**Chapter**

# Energy Storage System (ESS) in Residential Applications

*Ya LV*

## Abstract

This chapter looks into application of ESS in residential market. Balancing the energy supply and demand becomes more challenging due to the instability of supply chain and energy infrastructures. But opportunities always come with challenges. Apart from traditional energy, solar energy can be the second residential energy. But solar energy by nature is intermittent and available under solar irradiance only, so we need a solution to harvest all the solar energy generated in daytime and use it for supplying household load at high demand or backup at power outage, this solution is ESS. Most residential ESS solutions are Lithium-ion battery (LiB) based due to its high energy density and small footprint. But degradation of LiB system is quite sensitive to application conditions like temperature, and the lifespan of most LiB systems is between 10 and 20 years. Looking at future trend, the residential renewable energy solution (RRES) will become more flexible, compatible and reliable. Digitalization, as development trend, will enable end-users remotely monitor and manage different operation modes of RRES. The RRES suppliers will also offer most economic operation plan for end-users given their geography locations and household energy consumption habit.

**Keywords:** ESS, RRES, solar energy, LiB storage system, digitalization

## 1. Introduction

Energy supply shortage and environment deterioration are two serious issues that deserves our attention. Our daily life continuously consumes electrical energy, the main electricity supply in US come from natural gas, nuclear, and coal in 2020 according to US Energy Information Administration. These supply sources all pollute environment by generating greenhouse gas and poisoning plants and animals in nature. This is driving us to explore clean energy, such as solar energy, wind energy and hydropower. The renewables are the fastest growing sector and comprise the biggest portion of new energy sources deployed on the grid.

By generating electricity from converting hydropower, wind energy and solar energy, the development of renewable energy originates from 19th century [1]. Going through two-decades efforts, in different countries inclusive of China, US and UK, large Dams were built up for harnessing hydropower, different scales of wind farms and solar plant were developed for converting wind energy and solar energy into electricity.

But in residential applications, currently solar energy is the sole renewables for being deployed. In 2021, deployment of photovoltaic (PV) modules was expanding rapidly in various countries, amounted 433 MWp in Singapore [2], 54.9 GWp in China [3], 730 MWp in UK [4], 25.9 GWp in EU [5], 23.6 GWp in US [6], 12 GWp in India [7]. Until 2022, PV module design efficiency stands at 15–27%, in which monocrystalline module efficiency can reach 22–27%, polycrystalline and thin film module efficiency is between 15% and 22% [8]. Researchers worldwide are dedicated to push boundaries of efficiency in solar cell and PV module by studying materials and processes. In addition, PV modules' application performance is inevitably affected by weather conditions like solar irradiance and shading. As a result, PV modules always generate electricity in an intermittent way.

ESS is the effective solution of storing intermittent electricity generated by PV modules. In residential applications, the power flow within household is within 7.36 kW for single-phase, so the residential ESS power is in similar scale, in which Li-ion battery (LiB) based ESS is the most popular solution.

In this chapter, we will begin with introduction of residential renewable energy solution (RRES), next focus on understanding of LiB based ESS, and end with discussion of future solutions and technical trends in RRES and residential ESS.

## 2. What is residential renewable energy solution (RRES)?

The RRES is an energy optimization solution for household users that integrates solar energy, power grid and ESS altogether. Without the RRES, we pay higher electricity bills at grid peak hours and lose power supply at grid outage times. The invention of RRES cuts our electricity bills by selling back solar energy and guarantees a backup power supply at blackout times. The residential ESS functions to store intermittent electrical energy from PV modules and provide power supply for backup loadings. The current RRES market is dominated by players from APAC region, North America and Europe, such as LG Electronics, Tesla, Huawei, Enphase, and Siemens [9].

In the RRES, PV modules and battery storage can be coupled in a DC or AC way, as shown in **Figure 1**. The solar energy will be transmitted to grid in default mode, the timing of when to charge the battery storage is determined by the optimized e-bill. If DC coupled system, PV modules charge the battery storage via a maximum power point tracking (MPPT) solar charge controller and DC-DC converter that is embedded into the Hybrid bi-directional Inverter; in an AC coupled system, battery storage will be charged via the DC-AC Inverter.

