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1 PROJECT DETAILS

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2 DEFINITIONS

AEMO	Australia Energy Market Operator
AC	Alternating Current
ARENA	Australian Renewable Energy Agency
BMS	Battery Management System
BESS	Battery Energy Storage System
DC	Direct Current
EPC	Engineering Procurement Construction
FCAS	Frequency Control Ancillary Services
KV	Kilovolt
KW	Kilowatt
KWh	Kilowatt hour
MASS	Market Ancillary Services Specification
MW	Megawatt
MVA	Mega Volt Amp
MVAr	Mega Volt Amp Reactive Power
MWh	Megawatt hour
MWp	Megawatt Peak
MPPT	Maximum Power Point Tracking
MVPS	Medium Voltage Power Skid
MVT	Medium Voltage Transformer
OEM	Original Equipment Manufacturer
PCS	Power Conversion System
PPM	Power Plant Manager
PV	Photovoltaic
SAPN	South Australia Power Networks
SCADA	Supervisory Control and Data Acquisition System
SVG	Static VAR (Volt-Ampere Reactive) Generator
VFB	Vanadium Flow Battery
W	Watt

3 EXECUTIVE SUMMARY

This report gives an overview of the process and learnings acquired by the Yadlamalka project team for the design, development, delivery and commissioning of the collocated PV plant and Vanadium Flow Battery system located in Port Pirie, South Australia.

The report provides a description of the innovative system architecture that was developed for the project. Combining PV to battery direct DC coupling and Vanadium Flow Batteries (VFBs) had not been done before in Australia or globally.

An account of the design, delivery and commissioning phases performed by the project team during the last 3 years by the is given in the report. Lessons learned during each phase are outlined for the benefit of future projects.

The project demonstrated that VFBs and PV DC couples systems could be integrated successfully. The project team developed the key design and development knowledge required to create such a system. Challenges were overcome in electrical and control software engineering as well as in production and supply chain management for the delivery of the system. Installation and commissioning on site brought DC coupling systems from theory to practice, resulting in a renewable energy asset that meets the requirements for commercial trading and the supply of ancillary services on the South Australia grid.

This report is part of the knowledge sharing activities as specified in the agreement between ARENA and Yadlamalka Energy.

Figure 1: Aerial view of the Yadlamalka Vanadium Flow Batteries

4 PROJECT OVERVIEW AND OBJECTIVES

Ther Yadlamalka Energy project comprises co-located Vanadium Flow Battery (VFB) energy storage system (2 MW – 8 MWh AC) and Solar Photovoltaic (PV) plant (6 MWp DC), integrated behind a DC-coupled Power Conversion System (PCS). It is located at Port Pirie, South Australia.

This architecture presents significant advantages. Vanadium is abundant in Australia and worldwide. The water-based chemistry of VFBs offers a safe alternative to Lithium batteries, particularly in hot climates. VFBs do not degrade with cycling and have an estimated life of 25 years. The VFBs use for the Yadlamalka project have nominal power of 2 MW for 4 MWh of energy capacity. The PV plant has a peak power of 6 MW. The Power Conversion System (PCS) assuring the connection of both PV and batteries to the SAPN grid has a rated power of 4.6 MVA. The batteries maximum power reaches nearly 3 MW, providing flexibility to operate both in energy trading and FCAS services.

The project will supply a combination of solar power and battery storage services to the grid. The vanadium flow battery will take advantage of the significant intraday price variation in South Australia to time shift power from midday to peak periods in the evenings and mornings. The project will also participate in the Frequency Control Ancillary Services (FCAS) market which helps maintain stability of the South Australia electrical grid operated by SAPN. Beyond the renewable energy generation and storage investment, the project demonstrates an alternative energy system combining storage and power generation, using a particularly innovative solution: direct DC coupling architecture combined Vanadium Flow Batteries (VFBs).

Direct DC coupling allows the batteries and the PV to share a common PCS, connected to a single point of connection to the grid instead of the two points of connections that such a PV plus battery system would usually require when using a more conventional AC coupled architecture. This allows the operator to maximize generation and storage for a single point of connection. The batteries and the PV plant are connected directly in DC instead of AC. This allows the PV to charge the batteries directly using DC current, avoiding DC to AC conversion found in conventional architectures, thus reducing energy losses during charging.

VFBs are used for energy storage instead of the more conventional lithium batteries. DC coupling had already been done using lithium battery technology, but the Yadlamalka project is the first time this coupling method was used with Vanadium Flow Battery technology. VFBs present significant advantages in terms of energy security, operational safety and flexibility in operation. VFBs use vanadium, an abundant metal with significant, albeit not fully exploited yet, deposits in Australia. Batteries using vanadium-based electrochemistry are future proof technology for Australia energy security. The significant safety advantage of VFBs resides in the extremely low fire risk they present compared to lithium batteries. VFBs use a water-based electrolyte that negates any chemical fire hazard, even in case of intensive duty cycles in high temperature conditions. They offer flexibility of operation because power and energy capacity are decoupled, allowing longer duration. In the case of the

Yadlamalka project, the Invinity VFBs batteries have a nominal discharge duration of 4 hours at 2 MW AC power at the point of connection to the grid. They can be charged and discharged at up to 2.95 MW DC power. VFBs do not degrade with cycling and do not degrade with each cycle, offering the flexibility of doing multiple cycles per day without shortening the life of the batteries. The long duration is very well suited to extending energy arbitrage capabilities over several hours. It also extends the time during which FCAS services can be supplied.

The project team anticipated challenges with the electrical integration of this new type of batteries with off-the-shelf Power Conversion System (PCS) that is typically designed to be coupled with shorter duration batteries such as lithium-ion. The hot environmental conditions were also a concern, despite the fact fire risk is extremely low, the battery's electrolyte temperature still needs to be maintained within operational range. These challenges were addressed early in the project through a test lab trial with the PCS, and digital modeling of the batteries in terms of electrochemistry behavior in hot conditions. Response time of the system for FCAS services, combined PV and battery power flows were also identified as potential challenges and validated through analysis.

