Energy Storage Systems Technology Roadmap for Singapore

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PUBLIC VERSION

Prepared for

Energy Market Authority (EMA)

by

Experimental Power Grid Centre (EPGC),
Energy Research Institute at NTU (ERI@N)

and

Urban & Green Tech Office (UGTO),
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Table of Contents — Page No

List of Abbreviations

AC	Alternating Current
AGC	Automatic Generation Control
AGV	Automated Guided Vehicle
BCA	Building and Construction Authority
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
BMS	Battery Management System
BSUoS	Balancing Services Use of System
BTM	Behind-the-Meter
CAES	Compressed Air Energy Storage
CCGT	Combined Cycle Gas Turbine
CCTV	Close Circuit Television
CSA	Canadian Standards Association
CSP	Concentrated Solar Power
DBOM	Design-Build-Operate-Maintain
DC	Direct Current
DER	Distributed Energy Resource
DOD	Depth of Discharge
DUoS	Distribution Use of Service
E/P	Energy to Power Ratio
EDB	Economic Development Board
EFR	Enhanced Frequency Response
EMA	Energy Market Authority
EMC	Energy Market Company
EOL	End-of-Life
EPC	Engineering, Procurement and Construction
EPGC	Experimental Power Grid Centre
ESG	Enterprise Singapore
ESS	Energy Storage Systems
EV	Electric Vehicle
FAT	Factory Acceptance Test
FCAS	Frequency Control Ancillary Service
FCL	Final Consumption Levy
FERC	Federal Energy Regulatory Commission
FFR	Fast Frequency Regulation
FiT	Feed-in Tariff
GENCO	Generation Company
GRF	Generation Registered Facility
GFA	Gross Floor Area
HDB	Housing and Development Board

HT	High Tension
ICC	International Code Council
ICE	Internal Combustion Engine
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IFC	International Fire Council
IGS	Intermittent Generation Source
IHL	Institute of Higher Learning
IMO	International Maritime Organisation
JTC	JTC Corporation
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LCO	Lithium Cobalt Oxide
LCOS	Levelised Cost of Storage
LFP	Lithium Iron Phosphate
LLE	Large Local Enterprise
LMO	Lithium Manganese Oxide
LMFP	Lithium Manganese Iron Phosphate
LNG	Liquified Natural Gas
LTA	Land Transport Authority
LTO	Lithium Titanate Oxide
MNC	Multinational Corporation
NCA	Lithium Nickel Cobalt Aluminium Oxide
NEA	National Environment Agency
NECA	National Electrical Contractors Association
NEMS	National Electricity Market of Singapore
NFPA	National Fire Protection Association
NMC	Lithium Nickel Manganese Cobalt Oxide
NParks	National Parks Board
NTU	Nanyang Technological University
NUS	National University of Singapore
NVP	Sodium Vanadium Phosphate
O&M	Operation & Maintenance
OTR	Operation & Technology Roadmapping
PE	Professional Engineer
PHS	Pumped Hydro Storage
POC	Proof of Concept
PPP	Public-Private Partnership
PSO	Power System Operator
PUB	Public Utilities Board
PV	Photovoltaic

QP	Qualified Persons
RO	Renewables Obligation
RSA	Resource Sustainability Act
SAT	Site Acceptance Test
SCADA	Supervisory Control and Data Acquisition
SCARCE	Singapore-CEA Alliance for Research in Circular Economy
SCDF	Singapore Civil Defence Force
SEI	Solid Electrolyte Interphase
SIEW	Singapore International Energy Week
SME	Small Medium Enterprise
SMES	Superconducting Magnetic Energy Storage
SNG	Synthetic Natural Gas
SPPG	SP PowerGrid
STEEL	Sustainability & Circularity – Technologies – Economics – Enabling Policies – Land
TEA	Techno-Economic Analysis
T&C	Testing and Certification
TIC	Testing, Inspection & Certification
TMS	Thermal Management System
TNUoS	Transmission Network Use of System
UL	Underwriters Laboratories
UPS	Uninterruptible Power Supply
URA	Urban Redevelopment Authority
V2G	Vehicle-to-Grid
VPP	Virtual Power Plant
VRB	Vanadium Redox Battery
VRLA	Valve Regulated Lead Acid
ZEBRA	Zero Emissions Batteries Research Activity, a type of Sodium Nickel Chloride battery

Executive Summary

Energy Storage Systems (ESS) has been identified as an essential technology to manage solar intermittency and maintain grid stability. Its ability to store energy for future use and rapidly respond to power fluctuations can help facilitate the integration of intermittent generation sources (IGS), while maintaining system stability and reliability.

Singapore has set a deployment target of 200 megawatt (MW) of ESS beyond 2025. To achieve this ambition, EMA has commissioned ERI@N and A*STAR to develop an ESS Technology Roadmap to:

a) Provide insights on the global technological development and economics of ESS technologies; and
b) Provide recommendations on the capabilities to support the local ecosystem and identify solutions that can be exported to the region.

Key stakeholders from government agencies, solution providers, end users, researchers and academia were consulted to provide views and feedback to the roadmap. Key recommendations include:

Category	Recommendations	Time
Technology Development	Support research in relevant ESS technologies, including next-generation batteries, second-life and recycling technologies.	S-M-L
	Develop test-bedding opportunities for new ESS technologies and applications.	S
	Commission detailed techno-economic study of ESS in local context.	S-M
Regulations	Review policies and regulations in the electricity market for ESS.	S-M
	Refine local ESS standards to provide guidance for safe deployment and maintenance	S
	Review policies and regulations on recycling and disposal at the end-of-life of ESS.	M
Ecosystem Development	Develop a one-stop portal for ESS-related information.	S
	Develop a Testing and Certification hub through partnerships with both international and local players.	M
	Support the development of ESS prototyping facilities / pilot lines to fabricate large size cells, battery packs and auxiliary systems.	M
	Develop communication infrastructure to support the growth of emerging ESS technologies and business models.	S-M
	Align relevant ESS curricula and develop training programmes in IHLs and other training institutes for students and professionals.	S

1. Introduction

The global energy sector is undergoing drastic changes driven by climate change and technology improvements. The power grid is transitioning from a highly centralised architecture powered by large power plants, to a more distributed architecture with renewables (e.g. solar) and variable loads (e.g. electric vehicles (EVs)). ESS is seen in many jurisdictions as a key technology to ensure system flexibility, reliability and resilience as depicted in Figure 1.1. It is notable that the global adoption of ESS has increased significantly since 2010, arising from two key trends:

a) **Decrease in battery prices.** Increased adoption of EVs has led to mass production of batteries and significant reduction in prices, especially for lithium-ion batteries [1].

b) **Increase in integration of intermittent renewables into the grid.** When solar photovoltaic (PV) penetration reaches higher levels, the intermittent nature of solar PV generation can start to have noticeable impact on the grid (i.e. fluctuations in grid voltage and power factor) [2]. ESS is thus required to manage the intermittent nature of solar energy generation.

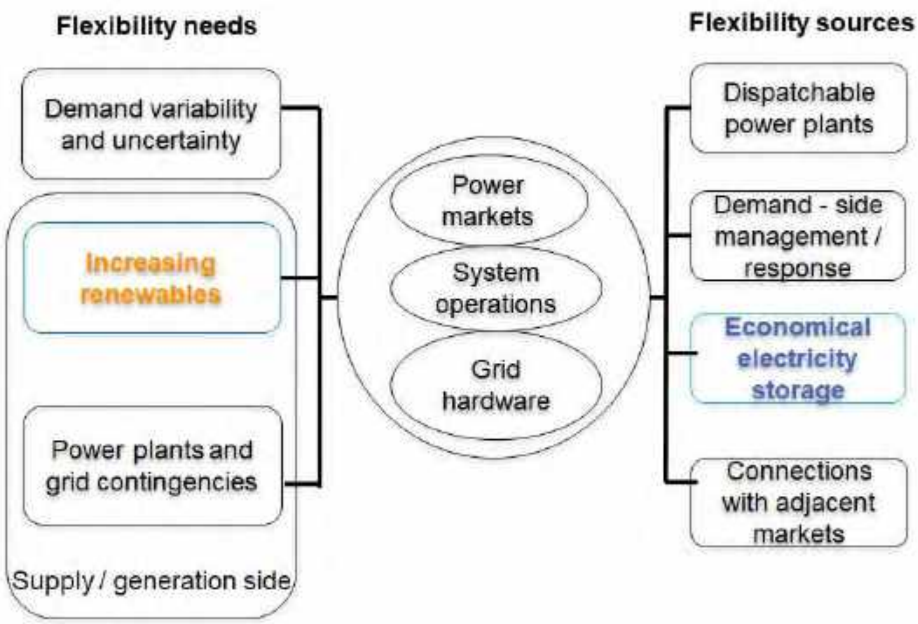


Figure 1.1 Key components of a smart flexible grid [3]

During the 12th Singapore International Energy Week in 2019, Minister for Trade & Industry, Mr Chan Chun Sing spoke about Singapore's Energy Story [4]. This was about transcending the challenges of the energy trilemma - to keep our energy supply affordable, reliable and sustainable. He also announced that Singapore would set its installed solar PV capacity target to at least 2 GWp by 2030, enough to power about 350,000 households for a year. To overcome the challenge of solar intermittency, Singapore has put forth a target to deploy 200 MW of ESS beyond 2025.

1.1 Objectives and Scope

EMA commissioned ERI@N and A*STAR to develop an ESS Technology Roadmap for Singapore. Key objectives of the ESS Technology Roadmap include:

a) Provide insights on the global technological development and economics of ESS technologies; and

b) Provide recommendations on the capabilities to support the local ecosystem and identify solutions that can be exported to the region.

In framing the roadmap, five focus areas (abbreviated as STEEL) were identified as key contributing factors to the development of Singapore's ESS ecosystem:

a) <u>S</u>ustainability and Circularity
This area covers the planning required to handle the End-Of-Life (EOL) of ESS and emerging opportunities for the reuse and recycling industry. This includes creating capabilities and supply chains to (i) optimise used batteries for second-life applications; and (ii) recycle EOL ESS to extract valuable resources.

b) <u>T</u>echnologies
This area covers the type of ESS technologies that are most suitable for deployment in Singapore in the short, medium and long term, taking into consideration the safety requirements of an urban city. It will also cover the sub-systems and services that Singapore should build locally to accelerate ESS deployment.

c) <u>E</u>conomics
This area covers the relevant ESS applications in Singapore's context. It will also identify business models to reduce the cost of ESS deployment.

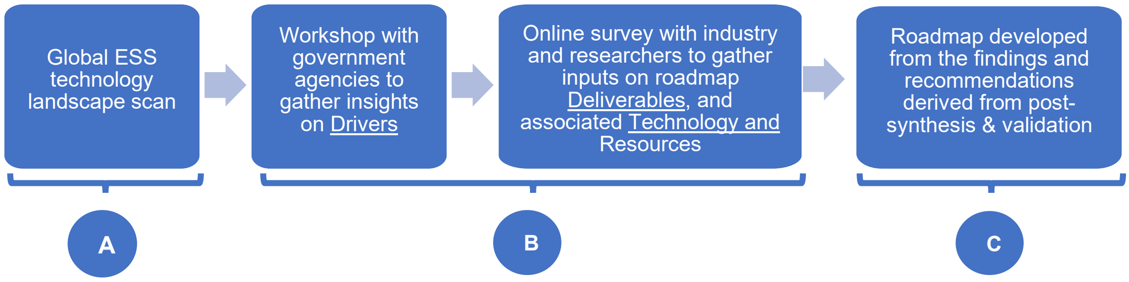
d) <u>E</u>nabling Policies and Regulations
This area covers the best practices from other jurisdictions which can be used to enhance existing frameworks in Singapore.

e) <u>L</u>and
This area covers the potential locations suitable for large-scale ESS deployment.

1.2 Roadmap Methodology

A three-step approach was adopted in crafting the roadmap, as shown in Figure 1.2.1.

Figure 1.2.1 Roadmap methodology process flow



A) An **ESS technology landscape scan** was conducted to provide a reference for Singapore and benchmark local developments against the global scene. This was done through reviewing literature including ESS roadmaps, consultant reports and academic publications from other jurisdictions.

B) A (i) **brainstorming workshop** and (ii) **thematic driven online survey** were conducted to garner inputs to construct this roadmap. For (i), government agency representatives were invited for a workshop to gather perspectives on key drivers to grow Singapore's ESS ecosystem. This was followed by (ii), involving academic researchers and industry (i.e. ESS vendors and end users). The survey identified the needs, challenges and gaps in Singapore's ESS ecosystem and proposed solutions to address them.

C) An **ESS technology roadmap** was developed using A*STAR's Operation & Technology Roadmapping (OTR) methodology, and findings from the landscape scan, workshop and survey were assigned to the three layers of Drivers, Deliverables and Tech & Resources as illustrated in Figure 1.2.2 and enclosed in Annex 1. The layers are subsequently synthesised to yield short-, medium- and long-term recommendations.

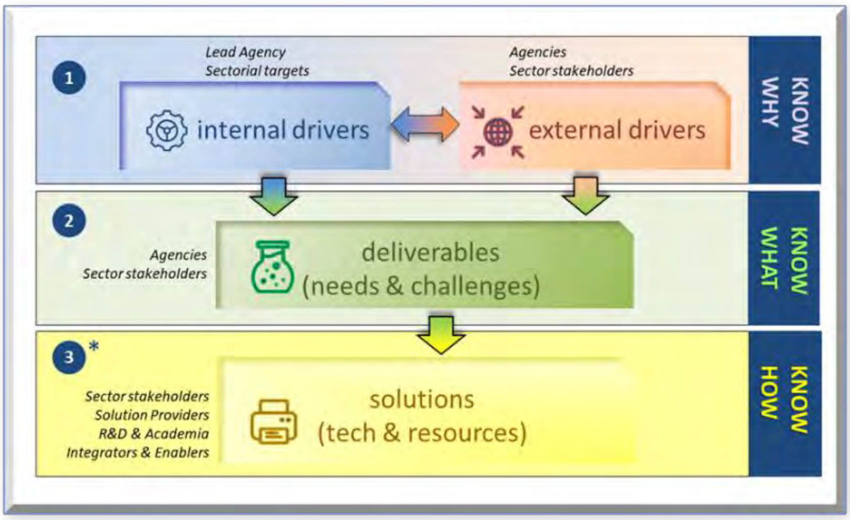


*Figure 1.2.2 Process framework leveraging of A*STAR's OTR methodology*

2 Survey of ESS: Global Trends and Relevance to Singapore

2.1. Technology Trends – Short/Medium/Long term

Energy can be stored in various forms and converted to electrical energy using suitable conversion devices when required. For example, we have broadly classified the technologies into mechanical, thermal, electrical and electrochemical as shown in Figure 2.1.1.

Mechanical storage	• Pumped Hydro Storage (PHS) • Compressed Air Energy Storage (CAES) • Flywheels
Thermal storage	• Hot water storage • Molten salt energy storage • Phase change material storage
Electrical storage	• Supercapacitors • Superconducting Magnetic Energy Storage (SMES)
Electrochemical storage	• Sodium sulfur batteries (NaS) • Lithium-ion batteries • Vanadium redox-flow batteries (VRB)

Figure 2.1.1 ESS technology classification [5]

Annex 2 provides a description of each of these technologies, and their advantages and challenges. EMA's Deployment Handbook for ESS (go.gov.sg/ema-ess-handbook), and ESS Technology primer [6] also serve as good resources to explain the various ESS technologies.

<u>Comparison of Various Technologies</u>

A review of the various ESS technologies and their applicability to Singapore to support national solar ambitions was completed and summarised below:

- PHS and CAES are geographically dependent and are not suitable for Singapore which is relatively flat and does not have naturally forming underground caverns.
- Hot water thermal storage is less relevant to Singapore due to the limited scope for concentrated solar power (CSP) in Singapore. Diffused irradiation due to mostly cloudy conditions and non-availability of large open land limit the potential of any sizeable CSP plant implementation in Singapore.
- SMES is a complex technology owing to the need for very low operating temperatures and associated operational energy and cost. SMES is still a developing technology and currently has limited deployment globally.

A comprehensive landscape scan was conducted on the technical performance and cost of the other ESS technologies listed in Table 2.1.1. While there are variabilities in the cost and performance parameters across the different literatures [1], [2], [5], [7], [8], there was consensus in terms of qualitative trends. Typical qualitative figures representing cost and performance of various technologies are listed in Table 2.1.1.

Table 2.1.1 Techno-Economic Parameters of ESS Technologies adapted from US Hydrowires Report [8] and other sources [9]

More favorable

Parameter	Flywheel[(a)]	Super Capacitor[(b)]	Lead Acid Battery[(c)]	Lithium-ion Battery[(c)]	ZEBRA (NaNiCl) [(c)]	Flow Battery[(c)]
Efficiency* (%) (DC+AC)	70-95	80-95	70-75	85-90	80-85	65-70
Response (seconds)	0.25	0.016	0.1-1	0.1-1	0.1-1	1-10
Lifetime (cycles to 80% DOD)	100K	100K	0.5K-0.9K	2K-4K	3.5K	10K
Lifetime (years)	20	40	3	10	10-15	15
CAPEX (DC+AC) (USD/kW)	1080-2880	835-930	1430-2522	1570-2322	2810-5094	2742-5226
CAPEX (DC+AC) (USD/kWh)	4320-11520	66K-74K	358-631	393-581	703-1274	686-1307
Energy Density (Wh/L)	20-80	10-20	50-90	200-800	170-190	20-70
Power Density (W/L)	5000	40K-120K	90-700	100-10K	250-260	0.5-2
Self-discharge per day (%)	1.3-100	20-40	0.1-0.3	0.2	1-14	0.2
Typical charging rate* [10], [11],[12]	N.A.	N.A.	0.1-0.3 C	0.2-0.8 C	0.1-0.15 C	0.1-0.15 C

(a) E/P = 0.25 h, (b) E/P = 0.0125h, (c) E/P = 4 h

E/P refers to Energy to Power ratio which represents the discharge duration of the ESS.

- 4-hour discharge period is chosen for lead acid, lithium-ion, ZEBRA and flow battery as 4 hours represents the transition point between short term discharge period (< 4 hours) and medium-term discharge period (4 to 8 hours).

- Flywheel and supercapacitor are more suited for power intensive applications, and smaller discharge durations are chosen as indicated above.

- It is to be noted that costs indicated are for E/P =4. For other E/P ratios, the actual project cost will have to recalculated based on individual components like battery costs (B) ($/kWh), installation and commissioning (I&C) ($/kWh), PCS cost ($/kW), balance of plant (BOP) ($/kW) using the relation:
  [(B+(I&C)) + {(PCS +BOP) / (E/P)}]. If the E/P ratio is 1, costs of lithium-ion-based BESS (based on 2019 market prices) becomes 760 USD/kWh (about 1000 SGD/ kWh).

*Actual charging rates vary with manufacturer specifications to improve system lifetime. Special chemistries under each category can have different C rates (For example, lithium-titanate-oxide (LTO) can charge at high rates, 2-10 C).

Based on power and energy capacity, flywheels and supercapacitors are suitable for high power and fast response applications, as shown in Figure 2.1.2. Flow and ZEBRA batteries are suitable for medium duration storage i.e. for discharge periods of 4 to 8 hours. Lithium-ion batteries, on the other hand, can cover a wide duration range, serving both short (e.g. power quality) and medium (e.g. reserves) discharge period applications. These applications are elaborated in Section 2.2 and Annex 3.

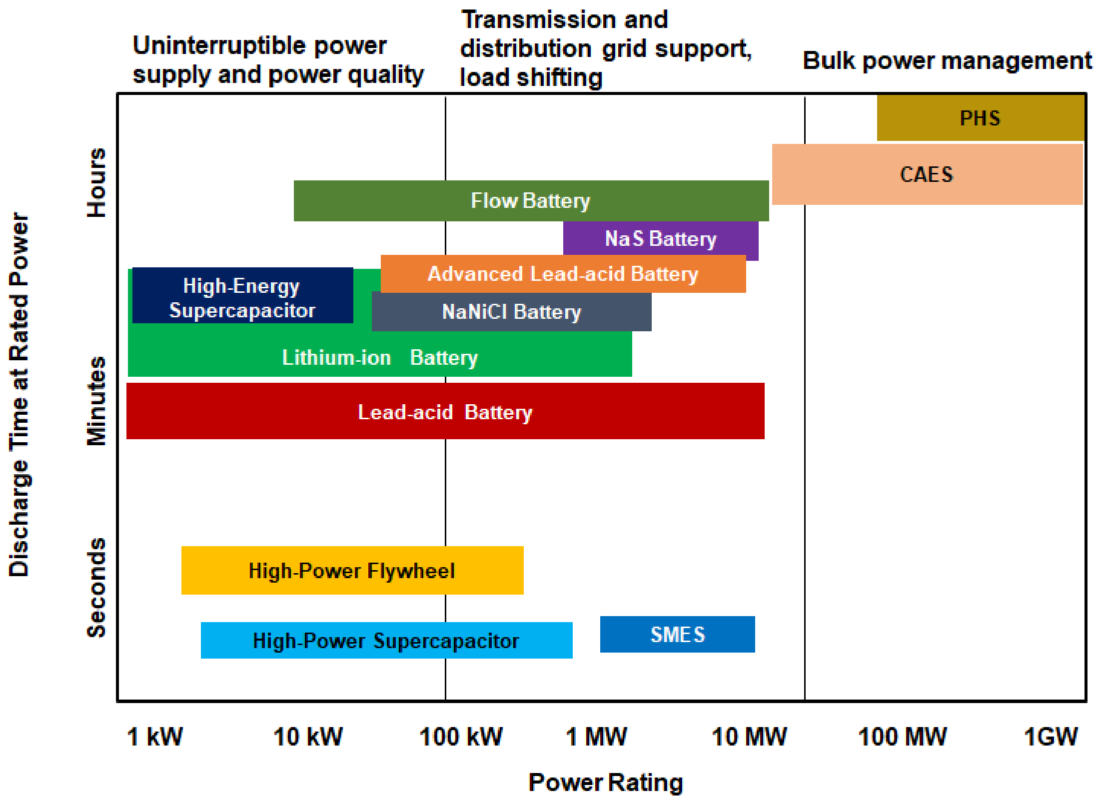


Figure 2.1.2 ESS technology suitability depending on discharge duration [13]

From a data published in a recent cost characterisation report [8], the normalised data of the six technologies are listed in Table 2.1.2. Relative to other technologies, lithium-ion has the lowest capital expenditure (CAPEX) costs (based on 2019 data). Supercapacitors may be considered for high power applications as it has the cheapest cost in terms of $/kW (as seen in Table 2.1.1) but is limited by its ability to store energy (i.e. most expensive CAPEX for $/kWh).

Table 2.1.2 Comparison of ESS technologies with normalisation with respect to lithium-ion battery

	Lithium-ion battery (*Reference point*)	**Lead acid battery**	**Flow battery**	**ZEBRA battery**	**Super Capacitor**	**Flywheel**
Energy density* (Wh/L)	1	0.10-0.25	0.10*	0.25-0.33	0.01	0.10
Capex Cost (E/P=4) $/kWh	1	0.9-1.1	1.7-2.2	1.8-2.2	70	15

Annualised Cost $/kWh per year	1	2.9	1.6	1.8	200	42

* It is useful to note that actual footprint of ESS system would include auxiliary systems like power conversion system (PCS) and fire safety systems, which are common to most technologies. Consequently, the actual ratio of footprint areas (at system level) between different technologies would be different. For example, lithium-ion battery ESS (BESS) would occupy one-third to one-quarter of the space compared to an equivalent-rated flow battery system. The actual footprint will also be influenced by the local safety requirements.

Short term (2020 – 2025)

Lithium-ion battery is currently the most viable technology in Singapore's context in the near future. Other ESS technologies such as flow batteries are maturing and is expected to be widely adopted as cost reduces in the medium term beyond 2025. Research has shown that lithium-ion battery is the dominant technology for stationary ESS (besides PHS) as seen in the data shown in Figure 2.1.3, which was released by International Energy Agency (IEA) in 2017. Lithium-ion batteries made up 88% of the global installed capacity in 2016. IEA's latest report in June 2020 also reaffirmed lithium-ion's dominance and observed that around 60% of grid-scale batteries were lithium-ion nickel-manganese-cobalt (NMC) blends.

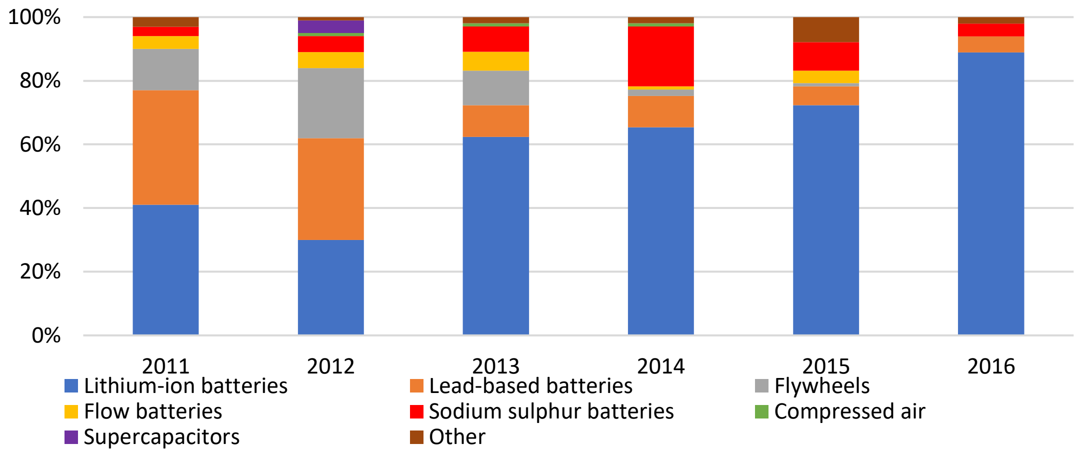


Figure 2.1.3 Technology mix of yearly installed capacity of ESS (excluding PHS) [14]

Within the lithium-ion family, there are variants depending on the cathode, anode, and electrolyte combinations. Popular variants include lithium-iron-phosphate (LFP), lithium-cobalt-oxide (LCO), lithium-nickel-manganese-oxide (NMO), lithium-nickel-manganese-cobalt (NMC), lithium-nickel-cobalt-aluminium-oxide (NCA) and lithium-titanate-oxide (LTO). Various public industry reports [1], [9], [15] were referenced and their advantages and challenges relating to stationary energy storage (sorted according to its disclosure year) are summarised in Table 2.1.3.

Table 2.1.3 Comparison of key lithium-ion battery variants

Chemistry	Energy density, Wh/L	Life cycle	Initial Cost	Safety	Remark
LCO	300-840	800	Very high	Poor	Very sensitive to overcharging; poor life cycle; and high cost.
LFP	150-350	4000-10000	Low	Good	Thermal runaway temperature at about 270 °C; safe and cost effective.
NMC	300-750	1000-6000	Low	Fair	Thermal runaway temperature at about 200 °C; More protection is needed for system safety.
NCA	300-750	500-2000	Moderate	Fair	Good thermal performance but poor life cycle.
LMO	200-400	1500	Low	Fair	Safety is not as good as LFP; poor high temperature performance; low cost.
LTO	100-200	15000	Very high	Very good	Low voltage; complicated integration; high cost.

LFP and NMC (highlighted above) are currently the more popular variants for stationary ESS due to their technology maturity, high cycle life and low cost. Comparing LFP and NMC, NMC has an edge over LFP in terms of energy density, whereas LFP has advantages in terms of life cycle and safety.

In terms of application, it is expected that NMC, with its higher energy density, will remain dominant for transportation applications such as EVs and planes, where mass and volume are important considerations. LFP, with better fire safety and cycle life, is expected to be a strong competitor for stationary grid applications.

Medium Term Technologies (2025- 2030)

In the medium term, most market analysis expect lithium-ion battery to continue to dominate, with flow battery as a potential challenger for its excellent cycle life and safety.

Table 2.1.4 Key Medium Term Battery Technologies

Medium Term Technologies (2025-2030)	
Battery Technology	**Description**
Flow Battery	Benefits: • Potential to offer unlimited energy capacity by using larger electrolyte tanks • Inherently safe (using aqueous electrolyte) • Excellent cycle life (15,000-20,000 cycles) • Suitable for long duration of more than 4 hours Obstacles: • Narrow operating temperature range (e.g.15-35 °C for VRB) • Low energy density (current state: 15-25 Wh/L, future possibility: 60 Wh/L)

Lithium-ion Battery -Silicon Anode -Lithium Rich Cathode - Anode-Free and Solid-State Batteries	Benefits: • High energy density • Current state - around 700 Wh/L. Future possibility - 900 Wh/L (all-solid-state battery), 1200 Wh/L (anode-free battery) Obstacles: • Volume change during cell operation (silicon anode) • Side reactions with electrolyte and cathode structure stability (lithium-rich cathode) • Formation of lithium dendrite (anode-free batteries) • Low ionic conductivity (all-solid-state batteries)

As mentioned in Table 2.1.4, flow batteries are promising ESS solutions, especially for applications requiring long discharge duration and storage. However, the typical energy density of 15-25 Wh/L for conventional vanadium redox batteries (VRBs) is low compared to lithium-ion batteries (i.e. 700 Wh/L). This is mainly limited by the low solubility of the vanadium species and the narrow electrochemical stability window of the aqueous electrolyte (1.23 V) [16]. To achieve higher energy densities, semi-solid flow batteries or non-aqueous electrolytes are being researched globally [17], [18]. Other potential candidates for next generation flow batteries include iodine, polysulfide and other organic redox-active materials [19].

Meanwhile, lithium-ion batteries are also seeing rapid technological advancements, mainly towards achieving higher energy density. Focus is in three areas:

- High silicon content anode. Silicon has a theoretical specific capacity of 4200 mAh/g that is 10 times higher than conventional graphite anode, and has currently been commercially used in high-energy batteries with a low weight ratio (~ 2 wt.%, Samsung 35E) [20]. A major obstacle in the development of silicon anode is the huge volume expansion (by 300%) when reacting with lithium ($Si \rightarrow Li_{4.4}Si$), resulting in the pulverisation of silicon grains and fast battery performance degradation.

- Advanced cathode chemistries. High Ni content is a trend in advanced cathode developments. One of which is the replacement of NMC532 (with 50% nickel, specific capacity: 170 mAh/g) with high-capacity NMC811 (with 80% nickel, specific capacity: 200 mAh/g), which can effectively boost the overall energy density by ~18% to 272 Wh/kg (cell level, with graphite anode) [21]. Cobalt-free approach is also possible in the medium term for lower raw material costs. $LiNiO_2$ (with 100% nickel) with a specific capacity of above 250 mAh/g is the best choice among all layered cathode materials. However, there are still challenges in the synthesis of stoichiometric $LiNiO_2$ [22], and reversibility of its multiple phase transition chemistries [23], [24].