Let's look at an example of deploying a RRES system in Singapore. The daily electricity system demand can refer to **Figure 2** [10], it can be seen that the usual grid peak hours are 18:00–24:00. The daily solar irradiance curve in Singapore can refer to **Figure 3**, the peak solar beam irradiance occurs between 11:00 and 16:00. By comparing **Figure 2** with **Figure 3**, we find that there are little or no solar energy at the grid peak hours, therefore, we need battery storage to store the solar energy generated from daytime. At grid peak hours, the battery storage, via an inverter, can provide energy supply to household loadings or feed energy back to grid for reducing the electricity bill. Moreover, the battery storage together with the inverter can work as uninterruptible power supply (UPS) to supply power at blackout or brownout times, this will become an emergency measure and also prevent equipment damage or data loss.

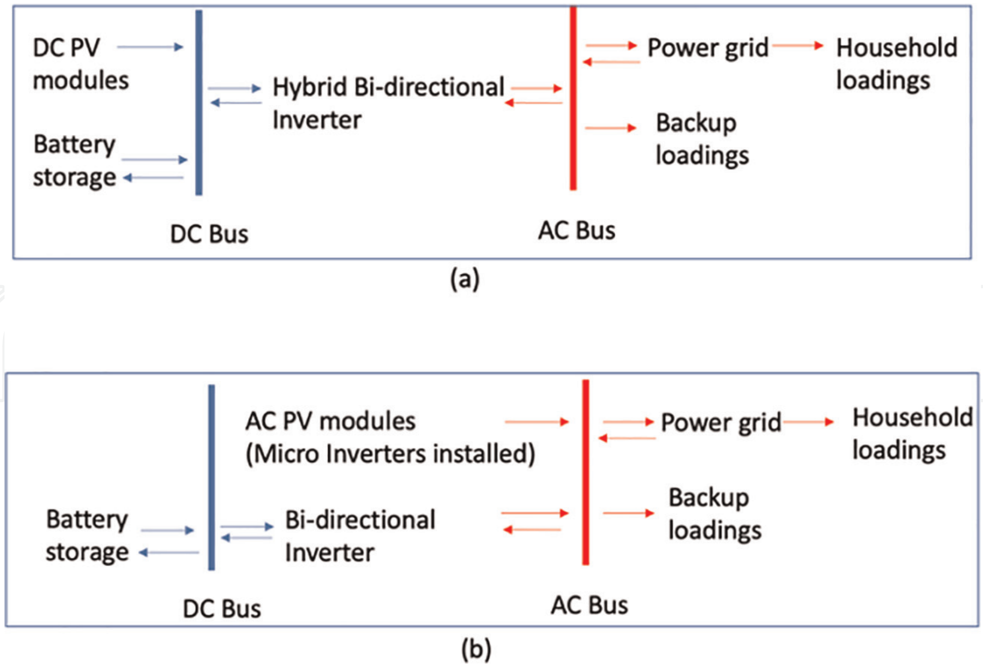


**Figure 1.**
*The RRES solution diagram (a) DC coupled solution and (b) AC coupled solution.*

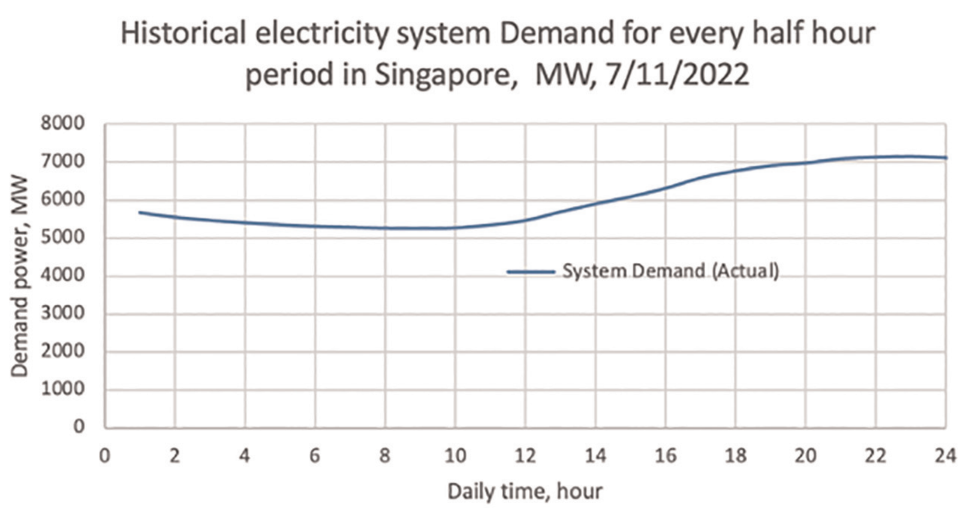


**Figure 2.**
*Singapore electricity system demand on 7/11/2022.*

## 3. About residential ESS-LiB storage

In **Figure 4** we compare the development history of LiB [11] to that of power electronics. The research of LiB began 10 years later after the Bell lab's development of Silicon transistor, similar to the