The principal objective of the project is to demonstrate the innovative solution constituted by direct DC coupling between PV and VFBs on a single point of connection can be used to deliver an enhanced commercial model, compared to PV only, for energy trading and ancillary services and the South Australian grid.

5 SYSTEM SPECIFICATIONS AND ARCHITECTURE DESCRIPTION

5.1 System Location and Characteristics

Yadlamalka Energy Pty Ltd's Spencer Energy Project is located at 375 Gulf View Road, Bungama SA 5540 South Australia. The installed generation system has a capacity of 4.6 MVA (SMA Sunny Central SC 4600 UP inverter) and comprises of a 6.01 MW DC solar PV system and a 2950 MW DC / 9.02 MWh DC-coupled battery storage system. The generation system is directly connected to the South Australia Power Networks (SAPN) Bungama - Gladstone 33 kV line via the onsite 0.69/33 kV step-up transformer.

The solar PV system consist of 11,128 × 540 W peak Longi solar PV panels which are connected to multiple DC combiner boxes on site. Each of the DC combiner box is then directly connected to the SMA Central SC 4600 UP inverter.

The 9.02 MWh DC Battery Energy Storage System (BESS) consists of 41 x 220 kWh DC Invinity Vanadium flow batteries split across six (6) DC-DC converters (SMA DPS-500) with each of these DC-DC converters directly connected to the SMA Central SC 4600 UP inverter.

5.2 System Specifications

The Yadlamalka PV and VFB system specification are as follows:

Parameter	Specification
Rated Storage Capacity AC	8,000 kWh AC
Rated Battery Storage Capacity DC	9,020 kWh DC
Rated Battery Power Charge AC	2,000 kW AC
Rated Battery Power Discharge AC	2,000 kW AC
Max Battery Power Discharge AC	2,850 kW AC
Max Battery Power Charge AC	3,200 kW AC
Max Battery Power Charge/Discharge DC	2950 kW DC
Number of VFB Containerised Units	41
DC Power per VFB Unit	75 kW DC
Energy Capacity per VFB Unit DC	220 kWh DC
RTE DC	>75%

5.3 Architecture Description

The Yadlamalka Energy project benefits from a novel architecture that uses direct DC connection of the PV plant to the VFB energy storage system, called Direct DC Coupling, that removes conversion to AC between PV and batteries. The principle of Direct DC Coupling is to have PV and batteries connected to the common DC bus of the PCS. Since PV and batteries have different voltages, DC-Converters are implemented between the batteries and the PCS.

The first advantage is that a single PCS can be shared by the PV plant and the battery storage system, using a single point of connection to the grid. Without Direct DC Coupling, collocating a PV plant and a BESS, that are both generating DC power, the DC to AC conversion for their connection to the AC grid would have required an inverter for the PV and a separate PCS for the BESS, with a separate point of connection for each. With DC coupling, a single PCS passures the bi-directional DC-AC conversion for both PV and BESS, necessitating only one point of connection to the grid. The second advantage is that all excess PV generation that is not exported to the grid can be charged directly into the batteries, without resorting to a DC to AC conversion between them. Directly charging PV to batteries is more efficient, since there is no conversion from DC to AC and back in this operation. Typical AC-DC converters, inverters or PCS, would typically have an efficiency of 98%. AC coupled system would go twice through the conversion, or 4% losses on all energy transferred from PV to batteries. With Direct DC Coupling, these losses are reduced to the 2% losses in the coupling DC-DC converters. A third advantage of Direct DC Coupling is that it maximises the PV array power compared to conventional AC coupled solutions. AC coupled solutions have a PV array peak power usually set circa 105 to 115% of the rated power of the PCS. The innovative architecture for the Yadlamalka power plant allows for a PV array sizing of 130% of the rated power of the PCS. This greater PV array sizing allows for a proportional increase of the yearly power output for the same 4.6 MW PCS. This output is further maximized due to the flow batteries technology that can be cycled several times a day if required. Compared to a PV only generator, the Yadlamalka solution maximises power harvesting from the PV array and enables nearly no power loss from the PV array.

The way Direct DC coupling works can be summarised as follows. The role of the DC-DC converters is to manage the batteries DC voltage for charge and discharge, regardless of the main DC bus voltage that is determined by the PV plant. The main DC voltage of the PCS follows the MPPT tracking to maximise PV generation. However, to charge or discharge, the DC voltage that the batteries are connected to must be controlled to specific points: above battery voltage to charge, below to discharge. The control of the batteries' connection DC voltage is assured by the DC-DC converters installed between the batteries and the main DC bus of the PCS.

The power conversion equipment required for this architecture consisting in the PCS and the DC-DC converters was procured from a SMA, a global OEM of inverters and PCS equipment. The PCS is grouped on a common skid with the Medium Voltage Transformer (MVT), constituting a Medium Voltage Power Skid (MVPS). SMA also supplied the Power Plant Manager and associated software that manage the power contribution of the PV and the batteries to fulfil the power setpoint requirements set by the Dispatch Optimiser. There are 41 VFB containerised units, each of them includes 6 individual VFB modules, for a total of 246 VFB modules. The 41 VFB units are divided in 6 clusters, 5 comprising 7 units and one of 6 units. The units in each cluster are connected to DC-DC converter. All 6 DC-DC converters are connected to the PCS DC bus, alongside with the PV plant. A diagram of this architecture is represented in Figure 2 below.