- Finally, a medium term cathode development direction is towards lithium-rich cathodes (Li_2MnO_3-$LiTMO_2$, TM=Ni, Co and Mn). Different from conventional cathode materials with only the redox of transition metal cations, lithium-rich cathodes involve additional oxygen-anion redox with specific capacities up to 300 mAh/g [25], which are even higher than the theoretical capacity of $LiTMO_2$. The commercial adoption of high-nickel cathodes is hindered by the poor thermal stability and recently there have been several fire accidents in EVs using NMC811 battery. For a high working voltage (> 4.5 V) and the release of oxygen in cell operation [26], lithium-rich cathode is even more challenging in terms of safety which may rely on the development of non-flammable all-solid-state electrolyte in the near future.

Long Term Technologies (2030 - 2050)

For the purpose of this report, we have identified a few technologies that have the potential for future ESS research, as listed in Table 2.1.5.

Table 2.1.5 Key Long Term Technologies

Long Term Technologies (2030 - 2050)	
Battery Technology	**Description**
Advanced lithium battery -Anode-free -Lithium metal -All-solid-state	Benefits: • High energy density (900-1400 Wh/L, 400-500 Wh/kg) Main challenges: • Irreversible lithium plating with limited cycle life • Formation of lithium dendrites raising safety concern • Side-reactions between electrolyte and electrodes
Sulfur-based battery	Current state: • Energy density - 400 Wh/kg and 272 Wh/L (data from Oxis Energy) Future potential: • Low cost battery • High specific energy density - (600 Wh/kg) Main challenges: • Low volumetric energy density due to excessive use of carbon to construct sulfur electrodes. Suited for mobile applications where weight is a concern. • Poor cycle life caused by the parasitic polysulfide shuttle
Metal-air battery	Current state: • Non-rechargeable battery with energy density at 1000 Wh/L and 800 Wh/kg (made by PolyPlus Battery Co.) Future potential: • Safer open system battery • Volumetric energy density can also be improved to 1000 Wh/L with a specific energy density of 800 Wh/kg Main challenges: • Oxygen separation from air • Side-reactions between cathode and electrolyte • Sluggish oxygen reduction and evolution reactions

Anode-free Lithium Battery

In a conventional lithium-ion battery, graphite anode works as a reservoir to alloy with lithium extracted from cathode during charging and it occupies around 50% of the total cell volume, with a typical thickness of 200 μm. Ideally, graphite can be removed with only an ultra-thin copper current collector (6 μm) left, on which lithium can deposit in its metallic form with a total thickness of around 40 μm (based on a single-side capacity loading of 4 mAh/cm^2). Such anode-free design could double the energy density to 1200 Wh/L (Figure 2.1.4) [27]. However, anode-free lithium batteries often exhibit fast capacity fading with quite limited cycle life (< 20 cycles) for the irreversible lithium plating [28].

Lithium Metal Battery

An alternative to anode-free design is to use lithium-metal as the anode. The lithium metal not only works as the current collector for lithium plating, but also compensates the lithium loss during cell operation [29]. The commercial adoption of lithium current collector faces the challenges of poor mechanical property (difficult to make a lithium foil thinner than 20 µm for high energy density) and highly reactive nature of lithium (needing an ultra-low, humidity-controlled room for lithium processing, which increases the production cost). The presence of metallic lithium in cell operation in both anode-free and lithium metal batteries also raises safety concerns.

Solid State Lithium Battery

A concurrent development is the use of solid-state electrolytes. In addition to replacing the highly flammable liquid electrolytes, solid electrolytes can address the technical challenges of reversible lithium plating. An all-solid-state battery often relies on the use of lithium-metal or an anode-free approach to boost its energy density. There are multiple technical routes for the development of solid electrolyte and some of them have been commercialised at a smaller scale. For example, STMicroelectronics has a thin film all-solid-state lithium battery (i.e. EnFilmTM with a capacity of only 0.7 mAh [30]. Scaling up such a technology for industrial size batteries is difficult as the growth of lithium phosphorous oxy-nitride electrolyte layer via sputtering is extremely slow [31]. Other chemistries such as poly (ethylene oxide)-based solid electrolyte coupled with lithium metal (LMP® Battery, developed by Blue Solutions, a subsidiary of the Bolloré Group) has been used in BlueSG (a local EV retinal company) with a lifespan of more than 3,000 cycles at 80% DOD [32].

In the long term, exploration of solid electrolytes is an active and important field that broadly includes oxide-based systems (e.g. $Li_{1.5}Al_{0.5}Ge_{1.5}P_3O_{12}$ and $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$) or sulfide-based systems (e.g. $Li_{10}GeP_2S_{12}$) [33]. Even though much progress has been made, like Samsung's recently reported a 0.6 Ah pouch-type all-solid-state battery with an energy density above 900 Wh/L [34], many problems still remain. Suppression of lithium dendrite via the high mechanical strength still poses a challenge as recent studies have shown that solid electrolyte may crack during cycling and lithium dendrites are formed inside [35]. Poly(ethylene oxide) and sulfide-based electrolyte also suffer from poor stability at the voltage above 4 V (vs. Li/Li^+) [36], [37].

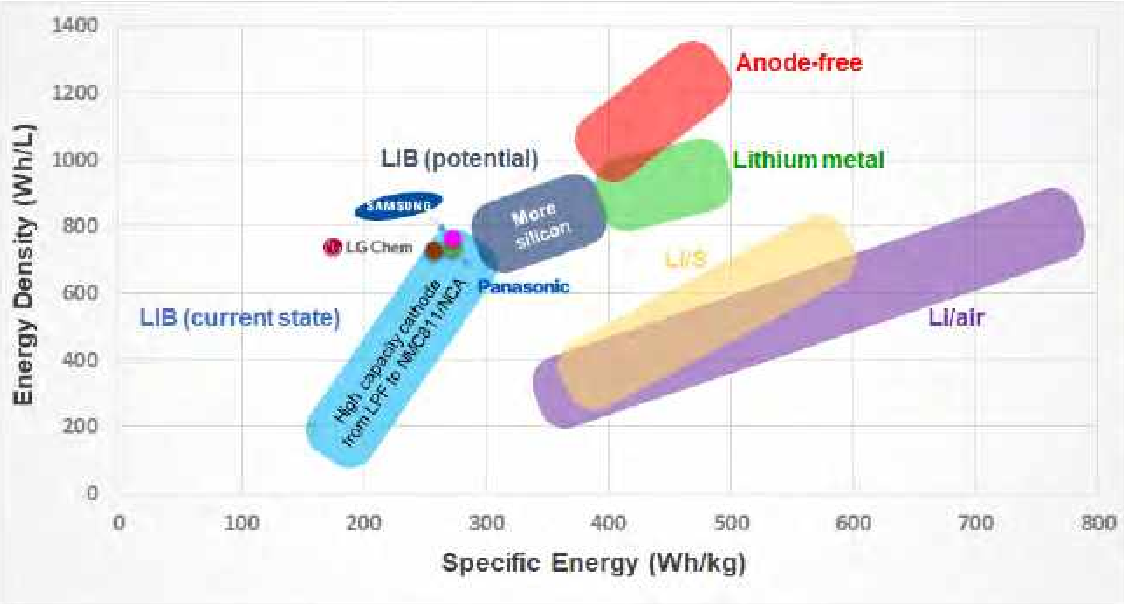


Figure 2.1.4 Energy density vs. specific energy of today's lithium-ion batteries and future battery technologies [38].
(The data of three commercial high-energy 18650 cells with capacities above 3.5 Ah (from LG Chem, Samsung and Panasonic) were shown as the benchmarks.)

Large-scale battery applications in electric vehicle and ESS may cause the short supply of raw materials for lithium-ion batteries, e.g. lithium, cobalt and nickel, which may drive cost up. Future large-scale deployments of ESS batteries may therefore rely on low-cost battery chemistry, i.e., sodium/aluminium-ion batteries or the use of sulfur and oxygen as cathode materials. Compared to lithium, sodium (6th most abundant element in Earth's crust) and aluminium (3rd one) are much cheaper choices. Especially for aluminium-ion battery, exchange of three electrons per ion ($Al \rightarrow Al^{3+}$) and high density (2.7 vs. 0.534 g/cm^3 for lithium) allow aluminium-ion battery to potentially deliver significantly higher energy density than lithium-ion battery.

<u>Sulfur-based battery</u>
Sulfur-based chemistry that deploys sulfur as the cathode is also much cheaper than LFP/LCO/NMC in conventional lithium-ion batteries. One of the most promising chemistries is lithium-sulfur. The main challenge of the lithium-sulfur battery is its short lifespan (60-100 cycles), which is caused by the dissolution and migration of intermediate polysulfides to lithium anode [39]. Another challenge is the need for a considerable amount of carbon (around 40 % by weight) to overcome sulfur's poor conductivity, which in turn reduces the overall energy density (only 272 Wh/L at commercial level). Meanwhile, the development of room-temperature sodium-sulfur battery with improved safety also warrants special attention, which may replace the high-temperature molten sodium-sulfur batteries commercially deployed in ESS by NGK Insulators, Ltd. (energy density: 367 Wh/L) [40].

<u>Metal-air battery</u>
Metal-air batteries utilise cathode reactants with air. This is a low-cost and open system, free from catastrophic explosion due to pressure build-up. Among them,

lithium-air battery can deliver a specific energy of 11,500 Wh/kg that approaches that of gasoline [41]. Primary lithium-air batteries, such as those developed by PolyPlus Battery Company, have already shown a promising high specific energy of 800 Wh/kg [42]. However, the development of rechargeable lithium-air battery is still at its early stages and faces several challenges. There are problems associated with electrolyte evaporation due to its half-open structure, a lack of efficient and cost-effective oxygen separation technology, severe side-reactions between cathode and electrolyte (forming irreversible Li_2CO_3), progressive lithium anode passivation due to the dissolved oxygen into electrolyte, sluggish oxygen reduction and evolution reactions, and low round-trip efficiency [43], [44]. Research on new lithium anode protecting technologies, such as ceramic coating, may be necessary for the development of these advanced lithium-air batteries.

2.2. ESS Applications

ESS applications can be broadly categorised into five categories, namely grid services, renewable support, utility support, transmission and distribution support, and customer-focused applications [45] [46] . Figure 2.2.1 shows the possible applications under each category. For more details, please refer to Annex 3.

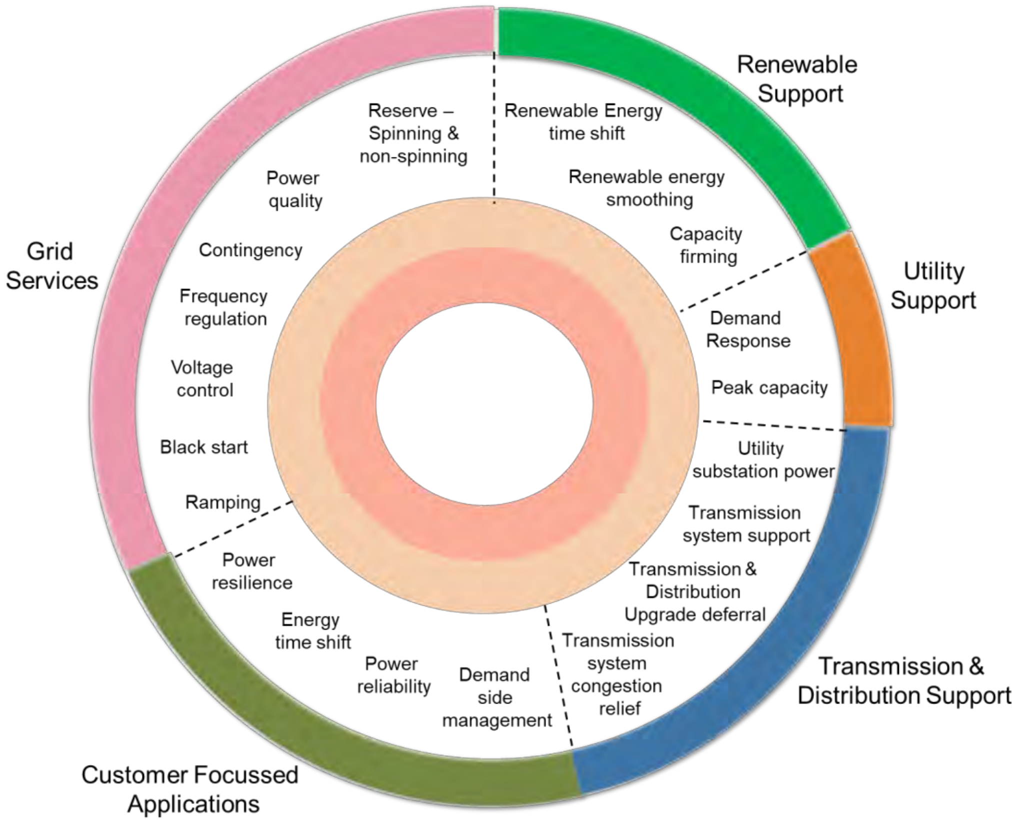


Figure 2.2.1 Energy storage system applications

Relevance to Singapore Utility Grids, Customers and Gencos

Table 2.2.1 describes the potential ESS applications in Singapore's context.

Table 2.2.1 Potential ESS applications in Singapore context

Applications	Description
Grid Services • Frequency regulation • Primary reserve • Contingency reserve	ESS can provide frequency regulation, primary (9 sec to 10 min) and contingency reserves (10 to 30 min) due to its fast responding capability [46]–[48], [49].
Renewable Support • Renewable capacity firming • Renewable energy smoothing	With Singapore aiming to install at least 2 GWp of solar PV by 2030 [50], we can expect increasing deployment of large-scale solar PV systems. However, solar PV output is affected by weather conditions and requires back-up capacity to balance such intermittency. ESS can mitigate this issue by buffering the intermittent energy and providing a stable output [51], [52].
Transmission & Distribution Support • Grid congestion relief • T&D system support • T&D upgrade deferral	ESS can help to offset the system peak load and potentially defer grid infrastructure upgrades where relevant.
Customer Focused Applications • Power Reliability • Energy time-shift • Peak shaving	End users can deploy ESS for a variety of purposes. For example, it can be used to improve power quality at user premises. It can also be used to mitigate solar intermittency for users with solar PV. For large consumers, ESS can help to reduce their peak load.

Based on industry feedback, the two most viable applications in Singapore's context are frequency regulation and peak shaving (that leads to savings due to reduction in contracted capacity). The deployment of ESS is dependent on the economic benefits that can be obtained either from revenue generation or cost savings.

Currently, around 8 to 25% of scheduled generation capacity is reserved for grid services such as reserve and regulation applications [53]. In Singapore, the average 2019 price for regulation and contingency reserve were $17.98/MWh and $16.30/MWh respectively. Regulation and energy prices are usually higher than reserve prices, making it the more lucrative market for interested ESS market participants.

2.3 Safety Aspects

2.3.1 Global Trends in ESS Safety

The safety of installed ESS is critical. It covers the entire lifecycle from installation and commissioning, operation and maintenance, to decommissioning by well-trained technicians – to avoid electrical shock, thermal reactions and/or the release of toxic/flammable gases. Key safety issues [54] in ESS are siting (e.g. location, loads, egress/access, maximum chemical density or separation), ventilation, exhaust and related thermal management issues, high charge or discharge scenarios, fire protection (e.g. detection, suppression, containment, smoke removal), and containment of fluids for liquid based ESS. This sub-chapter will first touch on safety issues of lithium-ion batteries. Safety of flow batteries and supercapacitors are covered in Annex 4. The last section will cover the various international safety codes and standards for ESS.

Thermal runaway is the key risk associated with lithium-ion batteries. It refers to a scenario where the cell temperature reaches a certain limit and causes an uncontrollable rapid release of energy, eventually leading to thermal events such as fire. Lithium titanate and lithium iron phosphate chemistries are reportedly less sensitive to thermal runaway. For other chemistries, thermal runaway typically occurs beyond 70 °C. Lithium-ion fires can be intense and may result in the emission of large volumes of toxic combustible gas. The main source of volatile organic content is the electrolyte solvents. Most commercial lithium-ion systems force a system shutdown beyond 50 °C [55]. More details on the possible failure modes of a lithium-ion battery system and the associated safety hazards along with their corresponding effects on the BESS are listed in Annex 4.

The safety risk of large scale and cascading thermal runaway should be managed with appropriate containment, thermal management systems, extinguishing and isolation procedures. Containment may include active cooling, metal or ceramic plates or heat absorbing materials.

In the event of thermal runaway (without proper safety systems), there is a potential fire hazard (fire type Class D - which involves combustible metals such as lithium and potassium). Hence, some factors should be considered when selecting the ESS container and fire extinguisher. They include:

a) <u>Averting a fire incident by taking into consideration</u>
- Cooling requirement;
- Gases released within enclosed spaces; and
- External fire threats;

b) <u>Handling fire incidents by taking into consideration</u>
- Chemical reactions between extinguishers and burning materials;
- Cascading protections in the system to limit fire propagation;
- Incipient fire versus full system fire extinguishers;
- Chemical contamination and collateral damage from non “clean agent” extinguishers;
- Hazardous materials and clean-up; and
- Risks to building occupants and first responders.

Most fire safety standards require the rooms containing ESS to be equipped with an automatic sprinkler system. Recently the National Fire Protection Association (NFPA) has suggested to deploy water sprinklers to cool down the ESS below the auto-ignition temperature of flammable gases released during a thermal runaway event. The current recommendation is to be able to dispense 0.3 gallons-per-minute-per-square-foot density over a 2,500-square-foot design area [56]. To minimise the spread of possible fires, some authorities prescribe a maximum concentration of battery power banks within a limited area (in terms of kWh/m^2) with minimum separation between two battery banks, and a minimum fire hour rating of the ESS containment. However, these requirements vary depending on the location of ESS. Systems installed far away from buildings (> 100 feet) have least constraints, followed by those situated in dedicated buildings (housing only ESS), but near other occupied buildings. ESS co-located in occupied buildings have the maximum safety requirements.

Vented batteries are required to be provided with flame-arresting safety caps. There should also be adequate ventilation, cooling and other thermal management solutions to avert thermal runaway [55]. Ventilation is key to dilute the potential off-gases from the ESS. Detection or monitoring equipment should be considered for off-gases and can be integrated with emergency shut-down or extinguishing systems. Fire safety standards also describe the use of approved BMS for monitoring and balancing cell voltages, currents and temperatures within the manufacturer's specifications. The system shall transmit an alarm signal to an approved location if potentially hazardous temperatures or other conditions (such as short circuits, over voltage or under voltage) are detected.

Safety Codes and Standards

There are various international safety codes and standards covering ESS. The following tables list the relevant standards, codes and certifications, classified by their scope or application domains.

Table 2.3.1.1 Codes and standards for built environment with sub-sections for ESS

Codes/Standards	**Coverage**
ICC IFC-2018	Covers safety guidelines for new and existing buildings, facilities, storage and processes.
NFPA	Covers various codes and standards like Fire Code 1-15, National Electrical Code 70-17, Building Code 5000-15.
IEEE C2-17 (National Electrical Safety Code)	Covers basic provisions to safeguard people from hazards arising from the installation, operation, or maintenance of (1) conductors and equipment in electric supply stations, and (2) overhead and underground electric supply and communication lines.

Table 2.3.1.2 Codes and standards for ESS installation

Codes/Standards	**Coverage**
NFPA 855 (2020) (Standard for Installation of Stationary Energy Storage Systems)	Covers the safety installation and operation of ESS (including dangers of toxic and flammable gases, stranded energy, and fire intensity).
NECA 416	Covers methods and procedures used for installing different types of ESS, which includes controlling, managing, commissioning and maintaining ESS. Technologies covered include batteries, flywheels, ultra-capacitors and vehicle-to-grid (V2G).

1635-2018 – IEEE/ASHRAE Guide for the Ventilation and Thermal Management of Batteries for Stationary Applications	Guide that bridges between electrical system designers and heating, ventilation, and air conditioning (HVAC) designers for the design of safe and optimal ventilation, and thermal management solutions.
P1578/D2, June 2017 – IEEE Draft Recommended Practice for Stationary Battery Electrolyte Spill Containment and Management	Covers factors relating to electrolyte spill containment and management for vented lead-acid (VLA), valve-regulated lead-acid (VRLA), vented nickel-cadmium (Ni-Cd), and partially recombinant Ni-Cd stationary batteries.

Table 2.3.1.3 System level codes and standards for ESS

Codes/Standards	Coverage
NFPA 791 (Recommended Practice and Procedures for unlabelled Electrical Equipment Evaluation)	Covers recommended procedures for evaluating unlabelled electrical equipment for compliance with nationally recognised standards.
UL 9540 (Standard for Energy Storage Systems and Equipment)	Covers both stationary ESS indoor and outdoor installations, and mobile ESS. The standard sets guidelines and standards to ensure overall safety of the ESS and its sub-systems.
UL 9540A	Specifies test method for evaluating thermal runaway fire propagation in BESS.
IEEE 1547, EN 50272, IEC 62485, IEEE 1375, IEEE 1184, and EN 50438	Relevant FAT standards. General system level requirements are covered by IEC 60529.
IEC 61508-4	For fail-safe operations testing at the system level.
IEC 61511	For implementation of safety instrumented processes.
IEC 62619	Specifies requirements and tests for the safe operation of secondary lithium cells and batteries for use in industrial applications.
IEC 62133	Specifies requirements and tests for the safe operation of portable sealed secondary cells and batteries, containing alkaline or other non-acid electrolytes.
IEC 63056:2020	Specifies requirements and tests for the product safety of secondary lithium cells and batteries used in electrical ESS with a maximum DC voltage of 1500 V. This document provides additional requirements for electrical ESS than the basic requirements specified by IEC 62619.
IEC TS 62933-5-1:2017	Specifies safety considerations (e.g. hazards identification, risk assessment, risk mitigation) applicable to EES systems integrated with the electrical grid.
IEC 62933-5-2:2020	Describes safety aspects for people and, where appropriate, safety matters related to the

	surroundings and living beings, in relation to grid connected ESS where an electrochemical storage subsystem is used.

Table 2.3.1.4 Codes and standards for specific ESS components

Codes/Standards	**Coverage**
UL 810A	Covers electrochemical capacitors.
UL 1642	Covers lithium batteries.
UL 1741	Covers inverters, converters, controllers and interconnecting systems.
UL 1973	Covers standards of batteries for use in stationary, vehicle auxiliary power and light electric rail applications.
UL1974	Standard for evaluating batteries for 2nd life applications.
UL 48 and CSA C22.2	Safety standards covering requirements for the design, construction, installation, and maintenance of electrical equipment, primarily to address fire and electrical shock hazards.
IEEE 1679.1-2017	Standard for the characterisation and evaluation of lithium-based batteries in stationary applications.

2.3.2. Singapore's ESS Safety Requirements

In Singapore, the Singapore Civil Defence Force (SCDF) oversees fire safety regulations. For the latest information on fire safety requirements in Singapore, it can be found on SCDF's website (https://www.scdf.gov.sg/firecode2018/firecode2018). Qualified Persons (QP) and / or Professional Engineers (PE) can consult SCDF for further enquiry on the fire safety requirements.

2.4 Land Aspects

Land usage is an important consideration for stationary ESS especially in urbanised cities. A comparison of the volumetric energy density of different stationary storage technologies under Figure 2.4.1 shows that lithium-ion batteries is well suited for land scarce countries.

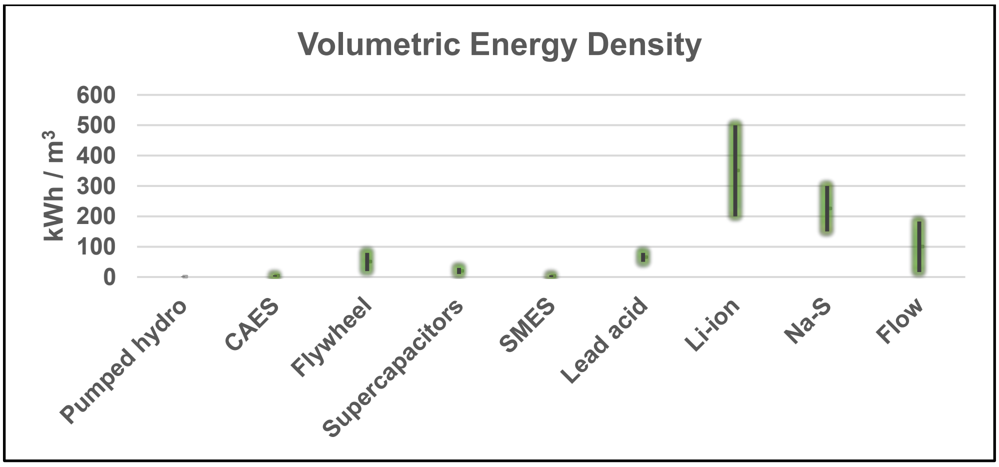


Fig. 2.4.1 Typical volumetric densities of different ESS technologies.[7], [57]–[61]

Optimising land usage often translates to lower capital cost and a lower levelised cost of storage (LCOS). For many countries, land is not a major issue for ESS deployment, and the overall non-engineering procurement and construction (EPC) cost (including land cost) for BESS is around 10-20% depending on various factors such as location and energy-to-power (E/P) ratio [62], [63].

On the other hand, Singapore is land scarce and ESS deployment needs to be carefully considered to minimise overall project costs [62], [64], [65]. The figure below depicts possible opportunities where ESS can be deployed in Singapore.

(Map credit: https://aseanup.com/free-maps-singapore/)

Figure 2.4.2 Potential areas for ESS deployment

To support Singapore's solar target, ESS can be deployed together with solar to manage solar intermittency and improve power quality. Depending on the locations (e.g. HDB switch-rooms, industrial space, green/brownfield districts, and reservoirs), site-specific considerations would need to be considered. For brownfield locations, there could also be space constraints as ESS was previously not factored into the building or site design.

Other sites that can be considered include underground space or offshore islands. The cost associated with these options, however, would likely be higher. For example, additional safety measures may be required for underground sites due to the need for better ventilation and access to fire engines. On the other hand, batteries on offshore islands would require undersea cables to connect the batteries to the mainland grid, which would increase the cost significantly.

One possible option to reduce land usage is the stacking of ESS, which is still relatively nascent. For projects by Mitsubishi Electric Corporation in Fukuoka, Japan (NaS batteries) [66] and Narada in Jiangsu, China (Advanced Lead-Carbon batteries) [67], specialised infrastructures with fire safety measures have been designed and built to allow for multi-storey stacking of ESS.

2.5 Policies and Regulations

2.5.1. Global trends in policies and regulations to boost ESS adoption

Policy Enhancements

ESS is a unique energy resource as it can operate as a generator, load or grid infrastructure. To maximise its benefits, it is important to consider the following:

- **Clear market rules defined for ESS to participate in the electricity market**, e.g. frequency regulation, reserves, and demand response. This would provide a source of revenue for ESS operators, improving its business case. For example, the Federal Energy Regulatory Commission (FERC) in US released Order 841 regulation, which directs regional transmission organisations (RTOs) and independent system operators (ISOs) to define market rules that would enable ESS to participate in wholesale, capacity and ancillary services market.

- **Revisions to ESS classification,** i.e. not merely as a generator but under a separate category. For most jurisdictions, ESS is classified as a generation asset, which narrows the list of applications it can serve. In recent years, countries have considered if ESS can be classified as a separate asset which acts as a generator, T&D infrastructure and/or load.

- **Whether grid operators should be allowed to own ESS assets in deregulated markets**. Advocates argue that it would facilitate faster deployment of renewables and other Distributed Energy Resources (DERs), while opponents argue that it would undermine competition and innovation. Some exceptions or hybrid approaches have been proposed. For example, grid operators in European Union countries can own ESS for transmission and distribution support purposes, but not for trading in the electricity markets or to provide grid services (as listed in Figure 2.2.1).

- **Potential to access multiple revenue streams.** ESS could also serve multiple functions concurrently and this translates to the possibility of generating multiple revenue streams. One example is the pilot ESS project in Xcel Colorado’s Pena Station Micro-grid, owned by Xcel (utility), Younicos (developer) and Panasonic (building owner). The ESS served multiple functions such as renewables integration, ramping, peak demand reduction, energy arbitrage, frequency regulation and backup power, allowing each owner to reap different benefits from it. To strengthen the business case for ESS, regulations that facilitate application stacking could also be considered.

- **Aggregation of multiple smaller ESS to serve a larger application**. Currently, many countries allow for service aggregation through aggregators. New regulations have been introduced to promote business models like virtual power plant (VPP) and enable residential ESS owners to become prosumers.

- **Double network charges** are currently imposed in certain countries (U.K., France, Germany, Netherlands) as there is lack of clear legislation regarding the charging arrangement of ESS [68]. Some proposed changes include - removing the TNUoS (Transmission Network Use of System) demand and generation residual charges, removing DUoS (Distribution Use of Services) demand residual charges, removing BSUoS (Balancing Services Use of System) demand charges, and introducing new fixed charges to cover the increased implementation of 'behind the meter' ESS.

- **Any upgrade to the communication infrastructures** used for Automatic Generation Control (AGC) of ESS need to comply with stringent data protection and cybersecurity protocol for system resilience. In Europe, some system operators [69] have implemented the 60870-5-104 communication protocol and TLS encryption based on the IEC 62351-3 standard, where relevant. This improved communication enables end-to-end encryption between remote units and the network control centre, providing data integrity, supported by digital certificates (X.509) and mandatory mutual authentication of client and server.

Incentives

Several jurisdictions have introduced various incentives to accelerate ESS deployments [70], [71], and they can be classified under the following four categories:

a) Renewable portfolio standards or clean energy standards. This involves mandating a minimum percentage of power to come from clean energy sources (e.g. South Korea).

b) Renewable energy credits. Additional credits are given to solar-ESS or wind-ESS deployment to mitigate the impact of renewables' intermittency to grid (e.g. South Korea, US).

c) Feed-in-tariff (FiT) for promotion of ESS. FiT is a policy mechanism used to incentivise the early deployment of renewable technologies such as solar. We are seeing the introduction of FiT for ESS such as the UK's Smart Export Guarantees.

d) R&D and innovation. The provision of R&D funding to develop and test-bed innovative ESS solutions and build local ESS capabilities.

Financial Schemes

Various financial schemes have been introduced to support the financing of ESS projects. Examples are listed below.