development of different types of transistors, the LiB experienced different recipes of the cathode materials. Nowadays, the solid-state battery (SSB) based on solid electrolyte has entered the residential market. Furthermore, the digital control and intelligent drive of power electronics originated in 1990s can represent one of the technology trends in future LiB system as well.

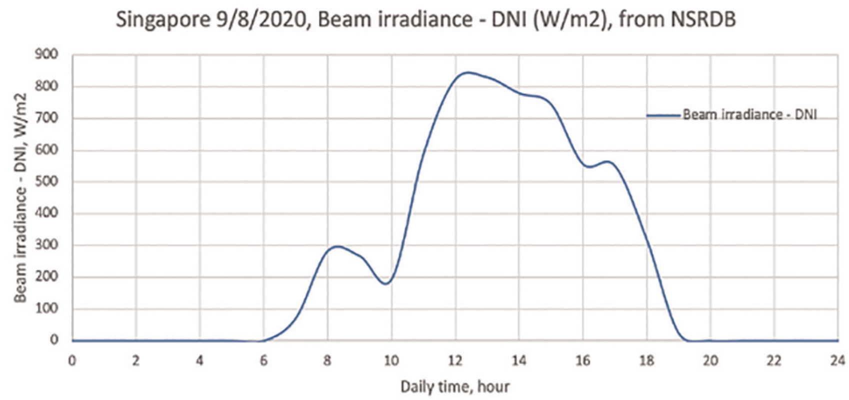


**Figure 3.**
*Solar beam irradiance in Singapore on 9/8/2020, data from NSRDB.*

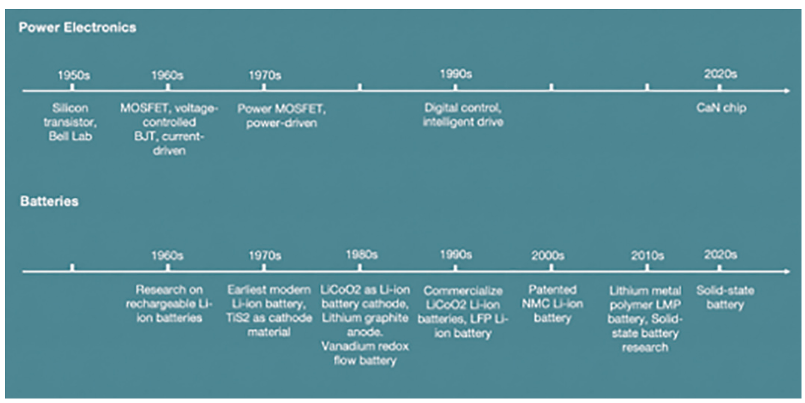


**Figure 4.**
*Main milestones in development of power electronics and that of LiB.*

The LiB is composed of a cathode, anode, electrolyte, separator and two current collectors. As indicated in **Figure 5**, the cathode material provides positively charged lithium ions and gets connected with the positive current collector; the anode material stores lithium ions and gets connected with the negative current collector; the electrolyte stays in between the cathode and anode for transporting lithium ions; the separator blocks the transportation of electrons between the two electrodes. During the charging process of LiB, lithium ions are released from the cathode and transported to the anode to be stored. With an external loading, the LiB can be discharged with the flow of electrons in an external circuit via the transportation of the released lithium ions from the anode to the cathode.

