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The Smart Sodium Storage Solution (S^4) Project

FINAL PROJECT REPORT

This project received funding from ARENA as part of ARENA's Research and Development Programme.

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Executive Summary

PROJECT OUTLINE

The core focus of the Smart Sodium Storage System (S^4) project was to develop a sodium-ion battery chemistry and production capacity to bring the technology to pre-commercialisation in the energy storage marketplace. This includes the value-add components of integrating sodium-ion battery cells into 5 kWh modules with built-in battery management systems, and demonstrating this technology in conjunction with a custom-developed Energy Management System coupled with renewable generation at Sydney Water's Bondi Sewage Pumping Station.

At its inception in 2016, the outcome targets for the S^4 Project were to:

- Develop a low cost sodium battery and battery architecture for use in energy storage solutions;
- Demonstrate the utility, cost and competitiveness of sodium-ion batteries for domestic-scale, commercial-scale and utility-scale renewable energy storage applications through the development of a novel, low-cost sodium-ion battery architecture;
- Develop an overarching energy management system including battery, load, generation and thermal management for sodium-ion batteries solutions in utility applications;
- Demonstrate the commercial application and market competitiveness of the turn-key energy management system with integrated sodium-ion battery technology through installations at the Illawarra Flame House and Sydney Water's Bondi pumping station SPS005;
- Identify the key areas for sodium-ion-based energy storage in domestic-scale, commercial-scale and utility-scale applications, and provide a techno-economic analysis of the impact of widespread adoption of sodium-ion-based energy storage could have on these markets; and
- Prepare an operational risk profile, establishing changes in operational risk (production, quality and cost) associated with the integration of sodium-ion battery technology within domestic-, commercial- and utility-scale renewable energy systems.

The S^4 Project was funded in part by the Australian Renewable Energy Agency (ARENA). Project Activities were undertaken by a consortium of Australian and international partners consisting of:

- the University of Wollongong
- Liao Ning Hong Cheng Electric Power Co., Ltd.
- Hebei ANZ New Energy Technology Co., Ltd.
- McNair Technology Co., Ltd
- Sydney Water

PROJECT RATIONALE

The project set-up and approval is timely and visionary if we want to achieve net-zero carbon emission by year of 2050, which has been set as a target by most countries around the world as a way to honour their commitments to the Paris Agreement. In recent the UN Climate Change Conference CO26 at Glasgow majority countries committed to secure net zero emission and keep temperature rise within 1.5 C by 2050. This challenging goal demands substantial change in energy production technology and generation sources. For the electricity generation the renewable energy source including solar, wind and other renewable will contribute more than 90% of total electricity generation as predicted by the International Energy Agency in its plan for achieving net zero emission. This is a very ambitious goal and will have significant impact on the demands of energy storage materials and systems in order to maintain the energy supply security. Figure 1 shows the magnitude of battery accumulative energy capacity growth to 2021 and projected out to 2050 – a perspective given by Bloomberg NEF. It is extraordinary to see energy storage capacity will increase by more than three to four orders of magnitude by 2050. Among energy storage technologies available to date battery technology is superior in terms of energy efficiency, cost, safety and feasibility.

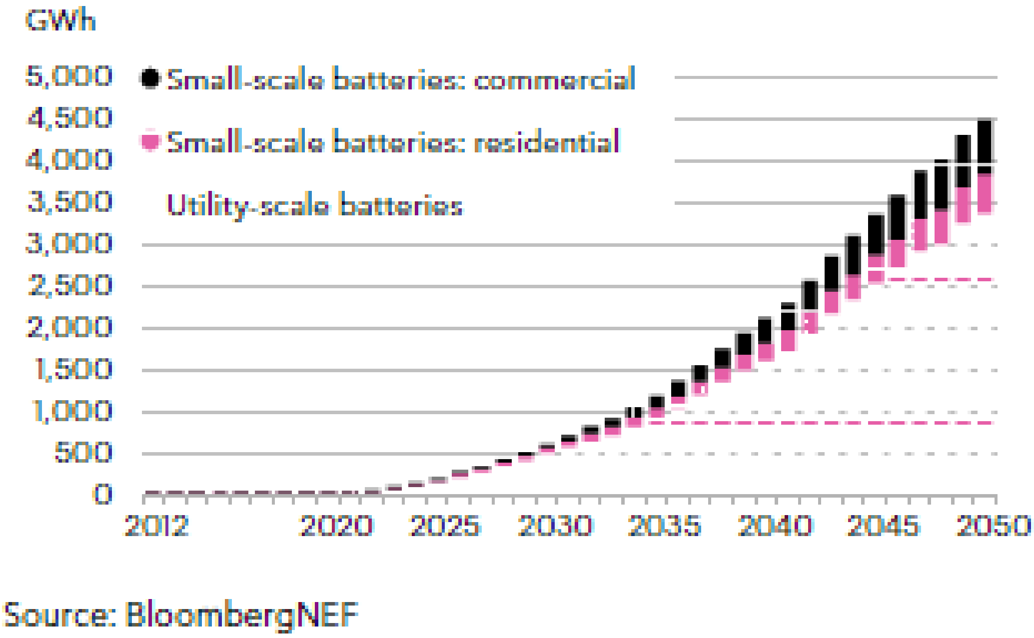

Figure 1- Global accumulative battery storage capacity prospect 2020-2050

Current lithium-ion battery technology has drawbacks – such as relatively high cost when compared to alternatives (an order of magnitude higher cost for raw lithium materials than sodium), material scarcity and a complex IP landscape – that provide an opportunity for alternative storage technologies to be developed and deployed.

Australia has unique environmental conditions that make it attractive to deploy renewables energy generation in a large array of applications; however the intermittent nature of these energy sources has hampered the uptake and limited the penetration of these technologies. To expand the usefulness and the value proposition of renewables generation, a low-cost, high energy density energy storage system is required to address the intermittent issues.