Table 2.5.1.1 Global financial schemes to boost ESS adoption [7]

Category	Financing Schemes	Description
International Agencies and Donors	• Scaling Solar – World Bank Group • InnovFin – European Investment Bank Group	• US$1billion fund to accelerate solar and ESS investments in developing and middle-income countries. • Provides loans, loan guarantees, and equity-type financing to support innovative demonstration projects such as ESS.
Government Financing	• USA Loan Programs Office • Australia Climate Bonds	• US Department of Energy programme that supports large-scale energy infrastructure projects. • Bond dedicated to support small-scale ESS projects and rooftop solar projects.
Energy Storage Funds	• SUSI Energy Storage Fund • Gore Street Energy Storage Fund	• One of the world's first ESS centric investment funds, managed by Swiss-based investment management company specialising in sustainable investments. • One of the first ESS funds listed in London Stock Exchange, this fund aims to provide investors with a sustainable and attractive dividend over the long term by investing in utility scale ESS projects.
Non-Governmental Funds	• Electric and Gas Industries Association (EGIA)	• A cooperative initiative introduced by EGIA offering financing plans/loans to support energy storage projects.
P2P Lending	• RateSetter	• Not widespread. RateSetter platform agreed to finance AU$100million as part of South Australian Government's Home Battery Scheme, supporting up to 40,000 households.

<u>Building Awareness and Education</u>

Beyond policy enhancements, incentives, and financial schemes, it is also important to build greater awareness and develop capabilities to facilitate ESS deployment.

For many in the ecosystem, the value of ESS may not be apparent, especially given its current high cost. To better understand the long term ecosystem benefits of ESS, system modelling that takes into account future grid scenarios such as high penetration of renewables, EVs and other DERs are required. For example, the state of Massachusetts, US, did a study (i.e. the "State of Charge" report in 2016), which articulated US$2.3bil in total benefits from widespread deployment of over 1.7 GW of ESS.

As a nascent technology, deploying ESS could be a daunting task due to the need to clear numerous regulatory requirements from different government agencies. It is therefore beneficial for all parties in the ecosystem to have a single portal on all ESS matters. One good example is the US Department of Energy's Energy Storage Database, which contains information on ESS deployments, test-beds, policies, publications and patents.

Another important component in growing the ESS ecosystem is in manpower development. As ESS projects gradually increase, we need to put in place education and training programmes to grow the talent pool to support manpower demand for ESS design, project management, operation and maintenance.

2.5.2. Singapore's Policies and Regulations

The sections below describe the current policies and regulations in Singapore.

Electricity Generation or Wholesaler Licence

Under EMA's current regulatory framework, the type of licence required by the BESS, where one unit of BESS is defined as one or more batteries connected to a single PCS, is dependent on the name-plate rating of the BESS. This is determined based on the lower of:

a. The aggregate of the batteries' installed capacity; or
b. the AC capacity of the PCS.

Any person who owns a BESS that is either directly or indirectly connected to the grid will be required to be licensed under an Electricity Generation Licence, or Wholesaler Licence, based on the following:

Name-plate rating per unit of BESS	Less than 1 MW	1 MW or more but less than 10 MW	10 MW or more
Type of Electricity Generation Licence Required	Exempted	Wholesaler Licence	Generation Licence

For multiple units of BESS, each unit having its own PCS and connected to the same grid connection point, the licensing requirement will be based on the name-plate rating of each unit of BESS.

For BESS that is paired with IGS[1] i.e. they share the same PCS/inverter, such a setup will be considered as a single generating unit with name-plate capacity determined as the lower of:

a. the aggregate installed capacity of the BESS and IGS; or
b. the AC capacity of the shared PCS/inverter.

Grid charges for ESS

Grid charges will be levied on ESS when it is acting as a load as per the current grid charge structure, either on a fully variable (Low Tension) or fixed-variable (High Tension and above) basis. This is the same treatment for all loads with embedded generators today. More information is found on the Resources within SP's eBusiness-Portal. https://www.spgroup.com.sg/resources?category=eBusiness+Portal

ESS in the Singapore energy market

Similar to conventional generators, ESS is required to register with EMC as a generation registered facility to provide ancillary services and prove that it is fully dispatchable and can continuously generate at its scheduled output throughout the

[1] Where the AC electricity output of an IGS and a BESS is through separate inverters and PCS, which are connected in parallel at the same grid connection point, the licensing requirement for the IGS and BESS will be assessed individually.

entire half-hour dispatch period for energy and reserves. Under the existing Market Rules, ESS is required to be registered as a Market Participant (MP) if it is at least 1 MW, or if it wants to be paid for any energy injected into the grid if it is less than 1 MW. There will be no changes to the minimum offer requirement of 0.1 MW in the market.

Market charges for ESS in Singapore

Both generators and loads are subject to reserve charges to ensure the reliable supply of electricity to consumers and the secure operation of the power system. ESS acting as either a generator or load will be subject to the same reserve charges. There are two broad categories of reserves – regulation and spinning reserves:

a) Regulation reserve: This refers to the amount of generation capacity needed to balance the minute-to-minute variations in electricity consumption of all loads and small variations in generating units' output. The cost of regulation reserve is recovered from all loads and the first 5 MWh of each generation facility in each half hour period on a "gross" basis. Given that the nature of ESS allows it to switch continuously between charging from and discharging to the network even within the half-hour trading period, gross settlement[2] for regulation reserves will apply. For example, if the ESS withdraws 2 MWh of energy and injects 3 MWh of energy within a particular trading period, the ESS will be charged 5 MWh for regulation reserves.

b) Spinning reserve: This refers to the amount of generation capacity required to correct large imbalances in the system due to significant reduction in generating units' output. The cost of spinning reserve is recovered from all generation facilities scheduled, including ESS (less the first 5 MWh of each facility, which is allocated the cost of regulation reserve) operating in that half-hour through a methodology that varies according to the scheduled/forecasted generation output based on its Reserve Responsibility Share.

On non-reserve market charges, ESS acting as either a generator or load will be subject to the same non-reserve charges based on gross generation and gross consumption. In the case where the ESS fulfils the requirements[3] for embedded generators, such non-reserves charges will be settled on a net basis.

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[2] To be consistent with the treatment for embedded IGS, net settlement of regulation reserves will apply for all residential consumers and non-contestable consumers with embedded ESS capacity less than 1 MW. For more information, please refer to EMA's Final Determination paper on Enhancements to the Regulatory Framework for IGS in the NEMS, 25 July 2017.

[3] For more information, please refer to EMA's information guide for embedded generation, February 2014. https://www.ema.gov.sg/cmsmedia/Consumers/Embedded%20Generation/GuideforEG.pdf

Other ongoing policies and regulation developments

In order to promote more innovative concepts like VPP and to make residential consumers into prosumers etc., there are ongoing consultations between EMA and EMC to develop regulatory standards and enhance market systems to aggregate ESS and DERs deployed across multiple sites.

There is also a rising need to recognise the fast response of ESS when acting as reserves or to maintain power quality in terms of payment proportional to the quality and speed of service provided. Such policies in future could recognise these special characteristics of ESS, creating a more favourable business case .

2.6 Circular Economy and Sustainability

The ability to reuse and recycle is an important consideration for ESS as it affects raw materials availability, sustainability, and our move towards a more decarbonised society. The use of ESS, especially to support renewables, will positively contribute to the sustainability of our planet. Figure 2.6.1 shows a summary of how environmental impact varies across different ESS technologies.

		Li-ion NMC	Li-ion LFP	Lead-based	Flow Batteries	Sodium-ion	PHES	CAES	Hydrogen	CSP with TES
Environmental Impact	Lifetime energy efficiency	Low	Low	Medium	Medium	Medium	Low	Medium	Medium	Low
	Lifecycle GHG emissions	Low	Low	Medium	Medium	Medium	Low	High	Medium	Low
	Supply chain criticality	High	Medium	Low	Medium	Low	Low	Low	Medium	Medium
	Material intensity	Medium	Medium	Low	Medium	Low	Low	Low	Low	Low
	Recyclability	Medium	Medium	Low	Medium	Medium	Low	Low	Low	Low
	Environmental health	Medium	Medium	Low	Medium	Medium	Low	Low	Low	Low
Social Impact	Human rights	High	Medium	Low	Low	Low	Low	Low	Low	Low
	Health & safety	High	Medium	Medium	Low	Low	Low	Low	Medium	Low
	Overall	High	Medium	Medium	Low	Low	Low	Medium	Medium	Low

Fig. 2.6.1 Qualitative assessment of environmental and social impact of ESS technologies [72]

Large scale technologies such as compressed air, pumped-hydro and thermal energy storage generally perform better in terms of lower negative environmental impact. Lithium-ion batteries have lower lifetime greenhouse gases emissions as compared to other ESS technologies, but performs poorly on supply chain security, toxicity, recyclability and responsible extraction. The circularity and recyclability of lithium-ion batteries are examined in detail in Annex 5, while other ESS technologies are discussed in Annex 6.

The growing demand for lithium-ion batteries have encouraged cell manufacturers to rapidly expand their production, with capacity increasing by twenty-fold from 14 GWh in 2010 to 285 GWh in 2019. Among the countries, China dominates lithium-ion battery production with a total production capacity of 131.6 GWh in 2019. As the major supplier of cell components, China produced 40,400 tonnes of cathode, 26,500 tonnes of anode and 18,300 tonnes of electrolytes in 2019 [73]. As of 2019, there are 115 projected lithium-ion battery “gigafactories”, with a global capacity of 2068.3 GWh by 2028 [74]. The rapid growth of production capacity challenges the supply chains of raw materials, especially for lithium and cobalt. A significant problem may also arise when these ESS start to reach EOL [75].

2.6.1. Raw Material Supply

The availability of raw materials and diversity of supply sources play a key role in determining lithium-ion battery prices, as well as influencing the dominant chemistry for large scale use in applications such as e-mobility and stationary storage. According to a US geological survey in 2018 [76], Australia, Democratic Republic of Congo, and China dominated the supply of key raw materials for ESS, producing 60-70% of world’s lithium (cathode), cobalt (cathode) and graphite (anode) supply respectively. Therefore, battery recycling to recover key elements such as lithium, cobalt and nickel will be important from both sustainability and supply chain security angles.

Projections were conducted to illustrate the consumption of lithium, cobalt and nickel if a particular battery chemistry were used to meet the global Li-ion battery demand, estimated at 285 GWh in 2019 [77]. The consumption is plotted and shown as a percentage of global mine production (Figure 2.6.1.1). The table inset in Figure 2.6.1.1 shows the estimated metal consumption (in metric ton) required per GWh for different cathode materials.

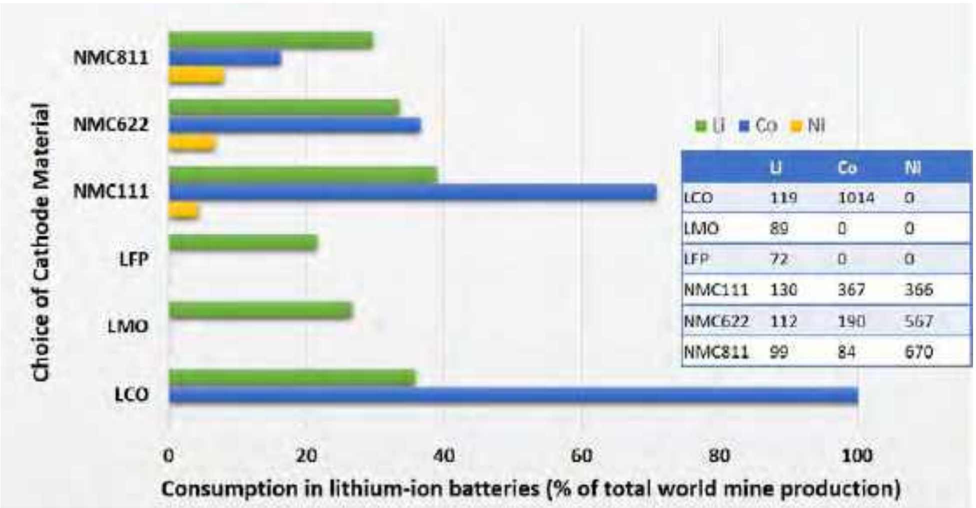

Figure 2.6.1.1 Consumption of lithium, cobalt, and nickel in the cathode of lithium-ion batteries (% of the global mine production) [76] *. Note that the Co consumption for LCO exceeds 100% (~196%) and is not shown for clarity of plot. Table inset: element requirements for the corresponding cathode in units of metric ton/GWh.*

Lithium Supply Projection. In 2020, lithium-ion batteries on a whole is expected to take up 65% of the global lithium demand [78], [79]. With demand for lithium projected to outstrip supply as early as 2025 [79], the recycling of lithium will become increasingly important. This is particularly so for high quality lithium carbonate equivalent (LCE) sources, which are location/mines specific and hard to be substituted.

Cobalt Supply Projection. The huge demand for cobalt has put the spotlight on the sustainable use of raw materials. If LCO is used to meet global ESS demand, the cobalt demand would require a doubling of current annual cobalt production. Replacing LCO with NMC111 can lower this to 70% of global cobalt output. Switching NMC111 (cobalt consumption: 367 tonnes/GWh) to NMC622 (190 tonnes/GWh) would further half the consumption of cobalt, while NMC811 uses the lowest amount at 84 tonnes/GWh, amounting to 16% of annual cobalt production.

Nickel Supply Projection. Nickel is rather abundant and there is currently little impetus to recycle nickel. However, this may change with a tightening supply market, e.g. banning exports of unprocessed nickel in Indonesia [80], and the expected rise in consumption with the adoption of NCM811 cathode in EV batteries.

2.6.2 Global Trends in Recycling of Battery ESS

Battery recycling can be economically beneficial. Figure 2.6.2.1 shows the cost breakdown of the lithium-ion cell with NMC811 cathode [81]. Among the components, the cathode (36%), anode (8%), Cu foil (9%), case (7%), and electrolyte solvents (7%, excluding lithium salts within), or two-third of the cell by value can be recycled. Given that the cost of these battery components using recycled materials is 50% lower than those directly from mining/petroleum, recycling can help reduce battery cost by 30%.

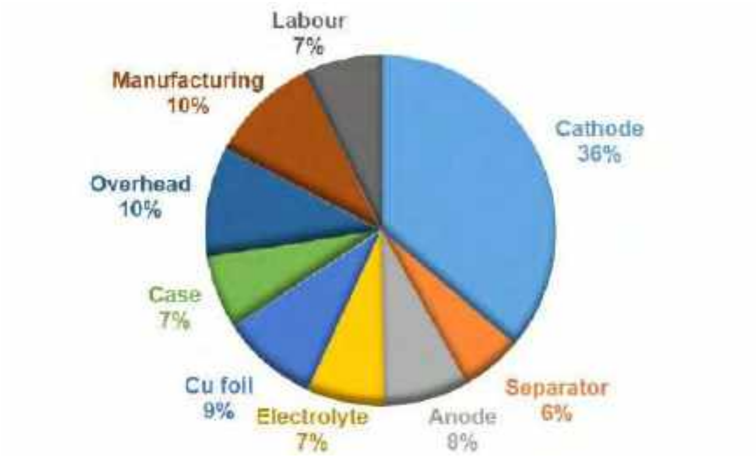

Figure 2.6.2.1 Cost breakdown of a lithium-ion cell with NMC811 cathode [81].

It is worth noting that the combined concentrations of lithium, cobalt and nickel in lithium-ion batteries far exceed natural ores. For example, to produce one tonne of lithium from mineral-rich brine, it requires 250 tonnes of spodumene ore or 750 tonnes of mineral-rich brine. By contrast, it only needs 28 tonnes of used batteries for the same amount of lithium [82].

As a result, the recovery of those metals from used batteries can stabilise the global supply chain and bring about sizeable economic benefits. According to a 2016 report by Sinolink Securities [83], the gross profit margin of NMC batteries recycling is about 50%. In 2019, around 100,000 tonnes of lithium-ion batteries reached their EOL globally. The market for lithium-ion batteries recycling was valued at US$1.5 billion and is projected to climb to US$12.2 billion by 2025 [84], growing at a compound annual growth rate (CAGR) of 34.9%. By 2030, the market volume of recycled lithium-ion batteries is estimated to be around 1.2 million tons and potentially half of the lithium consumption in batteries can be supplied from recycled lithium source [85].

<u>2.6.3 Global Trends in Reuse of EV battery for ESS</u>

EV batteries reach their EOL at ~ 80% of their original capacity. The rapid growth of the EV market offers a new opportunity in repurposing used EV batteries for less demanding applications such as stationary energy storage at home, solar/wind power plants and mobile base stations. Reuse of EV batteries potentially brings down the cost of the ESS project and provides environmental benefits by reducing battery waste and reducing carbon footprint [86]. In March 2019, the world's largest grid-scale ESS using second-life EV batteries was deployed in Nanjing, China, with 45 MWh of LFP and 30 MWh of lead-acid batteries [87]. As of September 2019, around 300,000 base stations operated by China Tower were powered by second-life EV batteries with a total capacity of 4 GWh [88]. McKinsey estimated that by 2030 the capacity of used EV batteries in ESS applications will exceed 200 GWh, with a global market value of US$30 billion [89].

The deployment of used EV batteries still faces some critical challenges, such as the uncertainty in the economics of reusing used batteries. An EV battery comes to the end of its first life in around 5-8 years. During this period, the price difference between used and new batteries may have narrowed. For example, the price of new EV batteries has dropped from above $1,100/kWh in 2010 to US$156/kWh in 2019 [90], and even below US$80/kWh in recent announcements by CATL (i.e. for LFP battery packs used in the latest version of Tesla Model 3 [91]). The collection, transportation, examination and repackage of second-life EV batteries is also both time and cost intensive. A recent study done by MIT using semi-empirical modelling set some boundaries for second-life batteries to be economically viable: (i) the reuse project should have a long project life (>16 years); (ii) second-life batteries should have at least 60% of their initial capacity (minimally 50% DOD) after 16 years of operation (in the second-life application); and (iii) cost of the spent batteries should be less than 60% of new batteries [92].

Another challenge is the difficulty in sorting and restructuring batteries. The voltage of a typical EV battery pack can go above 300 V. To redeploy them for stationary ESS applications (which may have significantly different voltage ratings), it will require disassembly sorting and re-configurations. Technologies are needed to accurately identify and sort batteries with different chemistry (e.g. LFP vs. NMC), resistance and lifecycle to prevent fast performance deterioration or even severe safety issues. The challenge is compounded by the lack of coherence in the EV battery pack designs that vary in their voltage platforms (e.g. 300 V for BYD e6 and 350 V for Tesla Model 3), battery types (e.g. cylindrical, prismatic and pouch), modular structures and cooling systems that increase the complexity in battery refurbishing [93].

Public perception and acceptance of repurposed batteries can be another challenge. Regulators and members of the public may not be ready to accept second-life batteries due to safety and quality concerns. As the batteries are no longer "new", they need to be requalified through a rigorous process. Standards for second-life batteries therefore needs to be calibrated, to avoid unnecessary costs, technical barriers and lead time.

2.6.4 Singapore's Reuse & Recycling efforts

In Singapore, the National Environment Agency (NEA) unveiled its Zero Waste Masterplan in 2019 with the aim of reducing the amount of waste per capita per day sent to landfill by 30% by 2030. One of the priority waste streams identified is electrical and electronic waste (e-waste). While e-waste typically accounts for less than 1% of the total generated waste in Singapore, the hazardous materials or substances present in certain types of e-waste requires careful management to prevent harm to the environment. Besides the environmental perspective, there is economic value to reuse and/or recycle precious metals and viable electronic components from e-waste. This offers an additional buffer against resource scarcity, volatile material prices, and environmental impact [94].

The Ministry of Sustainability and the Environment and NEA will implement an regulated e-waste management system based on the Extended Producer Responsibility (EPR) approach. The Resource Sustainability Act (RSA) was gazetted in October 2019 to provide legislative effect to the EPR scheme, where Producers of regulated electrical and electronic equipment (EEE) are to bear physical and financial responsibility for the collection and proper treatment of regulated EEE that reach their end-of-life.
The NEA will be appointing a Producer Responsibility Scheme (PRS) Operator, who will collect and send regulated consumer EEE from the public to NEA-licensed e-waste recyclers on behalf of the producers. More information is provided at https://www.nea.gov.sg/e-waste-epr for producer obligations and the roles and responsibilities of the PRS Operator.

Electrical and Electronic Equipment (EEE) Regulated under the RSA and Producer Responsibility Scheme (PRS) Collection Targets for Consumer EEE		
Product Category	**Product Types**	**Collection Targets for Consumer EEE**
ICT Equipment	Printers/Personal Computers/Laptops/Mobile phones/Tablets/Routers/Modems/Set-top boxes/Servers	20% of put-to-market (PTM) by weight
Large Appliances	Refrigerators/Air-conditioners/Washing Machines/Dryers/Televisions/Electric mobility devices	60% of PTM by weight
Batteries	Portable batteries	20% of PTM by weight
	Industrial batteries	NA
	Hybrid/electric vehicle batteries	NA
Lamps	Bulbs and tubes	20% of PTM by weight
Solar PV Panels	All types	NA

[Note: Not all regulated products are covered under the PRS. Collection targets are imposed on the PRS Operator only for consumer EEE as the PRS does not collect non-consumer EEE. Li-ion and nickel metal hydride Industrial batteries, as well as EV batteries used in motor vehicles that are more than 3,000 kg are considered non-consumer products and thus do not have a collection target.]

Figure 2.6.4.1 Singapore's PRS (Producer Responsibility Scheme) for EEE (Electrical and electronics equipment) as per zero waste master plan, 2019

Under the RSA, companies which manufacture (locally) or import hybrid or electric vehicle (EV) batteries (as part of EVs) for supply in Singapore, are required to register with the NEA as producers of regulated EEE before supplying the batteries in Singapore. Producers are required to report the weight of EV batteries supplied to NEA annually. EV batteries designed to be used in motor vehicles heavier than 3,000 kg are designated as regulated non-consumer EEE, while those used in motor vehicles less than 3,000kg are designated as regulated consumer EEE. Producers of non-consumer EV batteries will have to collect unwanted EV batteries from their clients upon request at no cost. The Producer must also dispose of the collected EV battery through either a waste collector or e-waste recycler licensed by the NEA.

EOL EV batteries will typically remain as part of the EV and taken back by automobile workshops (when the battery is to be replaced), car dealerships, (when a vehicle is traded-in/scrapped/battery is replaced) or scrapyards (when the car is scrapped). These commercial enterprises will then contact a licensed e-waste recycler to handle the disposal of the EV battery. In the future, these commercial entities can engage the PRS operator to send the collected EV batteries to licenced e-waste recyclers. Since the landscape for the disposal of EV batteries in Singapore is already well-defined, a collection target was not set for EV batteries as shown in (Figure 2.6.4.1).

There are also requirements on proper treatment and recycling of e-waste (including EV batteries) that would be imposed on e-waste recyclers, e.g. to meet a 50% material recovery target by weight and to remove mercury-containing components from e-waste prior to processing. There is currently no restriction on the repurposing of EOL EV batteries to other uses such as ESS that are imposed on e-waste recyclers. However, depending on the process to repurpose EV batteries, there may be a need to review the requirements imposed on recyclers to ensure that there is minimal environmental impact.

As the short and medium term ESS solutions proposed are likely to adopt Lithium-Ion batteries which are designated as industrial batteries, the producers of these batteries in the ESS (i.e. either the importer or entity that repurposed EV batteries for ESS) will be obligated under the RSA to take-back the batteries.

This is an opportunity for researchers and companies to propose protocols and solutions to address this burgeoning need within the next decade. One such initiative is the Singapore-CEA Alliance for Research in Circular Economy (SCARCE) research centre (a collaboration between the French Alternative Energies and Atomic Energy Commission and NTU), which aims to extract up to 75% of the useful metals by weight, like cobalt, nickel and lithium, from used batteries.

This is in line with NEA's Closing the Waste Loop R&D Initiative, and NEA has committed $12.5 million towards this $20 million centre. Companies like Arkema Pte Ltd, Virogreen Pte Ltd and SYH Resources Pte Ltd are already working or planning to work with SCARCE to develop and pilot e-waste recycling technologies [94]. In addition, TES has boosted the local battery recycling scene with the inauguration of the TES battery recycling facility in Singapore -- capable of recycling up to 14 tonnes of lithium-ion batteries per day. TES, in partnership with Genplus Pte Ltd, has also announced plans to develop second-life applications to offer a complete value chain for e-waste management [95], [96].

Local researchers are also actively pursuing more efficient recycling methods for lithium-ion batteries. For example, the National University of Singapore (NUS) is studying close-loop recycling of spent LFP batteries, with zero chemical consumption and emission by using a redox targeting-based process with a regenerative redox mediator [97]. Meanwhile, NTU has demonstrated the use of orange peels to extract precious metals from battery waste and created functional batteries thereafter [98].

With these initiatives, we can create a circular ESS ecosystem which develops capabilities and supply chains to (i) optimise used batteries for second-life applications; and (ii) recycle EOL ESS to extract and redirect valuable resources back to the economy.

3. ESS Roadmap for Singapore

The previous chapters covered global trends on ESS, taking reference from the STEEL focus areas and Singapore's existing efforts. To develop the ESS Technology Roadmap for Singapore, several rounds of consultations with stakeholders, comprising academia, industry and public agencies, were conducted. Their inputs were curated and consolidated into the roadmap framework shown in Figure 3.1, which comprises three layers – Drivers, Deliverables and Technology & Resources.

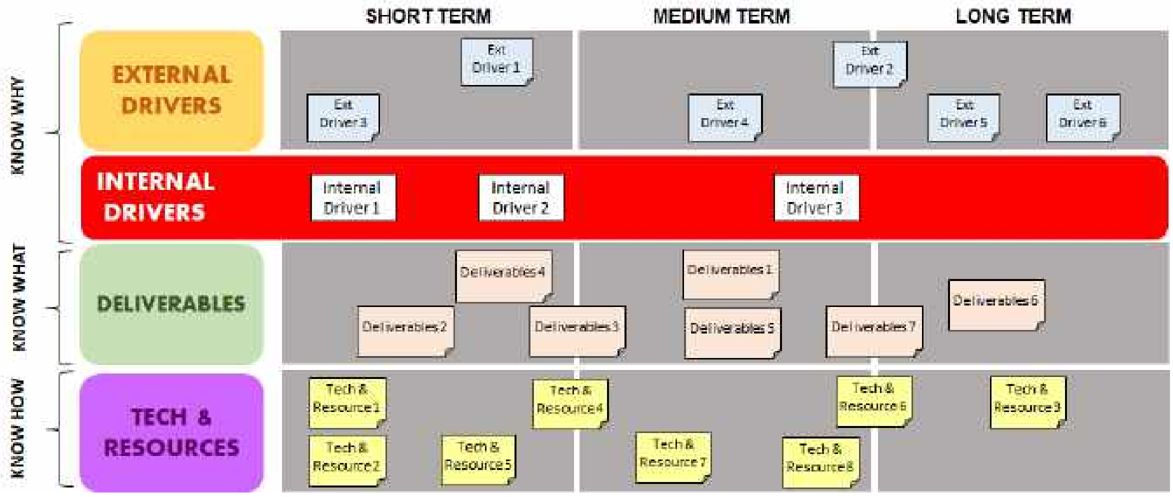

Figure 3.1 Roadmap Layout

The above layout outlines the roadmap structure where ideations are captured in the form of "post-it" markers, and clustered in accordance to the layers.

The first layer (i.e. **Drivers** layer) identifies the motivators or drivers:

- External Drivers refer to the global trends and applications of the technology.
- Internal Drivers refer to internal ambitions, aspirations, goals, vision, and milestone targets.

Collectively, the external and internal drivers provide the motivation from which the industry would operate within the future horizon.

The second layer identifies the current and future needs and challenges faced by Singapore's ESS industry and a solicitation of ideas to respond to the Drivers. These ideas are presented in the **Deliverables** layer which include the products, processes and/or services to respond to the Drivers. These Deliverables seek to eliminate or mitigate the risks and threats, and realise the opportunities presented.

The **Technology & Resources** layer covers initiatives, capabilities, technologies, and actions required to achieve the deliverables. This layer includes a compilation of views from participating stakeholders and the details can be found in Annex 1. Chapter 4 will provide a list of recommendations by the roadmap authors, taking into consideration inputs from the Technology & Resources layer, aligning them to the roadmap's objectives.

3.1 External Drivers

Eight cluster themes are identified for the external drivers, namely:

i) Applications and Use Cases;
ii) Business Models and Opportunities;
iii) Enabling Policies and Regulations;
iv) Sustainability and Circular Economy;
v) Economics;
vi) Technology;
vii) Manpower; and
viii) Land.

3.1.1 Applications and Use Cases

This cluster identifies problem statements and applications to drive the need for ESS deployment in Singapore.

Applications and Use Cases	Description
Solar intermittency management	ESS can mitigate solar intermittency i.e. to regulate frequency and maintain grid stability.
Peak shaving	ESS can provide for peak shaving which involves proactive management of overall demand to eliminate short term demand spikes.
Back-up	ESS can provide an independent source of energy that supports unanticipated outages or blackout events.
District cooling	ESS can be used in district cooling plants to optimise operating cost by storing non-peak power and using it for chilled water production during peak hours.
Optimise efficiency of power generation assets	ESS can complement power plants to replace the requirement for them to provide spinning reserves. This will allow the assets to run at higher utilisation rate.
Support EV charging infrastructure	ESS can be installed at charging stations to facilitate fast charging while avoiding localised grid congestion.
Relieve grid congestion and defer substation upgrade	ESS can relieve grid congestion and defer substation upgrades where relevant.

3.1.2 Business Models and Opportunities

This cluster identifies new avenues, business opportunities, commercial markets and services to act as drivers for local enterprises.

Business Models and Opportunities	Description
ESS as a service / battery leasing	Leasing or provision of energy as a service (i.e. providing services to consumers without them incurring upfront capital cost for ESS) is expected to grow with increased ESS demand.
Auxiliary equipment and services for installation, protection and maintenance of ESS	Demand for auxiliary equipment and services relating to the installation (e.g. containers, battery management systems, thermal management systems, transformers), protection and maintenance of ESS would rise.
Prosumer market	Consumers can install solar PV along with ESS and sell electricity back to the grid.

3.1.3 Enabling Policies and Regulations

This cluster discusses policies and regulations to facilitate ESS adoption, reduce operating costs, and ensure quality control over delivery of new ESS.

Policies	Description
Local ESS standards	There is a need for local standards to guide the safe installation and maintenance of ESS in Singapore.
Unique value of ESS in providing fast response	Regulations to recognise the unique ability of ESS to provide fast response to changes in electricity demand and supply.
Value stacking and aggregation of DERs for market participation	Existing regulations and communication infrastructures should be reviewed and updated to facilitate emerging business models such as power generation aggregators and value stacking (i.e. multiple revenue streams), while ensuring data integrity and cybersecurity.

3.1.4 Sustainability and Circular Economy

This cluster contains a holistic push towards reuse and recyclability of ESS.

Sustainability and Circular Economy	Description
Second-life applications for ESS	Used EV Batteries can be repurposed to serve second-life applications.
ESS recycling ecosystem in tandem with increased ESS deployment	Development of an end-to-end recycling ecosystem for EOL ESS will be important for a sustainable economy.