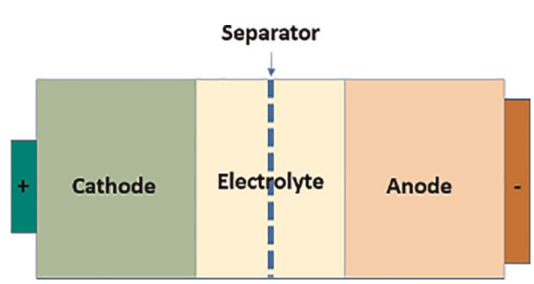


**Figure 5.**
*Simplified diagram for LiB composition.*

### 3.1 LiB storage system integration process

LiB storage system integrates different quantities of LiB cells in a functional and safe way. There are seven design perspectives to understand this integration process, that can be abbreviated as 'TEAMFCI.'

'T' is a thermal management solution. Because the round-trip efficiency of LiB system is around 92-95% in market products, there will be some amount of heat to generate in LiB system, but the LiB temperature is a critical stress factor that affects its working efficiency and reliability which affect lifespan, so we need to tackle the generated heat with efficient thermal management methods. In a LiB storage system shown in **Figure 6**, there are usually passive and active thermal management methods. Passive methods rely on heat conduction and natural heat convection whereby the heat is conducted from the LiB cells to system enclosure surfaces, then the heat is exchanged in a natural way between the system enclosure surfaces and the environment. Active methods include forced heat exchange between the LiB cells and a flowing fluid whereby the heat will be further exchanged out to ambient from the flowing fluid using fans/heat exchangers. The heat transfer efficiency between different objects can be described with thermal impedance which consists of both thermal resistance and heat capacity. At steady state, during long duration heat transfer, the heat capacity can be ignored in the heat transfer path. However, at transient states of short-duration heat transfer, the heat capacity needs to be considered. In the residential LiB storage system, the heat capacity of LiB cells cannot be ignored due to the cells' dominated mass in the system. The thermal network of passive and active thermal management solutions in such system can be simplified in **Figures 7** and **8**.

'E' is electrical connectivity. A configuration design of LiB storage system generates certain system-level voltage and current by connecting different number of cells in parallel and in series. Usually, the cells in parallel will be connected via bus bars, followed by serial connectivity via bus bars/electrical cables. In addition, there will be connectivity of data acquisition cables and power supply cables between cells and the battery management system (BMS), as well as connectivity of power cables between cells and the system terminals. BMS is a power electronic device that provides four main function blocks: (1) data acquisition for cell-level voltage, current and temperature; (2) cell-level voltage balancing during charging process to maximize the usable capacity in system; (3) functionality safety control for cell-level protection of overvoltage, undervoltage, overcurrent, overtemperature and under temperature; (4) communication with master control devices like energy management system (EMS)/master control computer/master BMS via protocols like CAN bus/Modbus.