A promising technology that has seen intense research and commercial interest is sodium-ion based batteries, which replace the relatively rare (<0.005 % of the Earth's crust) lithium with safe and abundant (2.6% of the Earth's crust) sodium. Several research groups – including the University of Wollongong's Institute for Superconducting and Electronic Materials – reported excellent capacity, cycling and manufacturing repeatability results from sodium-ion based batteries, and a number of commercial entities are in the process of bringing this technology to market. This provided a unique opportunity to develop this nascent technology and demonstrate its use and versatility in a number of energy storage systems.

PROJECT OUTCOMES

The S^4 Project commenced in April 2016 and was originally scheduled to finish in March 2020. Due to several unforeseen circumstances – in particular the withdrawal of a key battery production industry partner from the Project Consortium, and the COVID-19 pandemic and ensuing industrial and supply chain interruptions – the S^4 Project Activities continued through to December 2021. Significant progress was made throughout the S^4 Project against the initially-targeted Milestones and Deliverables, in particular through progress on:

- Critical sodium-ion batterie materials formulation and technologies,
- scale-up of sodium-ion battery production, and
- battery cell construction and demonstration.

The significant impact the S^4 Project has made is far beyond the original plan. The project has laid a strong foundation for the cutting-edge sodium-ion battery technology in Australia, and has positioned UOW and Australia in a leading rank for long-term exploitation of this potential energy storage alternative in the world. Furthermore, the experienced researchers and associated PhD graduates through the S^4 Project training are invaluable talent resources for Australia to remain at the forefront of the competitive field in the world.

S^4 Project background and context

The core focus of the S^4 project was to develop a sodium-ion battery chemistry and production capacity to bring the technology to pre-commercialisation in the energy storage marketplace. This included the value-add components of integrating sodium-ion battery cells into integrated modules with battery management systems, and demonstrating this technology in conjunction with a custom-developed Energy Management System coupled with renewable generation in residential and distributed infrastructure applications.

One of the key benefits of the sodium-ion battery technologies under development in the S^4 project is the cell manufacturing process is substantially similar to that of lithium-ion batteries. Although specific parameters, procedures and materials are slightly different, the same plant can – in theory – be used to manufacture either type of cell, and the expertise and knowledge garnered from developing lithium-ion battery manufacturing techniques can be broadly applied to sodium-ion batteries. This is a unique differentiator compared to other competing technologies (such as flow batteries, sodium aqueous, sodium-sulphur and others) where entirely different manufacturing techniques, plant and expertise is required to bring a product to market – along with developing the actual product.

MARKET OPPORTUNITY FOR STATIONARY ENERGY STORAGE

A comprehensive survey of the market opportunity for Energy Storage Systems was undertaken throughout the S^4 Project. The market for Energy Storage Systems (ESS) is increasing rapidly in Australia and many other regions around the world. There are many government schemes and incentives that encourage the deployment of ESS, and a wide range of commercial opportunities are becoming increasingly apparent. For example, the Renewable Energy Target (RET) scheme provides significant incentives for the installation of large-scale renewable energy generation capacity, which is largely intermittent in nature and therefore benefits from being coupled with large-scale energy storage. In the small-scale energy storage space, the elimination of Feed-in Tariffs for residential and commercial PV owners has led to a surge of interest in ESS for behind-the-meter (i.e. localised) applications.

There are a number of ways ESS can be deployed at a range of capacity scales (from several kWh up to tens of MWh) as outlined in Table 1

	Generation Level	Transmission Level	Distribution Level	Customer Level
Arbitrage	▲▲	▲▲		
Integration of Renewables to grid			▲▲	
Capacity firming	▲▲			
Curtailment reduction	▲▲	▲▲	▲▲	
Voltage Control		▲▲	▲▲	
Frequency Regulation		▲▲	▲▲	
Investment deferral		▲▲	▲▲	
Black starting		▲▲		
Peak shaving		▲▲	▲▲	▲▲
Time-of-use (TOU) Management				▲▲
Off-grid supply				▲▲

Table 1- Applications for Battery-based ESS[1], with the S^4 Project focus highlighted in red

The S^4 Project was developed from the outset to focus on the Residential and Commercial ESS (1-100 kWh capacity). The sodium-ion battery technology developed in the S^4 project is applicable to all scales of energy storage requirements, although the fundamental mass and volume premiums over lithium-ion batteries make it difficult to compete in the portable electronics area), ..

Current opportunity in Australia

The uptake of ESS at the residential and commercial scale is likely to primarily occur in concert with the installation of solar PV renewables generation, or as a retrofitted capability for existing solar PV installations. Most consumer-level ESS will be installed for time-of-use (TOU) energy management, with a small proportion being installed to take homes and businesses completely off-grid. Over 1.79 million homes currently have solar PV installed, and approximately 8% of all new solar installations in Australia in 2016 included battery-based ESS. In addition, 70% of solar PV system customers indicated they were considering installing an ESS. In total, over 6,750 new ESS were installed in Australia in 2016, 20,000 were installed in 2017, and this trend is anticipated to continue to grow rapidly.

