GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

TRANSFORMACIÓN DE LA MAYOR CENTRAL DE CARBÓN DE AUSTRALIA (ERARING) EN UNA PLANTA HÍBRIDA SOLAR FOTOVOLTAICA CON ALMACENAMIENTO Y PRODUCCIÓN DE HIDRÓGENO VERDE PARA GENERACIÓN DE AMONÍACO VERDE

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Madrid

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

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TRANSFORMACIÓN DE LA MAYOR CENTRAL DE CARBÓN DE AUSTRALIA (ERARING) EN UNA PLANTA HÍBRIDA SOLAR FOTOVOLTAICA CON ALMACENAMIENTO Y PRODUCCIÓN DE HIDRÓGENO VERDE PARA GENERACIÓN DE AMONÍACO VERDE.

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RESUMEN DEL PROYECTO

Este proyecto propone la conversión de la central térmica de Eraring en un centro de generación renovable mediante una planta solar fotovoltaica, un sistema de baterías redox flow y producción de hidrógeno renovable, destinado a sustituir el gas natural en la planta de amoníaco de Kooragang Island y descarbonizar la producción de fertilizantes.

Palabras clave: Sistema híbrido de energías renovables, Energía solar, Reconversión de centrales de carbón, Producción de hidrógeno verde, Descarbonización del amoníaco.

1. Introducción

La central térmica de Eraring, de 2,922 MW, es la mayor de Australia y una de las principales fuentes de emisiones del país. Su cierre previsto para 2027 abre la posibilidad de reconvertir el emplazamiento en un nodo clave de generación y almacenamiento de energía renovable. Este Trabajo Fin de Grado desarrolla un diseño técnico y estratégico para dicha transformación, integrando energía solar, producción de hidrógeno verde y almacenamiento a gran escala, con el objetivo de avanzar hacia un sistema eléctrico sostenible y resiliente.

2. Definición del proyecto

El proyecto plantea la sustitución de la central de carbón por un complejo híbrido compuesto por una planta solar fotovoltaica de 500 MW, un sistema de electrólisis PEM de 20 MW para producción de hidrógeno verde, y una batería redox-flow de 80 MWh. El diseño contempla el aprovechamiento de infraestructuras ya existentes —como la red de transmisión, el acceso al agua de refrigeración del lago Macquarie y las carreteras internas— para optimizar la inversión y reducir el tiempo de desarrollo.

3. Descripción del sistema

Generación solar fotovoltaica

La planta solar se ha dimensionado con más de un millón de paneles Aiko Neostar 2P de 475 W, instalados sobre estructuras con sistema de single-axis tracking, que permite seguir el recorrido del sol a lo largo del día. Este sistema mejora la captación de irradiación hasta en un 7.5% respecto a configuraciones fijas, sin aumentar de forma significativa el OPEX ni requerir complejos mecanismos de orientación. La capacidad total instalada es de 500 MWp, y la producción estimada alcanza los 769 GWh anuales.

Producción de hidrógeno verde

Se emplea un electrolizador PEM de 20 MW (Cummins HyLYZER 4000), capaz de producir 8.630 kg/día de hidrógeno a 30 bar, alimentado por la planta solar y respaldado por almacenamiento. El proceso requiere 77,670 litros diarios de agua tratada del lago Macquarie. Para almacenar la producción diaria, se seleccionan 3,753 tanques MAHYTEC tipo IV de 2.3 kg de capacidad cada uno, adecuados por su ligereza, compatibilidad con aplicaciones móviles y seguridad. El hidrógeno se destina a la planta de amoníaco de Orica en Kooragang Island, próxima al emplazamiento, lo que representa una oportunidad estratégica de suministro industrial.

Almacenamiento energético

Se integra una batería redox-flow Invinity ENDURIUM, de 80 MWh, que permite operar el electrolizador durante 4 horas en ausencia de irradiación. Esta tecnología se selecciona por su alta seguridad, larga vida útil sin degradación, escalabilidad flexible y capacidad para proporcionar soporte de red (control de frecuencia, potencia reactiva e inercia sintética). Frente a otras alternativas como ion-litio, presenta ventajas para aplicaciones estacionarias a gran escala.

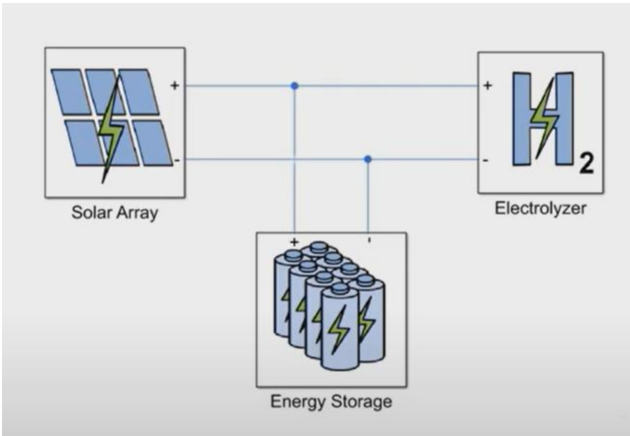

Figura 1. *Modelo conceptual del proyecto propuesto, compuesto por tres elementos principales: planta solar fotovoltaica (FV), sistema de almacenamiento de energía en baterías (BESS) y electrolizador para producción de hidrógeno verde.*

4. Resultados

- La planta solar de 500 MW generará aproximadamente 769 GWh al año, lo que representa una contribución relevante al sistema eléctrico nacional y permite cubrir el funcionamiento parcial del electrolizador y otras demandas del hub renovable, reforzando la seguridad de suministro a partir de recursos locales.

- La producción anual de hidrógeno verde se estima en 3.15 millones de kilogramos, los cuales se destinarán a la planta de amoníaco de Orica en Newcastle, sustituyendo de forma parcial el uso de gas natural en sus procesos industriales, lo que representa una reducción de emisiones significativa en el sector químico local.

- La reconversión del emplazamiento de Eraring permitiría evitar aproximadamente 293,500 toneladas de CO_2 directas al año: 262,000 toneladas de CO_2 por generación solar, 31.500 toneladas de CO_2 por hidrógeno verde en sustitución de gas natural, y un aporte indirecto del almacenamiento al reducir picos fósiles y mejorar la gestión renovable.

Source	Annual Production	Emission Factor	Estimated CO_2 Emissions Avoided Annually
Eraring Power Station (coal)	13,151,237 MWh	340.56 kg CO_2 / MWh	4.48 million tonnes CO_2 avoided
Solar PV Plant	769,128 MWh	340.56 kg CO_2 / MWh	262,000 tonnes CO_2 avoided
Hydrogen Production (Electrolyser)	3.15 million kg H_2	10 kg CO_2 / kg H_2 (natural gas-based)	31,500 tonnes CO_2 avoided
Vanadium Flow Battery	80 MWh storage capacity	0 kg CO_2 / MWh (no direct emissions)	Indirect emission reductions by reducing fossil backup

Tabla 1. *Emisiones de CO_2 evitadas anualmente por cierre de Eraring, planta FV, producción de H_2 verde y BESS. Fuente: elaboración propia.*

- El análisis económico del proyecto, bajo supuestos conservadores, arroja un CAPEX total estimado de 1,005 millones AUD, un OPEX anual de 24 millones AUD en el primer año, un VAN negativo de –351.9 millones AUD y una TIR del 2,64%, inferior al WACC del 7%, lo que indica que no es actualmente rentable sin apoyo financiero público.

Year	Energy (MWh)	Revenue (M AUD)	OPEX (M AUD)	Depreciation (M AUD)2	EBIT (M AUD)	Tax (M AUD)	Net Income (M AUD)	Cash Flow (M AUD)	Discounted CF (M AUD)
0	0	0.000	0.000	0	0	0.000	0.000	-1005.46	-1005.4600
1	593928	91.130	24515.000	40.218	26	7.919	18.478	58.696	54.8564
2	592443	90.957	24.760	40.218	25.978	7.793	18.185	58.403	51.0115
3	590962	90.784	25.008	40.218	25.558	7.667	17.890	58.109	47.4341
4	589485	90.612	25.258	40.218	25.135	7.541	17.595	57.813	44.1054
5	588011	90.440	25.510	40.218	24.711	7.413	17.298	57.516	41.0081
6	586541	90.268	25.766	40.218	24.284	7.285	16.999	57.217	38.1264
7	585075	90.097	26.023	40.218	23.856	7.157	16.699	56.917	35.4453
8	583612	89.927	26.283	40.218	23.425	7.027	16.397	56.616	32.9509
9	582153	89.756	26.546	40.218	22.992	6.898	16.094	56.313	30.6304
10	580697	89.587	26.812	40.218	22.557	6.767	15.790	56.008	28.4717
11	579246	89.417	27.080	40.218	22.119	6.636	15.483	55.702	26.4635
12	577798	89.249	27.351	40.218	21.680	6.504	15.176	55.394	24.5956
13	576353	89.080	27.624	40.218	21.238	6.371	14.866	55.085	22.8582
14	574912	88.912	27.900	40.218	20.793	6.238	14.555	54.774	21.2422
15	573475	88.744	28.179	40.218	20.347	6.104	14.243	54.461	19.7392
16	572041	88.577	28.461	40.218	19.898	5.969	13.928	54.147	18.3414
17	570611	88.410	28.746	40.218	19.446	5.834	13.612	53.831	17.0414
18	569185	88.244	29.033	40.218	18.992	5.698	13.295	53.513	15.8326
19	567762	88.078	29.324	40.218	18.536	5.561	12.975	53.194	14.7085
20	566342	87.912	29.617	40.218	18.077	5.423	12.654	52.873	13.6633
21	564926	87.747	29.913	40.218	17.616	5.285	12.331	52.550	12.6914
22	563514	87.583	30.212	40.218	17.152	5.146	12.007	52.225	11.7879
23	562105	87.418	30.514	40.218	16.686	5.006	11.680	51.898	10.9478
24	560700	87.254	30.819	40.218	16.217	4.865	11.352	51.570	10.1669
25	559298	87.091	31.128	40.218	15.745	4.724	11.022	51.240	9.4409
								NPV	-351.8991
								IRR	2.642%

Tabla 2. *Modelo de negocio del proyecto a 25 años bajo supuestos conservadores, incluyendo flujos de caja anuales, valor actual neto (VAN) y tasa interna de retorno (TIR). Fuente: elaboración propia.*

- A pesar de su rentabilidad limitada en el escenario base, el proyecto tiene alto potencial estratégico, con opciones de financiación a través de programas como Hydrogen Headstart, el Capacity Investment Scheme y la Electricity Infrastructure Roadmap, además de posibles ingresos futuros por certificados de hidrógeno verde y servicios de red.

- El proyecto contribuye directamente a los ODS 7 (energía asequible y no contaminante), ODS 9 (industria, innovación e infraestructura), ODS 11 (ciudades sostenibles) y ODS 13 (acción por el clima), reforzando el papel de Eraring como modelo de transición energética justa y sostenible a escala nacional.

5. Conclusiones

Este Trabajo Fin de Grado demuestra que la reconversión de la central de carbón de Eraring en un nodo de energía limpia es técnicamente viable, ambientalmente beneficiosa y estratégicamente acertada. El diseño propuesto responde a múltiples desafíos del sistema energético: reemplazo de generación fósil, integración de renovables intermitentes, almacenamiento de largo plazo, y producción de hidrógeno verde para producir amoníaco.

Desde el punto de vista ambiental, el proyecto reduce drásticamente las emisiones y contribuye al cumplimiento de los compromisos climáticos de Australia. Desde el punto de vista técnico, combina tecnologías maduras y emergentes, maximizando la flexibilidad operativa y la resiliencia del sistema eléctrico. Y desde una perspectiva de transición justa, representa una oportunidad para mantener actividad económica y empleo en una región históricamente dependiente del carbón.

A pesar de que el análisis económico indica rentabilidad negativa en condiciones conservadoras, el potencial de acceso a subvenciones, el descenso previsto de costes tecnológicos y el impulso normativo previsto para el hidrógeno y el almacenamiento convierten este proyecto en una inversión estratégica de alto impacto futuro. En definitiva, se trata de un caso emblemático que puede servir de referencia para la reconversión de otras plantas térmicas en desuso en Australia y otros países con objetivos de transición energética ambiciosos.

CONVERSION OF AUSTRALIA'S LARGEST COAL POWER PLANT (ERARING) INTO A HYBRID PHOTOVOLTAIC SOLAR FACILITY WITH STORAGE AND GREEN HYDROGEN PRODUCTION FOR GREEN AMMONIA GENERATION

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Supervisor: Navarro Ocón, Jaime Cristóbal.
Collaborating Entity: ICAI – Universidad Pontificia Comillas.