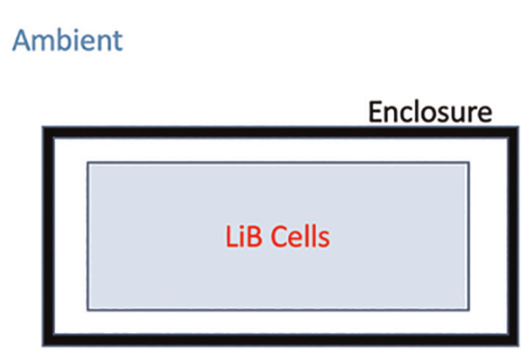


**Figure 6.**
*Simplified LiB storage system.*

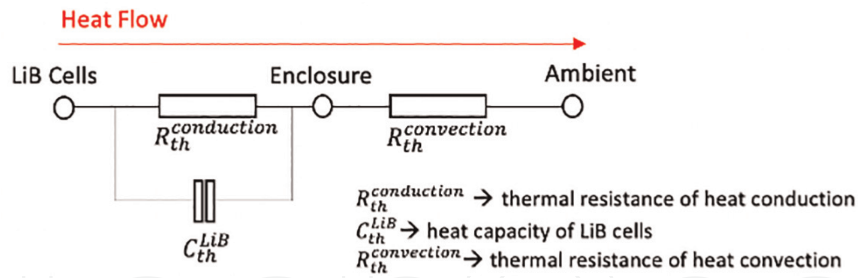


**Figure 7.**
*Foster thermal network model for passive thermal management solution.*

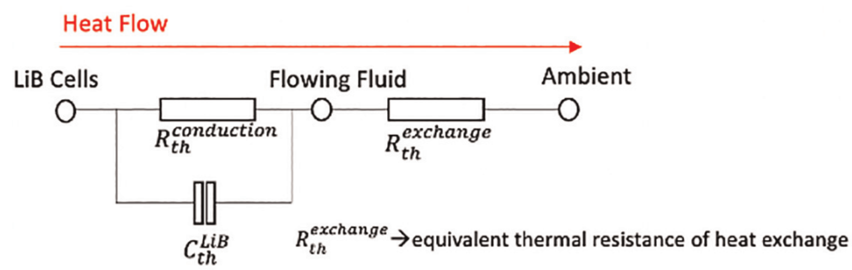


**Figure 8.**
*Foster thermal network model for active thermal management solution.*

'A' means algorithm of state of charge (SoC) and state of health (SoH) calculation in the BMS. With this algorithm, the BMS can record cell-level real-time charging/discharging status and calculate system health status along the lifespan for understanding the throughput energy. This algorithm can be further developed for serving preventive maintenance and predictive maintenance, in order to prolong the workable lifespan of LiB system via increasing the throughput energy.

'M' indicates mechanical design. In LiB storage systems, mechanical design mainly covers design of internal frame that is used for holding battery cells steadily and an external enclosure that demands good sealing and corrosion resistance.

'F' represents fire-safety design. All the plastic materials chosen for LiB storage system are required to be UL94 V-0 rated, so the burning can stop within 10 seconds during fire propagation.

'C' means certification. For LiB storage systems, there are at least three crucial certifications: (1) underwriters' laboratories (UL) 1642, the standard for Lithium battery-specific testing which tests the risk of fires and explosion. The equivalent international electrotechnical commission (IEC) standard is IEC 62133; (2) UL 1973, the standard for batteries for use in stationary/vehicle auxiliary power/light electric rail applications which certifies the capability of battery systems under normal and abnormal conditions. The equivalent IEC standard is IEC62619; (3) UL 9540, the standard for ESS to meet industry and regulatory needs. The equivalent IEC standard is IEC 62933-5. UL is an accredited standards developer in the US and Canada [12]. IEC works with accredited laboratories in Europe, Middle East and Asia [13].

'I' indicates an industrial design that places an impression to end-users on the whole system, this part becomes necessary for products that are targeted at residential applications.

### 3.2 LiB storage system performance indicators

The LiB storage system performance can be evaluated by five indicators, abbreviated as '4CS.'

The first 'C'—C-rate for continuous and maximum operation. The C-rate describes the charging/discharging speed, 1C-rate means fully charging/discharging the system within one hour, 2C-rate indicates double speed and half time of 1C-rate.

The second 'C'—capacity. A residential LiB storage system, as an energy supply device, seeks to have a small footprint and be able to wall-mounted. Moreover, low noise level is preferred in such LiB storage system, so the thermal management solution is prone to take passive measures, such as inside heat conduction and outside natural convection, even taking active measures, there won't be strong-forced fluid flow. As a result, in residential LiB storage systems, the continuous charging/discharging C-rate is usually constrained up to 0.5C, to maintain its workable lifespan and minimize thermal runaway risk. In residential applications, the circuit breakers of houses are usually 16A rated and 32A rated, based on the single-phase voltage of 230 V, the drained power from the grid is limited to 3.68 and 7.36 kW respectively, correspondingly, the residential LiB storage capacity per house is around 10 kWh. The 10 kWh can be one LiB storage module or a combined system of several modules, this configuration depends on the module's integration design in terms of 'TEAMFCI.'