[1] **EUROBAT - Battery Energy Storage for Smart Grid Applications**

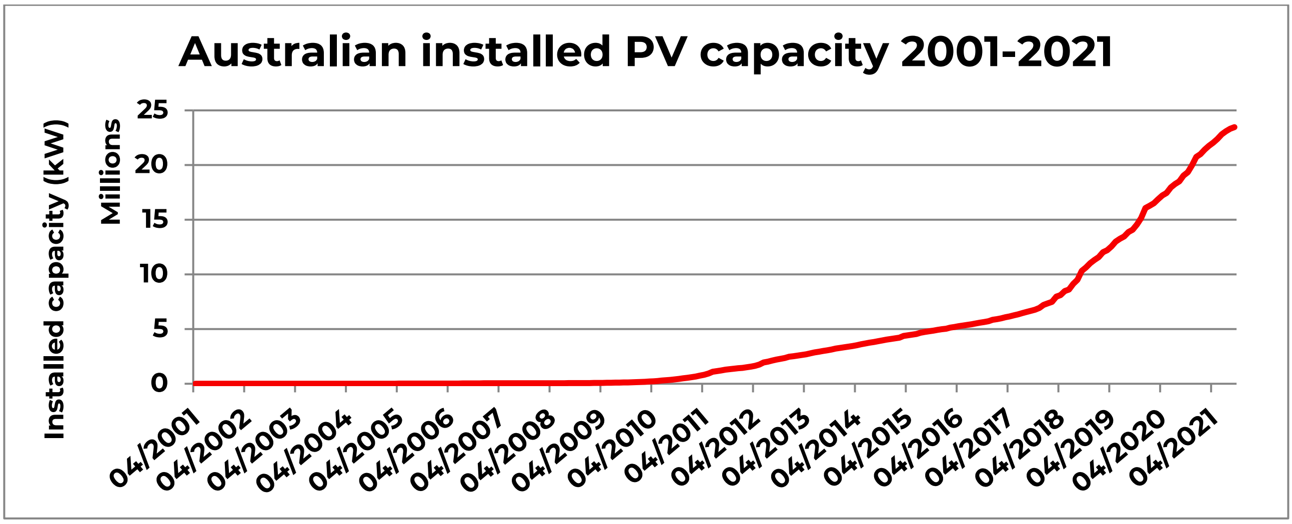

Figure 2- Australian installed PV capacity[2]

The average size of these installations is approximately 8 kW, which is consistent with most of these systems being installed in residential applications.

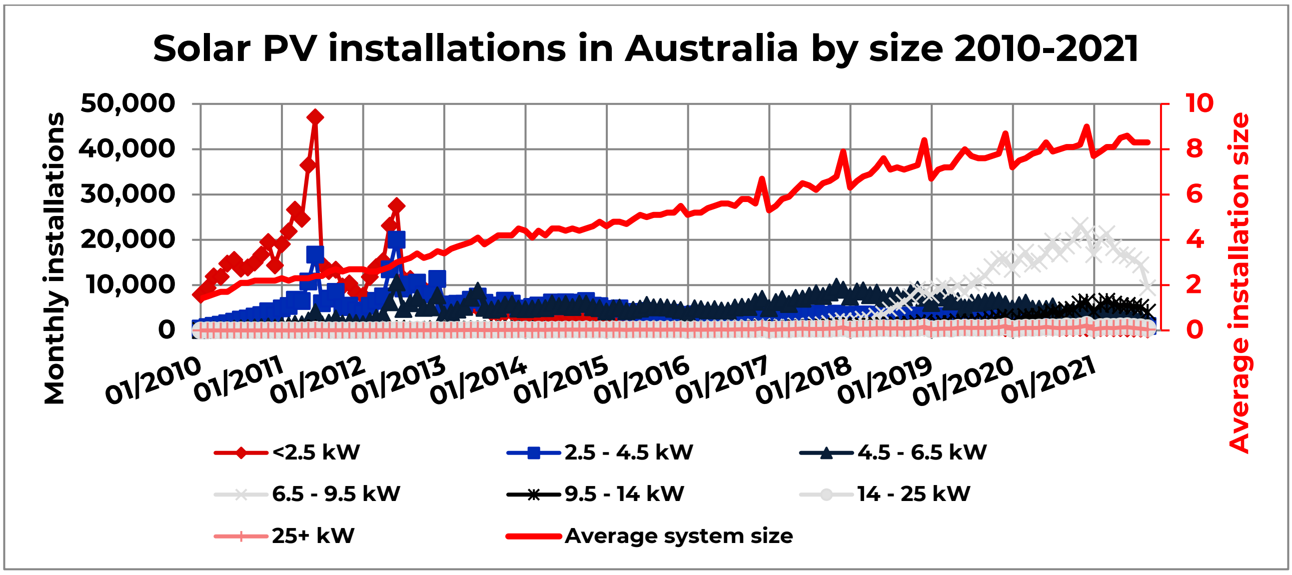

Figure 3 - Australian PV systems by size[3]

A typical Australian household uses approximately 16 kWh of energy per day, with a third of that being consumed during the day. A 6 kWh solar PV system coupled with a 10 kWh ESS would allow the household to self-generate 90% of their energy needs[4]. As such, it is anticipated the current market opportunity for residential battery-based ESS is up to 1.5 million 10 kWh systems.

The number of commercial-scale (i.e. 9.5 kW – 200 kW) solar PV systems is considerably smaller, approximately 76,000 as of 2019, and vary in capacity and application widely. For example, many commercial-scale systems are installed on office buildings or shopping centres that use energy primarily during daylight hours. As such, estimating the current market opportunity for commercial-scale ESS installations is problematic.

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[2] http://pv-map.apvi.org.au/analyses
[3] http://pv-map.apvi.org.au/analyses
[4] http://www.energymatters.com.au/solar-calculators/solar-battery-calculator.php

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Projected opportunity in Australia

There are a wide range of predictions and projections for solar PV and ESS uptake in the short- to medium-term future. For example, Bloomberg New Energy Finance estimate over 10% of global generating capacity will be small-scale PV by 2040, and in Australia that could be up to 50%[5]. Similarly, Energy Networks Australia (ENA) and the CSIRO have predicted there will be approximately 50 GW of solar PV and 65 GWh of battery storage installed in consumer applications by 2040[6]

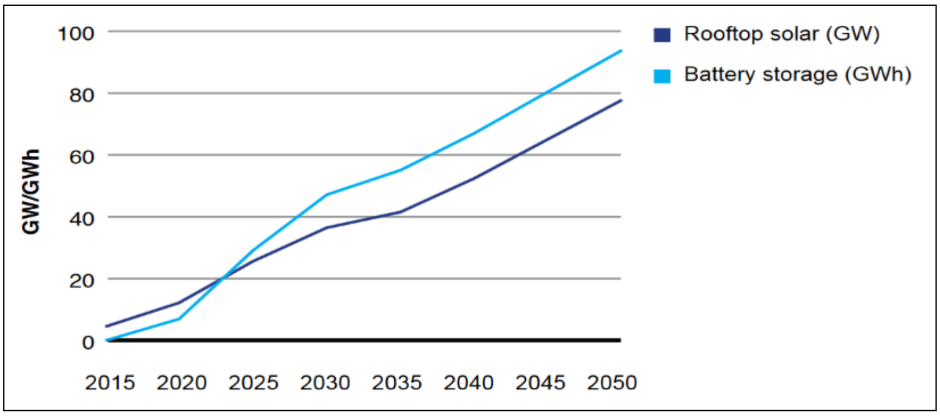

Figure 4 - CSIRO/ENA prediction for installed solar PV and ESS in Australia

Similarly, the Australian Energy Market Operator (AEMO) predicts 70 GWh of battery storage will be installed in Australia by 2037, with approximately 45 GWh of that capacity being in residential applications[7].