ABSTRACT

This project proposes converting the Eraring coal-fired power station into a renewable energy generation facility through a solar photovoltaic plant, a redox flow battery system, and renewable hydrogen production, with the aim of replacing natural gas at the Kooragang Island ammonia plant and decarbonising fertiliser production.

Keywords: Hybrid renewable energy system, Solar energy, Conversion of coal-fired power plants, Green hydrogen production, Ammonia decarbonisation.

1. Introduction

The 2,922 MW Eraring thermal power station is the largest in Australia and one of the country's main sources of emissions. Its planned closure in 2027 opens up the possibility of converting the site into a key hub for renewable energy generation and storage. This final degree project develops a technical and strategic design for this transformation, integrating solar energy, green hydrogen production and large-scale storage, with the aim of moving towards a sustainable and resilient electricity system.

2. Definition of the project

The project plans to replace the coal-fired power plant with a hybrid system consisting of a 500 MW solar photovoltaic plant, a 20 MW PEM electrolysis system for green hydrogen production, and an 80 MWh redox flow battery. The design takes advantage of existing infrastructure—such as the transmission network, access to cooling water from Lake Macquarie, and internal roads—to optimise investment and reduce development time.

3. Description of the system

Photovoltaic Solar Generation

The solar plant has been designed with more than one million 475 W Aiko Neostar 2P panels, installed on structures with a single-axis tracking system, which allows the solar system to follow the sun's path throughout the day. This system improves irradiation capture by up to 7.5% compared to fixed configurations, without significantly increasing OPEX or requiring complex orientation mechanisms. The total installed capacity is 500 MWp, and the estimated production reaches 769 GWh per year.

Green Hydrogen Production

A 20 MW PEM electrolyser (Cummins HyLYZER 4000) is used, capable of producing 8,630 kg/day of hydrogen at 30 bar, powered by the solar plant and supported by storage.

The process requires 77,670 litres of treated water from Lake Macquarie per day. To store the daily production, 3,753 MAHYTEC Type IV tanks with a capacity of 2.3 kg each were selected, suitable for their lightness, compatibility with mobile applications, and safety. The hydrogen is destined for Orica's ammonia plant on Kooragang Island, close to the site, representing a strategic industrial supply opportunity.

Energy Storage

An 80 MWh Invinity ENDURIUM redox-flow battery is integrated, allowing the electrolyser to operate for 4 hours in the absence of irradiation. This technology was selected for its high safety, long life without degradation, flexible scalability, and ability to provide grid support (frequency control, reactive power, and synthetic inertia). Compared to other alternatives such as lithium-ion, it offers advantages for large-scale stationary applications.

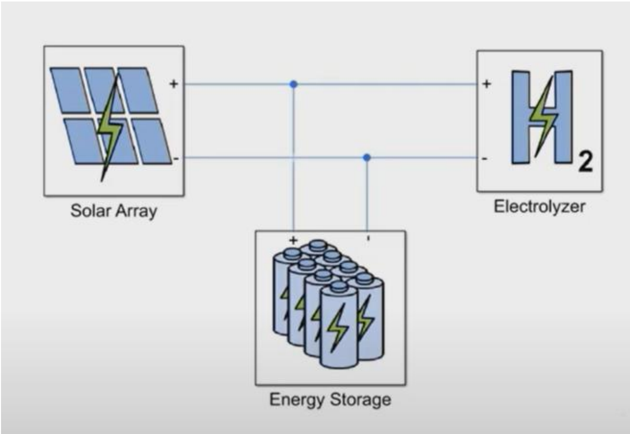

Figure 1. *Conceptual model of the proposed project, comprising three main components: photovoltaic (PV) solar plant, battery energy storage system (BESS), and electrolyser for green hydrogen production.*

4. Results

• The 500 MW solar plant will generate approximately 769 GWh per year, representing a significant contribution to the national electricity system and covering partial operation of the electrolyser and other demands of the renewable hub, strengthening security of supply from local resources.

• Annual green hydrogen production is estimated at 3.15 million kilograms, which will be used to supply Orica's ammonia plant in Newcastle, partially replacing the use of natural gas in its industrial processes, representing a significant emissions reduction in the local chemical sector.

• The conversion of the Eraring site would avoid approximately 293,500 tons of direct CO_2 per year: 262,000 tons of CO_2 from solar generation, 31,500 tons of CO_2 from green hydrogen replacing natural gas, and an indirect contribution from storage by reducing fossil fuel peaks and improving renewable management.

Source	Annual Production	Emission Factor	Estimated CO_2 Emissions Avoided Annually
Eraring Power Station (coal)	13,151,237 MWh	340.56 kg CO_2 / MWh	4.48 million tonnes CO_2 avoided
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Vanadium Flow Battery	80 MWh storage capacity	0 kg CO_2 / MWh (no direct emissions)	Indirect emission reductions by reducing fossil backup

Table 1. *Estimated annual CO_2 emissions avoided from the closure of the Eraring coal-fired power plant, PV generation, green hydrogen production, and indirect savings from BESS. Source: own elaboration.*

• The project's economic analysis, under conservative assumptions, yields an estimated total CAPEX of AUD 1.005 billion, annual OPEX of AUD 24 million, a negative NPV of -AUD 351.90 million, and an IRR of 2.64%, lower than the WACC of 7%, indicating that it is not currently profitable without public financial support.

Year	Energy (MWh)	Revenue (M AUD)	OPEX (M AUD)	Depreciation (M AUD)2	EBIT (M AUD)	Tax (M AUD)	Net Income (M AUD)	Cash Flow (M AUD)	Discounted CF (M AUD)
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19	567762	88.078	29.324	40.218	18.536	5.561	12.975	53.194	14.7085
20	566342	87.912	29.617	40.218	18.077	5.423	12.654	52.873	13.6633
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22	563514	87.583	30.212	40.218	17.152	5.146	12.007	52.225	11.7879
23	562105	87.418	30.514	40.218	16.686	5.006	11.680	51.898	10.9478
24	560700	87.254	30.819	40.218	16.217	4.865	11.352	51.570	10.1669
25	559298	87.091	31.128	40.218	15.745	4.724	11.022	51.240	9.4409
								NPV	-351.8991
								IRR	2.642%

Table 2. *25-year project business model under conservative assumptions, including annual cash flows, net present value (NPV), and internal rate of return (IRR). Source: own elaboration.*

• Despite its limited profitability in the base case scenario, the project has high strategic potential, with financing options through programs such as Hydrogen Headstart, the Capacity Investment Scheme, and the Electricity Infrastructure Roadmap, in addition to potential future revenues from green hydrogen certificates and grid services.

• The project directly contributes to SDG 7 (affordable and clean energy), SDG 9 (industry, innovation, and infrastructure), SDG 11 (sustainable cities), and SDG 13 (climate action), reinforcing Eraring's role as a model for a just and sustainable energy transition at the national level.

5. Conclusions

This thesis demonstrates that the conversion of the Eraring coal-fired power plant into a clean energy hub is technically feasible, environmentally beneficial, and strategically sound. The proposed design addresses multiple energy system challenges: replacing fossil fuel generation, integrating intermittent renewables, long-term storage, and producing green hydrogen for ammonia production.

From an environmental perspective, the project drastically reduces emissions and contributes to meeting Australia's climate commitments. From a technical perspective, it combines mature and emerging technologies, maximizing operational flexibility and resilience of the electricity system. From a just transition perspective, it represents an opportunity to maintain economic activity and employment in a region historically dependent on coal.

Although the economic analysis indicates negative profitability under conservative conditions, the potential for access to subsidies, the expected decline in technological costs, and the anticipated regulatory push for hydrogen and storage make this project a strategic investment with a high future impact. Ultimately, this is an emblematic case that can serve as a reference for the conversion of other disused thermal plants in Australia and other countries with ambitious energy transition goals.

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CHAPTER 1. INTRODUCTION

The energy sector is undergoing significant transformation due to the urgent need for decarbonisation. Coal-fired power plants represent a significant source of electricity on a global scale [1]. However, this type of plant has an important number of adverse effects on the environment, including pollution of water and air [1]. Furthermore, they are the primary consumers of coal and are responsible for approximately 30% of global emissions [2]. The combustion of coal is distinguished by a considerably higher concentration of CO_2 emissions in comparison to other fossil fuels [3]. It is therefore essential to phase out coal-fired power plants in order to combat climate change. In 2015, 175 countries signed the Paris Agreement, committing to take action to limit the global temperature increase to 1.5°C-2°C above pre-industrial levels [4]. The agreement promotes the transformation to low-carbon energy sources. One key strategy for achieving this objective is to replace coal-fired power plants by renewable energy power plants. In comparison to the secure, reliable, and predictable generation of electricity from coal-fired power plants, the generation of electricity from renewable energy sources is characterised by significant volatility and randomness [5]. As a result, relying solely on 100% renewable energy may not ensure a secure and stable power supply. The use of energy storage can help to reduce the variability of the power supply caused by the intermittent nature of electricity generated from renewable sources [6].

The 2922 MW Eraring power plant is the largest coal-fired power station in Australia, supplying approximately a quarter of the state of New South Wales' total power requirements [7]. The Lake Macquarie region in New South Wales, where the Eraring coal plant is located, offers considerable potential for the development of renewable energy projects [8]. The plant is scheduled to remain operational until August 2027, although its original closure date was planned for 2025 [9]. This decision was taken due to concerns that the power supply would be unreliable. The decision was made by Origin and the New South Wales government [9]. The initial phase of construction of a large-scale battery at Eraring is currently underway with the objective of promoting renewable energy projects [10]. During periods of daylight, when renewable energy sources such as solar are abundant, the battery will charge, and during periods of peak demand, it will discharge into the grid [11]. Furthermore, installing a battery system in Eraring takes advantage of the existing transmission and grid connection infrastructure, thus reducing the need to construct long transmission lines [11].

This project will analyse a number of potential methods for converting the Eraring coal-fired power plant, identifying the most efficient option by considering the meteorological conditions of the area and the environmental impact. This report will focus on an analysis of the potential of different renewable energy (solar photovoltaic, wind, biomass) and energy storage (flow batteries, green hydrogen, thermal storage) projects in Lake Macquarie. Furthermore, an economic analysis of the project will be presented, and a conclusion will be reached regarding the project's economic viability. The primary objective of the project is to present a renewable energy plan that is complementary to the ongoing construction of a large-scale battery, with the aim of ensuring energy reliability and contributing to the decarbonisation of the energy sector. Additionally, the project is intended to serve as an example for future energy transformation projects.

1.1 PROJECT MOTIVATION

This report is driven by three key motivations. The primary objective is to facilitate an energy transition and a reduction in CO_2 emissions. It also aspires to serve as a model for transformation in other thermal power plants. Secondly, the project aims to facilitate the creation of employment opportunities and the maintenance of existing jobs in the region. Thirdly, this project has been selected due to a strong personal motivation to learn about the energy sector and to understand the future changes, challenges and opportunities that it will face. Furthermore, I have selected this Australian coal plant due to my current exchange experience in Australia and my belief that it is a country with significant potential for growth in the renewable energy sector. Finally, I aim to investigate different energy storage technologies and assess the feasibility of green hydrogen projects or the Carnot battery, among others.

1.2 STATE OF THE ART

A significant number of thermal power plants are currently being dismantled [12]. In response to this, proposals are being put together for the conversion of these facilities to renewable energy power stations and the installation of large-scale energy storage systems [13]. The aim of these plans is to meet demand and reduce the fluctuations in energy supply that are caused by the intermittent nature of renewable energy sources. China has a substantial number of coal-fired power plants, and the retrofitting of existing coal-fired power plants is a crucial aspect of the transition to a decarbonised energy system [14]. Canada, the United States, Japan, India and China have all attempted to convert their coal-fired power plants to natural gas and biomass power plants [1]. Nevertheless, the environmental benefits of such conversions are a matter of contention [1]. The majority of existing conversion projects in the world are conversions to biomass fuel sources [15]. Examples of conversions from thermal power plants to renewable energy plants include the old coal power station in Ipswich, England [16], and the Matra Power Plant in Hungary [17]. Another example is the conversion of the Avedore power station in Denmark to a biomass plant [18].

The retirement of many CFPPs has resulted in a number of issues, including a reduction in synchronous inertia, frequency insecurity and a deficiency in regulation capability [19]. Recently, a number of studies have proposed a new technology for the transformation of retired coal-fired power plants, namely the reconstruction of these plants into Carnot batteries, also known as thermal storage power plants [20]. This approach is of particular interest as it addresses the issue of frequency security and uncertainty caused by the high proportion of variable renewable energy in the electricity system [21].