3.1.5 Economics

Upfront capital cost is a key hurdle for ESS deployment. This cluster looks at future cost trends for ESS and its competitiveness against other alternatives.

Economics	Description
Incentives for renewable energy coupled with ESS deployment	Some countries (e.g. South Korea and US) have started providing incentives such as renewable credits to encourage consumers to deploy renewable energy coupled with ESS.
Cost competitiveness of conventional generators vis-à-vis ESS	Decreasing ESS prices with advances in technology and manufacturing, coupled with emphasis on renewables, is expected to make ESS economically competitive with conventional generators in the near future in providing reserves.
Large scale EV adoption leads to drop in lithium prices	With accelerating fleet electrification globally, the resulting economies of scale will further drive down cost of lithium-ion ESS.

3.1.6 Technology

This cluster covers the various technological trends in ESS. In-depth discussion on the various ESS technologies is covered in Chapter 2.

Technology & Test-bedding	Description
Lithium-ion as dominant technology	Lithium-ion batteries are likely to dominate as the key battery technology for the short term.
Strengthen cybersecurity of ESS	Every single distributed point is an entry point risk and requires safeguards and technological solutions to prevent cyber-attacks.

	The communication infrastructure (from operator to ESS) also requires cybersecurity protection.
Advances in power electronics lead to lower lifecycle cost for ESS	Technological advances and scalability in power electronics will improve power conversion efficiency and lead to lower lifecycle costs for ESS.
Opportunities to test-bed innovative ESS solutions	Test-bedding will be important to support the commercialisation of solutions.
Alternative non lithium-based solutions for stationary ESS	Non lithium-based solutions such as aluminium / redox battery energy storage solutions may become viable in future with advances in technology.

3.1.7 Manpower

As the local ESS ecosystem develops, there is a need to develop a pipeline of manpower for designing, installing, operating and maintaining ESS.

Manpower	Description
Demand for manpower trained in ESS to support increased ESS deployment	A pipeline of manpower trained in ESS will be required to handle testing, certification, research and development, installation, security, maintenance, operation and decommissioning of ESS systems.

3.1.8 Land

This cluster investigates possible deployment options for ESS in land-scarce Singapore.

Land	Description
Alternative ESS deployment locations	Besides conventional land deployment, alternative sites should be explored to overcome Singapore's land constraints, including floating platforms, underground, rooftops and stacking of ESS. Such land saving solutions will need to meet local safety requirements.

3.2 Internal Drivers

Unlike external drivers which represent external forces (e.g. market trends, environment) acting upon the operating environment, internal drivers represent the roadmap owner's internal aspirations and vision, which sets the objectives of the roadmap. Consultation with the roadmap owner indicates the overarching internal drivers to be as follows:

a) Deploy at least 200 MW of ESS beyond 2025 in support of National Solar ambition;
b) Develop high Value-Added (VA) segments of the ESS value chain, such as battery R&D, Testing, Inspection & Certification (TIC) and second-life applications/ ESS recycling; and
c) Build up a vibrant ESS ecosystem to grow capabilities and develop innovative solutions to serve the local and global markets.

3.3 Deliverables

The deliverables refer to the solutions, products and/or services suggested by the stakeholders to address the External and Internal Drivers. Not all the drivers may be addressed, but the roadmap owner is to fulfil to the best of its ability (or allocation of limited resources) to meet national and economic needs.
Using affinity grouping, the ideations are clustered into 4 themes as follows:

i. Technology Innovation
ii. Business Models/Products & Services
iii. Infrastructure and Capabilities
iv. Policies and Regulations

3.3.1 Technology Innovation

Technology innovation seeks to foster technological growth and development in the local industry, market, or ecosystem. This may include schemes or initiatives designed to investigate forefront technologies or improve existing solutions. Innovation may extend beyond end-products or services to include integration and connectivity for delivery of such products and services.

Technology Innovation	Description
Optimise ESS performance in tropical climates	Develop ESS technologies suited for tropical countries, such as thermal resilient storage and low-maintenance applications.
Built-in safety and passive thermal management features	Explore built-in safety and passive thermal management features to enhance safety of ESS such as fire suppression. The thermal management solution should minimise or eliminate the use of active cooling measures.
ESS integration with conventional generators	Integrate ESS with smaller sized generators (e.g. for generators attached to cranes) to serve peak loads. Compatibility needed for such a system and its advantages can be an area of research.
Ultra-safe battery chemistries	Explore ultra-safe battery chemistries such as solid state, or sodium ion batteries whilst understanding the trade-offs (if any).
High performance battery chemistries	Explore alternative chemistries such as lithium-sulfur, solid state and metal-air, to enable greater energy storage and efficiency.
Hydrogen storage solutions	Explore hydrogen-based storage to provide clean fuel alternative. Hydrogen usage may become prevalent if cost and safety barriers are overcome.

3.3.2 Business Models/Products & Services

As ESS technologies mature and gain acceptance by consumers, new business models, products and services may arise. It is important to keep tabs on these developments to capture a greater share of the growing ESS market.

Business Models/ Products & Services	Description
Solar-ESS integration	Solar-ESS use cases can be showcased to demonstrate the positive economic benefits that such an integration can provide.
Aggregation of DERs (including ESS) for market participation	Distributed energy resources (including ESS) can be aggregated to participate in the energy market.

Backup for additional revenue stream and backup for critical services	ESS can serve as a backup in conjunction with standalone backup generation systems for critical infrastructure such as substations, communication towers and data centres.
ESS as a service / battery leasing framework	Design a framework for ESS as a service and other similar business models to proliferate. Additional services may include provision of O&M services to asset owners.

3.3.3 Infrastructure and Capabilities

This theme covers (i) the development of collaborative facilities, shared competencies, public collaborative projects and platforms for growing the local ESS ecosystem in Singapore; and (ii) cultivating of human capital and local expertise in ESS.

Infrastructure and Capabilities	**Description**
Domestic competencies to test, inspect & certify ESS batteries	Build domestic competencies in testing, inspecting and certifying ESS solutions at battery and system levels.
Communication of Automatic Generation Control (AGC) signals	Explore alternative remote communication technologies for transmitting PSO's AGC signals to the ESS, to bring down cost while maintaining reliability and cybersecurity of these communications.
Offshore floating ESS platforms	Explore offshore floating ESS platforms to support the national grid and marine and offshore operations, while overcoming land constraints in land scarce Singapore.
Common pilot line facility to prototype innovative ESS solutions	Build a common pilot line facility to prototype innovative ESS solutions to bridge the gap between research and commercialisation.
One-stop portal on ESS information	Develop a one-stop portal to house all ESS-related information, including regulations, standards, use cases. This may help to facilitate information sharing and partnerships among government, industry and academia.
Energy trading platform	Develop an energy trading platform to facilitate peer-to-peer energy trading and transaction of renewable energy certificates (RECs).
Tertiary education and training programme to develop manpower capabilities	Align curricula in the various IHLs and develop technical training programmes to groom local manpower to support the development of the local ESS ecosystem.
Raise awareness of the value proposition of ESS among financial institutions	Develop ESS term sheets and use cases to raise awareness among financial institutions on the value proposition of ESS and encourage them to provide financing options for future ESS deployments.

3.3.4 Policies and Regulations

In Singapore's energy market, regulators can contribute to a vibrant ESS ecosystem by establishing enabling policies, regulations and standards that recognise unique value add of ESS.

Policies and Regulations	**Description**
Recognise ESS' ability to provide fast frequency response	Recognise and price the unique ability of ESS in providing fast frequency response over conventional generators.
Structure capacity market with longer term (>1 year) Capacity Supply Obligation contracts to anchor investment	Include ESS for longer term contracts in the capacity market (e.g. 2-3 years). This will provide for a reliable stream of revenue for ESS deployment.

3.4 Summary

The earlier sections summarise the key inputs from stakeholders on the drivers and deliverables. The roadmap and detailed inputs for all three layers, namely Drivers, Deliverables and Technology & Resources layers can be found in Annex 1.

4. Recommendations

This chapter presents a set of recommendations by the roadmap authors based on data covered in Chapters 2 and 3. The recommendations include recommended actions and by when they should take place, taking into consideration the key drivers. The timeframes are as follow:

Timeframe	Time Horizon	Objectives
Short Term (S)	2020 to 2025	**Meet the 200 MW ESS deployment target to support national solar ambitions.** In the short term, the key focus is to accelerate ESS deployment to support solar targets. Initiatives would include test-bedding of new technologies and applications, and to have greater clarity in market regulations and safety standards associated with ESS. There is also a need to grow the ESS ecosystem and enterprises. This includes developing a one-stop ESS portal and building ESS manpower capabilities to support ESS deployment.
Medium Term (M)	2025 to 2030	**Build up a vibrant ESS ecosystem in Singapore to support national needs and economic growth.** In the medium term, as ESS adoption increases, more testing and certification facilities will be required. Emphasis should also be on initiatives to boost recycling capabilities and regulations for EOL batteries.
Long Term (L)	Beyond 2030	**Seed and develop future technologies that require longer development durations, so that our local companies and ecosystem remain vibrant and competitive in helping Singapore achieve its energy and economic ambitions.** In the longer term, it is important to focus on research programmes to develop capabilities in new technologies such as solid-state, metal air and hydrogen storage to capture opportunities in these emerging technologies.

A summary of the recommendations is enclosed in the following table. Each recommendation is further expanded in subsequent sections. It should be noted that the list of recommendations is non-exhaustive.

Category	Recommendations	Time
Technology Development	Support research in relevant ESS technologies, including next-generation batteries, second-life and recycling technologies.	S-M-L
	Develop test-bedding opportunities for new ESS technologies and applications.	S
	Commission detailed techno-economic study of ESS in local context.	S-M
Regulations	Review policies and regulations in the electricity market for ESS.	S-M
	Refine local ESS standards to provide guidance for safe deployment and maintenance	S
	Review policies and regulations on recycling and disposal at the end-of-life of ESS.	M
Ecosystem Development	Develop a one-stop portal for ESS-related information.	S
	Develop a Testing and Certification hub through partnerships with both international and local players.	M
	Support the development of ESS prototyping facilities / pilot lines to fabricate large size cells, battery packs and auxiliary systems.	M
	Develop communication infrastructures to support the growth of emerging ESS technologies and business models.	S-M
	Align relevant ESS curricula and develop training programmes in IHLs/RIs and other training institutes for students and professionals.	S

4.1 Technology Development

4.1.1 Support research in relevant ESS technologies

Singapore has existing ESS R&D capabilities in its IHLs and RIs, and it is imperative to continue investing in these capabilities to meet our national needs and economic objectives. Capabilities and knowledge built through R&D ensure sufficient local technical know-how to support the vibrant growth of ESS deployment. Developing new ESS technologies also enables new economic opportunities, which has a sizable global market (>US$50 billion). Key research areas include:

a) Next-generation battery technologies. In the near term, the R&D focus will be on improving energy density and safety of lithium-ion batteries. This includes the development of high-energy cathodes (e.g. lithium-rich layer cathode) and anodes (e.g. Si-based or Sn-based). To enhance safety, Fe-based cathode and/or TiO-based anode materials for lithium-ion batteries can be explored.

   In the medium term, further improvements in the energy density will require significant changes to the chemistry, such as adopting an anode-free or solid-state approach. Such efforts may boost the energy density further e.g. to 1200 Wh/L (or 400 Wh/kg). Challenges can include the need to develop (i) a suitable chemistry system (e.g. active electrodes, solid electrolyte) for solid-state batteries, (ii) electrolyte innovations such as hybrid electrolytes that allow fully reversible lithium plating/stripping, and (iii) advanced monitoring and detection technologies, for the side reactions between electrolyte and lithium for anode free batteries.

   In the long term, lithium-sulfur and metal air batteries are promising ESS solutions in terms of energy density and safety respectively. This requires well-constructed sulfur/air electrodes and efficient catalysts to overcome the sluggish kinetics of sulfur/oxygen reactions. Advanced solid-state battery, with its solid-state electrolyte, is also promising with better protection against internal short circuits. Other research areas include low-cost high-energy flow battery, and safer sodium-ion battery that is eco-friendlier, given its abundance and ease of extraction.

b) Second-life and recycling technologies. The local recycling industry currently faces technological challenges in recycling varied lithium-ion batteries, while keeping processing costs competitive. New recycling processes such as hydrometallurgy are therefore needed to increase the recovery efficiency of precious metals from lithium-based batteries without compromising environmental emissions targets.

   Repurposing used industrial and EV batteries for second-life applications (e.g. grid-related applications) would require the development of expertise and facilities to assess the existing state of health of these batteries and refurbish them so that they can be packed into new modules. Joint research and test-bedding efforts with the industry to assess the efficiency and safety of these second-life batteries will be important.

   Finally, given the rising demand for ESS, depletion of raw materials will increasingly be an important consideration. Singapore may combine its expertise in recycling and cell manufacturing to explore manufacturing of cells from recycled materials.

4.1.2 Develop test-bedding opportunities for new ESS technologies and applications

Notwithstanding the R&D efforts, ESS deployment remains limited in Singapore[4]. There is a need to continue test-bedding innovative and new business models to demonstrate the value-add of ESS. Test-bedding efforts could include:

- Mobile ESS capable of being deployed to a sub-station facing capacity constraints. When network augmentation at this sub-station is completed, the mobile ESS can be flexibly redeployed to support other sub-stations.
- ESS serving different applications at various time periods (albeit one application at a time) would be useful to better understand the design and operational planning for application stacking.
- Innovative ESS deployment options that can optimise land space such as stacking of ESS containers, deployment of floating or underground ESS, and co-location of ESS in commercial and residential spaces. Compliance to local standards and safety will be critical for such deployments.
- Hybrid ESS technology deployments like batteries with supercapacitors or lithium-ion batteries with flow batteries to showcase how synergy can be achieved with hybrid deployments.
- Business models that has not been demonstrated in Singapore, such as ESS-as-a-Service.

[4] ESS test-beds in Singapore include: (i) Self-Regulating Integrated Electricity-Cooling Networks at the Marina Bay district cooling system by Singapore District Cooling and the Institute for Infocomm Research; (ii) Distributed ESS under EMA's Energy Storage Grant Call in 2016 by NTU, Panasonic and Sunseap; and (iii) the ESS Test-bed jointly awarded by EMA and SP Group. There is also an ongoing sandbox trial with SP PowerAssets on ESS' ability to relieve grid congestion.

4.1.3 Commission detailed techno-economic study of ESS in local context

Commissioning a detailed Techno-Economic Analysis (TEA) will be useful to address the information gap and raise confidence among investors, end users, bankers and insurance companies. The study should consider localised costs and existing electricity demand and supply, and derive a market sizing for relevant applications described in Section 2.2. The study should also propose the sizing of the ESS, taking into consideration the application stacking and associated design and operation methodology for each specific combination of applications. The study should also consider the local safety standards and the associated land requirements, including the proportion of investment costs required to satisfy local safety standards. A simple techno-economic analysis tool can also be developed to assist end users to decide on optimum size of ESS to maximise their economic returns.

4.2 Regulations

As ESS technologies evolve and expand into new applications, regulations and standards would also need to evolve. This ensures that they remain fit-for-purpose and allows the benefits of ESS to be fully captured.

4.2.1 Review policies and regulations in the electricity market for ESS

The costs and benefits of introducing any new product and service should be considered along with the needs of electricity market. Where relevant, the unique ability of BESS to provide instantaneous response compared to conventional generators should be recognised and priced accordingly for ESS to participate competitively in the market.

Existing regulations can also be reviewed:

- To assign a more suitable asset type for ESS to recognise its unique dual identity as both a generator and load. There are currently differences in the charging mechanisms and regulatory frameworks for loads and generators.

- To provide clarity for behind-the-meter ESS participation in energy markets. While innovative business models (e.g. VPPs) enables the aggregation of distributed ESS to participate in the market, there are challenges for ESS to comply with the requirements, metering and settlement vis-à-vis the traditional generators. For example, existing settlement processes only allow one embedded generation group per site thus preventing the option of having multiple developers per site.

- For selective large solar generation users to install appropriate ESS systems along with solar deployments to cater for solar intermittency.

4.2.2 Refine local ESS standards to provide guidance for safe deployment and maintenance

There is a need to continue to review and refine our local ESS standards, with close collaboration with regulatory stakeholders, to provide guidance on the safe deployment and maintenance of ESS in Singapore's operating conditions. There is also a need to develop a set of performance standards, taking reference from overseas regulators, to ensure the reliability of the ESS. Close alignment with international standards will also give our local ESS companies an advantage when exporting their solutions to the regional and global market.

4.2.3 Review policies and regulations on recycling and disposal at the end-of-life of ESS

In the longer term, as more EV and industrial ESS reaches the end of their useful lifespan, there will be a need to regulate the recycling and disposal of these ESS in a sustainable manner. To support the recycling ecosystem, the following can be explored:

- While the Lithium-Ion batteries in the ESS are covered by the RSA, a possible option could be to introduce requirements to make manufacturers responsible to collect, recycle and dispose of the EOL ESS as a whole (not only the battery), as the use and adoption of ESS becomes more prevalent in the future. However, this should be done in tandem with available capability and capacity to treat and recycle such EOL ESS. This can take reference from regulations practised in other economies such as EU and China. Such regulations may also spur manufacturers to redesign their ESS solutions to be more recyclable.

- Setting an industry-wide target for collection of used ESS, supported by appropriate incentives, to mobilise the industry to increase the volume and efficiency of ESS recycling.

4.3 Ecosystem Development

4.3.1 Develop a one-stop portal for ESS-related information

A one-stop portal to aggregate ESS-related information would facilitate information sharing between the government, industry and academia, and encourage further partnerships and development of the ESS ecosystem. The portal may include, but not limited to, the following information:

- Local directory of ESS suppliers, system integrators, and academics involved in ESS research;
- ESS-related standards and regulations (e.g. fire safety, installation and maintenance);
- Research focus areas of local companies to promote collaborative efforts between industry and RIs/IHLs;
- Repository of past and present ESS research, test-bedding projects and commercial deployments;
- Techno-economic analysis tool for optimal sizing of ESS requirements;

- Financing and insurance options for ESS deployment; and
- Training programmes and seminars on ESS.

4.3.2 Develop a Testing and Certification (T&C) hub through partnerships with international and local players

Currently, the T&Cs of ESS deployed in Singapore are done overseas, which increase the compliance cost and the project timeline. The development of a local ESS T&C hub can be achieved by leveraging partnerships with international safety and certification companies in Singapore, government agencies (e.g. EMA, SCDF) and research institutes (e.g. EPGC/ERI@N). The scope of the T&C hub would include but not limited to:

- Testing and certifying the safety of new ESS before onsite deployment;
- Conducting benchmarking tests across different technologies or brands;
- Ascertaining state of health of first and second-life batteries; and
- Training operators and maintenance personnel to handle ESS.

4.3.3 Support the development of ESS prototyping facilities / pilot lines to fabricate large size cells, battery packs and auxiliary systems

Currently, Singapore lacks a common testing and development facility to develop and prototype commercial scale ESS packs (more than 3-5 kWh) or industrial size cells (20-30 Ah). The development of an ESS prototyping facility or pilot line will bridge the gap and facilitate the translation of technological developments at the battery cell and pack level.

The facility can also expand into prototyping and optimisation for novel auxiliary systems, such as BMS with data-driven control and optimisation features and advanced liquid cooling systems.

The proposed facility will also provide a good training ground for manpower development and complements efforts to establish an ESS T&C hub in Singapore. The proposed facility can be jointly developed by the industry and IHLs/RIs in a consortium setting.

4.3.4 Develop communication infrastructures to support the growth of emerging ESS technologies and business models

Today, the cost of communication infrastructure (comprising pilot wire connection, system security including cyber security, and low latency signals for AGC operations) between PSO and BTM ESS is high, albeit necessary. With the envisaged proliferation of ESS across the network, the existing network of pilot wires is also likely to be insufficient.

System operators and consumers can collaborate to test-bed emerging technologies, such as optic fibre or remote communication to overcome these constraints while maintaining minimum performance standards (e.g. low latency). Cyber-security measures should be taken into consideration to maintain the system security of the network.

4.3.5 Align relevant ESS curricula, and develop training programmes in IHLs and other training institutes for students and professionals

A pipeline of talent trained in ESS will be key for the growth of the local ESS ecosystem. To support a vibrant ecosystem, the following can be explored/sustained:

- To incorporate relevant curricula on ESS (e.g. PCS, BMS, TMS etc.) into relevant IHL's engineering courses to build a pipeline of manpower with sufficient knowledge to work in this field;
- To work with training institutes (e.g. Singapore Institute of Power and Gas) to develop ESS-related courses to equip the workforce with required knowledge, of which training subsidies can be sought from SkillsFuture Singapore (SSG);
- To encourage companies to work with Workforce Singapore (WSG) to develop ESS-related Professional Conversion Programme to support mid-career switch; and
- To continue identifying ESS-related competencies as essential skillsets in the energy sector through the Skills Framework for Energy and Power.

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Annex 1: ESS Roadmap for Singapore

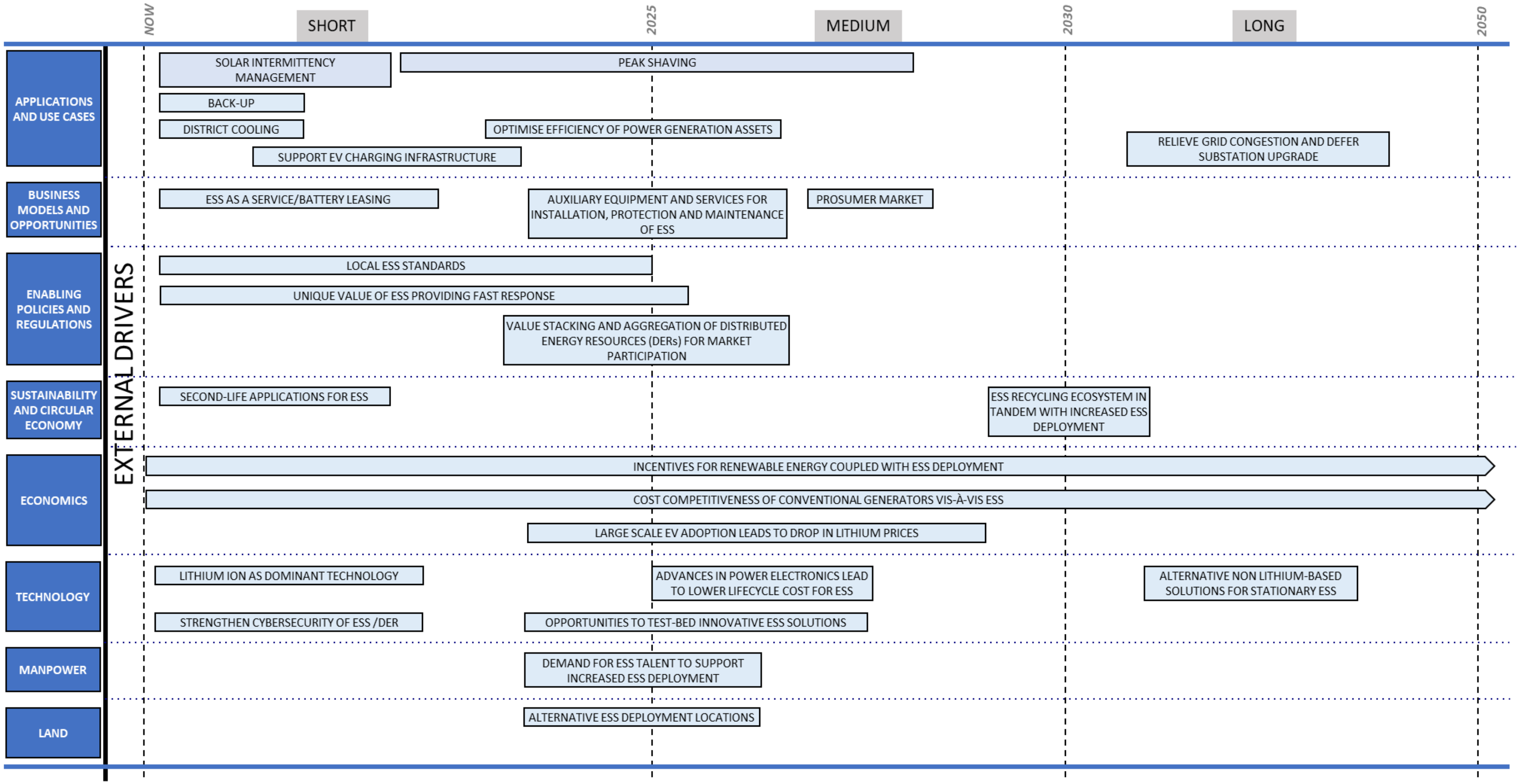
Foreword

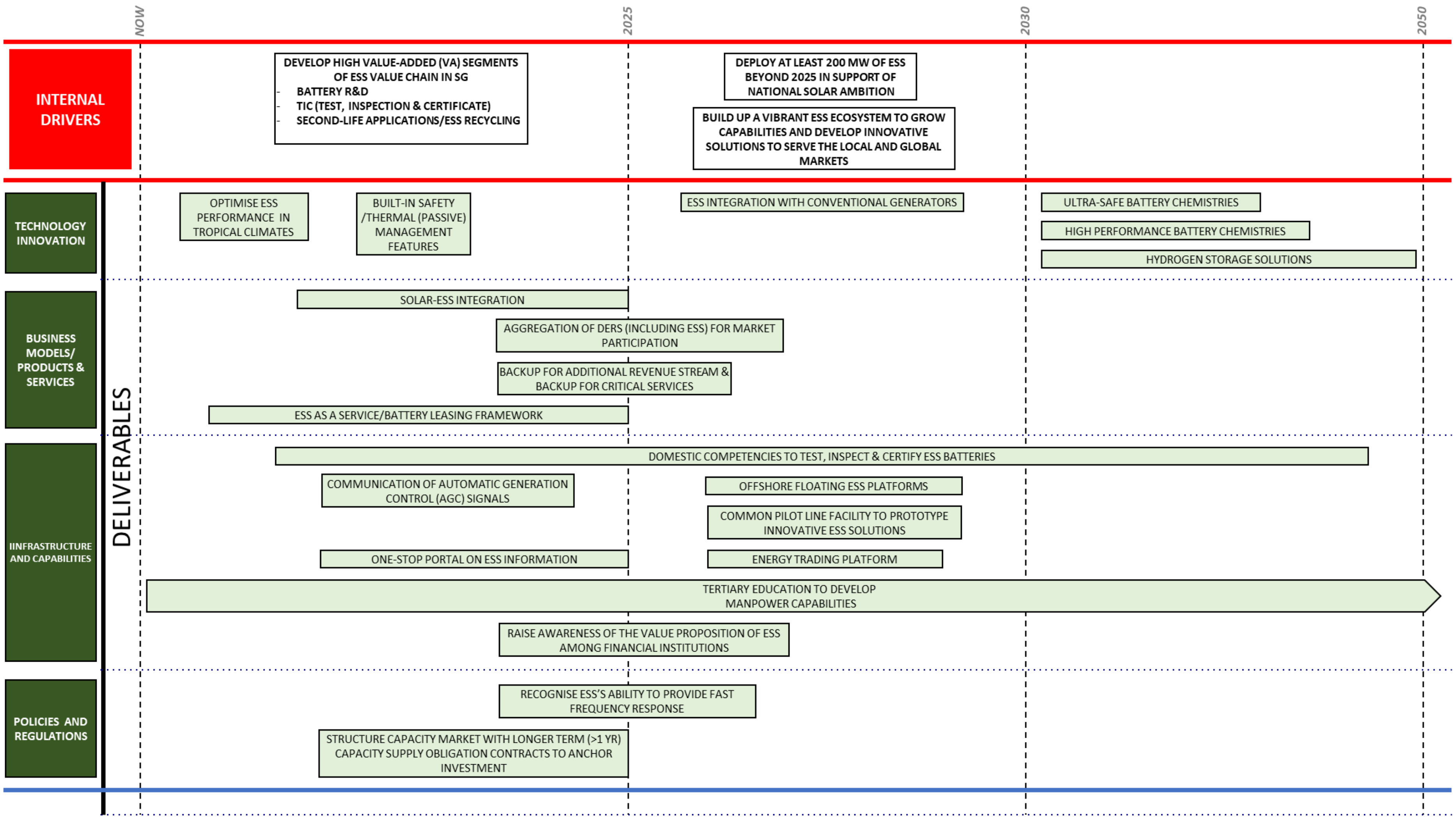
The External Driver, Deliverables and Technology & Resource layers for the roadmap are described here. It should be noted that while this constituted a consolidated discussion drawn from the workshop and survey, this is presented in its raw form and not all ideations are presented into the roadmap (shown in the next page).