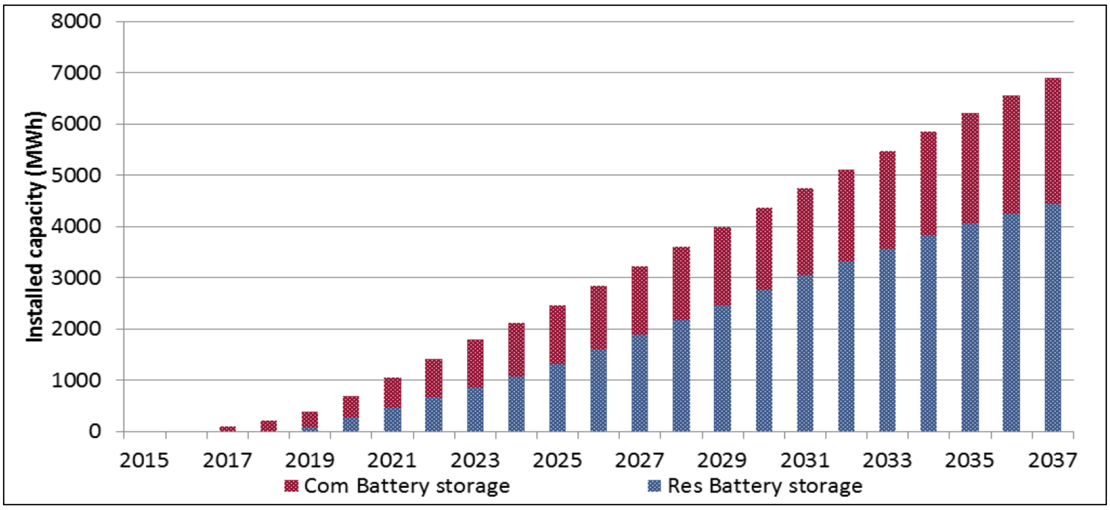

Figure 5 - AEMO prediction for installed ESS in Australia

Tesla, one of the major battery-based ESS suppliers in Australia, predicts 100 per cent of homes with solar PV installations will have battery-based storage within 10 years[8]. This is an extremely optimistic prediction, however it does highlight the confidence in the market displayed by the largest ESS supplier.

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[5] **Bloomberg New Energy Finance -** ***New Energy Outlook 2016***
[6] **CSIRO/ENA -** ***Electricity Network Transformation Roadmap: Key Concepts Report***
[7] **AEMO –** ***Projections of uptake of small-scale systems***
[8] **http://reneweconomy.com.au/tesla-launches-powerwall-2-says-all-solar-homes-will-have-storage-53696/**

Projected opportunity worldwide

China added 34.2 GW of Solar PV generation in 2016[9], and is predicted to reach 236.7 GW of installed PV by 2025[10]. China currently uses a feed-in tariff (FIT) arrangement similar to the scheme recently phased-out in Australia for residential PV installations, and appears to be rolling back its FIT prices for 2017 currently[11]. China will likely phase out the FITs by 2020[12], which will further increase the demand for ESS at residential and commercial scales.

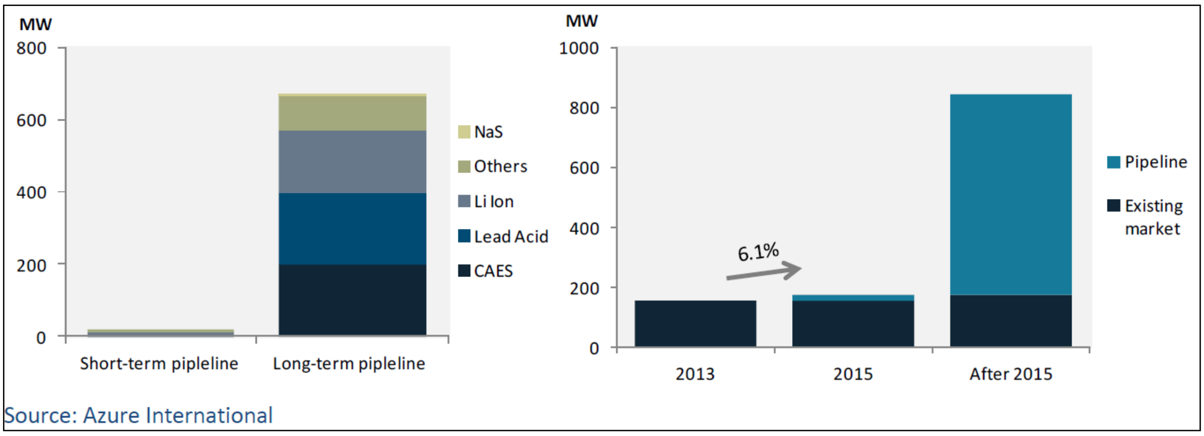

Figure 6 - Pipeline and projections for energy storage in China[13]