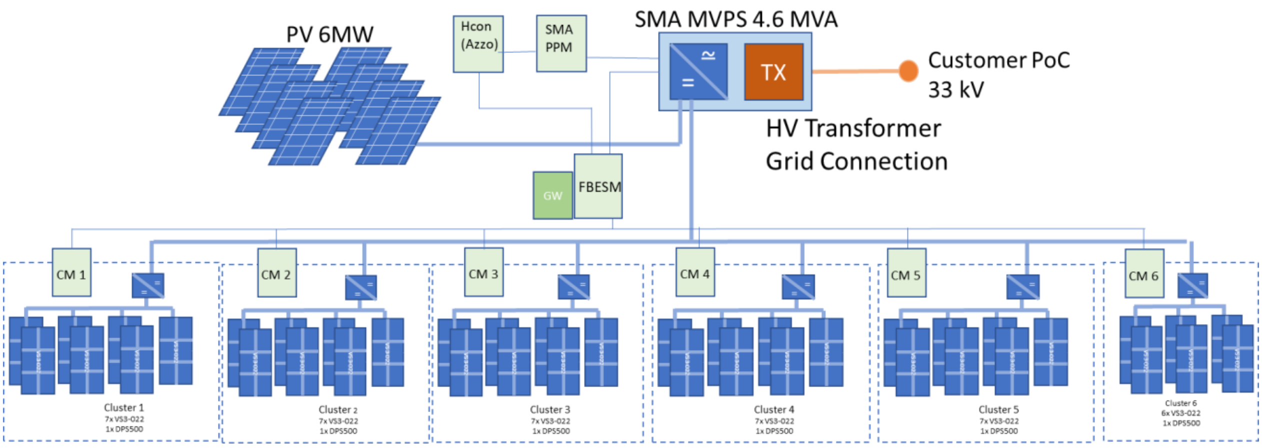

Figure 2: PV and VFB System Architecture

5.4 Grid Connection and Metering

The DC coupled architecture described above allows both PV and VFB energy storage system to be connected to the grid using a single point of connection. An SAPN approved meter is installed at the point of connection to measure energy and power exported/imported to/from the grid. The connection is equipped with a Static Var Generator (SVG) to manage the power factor at the point of connexion. In addition, SAPN has implemented a control device that can override the operators control system to for example curtail PV or battery export if required by the network. Internally to the system, 6 DC meters are installed at the connection of the 6 DC-DC converters between the battery and the inverter DC bus. This allows an accurate measurement of power and energy that charged/discharged into/from the batteries. In addition, power and frequency measurements are done by the PCS. This allows the PCS controls to respond to frequency variations accurately and within the required response time for FCAS services.

5.5 Battery System Layout

There are 41 Vanadium Flow Battery units, each unit is materialised in the form of a standard 20 ft container. The VFB units are stacked 2 high and arranged in 2 parallel rows as shown in Figure 3 below. Safety of personnel during installation, commissioning and maintenance is the primary factor in defining the layout of the system. The layout design was done in accordance with Invinity's specifications. For example, a 2 meters distance is kept between containers to allow ease of access for equipment and personnel, and all electrical and control panels are located at ground level. The MVPS, that includes the PCS and the MVT, is located centrally to optimise the DC power cabling network. The 41 VFBs are connected in 5 clusters of 7 units and 1 cluster of 6 units. All the VFB units from each cluster converge into a DC recombiner that is in turn connected to one of the 6 DC-DC converters used for DC coupling. The DC recombiners and the 6 DC-DC converters are located centrally, close to the MVPS, again to optimise the cabling network. Shading was initially considered for all equipment on site: MVPS, DC-DC converters, batteries and interconnection panels. After careful thermal modelling and analysis of the energy flows, ambient temperatures and taking into account solar gain, if was found that shading was only required on the interconnection panels.