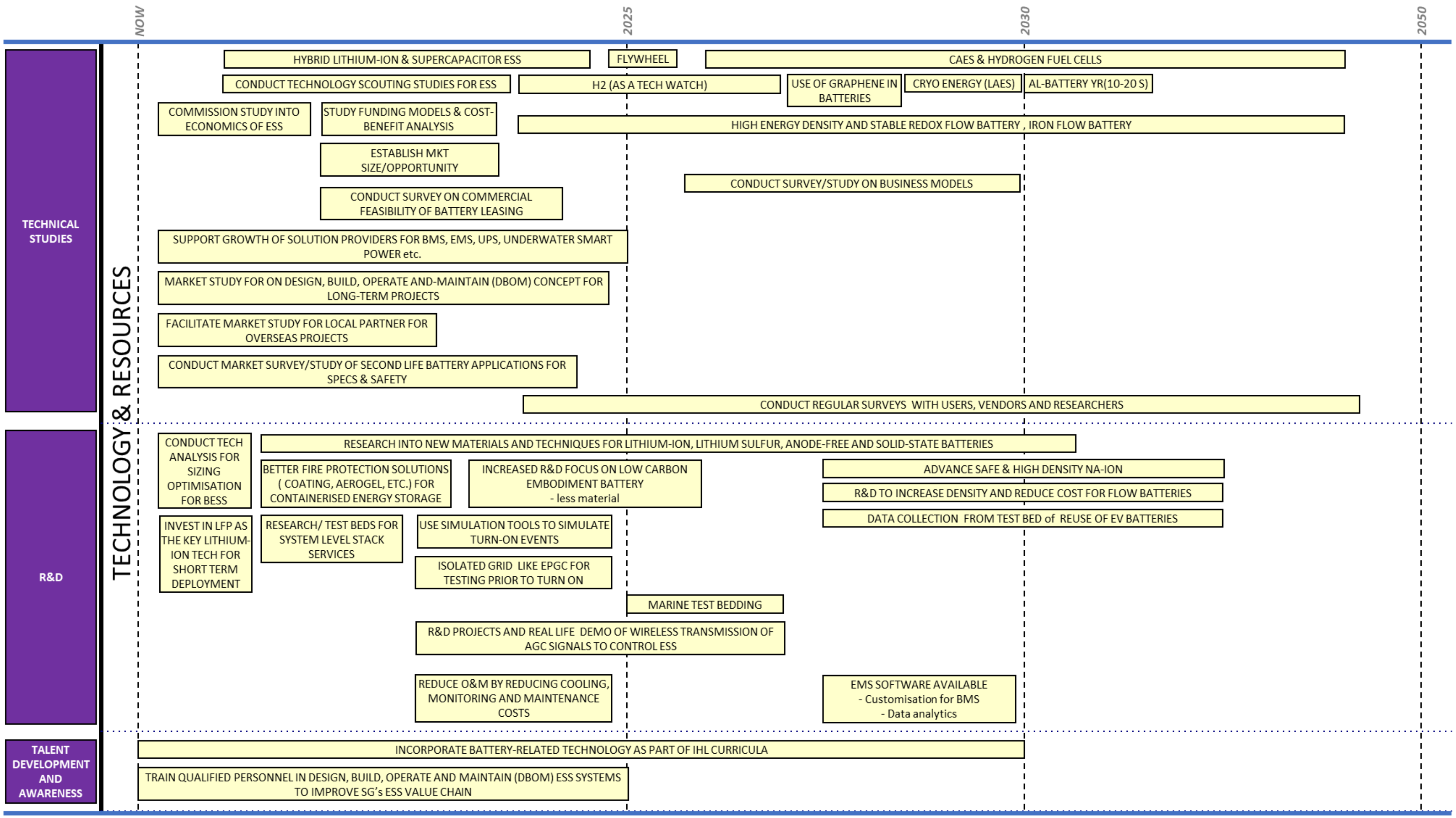
Considerations for assigning the timeline placement are as follows:

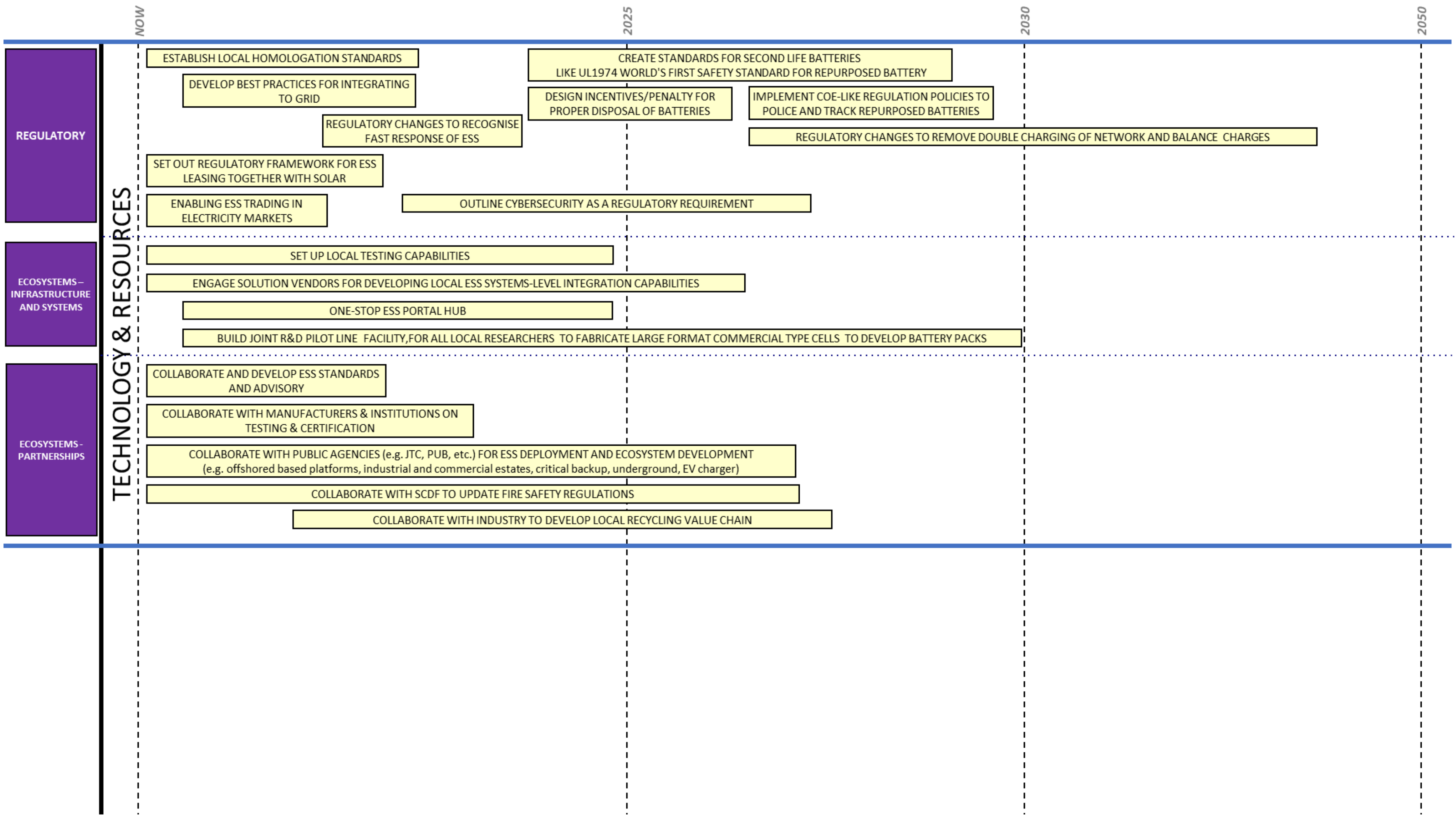
Layer	Time Assignment Guideline
Drivers	When does the inflection point occurs? When does this driver hit critical mass for adoption (e.g. technology)? When would this objective be achieved or met?
Deliverables	When do we want to launch this product/service/platform? When should we roll out this programme or scheme?
Tech & Resources	When do we need to kick-start the action item? When do we need to start staging the necessary resources to deliver the product?

ESS ROADMAP FOR SINGAPORE




NOW
2025
2030
2050
INTERNAL DRIVERS
DEVELOP HIGH VALUE-ADDED (VA) SEGMENTS OF ESS VALUE CHAIN IN SG
- BATTERY R&D
- TIC (TEST, INSPECTION & CERTIFICATE)
- SECOND-LIFE APPLICATIONS/ESS RECYCLING
DEPLOY AT LEAST 200 MW OF ESS BEYOND 2025 IN SUPPORT OF NATIONAL SOLAR AMBITION
BUILD UP A VIBRANT ESS ECOSYSTEM TO GROW CAPABILITIES AND DEVELOP INNOVATIVE SOLUTIONS TO SERVE THE LOCAL AND GLOBAL MARKETS
DELIVERABLES
TECHNOLOGY INNOVATION
OPTIMISE ESS PERFORMANCE IN TROPICAL CLIMATES
BUILT-IN SAFETY /THERMAL (PASSIVE) MANAGEMENT FEATURES
ESS INTEGRATION WITH CONVENTIONAL GENERATORS
ULTRA-SAFE BATTERY CHEMISTRIES
HIGH PERFORMANCE BATTERY CHEMISTRIES
HYDROGEN STORAGE SOLUTIONS
BUSINESS MODELS/ PRODUCTS & SERVICES
SOLAR-ESS INTEGRATION
AGGREGATION OF DERS (INCLUDING ESS) FOR MARKET PARTICIPATION
BACKUP FOR ADDITIONAL REVENUE STREAM & BACKUP FOR CRITICAL SERVICES
ESS AS A SERVICE/BATTERY LEASING FRAMEWORK
IINFRASTRUCTURE AND CAPABILITIES
DOMESTIC COMPETENCIES TO TEST, INSPECT & CERTIFY ESS BATTERIES
COMMUNICATION OF AUTOMATIC GENERATION CONTROL (AGC) SIGNALS
OFFSHORE FLOATING ESS PLATFORMS
COMMON PILOT LINE FACILITY TO PROTOTYPE INNOVATIVE ESS SOLUTIONS
ONE-STOP PORTAL ON ESS INFORMATION
ENERGY TRADING PLATFORM
TERTIARY EDUCATION TO DEVELOP MANPOWER CAPABILITIES
RAISE AWARENESS OF THE VALUE PROPOSITION OF ESS AMONG FINANCIAL INSTITUTIONS
POLICIES AND REGULATIONS
RECOGNISE ESS'S ABILITY TO PROVIDE FAST FREQUENCY RESPONSE
STRUCTURE CAPACITY MARKET WITH LONGER TERM (>1 YR) CAPACITY SUPPLY OBLIGATION CONTRACTS TO ANCHOR INVESTMENT


NOW
2025
2030
2050
TECHNOLOGY & RESOURCES
TECHNICAL STUDIES
HYBRID LITHIUM-ION & SUPERCAPACITOR ESS
FLYWHEEL
CAES & HYDROGEN FUEL CELLS
CONDUCT TECHNOLOGY SCOUTING STUDIES FOR ESS
H2 (AS A TECH WATCH)
USE OF GRAPHENE IN BATTERIES
CRYO ENERGY (LAES)
AL-BATTERY YR(10-20 S)
COMMISSION STUDY INTO ECONOMICS OF ESS
STUDY FUNDING MODELS & COST-BENEFIT ANALYSIS
HIGH ENERGY DENSITY AND STABLE REDOX FLOW BATTERY , IRON FLOW BATTERY
ESTABLISH MKT SIZE/OPPORTUNITY
CONDUCT SURVEY/STUDY ON BUSINESS MODELS
CONDUCT SURVEY ON COMMERCIAL FEASIBILITY OF BATTERY LEASING
SUPPORT GROWTH OF SOLUTION PROVIDERS FOR BMS, EMS, UPS, UNDERWATER SMART POWER etc.
MARKET STUDY FOR ON DESIGN, BUILD, OPERATE AND-MAINTAIN (DBOM) CONCEPT FOR LONG-TERM PROJECTS
FACILITATE MARKET STUDY FOR LOCAL PARTNER FOR OVERSEAS PROJECTS
CONDUCT MARKET SURVEY/STUDY OF SECOND LIFE BATTERY APPLICATIONS FOR SPECS & SAFETY
CONDUCT REGULAR SURVEYS WITH USERS, VENDORS AND RESEARCHERS
R&D
CONDUCT TECH ANALYSIS FOR SIZING OPTIMISATION FOR BESS
RESEARCH INTO NEW MATERIALS AND TECHNIQUES FOR LITHIUM-ION, LITHIUM SULFUR, ANODE-FREE AND SOLID-STATE BATTERIES
BETTER FIRE PROTECTION SOLUTIONS (COATING, AEROGEL, ETC.) FOR CONTAINERISED ENERGY STORAGE
INCREASED R&D FOCUS ON LOW CARBON EMBODIMENT BATTERY
- less material
ADVANCE SAFE & HIGH DENSITY NA-ION
R&D TO INCREASE DENSITY AND REDUCE COST FOR FLOW BATTERIES
DATA COLLECTION FROM TEST BED of REUSE OF EV BATTERIES
INVEST IN LFP AS THE KEY LITHIUM-ION TECH FOR SHORT TERM DEPLOYMENT
RESEARCH/ TEST BEDS FOR SYSTEM LEVEL STACK SERVICES
USE SIMULATION TOOLS TO SIMULATE TURN-ON EVENTS
ISOLATED GRID LIKE EPGC FOR TESTING PRIOR TO TURN ON
MARINE TEST BEDDING
R&D PROJECTS AND REAL LIFE DEMO OF WIRELESS TRANSMISSION OF AGC SIGNALS TO CONTROL ESS
REDUCE O&M BY REDUCING COOLING, MONITORING AND MAINTENANCE COSTS
EMS SOFTWARE AVAILABLE
- Customisation for BMS
- Data analytics
TALENT DEVELOPMENT AND AWARENESS
INCORPORATE BATTERY-RELATED TECHNOLOGY AS PART OF IHL CURRICULA
TRAIN QUALIFIED PERSONNEL IN DESIGN, BUILD, OPERATE AND MAINTAIN (DBOM) ESS SYSTEMS TO IMPROVE SG's ESS VALUE CHAIN


NOW
2025
2030
2050
REGULATORY
ECOSYSTEMS – INFRASTRUCTURE AND SYSTEMS
ECOSYSTEMS - PARTNERSHIPS
TECHNOLOGY & RESOURCES
ESTABLISH LOCAL HOMOLOGATION STANDARDS
CREATE STANDARDS FOR SECOND LIFE BATTERIES LIKE UL1974 WORLD'S FIRST SAFETY STANDARD FOR REPURPOSED BATTERY
DEVELOP BEST PRACTICES FOR INTEGRATING TO GRID
DESIGN INCENTIVES/PENALTY FOR PROPER DISPOSAL OF BATTERIES
IMPLEMENT COE-LIKE REGULATION POLICIES TO POLICE AND TRACK REPURPOSED BATTERIES
REGULATORY CHANGES TO RECOGNISE FAST RESPONSE OF ESS
REGULATORY CHANGES TO REMOVE DOUBLE CHARGING OF NETWORK AND BALANCE CHARGES
SET OUT REGULATORY FRAMEWORK FOR ESS LEASING TOGETHER WITH SOLAR
ENABLING ESS TRADING IN ELECTRICITY MARKETS
OUTLINE CYBERSECURITY AS A REGULATORY REQUIREMENT
SET UP LOCAL TESTING CAPABILITIES
ENGAGE SOLUTION VENDORS FOR DEVELOPING LOCAL ESS SYSTEMS-LEVEL INTEGRATION CAPABILITIES
ONE-STOP ESS PORTAL HUB
BUILD JOINT R&D PILOT LINE FACILITY,FOR ALL LOCAL RESEARCHERS TO FABRICATE LARGE FORMAT COMMERCIAL TYPE CELLS TO DEVELOP BATTERY PACKS
COLLABORATE AND DEVELOP ESS STANDARDS AND ADVISORY
COLLABORATE WITH MANUFACTURERS & INSTITUTIONS ON TESTING & CERTIFICATION
COLLABORATE WITH PUBLIC AGENCIES (e.g. JTC, PUB, etc.) FOR ESS DEPLOYMENT AND ECOSYSTEM DEVELOPMENT (e.g. offshored based platforms, industrial and commercial estates, critical backup, underground, EV charger)
COLLABORATE WITH SCDF TO UPDATE FIRE SAFETY REGULATIONS
COLLABORATE WITH INDUSTRY TO DEVELOP LOCAL RECYCLING VALUE CHAIN

Annex I

External Drivers

Applications and Use Cases	
Solar intermittency management	For large scale solar deployment, the output is intermittent in nature. There is a need for an intermediary by using frequency regulation at many levels and to smooth out the irregular downstream loads (e.g. EV charging) to maintain grid stability. Moreover, provision of grid ancillary services is a key segment in the BESS market as can be seen in neighbouring countries like Philippines as well as in maturing BESS markets like Australia. There are significant efforts in this sector by Singapore government and authorities which is a welcome move. Deployment of storage and associated applications are both a function to cleaner and renewable energy targets, requiring flexibility of existing infrastructure (including grid capabilities) to match the types and predictability of renewables being targeted. Without commenting directly on Singapore's goals or needs, higher penetrations of renewables which have elements of unpredictability across seconds, minutes, days and weeks, ultimately lead to longer duration storage applications to support renewable production predictable variations within a day (classically the "duck" curve) but also expected variations (firming wind production). For overseas deployment, one has also to contend with seasonal variations with longer duration storage and/or the ability to run a few highly efficient thermal generation assets to replace seasonal or unexpected gaps in renewable production by charging the mid-duration storage assets. The push toward cleaner modes of storage as an alternative to diesel genset cannot be overemphasized to meet carbon savings and resilience. Cost saving may be reaped by storing excess solar energy for consumption during other hours.
Peak shaving	With peak shaving, there is little need to run expensive power plants in the systems, and hence can aid to lower the costs of renewable generation in the system. With fast frequency regulation coming into play, the challenge in combining these two applications lies in their vastly different timescales: peak demand charge is calculated every month on a smoothed power consumption profile (e.g. 15-minute averages), whereas fast frequency regulation requires a decision every 2 to 4 seconds. Regulation aspect also weighs in; there is no commercial benefits to use ESS to do peak shaving if potential customer is on Summation Scheme. Peak shaving, if deployed properly, can be used to replace energy generator sets. Some usage for peak shaving is especially important as electric cars proliferates, implying the potential use of batteries to offset or defer electrical substation upgrades at existing estates. Instead of building or upgrading substations, batteries are deployed as temporary load enabler. Network infrastructure capex deferral also infers to adopting peak shaving as an alternative mean to enable networking reinforcement, by enabling voltage regulation, supporting solar intermittency management and providing localised backup energy supply.
Back-up	Black start resilience dictates a provision of an independent source of electricity which aids in the resilience of the network, such as unanticipated blackout events. If successful, the ESS owner can reduce having to buffer in fixed capacity in the national grid.
District cooling	ESS can be used in district cooling plants to optimise operating cost.
Optimise efficiency of power generation assets	There is a need to balance load continually during peak demand. Some ESS options would enable managing of peak loads but also to maximise whatever amount of energy generated and stored by Gencos. Rather than just managing big loads, it is possible to run it at consumer load and redirect to

	ESS if there is little consumer load such that utilisation rate can reach 80-90% all the time. During peak loads, the energy storage can be used to resupply during the period when the energy is not so high. If there is solar as well as Genco, at night when solar is down - the energy storage can used to supply extra loads without building additional Gencos. "Switchability" is an important component that yields a lot of flexibility to the grid operators, as well as the business operator and the township.
Support EV charging infrastructure	Fast charging may cause instability and need to cater for buffer management. That may entail strategies like peak shaving. The rollout of DC fast charger for EV could cause instability, and ESS can be used as a "battery buffer" to address the charging irregularities. Another scenario is to designate or align the time to use - start - or even charging; to aid in frequency regulation by zone/locations. The current situation is highly challenging though. LTA reported that based on their experience in working with BlueSG to roll out EV charging stations as part of their car-sharing programme, it was observed that many public car parks (e.g. HDB multi-storey car parks), the older ones, are generally not designed to even support slow EV charging (i.e. 3-phase 40A; 1-phase 100A). ESS deployment could be a viable solution for rendering such peak shaving purposes. As Singapore promotes the use of EV to eventually replace ICE altogether, the availability of EV chargers is an important factor to achieve this, and the use of ESS could be considered to overcome infrastructure constraints for pervasive installation of EV chargers.
Relieve grid congestion and defer substation upgrade	ESS could also be used to release the grid congestion in some quick-expanding area e.g. Orchard road where some substations are already facing stress but difficult to be upgraded due to space limitations. ESS solutions shall shave the peak demand and therefore defer the substation upgrading.
Demand response model and other applications	ESS can serve for various miscellaneous applications like demand response, quick and portable storage (e.g. CCTV supply), EV batteries, backup solutions & networks, and diesel genset solutions with emergency handling. These applications are elaborated below: If ESS can be made portable, it can be immediately set up for premises or construction site, as well as remote areas with lesser demands. If ESS can be scaled towards more stability, it may be rendered permanent. For remote site that is not serve by any power network, containerised ESS may be deployed to provide supply on site i.e. without the need for SP to lay power cables. Another possibility is redeployment for second-life use in areas such as CCTV surveillance or power up fireman lifts (that does not use high loads). EV batteries may service as sub-storage containers as akin to dry cells. This creates a new business model, where rather than EV charging from electrical chargers, EV drivers can just simply swap out their drained batteries for charged batteries at a kiosk/battery station. Other applications shall include support of critical services during emergency as a diesel generator substitute or other low load demand applications. Emergency use is viewed as recharging back of substation in events, and if the long-term energy storage is there, it can be deployed in a similar fashion as an UPS serving as a district level substation setup. Though the local grid is stable, ESS can serve as an interim supply at district level substation, instead of relying on diesel generators. With increase of solar deployment, more ESS deployment in support applications such as backup/recovery power and UPS, intermittency management can be expected. Backup can take the form of distributed storage for EV charging. Deployable ESS help as backup power during maintenance / construction work, and as emergency power for essential services (e.g. elevators).

Support local transport charging infrastructure	Building of ESS solutions shall factor in emerging trend of how charging stations may be linked to the ESS solution. This may require co-ordinated efforts between energy and transport authorities to design local charging facilities on land, offshore or marine. The implementation of charging stations may be zonal driven, before extending to country for specific stakeholders.
Government procurement for transport fleet and carpark charging	Government may step in to take over bulk-buying of transport operators on EV-based vehicles; thereupon merging public transport ownership and having the opportunity to fuse with ESS infrastructure. They can be part and parcel of portable charging avenues. Car parks and bus depots are facilities where peaky power consumptions are expected as Singapore pushes for vehicular electrification; and these facilities are increasingly built closer to residential areas.

Business Models and Opportunities	
ESS as a service / battery leasing	Energy as a Service / Energy Storage as a Service (as akin to AirBnB) may be a viable operating model to emulate or establish. This includes other contingencies measures such as battery swapping and leasing. Containerised ESS can be leased out to customers by people selling the batteries. ESS can be potentially co-located with solar farm and operates by selling a stabilised solar PV supply source to consumer (as a service).
Auxiliary equipment and services for installation, protection and maintenance of ESS	New businesses related to battery protection / maintenance / second-life reuse would become important in this part of the world. This necessitates formation of a robust and thriving ESS ecosystem.
Prosumer market	Consumers can also become producers. For example, each (household) may install their own solar PV, where one uses a certain amount whereas the rest may be stored and use/sold later to the grid. New policies and tariffs are needed to encourage these entrepreneurships (with collaboration of many agencies) in which peer-to-peer trading may be facilitated. This may warrant a change in mindset with regards to building owners versus tenancy market forces.
Demand for system integration – Design for tropics, infrastructure, integration connectors, communications & local ecosystem growth	A success demonstration or delivery within the tropics would form a competitive advantage for export opportunities in similar tropics environments. Infrastructure is key for ESS design and engineering but equally importantly would be the skillsets and competency building. Integration connectors are critical to the developed battery systems, and the integrator role is a potential space for local SMEs/LLEs to operate and thrive. Compounding the growth of ecosystems is the shortage of experienced and capable local System Integrators / EPCs to support large scale ESS projects. The current integrator space is relatively fragmented, but the battery technology is concentrated. Since ESS solution is still considered relatively new in power industry, customers prefer to have a turnkey solution rather than equipment supply. Hence, the solution provider needs to have the capability of undertaking the entire turnkey project, implying expectation for contractual coverage from installation, commissioning, operating, maintaining, and decommissioning. It happens not only in Singapore but also in many Asian countries. While it is good to have local system-level capabilities, investments by business owners needs to be supported by a strong business case. Typically, the system-level ESS testing is conducted at the factory (FAT) and at customer's (SAT) location. Furthermore, to reduce shipping costs, type testing should be performed near the factory location. MNCs may partake as providers with local SME/LLEs supporting the former. Most companies are generally looking for "product-like" technology ready for deployment and by this nature the undertaking is normally incremental. On the academia front dabbling with larger innovation research, there exists a gap between lab prototyping to actual productisation.

	BESS deployment must be fast-tracked. Major regulatory changes, involving communication networks, infrastructure, etc. will be needed to integrate BESS effectively in Singapore power grid. Singapore is the perfect example for BESS in urban environment and therefore, may serve as a business impetus for ESS vendors to work with the local regulators regarding developments required in terms of safety, space required and applications within a city environment.
Business opportunity to build BMS, TMS enterprises	EPC awarded projects may need to be customised for integrated solutions that not only satisfy both operational and maintenance functions but shall be able to meet minimalistic requirements for a standard BMS framework. From a long-term perspective, the recurring OPEX in various ESS application, such as in the areas of electrifying of batteries, infrastructure and O&M, requires a clear grasp on the part or ESS companies due to the limitation in the field of knowledge for installation and maintenance. Poor facility setup may lead to subsequently higher costs to operate and even more maintain the facility. In addition, EMS system integration shall meet functional requirements for a good TMS and encompasses sustainable cooling technology. This entails a high degree of scalability in selecting the right systems solutions.
Growing ASEAN BESS Market	Today, ASEAN is a developing market for BESS. Majority of the opportunities in this market are driven by the utilities. However, the market growth in commercial and industrial sector is slow and must catch up with how the market is expanding in US/Australia. To address the competitive market and challenges effectively, global MNCs need to make Singapore a regional supply unit for all BESS projects in the region. This opportunity entails building local capability as well as investing in BESS technology development in Singapore.

Enabling Policies and Regulations	
Local ESS standards	There are no clear standards / regulations for spelling out containerised energy storage limitations. Current guidelines adopted by local authorities are largely based on globally recognised standards and practices. One challenge is a reluctance of manufacturers and developer to engage independent quality assurance beyond the service standards stipulated by law. As such product specifications are usually proposed by the manufacturers than regulators. Adding to the complexity are tough regulations on energy storage system that caters differently to various types of batteries because each of them has a different type of risk (e.g. fire hazard). A proper certification body to perform full system testing locally is needed. Efficacy of such safeguards is another metric to investigate. Singapore has the most stringent fire safety requirement such as 2-hr fire rating, no direct stacking of ESS, air-ventilation with sensors etc. Evolving fire safety requirements complicates information access, as coupled with difficulty in locating fire safety specifics on ESS in public domain. For niche installations such as a shipyard plant, it may be imperative to address reliability track record & safety from a product range perspective; as well as to pursue multiple statutory approval for installations & operations. Industry estate owners such as JTC should be roped in to jointly develop the criteria for determining which type of ESS is suitable for deployable for the said environmental sustainability. This includes looking further into R&D and design safer ways to house the energy (e.g. chemical aspects) and deploy it. Regulatory framework may be modified to provide an enabling function – for instance as how to extend beyond 600 MW with new statutory guidelines. Other aspects should include contingency process on managing chemicals (spills) etc. SCDF's fire safety requirement currently constraints ESS deployment to just ground level. More research should be done to overcome this if it is a technical constraint due to current fire suppression solutions.

Unique value of ESS providing fast response	Singapore lacks a specific reserve/regulation market with economically viable projects, beyond ad-hoc sandboxes, test-beds, and pilots. Current regulation with regards to capacity charges for customers connected to HT (High Tension) and above has also hugely impaired the economic viability of ESS projects in Singapore. For example, in the UK EFR programme to provide fast FR with minimum contract of 3 years can be developed to make ESS projects feasible. An observation made by the survey respondent indicates that the increased cost of implementation is attributable to kWh threshold per regulation barriers that further inhibits development of capabilities and its proliferation in say, the area of battery reusing/recycling. There is lack of route-to-market mechanism, especially for behind-the-meter deployment. The current regulation framework only permits behind-the-meter ESS to participate the power market / grid ancillary service from a "load" perspective, i.e. interruptible load, or demand response. Peak shaving will be useful ESS application for company with variable power demand load, but, currently, its application is hindered by SPPG existing metering regulation to treat ESS as generator. ESS is useful for power demand management if the electrical installation has many high power EV chargers.
Value stacking and aggregation of DERs for market participation	The current regulation and communications infrastructure need to be reviewed for development of emerging business models such as power generation aggregator / virtual power plant. Regulations that recognise and facilitate value stacking (multiple revenue streams) must be developed. Policies for wide scale deployment shall drive MNC involvement. Creating demand via policies (e.g. building must have secondary supply in the form of ESS) means that if buildings have a requirement for secondary power source, and if battery is to be used as replacement for say diesel generator sets, this would create the demand side across the island and hence help to pull/attract MNCs (as from the supply side) in. There is also an option to decentralise ESS at large load by means of deploying ESS to trial ancillary services. There are always pervasive needs for BESS to replace diesel generators as backup alternatives.
Need for incentivised roll-out of ESS in buildings	To zone an area of testing bedding site, buildings owners (residential, industrial and commercial) need to be incentivised to procure and obtain necessary battery solutions. One possible approach is infusing a certain metric (e.g. by so how many kWh/sqm or % kWh of daily consumption) into the Green Mark qualification through incentivisation to procure and obtain the battery solutions. The battery solution can easily take up two to three times the footprint of an equivalent transformer. This means for infrastructure, two to three times the amount of floor/land areas would be needed and consequently there would additional GFA incurred with driven-up costs. By increasing energy density for a certain unit of area, more energy can be designed to this fixed area. Conversely, ingenuous land optimisation may be enabled for a given energy capacity; there creates the opportunity to explore research to tighten the floor space.

Sustainability and Circular Economy	
Second-life applications for ESS	Battery systems may deteriorate with varying usage over time and result in decreased capacity available for storage. For instance, the Tuas mega port will be operating a large fleet of electric AGVs, each running on about 200kWh of lithium battery pack, with an average lifespan of 8 years. At the EOL for AGV batteries, the remaining battery capacity will be about 80%. Hence, several thousands of AGV battery packs will need to be replaced every 8-10 years. If such used battery packs

	can be recycled into second-life batteries for BESS applications, they can contribute significantly to the sustainability for Tuas port operation. Moving to the transportation scene, the Singapore Government has outlined its vision in the 2020 Budget to gradually phase out ICEs (Internal Combustion Engines) by 2040. On the infrastructure front, the Government shall work with private sector to step up the deployment of chargers in public car park with an interim target of 28,000 chargers from the current 1,600. This would drive high adoption for EV vehicles and charging facilities, and consequently high demand for ESS aligned solutions. Re-purposing of EV batteries for second-life usage for stationary applications serve to reduce waste. By 2030, additional battery cost (US$/kWh) reduction about 23% is proposed by potential areas like (i) recycling of battery materials (-6.1%), (ii) reuse/second-life (-5.3%) and (iii) vehicle to grid (-4.7%). In other cities, second-life batteries from EVs have been used as ESS for backup energy storage for shaving of peak power consumption, or for storage in less demanding ESS applications such for solar photovoltaic system. If the EV batteries can be recycled for BESS application in Singapore, it will also contribute significantly to Singapore environmental sustainability effort. However, performance, safety and maintenance cost associated to the conditions of these second-life batteries are key considerations for feasibility. World-wide, there is no global standards for repurposed batteries. Singapore, being nimbler for its size, can strive to become a first mover in this space, especially for regional markets. This is an emerging area and needed now. Some incentives or subsidies must be given to recycling company to spur sectoral growth, particularly in this sector, as it is at very immature stage.
ESS recycling ecosystem in tandem with increased ESS deployment	A solution for near or fully exhausted battery systems is required not only in the process development but also on an ecosystem management level. While this may be initially funded (or supported by government or environmental agencies), the long-term prospect of sustaining private sector interest shall befalls on ensuring profitability from the business operations.
Enabling V2G market to tap revitalised EV batteries	Greater EV adoption would lend to more opportunities. A V2G infrastructure would enable a new market for grid-based charging for EVs. The grid model needs to be established. As EVs become more common, the need of an ESS facility or buffer may be tapped to support V2G applications and fast charging. There is an opportunity to revitalise EV batteries into second-life applications. Some ESS battery vendors are fully engaged across all domains associated with energy storage through leadership roles and sponsorship of organisations such as the Energy Storage Association. In those dialogues, topics such as recycling and reusing to promote industry-wide solutions are covered. As the EV market continues in its rapid growth, both reuse and recycling across industries will be enabled and in effect define the deployment of energy storage.