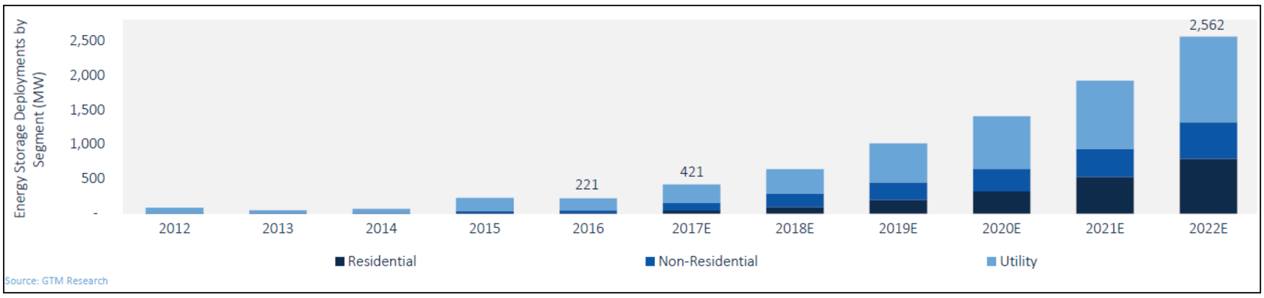

Figure 7 - Projected energy storage demands and applications in the USA[14]

In dollar terms, a BNEF report outlines a number of encouraging signs in the energy storage market, which has led to predictions of a market valued at $250 billion or more by 2040[15].

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[9] The Climate Council - *State of Solar 2016: Globally and in Australia*
[10] http://asian-power.com/ipp/news/chinas-installed-solar-pv-capacity-predicted-almost-quadruple-2025
[11] https://www.pv-tech.org/news/chinas-nea-proposes-significant-solar-feed-in-tariff-cuts-for-2017
[12] https://cleantechnica.com/2014/10/17/china-phase-financial-support-solar-power-sector-2020/
[13] Energy Storage World Forum – *Energy Storage World Markets Report 2014-2020*
[14] Green Tech Media – *Energy Storage Market 2017*
[15] Bloomberg New Energy Finance - *New Energy Outlook 2016*

Major achievements and outcomes

The S⁴ Project Consortium made tremendous efforts, contribution and dedication to the delivery of the Project Milestones. The vast majority of the project Milestones were completed, and a brief outline of the core outcomes from the S⁴ Project are summarised in this section.

SIB MATERIALS DEVELOPMENT

Although the original proposal had paid some attention to the development of the sodium-ion battery architecture and overall system, early in the project activities it became apparent additional focus on the core sodium-ion battery materials was also required. This was important and realistic decision. Figure 7 shows the brief schematic of the sodium-ion battery (SIB) cell materials. Same as LIB the SIB has three main components: anode, cathode and electrolyte. The S⁴ Project has focussed on material development - in particular cathode and anode materials, lab cells and industry cells. These are the building blocks for battery cell construction and pack applications. We have screened all options for applications in early-stage work. Through this foundational work we have identified two candidates for cathodes: layered oxides and Prussian Blue, and hard carbon for the anode. The choice of two cathode materials has diversified our effort with the limited funding that is one of the technical problems we have faced. Other materials were investigated through other PhD student projects alongside S⁴ Project activities as complementary efforts.

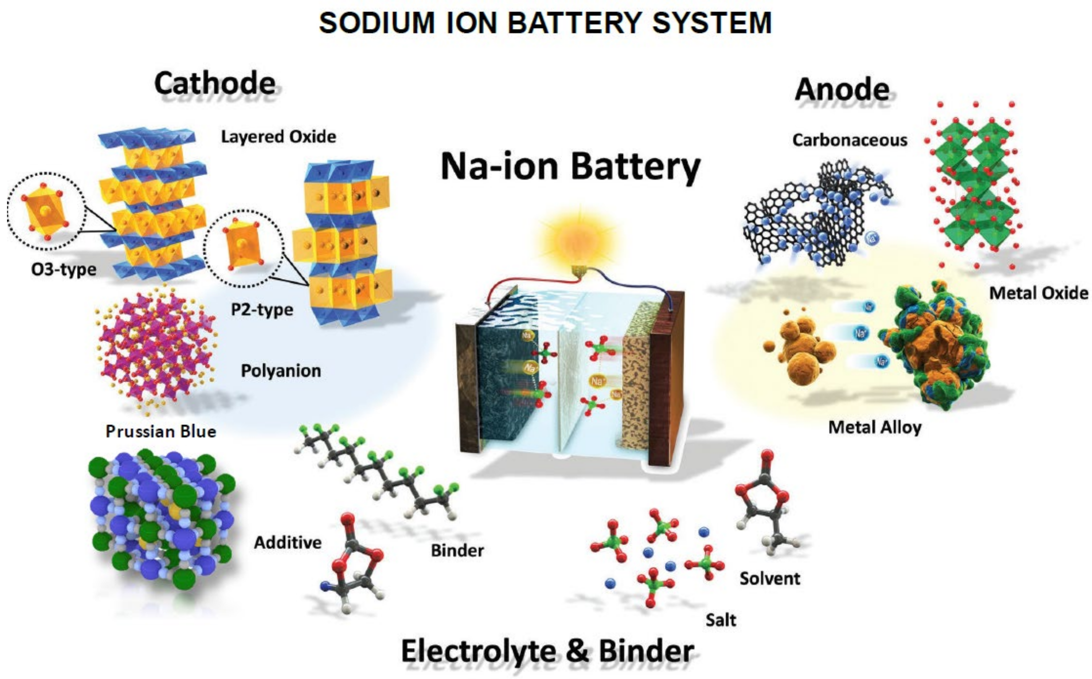

Figure 8 - SIB system (Joule, 2018, 2, 1-11)

Special attention was paid to study oxide based cathode with clear target to reduce the cost by using low cost abundant materials such as iron, manganese, magnesium and copper instead of nickel and cobalt. Low-cost iron and manganese-based sodium transition metal oxides have been successfully developed and evaluated as high-performance cathode materials for sodium-ion batteries. One of important advances we have made is to identify oxygen anionic redox reaction that may happen at high voltage, providing extra capacity to the ordinarily basis of transition metal reduction and oxidation processes. But this anionic redox is not easy to stabilise so some efforts have been made to solve this problem and good progress was made at least at lab scale. The cycle life may require more work.