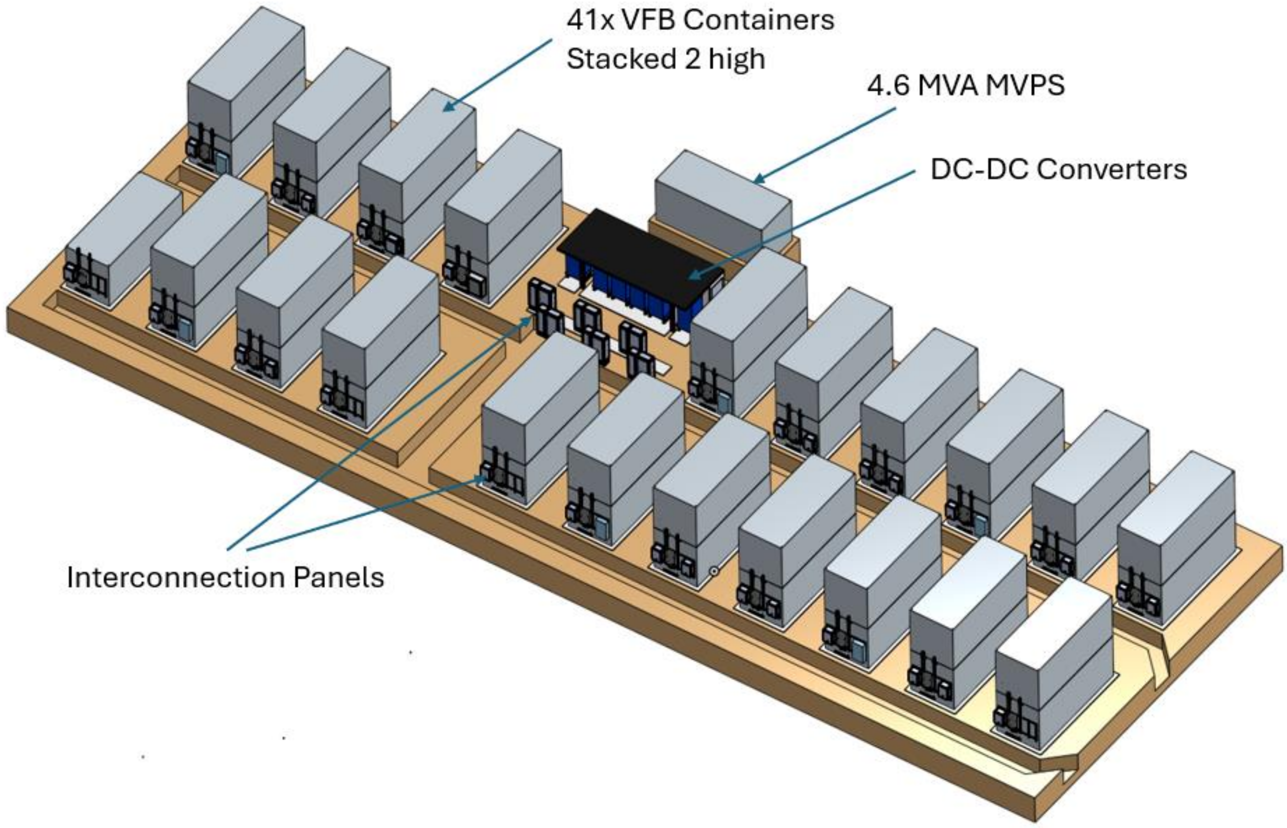

Figure 3: VFB Layout General View

5.6 Power Flows

The direct DC coupling connection in capable of 6 fundamental power flows, using PV and Batteries to import, export, charge and discharge, to and from the grid, enabling maximum flexibility for the operator, hence allowing optimum support to the grid, and maximizing operation revenues from the asset. The power flows are described below. Direct DC coupling allows the batteries to be charged both by the PV and by importing from the grid, since the MVPS. The MVPS is bi-directional, it can export PV production and battery discharge, separately or simultaneously.

They will be utilised, in various combinations of power from/to PV and VFBs, for energy trading and FCAS. The flexibility offered by the system is essential today to maximise revenues in both energy trading and FCAS. It is also future proof since it can adapt to energy market changes, running a large variety of duty cycles in terms of power, charge/discharge time and number of cycles per day.

#	Power Flow Reference*	Power flow Description
1	PV Export, Battery Charging, Grid Export	PV power partly exported, partly charging battery
2	PV Export, Battery Discharging, Grid Export	Both PV and Batteries are exporting
3	PV Production, Grid Import , Battery charging.	Battery charging from PV and from Grid
4	PV Export, Battery Charging, Grid Curtailment	PV power partly exported, partly charging batteries
5	PV Disconnected, Battery Discharging, Grid Export	Battery only export to grid.
6	PV Disconnected, Battery Charging, Grid Import	Battery import from grid.

5.7 ARENA Test Packages Definition

An important part of the project innovation and Knowledge Sharing (KS) activities is the specific test plan that was defined for ARENA. The goal of the test plan is to characterise the performance of the DC coupled system both in terms of energy and power, and its FCAS capabilities. To execute this test plan, the PV and the VFBs need to be fully commissioned and in operational conditions.

This test plan was first defined by Invinity on behalf of Yadlamalka Energy in 2021. The level of knowledge about the system was relatively low in 2021. By 2023, the understanding of the system functionality had significantly increased among the project team. In collaboration between all team members, Habitat, Invinity, NGE/AZZO and SMA, the test plan was simplified, bringing the test duration from 22 days to 9 days of effective testing, without compromising the test coverage and results.

Test Package 1: VFB Testing with SMA PCS Equipment at SMA Power Lab in Germany

Test Package 2: VFB Energy and Power Testing

Test Package 3: PV + VFB Energy and Power Testing

Test Package 4: FCAS Performance Testing

Test Package 1 was done by Invinity and SMA in 2021. To do this test, 3 VFB battery modules were shipped from Invinity's factory in the UK to SMA's power lab in Germany. The test was performed by a team of engineers from Invinity and SMA together. The main goal of the Test Package was to verify the compatibility of interfaces, both electrical and controls, between the SMA power electronics equipment and the VFBs. Such combination with VFBs had never been done before. The test was successful, only highlighting minor controls interface adjustments. This was an important step in the development of the project.

Test Packages 2 and 3 were simplified using the better understanding of the full system controls functionality and its the data logging capability, that allows the operator to visualise and log the performance of each battery cluster separately. Test Packages 2 and 3 consist in charging/discharging cycles of the 6 VFB clusters at various levels of power: 1 MW, 2 MW and maximum power close to 3 MW. Charging is done using PV and grid imports, separately or combined. Export to the grid is done using PV and battery export, separately or combined.

Test Package 4 aims at verifying the FCAS capabilities of the system. The full FCAS test plan includes both the SAPN FCAS qualification testing, and the test cases defined as part of Test Package 4.

6 PROJECT DESIGN AND DEVELOPMENT

6.1 Project Delivery Team

During the whole project to this day, since inception in 2020, the project team has acted as a consortium under the leadership of Yadlamalka Energy. The contractual relationships between the consortium members are described in Figure 5. However, the great communication and mutual support spirit that was formed among the team members across all organisations involved was a key factor in the success of the project. The project team started with a solid experience of energy systems, each organisation an expert in their own domain: Yadlamalka Energy in project development, Switchco is large project management methodology, Habitat in energy asset optimisation, Invinity as an OEM in VFB technology, product and energy storage systems, SMA with their advanced and proven power electronics equipment, NGE in construction, logistics and installation large PV and battery systems, and Azzo as a control system developer. Some of the companies had already worked together on previous projects: Habitat and Invinity, NGE and SMA, AZZO and Invinity. The core team personnel developed great working relationships during the last 3 years, overcoming difficulties and celebrating success. Although such an innovative system had never been done before, the solid experience brough by each team member in their own domain was the foundation the project was built upon.