Economics	
Incentives for renewable energy coupled with ESS deployment	Regulator or government may offer incentives to enable ESS adoption. Externally, green bonds may be issued to help infrastructure development. Such provisions for sectoral support are deemed as a perpetual undertaking. More importantly, the incentives shall ultimately lead to self-driven profitability by private enterprises, but with government-led projects as kick-starter initiatives.
Cost competitiveness of conventional generators vis-a-vis ESS	Financing and lack of commercial case pose the greatest challenge to choosing the right BESS solutions, constantly requiring economic benchmarking to pre-existing and conventional solutions but normalising for useful life and applications. Adding to the challenge is land scarcity, and henceforth deploying a BESS in Singapore and Australia would require a

	present-and-future cost analysis. On the other hand, policies such as mandatory stipulation for diesel generator set replacement by battery systems (e.g. Lithium-ion) can help push the deployment. Several considerations need to take place, foremostly to weigh in the choice of value-add via ground-up development or to simply 'buy-and –deploy'. High deployment costs inhibit proliferation of ESS solutions, and the life cycle costing may not make sense, if the renewable (e.g. solar PV) generation could be sold (fed) directly to the grid. On top of that, there is little clear regulatory guidelines on the type of ESS that could be acceptable by the authorities. Stringent fire safety requirements for equipment, coatings and storage also limit ESS deployment. Finding sufficient space to house ESS often pose a challenge in a land scarce Singapore. Other cost considerations include expenditure for expertise, logistics, fire risk prevention and initial investments. Installation costs also remain high for both front-of-the-meter and behind-the-meter deployment. EPC cost is expected to remain high and increasing, even though the ESS system may be reducing its cost through gradual price reduction in power electronics. ESS is relatively heavy and thereof making stacking options expensive. From a long-term perspective, the recurring OPEX, e.g. electrifying of batteries and O&M, are costs that companies need to have a clear grasp on. O&M electrification as well as integration to connect to different energy sources would contribute to this challenge largely because knowledge in this field is limited. The total costs need to be compared to conventional grid reinforcement for it to be economically viable. Natural gas price is still a cost-effective strategy for Singapore energy needs, given the current prices. However, should the price surges to a higher level, then the BESS approach could lower such gas consumption by providing some spinning reserve at the generation side. With the potential of carbon tax & rising IMO requirements, electrification through the development of renewable energy coupled with sufficient sized ESS might be another potential application. This can play a strong effort in the decarbonisation efforts for Singapore. With possible scenario of further energy market liberalisation, tariff might get more dynamic. Should that be the case, ESS will come in handy to allow end users to fully leverage and drive down energy costs. Ultimately, cost effectiveness must be weighed against a few parameters, mainly the service lifespan of the BESS solution but with due considerations given for reliability and safety. The lack of local use cases matters too to provide a preliminary proposition to switch.
Large scale EV adoption leading to drop in lithium prices	As EV vehicles become more popular by the end of the next decade, prevalent adoption of lithium as a raw material supply may facilitate higher economies of scale in its extraction, refining and manufacturing techniques, and subsequently a drop in lithium BESS prices. This may require further recycling of lithium to sustain demand.
Costs-down by progressive scaling up of ESS solutions using economies of scale	The costs of installation can be reduced through scaling up the market in Singapore to stimulate learning by doing. As potential contractors involved in ESS-related projects accumulate experience/ capabilities and engage in economies of scale leaned towards building up a sustainable ecosystem, mass production shall help to reduce total system costs.

Technology	
Lithium-ion as dominant technology	As covered in chapter 2, lithium-ion batteries are perceived to be the key battery technology for the next 3 to 5 years, being the most stable option for onshore deployment and given its fast charge and discharge speeds. While alternative options such as LFP and advancement in NMC batteries exist, these are still largely deployed at a R&D pace in lieu of stability and fire safety

	risks (such as liquid cooled battery modules). For such alternative media of storage, these would require some disruptive technological breakthrough to enable it to supplant lithium-ion batteries as a viable choice for ESS storage. The adoption of lithium is also accelerated by the e-mobility sector where vehicle electrification would strengthen research areas for the battery R&D. Its suitability for Singapore is unchallenged due to its high energy density over a small footprint as compared to prevailing alternatives. It is equally important to adopt an agnostic approach to battery/storage technology with platforms and controls that can easily adapt to the next technical evolution in the space. With battery manufacturers still continuously working to improve their formulation and manufacturing techniques, lithium-ion battery technology is still maturing and hence it will continue to be dominant in the short term. Material research in this field is rapid, improved versions of lithium-ion-based BESS can be available before 2025 and represents a potential R&D avenue to engage.
Strengthen cybersecurity of ESS	Every single distributed point is an entry point risk; and requires safeguards to eliminate hacking or sabotage. This necessitates a re-look into how ESS networks shall be protected from cyber-risks and unauthorised data access e.g. how the power grid can be crippled via V2X systems used for charging electrical bus fleets.
Advances in power electronics lead to lower lifecycle costs for ESS	Power electronics continues to gain technological and scale efficiencies from solar in addition to the emerging growth in ES deployments, major opportunities in design simplification for installation. The critical task is to maximise topline value of a system leveraging key trades such as degradation vs market participation (multiple cycles/day for example) in addition to overall life cycle cost reduction.
Opportunities to test-bed innovative ESS solutions	To cultivate and grow a vibrant ESS start-up ecosystem, new emerging technologies should be identified and provided access to test-bedding solutions. Flexible guidelines may be accorded to promote entrepreneurial innovation.
Alternative non lithium-based solutions for stationary ESS	The ESS industry players should note that while there is much research emphasis on lithium-ion, other form of batteries may require continual fore sighting to stay relevant. Stationary ESS could expand beyond lithium-ion to include hybrid solutions. This may include how storage integration can be built or integrated with alternative battery medium, such as fuel cells, zinc air, solid state batteries, or sulfur chemistries. Other electrode chemistries may include LMFP and TiO_2. Other battery technologies shall include Al-battery, sodium-ion, cyro-based energy (e.g. CAES, LAES), iron redox flow and flywheel that shall meet high energy, quick charging/discharging, stability for thermal and intermittency. While these technologies are still evolving, the enabled solution should factor in cost and ease of development before it becomes mainstream for adoption.

Manpower	
Demand for manpower trained in ESS to support increased ESS deployment	With ESS solutions in place, there must be home-grown manpower resource capability and competency to handle such securities. Regulators should consider nurturing a talent pool to meet scalability and global needs. Local talent development needs to be built factoring the life cycle of the ESS solutions, covering installation, commissioning, operating, maintenance, and decommissioning. Domain expertise across various domains is critical, especially for grid-to-grid integration, alternate source connectivity, regulation knowledge, and storage functions. Another aspect is growing a competent pool of research expertise for invention and innovation.

Land	
Alternative ESS deployment locations	Aside from tapping “real estate” such as co-located public housings, the following alternatives may be considered, namely (i) Marine or offshore deployment where the designed building needs to be self-sufficient outside the grid, and to be “living”. (ii) Floating ESS within the main load in lakes and reservoirs. While this is somewhat aspirational, ESS initiatives such as Keppel Offshore Marine Living Lab, are already tested over water than on land (e.g. next to solar floating grid). (iii) Stacking of ESS through rebuilding or modifying of existing infrastructure; such space utilisation can be maximised, subjected to safety and health considerations. (iv) Moving ESS to underground space would entail careful connection and steering clear of other utility grid and rail networks, regardless of its high cost. This also warrants an aligned rethink into centralised planning involving relevant regulators to design common service tunnels in densely populated areas. (v) Roof tops ESS deployment for solar PV panels can offer resolution for frequency regulation and space constraints. The challenge lies in the space already taken up by solar systems; there would not be much improvement to land requirement, even if one were to couple solar PV with a high energy density battery (i.e. battery only make up 5% of overall solar deployment footprint). That said, one in two HDB rooftops shall have solar panels installed by 2021 according to announcement made in Singapore International Energy Week 2019.
Need for place to test-bed ESS solutions (e.g. for start-ups)	To build a reliable and thriving industry for ESS solutions would require allotting a space for sandbox, digital twin or test-bedding for start-up technology and solutions.

Deliverables

Technology Innovation	
Optimise ESS performance in tropical climates	This entails development of R&D capabilities for optimising performance and design of BESS technology and systems for the tropics. This may include looking into summer-resilience battery cells or novel designs for sealed maintenance-free batteries.
Built-in safety and passive thermal management features	Safety management protocols can be rolled out by first involving potential research into scaling down battery sizes, or alternatively identifying features for fire suppression or embedding of thermal management components inside ESS. Safety requirement is paramount, and a definitive size (for scaling) must meet SCDF regulations. New localised standards conditioned to the Singapore context must be crafted out for safety management.
ESS integration with conventional generators	To improve efficiency of generator such as those for powering up cranes, ESS can be integrated with a smaller sized generator with dual connectivity to ESS as a source inlet, to provide sufficient peak power when hoisting up heavy loads. This can help to improve environment sustainability while minimising land footprint.
Ultra-safe battery chemistries	The criteria are capacity, performance stability and safety. To avail continual tracking of Lithium alternatives, innovative research for development of (i) ultra-safe lithium-ion battery with high energy and high power (e.g. using titanate anodes) and (ii) safe high energy lithium-ion battery, and all-solid-state battery with enhanced energy density should be undertaken and supported.
High performance battery chemistries	This requires a longer time horizon by investigating the advantages forthcoming from research into safe Na-ion battery, as well as lithium-sulfur battery with enhanced energy density. A requisite of potentially enhanced energy density must be established.
Hydrogen storage solutions	One way to improve sustainability is to integrate ESS with hydrogen fuel cells for EV charging, thus implementing a carbon-free option for EVs. Hydrogen storage solutions are already on the horizon, but paramount to its feasible deployment would be safety.

Business Models/Products & Services	
Solar-ESS integration	Other possible applications for BESS are to support integration of rooftop solar in Singapore power grid; supporting electricity supply to critical infrastructures (e.g. transport) where there are frequent faults. Alternative, this can support applications demanded by other business models.
Aggregation of DERs (including ESS) for market participation	Stack services through lifecycle of ESS can be offered to maximise usage and return of investment. The provision of BESS shall consider the framework design for energy arbitrage, fast frequency response (FFR); and both regulation & contingency frequency control ancillary services (FCAS) market registration. Regulation markets shall allow management of small-scale variability of load-versus-generation whereas contingency markets must respond to sudden outage of generators, loads or transmission lines. In the case of the latter, there is implied correction of active power (whether increasing or decreasing) which must be configurable to handle the local frequency. From an aggregator viewpoint, multiple ESS and other distributed energy resources can be aggregated to form a virtual power plant. At a business/household residential level, such virtual power plants shall enable greater diversity of generation supply for Singapore's power grid. Transmission and grid investment deferral are also key use cases for ESS. For provision of distributed energy storage, one survey respondent cited capacity to handle 50kW/138kWh.
Backup for additional revenue	ESS can be used as standalone backup generation system for infrastructure such as substations, communication towers, data centres etc. Other

stream and backup for critical services	considerations would be integrating of smaller scale compact BESS like carpark chargers. A point to note is that ESS is deployed as a tool for power demand management. It is mainly a storage system, not a replacement for generators, as BESS cannot generate energy on its own. ESS, however, when used as an emergency energy storage system during power failure, can replace the need for standby diesel generators.
ESS as a service / battery leasing framework	ESS is owned by service provider, thereupon relieving the service receiver (e.g. industry user or utility) from the financial burden and other risks. Local players such as Singapore Power or SembCorp Industries may fulfil the role of end-to-end energy provider for behind-the-meter districts, which ESS is a part of. Energy as a service shall include provision of O&M services to the asset owner, regardless of its deployment for solar or independently for consumers. Battery leasing can be offered as a viable business offering. While it is not novel for most private markets, a "bank" system can be set up to offer battery leasing, repurposing of EV batteries, battery power purchase agreements (e.g. consolidated battery banks by a company to sell excess power back to the grid or local residents). The market shall extend to large-scale batteries for third-party market buyers. Other forms under the leasing model would be swappable batteries for lower power consumption applications, as well as renewable generation such as solar PV coupling. In view of economic of scale, one could procure the service centrally and deploy the ESS over respective solar generation initiative (or site). Various financial arrangements for BESS system procurement can be proposed based on the customer requirements, and 10 years leasing model is very common. The framework for managing and leasing of spare ESS capacity should allow cross-sharing, especially on competition in the generation markets.
Support diesel generators replacement and peak shaving	Support may be provided to encourage diesel generators replacement, by providing sustained delivery to and from Singapore's solar strategy through intelligent peak shaving measures.
ESS to meet transient needs	Part of the ESS solution roll-out shall cater to working with challenging brownfield sites, by ensuring the industry does not build too much localised energy infrastructure catered to transient requirements. An example is vehicle electrification. With ICE vehicles progressively phased out, there would be rampant growth in the EV chargers in Singapore and this will put pressure on Singapore's distribution network such as in HDB estates, condominiums, office buildings etc. A BESS system can solve this problem of peak load shaving by supporting the charging of EVs for private and bus fleets. By making ESS solution or sub-systems easily deployable, this would drive electrification targets by relieving the need to use fixed chargers. The infrastructure shall be connected to Singapore's distribution network such as HDB estates, condominiums, industrial or office buildings. Such demands require a robust grid network resilience to manage variability in demands, and the BESS system can solve this problem of peak load.

Infrastructure and Capabilities	
Domestic competencies to maintain, test, inspect and certify ESS batteries	As ESS technology becomes widely accepted in Singapore, safety / maintenance of the ESS battery will come to the fore. It is imperative that domestic capabilities be developed to realise such operations. This is about creating a value chain for battery systems and sub-systems in the field of testing, inspection, and certification. An ESS-associated platform or centre can be set up to provide support into promotion of ESS products and services by local companies. The centre shall oversee aspects pertaining to R&D, manufacturing, TIC, system integration, enabling of shared resources framework, and even curriculum development for IHLs. This "one-stop shop"

	shall also cover qualifying second-life applications for the expired systems or battery modules and requires reframing the lifecycle of batteries, reuse assessment, systematic provision of management guidelines for handling & disposing, and collaborating with recycling partners. Ultimately, the country can create a regional converging destination for high competency in lithium-ion battery recycling and reusing. To sustain Singapore as a go-to hub for BESS solutions require a clear demonstration for successful ESS delivery that considers factors such as management of homologation standards, talent expertise development, supply chain setup with manufacturing capabilities, as well as reliability grading with minimal dynamic tariffs. This requires a pitch into business case to inspire entrepreneurship in ESS. A further extension to internationalisation is for collaborative tie-ups in foreign markets through local presence and participation and representation. System integration, testing & certification can be turned into Singapore's strengths, by taking advantage of its strategic location and branding of trust to perform due diligence and more notably, system integration and TIC (Test, Inspection & Certification) functions.
Communication of AGC Signals	This concerns leveraging alternative communication technologies to transmit PSOs AGC signals, as well as addressing CCGT equipped with ESS to improve efficiency.
Offshore floating ESS platforms	Designing and putting ESS avenues near shipyard plants and offshore-based product range would provide a pivoting role to support both efficient dispatch of energy and improve the operations of port/offshore operations (e.g. grid resilience). This would drive hybrid vessel designs to aid in decarbonisation of harbour waters, including LNG/battery vessels that fulfil zero emission on the part of ports and harbourcrafts. Other aspects include renewable energy deployment such as floating solar PV platforms or wave energy generation in the maritime areas.
Common pilot line facility to prototype innovative ESS solutions	Several ideas on lithium-ion battery, as well as Na-ion battery have emerged out of academic institutions and Research Institutions in Singapore in the form of IP/patents. These ideas are well presented in international conferences and well recognised by international community. However, those ideas do not move forward to commercial phase unless they are translated into prototype at pack level and deployed for real world applications. Few institutions have prototype lines to developing few cells per batch which are insufficient to develop higher capacity packs (3-5 kWh). What is lacking is a pilot line facility to fabricate large format commercial type cells (20-30 Ah) for pack development within Singapore. NUS has reported great difficulties in developing packs using non-flammable Na-ion cell technology. Cross-national collaborations did not help, and the IP details were not retained. It would be beneficial if a common pilot line facility can be set up locally to cater to battery research in Singapore in fabricating large format cells and developing packs (3-5kWh) for test-bed.
One-stop portal on ESS information	This pertains to a creation of accessible knowledge-based repository for storing demonstrated used cases for industry stakeholders to infer to or be made aware of. Example of such knowledge may include avenues for services/products directory, blacklisting, advisory, projects and standards library for operation consultancy. The portal shall include promoting consumer awareness. This deals with changing the mind-set for end users and market adopters for using ESS products/services within the shared environment. In this aspect, consumer education at the onset may need regulations to push the start/encouragement in adopting second-life batteries. While the overarching objective is to reuse and recycle, prosumers need to understand benefits of recycling, how to

	process them and obtain monetary benefits in the form of back selling or repurposing.
Energy trading platform	ESS is to be coupled with an energy trading platform to allow energy trading. For instance, EV or hybrid vehicle is regarded as a consumer load today, but EVs can become supply source if such a platform becomes available to facilitate energy sell-back to the grid (e.g. peer-to-peer trading). One may not drive the vehicle but can utilise it to storage and sell energy. The key players need to have that resource (as in form of stored energy storage). In the far future, portable battery source would be accessible everywhere.
Tertiary education and training programme to develop manpower capabilities	Technical skills are required not only to design, but also to install, operate, maintain, and even dispose the developed ESS solutions. As this field of ESS (including second-life knowledge) is relatively new in Singapore, operators or even end users may need to import such know-how and proliferate internally within the energy sector.
Raise awareness of the value proposition of ESS among financial institutions	Awareness regarding the technology and risks shall be imparted to financiers or insurance companies to allow these funding bodies to support the industry partners or companies to grow at its infancy. This entails provision of the said technology to the lenders to help understand plausible business model and even capital recovery. For example, battery module cost is certainly the main driving factor of overall cost, other aspects such as costing of power electronics and other system components will also take some portion of it. Such transparency shall encourage bankability of ESS solution and making the market more accessible for newcomers
Build / develop local capabilities for EMS	The essence of ESS system is ultimately its Energy Management System (EMS), comprising its software algorithm portion. This represents the brain of the entire system, where battery module/subsystems and balance of industry plant can be developed. Local competency in this area is needed to confer a competitive edge through optimisation of the control and communication of battery module/subsystems, and the balance of the system/plant.
Build up marine charging infrastructure	Standardisation is needed locally to promote ESS adoption in the marine sector. This includes establishing the requisites for built-up of the charging ESS in the marine segment. The infrastructure for marine deployment shall include consideration of the source generator (e.g. solar PV floating platform, wave energy harvesting, etc.) and its interconnectivity and delivery to the storage entity. Proximity to water sources provide instant access to cooling sources.

Policies and Regulations	
Recognise ESS' ability to provide fast frequency response	Policy to incentivise battery ESS for grid ancillary service on its fast response over conventional generators. Regulation support may be provided to allow behind-the-meter ESS solution vendors and their respective contractors to participate into various wholesales and grid ancillary services.
Structure capacity market with longer term (>1 year) Capacity Supply Obligation contracts to anchor investment	The upcoming capacity market provides an opportunity to not only secure greater CCGT investment, but if structured well, can also provide the right investment signal for ESS to be deployed at large scale. In particular, the security of longer-term contracts with agreed prices (instead of typical 1-year Capacity Supply Obligation contracts) to underpin investment. This is crucial for many developers that are seeking financing. It should be noted that currently, multi-year contracts are only available for H-Class CCGTs.

Technology & Resources

Technical Studies	
Monitor Advances in Hybrid lithium-ion and supercapacitor ESS	As stated in chapter 2, lithium-ion batteries will be prevailing choice for ESS solution enabler. For grid storage purpose, hybrid lithium-ion battery and capacitor system may be an area of interest as it combines the advantages of lithium-batteries as well as capacitors. Technology in this area is quite mature and may become mainstream in 5 years' time.
Monitor Advances in Flywheel	Flywheel technology are increasingly adopted for frequency regulation applications. These are all in overseas but none in Singapore. A mid-term check on this technology is planned to see if the disadvantages (such as short discharge times, high parasitic and intrinsic losses) surrounding this solution have been overcome to be viable for the longer term.
Monitor Advances in CAES & hydrogen fuel cells	Review into compressed-air energy storage & hydrogen fuel cells present an interesting case through hydrogen economy. For the former, CAES systems efficiency presents a strong challenge and is currently not applicable for small-scale residential usage. Another limitation is storage, typically as practiced in underground steel tank containers. The compounding factor is a pervasive effort require to effect individual component optimisation, considering that CAES is a complex system with mixed components and processes from mechanical, electrical, and thermal engineering. Hydrogen fuel cells present a renewable solution to the energy intermittency problem consider that it is tenably based on water electrolysis technology. Like CAES, the challenge is safety and storage scalability. A pervasive scan in closing such gaps for these storage alternatives shall be considered. This is a low priority.
Monitor Advances in Hydrogen (as a tech watch)	Different ESS technologies such as different chemistry ESS, power to gas, flow battery, compressed / liquefy air ESS for various applications should be explored, if the technology has improved in various performance parameters. Lithium should not be looked as the sole option. As highlighted in the earlier point, H_2 can be a potentially disruptive technology to park under the R&D radar. While this is not what Singapore should implement, it should be on industry tech-watch because there may be a potential that the gas become importable. This is an ongoing endeavour as a low priority.
Monitor Advances in Use of graphene in batteries	Graphene offers an appreciable option, but electrode degradation is a concern. A "stock take" review into reviewing capacitor cell's graphene electrodes performance may be done in medium term to assess its viability for urban deployment (versus alternatives). It is believed that by employing innovative manufacturing processes and material optimisation, the initially set objectives for demonstrating clear performance advantages over existing commercially available ones were designed and developed.
Monitor Advances in Cryo-Energy (LAES) Storage	There are a few field demonstrations covering LAES, aside from back-up energy storage application - it can be used to manage renewable energy and give new applications-insights. Current efficiencies are less (about 25%) unless coupled with low grade cold store that would improve efficiency up to 50%. Using waste heat sources for evaporation can push efficiency to 70%. Globally 1 or 2 pilot demonstrations have been done so far, so more used cases are warranted.
Monitor Advances in Aluminium battery (10-20 years)	Al-based battery may be worth a relook, or at least be kept under the radar for technological fore sighting. While there is little traction compared to lithium-based solutions, future breakthrough may provide renewed consideration over the long term, i.e. 10 to 20 years range.
Monitor Advances in High energy density and stable redox flow battery, iron flow battery	One survey respondent shared that other battery technology to test out will include iron flow batteries. A good time horizon from test-bedding, troubleshooting, regulation, market introduction to mainstream adoption (that makes financial sense from a pure commercial angle) will take at least 3 years.
Conduct technology scouting studies for ESS	A technology feasibility study can be conducted together with EV manufacturers and ESS developers to ascertain benefits and effectiveness of re-deploying EV battery cell for some specific application in ESS, e.g.

	solar/wind ESS or solar PV plus ESS (including those which requires 0.5C or below). Theoretically, it could bring costs down, but this will require data collection over the operational lifespan of batteries to support such claims.
Commission study into economics of ESS	This is to address mainly financing and the lack of commercial cases. While the procurement model is most applicable to ensure performance stability and consistency, the power electronics, CAPEX, and life cycle costs for ESS ownership must be accounted as well to make full economic sense. The study should include accurate Life Cycle Analysis (LCA) and Techno-Economic Analysis (TEA) with provisions, as well as to provide cost assurance and visibility for certain initiatives such as delivery of varying business model (e.g. Energy as a Service) to the energy market.
Study funding models and cost-benefit analysis	This concerns initiating market research to study commercial used cases of different funding models adopted by mature markets, and to make sense of cost-benefit analysis for decentralised ESS.
Establish market size / opportunity	While it is desirable to a range of business models to suit market needs, it is advisable to establish an optimum market size that will allow large-scale ESS to be building blocks for district and building level deployment. On the other hand, the smallest scale can be envisaged as a battery swap, with the big end supplying energy from a grid. There are always niche markets and there should be an optimum size to determine the building blocks for the business model. One can do it at an island, or district /precinct levels or at a building level. Export considerations should also be given for internationalised deployment of Singapore-developed solutions – in lieu of geographical space and legislative differences.
Conduct survey on commercial feasibility of battery leasing	A clearer commercial feasibility on ESS for leasing is the pre-requisite of these new business models. Over avenues such as hire-purchase agreements or even second-life batteries are to be considered. The survey shall capture and recommend best framework or practices to adopt as used case references.
Support growth of solution providers for BMS, EMS, UPS and underwater smart power etc.	Current vendors and system integrators can come up with designs and assemble battery energy storage systems possessing their unique and proprietary battery management for energy management system and thermal management system. While designs can be highly flexible, agreement among battery cell manufacturer and other system component vendors shall be agnostic and easily transferable, especially for unique deployment scenarios such UPS, underwater or deep-water smart power systems or systems with active balancing features.
Market study for Design, Build, Operate and Maintain (DBOM) concept for long term projects	One proposed model for utility enterprises will be DBOM, i.e. Design, Build, Operate and Maintain. This ensures that the company's long-term commitment to the project, but enabling services for testing and certification, system integration and R&D (in order of priority).
Facilitate market study for local partner for overseas projects	The biggest challenge for export opportunities is limited access to information on potential overseas projects. Regional alliances among energy stakeholders may be formed with the help from relevant authorities (e.g. ESG, EDB or EMA) by connecting Singapore firms with local players in targeted countries. This could take several forms, ranging mission study fact-finding to establish collaborative joint ventures for the targeted sector. Conversely, Singapore can be a hub of technology development, with some initial design can be done here, but with the manufacture and testing conducted overseas. If a local vendor wants to deploy globally, it should know how to get the necessary information and access to resources.
Conduct market survey/study of second-life battery applications for specs & safety	If the cost of deployment of second-life batteries are much cheaper with the same guaranteed performance and lower carbon footprint, it would be worth considering for deployment in replacement of brand-new batteries. On top of that, safety aspects as well as clarity on regulatory requirements would need to be crafted for the repurposing of the EV batteries.

	Specifications such as defining fewer intensive applications using second-life batteries can be supported as part and parcel of R&D work. Of which, the key considerations shall be: (i) that the performance of the batteries meets the application requirement and it does not exceed the batteries design limit; (ii) it is cost effective in order to impose a premium over its performance and remaining life and (iii) fire safety is not compromised. Market insights into business opportunities may be provided so that companies will be keen to enter this "repurposed battery" market.
Conduct regular surveys with users, vendors and researchers	This is perpetual undertaking to periodically conduct survey scans with key energy market stakeholders to understand the unique challenges associated with the emerging renewable-based grid(s). By constantly engaging customers, academia and regional players or regulators, practiced knowledge can serve as an invaluable asset in delivering the sectoral depth and breadth across the worldwide grid systems.
Conduct survey/study on business models e.g. volume available for battery recycling industries, collaborative recycling setup, import from ASEAN, etc.	Government bodies may provide regional and global market insights framed towards business opportunities so that companies will be keen to enter this market as it requires significant investment. Partaking into trade missions and exhibitions would help to establishing international networks of collaboration to grow bilateral ecosystems. This shall foster understanding into commercial and environmental factors of the ecosystem set-up.

R&D	
Conduct tech analysis for sizing optimisation for BESS	Optimising the size of BESS system is one important aspect for potential cost reduction. If the BESS size is optimised and benchmarked, the revenues are maximised and results in better ROI. In addition, value stacking by innovation is another way to extract maximum value from the investment in BESS. Many tools exist for this and the regulator shall assess which to adopt.
Invest in LFP as the key lithium-ion technology for short term deployment	On a shorter horizon, there is no doubt that LFP would have deeper penetration to the large-scale energy storage application as compared to non-Lithium solutions. LFP has better safety, longer life span and lower cost than NMC despite its relatively low energy density (note for stationary energy storage, it is not the most important factor). For large-scale energy storage, the three indicators in the priority sequence of safety, cost and performance should be considered. This is different from energy storage for portable electronics, where performance is deemed more important, and cost is not the first thing to consider. Singapore must consider alternative technology in the long run given the limited lithium abundance and the inherent safety concern. Further tech scan may include redox flow batteries using "dirt" cheap materials and aqueous electrolytes.
Research into new materials and techniques for lithium-ion, lithium-sulfur, anode-free and solid-state batteries	There is a tremendous market for energy storage materials. There exists a huge demand for increased capacity and better safety. Hence, it would be critical to develop solid-state or quasi-solid-state batteries. Such research scope shall cover lithium-sulfur and lithium-solid state batteries with experimentation on new materials or alloys, as well as specific solid-state technologies. Other considerations include looking into safety and eco-friendly aspects.
Better fire protection solutions (coatings, aerogel, etc.) for containerised energy storage	Further research may require further study into alternative materials to improve safety and fire protection. Enhancing fire resistance or thermal insulation properties of coating, blankets, mat, board or sheet forms is paramount for passive fire protection; thermal insulation for building containers would help to prevent spread of fires as they can be sufficiently contained in a thermal runaway situation. One such example is aerogel powder, i.e. SiO_2 material which has open cell multi-porous structure and superhydrophobic surface. Due to its unique physical and chemical characteristics, it is used as an additive to enhance

	insulation / heat resistance / fire resistance / water resistance of the end-product. This can be applied in paints, blankets or sheet forms for fire suppressor equipment.
Increased R&D focus on low carbon embodiment battery – less material	This research topic shall investigate the use of lesser material (such as low carbon embodied storage material) for energy storage purposes.
Advance safe and high-density sodium ion	Research may be focused on developing safe lithium-ion battery (high energy and high power) and non-flammable Na-ion battery. The research emphasis herewith is safety; while developed commercial type Na-ion cells as well as lithium-ion cells has been around in the past decade, the safety gap - as compared to conventional storage solutions - needs to be reduced or closed.
R&D to increase density and reduce cost for flow batteries	Beyond lithium-ion, one should look at sodium-ion (Na-ion) and flow batteries whose current drawback lower energy density (thereupon requires a larger footprint). However, it may be worthwhile to investigate such alternative assuming a decade is required for maturing of these technologies.
Data collection from test-bed of reuse of EV batteries	One survey respondent indicated that feasibility studies with EV manufacturers and ESS developers may require to use EV battery cells for some specific application in ESS, e.g. wind plus ESS or solar PV plus ESS which requires 0.5C or below environment. Theoretically, this would bring costs down but needs to be validated by experimental data collection over the operational lifespan of batteries.
Research/test-beds for system level stack services	Smart ESS may entail running a set of grid services such as frequency regulation, distribution investment deferral and energy arbitrage. Depending on different demand scenarios and dispatch schedules, revenue streams of the stacked services are aggregated and compared for efficiency and costs (both capital and operating) over the ESS system level life cycle.
Use simulation tools to simulate turn-on events	The simulation of how the battery would behave in an ESS system or sub-system could be done in a software simulation. If all the parameters in the model in the software has been done correctly then the result should be enough to give some indication of its performance prior to installation. As akin to a digital twin, this may apply to simulation of foreign systems in local systems with adjusted parameters (e.g. climate, altitude, etc.).
Isolated grid like EPGC for testing prior to turn on	ESS solution developers may leverage on energy research entities like EPGC (Experimental Power Grid Centre) to use isolated grids for testing prior to turning on.
Marine test-bedding	An ESS solution may be developed or investigated for isolation distancing (for safety) or renewable (wave power generation) purposes. In this context, permission needs to be sought with defined zoning safeguards to allow feasibility study evaluations of ESS under the marine setting.
R&D projects and real-life demonstration of alternative transmission of AGC signals to control ESS	To fully utilise the fast response feature of ESS systems, there is a need to have real time remote transmission of AGC signals to control ESS system. So, R&D projects followed by real life test-bedding of the same is required to make it a reality, as this will increase ESS revenues and hence more adoption.
Reduce O&M by reducing cooling, monitoring and maintenance costs	A better integration of ESS with the solar PV panel would require choosing the ESS technology that needs less maintenance (such as cooling, rigorous monitoring, etc.) that would effectively reduce the levelised cost. This is challenging because differing battery configuration and chemistries offered by various vendors. Considering the long lifetime usage for large-scale ESS solutions, research investigation shall investigate maintenance technology in the areas for cooling (for thermal management), monitoring and maintenance (preventive or predictive). Ultimately, the development of battery cell capacity along with battery maintenance technology, would also bring down the overall cost of ESS in terms of logistics / storage / life cycle.