The third 'C'—cyclability. Lifespan of a LiB storage system is measured by its operation cycles. Manufacture of LiB cells can provide testing report of cell-level operation cycles under certain conditions, for instance, 6000 cycles under room temperature and 0.5C-rate charging and discharging. Integrating LiB cells to a LiB storage system, generates a cell-to-system cyclability loss caused mainly by the SoC difference and temperature non-uniformity among all cells. Moreover, the LiB storage system will fade along with its lifespan via cycling degradation and calendar degradation. The cycling degradation can be measured by system SoH that describes the change of system throughput energy by comparing the current value to the beginning-of-life (BoL) value. The key stress factors associated with system SoH are temperature, SoC and current. Their respective influence is elaborated as below:

1. Temperature—The optimal operating temperature of LiB cells is between 15 and 35°C, in order to guarantee its working reliability and maintain its maximum cyclability [14]. Temperature effects exist in both calendar aging and cycling aging modes. At high temperature [15], the solid-electrolyte-interfacial (SEI) layer at the anode will deteriorate and gradually dissolve into the electrolyte The damaged SEI layer will be restored from the side reactions between the exposed active anode material and electrolyte, but this process will induce the difficult intercalation and lower ionic conductivity at the anode. The same degradation mechanism occurs at the cathode side with solid-permeable-interface (SPI) layer This can cause structural damage to the active cathode material. At low temperature, there is sluggish electrochemical reaction [16], which will induce output power degradation and irreversible capacity loss. The relationship between the capacity fading and temperature can be represented in Arrhenius equation [15], $A = A_0 * \exp\left(-\frac{E_a}{RT}\right)$, Where $A$ is the amount of capacity fading, $A_0$ is the pre-exponential term, $E_a$ is the activation energy, $R$ is the gas constant and $T$ is the temperature in Kelvin. This equation is applicable to describe both calendar fade and cycling fade. The activation energy $E_a$ decreases at higher battery SoC, which means that capacity fades faster at higher SoC.

2. SoC—LiB SoC represents the available capacity in the LiB cells. At high SOC [14], more electro-chemical reactions will take place and the SEI layer will grow faster, as well as the aggravating self-discharge. In cycling mode, the SoC effect on LiB cells degradation cannot be described well owing to short maintaining time at different SoC levels. Usually, there is an advised operation SoC range in LiB storage system, namely the depth of discharge (DoD), in order to minimize the negative impact on system SoH.

3. Current—Current inevitably affects system SoH given the generated ohmic heat power and thus makes the current effect become part of the temperature impact.

Based on above analysis of key stress factors, the LiB storage system SoH can be calculated and predicted if the system temperature can be obtained and predicted as well as an equivalent system-level activation energy. A semi-analytic methodology (SAM) [17] can be utilized to quickly calculate LiB storage system temperature. This SAM is extracted by studying active thermal management in the LiB storage system. In the active thermal management, the main heat exchange happens at the interface between solid and fluid. This SAM article [17] analyzed thermal networks for both steady-state and transient-state heat transfer situations, as well as studying the influence of different input parameters on system temperature. Compared to complicated computation resources and long computation time in numerical simulation, this SAM can calculate the thermal outcome based on variable inputs within a few minutes. This SAM can be part of an algorithm for SoH calculation and prediction in LiB storage systems while also potentially optimizing the system operation cyclability and workable lifespan.

The fourth 'C'—cost. The cost breakdown in LiB storage system are mainly from battery cells, BMS, and system integration. On top of concern of battery cost and BMS cost, the cost of system integration needs to be balanced and considered, especially the cost of thermal/electrical/mechanical solutions. In additions, the cost of system lifespan and that of system scalability are required to be counted into the calculation. In residential markets, some low-price LiB storage systems have not covered scope of long lifespan and system scalability.

The 'S'—safety risk. Temperature of LiB storage system is crucial given its direct triggering of thermal runaway. Thermal runaway of LiB cells can be triggered at about 85–120°C owing to the solid-electrolyte interface decomposition, followed by battery separator melting at about 130°C, then the cathode decomposition and electrolyte oxidation will occur at above 150°C, this is the timing of entering thermal runaway and catching fire. Thermal runaway in LiB storage system can be caused by factors like internal short circuit/functionality safety malfunction/overheating/mechanical damage of batteries. The Lithium Ferro Phosphate (LFP) cathode-based LiB is more electrochemical stable and more suitable for residential applications compared to the Nickel Manganese Cobalt Oxide (NMC) cathode-based LiB. The fire-safety design in LiB storage system covers fire propagation mitigation. Meanwhile, the safety evaluation of LiB storage systems can be certified with UL 9540/IEC 62933-5 whose testing scope covers system thermal runaway, so as to better prevent from danger.