Prussian Blue consists of (PB) only of low cost elements iron, manganese, phosphor and carbon and one of best option for cathode of SIB. A great effort has been made to optimise the compositions, processing routes and various phases and structure. Through series of joint efforts from both lab work and factory work coprecipitation technique was optimised to provide reproducible processes for PB cathodes. One of important advances is to stabilise the second sodium atom to be able to participate in the cathode reaction without structure damage. This gives a capacity of 140mAh/g, very close to that for lithium iron phosphates in LIB. A number of strategies have been tried to stabilise the structure during the second sodium ion participating the redox processes.

A significant progress has been made to search for low-cost materials options. One option is the iron-phosphor based sodium super ionic conductors consisting of sodium, iron, phosphor-oxygen system which has displayed extraordinary long cycle life at 4400 cycle with > 70% retention.

In anode research a number of candidates have been explored including carbon based materials, sodium titanates, phosphor and various alloys. Development of double shell structure with sulphur doping for sodium titanates delivered superior performance at high rate capacity at 10 C for 15000 cycles. This anode is particularly useful for safety applications. Some trace amount of elements can have a significant effect for improvement of the electrode performance. For example, the small amount of sulphur doping in this anode has dramatically reduced the energy gap so improve the electronic conductivity, leading to high rate performance.

Elemental phosphorus (P) is the most promising anode materials for SIBs with the highest theoretical capacity of 2,596 mAh/g, but the commercially available red phosphorus cannot react with sodium reversibly. Novel phosphorous-based alloy anodes for SIBs were prepared in large quantities by direct low-speed ball milling, achieving superior high rate capability, with a stable capacity of 165 mAh/g at the 10C rate. The practical application of red phosphorus for SIBs is retarded by its poor reversibility and its unstable cycling life derived from its poor conductivity and huge volume expansion. Graphene is considered as an ideal matrix to remedy these weaknesses due to its excellent conductivity and two-dimensional structure. Its $\pi-\pi$ restacking causes spatial collapse. Multifunctional titanium nitride (TiN) is introduced into a phosphorous composite to fix this issue. TiN acts as conductive pillars, electron transfer bridges, and a chemical adsorbent of phosphorus in the composite, to prevent the graphene nanoplates from restacking to bridge gaps between the graphene nanoplates, and to chemically adsorb the phosphorous, resulting in the formation of a three-dimensional electronic network and endowing the pulverized phosphorous particles with excellent performance for SIBs.

The main emphasis for anode was put at hard carbon study and scale-up. In close collaboration industry partner Hong Cheng Electric Power Co., Ltd. we have achieved the performance of hard carbon to the best commercially available products,

SCALING UP FOR LARGE BATCH PRODUCTION:

Scale-up synthesis is not feasible by simply multiplying the amount of raw materials. Some of the parameters need to be taken consideration, such as homogeneity of solution, temperature variation, etc. It is a process of trial and error. The optimized synthetic route is capable to produce kilogram to ton scale product at low cost. Competitive energy density has been achieved and expected to be usable in stationary energy storage devices. Aside from extensive lab optimization, our main efforts have been devoted to scale-up of material production that is a very challenging process – from lab-scale milligram manufacturing to industry-scale kg-100kg manufacturing. Substantial experiences and expertise have been established through all these processes. The second part of the S^4 project is the industry cell design, scale-up and production. This requires not only the technology but also demands large-scale facilities to be established.

This has been a serious problem after the withdrawal from the Project Consortium of McNair, as McNair is main party responsible for scaling up battery cells production. Hong Cheng Electric Power Co., Ltd. filled in this huge gap by investing significant CAPEX and in-kind to establish SIB production facilities. Hebei ANZ has also equipped with the production facilities for oxide material system manufacturing.

SODIUM-ION BATTERY AND ENERGY MANAGEMENT SYSTEM TESTBED AND DEMONSTRATORS

Two sites were selected to demonstrate the sodium-ion battery packs and technologies – a ‘residential’ demonstrator in the University of Wollongong’s *Illawarra Flame House*, and a ‘distributed infrastructure’ in Sydney Water’s *Bondi Sewage Pumping Station*.

The Illawarra Flame House was designed, developed and built by a student-led team at UOW’s Sustainable Buildings Research Centre as part of the international Solar Decathlon competition. The team took up the challenge of choosing to demonstrate how to retrofit a 'fibro' home, to transform it into a sustainable 21st century net-zero energy home. The aim was to upgrade an existing building to inspire Australian homeowners and the local and national building industry, and to accelerate the development and adoption of advanced building energy technology in new and existing homes. The Illawarra Flame house is currently set up on the University of Wollongong’s Innovation Campus (iC), within walking distance of the ISEM and SBRC facilities.

The Illawarra Flame house has a 9.4 kW solar PV system installed and has the infrastructure in place to integrate a battery storage system into the existing building management system. The SBRC has extensive historical data on the generation capacity of the PV system, and usage data on the house when occupied.

A laboratory-based testbed was developed as part of the S^4 Project Activities to operate as a “twin” of the Illawarra Flame House renewable energy generation and storage system – replicating the core components and providing an offline and controllable apparatus for characterising and operating the S^4 SIB packs and EMS. Doing so afforded the capability of running tightly-specified load and insolation profiles at arbitrary times (rather than waiting for actual insolation during daylight hours), and the opportunity to run identical test protocols repeatedly to allow comparing and contrasting key component behaviour.

Figure 9 – Illawarra Flame House ‘lab twin’ system developed as part of S^4 Project activities

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SODIUM-ION BATTERY MODULES

Two sodium-ion battery packs were produced by Hebei ANZ, containing sodium-ion batteries with oxide-based cathode chemistry. The sodium-ion battery packs were characterised using the Illawarra Flame House 'lab twin' testbed.