Customisation for BMS and data analytics	The BMS software must be highly customisable to meet varying needs, and the data be systems-compatible; the data shall be format-friendly to be deployable for analytics and optimisation. This should be preceded by regulator soliciting the proper standards and ensuring what data to collect and manage at a holistically integral level.
R&D projects and real-life demonstration of CCGT ESS hybrid installation	Co-locating battery BESS with CCGT can further enhance startup of CCGTs through faster services such as FFR, as well as to provide longer running duration services to merit black cold start events. The research may also cover asset optimisation looking into flexible and modular design in operating mode.
Advancing R&D on recycling through tech, non-lithium with cross-cutting apps	Industry should be prepared for influx of used EV batteries starting from 2030, i.e. research and standards development should begin by 2025. This may require collaboration with industry partners, or the creation of industry stakeholders locally.
EV chargers and testing products	There is a need to develop products and technologies in the space of V2G (such as bidirectional charging) technologies, charger design, charging supply etc. There also need to be local testing capabilities to test EV chargers.

Talent Development and Awareness	
Incorporate ESS technology as part of IHL curricula	As Singapore develops its ESS sector, relevant skillsets and expertise need to be groom for various activities such as research, engineering, operation, and management of ESS infrastructure and systems. This would involve creation of tertiary educational curriculum with various IHLs to build a steady pool of local talent. Universities or trade schools need to create courses and certifications for members of the workforce to become ESS experts. This could be done in collaboration with large ESS vendors and colleges abroad. It is important to include relevant power electronics (e.g. DC-DC and DC-AC converters) syllabi as part of IHL curriculum.
Train qualified personnel for Design, Build, Operate and Maintain (DBOM) ESS systems to improve SG's ESS value chain	A clear and standardised guideline is needed for ESS deployment, and for near term, it is essential to identify the technology to go for. SOPs crafting and training procedures for system level testing is a complex process and that early identification for the ESS solution (battery, modules, systems) would require Singapore to build its manpower capabilities with first-hand information. Another talent skillset development is for second-life application. Furthermore, awareness may be infused to end users, with targeted consumer understanding of ESS solutions and applications.

Regulatory	
Establish local homologation standards	Local homologation standards shall recognise approval of authorised bodies for rules and guidelines collectively or independently crafted by government, academic or professional body. These rules shall require ESS products to be in full compliance with relevant Singapore standards. On the standards front, one should explore safe battery chemistries, safer containment, cooling systems, as well as potential leeway in policies to facilitate such R&D. SCDF have a current requirement that the placement of the battery has to be at the lower or floor level where fire trucks are able to reach. It may not necessarily demand the fire truck to be located at higher levels, but it is a matter of fire suppression systems. It is all about work jointly with safety regulators such as SCDF through various approaches, such as a joint consultancy effort to lead to/from R&D space in terms of looking into deployment. Containerised ESS is treated as permanent infrastructure and regulatory approval from various government agencies (e.g. BCA / URA / PUB / NEA / SCDF / LTA / NParks) is compulsory, thereby making the process tedious and

	costly. If the Singapore Government could simplify the regulation process, the ESS cost could be greatly reduced.
Develop best practices for ESS integration to grid	Singapore pays extra attention on safety, which is important for it to become a “go-to” hub for system-level ESS testing & certification. To do this, leveraging on the renowned international safety & certification companies (e.g. UL) would be an efficient way for Singapore to catch up and build the system up to the local or even regionalised standards. The developed technical framework should be accompanied by regular inspections and system-level reinforcements. Ideally, Singapore should implement a "best practice guideline", either from its own or based on other countries' synergised experiences.
Regulatory changes to recognise fast response of ESS	ESS systems have very fast response compared to other conventional sources like gas turbine or diesel generators. If regulatory changes are brought in to recognise this feature it will make ESS adoption attractive.
Set out regulatory framework for ESS leasing with solar	For large scale batteries, asset owners can lease out excess battery capacities to third parties for market participation. This requires building up the infrastructural framework to stipulate guidelines and procedures such as solar coupling or delivery/billing processes for selling to grid.
Enabling ESS to participate in electricity market.	With the energy trading platform put in place, what follows shall be legal guidelines requiring the framing of specifications and out-of-bound markers to substantiate the market, whilst assuring with a certain level of confidence for targeted long-term revenue generation. This includes predefining the types of suitable market products for supporting favourable conditions which can enable ESS to trade in electricity markets. From the perspective of a project investor, a suitable long-term revenue certainty (for contracts) for ESS would greatly improve bankability of projects.
Create standards for second-life like UL1974 world’s first safety standard for repurposed battery	World-wide, there is little global standards for repurposed batteries, Singapore, given its strength for nimbleness and response, can strive to be a first mover in this space. To avoid re-inventing the wheel, existing standards like UL 1974 may be adopted to further shorten the development time. In developing a new standard with UL1974 as a reference, Singapore can influence international standards in this space. The regional markets are an emerging area for engagement. Regulator and standard holders may collaborate to work towards standards creation for retired battery evaluation and repurposing. Developing a local standard that would allow the safe deployment of retired batteries within Singapore. The standards shall also allow Singapore to develop a healthy ESS ecosystem driven by both economics and safety; with the former encouraging volume of project undertakings thereupon leading to increased entrepreneurship, and the latter concerning test and certification. Such standards should serve to promote environmental protection for both land and maritime applications. Regulators may also consult with members of the Singapore Battery Consortium for advisory and standards development for repurposing of batteries.
Design incentives/penalty for proper disposal of batteries	Safety is paramount consideration for ESS deployment, but to actively ensure quality assurance for exhausted or repurposed batteries, incentives or even penalties are needed to force the reusing or recycling of batteries, and prevent them from ending up in a landfill somewhere overseas - e.g. restrictions on exporting depleted / used batteries
Implement COE-like regulation policies to track repurposed batteries	One idea is to implement somewhat a COE-like policy to police and track usage of repurposed batteries. The first key initiative will be to regulate the first-useful-lifespan of batteries (particularly large-scale ones) and make that traceable. The idea here is akin to the Singapore’s COE model for cars - 1st 10 years of COE and thereafter allowing users to renew COE for lowered costs. This 'frames' the way people look at cars, and similarly how end users would view and deploy these batteries.

Regulatory changes to remove double charging of network and balance charges etc.	Current regulations charge the network and balance charges etc. onto ESS systems twice once they get charged from grid and once when they discharge to grid. Such costs may increase the operating costs of ESS, and appropriate regulatory changes may help.
Outline cybersecurity as regulatory requirements	It is not feasible to have the whole ESS system tested in the lab due to its size and weight. However, site inspection or field evaluation can be done to ensure the interoperability of the system between itself and external systems (e.g. solar coupling). Aside from ensuring data compatibility across differing vendors' ESS systems, cybersecurity protocols must be considered on how data is to be managed. This may include initiatives such as hack-proofing on a digital twin for robustness monitoring.
Allow flexibility on system test location (manufacturers' facilities or on-site)	Existing system level standard such as IEC 62619, UL9540 and UL9540A already provides assurances for safety. Furthermore, site installation should also adhere to NFPA 855 recommendations. System-level ESS testing is a common industry practice prior to turning on and is usually part of developers and investors requirements. For it to be cost effective, any requirements or rules and regulations should allow flexibility on the location of full system tests (for it to be carried out in the manufacturers facility or on site).
Implement PPP model where costs are co-shared by government	This is a PPP model where the cost is partly borne the government. Procurement of raw material and construction costs with respect to explicit enabling criteria demanded by legislative must be met by ESS solution providers.
Activation of contingency reserves through alternative communications	Solutions should be developed in order to overcome limitations in communications infrastructure – such as wireless communications.
Reconcile regulatory differences between local and regional markets	Regulations of local/regional markets differ from one another and local regulator must establish which framework to adopt or even tweak to fit Singapore ESS sectoral needs. Furthermore, there must be a measured effort to ensure that regulations dictating local designs are compatible to operate in overseas export markets.

Ecosystems – Infrastructure and Systems	
Set up local testing capabilities	Singapore shall build a Safety Test and Certification Centre if it is to move forward to set up more cell production facilities locally. Capabilities in testing methods must be draft or created through consultative engagement of experts in initial trials, with its operations framed towards system integration to applications with business case in the region. A fast-track approach is to leverage on overseas vendors experience and to curate relevant context applicable to the tropics. While it may be inevitable that problems may occur at some point is when the system first comes online to the grid, the build-up of local test and certifying capabilities should provide solutions for workarounds and recovery. The Centre may be equipped with due diligence experts and test advisory consultants.
Engage solution vendors for developing local ESS systems-level integration capabilities	Singapore has a well-established network of systems-level integrator serving other industry clusters and sectors. Such supply chain can be drawn from these resource points to enable capability building in the areas of BESS, control systems, SCADA, power conversion, energy & thermal management, remote monitoring, and even cloud-based control systems. Aside from these, a full range of utility scale energy storage technologies for stand-alone or hybrid (e.g. wind, solar and gas driven) generators or even dispatchable grids may be tapped upon from solution vendors. Alternatively, explicit Service Level Agreements may be offered to import solutions and services (such as 24-7 remote support) to help run BESS systems. Prior to engaging such solution vendors, multiple market study may be conducted to compare and benchmark viable options or alternatives. A

	general pre-requisite is to underpin the suitable technology solution type to adopt and create specifications to identify viable candidates for the project works.
One-stop portal hub	The Government or regulator can investigate creating a one-stop hub providing multi-faceted synergies to support the local ESS ecosystem). Such hub may take the form an e-platform or centre for housing databases (including used cases) for past project, a repository provides technical knowledge sharing in regulatory and technical specifications, requirements, and standards. Apart from helping to enabling education (through workshops) to upskill the sector, it shall also house a validated directory to linking ESS-related vendors, customers and suppliers together. Lastly, such a hub shall also provide advisory and assistance (especially for systems integration) to end users.
Build joint R&D pilot line facility for all local researchers to fabricate Large format commercial type cells to develop battery packs	To meet test-bedding needs, a joint pilot line may be created exclusively to cater for research working to optimise cell fabrication just prior to cell production. Due consideration is given for capacity underpinning, such as 2-5 GWh cell production facility for lithium-ion battery and Na-ion battery. This should lead to viable commercially compliant development of battery packs.
Develop local recycling ecosystem – Engage manufacturers, suppliers, researchers	An issue perceived by solution vendors is that while Singapore is an excellent place to conduct ESS businesses, it may not be the destination for building battery recycling plants. As the battery recycling (especially for spent LFP and other lithium-ion-based batteries) involves multiple steps from mechanical crushing to chemical treatment, the processes would require entirely different expertise, and thereof a consortium for cross-country collaboration would be useful. This ensures not only a local thriving sector but with an assured manufacturing capability that can be supported overseas, if not locally. Ultimately, the local ecosystem should roll strategies for the ESS solutions on the manufacturing activities. This covers R&D, manufacturing, testing & certification, and system integration. Furthermore, continuous promotion of local companies would improve market penetration to undeveloped regions.
Multiple ESS and DER aggregation to form virtual power Plant(s)	As an aggregator, multiple ESS and other distributed energy resources can be aggregated to form a virtual power plant. This project may be consigned to a grouped entity (e.g. consortia) to manage and work upon especially if the systems are non-generic.
EV infrastructure development	With EV industry is set to grow in future and impetus by Singapore government to go zero on ICE, V2G products such as EV chargers need to be bi-directionally linked to the ESS systems. Furthermore, local testing capabilities need to be developed to test these chargers. This project shall entail collaboration with the land transport regulator to deliver cost-effective V2G solution(s).
Provide opportunity to test-Bed solutions	To encourage the development and test-bedding of new technologies in Smart Grid, ESS and VPP, regulators can take a lead approach to support innovative ideas/POC schemes that may deviate from existing regulations, which may not be fully relevant to new emerging technologies. These may include sandboxing trials of VPP concepts such as sharing of power capacity among users in the same vicinities. If the POC is successful, it could help Singapore to better optimise power demand between different Smart Grids within the same vicinity/region (an extension of micro-grid concept), thereby fulfilling more efficient use of national electrical infrastructure assets

Ecosystems – Partnerships	
Collaborate and develop ESS standards and advisory	In the areas of standards development, advisor services, testing-inspection-certification, a partnership framework can be established as one focal area to build up a one-stop non-profit hub for standards sharing, audit, validation & verification, knowledge depository (such as various UL document standards), shared test facility, safe research, public education & training and business initiatives (such as project, risk management, financing and partnership advisory). This would require a stock-take on earmarking essential and complementary standards to implement, and pairing of full-suite products or services that would adhere to international standards for all ESS battery options (e.g. lead acid, lithium-ion, redox flow battery etc.)
Collaborate with manufacturers & institutions on testing and certification	Vendors or agencies involving test, inspection and certification can be roped in to enable wider cooperation with battery manufacturers. This cover works on battery safety related technology, or even sharing and licensing of test methodologies and processes. A consortium may be formed to take up ownership for intra-industry ESS development.
Collaborate with public agencies (e.g. JTC, PUB, etc.) for ESS deployment and ecosystem development	Multi-agency (as relevant stakeholder) involvement for ESS deployment in various avenues must be considered. This includes (while not exhaustive): (i) Deployment of ESS in JTC industrial or commercial estates for critical and backup application. ESS (used in the form as UPS) is often deployed within JTC buildings and estates to support critical building systems such as building management system (BMS) and security systems. JTC would install the UPS to ensure the continual operation of such critical systems (e.g. Lifts, CCTV, chiller plant controls, etc.) during any power trip or shortage situations, mainly for backup purpose. (ii) Offshore-based platform where one can work with PUB or other marine-relevant agencies to install ESS to couple with floating solar PV. This shall be driven from a performance delivery and O&M standpoint. (iii) Underground co-location of ESS where technical agencies (such as PUB, SCDF, URA or HDB, etc.) must review the requirements to support a feasible cost-effective underground deployment. (iv) Integration to EV infrastructure such as HDB carpark chargers.
Collaborate with SCDF to Update Fire Safety Regulations	The lead authority (EMA or other agency involved) shall have closer collaboration with SCDF for new projects and development of appropriate regulations.
Collaborate with Industry to Develop Local Recycling Value Chain	From the company point of view, partnership with regulator-endorsed recycling company would be a good start. The challenge is that local battery recycling firms are very few in Singapore, and incentive schemes may be introduced to build up this recycling value chain in the ESS sector, which is still at a very immature stage.

Annex 2: ESS Technologies

The following section provides brief description of various ESS technologies and their advantages and disadvantages.

Mechanical:

Pumped hydro storage (PHS) makes use of two water reservoirs. It uses low cost, excess electricity to pump water from the lower to the higher reservoir. During peak demand water is released to drive turbines. Pumped hydro storage is a mature technology that has been adopted in many countries especially for bulk storage due to its long lifetime, high efficiency and low cost. However, it requires natural resources like water bodies and natural reservoirs to store water at elevated heights. Creating artificial reservoirs or underwater tunnels or caverns require high investment costs. Also, the energy density of this technology is quite low. So, this technology though mature is not very locally relevant at the near to medium term in Singapore's context. In the long term if there are other needs (like storing water backups etc.) that necessitates building underground water reservoirs, then they can be used additionally for energy storage as well.

Compressed Air Energy Storage (CAES) refers to method of storing energy in the form of compressed air into a confined space (underground mines, salt caverns or underground aquifers), and then re-using them to drive the compressor of a natural gas turbine, thereby creating electricity. The technology is mature and cheap, but the overall efficiency is only about 40%. New advanced adiabatic-CAES systems which can capture the heat of compression to be reused later during expansion/discharge has potential to reach efficiency levels of 70%. However, like pumped hydro, this technology also requires suitable geographic prerequisites to be implemented economically. Since, Singapore does not have natural caverns, the cost for implementation may be high. A trial test-bed is being developed and tested by ERI@N team.

Flywheels are large spinning wheels rotating inside a container with minimal friction. The energy is stored in the form of kinetic energy. This is mainly used for high power and low energy applications. The high cost, associated safety risks and very few global vendors has led to limited deployments globally.

Thermal:

Heat energy produced by solar is stored as hot water or as heat in the form of molten salt or Phase change materials. This is necessary in places where there is high quality and quantity of solar energy available and makes Concentrated Solar Power (CSP) systems as an economical solution. But CSP systems require very large land area for installing them. So, this technology is not relevant to land scarce Singapore.

Chilled water can be stored in chilled water tanks, ice tanks or in PCM. This can help in reducing peak demand requirements. They cannot directly help the power grid but can indirectly help by shifting peak demands and can help the consumer to make use of low-cost off-peak electricity to produce chilled water. Currently most of the district cooling plants that are being set up in Singapore do come up with thermal storage (chilled water/ice/PCM) tanks. Since this solution is already in place and is tied with district cooling plants and cannot directly help in power quality etc., this solution is not further analysed in this roadmap.

Liquid Air Energy Storage (LAES) is a new upcoming technology where in electricity is used to compress air and store liquified air. When electricity is required the compressed air is heated and expanded in an air expander. The technology is nearing commercialisation and there are few prototypes globally.

Electrical:

To store energy in electrical form currently two popular technologies exist- supercapacitors and Super conducting Magnetic Energy storage (SMES).

Supercapacitors are also known as ultra-capacitors or electrochemical double-layer capacitors. Supercapacitors utilise an electrochemical double-layer of charge to store energy. As voltage is applied, charge accumulates on the electrode surfaces. Ions in the electrolyte solution diffuse across the separator into the pores of the electrode of opposite charge. However, the electrodes are engineered to prevent the recombination of the ions. Thus, a double layer of charge is produced at each electrode. Supercapacitors are high-power, low-energy devices that can react very quickly. They have high cycle life and are highly efficient (from 80% to 95%), but, because the voltage varies linearly with the charge contained in the system, they require power electronics to ensure steady output [5]. This technology is more suitable for high power fast response applications like frequency regulation and can be combined with other battery technologies to make them more economical and practical to meet the energy and space constraints.

Super conducting Magnetic Energy storage (SMES) store electricity in a magnetic field generated by current flowing through a superconducting coil constructed from a superconducting material, to have almost negligible resistance. A refrigeration system (e.g. using liquid nitrogen) is required to maintain the superconducting quality of the coil.

SMES has very quick response time and a very high cycle life with very minimal losses. However, due to high power required for refrigeration, the complexity of the system and due to high cost of superconductors, SMES has limited deployments globally.

Electro-chemical:

Electro-chemical energy storage systems commonly known as batteries use reversible electro-chemical reactions to store and discharge energy. They usually constitute two electrodes- anode, cathode, and an electrolyte to facilitate the electro chemical reactions in both the forward and reverse directions. The reaction requires active components (i.e. ions, contained in the electrode material and electrolyte solution) that will combine with electrons flowing in the external circuit. Batteries are highly efficient (60-95%) and have usually quick response. The chemical composition of their electrodes and electrolyte determine the performance and lifetime of the battery. Lifecycle limitations, environmental impact, safety hazards and cost reduction are some of the challenges that industry players and academic researchers are attempting to resolve to accelerate the adoption of this technology in mass scale.

There are multiple variations of batteries depending on the electrode and electrolyte combinations. The major types which are currently popular are - lead acid, lithium-ion, sodium-ion and flow batteries.

Lead acid

Lead acid is an electrochemical battery that typically uses lead(IV) oxide as the cathode, metallic lead as the anode and sulfuric acid as the electrolyte. It provides a nominal cell voltage of 2.1 V and gives an energy density as high as 80-90 Wh/L. The abilities to supply high surge currents and to tolerate wide temperature range (-35 to 45 °C), together with low cost, make it widely used as the starter battery. Nevertheless, lead acid battery suffers from limited cycle durability (typically only around 300 cycles at 100% DOD, low specific energy (30-40 Wh/kg) and poor charge/discharge efficiency (70%) [99]. These disadvantages may hinder its adoption in large-scale applications. For example, a former world largest BESS using lead acid technology (36 MW-Notrees Battery Storage Project, installed in 2012) has now been thoroughly upgraded to lithium-ion batteries in 2018 [100].

Lithium-ion

Lithium-ion battery is an electrochemical battery that typically comprised of lithium-intercalated cathode (LCO, LFP, NMC, NCA and LMO), graphite anode and organic carbonate as the electrolyte. The nominal cell voltage ranges from 3.2 V (for LFP) to 3.6-3.85 V (LCO, NMC, NCA, LMO). Lithium-ion battery can deliver high energy density (690 Wh/L or 260 Wh/kg, [101]) and can retain 80% of initial capacity after 500 cycles at 100% DOD (for NCA cathode, [102]). A battery with LFP cathode can potentially exhibit even better cycling stability, with > 90% capacity retention over 1,700 cycles (data from [103]. Currently most of the deployed energy storage projects all over the world are equipped with lithium-ion batteries and notably, Tesla has built the world's largest lithium-ion battery energy storage system in Australia (100 MW/185 MWh-Hornsdale Power Reserve) in 2018.

Molten sodium batteries

The most common sodium based electrochemical battery is based on molten sodium and they operate at elevated temperatures (270-360 °C). The anode is molten sodium. There are two types of molten sodium batteries, sodium-sulfur and sodium-nickel chloride (also known as ZEBRA, invented by Zeolite Battery Research Africa in 1985). Sodium-sulfur batteries have been widely used in BESS with over 200 projects (> 500 kW) and the total deployed capacity reaches 580 MW / 4 GWh globally. NGK is the largest sodium-sulfur battery manufacturer and its battery can deliver an energy density of 367 Wh/L or a specific energy of 222 Wh/kg [104]. They reported a lifetime of 15 years or 4500 cycles. NGK's sodium-sulfur batteries have equipped the world-largest BESS 108 MW/648 MWh in 2019 in Abu Dhabi [105]. Sodium-nickel chloride batteries were commercially launched by General Electric (GE, known as Durathon battery) and equipped the Wind Energy Institute of Canada (WEICan) project, but GE ended the production in 2015. A major concern of molten sodium battery in general is safety. This is because molten sodium is highly reactive and spontaneously burns in contact with air/moisture. On Sep. 21st, 2011, a 2 MW sodium-sulfur battery system (manufactured by NGK) installed at the Mitsubishi Tsukuba's plant caught fire and NGK had temporarily suspended the battery production for 8 months [106].

Sodium ion batteries

Sodium ion batteries differs from the molten sodium and operates at room temperature. Similar to a lithium-ion battery, a sodium ion battery consists of sodium-intercalated cathode, graphite anode and organic electrolyte. Since sodium is an earth-abundant element (from seawater), the cost of sodium-ion battery is considered to be lower than that of lithium-based one. However, lower energy density (typically 120 Wh/kg) and less mature technology hinder its fast adoption. In 2019, the first sodium ion BESS with a storage capacity of 100 kWh was installed by HiNa battery (a spin-off from the Chinese Academy of Sciences) in Jiangsu Province, China [107].

Flow batteries

Flow batteries is an electrochemical battery whereby the cathode and anode component in a typical cell are dissolved in liquids (known as catholyte and anolyte). These are stored externally in two separate tanks. During operation, the two liquids are pumped through the reactor separated by an ion exchange membrane to generate power. This can also be reversed to separate and store the energy in the tanks. Since the stored energy is only related to the volume of tanks, flow battery can offer scalability when spaces are available. There are a few major chemistries used in flow batteries, namely iron-chromium, sodium-bromine polysulfide, zinc-bromine/cerium and organic molecules, and vanadium redox battery (VRB). VRB is the most marketed technology in flow batteries due to its potential long cycle life (15,000-20,000 cycles), short response time and low maintenance. VRB has two electrolyte tanks (positive tank containing VO_2^+ and VO^{2+} ions, negative tank with V^{3+} and V^{2+} ions) and an open-circuit voltage of 1.41 V at 25 °C. The use of aqueous electrolyte (in sulfuric acid) makes VRB inherently safe and non-flammable.

VRB system needs a good control of temperature for optimal performance and the cell needs to be kept at 15 to 35 °C for the solubility limit of electroactive species. In addition, the current energy density of VRB is not attractive at ~35 Wh/L [108]. At present the world's largest VRB ESS (15 MW/60 MWh) was installed in Minami-Hayakita substation in Japan in 2016. This is expected to be surpassed by a VRB project in Dalian VFB-UET/Rongke Power (200 MW/800 MWh) in China that will be commissioned later this year (09-2020) [109].

Chemical:

For long term energy storage and bulk energy storage, energy can be stored in the form of chemical energy in the form of hydrogen or as synthetic natural gas.

Hydrogen energy storage technologies are based on the fact that excess electricity can be used for electrolysis, to split water (H_2O) into its constituent elements, hydrogen (H_2) and oxygen (O_2). The reverse process (i.e. hydrogen and oxygen generate electricity and water) is used to produce electricity using a fuel cell to feed to the grid.

Hydrogen can also be used in heat engines like natural gas, to produce electricity. The various options for hydrogen storage - as a gas in very large underground caverns or in man-made high-pressure tanks; as a liquid in cryogenic tanks; or as solid or liquid hydrides (e.g. ammonia, magnesium). These technologies are environmentally friendly and reliable. But the key obstacle to overcome are the safety hazards and the conversion efficiency (fuel cells or hydrogen-based heat engines).

For Synthetic Natural Gas (SNG) storage, energy is stored in the form of methane (CH_4) produced from hydrogen and CO_2. Excess energy is used for electrolysis to produce hydrogen which is then synthesised with CO_2 to produce SNG through methanation. The key advantage is that it can make use of existing natural gas infrastructure. Methane can also be passed through conventional gas turbines. However, SNG otherwise known as power-to-gas faces strong competition from natural gas and can be economical when there is cheap CO_2 available.

Annex 3: ESS Applications

The ESS applications discussed in section 2.2 and Figure 2.2.1 are broadly classified into customer-focused, renewable generation, grid balancing, energy transmission and distribution, and utility-related applications. This section briefly pinpoints the scope and functionalities of critical applications suitable for ESS adoption.

Customer Oriented Applications

Building and group of buildings adopt ESS technologies to gain cost and reliability benefits. ESS can offer power reliability and resilience to buildings against the weak utility grid. The ESS also provides cost savings through energy time-shift and demand-side management capability to take advantage of price arbitrage [1], [51]

- Energy time shift: In this application, the ESS is commonly installed at the consumer site to cover the peak loads. Usually, the ESS is charged during the off-peak period that is partly shifting the building loads to the off-peak period. Building requires additional energy can still use normal grid capacity and employ ESS to support the peak demand. Implicitly, it also reduces the stress on the utility grid during peak periods [1], [45]. (Note: The energy time-shifting is also referred to as load shifting, load levelling, and peak shaving).
- Demand Side Management: This application is like energy time-shifting but focuses mainly on cost benefits by exploiting differential pricing during peak and off-peak hours. The ESS is utilised in demand-side management to take advantage of the uncertain wholesale price and mainly stay away from price spikes during peak hours[52].
- Power reliability: The principle of power reliability is the uninterruptible supply of quality power. ESS provide reliability support during grid interruption and power quality issues. This application is under customer control to stay firm against unreliable utility grids and local renewables [1], [52].
- Power resilience: It is the ability to restore during utility grid disruption or blackouts. This application employs ESS as a backup generator during the interruption of the utility grid. However, the support duration depends on the load curve, ESS capacity, and disruption duration [52] .
- Off-grid services: In remote areas where the utility grid is not accessible, the energy storage supports standalone generation or local renewable energy systems. This application requires ESS to respond quickly to changes in supply or demand and make a good balance of energy capacity and power output. For remote applications, the ESS faces longer payback because ESS required in small units for which the unit cost is high [1], [46], [48], [52].

Renewable Generation Focussed Applications

The renewable energy cost is competing and reaching grid parity. However, the intermittent nature of renewables limits its competitive advantage compared to dispatchable generators. By pairing with ESS, the fluctuations in the renewables can be covered to gain competitive advantage through capacity firming, renewable integration, and energy arbitrage [48], [51].

- Renewable energy time-shift: This time shift application stores renewable energy during low demand periods and injects this stored power into the system during the rise in demand. This shift not only from one period to another period of the day, but this can also extend shifting renewable energy from weekends to weekdays. The EES can be installed anywhere in the system, whether near to the source or the load. This application not only helps in reducing unwanted overloading of grid components but also provides higher benefits for the ESS stakeholders, by selling more energy and at a higher cost [45], [110].
- Renewable energy systems smoothing: In this application, the ESS is used to smooth the effect of short intermittency from renewables such as fast-moving clouds over the solar PV plants and wind speed variations. Smoothing the short intermittency using ESS is like a filtering process results in less fluctuating output over a short period. The renewable output power with energy storage improves power quality considerably [110] .
- Renewable energy capacity firming: The ESS helps low renewable power generation periods by discharging energy stored during the period of excess generation. Renewable source integrated with ESS becomes more 'firm' and provides stable output power. This integration empowers renewable sources to participate in the energy market with power quality and firm capacity [52], [110].