In regard to the current status of Eraring Power Station, the facility is scheduled for closure in 2027 as part of New South Wales' transition to renewable energy sources [7]. A 700 MW/2.8 GWh battery energy storage system (BESS) is being developed on-site to replace the coal-fired generation [11].

1.3 ERARING POWER PLANT

Eraring Power Station is a currently operational power station that utilises black coal as a fuel source [7]. It is located in New South Wales (NSW) on the shores of Lake Macquarie, approximately 120 kilometres north of Sydney and 40 kilometres south of Newcastle [7]. It is the largest power station in Australia, and it accounts for approximately 25% of New South Wales' power requirements [22]. The station is composed of four 720 MW coal-fired generator units and one 42 MW diesel generator [7]. This results in an overall generating capacity of 2,922 MW, making it the largest power station in Australia.

The construction of the power station was completed at a cost of $1.65 billion [23], and it was fully commissioned in 1984 [23]. Eraring has supplied power to New South Wales for a period exceeding 40 years [23]. Eraring was previously under public ownership. In 2013, Origin Energy acquired Eraring from the NSW Government for $50 million, representing approximately 3% of the power station's construction costs [24]. The power station is now owned and operated by Origin Energy [25].

1.3.1 TECHNOLOGICAL UPGRADES

Throughout the years, the power station has undergone several upgrades to enhance efficiency and reduce emissions [22]. These upgrades have included the installation of advanced control systems and high-efficiency boilers [22]. The process of upgrading the control room to a fully digital system was completed in 2005 [25]. Furthermore, between 2011 and 2012, the generating capacity of each of the four turbines was upgraded from 660 MW to 720 MW [25].

1.3.2 PRIMARY FUEL

Eraring is currently the primary coal-based energy supplier to the national grid. The coal is obtained from five mines within the region, and is transported via conveyor belt, rail, and private road [25]. The site is equipped with significant coal storage capacity [25].

1.3.3 EMISSIONS AND WASTE MANAGEMENT

The Eraring station is a significant contributor to Australia's carbon dioxide emissions, ranking alongside the Bayswater Power Station in Muswellbrook as one of the largest emitters [26]. The Eraring station emits approximately 15 million tonnes of carbon dioxide annually [26]. The majority of the waste produced is coal ash, which consists of both fly ash and bottom ash [27]. The average ash content for coal burnt in Eraring Power Station is between 20% and 25%, with the station producing more than 1.5 million tonnes of Coal Combustion Products (CCPs) per year [27]. At selected power stations, some of the ash is classified and transported to cement batching plants, where it is used as a cement extender [28]. The Eraring power station is of particular interest in this regard, as it demonstrates the benefits of being located close to markets, and consequently able to exploit the opportunity to sell its ash due to its close proximity to Newcastle. Approximately 35% of the fly ash is sold for use in the manufacture of concrete and building products and in road base [29].

1.3.4 CLOSURE OF COAL-FIRED OPERATIONS

Origin Energy has announced its intention to close Eraring's coal-fired units by 2027, in a move to transition towards more sustainable energy sources [30]. The closure of Eraring and other coal-fired power stations is a significant move towards a clean energy future [22]. The closure of the power station will lead to a significant reduction in greenhouse gas emissions, which will have a positive impact on the health of surrounding communities [22]. The scheduled closure date was mid-2025. However, the New South Wales Government has decided to extend the operational life of Eraring to August 2027, with a view to ensuring a stable power supply [30].

1.3.5 EMPLOYMENT

The Eraring Power Station has been a significant employer in the region, offering employment opportunities in various fields such as plant operation, maintenance, engineering, administration, and environmental management [22]. It has supported a range of skilled trades and professions, thus making a major contribution to the local job market and economy [22]. The facility currently employs 240 workers and another 200 contractors [31]. However, the future security of these positions is now uncertain [31].

1.3.6 Eraring power station battery

The Eraring site is intended to be used beyond the retirement of the coal-fired power station, and a large-scale battery is currently being installed [11]. The development of large-scale battery at Eraring is expected to enhance grid stability and support the integration of intermittent renewable energy sources [11]. Origin is constructing a 700 MW / 2100 MWh grid battery at the site. The second stage of the Eraring battery will add a 240 MW four-hour duration battery [11]. The combined energy storage of all stages will be 2.8 GWh [11]. The Eraring battery stage two will operate in Virtual Synchronous Machine (VISMA) mode, which enables the battery to support grid stability and security by providing short circuit current capabilities such as reactive current, droop control, and synthetic inertia [32]. The strategic positioning of the battery at Eraring utilises existing transmission and grid connection infrastructure, thereby minimising the necessity for constructing long transmission lines [11]. Once complete, the project will facilitate the advancement of renewable energy development by utilising the energy stored during daylight hours for discharging the grid during peak periods, thereby ensuring the reliable and sustainable operation of the energy system.

1.3.7 Possible conversion

The location is considered to be a strategic site, with high-quality connection infrastructure. The development agenda for Eraring includes initiatives such as the establishment of renewable energy projects and energy storage solutions, with the objective of replacing the coal-fired generation capacity [22]. This strategic approach is expected to ensure a sustainable and reliable energy supply for the region [22]. This transition is expected to generate employment opportunities, specifically in the fields of construction and operation of renewable energy infrastructure such as solar farms, wind turbines, and energy storage facilities.

1.3.8 TECHNICAL INFORMATION

- Description: the plant is characterised by the presence of two smokestacks, which reach a height of 200 metres [25].
- Steam: the process of generating steam for the turbines involves the use of reclaimed sewage water from the Dora Creek Waste Water Treatment Works. This water undergoes a rigorous purification process to ensure its purity and safety [25].
- Transmission Infrastructure: as illustrated in Figure 1, turbines 1 and 2 are connected to a 330kV transmission line, whereas turbines 3 and 4 are connected to a 500kV transmission line [25].
- Commission date: 1984 [25].
- Owner: Origin Energy [25].
- Primary fuel: the primary fuel source at Eraring Power Station is bituminous coal [25]. The Eraring Power Station consumes an annual total of 5.2 million tonnes of coal, which is supplied by five local mines [33].
- Turbine technology: subcritical steam turbine [25].
- Power generation: Four 720 MW and one 42 MW turbines [25]. The plant is equipped with four 720 MW Toshiba steam-driven turbo-alternators, which combined provide a capacity of 2,880 MW [25]. Additionally, a 42 MW diesel generator is included in the configuration [25].
- Model: Tokyo Shibaura Electric (Japan) [25].
- Capacity: 2,922 MW [25].
- Capacity factor: 57% (average 1999-2023) [25].
- Annual net output: 16,012 GW·h (average 2017-2021) [25].
- Status: operating [25].
- Cooling: salt water from Lake Macquarie is used for cooling. The salt water helps to both reduce the temperature of superheated steam and regulate the outlet water temperature to mitigate the potential for thermal pollution [25].
- Environmental Initiatives: the Eraring Power Station has implemented several initiatives to minimise its ecological footprint. These include the installation of low nitrogen oxide

(NOx) burners, the construction of ash storage facilities, and investments in renewable energy projects and energy storage solutions [22]. The Eraring Power Station employs the Fabric Filter system of dust collection, in which particulate emissions resulting from coal combustion are captured instead of being released into the atmosphere [25]. A proportion of this material is stored in an area nearby, while the rest is utilised as a component of road base [25].

1.4 OBJECTIVES

The principal objective of this project is to develop a plan for the conversion of the Eraring coal-fired power plant into a renewable energy and energy storage facility. The following objectives have been identified:

1. Identify the potential of the region for future renewable energy and energy storage projects. This will be achieved through an analysis of the geographical characteristics and meteorological conditions of the region.
2. Assess the potential for reutilizing existing infrastructure and resources at the Eraring power plant site. While the objective of this project is not to develop a decommissioning plan, it is essential to evaluate which key components and systems of the current facility could be repurposed or integrated into the design of a new renewable energy plant. The focus is on the development of a clean energy hub incorporating renewable energy generation, battery energy storage, and green hydrogen production, along with the appropriate selection of new equipment and technologies.
3. A study will be conducted to evaluate the technical feasibility of the proposed projects. A comprehensive examination of diverse renewable energy initiatives and energy storage technologies will be conducted, and the most suitable project will be identified, considering the region's resources, efficiency, and positive environmental impact. The selected project will be chosen based on a thorough evaluation of these factors.
4. A study of the economic feasibility of the project is required. Once the transformation project has been selected, a comprehensive economic analysis will be conducted to determine the project's economic viability. The economic analysis will begin with a set

of conservative financial assumptions. Other sections will address capital expenditures (CAPEX), operational expenditures (OPEX), and projected revenue streams. Finally, financial indicators such as Net Present Value (NPV) and Internal Rate of Return (IRR) will be calculated and interpreted to evaluate the project's investment potential, associated risks, and long-term economic viability.

5. Calculate the emissions saved. An estimation of the emissions saved with the implementation of the project will be made in order to measure the impact of the project on the environment and its contribution to the reduction of carbon emissions or other greenhouse gases.
6. One of the key objectives of the proposed transformation of the coal-fired power station into a renewable energy hub is to evaluate the project's alignment with the United Nations Sustainable Development Goals (SDGs). This includes assessing how the transition supports targets such as affordable and clean energy (SDG 7), climate action (SDG 13), and sustainable cities and communities (SDG 11).

CHAPTER 2. NEW PROJECTS

2.1 BIOMASS POWER PLANT

This section analyses the feasibility of converting the Eraring coal power plant to a biomass power plant. This transition in technology is not simple and requires technical and operational adaptations as well as significant investments.

The proposed strategy has the potential to contribute to the generation of renewable energy and the energy security of supply. Moreover, it offers a temporary solution that could extend the life of the plant. This type of conversion has been successfully implemented on a large scale. A notable example is the Drax Power Station in the UK, which contributes approximately 6% of the nation's electricity [34].

Availability of Biomass Resources

The first step is to assess the availability of biomass resources in the region [35]. Biomass sources can be categorised as agricultural, forestry, organic, energy crops or industrial waste [36]. The Lake Macquarie region, where Eraring is located, is predominantly urban and suburban, with limited agricultural and forestry activity. Consequently, the availability of biomass resources in this region is very limited [37]. However, with regard to municipal waste, proximity to Sydney and Newcastle (densely populated urban areas) could potentially open up access to a source of biomass. However, logistical challenges and additional costs may arise from the collection and transportation of this waste. Furthermore, the environmental impact of transporting biomass sources to the power plant must be considered.

When comparing this region to other regions in Australia, there are rural parts of New South Wales and other Australian states, such as Victoria and Queensland, which have greater availability of agricultural and forestry waste for biomass generation. Consequently, these regions are more favourable for biomass projects due to the greater availability of resources. It is essential to ensure uninterrupted availability to avoid disruptions. The following table illustrates the biomass resources located within a 50 km radius in 11 regions of NSW. This analysis highlights the scarcity of biomass sources in NSW when compared to other regions.

SA4 region	New connection capacity at substations [MW_e]	Number of substation with new connection capacity	Biomass resources in 50 km [t/a]	Direct normal irradiation [kWh/ m^2/year]	Capacity of HCSB plants [MW_e]	Capacity of HCSB plants [MW_e], agricultural residual fed	Capacity of HCSB plants [MW_e], forestry residual fed
Riverina	358	25	4,476,739	1,857 – 2,181	193.9	155.5	38.4
Murray	294	19	2,669,242	1,643 – 2,139	165.5	165.5	0.0
Central West	324	25	2,309,104	1,620 – 2,166	109.2	90.6	18.6
Richmond – Tweed	380	23	2,067,656	1,625 – 2,480	15	15	0.0
Coffs Harbour – Grafton	186	12	1,843,393	1,618 – 2,480	31.5	11.1	20.4
New England and North West	309	31	1,825,087	1,778 – 2,480	117.1	117.1	0.0
Capital Region	441	31	1,347,299	1,580 – 2,480	15	15	0.0
Far West and Orana	398.5	27	1,294,637	2,050 – 2,333	97.1	97.1	0.0
Mid North Coast	132	9	918,240	1,705 – 1,811	10.9	0.0	10.9
Newcastle and Lake Macquarie	15	1	172,229	1,787	0.0	0.0	0.0
Sydney - South West	10	1	152,381	2,013	0.0	0.0	0.0

Figure 2.1. *Table of biomass resources located within a 50 km radius across 11 regions of New South Wales. Source: [37].*

With regard to biomass projects in the region, none have been identified in the proximity of the study area [38]. The scarcity of local resources may act as an impediment to the development of biomass plants in this region. The map below illustrates the distribution of biomass plants in Australia, clearly indicating the absence of any such facilities in the region under study.