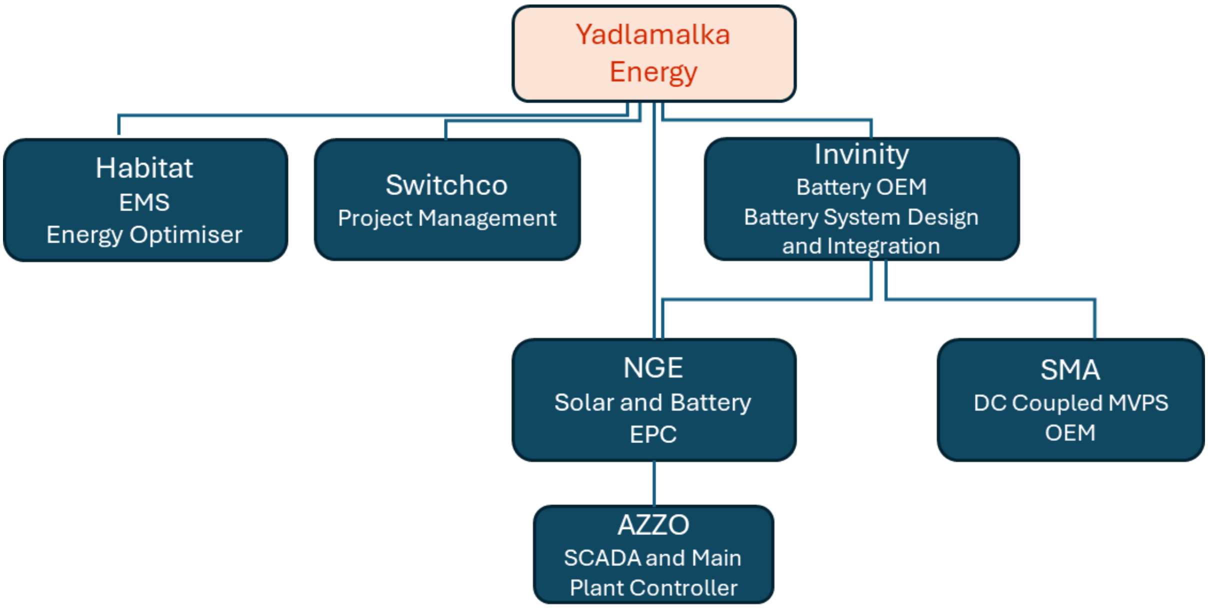

Figure 5: Project Team Contractual Structure

6.2 Technology Selection and Qualification

The selection of Vanadium Flow batteries as the technology for the energy storage system part of the project was done based on the merits promised by this relatively new technology: safety, longevity, longer charge/discharge duration. A smaller VFB system of smaller capacity, 5 MWh using 27 VFB units, had been delivered a year before by Invinity in Oxford, UK, for the Energy Superhub Oxford project. This VFB system was providing grid services but wasn't coupled with PV. It was using an identical battery product, in a very similar configuration, stacked 2 high and arranged in 2 rows. Members of the Australian project team visited the plant in Oxford, UK. The VFB technology considered for the project as such was well proven, similar modules having been used on multiple projects in the past 5 years. However, never at the scale of 8 MWh used for the Yadlamalka project.

The SMA DC coupled system was also an existing and proven system, although never used with VFBs. SMA has a long history of supplying PCS on the global market, and a significant market share in Australia. As mentioned above the Test Package 1 was specifically created to verify the compatibility of Invinity and SMA technologies well in advance in the project.

NGE has a long experience in installing PV plants in several Australian states, including South Australia, working with SAPN for all regulatory and connection aspects. There is no specific technological innovation related to the PV part of the project, but having NGE experience in deploying PV plants was crucial for success.

The project configuration, using Direct DC coupling between PV and VFBs, is a first in Australia and worldwide. However, all components of it were selected to be well proven technologies and products, limiting the overall project technical risks.

6.3 System Integration and Site Design

The site design was done in conjunction between all project participants. Sizing the battery and PV plant was done between Habitat and Invinity, considering the use cases, the power, the energy capacity required, and specific South Australia electrical system situation to maximise revenues. In South Australia several non-pilotable renewables have been installed since the 2010. It is frequent that SAPN requires renewable production curtailment that can affect renewables power plant economic performances. The connection agreement with SAPN allowed for a maximum of 5 MVA generation at the connection point. The PCS was selected to be below this maximum value, and to match the PV and battery available power. PV was oversized to 6 MW power generation, anticipating that excess or curtailed PV would be charged in the batteries directly through the DC coupling connection.

Integration and site design was done in conjunction between NGE and Invinity. The site configuration was considered, starting with a geotechnical study of the terrain. Each battery containerized unit has a weight of 25 tons. When stacked two high, the weight to be supported by foundations is 50 tons. The stacked configuration was adopted because it reduced both footprint and cost of the foundations. All cable routing and containment was studied together by Invinity and NGE to minimize costs. The interconnection hardware for DC power, AC auxiliary power and controls was designed to Australian standards by specialist companies under NGE subcontracts, with interconnection concepts supplied by Invinity.

The control system was developed in a joint effort by Habitat, NGE and their subcontractor AZZO, Invinity and SMA, as described in the next section.

To develop such a complex system, the team defined clear interfaces and requirements for all parts of the system, applying proven systems engineering methodology, and constant communication between all partners, through daily email and weekly video calls.

6.4 Control System Design

The control system needs to integrate multiple functions and interfaces. The whole plant control architecture is shown in Figure 6 below. The top level of the control hierarchy resides with the generator controls from AEMO to manage the plan as part of the Australian energy network. Local network constraints, in terms of maximum power import and export but also power factor, are set by SAPN. The second level of control is done by Habitat's Dispatch Optimisation platform, that determines what the plant should do to maximise revenues: charge, discharge, export, import, or idle are defined with intervals of 5 minutes. The signals from AEMO and SAPN are received by the on-site Plant controller supplied by Habitat. SCADA system developed and provided by AZZO can override the Dispatch Optimiser's platform decisions if required by SAPN to protect the network. The third level of control is provided by the SMA Power Plan Manager, that is managing the power flows from/to PV and

VFBs, to meet the Dispatch manager's commands. The fourth level of control is done by the SMA PCS that defines how much power is driven from/to the PV and each of the 6 battery clusters. Finally, the 5th level of control is done by the Battery Management System (BMS) provided by Invinity, that provides in real time the available DC power at battery terminals, available energy capacity and other telemetry data from the batteries to the SMA PCS.