Grid Balancing Applications

The utility grids are prone to fluctuations from generators, renewable, and loads. Even unexpected events and unforeseen circumstances disturb the grid stability, so perfectly matching the generation and electricity demand always is necessary to maintain reliable power system operations. Various categories of operating reserves and ancillary services are required to function on different timescales, from sub-seconds to several hours to ensure grid reliability [47]. ESS can respond faster than conventional power plants through rapid charging or discharging. The faster response in a fraction of a second makes energy storage as a suitable resource for short term reliability services like frequency regulation. Appropriately sized energy storage can also provide longer-duration services like load-following, and ramping and contingency reserves [1], [45], [51].

- Frequency regulation: The frequency regulation is crucial in power systems for dealing with the many small variations. Commonly, the generator control creates a balance between generation and demand and restores the frequency within 5-30 s. The energy storage system in a frequency regulator can respond faster and correct the frequency deviations within the permissible limits [46].
- Spinning reserve: The spinning reserve is a part of capacity in online generators not used during normal operations. This reserve capacity is used to inject power for a specific period during power shortage in the system. With the advantage of fast response capability, ESS can efficiently replace the spinning reserve. However, the ESS capacity must be able to provide continuous power until the backup system reaches its nominal value. This application releases the reserve capacity in online generators to operate efficiently [46], [47], [49].
- Non-spinning reserve: The non-spinning reserve is a fast-start generator (Peaker plants) that usually in standby mode during normal operation. During the event of

online generator trips or failure, the non-spinning reserve kicks within few seconds to stabilise frequency and cover the power shortage in the utility grid. This reserve is expected to start injecting the power from 9 sec – 10 min and capable to support at least 20 mins or till the contingency reserve takeover. Technically, ESS can respond faster and provide stable power quickly than fast-start generators. However, ESS energy and power capacity must be sized appropriately to ensure stable output power for the required duration [47], [49].

- Contingency Reserve: During unforeseen situation like generator trips, the contingency reserve is usually triggered by the primary reserve. It takes adequate time around 10 min to come online and expected to support at least 30 minutes. The contingency reserve must be at least equal to the capacity of the biggest online generator to ensure N-1 contingency performance [47], [49].
- Ramping Reserve: This reserve is also known as load following or flexibility reserve used to cover slower variations in the net loads arising from renewable sources. The ramping reserve is to maintain a balance between the generation and the loads. ESS can quickly cover both ramp-up and ramp-down variations and promptly responds to load and generation variations [45], [46].
- Voltage support: The reactive power management is a requirement for grid stability which can be achieved by maintaining the voltage within the permissible limits. The grid stability is important to maintain proper operation of equipment, prevent generators from overheating and reduce losses. ESS can provide voltage support by providing or absorbing reactive power. Usually, voltage support is used locally because reactive power cannot reasonably be transferred over long distances [45], [46], [48], [51].
- Black start: The power grids are prone to unexpected events causing interruptions in power throughout the whole system or part of the system. The blackouts situation compromises the grid stability. The black start is a process of restoring the affected system that carries obligations of systematic restoration of power management, voltage control, and balancing from the affected state of the grid. The energy storage system can supply active power to energise the distribution lines or provides startup power for large power plants [48], [51].

<u>Energy Transmission and Distribution Applications</u>

The transmission and distribution system face congestion or overloading when the capacity is insufficient to supply the customer loads. Interestingly, congestion occurs only a few hours a year during specific periods of peak demand. The transmission and distribution system upgrades decision are rational when additional energy requirement from new and existing customers is substantial and steady. Otherwise, expensive investment is insensible to address the congestion problem that occurs infrequently. The generation curtailment, demand response, and supplementing distribution generation close to the loads are choices to alleviate the issue. With the help of energy storage, the infrequent congestion and overloading problem can be addressed to a certain extent and avoid expensive system upgrades [1], [47], [110]. The ESS capacity can be easily extended to meet the peak demand growth.

- Grid Congestion relief: The grid congestion occurs during the process of balancing supply and demand. Even at times, high renewables generation can cause transmission system congestion. Deploying ESS at heavily loaded substations and transmission lines would relieve congestion and improve the useful life of grid equipment. It can also help utilities to defer or suspend the reinforcement of existing power networks [48], [111].
- Transmission and distribution upgrade deferral: Upgrading the transmission and distribution systems are expensive and time-consuming decisions. Especially, when the overloading of transmission and distribution system are marginal compared to the existing capacity. Utilities facing this situation would rather aim to defer the upgrades in other means to utilise their existing resources. Placing ESS close to the proximity of the loads would address the overloading of grid components to a certain extent and extend the useful life of grid equipment such as transformers. The installed ESS must charge during low demand conditions and discharge during grid overloading. The deferral strategy would prevent utilities from expensive investment and benefits customer through low energy costs due to infrastructure deferral [48], [52], [111]
- Transmission support system: ESS can support the transmission and distribution grids by smoothing and controlling the power supply from variable renewable sources to appropriate (low and medium voltage) grid as per the demand.
- Utility substation power: The substations operating close to full loading conditions need to reject the additional energy required by the new and existing customers to meet the substation capacity constraints. Energy storage can economically support additional energy requirements in substations rather than costly upgrades [112], [113].

<u>Utility related Applications</u>

Utilities face supply-demand mismatch when the total generation capacities are inadequate to meet the peak loads. The traditional prospects to address this problem are load curtailment or expanding generation capacities. In the short term, the load curtailment makes economic sense than investing in new generation plants. The utilities are also exploring the opportunities to manage loads by collaborating with the customers [46].

- Demand response: This application helps power system planners and operators for balancing the supply and demand through customers. The demand response provides the customer with an opportunity to shift their usage in response to time-based electricity prices and incentives. The grid operators either send the demand response signal to contestable customers or directly manage their loads during price spikes. This method provides cost benefits to all stakeholders by reducing the wholesale price and retailer price and also helps service providers to defer new power plant construction and delivery systems. However, the customer load reduction capability depends on their load characteristics, critical and shiftable loads. The customer can use ESS to increase contestable capacity and improve value streams [110], [114].

- Peak capacity: During high demand periods, the simple-cycle gas turbines, gas, and oil-fired steam plants and reciprocating engines provide peaking capacity. Technically, energy storage can replace conventional Peaker plants comfortably. However, the cost benefits of energy storage over Peaker plants depends on the load pattern [46].

Value stacking

Some of the grid services like black start, contingency reserve, congestion relief occur infrequently results in ineffective utilisation of energy storage and longer payback. Providing multiple services using ESS could maximise the value to the grid and project developers. The multi-use approach is referred to as value-stacking. For example, ESS employed to defer the need for new transmission by meeting a portion of the peak demand (few hours in the year) can also earn additional revenue by serving the contingency and operating reserves.

Annex 4: Safety Hazards and Failure Modes for Lithium-ion Batteries

The following tables list the safety hazard and failure modes for lithium-ion batteries along with the associated system level impact/effect.

Table .1 List of safety hazards and failure modes for lithium-ion batteries [55]

Safety Hazards	Over Voltage	Under Voltage	High C -rate	High Temperature	Mechanical damage
Mechanical	Mechanical fatigue of cell structure		Mechanical fatigue; self-heating; separator breakdown	Separator breakdown (typically melting at 120-135 °C	Electrode cracking. SEI breakdown
Electrical	Dendrite formation can short anode to cathode	Dendrite formation under high currents can short anode to cathode			
Electrochemical	Lithium plating and Lithium-accumulation on anode leads to dendrite formation / electrolyte decomposition.	Cathode decomposition/ oxygen generation. Anode decomposition/ potential short circuit	Lithium plating; electrolyte breakdown	Breakdown temperature of different elements: SEI (60-80 °C) electrolytes (70 °C); Cathode (200 °C)	
Thermal	Overheating at 120-160% overcharge			Self-heating, thermal runaway, exothermic behaviour	Self-heating, thermal runaway, exothermic behaviour

Table 2. List of system level effects due to the various failure modes for lithium-ion batteries [55]

Flow Batteries: Flow batteries have relatively fewer safety hazards compared to lithium-ion batteries. The hazards arise from the toxicity and acidity of the electrolytes. All chemistries have associated risk of release of explosive gases (oxy-hydrogen). Certain chemistries have an additional risk arising from liquid corrosivity and release of toxic gases. The chances of electrocution hazard are increased in flow batteries due to possible spilling of conductive electrolyte. Zn-Br batteries must be operated at temperatures below 50 °C to avoid Br evaporation. Classification of electrolytes for redox flow batteries is made as per UN 1760 or UN 3260.

Main safety measures that can be adopted for managing electrolytes in flow batteries range from spill tray, system containment with active adsorbent/absorbent materials and personal protective equipment for operating personnel. Also, adequate ventilation should be ensured to manage evaporated electrolyte. Detection and monitoring equipment to monitor gas concentration can also be deployed and linked to emergency shut-down control systems.

Supercapacitor: Supercapacitor batteries are safer than ordinary batteries. Supercapacitors have low internal resistance and so do not get heated. Shorting a fully charged supercapacitor can cause electrical arcing, and might cause damage to the device, but the generated heat is manageable. UL 810A is a standard that can be referred to for performance tests and safety considerations of supercapacitors. IEC 61000-4 can be referred to for general electrical safety testing of supercapacitors.

Cybersecurity: Additionally, precautions against unauthorised access to data and controls should be taken. Any software that has network access, security safeguards and sensitive data infrastructure should be continuously monitored and kept up to date with its security updates, to ward against the latest cyber threats. For increased cybersecurity, three levels of connectivity of the ESS to the outside world may be considered: bi-directional connection, unidirectional connection (outward) and finally the safest (but demanding to operate remotely) via the “no external connection” mode. It may be considered to allow only ESS devices (e.g. BMS, converter) to connect to the internet after they are disconnected from the actual physical ESS.

Annex 5: Recycling of lithium-ion ESS

Key observations regarding raw material supply of critical materials used in current lithium ion battery technology is presented and subsequently the details of recycling process of lithium ion batteries are also presented.

Raw Materials Supply

There are four major types of cathode materials for Lithium-ion batteries, including $LiCoO_2$ (LCO), $LiMn_2O_4$ (LMO), $LiFePO_4$ (LFP) and $Li(Ni_xMn_yCo_z)O_2$ (NMC), whereas the anode is typically made of natural or synthetic graphite. The figure below shows the main suppliers of lithium, cobalt, nickel, and graphite (natural) in 2018 and 2019. In general, supplies of manganese and iron are sufficient (18.9 and 1470 million tonnes per year, respectively). The consumption of manganese and iron in lithium-ion batteries are less than 0.5% of their total production capacities according to US Geological Survey [76].

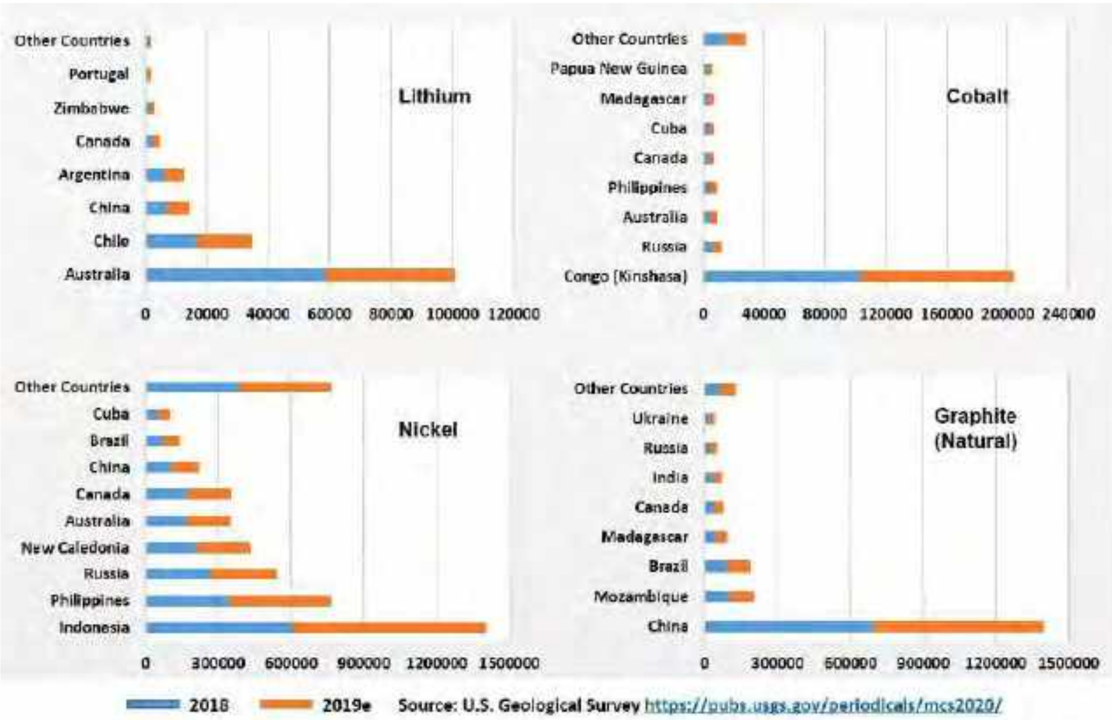


Figure A5.1 Annual mine supplies of lithium, cobalt, nickel, and graphite (natural) in metric tons.

Table A5.1 Key producers and prices of critical battery elements

Battery Element	Main Producers/Suppliers	Price Range (USD/tonne) (2015-2020)
Lithium	Global output: 77,000 tonnes (2019) [115] Australia (~60% of global output followed by Chile) [116]	Lithium carbonate: 6,400 -17,000
Cobalt	Global output: 200,000 tonnes Democratic Republic of the Congo (~70% of global output)	LCO: 27,500 - 95,000 [117]
Nickel	Indonesia (~30% of global output) Philippines, Russia, New Caledonia, Australia, Canada, China	Nickel: 8000-18000
Graphite	China (~60% of global output at 1,100,000 tonnes)	Graphite anode: 3,000-10,000

Table A5.2 Key challenges with critical battery elements

Battery Element	Challenges
Lithium	• A key component of lithium-ion batteries. • Battery-grade lithium raw material prices is prone to significant fluctuations, e.g. price drop in lithium carbonate due to the oversupply of Australia's spodumene (from US$17,000 tonne in 2018 to US$6,400/tonne in May 2020).
Cobalt	• Cobalt is significantly more expensive than other components: LCO (highest Co content) at USD 27,500/tonne, ~40% pricier than NMC622, 4 times higher than LFP and 6.4 times higher than LMO cathode materials. • Supply chain is also vulnerable to corruption, political instability and regional armed conflict. The use of child labour in cobalt mining also raises ethical concerns [118]. • NMC (lower Co content) and LFP (cobalt-free) cathodes are currently the preferred cathode chemistries for large-scale applications to address supply chain issues and reduce battery cost.
Nickel	• A key element in lithium-ion and Ni-Cd/MeH batteries, as it provides a higher energy density at a lower cost. • With global nickel production concentrated in a few countries, the supply is subject to domestic considerations. In January 2020, the largest producer, Indonesia, announced the halting of exports of unprocessed nickel to accelerate the establishment of the local smelting industry [119].
Graphite	• Most common material for anode of lithium-ion batteries. • Synthetic graphite is considered superior to natural graphite in terms of providing quality control, ability to provide fast charging, and longer cycle life. • However, the average price of synthetic graphite is about 30~40% higher than natural graphite.

Battery Recycling Technologies

A typical battery recycling process is shown in Figure A5.2, and there are two different methods of raw materials extraction, namely pyrometallurgy and hydrometallurgy [120]. The elaboration of the process is found in Table A5.3.

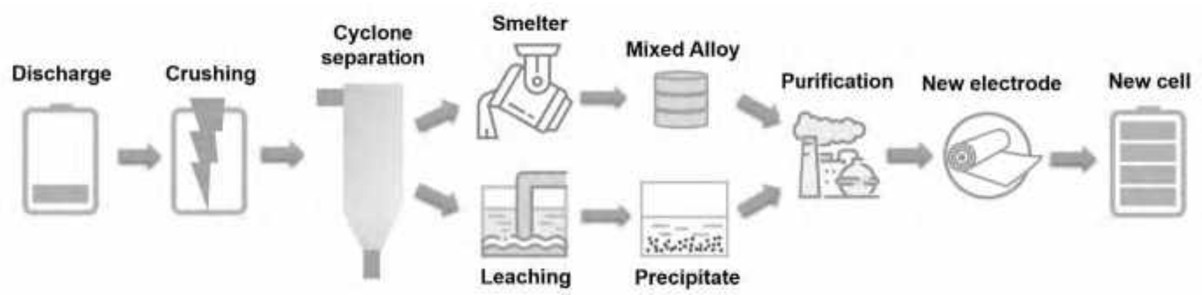


Figure A5.2 Recycling process of lithium-ion batteries

Table A5.3 Key stages in the recycling [121]

Process Step	Description/Notes
Cell discharge and battery crushing	Fully discharged cells contain active lithium; hence the crushing process is carried out in a vacuum or inert atmosphere. Organic electrolyte solvents are recovered by evaporation and condensation.
Material separation	Dust comprising stainless steel, nickel, aluminium, copper, polymer film, graphite, and cathode powder (with lithium, cobalt and nickel compounds) is put into a cyclone system and filtered by electromagnets. Stainless steel casing parts, polymer separators, current collectors (aluminium, copper foils) and nickel tabs for cell connection are directly separated for recycling.

Metal recovery—Pyrometallurgy	Residues are heated and reduced in a smelter to form a mixed alloy, which can be further purified/processed to sulfate as the precursors of cathode materials. Pyrometallurgy can effectively recover cobalt, nickel and copper, but leave lithium compounds in the slag due to a lower reduction potential.
Metal recovery—Hydrometallurgy	A moderate and green process: the electrode powder waste is first calcined at around 700 °C to remove carbon and polymer binder. It is then immersed into a solution with acid and hydrogen peroxide. Almost all lithium-ions can be leached out to form a lithium carbonate precipitate for reuse.

Recycling of lithium-ion batteries via pyrometallurgy has been commercially adopted by major players such as Umicore, BATREC, Mitsubishi and GEM. In particular, GEM is the world's largest battery recycler, which operates 13 battery recycling facilities globally with an annual production capacity of cobalt, nickel precursors exceeding 1,000,000 tonnes [121].

For hydrometallurgy, several companies, such as Fortum (Finland), Duesenfeld (Germany), Ganfeng (China) and Brunp (China) have industrial-scale recycling facilities. Additionally, a new plant has been set up by TES-AMM (Singapore) Pte Ltd (TES) in Singapore recently. Compared to conventional pyrometallurgical process, hydrometallurgy can save 4.8 tonnes of CO_2 per tonnes of recycled batteries (calculated by Duesenfeld [122]).

<u>Environmental Impact and Challenges ahead</u>

A circular economy requires a full cycle in feeding back of materials/resources into the product value chain as shown in Fig. A5.3. For lithium-ion batteries, recycled raw materials typically refers to the extracted metal. Electrode suppliers (typically cathode) process the extracted metal, and the processed metal is subsequently developed into cells/packs by battery manufacturers as products for the end users. The EOL batteries then enter disposal and collection, prior to dismantling and recycling in a circular loop.

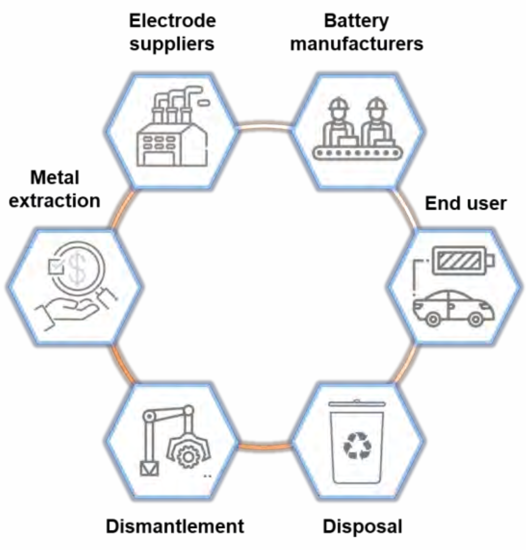


Figure A5.3 Circular economy for lithium-ion batteries: reducing the waste and recycling the components of value.

Lithium-ion batteries have a lower recycling rate, ranging from 5-50% [123]. Some of the key challenges include:

a) Large-scale storage and transportation of lithium-ion battery waste pose safety concerns since the highly active lithium within the battery remains a fire hazard;
b) There is a lack of government policies and regulations to incentivise or mandate battery recycling;
c) Complex battery structures (i.e. pouch, prismatic and cylindrical), different sizes and cell chemistry further complicate recycling efforts.

Current battery recycling focuses on the extraction of cobalt and nickel for its mature technology and high value. However, there are still considerable amounts of LFP and LMO batteries in the market. It is difficult to make recycling business profitable due to the low intrinsic value of iron and manganese without incentives or subsidies. Governments have been pushing both technologies and legislation to improve the collection and recycling rates. For example, the European Union has an overall aim to recycle 50% of lithium-ion batteries by 2030 while China has applied a tracking system from cell production to second-life use and eventually recycling to boost the circularity of batteries.

Lithium-ion batteries have significant negative environmental impacts in its production, use and EOL management [124]. Some of the concerns include:

a) The production of battery raw materials is a strain on water resources. 1900 tonnes of water are required to extract one tonne of lithium from brine.
b) Sulfide ores are the major sources of cobalt and nickel. Their mining and processing are toxic with the emission of SO_x, causing acid rain.
c) The mining, conversion and refining steps of lithium, cobalt and nickel are highly energy-consuming, contributing to 21% (181 MJ/kWh) of the total energy used for the cell production (estimated by Circular Energy Storage [125]).
d) At the batteries' EOL, possible leakage of metals/metal ions (such as cobalt, nickel, manganese, copper and aluminium) in large amounts can contaminate soil and groundwater causing harm to the ecosystem and human health. The organic electrolyte is also detrimental to the environment since the lithium conducting salt ($LiPF_6$ in common) in the electrolyte can react with water and form hydrofluoric acid, which is a controlled hazardous substance.

The reuse and recycle of lithium-ion batteries is thus vital in reducing the quantity of waste going into landfills, preserving raw materials and protecting the environment. However, one has to be wary of the CO_2 footprint in recycling. Currently, recycling of lithium-ion batteries leaves a carbon footprint of ~110-200kg CO_2/kWh, which is about 10-20% lower than the CO_2 emissions in cell manufacturing using non-recycled materials [126]. This is especially the case when raw materials are extracted using high energy process such as pyrometallurgy. The overall CO_2 emission contributions for battery energy storage systems in a solar PV deployment is also relatively low (less than 10%) [127]. In addition, second-life reuse of batteries has the potential to further reduce the overall CO_2 footprint, aiding to overall beneficial of use of ESS [86].

Annex 6: Recycling of other ESS Technologies

Beyond lithium-ion batteries, the environmental impact of other energy storage can be relatively lower as shown previously in section 2.6. The production burden in CO_2 emission may also be higher for lithium-ion even though the reported ranges are quite wide. As a snapshot, the production burden for lithium-ion batteries at ~61,000 – 487,000 CO_2/MWh, while vanadium redox batteries are ~47,400-161,000 CO_2/MWh and lead acid is at ~18,000 – 211,000 CO_2/MWh [128]. Here, we give a brief overview on the recycling aspects of selected energy storage technologies.

1. <u>Vanadium Redox Batteries</u>

Vanadium redox batteries (VRBs) are considered as a promising technology for grid energy storage due to their scalability and long cycle durability. The storage capacity of VRB is only related to the size of electrolyte tanks. The world's largest VRB system (800 MWh) is being deployed in China and will start operations in 2020. Most commercial VRBs can last for 15,000-20,000 charge/discharge cycles, far beyond lithium-ion batteries (< 5,000 cycles). The use of non-flammable aqueous electrolyte also makes VRB inherently safe. The worldwide market for VRBs is expected to reach from US$320 million in 2019 to US$2800 million in 2024, growing at a CAGR of roughly 43.7% [129].

Different from lithium-ion batteries with solid cathode and anode, the electrochemically active materials in VRBs are in liquid form, also called catholyte (cathode electrolyte, containing VO^{2+} and VO^{2+} ions) and anolyte (anode electrolyte with V^{3+} and V^{2+} ions). The electrolytes are usually prepared by directly dissolving vanadium (IV) oxide sulfate or reducing vanadium pentoxide in sulfuric acid. As of 2019, the market share of VRB electrolytes made in China is above 90%. Since the carbon electrode and Nafion separator are relatively stable in cell operation, battery performance degradation is mainly caused by the changes of electrolytes in the following aspects: 1) pentavalent vanadium precipitation blocking the battery stacks and pumps; 2) contamination of impurities retarding the kinetics of the redox reactions; 3) crossover of vanadium ions leading to a high self-discharge rate; and 4) water migration [130]. The recovery or recycling of VRBs can be readily achieved by remixing of the catholyte and anolyte (electrolyte rebalancing) and/or by replacing new carbon electrodes/Nafion membranes. Even for the electrolytes with impurities, the vanadium species can be almost completely extracted by recrystallisation to the form of $VOSO_4$ or oxidation into pentavalent vanadium precipitations. The long calendar life (>15 years) and recyclability of VRBs could significantly reduce the environmental impact of potential vanadium pollution.

2. <u>Flywheels</u>

Modern flywheel technology has many advantages that reduce its environmental footprint: flywheels mainly consists of inert and non-toxic materials (such as metals and ceramics) which are easily recycled and are typically closed system devices which require little maintenance with a long operating life of typically more than 20 years or even longer. The main environmental footprint of flywheels arises from its production process, with a typical value of around 160 g(CO_2-eq)/kWh [131] In its life assessment cycle (LCA), which puts it on par with technologies such as lead-acid batteries and higher than VRBs. However, this can be mitigated by sourcing steel and/or carbon fibres from recycled sources which would decrease the carbon footprint of the production process. For example, there have been proposed commercial processes to recycle carbon fibre reinforced polymers from used wind turbines into carbon fibres for the flywheel rotor components, thus creating a new circular economy from a renewable energy sector into a new ESS ("Recycled carbon fibre substitution in flywheels" [132].

Furthermore, flywheels can indirectly reduce the environmental impact of other energy storage systems when used in tandem in a distributed ESS. For instance, flywheels can extend the lifetime of electrochemical batteries by reducing the cycling load, thus decreasing the demand on extracting critical raw materials used in batteries [132]. Thus, flywheels' circular economy model is predicated on 1) using production material from recycled sources, and 2) reducing load demand on other ESS with higher environmental impacts whilst operating with almost zero emissions during its lifetime.

3. Superconducting Magnetic Energy Storage (SMES)

The material technology used in SMES has a huge impact in not only its economic feasibility for large scale grid applications, but also in the environmental impact of the production process, as well as the recyclability of the required coolants in its operation. Currently, the most established material technology used for SMES are low temperature superconductors (LTS) such as niobium-titanium (NbTi), which requires liquid helium as a coolant for it to reach a superconducting state. The superconducting material is easily recycled, since the materials are not dispersed over the lifetime of its operation [131], [133]. However, the cooling requirements creates two main disadvantages regarding carbon footprint and helium recyclability. Firstly, LTS requires huge amounts of refrigeration whilst in operation, and while the electrical efficiency of SMES is essentially 100%, inefficiencies in the refrigeration process (through environmental heat exchange and inevitable helium loss) results in a significant carbon footprint of around 420 g(CO_2-eq)/kWh [131]. Secondly, helium is a very expensive resource (with depleting natural mines in the world) since helium loss into the environment is irreversible, and helium recovery systems are costly to build while still having inevitable small losses over time.

High temperature superconductors (HTS) play a very important role in overcoming the cost and operational barriers of SMES using LTS. While the materials used in HTS (such as YBCO) consists of rarer earth metals, the non-dispersion of the materials makes it easily recovered and recycled at the end of the SMES lifetime [133]. The main advantage (theoretically) comes from the much less stringent coolant requirements for the HTS to reach its superconducting state, which is especially important if its critical temperature is above 77K, a temperature which can be obtained by liquid nitrogen. The abundancy of nitrogen removes scarcity concerns, and production of liquid nitrogen is vastly cheaper when compared to liquid helium. This also reduces the refrigeration requirements greatly, creating a much smaller carbon footprint as compared to LTS SMES.

If SMES becomes technologically mature, the potential of a circular economy with other forms of ESS exist, in particular in the area of cryogenic energy storage (CES). SMES can take advantage of existing cooling infrastructure that are already used in areas such as industrial sectors and hospital to reduce the built-in cooling cost. Furthermore, the expansion of the liquid nitrogen during the magnet cooldown process, can be used to drive turbines to provide additional electrical energy, forming a hybrid SMES-CES electrical storage and production system. However, the performance and production of HTS materials are still technologically immature, with much research and development still required.

4. Thermal Energy Storage (Molten Salt Energy Storage)

Although there are many forms of thermal energy storage (TES), the most established TES is the molten salt energy storage (MSES) system, which stores thermal energy produced by concentrated solar power (CSP) through the use of mirrors and focusing techniques. While CSP can be used as a standalone technology, the concurrent use of MSES allows operation of CSP plants beyond limited daylight hours to have constant electricity output throughout the day. MSES usually uses nitrate salts (e.g. nitrates of sodium, potassium, and calcium) which have some desirable properties. These include 1) high operating temperatures which increases electricity production efficiency, 2) low material cost, and 3) non-toxic and environmentally benign. Heat from these molten salt tanks is transferred to turbines via heat transfer fluids (HTF), of which currently mineral oils are the most commonly used. However, these oils are highly toxic and highly combustible, which leads to many environmental and safety concerns. Based on current technologies and CSP-MSES projects around the world, the typical carbon footprint is around 120 g(CO_2-eq)/kWh ([134], which technically makes it one of the greener electrical sources. However, safety concerns (especially after high profile fire accidents) have made many view the technology with a certain amount of scepticism.

However, recent research and development have made advances in replacing the HTFs with a safer alternative: the molten salt itself. Research includes 1) reducing the freezing point of the molten salts, which alleviates the heating requirements of the pipes and tanks to prevent freezing, and 2) better parabolic mirror production and focusing techniques which enables elevated operating temperatures of the CSP-MSES system [134]. Using molten salts as HTFs eliminates the fire risks associated with mineral oils, as well as increasing heat transfer efficiencies due to the elevated operating temperatures, enhancing both economic and environmental impacts per kWh of electricity produced.

CSP plants form a natural co-generation system with solar PV generation plants, since the Sun is the main energy source used in both technologies. However, the use of different ESS for the two technologies (MSES for CSP, LIB for solar PV) enables different optimisation of economic and environmental strategies depending on specific geographical and socio-political climates. In particular, while the efficiency of solar PV is typically higher than CSP, materials required for MSES are cheaper and have lesser environmental impact compared to lithium-ion batteries. Thus, allocation of solar resources can be altered according to material scarcity and new environmental regulations [134].

END OF REPORT