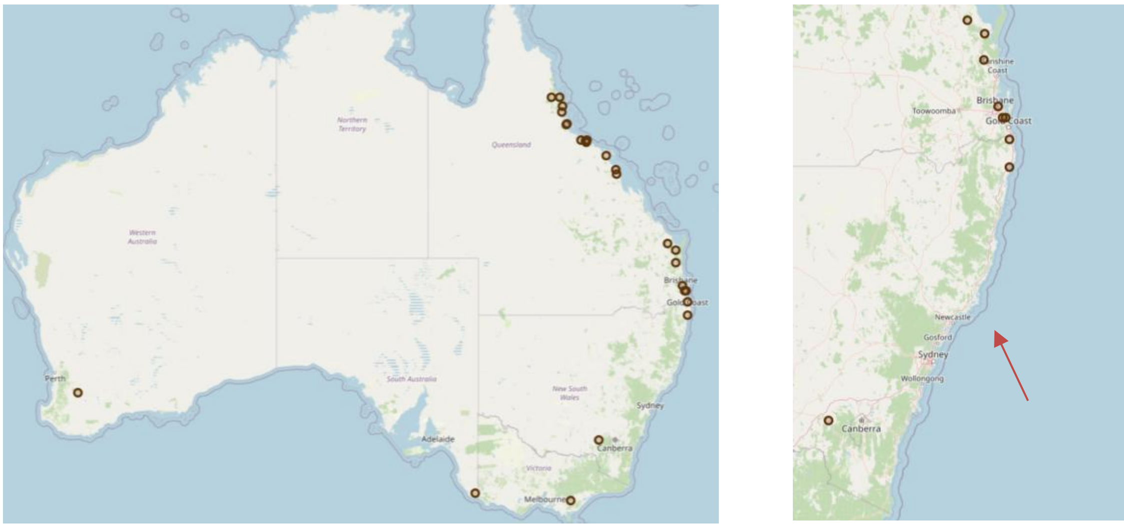

Figure 2.2. *Map illustrating the distribution of biomass plants across Australia. Source: [38].*

Technical Adaptations

The conversion of a coal-fired power plant to biomass involves a number of technical and operational changes affecting the boiler, turbine, operating point, temperature and pressure, as well as the addition of biomass preparation processes [39]. The principal changes that would be required are described below:

Coal-fired boilers are designed to handle pulverised coal. The inherent differences in moisture content and density between biomass and coal require adjustments to ensure efficient combustion [40]. Consequently, modifications would be necessary to facilitate the combustion of this fuel. Specifically, the coal boiler would need to be adapted to operate at lower temperatures, given the lower energy density of biomass, which means it produces less heat per unit mass [40]. Furthermore, measures must be implemented to prevent corrosion [40].

The steam turbines would also need to be adapted to the lower operating pressure and temperature due to the lower combustion temperature of the biomass, which would reduce the efficiency of the turbine.

The biomass power plant would also require fuel management systems. The storage, internal transport and processing of biomass would need the right equipment. Due to the high moisture content of biomass, a first stage in the processing of biomass is drying [40]. Furthermore, biomass generally requires shredding or grinding to a size suitable for efficient burning.

The high variability of biomass implies stricter control of fuel quality. This may involve the addition of systems to monitor the characteristics of the biomass.

With regard to emissions control, while biomass is generally considered cleaner than coal, it still produces gases and particles that need to be treated, so filters and systems to reduce particle emissions are needed.

The efficiency of biomass plants is often lower than that of coal plants, due to the characteristics of the fuel [40]. The requirement for a larger combustion space and a lower combustion temperature result in lower thermodynamic efficiency [40].

Economic Analysis

The process of converting to biomass requires a significant initial investment. This subsection analyses whether such an investment is justifiable.

The initial costs are primarily attributable to three factors: the renovation of the boiler and turbines, the installation of biomass transport and processing systems, and the adaptation of control systems.

With regard to operating costs, biomass is generally more expensive than coal, especially if the resources have to be transported over long distances. Ensuring a reliable and cost-effective supply of biomass is therefore essential for the economic viability of switching from coal to biomass.

Two potential revenue streams are identified as drivers for such a project: carbon credits (given the carbon neutrality of biomass) and government subsidies to encourage the transition to renewables.

Environmental analysis

Biomass, if sourced sustainably, can be a renewable and carbon neutral source, as the CO_2 released during combustion is reabsorbed by plants [41, 42]. Furthermore, the conversion process has been shown to reduce coal pollutants such as sulphur and mercury.

On the other hand, biomass combustion still emits particles and CO_2, although to a lesser extent than coal. However, if biomass extraction is not sustainable, it can lead to deforestation. Finally, indirect emissions resulting from the transportation of biomass over long distances must be considered.

Conclusion

Biomass is considered to be carbon neutral and provides an alternative solution to coal burning while maintaining existing infrastructure [42].

However, the study region experiences a scarcity of biomass resources due to its urban nature. However, there are other rural areas of Australia where agricultural and forestry resources are much more abundant and where the justification for such a project is more compelling. The absence of biomass projects in the region indicates limited feasibility of the project.

The economic analysis indicates that the transformation of the plant would require significant initial investment and high operating costs.

It is recommended that newer coal-fired power stations be considered as potential candidates for conversion to biomass, as these plants are the most suitable for conversion [42]. However, conversion to renewable energy sources such as solar or wind is more appropriate for older coal-fired power plants such as Eraring, where most of the equipment has reached the end of its useful life and is scheduled for decommissioning [42]. The conclusion drawn is that the maintenance of existing equipment at Eraring would be both inefficient and costly.

The overall conclusion is that converting Eraring to a biomass facility is not a feasible proposition, primarily due to fuel scarcity, environmental impact, high investment, and low energy output, as well as the fact that it is a very old facility where the equipment has reached the end of its useful life.

2.2 WIND FARM

This section considers the feasibility of developing a wind farm in the area of the Eraring power station.

Wind resource evaluation

Wind speed is the most important parameter in characterising the wind resource [43]. The study of the average wind speed indicates whether the wind resource of the site is suitable for such an installation. While the mean wind speed alone is insufficient to evaluate the wind resource, it is a first indicator of its potential.

The Global Wind Atlas (GWA) is a digital tool that will be used to assess the wind potential of the study region [44]. The Global Wind Atlas facilitates the identification of regions worldwide with high wind potential for wind power generation [44]. It is designed to facilitate the preliminary assessment of wind potential for the development of renewable energy projects. In addition to this, it facilitates wind power density calculations and allows analysis of wind seasonality and variability. The application provides information on wind speed and direction at 10 m, 50 m, 100 m and 200 m (reference heights).

The feasibility of a wind project depends on the average wind speed at hub height [45]. Consequently, the most relevant reference height for assessing the wind resource is 100 m, as this is the mid-point of the typical range of hub heights for modern commercial wind turbines (80 m - 120 m) [46, 47]. This section presents a detailed study of the wind resource in the study area.

The following figure shows the map of the study area.

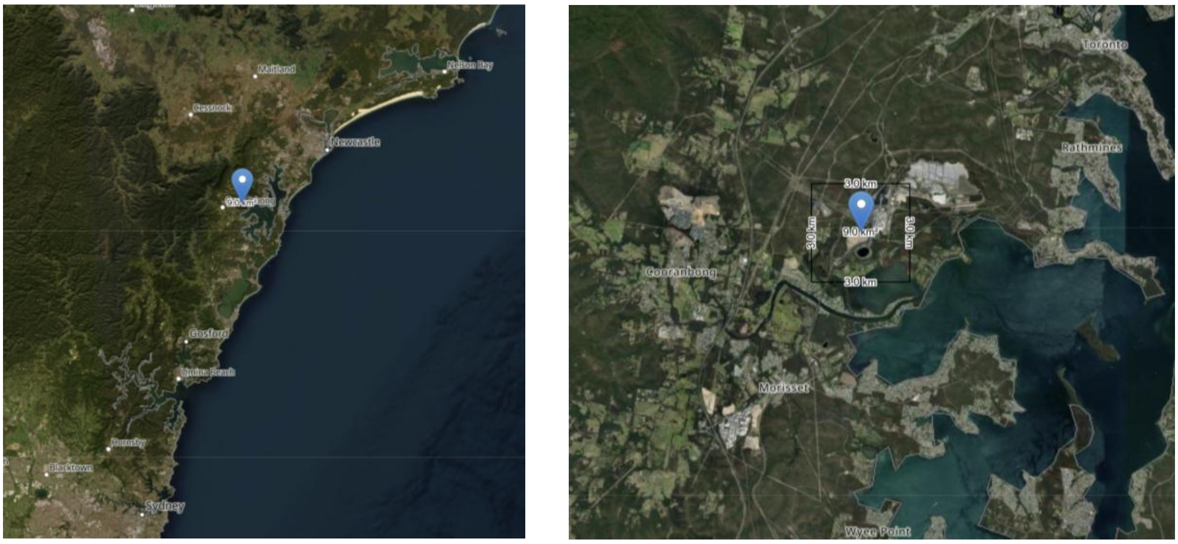

Figure 2.3. *Map of the study area: Eraring region. Source: [44].*

Vertical Wind Profile

The vertical wind profile shows the average wind speed at different heights. The reference height for this study is 100 metres, and according to data from the Global Wind Atlas, the average wind speed in the study region at 100m is 5.52m/s [44]. The minimum wind speed for a wind turbine to initiate power generation, designated as the 'cut-in speed', is typically between 3 and 4 m/s [48]. However, a common threshold to ensure commercial viability is 6-7 m/s at 100 m height [49]. This parameter is a primary indicator that the project is not viable.

Height	10m	50m	100m	150m	200m
Mean Power Density	26 W/m²	110 W/m²	181 W/m²	276 W/m²	381 W/m²
Mean Wind Speed	2.57 m/s	4.43 m/s	5.52 m/s	6.51 m/s	7.24 m/s

Table 2.1. *Vertical wind profile showing average wind speed at different heights. Source: [44].*

Wind Rose

The wind rose represents the frequencies and speeds for each wind direction [50]. The analysis of these graphs enables the extraction of the predominant wind direction and frequency. This is important for orienting the wind turbines perpendicular to the predominant wind direction to maximise wind capture and reduce wake effects [51].

This wind rose illustrates wind direction frequency, with predominant winds from the south and southwest, peaking at around 15%.

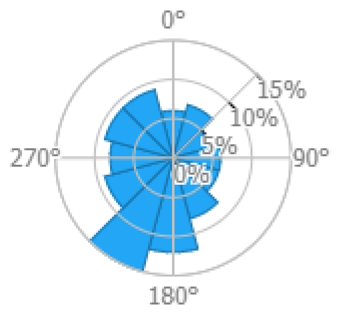

Figure 2.4. *Wind rose illustrating wind direction and speed distribution at the study site. Source: [44].*

Seasonality and variability analysis

In this sub-section, a study of diurnal, nocturnal and seasonal wind variations is carried out, which is crucial for estimating energy generation.

The diurnal profile shows how the wind speed increases in the morning, peaks between 06:00 and 12:00 UTC and then decreases in the afternoon and evening. This suggests that the wind follows a daily cycle influenced by temperature.

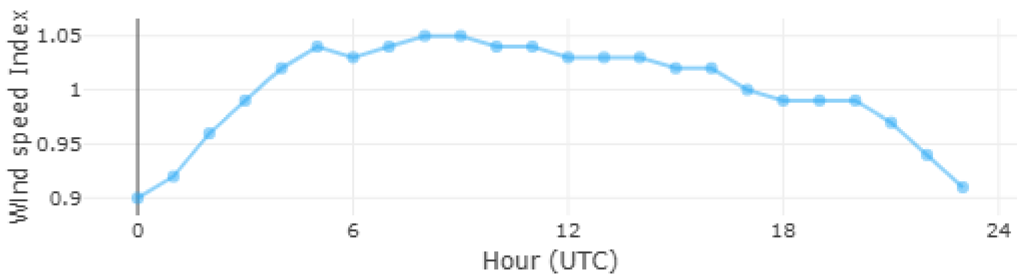

Figure 2.5. *Daily wind speed variation by hour. Source: [44].*

The annual profile shows that wind speed is lowest in autumn (March-June), increases in winter (June-September) and peaks in spring (September) before decreasing in summer (December-February). This reflects the seasonal variability of wind.