The Project team applied proven software development methods to develop the control system. Coordination between the key personnel in each team was essential to achieve a successful deployment.

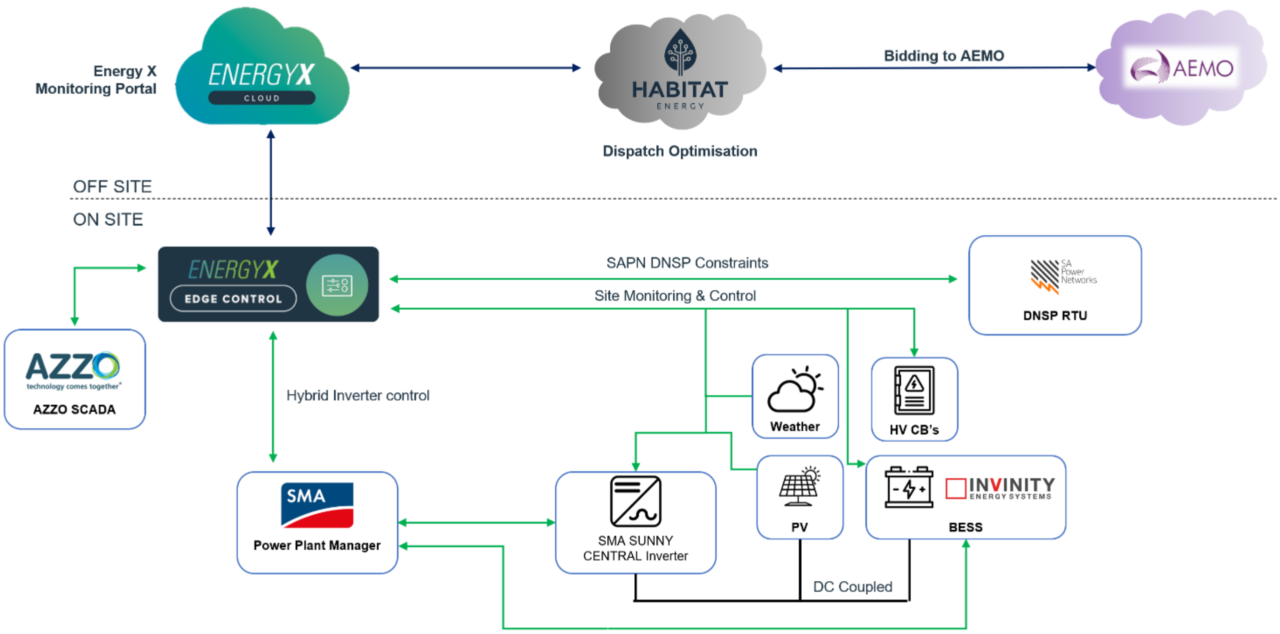

Figure 6: Full Site Control System Diagram

6.5 Lessons Learned during Project Design and Development

Lesson Learned: Team Composition and Cooperation. The team was constituted with experts who together brought the full set of complementary skills to deliver the project. Cooperation was achieved through regular video calls. It is essential that the key personnel involved develop a relationship based on trust and technical competence. This was an essential aspect of the project's success.

Lesson learned: System integration. Careful consideration had to be given to all aspects of the PV and VFB system. Engineers from each to the project participants regularly met online, and sometimes in person. COVID 19 prevented travel to/from Australia and between states for a large portion of the project duration. The project team had to maximise virtual communication through video calls, and a comprehensive set of technical documentation.

7 PROJECT DELIVERY

7.1 Vanadium Battery Deliveries

The VFBs were produced in China by Invinity's contract manufacturer, and directly shipped to Australia. The batteries are a standard design, no customisation of any kind was done for the project, except the colour of the external panels, that was a planning requirement associated with the original site at Yadlamalka station. During the entire production phase however, all aspects of the supply chain of the batteries were constrained by the COVID 19 global crisis. Electronics were the most impacted supply chain, with some key components of the internal battery controls becoming unavailable. Limited quantities of components were acquired, enough to complete the project, but delays were inevitable. Other components had to be entirely designed out and replaced by alternative ones. Besides the supply chain aspects, logistics for shipping the batteries from China to Australia were significantly constrained by the global shipping disruption caused by the COVID 19 crisis. Thorough planning and project delivery management was done by Invinity to mitigate these adverse effects. The batteries were delivered in several batches, the first batch of 14 units were delivered to Port Pirie in December 2022 and the remaining batteries during Q1 2023. The batteries were stored locally for a few months prior to installation to site. It is to be noted that VFBs, unlike lithium batteries, due to their water-based chemistry and because they are deliverer without any charge, are safe to store in general outdoors conditions. Coordination between Switchco, NGE and Invinity was essential to overcome the challenges. Local companies in Port Pirie were instrumental in assisting with logistics, storage and handling of the batteries.

7.2 PV Deliveries

NGE has a long experience of delivering PV plants in South Australia. Construction of the plant, started with the creation of an access road that was capable of accommodation the trucks and heavy machinery required to proceed with the civil works. There were no particular issues with the construction of the PV foundations. Procurement of the PV panels, and their supporting structures was affected by supply chain delays resulting from the COVID 19 crisis. The project was delayed by 8 weeks due to supporting structures deliveries only that had become critical path.