## 4. Future of residential ESS

The whole RRES is developing towards higher and higher flexibility, compatibility and scalability.

1. The high flexibility means that a friendly user interface can be accessed to monitor and manage system operation modes, in order to optimize electricity bills to the biggest extent. This can include choosing solar irradiance peak hours to charge LiB storage and selecting grid peak hours to discharge LiB storage. By collecting and analyzing the big data from end-users, different user portrait models can be generated for realizing automatic optimization of system operation modes.

2. The high compatibility aims at including more user demand into this eco system, like heat pump and EV chargers. Apart from energy management system (EMS), there will be a central/distributed Gateway solution that is embedded with data analytics models. This Gateway solution can communicate among different products in the eco system.

3. The high scalability means to build up a bridge between the RRES and utility renewable energy system (URES), the RRES and URES can become each other's power source or power demand, which helps us to connect the distributed RRES dots and knit a bigger eco network.

Based above understanding of future RRES, we can sense that the future residential ESS will become more and more intelligent and diverse.

### 4.1 Future of LiB storage system

In LiB storage solution, there are two key constituents, one is LiB cells, the other is BMS. The future of LiB cells and that of the BMS represents the future of LiB storage solution.

Climate change affects all aspects of civilization and where LiB are concerned the LiB cells that can sustain at higher average temperature will be one of the future needs. The other trend of future LiB storage in residential markets is to repurpose the e-mobility LiB storage systems. The LiB share in e-mobility market will reach up to 2333 GWh by 2030 [18], Worldwide, it is expected to produce over 2 million metric tons of used batteries per year by 2030 [19]. The retired LiB storage systems still retain 70–80% of BoL throughput energy. Compared to directly recycling the retired systems, repurposing them into less-challenging applications will be better way in terms of environmental friendliness and supply chain stability. This repurposing strategy will facilitate the spread of RRES over the world as well. There are a plethora of research work on the repurposing methodologies. The sequence starts from quality checking and goes through classification, integration and commissioning. The quality checking includes both cosmetic checking and functionality validation. Because the SoH of retired system is usually limited by the weakest cell, the identification of healthy cells in a system can help to improve the throughput energy via replacing the weak cells or bypassing them in the repurposed electrical circuit. A non-invasive battery grading algorithm can be found in reference [20]. In this proposed battery grading algorithm, cell-level historical voltage data as a reflection of cell degradation is investigated as well as cell-level historical maximum temperature data calculated with the developed SAM methodology [17]. The LiB cells in the retired system can be graded to three levels by analyzing their historical voltage fluctuation and working temperature variation. The rationality of this algorithm was validated in the 'Battery Grading Algorithm' work by Ya et al. [20].

An intelligent BMS that can sync real-time cell-level data to remote cloud and accept remote operation command will be the future trend. The boundary between BMS and EMS will be more and more blurred over time. The existing BMS solutions include four function blocks. The first function block is to collect cell-level sensing data from sensors of voltage, current and temperature. The second function block is to balance the voltage among different LiB cells in order to optimize lifespan of the whole system, otherwise the lifespan will be affected by the weakest cell which experiences over charge or over discharge. The third function block is to safeguard the whole system by monitoring the collected data form the first function block. Usually there are two-levels warnings if the threshold values of voltage/current/temperature are triggered, if the warnings are maintained, the BMS will force the system to power off via relays. The fourth function block is for the BMS to communicate with external system like EMS or the other BMS. In future BMS solutions, it is hoped to sync real-time cell-level data to remote cloud for analytic models, and the weak battery cells can be bypassed via accepting remote command once it is diagnosed as unhealthy or abnormal, in this way, lifespan of the whole LiB storage system will be extended to the biggest extent.