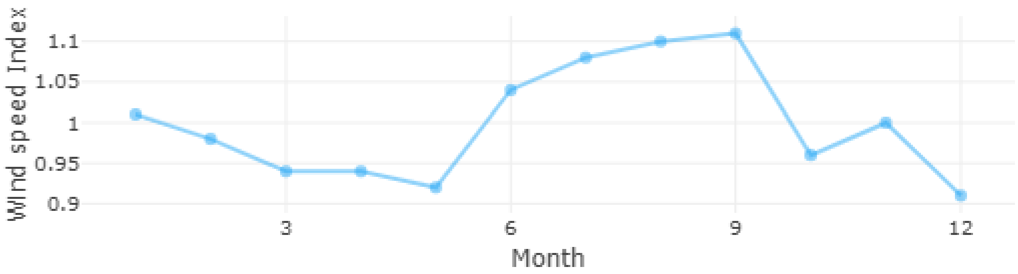

Figure 2.6. *The annual profile reflecting the seasonal variability of wind. Source: [44].*

Estimation of potential generation

According to data from the Global Wind Atlas, the average wind power density in the study area at 100 m altitude is 181 W/m² [44]. In terms of wind power density, a site with values above 200 W/m² at hub height is considered viable [52]. This indicates that the study area is not suitable for a wind project.

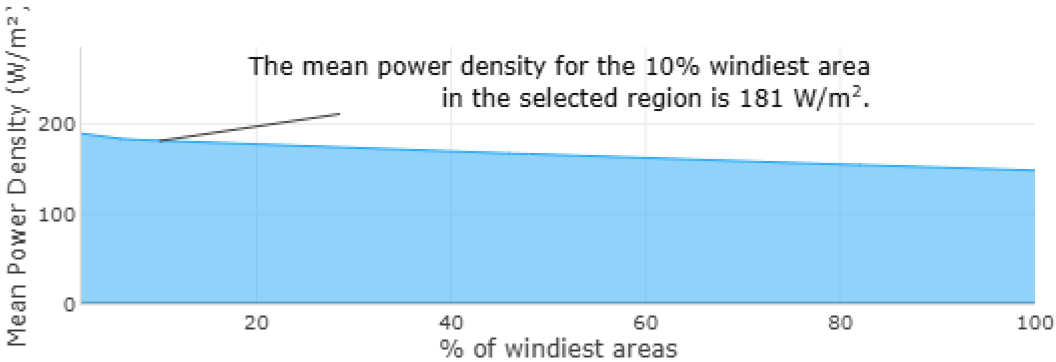

Figure 2.7. *Average wind power density in the study area. Source: [44].*

Large Scale Wind Farm Map of Australia

The following figure shows a map with large-scale wind farms in Australia. The figure shows that there are no wind projects in the surroundings of the study area, which consolidates the wind resource study, indicating that it is not a suitable location for large scale wind projects.

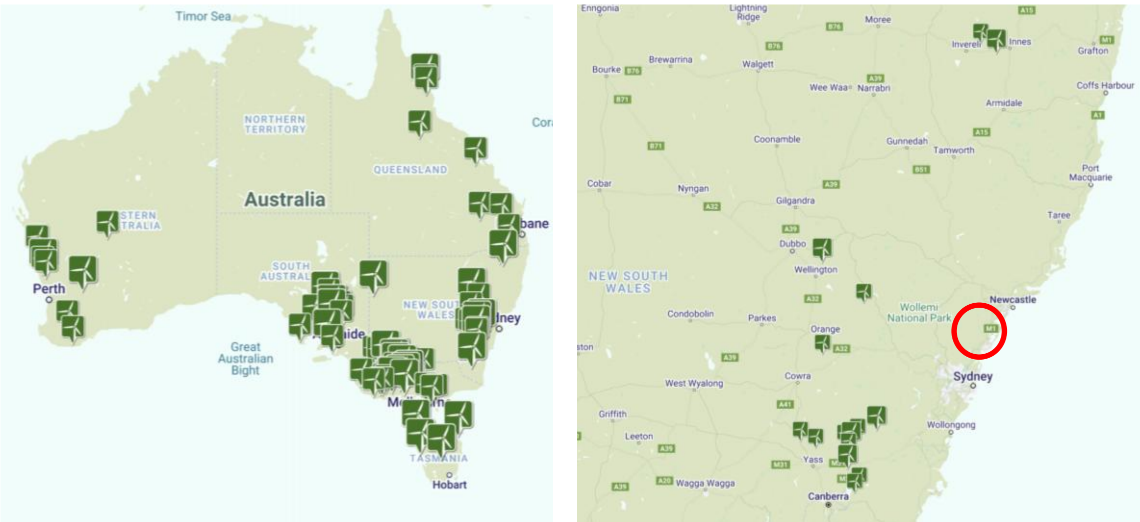

Figure 2.8. *Map showing large-scale wind farms in Australia. Source: [53].*

Conclusion

The study indicates that a large-scale wind project in the study region is not feasible as the wind resource is insufficient.

2.3 PV SOLAR FARM

This section considers the technical feasibility of developing a solar PV farm at the Eraring power station site.

Large Scale Solar Farm Map of Australia

Australia is a global leader in solar PV, with more than 30 GW of installed capacity and a high level of residential installations (+30% of households with panels) [54]. Australia has the highest solar energy per capita in the world [54]. Government incentives have stimulated the sector's growth, and the future focus is on storage, green hydrogen and decarbonisation [55].

The figure below includes all utility-scale solar projects of 10 MW or more in Australia.

Figure 2.9. *Map of utility-scale solar projects of 10 MW or more in Australia. Source: [56].*

Site Assessment

The Eraring power plant has approximately 1,147 hectares of land [57]. This is a large area, suitable for the installation of a large-scale solar farm. The land features are ideal, with no significant shading, flat topography and proximity to grid infrastructure to facilitate power transmission.

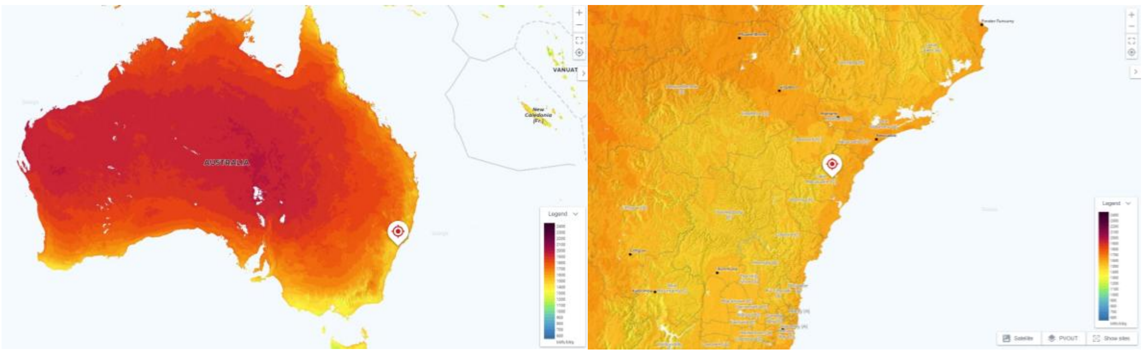

Figure 2.10. *Map of Australia indicating solar radiation intensity (kWh/kWp). Source: [58].*

Solar Resource.

To assess the solar potential in the study area, data from the Global Solar Atlas was used.

Global Solar Atlas

The Global Solar Atlas is an application that provides information on the solar resource and photovoltaic energy potential worldwide [58].

The Global Solar Atlas report for the study region provides detailed data on solar irradiation and the estimated production of a large-scale PV system. The solar resource is then analysed based on the tables and graphs in this report.

According to the Global Solar Atlas, the Eraring region has an average annual global horizontal solar irradiation (GHI) of 1653.3 kWh/m² [58]. This value indicates a favourable solar resource for photovoltaic power generation.

Map data			Per year
Direct normal irradiation	DNI	1813.9	kWh/m^2
Global horizontal irradiation	GHI	1653.3	kWh/m^2
Diffuse horizontal irradiation	DIF	583.1	kWh/m^2
Global tilted irradiation at optimum angle	GTI opta	1890.9	kWh/m^2
Optimum tilt of PV modules	OPTA	32 / 0	°
Air temperature	TEMP	18.1	°C

Figure 2.11. *Solar radiation data for Eraring region from Global Solar Atlas. Source: [58].*

The report recommends an inclination of 32° to maximise solar capture. At this inclination, the module surface irradiation (GTI) increases to 1890.9 kWh/m²/year. The GTI is the most accurate indicator of the solar energy available to the panels because it takes into account the optimal inclination of the solar panels, which reflects the amount of effective radiation they will receive.

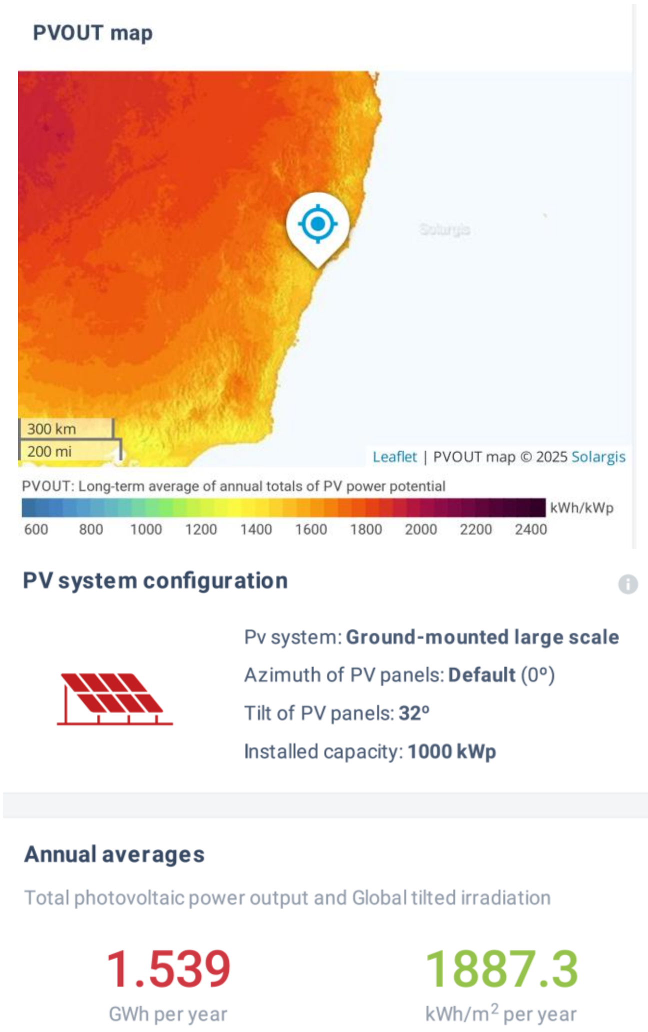

Figure 2.12. *PV power output map showing solar irradiation (kWh/m²) in the Eraring region. Source: [58].*

The specific output of 1887.3 kWh/kWp/year is very favourable compared to viable solar parks in other regions of the world.

Monthly Variability of Production

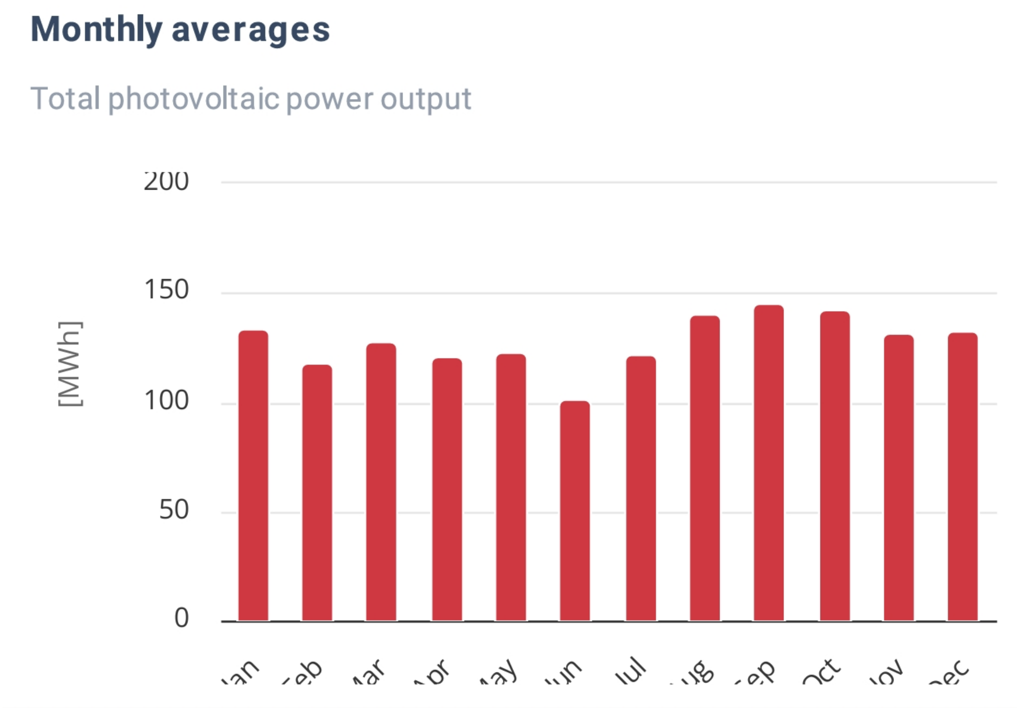

Figure 2.13. Seasonal variation in PV output at the Eraring site. Source: [58].