7.3 MVPS and DC Converters Procurement

The MVPS and DC Converters procured from SMA were ordered for the original site at Yadlamalka station. Although MVPS are long lead items with 9 to 10 months lead-times and usually is the critical path of similar projects, it didn't affect the Yadlamalka project. This is because the project was originally planned to be located at Yadlamalka Station but had to be relocated to Port Pirie for planning issues. This meant that the MVPS was delivered 12 months before its delivery to site. To be noted that fumigation was required to allow the equipment to be imported in Australia. This was anticipated and done accordingly, avoiding import clearance issues on arrival in Australia. The main issue then was to ensure that storage conditions and preventative maintenance was done in accordance with the manufacturer's guidelines during the 12 months long storage. This was assured by Invinity, and locally supported by NGE. The DC-DC converters were also delivered in advance and were not affected by the electronics supply chain delays caused by COVID 19. One of the DC-DC converters was damaged during handling. A cooling fan was damaged inside the DC-DC converter, that needed to be replaced, but had a relatively long lead time, causing a few weeks delay on final commissioning.

By the time the equipment was installed on site, the MVPS software was obsolete and required several software updates to be brought up to date. Generally, the procurement and delivery of the SMA DC coupling equipment didn't present any issues since the equipment is proven and was removed from the critical path due to the change of site. To be noted that for similar projects in the future, the MVPS and DC-DC converter procurement will likely be, or very close to, the critical path of the project and planned accordingly.

7.4 Interconnection Electrical Panels Procurement

To connect the 41 battery units to the DC-DC converters and these to the MVPS, to the site's auxiliary power supply and to the site's communication and control network, a set of interconnection panels are required. Invinity had defined a set of standard interconnection panels for the UK project in Oxford mentioned above. There are 3 categories of panels: DC panels, AC auxiliary connections, and control panels. Functionally equivalent panels needed to be designed to Australian standards and procured. This was managed by NGE, under a subcontract from Invinity. The DC and AC panels were procured from a global specialist supplier. The control panels were procured from an Australian supplier. The control panels were particularly affected by the electronic component shortages that resulted from the COVID 19 crisis. Other delays on the project masked this issue, and the control panels were delivered in time for installation to site.

7.5 Control Software Delivery

The development of the control software was a more a challenge of integration of existing software packages as described in the section 5.4 than an intensive programming excercise. The first step for this integration work was for Habitat, Invinity, Azzo and SMA to understand the functionality of each other's software package in sufficient detail to define the interfaces between each package. This was done over a period of a year, with regular video calls and documentation reviews. The main plant controller was developed by Azzo based on their ENERGYX platform. There are a few notable differences between the controls of VFBs and lithium batteries. The main ones are the ability to start and stop VFBs at will and at short notice to reduce auxiliary loads, and the need for such a start-stop signal to enable and disable the batteries from the main plant controller developed by Azzo. Integrating inputs from AEMO and SAPN in the control system was also a task taken by the main plant controller. The integration role done by Azzo, in close cooperation with Habitat, Invinity and SMA control teams, was essential for the success of the project. It was important to minimise the modifications to other standard packages. SMA software is standard, follows regular software upgrades. Customising it would present significant effort and risks. Invinity BMS software is standard too. It is parametrized for the size of the battery system but remains standard in terms of functionality. Habitat's Dispatch Optimiser required adaptations, to implement the uses cases resulting from the operational plan for the PV and VFB system. Finally, thorough testing of the software was done prior to site delivery, and continued during the first few weeks after site energisations to ensure all issues were found and resolved.

7.6 Lessons Learned during Project Delivery

Lesson learned: VFB deliveries. Thorough planning of the shipping requirements was required to avoid delays importing the batteries to Australia. Part of the issue was the difficult process for Invinity to obtain an ABN number for GST payments. This is now resolved for further projects.

Lesson learned: VFB deliveries. Supply chain constraints, particularly electronics components, were exacerbated by COVID 19, but remain today. Although the extended lead times were unexpected when the pandemic started, they are now taken into account in Invinity's supply chain planning. For future projects, Invinity can order the long lead time components in advance, because the VFB products are 100% standard, and the bill or materials for each battery remains unchanged throughout the production phase.

Lessons learned: MVPS and DC-DC converter procurement. This category of equipment is always a long lead item. It is likely to become the critical path of future projects. This procurement needs to be one of the first actions to implement when starting a new project.

Lesson learned: interconnection panels procurement. Invinity has created supply chain of standard electrical panels for the Australian market. Such ancillary equipment needs to be planned well in advance, since many electrical components are long lead items.

Lessons learned: Control software delivery. When integrating a complex system, using multiple standard equipment and their associated software packages, contracting a software integration specialist firm with experience in large energy systems is essential. Nothing is plug and play. Software integration work needs to start very early in the project as soon as all standard software packages are selected.

8 PROJECT INSTALLATION AND COMMISSIONING

All installation of equipment on site was done by the EPC, NGE. Each specialist equipment supplier sent their commissioning teams to site for final site commissioning and acceptance of their equipment. Safety of personnel was the primary factor during all operations on site. As stated above, the layout of the batteries was designed for safety. This design was implemented on site and verified by NGE and Invinity engineers. All site operations were done under NGE's authority as principal contractor, in accordance with South Australia's Health and Safety requirements.

All large equipment, namely the MVPS and the containerised battery units, were handled on site using a crane, as shown in Figure 7 below.

Figure 7: Handling of battery units on site using a crane

8.1 MVPS and DC-DC Converters Installation and Commissioning

The bulk of the work with MVPS and DC-DC converters installation was the cable connections to each equipment. The manufacturer specifies connection details in a precise manner that must be implemented on site accurately. A couple of relatively minor errors during connection works were found and connected, with minimal impact on the schedule. SMA personnel attended site to perform the standard commissioning procedure for their equipment. This is clearly specialist work that was carried out successfully thanks to NGE's experience in the field.

8.2 PV Installation and Commissioning

NGE's experience in installation and commissioning of PV plants was instrumental in the smooth installation and commissioning. No significant issues were encountered during the construction of the PV plant. The commissioning stated with the witnessed test of the connection by SAPN. The requirements were well understood and the team addressed all questions on site. The commissioning of the MVPS by the manufacturer, SMA, was then done, with SMA engineers attending site. The SMA engineers also did the commissioning of the

DC-DC converters between batteries and the MVPS. This put the site in ready state to start commissioning the batteries.

