Renew Sustain Energy Rev 35:499–514

[9] A. Affanni, A. Bellini, G. Franceschini, P. Guglielmi, C. Tassoni. Battery choice and management for new-generation electric vehicles. IEEE Trans on Industrial Electronics, 52 (5), 1343–1349, 2005.

[10] J.P. Dunlop, 'Batteries and charge control in stand-alone photovoltaic systems'. Fundamentals and Application, Sandia National Laboratories, 1997

[11] G. Bopp, H. Gabler, K. Preiser, D. U. Sauer, H. Schmidt, ‘Energy storage in photovoltaic stand-alone energy supply systems’, Progress in Photovoltaics: Research and Applications, vol. 6, no. 4, pp. 271–291, 1998.

[12] Y. Zhang, J.N. Harb. Performance characteristics of lithium coin cells for use in wireless sensing systems: Transient behavior during pulse discharge. J of Power Sources, 229, 299–307, 2013

[13] Ahern EP, Deane P, Persson T, Gallachóir BÓ, Murphy JD (2015) A perspective on the potential role of renewable gas in a smart energy island system. Renew Energy 78:648–656

[14] Benjaminsson G, Benjaminsson J, Rudberg RB (2013) Power-to-Gas–A technical review. Tech. rep., Svenskt Gastekniskt CenterAB (SGC).

[15] I. Hadjipaschalis, A. Poullikkas, V. Efthimiou. Overview of current and future energy storage technologies for electric power applications. Renewable and Sustainable Energy Reviews, 13(6–7), pp.1513–1522, 2009

[16] W. Abrahamse, L. Steg, C. Vlek, T. Rothengatter. A review of intervention studies aimed at household energy conservation', J of Envir Psychology, 25(3), pp.273–291, 2005

[17] W. Abrahamse, L. Steg, C. Vlek, T. Rothengatter. The effect of tailored information, goal setting, and tailored feedback on household energy use, energyrelated behaviors, and behavioral antecedents', J of Envir Psychology, 27(4), pp.265–276, 2007

[18] Vo, T.T.Q., Xia, A., Rogan, F. et al. Sustainability assessment of large-scale storage technologies for surplus electricity using group multi-criteria decision analysis. Clean Techn Environ Policy (2017) 19: 689 - 703

[19] Denholm P, Kulcinski GL (2004) Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. Energy Convers Manag 45:2153–2172

[20] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y (2009) Progress in electrical energy storage system: a critical review. Prog Nat Sci 19:291–312

[21] Barin A, Canha LN, Abaide AR, Magnago KF, Wottrich B, Machado RQ (2011) Multiple criteria analysis for energy storage selection. Energy Power Eng 3:557

[22] Wimmler C, Hejazi G, de Oliveira Fernandes E, Moreira C, Connors S (2015) Multi-criteria decision support methods for renewable energy systems on islands. J Clean Energy Technol 3:185–195

[23] Zhao H, Wu Q, Hu S, Xu H, Rasmussen CN (2015) Review of energy storage system for wind power integration support. Appl Energy 137:545–553.

[24] Deane JP, Gallachóir BÓ, McKeogh E (2010) Techno-economic review of existing and new pumped hydro energy storage plant. Renew Sustain Energy Rev 14:1293–1302

[25] K. Appunn. Sector coupling – shaping an integrated renewable energy system. Journalism for the Energy Transition. Clean Energy Wire CLEW, 2018.

[26] A. Gonzalez, E. Goikolea, J.A. Barrena, R. Mysyk. Review on supercapacitors: technologies and materials. Renewable and Sustainable Energy Reviews, vol.58, pp.1189-1206, 2016.

[27] L. Lu, X. Han, J. Li, J. Hua, M. Ouyang. A review on the key issues for lithium-ion battery management in electric vehicles. J of Power Sources, 226, 272–288, 2013.

[28] K.C. Divya, J. Ostergaard. Battery energy storage technology for power systems—An overview. “Electric Power Systems Research,” vol. 79(4), pp.511-520, 2009.

[29] P.F. Ribeiro et al.,. Energy Storage Systems for Advanced Power Applications. Proc of the IEEE, vol.89 (12), pp. 1744-1746, 2001.

[30] X. Li, D. Hui, M. Xu, L. Wang, G. Guo, L. Zhang. Integration and energy management of large-scale lithium-ion battery energy storage station. 2012 15th int conf on electrical machines and systems (ICEMS), Japan., pp. 1–6, 2012.

[31] LATimes. Tesla builds world’s largest batter in Australian outback. Technology, Assoc Press, Dec 2017.

[32] A. Mariani, K. Thanapalan, P. Stevenson, J. Williams. An advanced prediction mechanism to analyse pore geometry shapes and identification of blocking effect in VRLA battery system. Int. J of Automation and Computing, vol 14, no. 1, pp. 21-32, 2017.

[33] Zhi Sun, Hongbin Cao, Xihua Zhang, Xiao Lin, Yi Zhang: Spent lead-acid battery recycling in China – A review and sustainable analyses on mass flow of lead: Waste Management, Vol 64, 190-201, 2017.