The graph shows seasonal variation in PV output at the Eraring power station site, based on an installed capacity of 1 MWp. Generation peaks in spring and early autumn (September, October, and January), reaching around 140–145 MWh. The lowest output occurs in winter (June), at about 100 MWh. This suggests that milder temperatures and higher solar irradiance in spring and autumn enhance performance, while shorter daylight hours in winter reduce output. The trend reflects typical seasonal patterns in the Southern Hemisphere.

Capacity Factor

The capacity factor (CF) indicates the ratio of the energy produced to the energy that would be produced if the plant operated at full capacity throughout the year [59]. The capacity factor is a key indicator for assessing the efficiency of a PV plant.

$$CF = \frac{Actual\ Energy\ Output\ (MWh)}{Installed\ Capacity\ (MW) \times Total\ Hours\ in\ a\ Year}$$

$$CF = \frac{1539\ MWh}{1\ MW \times 365 \times 24\ h} \times 100 = 17.56\%$$

The following chart presents the solar PV capacity factor (CF) for various ACCIONA plants from 2021 to 2023, with values ranging from 8.5% to 27.8%. The calculated CF of 17.56% falls within the mid-range, indicating standard or moderately efficient performance.

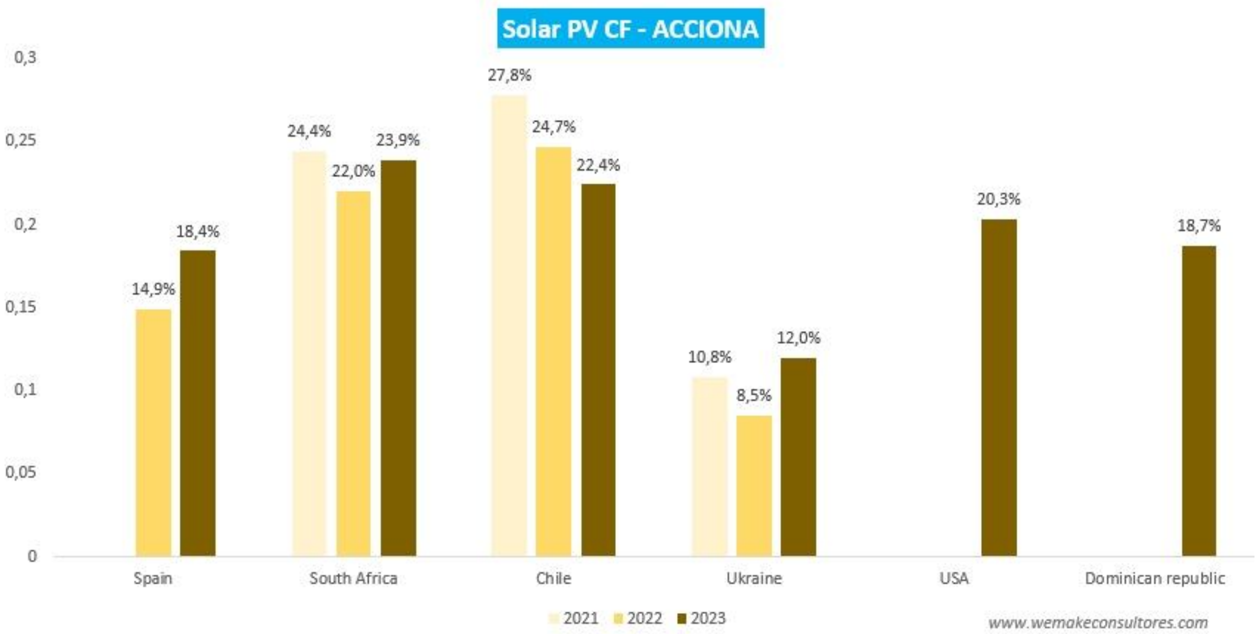

Figure 2.14. *Solar PV capacity factor (CF) for various ACCIONA plants. Source: [60].*

PVGIS

PVGIS is a web-based tool that provides solar irradiation and energy yield data for a chosen geographical location [61]. The PVGIS software aims to facilitate the study of the solar resource and the potential of photovoltaic energy [61].

Structures

The PVGIS report evaluates three types of configurations for the PV installation:

- Fixed tilted structure.

- Single-axis solar tracking.

- Two-axis solar tracking.

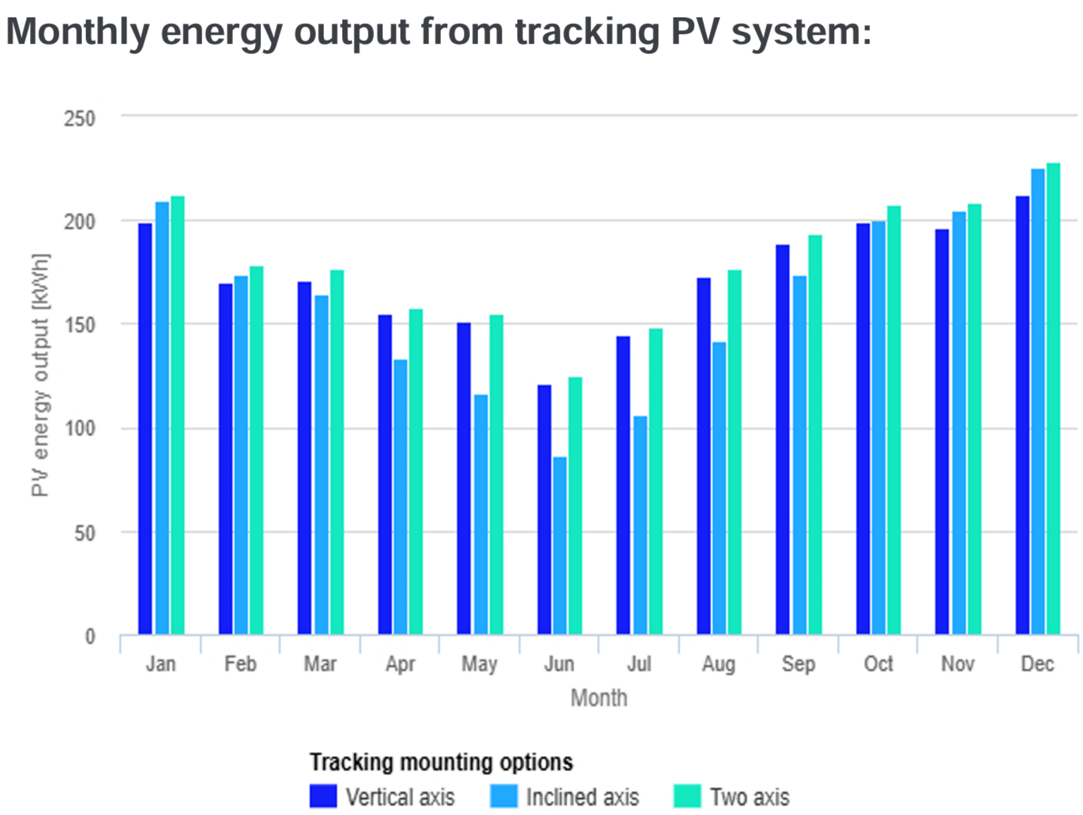

Figure 2.15. *Chart comparing energy output from different tracking systems. Source: [61].*

Provided inputs:

Latitude/Longitude:	-33.056,151.521
Horizon:	Calculated
Database used:	PVGIS-ERA5
PV technology:	Crystalline silicon
PV installed:	1 kWp
System loss:	14 %

Simulation outputs

	VA*	IA*	2A*
Slope angle [°]:	53 (opt)	0 (opt)	-
Yearly PV energy production [kWh]:	2082.91	1936.55	2167.09
Yearly in-plane irradiation [kWh/m²]:	2623.84	2437.31	2735.3
Year-to-year variability [kWh]:	77.7	73.2	81.3
Changes in output due to:			
Angle of incidence [%]:	-1.25	-1.44	-1.17
Spectral effects [%]:	NaN	NaN	NaN
Temp. and low irradiance [%]:	-6.52	-6.26	-6.78
Total loss [%]:	-20.62	-20.55	-20.77

* VA: Vertical axis
IA: Inclined axis
2A: Two axis

Figure 2.16. *PV energy production (kWh) from different tracking systems. Source: [61].*

Calculation of Production Increase

The following table compares the three types of configurations for the PV installation.

Structure Type	Annual Energy Production (KWh/KWp)
Fixed Tilt (IA)	1936.55 KWh/KWp
Single-Axis Tracking (VA)	2082.91 KWh/KWp
Dual-Axis Tracking (2A)	2167.09Wh/KWp

Table 2.2. *Annual energy production of fixed, single-axis, and dual-axis PV systems. Source: [61].*

- Fixed tilt mounting systems are more simple, less expensive and require less maintenance than tracking systems.
- 1-axis (vertical) solar tracking improves production by 7.5% over fixed structure:

$$\frac{2082.91 - 1936.55}{1936.55} \times 100 = 7.5\%$$

- 2-axis solar tracking offers a 12% increase over fixed structure. However, the cost and maintenance of the 2-axis system are high, which can reduce profitability.

$$\frac{2167.09 - 1936.55}{1936.55} \times 100 = 12\%$$

Proposed capacity

Considering a typical installation density of 1 MW per 2 hectares, it is proposed to install 500 MW on the 1,147 hectares available.

For instance, the Núñez de Balboa PV solar plant in Extremadura, Spain, has a capacity of 500 MW and occupies approximately 1,000 hectares, resulting in a density of 0.5 MW per hectare [62].

Estimated Annual Production

Considering an installed capacity of 500 MW and a capacity factor of 17.56%, the estimated annual production is:

$$Annual\ Production = Installed\ Capacity \times CF \times Total\ Hours\ in\ a\ Year$$

$$Annual\ Production = 500\ MW\ \times 17.56\%\ \times 365 \times 24\ \text{h} = 769.128\ \text{GWh}$$

Therefore, the estimated annual production of the solar PV project would be approximately 769,128 MWh (769.1 GWh).

Conclusion

The analysis indicates that the development of a large-scale photovoltaic farm on this site is feasible in terms of solar resources and site characterisation. The report's data indicates that the expected irradiation and production levels are at optimal levels for the profitability of a PV project.

However, due to the intermittent nature of solar energy and the production peaks in summer, a hybrid system combining solar energy with a storage system is needed to achieve greater stability and efficiency. A detailed economic analysis is also required, which will be presented in chapter 4.

2.4 LARGE-SCALE PRODUCTION OF GREEN HYDROGEN

This section provides a detailed analysis of the integration of a photovoltaic system with electrolysis technology to produce green hydrogen in the region under study.

Green Hydrogen

Hydrogen is a clean energy carrier with a high energy content (33.33 kWh/kg) [63]. Green hydrogen, produced using renewable energy sources such as solar PV, does not generate carbon emissions, therefore supporting climate targets [63]. Hydrogen is an effective solution for long-duration storage, addressing the challenges posed by the intermittent nature of renewable energy [63]. It is regarded as a promising alternative to fossil fuels in various sectors. Green hydrogen is extracted from water using electrolysers that are powered by surplus renewable energy. The potential positive impact of this project on coal-region economies such as Eraring, including job retention and infrastructure reuse, could be a valuable opportunity for the region.

The figure below illustrates the volumetric and specific energy densities of various energy carriers. As the table shows, hydrogen has a much higher energy density per unit mass than any of the other elements in the table. However, when evaluated based on volume, its energy density is significantly lower compared to other fuels, such as diesel or LNG. Therefore, hydrogen is a viable solution for applications where space availability is not a limiting factor or a scarce resource.