### 4.2 Future of other residential ESS

Following the diverse trend of residential ESS, other types of ESS may enter residential market in one way or the other, such as Vanadium Redox Flow (VRF) ESS and Supercapacitor. Compared to LiB storage, VRF ESS and Supercapacitor have lower gravimetric energy density and corresponding bigger footprint, however, both VRF ESS and Supercapacitor can provide longer cyclability and more stable safe operation. The three types of ESS have different cycling speed, Supercapacitor has the highest speed, followed by LiB, the VRF has the slowest speed, as shown in **Table 1** [21].

Solid-sate battery (SSB) broke into our view since 2020. Different from LiB, the electrolyte in SSB is solid state. Based on different materials used in SSB Anode and Electrolyte, the SSB can be categorized as Li metal Sulfide SSB, Li metal Oxide SSB, and Anode free SSB [22]. Compared to LiB, the gravimetric energy density of SSB is about 1.7–2 times bigger, the volumetric energy density of SSB is about 1.1–1.6 times bigger, moreover, the SSB can operate under higher temperature of above 100°C [22]. SSB market size is predicted to be around USD 1645.6 million by 2030 [23]. The technology challenge for SSB is to combine both organic and inorganic solid electrolytes for obtaining both lower flammability and higher energy density [22]. Silicon Anode is also a technology trend due to its lower cost, non-flammability, and slower degradation. But Silicon Anode can bring in mechanical issues like voids and cracking [22]. In residential

| | LiB storage | VRF ESS | Supercapacitor |
|---|---|---|---|
| Gravimetric energy density, Wh/kg | ~150–250 | ~10–20 | ~1–10 |
| C-rate | ~0.2–3C | ~0.1–0.3C | ≥10C |
| Cyclability, years | ~10–15 | ~20–30 | ~15–20 |
| Therma runaway risk | Yes | No | No |
| Cost, USD $/kWh | ~0.07–0.2 | ~0.05 | ~0.006 |

**Table 1.**
*Performance comparison among different ESS solutions.*

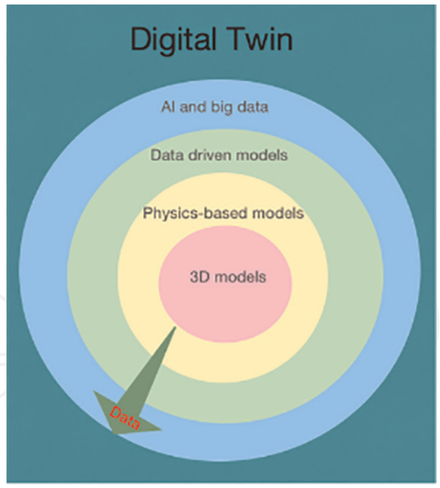


**Figure 9.**
*An understanding of Digital Twin architecture in RRES.*

market, there already exists SSB based products, this will motivate the development of residential ESS towards better safety, better reliability and smaller footprint.

Apart from different residential ESS solutions, the intelligent BMS will also dominate future technology trends by enabling predictive maintenance models in the cloud. The predictive maintenance model can generate adaptive warranty models and optimize quotation in product proposals. This will greatly sharpen company's business competency and enhance more opportunities.

Overall, a virtual system is anticipated to upgrade system performance, improve system operation efficiency and detect potential safety risks. It will be a bonus to have the virtual system alive to simulate different what-if scenarios. Thanks to all the research work published, we can now imagine such a virtual system architected with multi-discipline simulations and AI big data models using real-time data, as demonstrated in **Figure 9**. The virtual system also ages along with time and evolves to always mirror the physical system. In addition, the virtual system can have real-time communication with the physical system. This virtual system is widely recognized as 'Digital Twin.' We may not be able to develop fully working Digital Twin at this moment, however, some promising progress is already done by experts and colleagues in this field.

## 5. Conclusion

This chapter introduces the residential renewable energy solution (RRES) and the indispensable energy storage system (ESS) in RRES. The Li-ion battery (LiB) storage system, as the main focus, is introduced and analyzed with summarized methodology. The future development trend in RRES and residential ESS is discussed as well. I hope this chapter can help the people who are interested to learn renewable energy applications, as well as the people who want to push the existing boundaries in RRES.

## Thanks

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