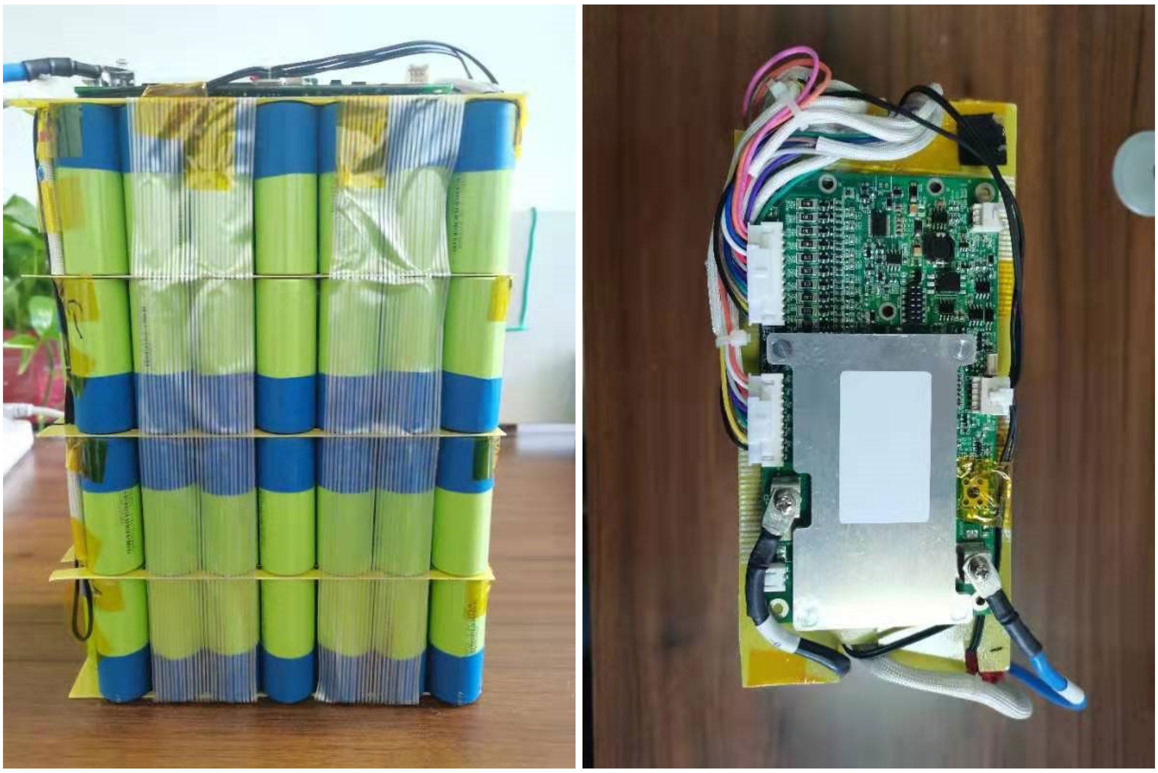

Figure 10 – internals of the sodium-ion battery packs, including the cells and battery management system

RESEARCH TRAINING OF FUTURE TALENTS FOR SIB R&D

Although not explicitly targeted by the outcomes and objectives originally set for the S^4 Project, the Project Activities have resulted in a significant expansion and upskilling of Australian sodium-ion battery expertise, as over the project duration more than forty researchers – including post-graduate researchers, post-doctoral researchers, and senior staff – have participated in Project Activities. This participation has covered the gamut from cutting-edge laboratory-based research to developing industrial battery materials production processes, and from developing innovative energy management algorithms through to specifying and characterising renewable energy generation systems for distributed infrastructure applications.

A number of researchers have built their expertise and experiences through the project and have taken leadership role in Australia and overseas. This is important for Australia to explore further commercial exploitation of the SIB energy storage technology. In addition to the seven chief investigators eleven researchers have been employed in full or part time on the project. Ten PhD students have worked on the project in full time and part time capacity. Alongside the S^4 Project there have been more than ten researchers and PhD students working on the project closely related to S^4 Project but on more fundamental nature. The S^4 Project has generated the largest group of researchers and experts in the SIB storage field in Australia and one of largest in the world. These researchers will make significant contribution to the whole energy storage field in the coming years.

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BROAD IMPACT OF THE S^4 PROJECT

The S^4 Project has made enormous impact on the research and development of the sodium ion battery (SIB) technologies. The significance of the S^4 Project far surpasses the original plan. Most important outcomes of the ARENA project is the demonstration of feasibility of SIB technology as one of most significant alternatives to LIB in energy storage field.

The significant research achievements on SIB materials, scale-up production technology, system design and construction have been well established throughout the project activities. The project has made substantial advances and breakthroughs in broad aspects of SIB, in particular in materials areas which should actually be the central theme of our research and still are main focus of >95% SIB R&D in today's world. These outstanding outcomes have laid a strong foundation in a critical field of SIB storage for Australia and UOW to remain at leading position of this cutting-age technology in the years to come.

This project has acted as a driver, stimulator, promotor and pioneer in the advancements of the SIB technology in Australia and the world. From the published data on SIB from 2016 to 2021 it is clear that the S^4 Project has put UOW and Australia within the world top four and five in terms of research outputs among all the countries and institutions, respectively. UOW has contributed to Australia in the research outputs – currently standing at more than 40%. This would not have achieved without the S^4 Project activities. When we evaluate a project success, we must pay great attention to the overall impact and significance.

Knowledge Sharing

A core focus throughout the S^4 Project has been the dissemination and sharing of knowledge related to sodium-ion batteries, renewable energy generation and storage technologies, energy resilience in distributed infrastructure and residential applications, and the value of Australian innovation in the energy materials and storage space.

A comprehensive Knowledge Sharing Plan was instituted and implemented throughout the S^4 Project to ensure stakeholders were engaged in a tailored manner.

SCHOLARLY PUBLICATIONS

The core of the knowledge sharing activities consisted of publication of scholarly articles and participation in industry-specific conferences – positioning Australia at the forefront of sodium-ion battery research and development.

The S^4 Project has generated enormous research outputs from Australia. Details from the Clarivate Analytics *Web of Science* database shows 84 high quality publications from 2016-2021 in the sodium-ion battery area, which have attracted more than 6,400 citations and h-index of 45. In particular, there are 14 'highly cited' publications among these published papers, which have made strong impact on the broad research community of energy storage field.