Fuel	Volumetric Energy Density (kWh/m³)	Gravimetric Energy Density (kWh/kg)
Diesel	10,044	12.0 [18]
Heavy Fuel Oil	10,938	10.8 [25]
Liquefied Natural Gas (111 K)	6165	13.9 [18]
Liquefied Ammonia (10 bar or 239 K)	3528 [27]	5.2 [18]
Hydrogen (350 bar)	766	33.3 [22]
Hydrogen (700 bar)	1309	33.3 [22]
Liquefied Hydrogen (20 K)	2363	33.3 [22]
Methanol	4424	5.6 [18]
Liquid Organic Hydrogen Carrier (here: Dibenzyltoluene)	1886	2.1
Metalhydride (here: MgH_2)	3672 [29]	2.5

Figure 2.17. *Comparison of energy density for different energy carriers. Source: [64].*

Practical Applications and Case Studies

Hydrogen is pivotal to the decarbonisation of numerous sectors that cannot be electrified, including non-road transport (aviation and shipping), the steel industry, and ammonia production [63]. Furthermore, its application for energy storage and grid stabilisation is essential for complementing renewable energy production from intermittent sources and ensuring a secure energy supply [63].

The Catalina project, one of the largest green hydrogen projects in Spain, is a reference for this study and has inspired this section of the paper in a way. The Catalina project integrates 1.5 GW of wind and solar power to feed a 500 MW electrolyser [65]. The project has set an ambitious target of achieving 15% of the current hydrogen demand in Spain [65].

Figure 2.18. *Illustration of the Catalina green hydrogen project in Spain. Source: [65].*

National Hydrogen Roadmap

The National Hydrogen Roadmap is a strategic plan developed by CSIRO (Commonwealth Scientific and Industrial Research Organisation) that details how Australia can develop a sustainable hydrogen industry [66]. It is of particular significance for green hydrogen projects as it provides guidance on policy, attracts investment, and provides support for infrastructure and innovation [66].

For a hydrogen plant at Eraring, the Roadmap is important because it encourages the reuse of existing energy sites, aligns the project with national goals, and helps secure funding and regulatory support.

Site Overview

Existing assets that can be reused include:

- Existing grid connection and transmission systems: electrical connection to the grid via overhead conductors (330 kV and 500 kV).
- Water supply infrastructure and cooling water system: the main water supply for Eraring Power Station is from Lake Macquarie (circulating water system cools the turbines through the condensers and is returned to Lake Macquarie via an outlet canal).
- Access to roads and substations.
- Cooling infrastructure: cooling towers.

Solar PV-Powered Electrolysis

PV systems transform solar energy into electricity, which is then used to supply direct current (DC) to electrolysers for the water splitting process. This process produces hydrogen and oxygen.

Electrolyser Technology

The most common electrolyser technologies studied are Proton Exchange Membrane (PEM) and alkaline electrolysers.

- **PEM (Proton Exchange Membrane):** offers higher efficiency, system flexibility and dynamic performance [67].

- **Alkaline Electrolyser:** a more mature technology with lower capital costs, but with lower current densities, higher minimum load requirements, longer start-up times, and lower efficiency [68].

PEM technology is expected to be the dominant electrolysis technology due to its ability to better manage the intermittent nature of renewable electricity [67].

The unfavourable operating conditions of the ALK electrolyser result in increased electricity costs. Consequently, the reduced capital expenditure of ALK cannot fully offset the increased electricity costs, resulting in comparable LCOH values between the two technologies.

Due to its higher efficiency and dynamic performance, the PEM electrolyser technology has been selected for this project, as it is particularly well-suited for hybrid renewable configurations.

Grid and Electrical Integration

- PV-electrolysis coupling via DC-DC converters.
- Existing electrical infrastructure allows direct injection of surplus PV to the grid.
- Import of backup power during low solar conditions.
- Power electronics: Interface between DC PV, electrolysers, and AC grid via inverter–rectifier setup.

Impact of the Battery Energy Storage System (BESS)

A BESS is integrated to ensure consistent output from renewable energy sources. The battery reduces power fluctuations, ensuring the system runs smoothly even during periods of low solar activity. This will reduce wasted energy and improve hydrogen production.

System Performance and Optimization Strategies

- Maximum Power Point Tracking (MPPT) algorithms improve system efficiency by matching the PV output to electrolyser requirements dynamically. A power electronic converter will accomplish this task [69].
- Cooling mechanisms (e.g. water flow, heat exchangers) are key to reducing PV temperature and improving efficiency [70].
- Dual-axis PV tracking has been shown to collect maximum solar radiation [71].

Operational Strategy

- Sunny days: the electrolyser operates at maximum capacity, with any surplus solar power being utilised for either charging the battery or providing direct grid supply.
- Cloudy days: whilst hydrogen production is decreasing, the battery provides backup power to ensure the system remains operational.
- Nighttime: stored hydrogen and BEES should be used to meet local demand.

Proposed Control Strategy

Electrolysers suffer from efficiency losses and wear due to the fluctuating power supply from renewable sources. Electrolysers are typically designed to switch on and off suddenly, depending on the availability of solar power (resulting in a choppy control). Frequent switching can reduce efficiency and shorten equipment lifespan. A superior control strategy is presented to stabilise electrolyser operation and enhance hydrogen production. [72]

Segmented control is a method used to regulate the operation of large electrolysers. This control improves the yield and efficiency of green hydrogen production, extends the lifespan of electrolyser units, and reduces operational costs. [72]

The proposed segmented control method improves this by:

- Increasing the power to electrolysers gradually, rather than being switched on and off abruptly. This approach enables the system to make smooth adjustments rather than sudden changes. [72]

- Implementing a battery energy storage system (BESS). This facilitates the capture of excess solar energy and ensures uninterrupted power supply during periods of reduced solar production. [72]

The segmented control strategy is a more efficient alternative to traditional choppy control. This product has been shown to improve the efficiency of electrolysers, increase hydrogen production, and reduce wear and tear on equipment. The study demonstrates that integrating solar energy with an optimised control system and battery storage can enhance the reliability and cost-effectiveness of large-scale green hydrogen production. [72]

Challenges and Proposed Solutions

The production of hydrogen from solar PV power is an exciting potential solution for the clean energy sector, but it is important to note that there are still technical and economic challenges to overcome.

- The cost is high in terms of capital expenditure, especially when it comes to electrolysers and dual-tracking technologies. A potential solution to this issue could be to introduce a carbon cost based on the carbon intensity of hydrogen production methods. This could significantly enhance the cost-competitiveness of green hydrogen.
- Safety: the handling, storage and compression of hydrogen [64].
- Efficiency losses resulting from mismatches between photovoltaic (PV) and electrolyser systems. The proposed solution is to integrate a MPPT (Maximum Power Point Tracking) algorithm.
- Stability issues: the degradation of membranes and catalysts over time can be addressed by implementing a segmented control strategy [72].
- Commercialization of green hydrogen: needs better system integration, standardization and infrastructure. The solution to this issue is to implement the relevant policies and make the necessary investments.

2.5 ENERGY STORAGE

This section proposes incorporating Battery Energy Storage Systems (BESS) into the project. The integration of renewable energy plants with batteries is a highly effective solution for advancing a cleaner, more secure, and affordable electricity system [73]. Furthermore, storage and strategic deployment of renewable energy can reduce reliance on fossil fuels, lower greenhouse gas emissions, and mitigate peak electricity prices.

Advantages of integrating a BESS

The integration of BESS offers a wide range of benefits:

- Grid stability and flexibility: makes the system more reliable by balancing supply and demand, reducing congestion, and supporting decentralised generation models [73].
- Market volatility protection: helps stabilize electricity prices and avoid consumer bill spikes during high-demand periods [74].
- Operational flexibility: improves the responsiveness and control of renewable plants [73].
- Revenue opportunities: opens new income streams by providing grid services such as load balancing and frequency regulation [73].
- Fossil fuel reduction: reduces emissions and dependence on gas-fired generation during periods of low renewable output, contributing to a more sustainable energy system [73].
- Lower consumer costs: battery-equipped renewable plants can inject clean energy during critical periods, easing pressure on wholesale prices [74].
- Enhanced demand response: strengthens the system's ability to react to sudden demand variations, improving overall energy security [73].

Challenges of integrating a BESS

Despite their advantages, BESS deployment faces several challenges:

- High initial costs: significant CAPEX is required to add battery units and associated infrastructure [74, 75].

- Technical complexity: managing photovoltaic and battery systems requires advanced control systems and coordination.
- Permitting challenges: separate, often long approval processes may be required for each system component.
- Limited Battery Lifespan: Current battery technologies have finite cycles and face recycling challenges [74, 75].
- Safety concerns: risk of fires [75].

Large-Scale Battery Adoption in Australia

Australia is well-positioned for substantial BESS expansion, driven by market volatility, supportive government policies, and the progressive decommissioning of coal-fired plants [76]. According to BloombergNEF, almost 70% of Australia's coal power stations could be decommissioned by 2035, highlighting the pivotal role of batteries in facilitating a smooth and sustainable energy transition [77]. The rapid growth of wind and solar in the National Electricity Market (NEM) has increased the value of flexible storage, especially as renewable oversupply reduces prices while fossil generation increases them during shortfalls. With over one-third of Australian rooftops equipped with solar panels, the country is a global leader in distributed generation [78].

Long-Duration Energy Storage (LDES)

Beyond lithium-ion batteries, growing research supports long-duration storage technologies such as redox-flow batteries (RFBs), thermal storage, and hydrogen to enhance grid resilience and flexibility [79].

Electrochemical Energy Storage

Electrochemical storage technologies offer high round-trip efficiency, pollution-free operation, and modular scalability. Their flexibility makes them ideal for renewable integration and frequency control. Lithium-ion and redox-flow batteries stand out due to their energy density and customizable configurations. At present, lithium-based storage devices represent 99% of domestic storage, but they are not ideal for long-duration, large-capacity storage due to high costs, short lifespan and safety issues [80].

2.5.1 Redox Flow Batteries

RFBs are specialized electrochemical energy storage systems [81]. They store energy in external electrolyte tanks and operate through reversible redox reactions [82]. Their modular architecture allows independent scaling of power and capacity [82]. Key system components include electrodes, an ion-selective membrane, and two separate storage tanks for the anolyte and catholyte.

During charging, renewable energy drives oxidation in the anolyte and reduction in the catholyte. The ion-exchange membrane ensures electrochemical stability by allowing ion transfer while preventing electrolyte mixing. Discharging reverses the redox process, generating electricity through an external circuit.

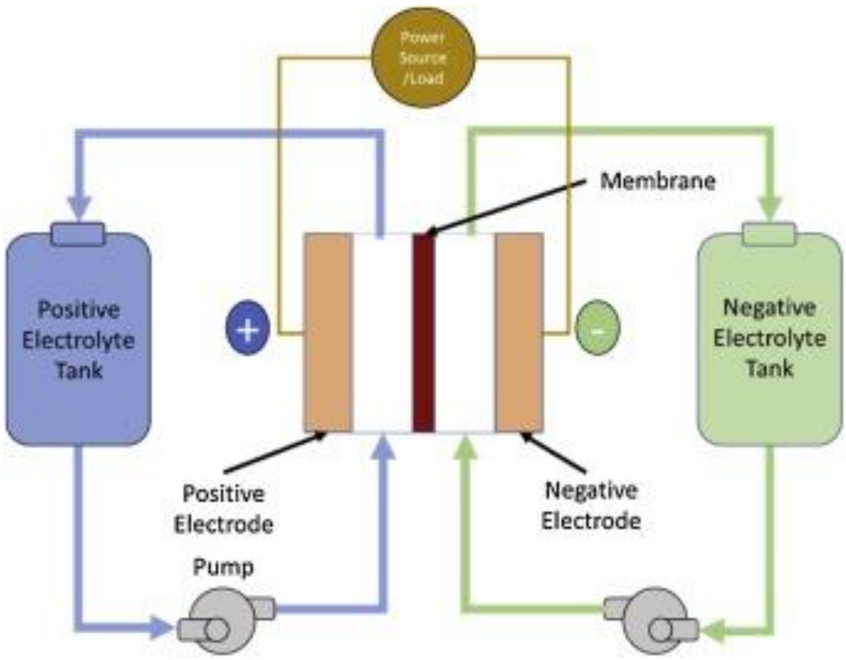

Figure 2.19. *Schematic diagram of a redox-flow battery. Source: [83].*

Advantages of RFBs

- Scalability: energy capacity can be increased by enlarging electrolyte tanks [84].

- Long Duration and High Efficiency: storage durations from days to months with efficiencies of 65–80%.
- Operational safety: non-flammable electrolytes and minimal heat accumulation ensure high safety [82, 84].
- Durability: long cycle life (>15,000 cycles) with negligible performance degradation [82, 84].
- Full discharge capability: allows deep discharge without damaging cells or reducing lifespan.
- Sustainability: vanadium electrolytes are non-toxic and recyclable, aligning with environmental goals [84].
- Cost-effectiveness at scale: lower per-unit costs as system size increases.

Table 4. Comparison of LDES technologies.