8.3 Vanadium Battery Installation and Commissioning

The VFBs were located on site in accordance with the site layout design and harnessed with the DC-DC converters, the AC auxiliary power supply network and the Control panels. The panels themselves were mounted at the front of the containers in accordance with Invinity's standard design. This had been done previously by Invinity in Oxford, UK for the ESO project. This experience was shared with NGE through dedicated training sessions. The installation procedure is thoroughly documented by Invinity and was implemented by NGE personnel without any particular difficulties. Since it was NGE's first installation of Invinity batteries, two Invinity customer support technicians attended site to provide guidance. During power up and battery commissioning, a system engineer from Invinity also attended site to configure all levels of the Invinity BMS: the principal Flow Battery Energy Storage Manager (FBESM), the 6 Cluster Managers and each of the 246 Battery modules inside the containerised battery units.

8.4 Connection Point Equipment Installation and Commissioning

An SVG is installed at the connection point to manage reactive power generated by the plant, in accordance with SAPN signals. The control philosophy is to use the Sinopak SVG Equipment as the primary equipment for reactive power, up to 2MVAr. If more than 2MVAr of reactive power is required, the additional reactive power will be provided by the SMA Inverter (managed by the PPM). On-Line Commissioning checks were witnessed by the SAPN Witnesser prior to proceeding to Final Sign-Off.

This process was managed by NGE's team.

8.5 Lessons Learned during Project Installation and Delivery

Lesson Learned: Battery installation. Scheduling hiring the crane required to position the batteries on site was a challenging exercise. The solution for this project was to hire the cranes from a local company (Max Cranes) in Port Pirie. The project was also able to use their storage yard as a temporary landing area to hold the containers prior to bring them to site. Securing support from local companies is essential for a successful installation operation.

Lesson Learned: Battery Commissioning. Invinity trained local engineers during the commissioning of the batteries. They are trained to do most common interventions and repairs on the batteries. This has proven extremely useful to address a few minor issues during the weeks after Invinity engineers had left site post commissioning.

9 ARENA TEST PACKAGES AND FCAS TESTING

9.1 ARENA Test Package #1 VFB Qualification with PCS

Test Package #1 was performed in 2021 by sending 3 VFB battery modules to be tested with the SMA PCS at SMA's power laboratory in Kassel, Germany. The detailed test plan was developed jointly by Invinity and SMA engineers. Testing highlighted software controls adjustments that were identified very early in the project, avoiding delays later in the project. Shipping the batteries from Invinity's UK factory to Germany and sending a team in Invinity engineers there for 2 weeks was a small investment in regards with the overall project, but proved to be extremely beneficial, giving the team confidence that there were no fundamental technology compatibility issues that would present a risk to the project.

9.2 ARENA Test Packages #2 and #3 Power and Capacity Testing

The test plan was reviewed during the 2 months preceding commissioning, such that testing could be started as soon as possible after the batteries were fully functional and commissioned. Prior to start testing on site, an in-depth review of each test, it's goals and pass/fail criteria, and the precise method to control the plant to execute each test case was done jointly by Invinity, Habitat and Azzo. The final test plan includes several test cases, measuring the actual energy capacity and efficiency obtained when charging and discharging the batteries at 1 MW, 2 MW and at maximum power 3 MW. At the time of writing this report, all test cases were done successfully, test report pending.

9.3 ARENA Test Package #4 FCAS Test Cases

The FCAS tests that were specified in the original 2021 test plan was very preliminary. During the 3 months preceding the start of testing, the FCAS test cases were updated in detail based on a detailed review of AEMO's documentation: MASS document and Battery Energy Storage System requirements for contingency FCAS registration . The resulting final test plan was documented and reviewed by engineers from Habitat, Azzo, Invinity and SMA, before submission to ARENA. The FCAS test plan goes beyond the requirements of Test Package #4, since it also covers the tests required by SAPN for FCAS qualification. The project team from Habitat and Invinity have climbed a very steep learning curve to understand the test requirements and expected outcome. Together with AZZO and SMA, how to pilot the plan conduct the tests required advanced engineering work and an in-depth knowledge of how the plant operates, and particularly the SMA system. Very helpful video calls with AEMO specialists were done to ensure the test plan meets AEMO's requirements for Delayed, Fast and Very Fast services. To be noted that back in 2021 when the project started and the original test plan was defined, the Very Fast FCAS regime wasn't implemented. It was nevertheless added to the final test plan.

At time of writing, the requirements and method to FCAS is well understood. The project team have engaged with SAPN to organise the required authorisations to proceed with FCAS testing.

9.4 Lessons Learned during ARENA Test Packages

Lessons Learned: Test Case Scheduling. The test team worked together with the trading team to schedule tests at times when energy prices would allow the tests to be conducted at a reasonable cost. Although test time was estimated to 9 days for all energy tests in Test Package #2 and #3, it took 3 weeks to run all of them, having to schedule them at the right time. Contingency must be planned in the test schedule to accommodate trading prices constraints.

Lessons Learned: FCAS Test Case Definition. There are very few people in Australia who have expertise in FCAS requirements. The project team from Habitat and Invinity have climbed a very steep learning curve to understand the test requirements and expected outcome. Support by the AEMO experts was crucial to understanding the test requirements.

10 CONCLUSIONS

The Yadlamalka Energy project was delivered thanks to a close collaboration between all project partners. The innovative solution using direct DC Coupling between batteries and PV plant was implemented with a risk limiting approach, using existing products and techniques, that put together would deliver a first of a kind renewable energy system. The state-of-the-art processes used by each project partner, and coordinated by Yadlamalka Energy ensured a safe delivery and commissioning of the system. Preparation for the next phase were done, with the definition of a clear test plan, to ensure the Yadlamalka Energy project will be operating successfully for many years to come.