As a targeted method of building a critical mass of sodium-ion battery research in Australia, several review papers (Energy Environ. Sci., 2021, 14, 158; Adv. Funct. Mater. 2020, 30, 1909530; Small 2019, 15, 1805381 etc.) were published – outlining the progress, challenges, perspectives, and commercialization of transition metal oxides and Prussian blue and its analogues as cathode materials for sodium-ion batteries. Again, some have been selected as highly-cited papers, which indicates the importance of the S^4 Project in frontier research. Instructive information and guidance are provided to proceed the development of high-performance electrode materials for sodium-ion batteries. For example, various elements have been involved in the study and development of sodium transition metal oxide cathodes for sodium-ion batteries, which has been summarized in the Energy Environ. Sci., 2021, 14, 158, highly cited paper.

INDUSTRY ENGAGEMENT

The partnership with Sydney Water on this project opened opportunities to understand and work with the unique requirements for energy resilience within the utility and distributed infrastructure sectors. Knowledge sharing and engagement with organisations and industry groups in these sectors was achieved through a multi-faceted strategy – including authoring articles in industry magazines, presenting at the OZWater conferences, hosting a booth at an energy industry conference, and participating in a 'technology roadshow' presenting to the major Australian water utilities.

This engagement strategy has resulted in additional engagement within the Australian water utility space, with projects around renewable energy generation and storage, and in energy resilience solutions.

PUBLIC ENGAGEMENT

A key component of the S^4 Project Knowledge Sharing Plan was to engage and inform the public on sodium-ion battery technology and project developments specifically, and on the value of renewable energy storage technologies and solutions in a range of Australian applications. An S^4 Project website was developed and taken live early on in the project, with articles and 'explainers' aimed at informing members of the public and other stakeholders in the critical details pertaining to the S^4 Project.

Lessons Learned

A range of technical, commercial and organisational lessons were learned throughout the delivery of the S^4 Project.

➢ THE PROJECT OUTCOMES WERE AMBITIOUS

We must admit that the research team was somewhat over-optimistic on SIB commercial prospect when we put the initial project proposal to ARENA. This was partly due to misleading information of the rapid increase in battery materials prices, in particular lithium price more than tripled in 2015-2016. This skyrocketing increase in lithium price gave us a strong impression that lithium-ion batteries could not sustain the high demands on energy storage, opening the door for alternatives to be developed as a matter of urgency. We expected the speed of SIB commercialisation will be in next 5 years so this is overly optimistic at that time. So, we should learn from this that we need to have more information and careful analysis on the goal settings when a project is at planning stage.

➢ UNDERSTIMATE THE TECHNICAL CHALLENGES

We had underestimated the technological challenges as we would expect most LIB technologies and production methodologies could be simply adopted to SIB. Although there is only one major difference that is change from lithium to sodium as central element of the battery materials. This has caused a significant change of the requirements for all materials associated with SIB including cathode, anode and electrolytes. The ARENA assessment committee had objective feedback to our proposal as ambitious for targeting such large packs at that stage. We felt that their comment was correct and we should have accepted their comments and reschedule our goals setting on packs. But we faced serious problem with two key industry partners: Sydney Water and Hong Cheng Electric Power. They would decline from the project if there were no energy storage packs as main outcomes as they are the key end-users and only join in if they can have benefits to demonstrate the energy packs at their premise. This is why we have ended up with the most challenging milestones, in particular for the last milestone with these two packs. Upon reflection, the S^4 Project should have primarily focussed on the development of electrode materials, scale-up and at the most to demonstrate industry-level single cells, rather than the commercial level packs with our limited funding. This lesson is difficult one the partners participation is critical.

➢ PARTNERS' WITHDRAWAL

- ➢ McNair withdrew in the end of 2018. This had serious impact for the battery cell scaling up and batch production as McNair which has well established cell production line for lithium-ion batteries that is very close to sodium-ion battery production. We have underestimated the impact on the scaling battery production as a result of the withdrawal of this main industry partner.
- ➢ Hong Cheng Electric Power is not a battery company and has no any expertise and experiences on battery production, while Hebei ANZ is battery materials company with only small scale LIB production line. Hebei ANZ is committed to deliver the final two packs with its battery production line.
- ➢ The two Industry Partners have made enormous efforts to deliver the final milestones for the SIB packs. There have been several serious problems to make consistent cells as either companies are not in the battery production companies and have not well-established facilities. Hong Cheng is Power Grid Company and has indeed invested more than $A10m to establish the battery production facilities but these are mainly second hand facilities and consistency of the cell production is very difficult. However, Hong Cheng has decided to close its battery line in March 2021, which will no longer be able to produce batteries.
- ➢ From our experiences one should carefully evaluate the partner companies financial status and reliability in the planning processes.

➢ COVID-19 IMPACT

- ➢ Due to the impact of COVID-19 the two industry partner companies had stopped for around four months and there was still serious restriction even after returning to work. This has caused serious delay on full production process.
- ➢ In addition there are problems for supply chain due to both the lack of commercial availability of supplies of parts as SIB is not on commercial stage and there is not standard and established supplies such as electrolytes and COVID -19 restriction which has further made the situation more difficult.
- ➢ There is transportation issue as there is no routine flights between Australia and China. Prolong transport processes and great uncertainty may cause damage of the battery cells during long storage in the transportation.

➢ MANAGEMENT OF COMMERCIAL RESEARCH PROJECT IN ACADEMIC ENVIRONMENT:

It has been very difficult task to manage the research incentives of researchers and PhD students for the goals of ARENA project. As ARENA project is targeted on commercial applications that is either demonstration of devices and scaled production of materials. However, the purpose of the research fellows and PhD students is to publish papers that will be essential for them to get job after postdoc or PhD completion so the incentives for applications that do not result in publication is very low. So some of the fellows and PhD students are not well committed to the ARENA project goals so this is one of common problems for most commercial project at university environment. We still do not have a good solution as it is difficult to hire a fellow who is not committed on publications.