LDES Technologies		Storage Medium	Storage Form	Storage Duration	Storage Efficiency (or Self-Loss Rate)
Mechanical energy storage	PHES	Water	Gravitational potential energy	Several hours to several days	~80%
	CAES	Air	Elastic potential energy	Several hours to several days	55–75%
Chemical energy storage	Hydrogen energy storage	Hydrogen	Chemical energy	Several months or longer	Liquid hydro-gen evaporation loss ~3%/day
	Synthetic Fuel Storage	Fuel	Chemical energy	Several months or longer	—
Electrochemical energy storage	LIB	Lithium salts	Chemical energy	Several hours to several days	~97%, self-discharge rate as low as 0.03%
	RFB	Electrolyte	Chemical energy	Several days	65–80%
Thermal energy storage	ATES	Water	Thermal energy	Seasonal (several months)	67.5–87%
	TTES	Water/water-Gravel	Thermal energy	Seasonal (several months)	45–65%
	BTES	Subsurface	Thermal energy	Seasonal (several months)	40–60%
	Molten salt energy storage	Molten salts	Thermal energy	Seasonal (several months)	5–8%/month
	Gravel thermal storage system	Gravel	Thermal energy	Seasonal (several months)	—
	LHS	Chemical materials	Chemical energy	Several months or longer	—
	THS	Chemical materials	Chemical energy	Several months or longer	—

***Table 2.3.** Comparison of long-duration energy storage technologies. Source: [85].*

Limitations of RFBs

- Limited field deployment: compared to other technologies, RFBs have fewer commercial deployments and less development history in portable or automotive sectors.
- System complexity: requires additional components such as pumps, sensors, and flow controls [84].
- High investment: involves significant CAPEX [82, 84].
- Lower energy density compared to lithium-ion batteries [84].

Applications

RFBs are well-suited for:

- Renewable Energy Storage: smoothing intermittency from wind and solar sources [84].
- Grid Support: It provides frequency regulation, peak shaving and load levelling with fast response times [84].

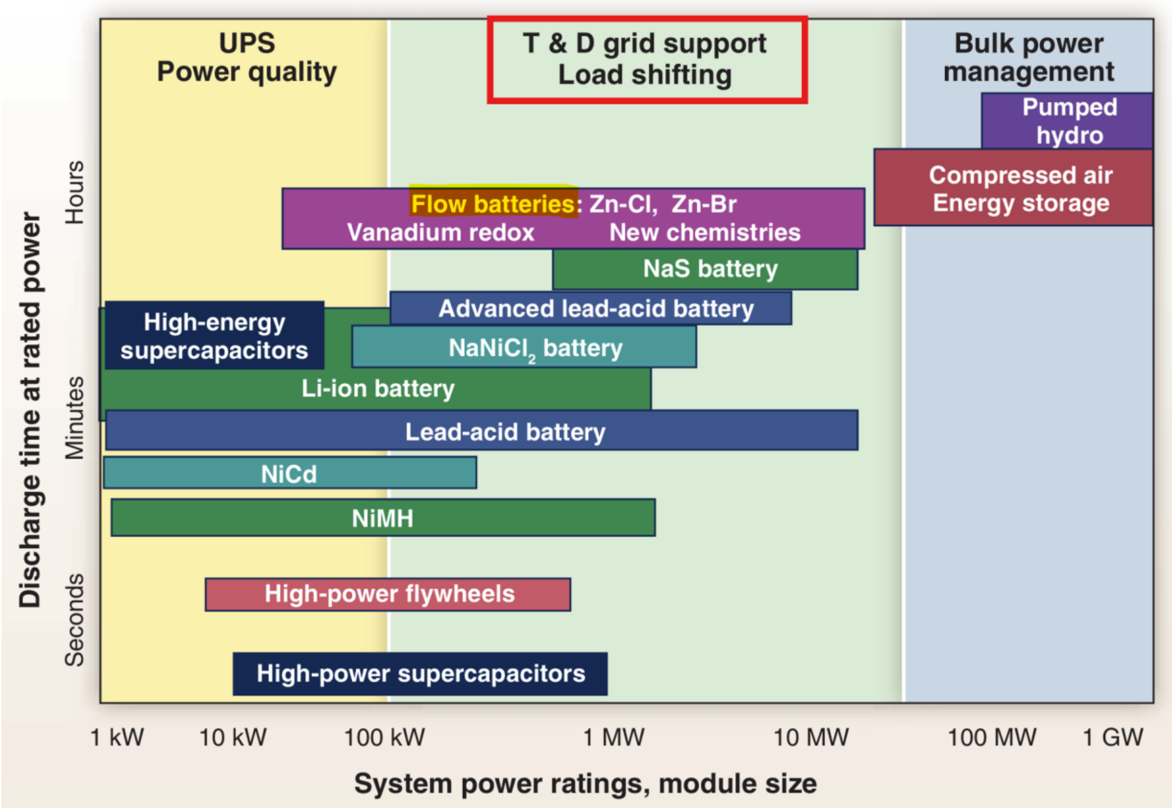

Figure 2.20. *Power rating versus discharge time graph illustrating the suitability of flow batteries for grid support applications. Source: [86].*

Common Types of RFBs

1. Vanadium Redox Flow Batteries (VRFBs): Most mature and widely adopted due to their chemical stability and long cycle life [87].
2. Zinc-Bromine Flow Batteries: Offer higher energy density but require more maintenance [87].

Among advanced types, VRFBs are particularly noteworthy. They utilize four vanadium oxidation states for energy storage through redox reactions [83]. This chemistry allows for high performance, low degradation, and safer operations compared to lithium-ion batteries [83].

Conclusion

Redox-flow batteries, with their scalability, safety, and durability, represent a promising solution for large-scale, long-duration energy storage. Their modular design and unique chemistry make them ideal for integrating renewable energy into stable, low-emission power systems.

2.5.2 CARNOT BATTERY

In this section, a novel thermal storage reconstruction scheme, known as the Carnot battery, is proposed for CFPP reconstruction.

Carnot Battery Reconstruction Model for Coal-Fired Power Plants

The Carnot Battery (CB) is a thermal energy storage concept that is increasingly being explored to repurpose coal-fired power plants (CFPPs) for renewable energy integration [20]. It offers a pathway to reduce carbon emissions while maintaining some of the technical advantages of conventional CFPPs, such as synchronous inertia and flexible regulation capabilities.

In this configuration, the conventional boiler of a CFPP is replaced by an electric heat transfer (EHT) system and a thermal storage (TS) unit [88]. During the charging phase, surplus renewable energy electricity is used to generate heat via electric heaters or heat pumps. This thermal energy, often exceeding 600°C, is stored in media such as molten salts, rocks, or metals. During discharge, the stored heat is converted back into electricity using thermodynamic cycles, typically the Rankine or Brayton cycles [88]. The system retains the original steam-water cycle, including components such as feedwater heaters, condensers, and turbines, along with the control and grid-connection systems [88].

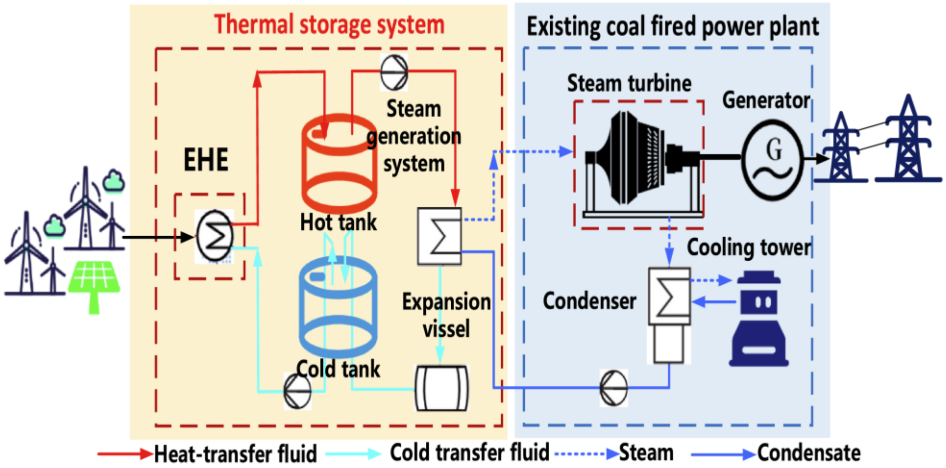

Fig. 2. Carnot battery structure.

Figure 2.21. Carnot battery illustration. Source: [88].

The concept makes use of the infrastructure of existing CFPPs, reducing the need for extensive new construction. By maintaining key plant components and replacing only the combustion system, it enables a lower-carbon transition while preserving frequency stability and grid services [88].

Although still at an early stage of development, Carnot Batteries are expected to store large amounts of energy for durations exceeding 10 hours, with operating costs that could become competitive with pumped hydro storage.

Frequency Security

In power systems with high shares of VRE, frequency stability becomes a critical operational challenge due to the reduced availability of inertia [88]. Since synchronous inertia is essential to maintaining system frequency, low-carbon generation planning must address this gap. The Carnot Battery, by retaining synchronous rotating mass from repurposed CFPPs, provides a promising solution to support grid stability in future power systems [88].

Advantages of Carnot Batteries

- Grid support capabilities: provide inertia and fast frequency response, utilising the existing rotating machines of CFPPs [88].
- Low operating costs: potential for cost-effective long-duration storage [88].
- Geographically unconstrained: unlike pumped hydro, Carnot Batteries are not limited by specific terrain or water availability [88].
- Reuse of existing assets: makes use of existing resources in decommissioned CFPPs, preserving valuable infrastructure [88].
- Integration: Can be integrated with other energy systems [88].
- Sustainable and safe materials: utilizes widely available, non-toxic, and low-cost storage media such as sand, stone, or molten salts.
- Technological synergies: builds on established technologies from the concentrated solar power (CSP) sector, particularly in thermal storage methods.

Disadvantages of Carnot Batteries

- Early development stage: currently limited to demonstration and pilot-scale projects, with no full-scale commercial deployments in CFPPs.
- High capital costs: initial investment remains significant, especially when compared to more mature storage technologies.
- Limited commercial experience: the technology has not yet reached commercial maturity [89].

Case Study: Siemens Gamesa Pilot

The most advanced example of a Carnot Battery system is the 5.4 MW / 130 MWh pilot project developed by Siemens Gamesa in Germany [90]. This facility demonstrates the feasibility of converting renewable electricity into stored thermal energy and later back into electricity using existing thermal power plant infrastructure.

Case Study: Eraring Power Station

The Eraring Power Station, Australia's largest CFPP, experienced approximately 6,000 hours of outages across its four units in 2024. These interruptions, resulting from both maintenance and unexpected failures, indicate that the plant, already 43 years old, is no longer reliable or suited for continued operation. While in theory, CFPPs with high capacity and efficiency could be candidates for Carnot Battery conversion, Eraring does not meet the efficiency or reliability criteria necessary for such a reconstruction.

Given the plant's advanced age and frequent outages, repurposing Eraring as a Carnot Battery is not a viable investment. Instead, the installation of a Battery Energy Storage System (BESS), such as a redox flow battery, presents a more promising and appropriate solution for the site.

Conclusion

The Carnot Battery represents an innovative and promising solution for decarbonizing the power sector by repurposing decommissioned CFPPs. However, the technology is still in an intermediate stage of development, situated between advanced research and early demonstration. Its application in large, aging plants like Eraring is currently unjustified.

While not yet commercially viable on a large scale, the technology holds significant potential for application in countries like China, which possess a large fleet of relatively modern and efficient CFPPs [91]. In such contexts, Carnot Battery systems could provide a strategic pathway to low-carbon grid flexibility and energy storage.

For now, more mature and commercially proven technologies such as BESS may offer better near-term solutions, particularly in cases where CFPPs are no longer technically or economically viable for conversion.

CHAPTER 3. SYSTEM DESIGN AND EQUIPMENT SELECTION

In this section, the selection of the equipment for the study project is carried out. The new installation to produce green H2 from 100% renewable sources consists of a 500 MW solar photovoltaic plant, a Vanadium Flow Battery system with a storage capacity of 80 MWh and a 20 MW hydrogen production system by electrolysis.

The hydrogen will be used for the generation of green ammonia and emission-free fertilisers. A green hydrogen business opportunity has been identified for Orica's Kooragang Island ammonia plant in Newcastle, located just 40km away. This geographical proximity suggests that it is feasible to consider supplying green hydrogen from an electrolysis plant located in the region of the Eraring plant to Orica's Kooragang Island ammonia plant. Hydrogen is an essential component in the production of ammonia, and is currently obtained mainly from natural gas. Replacing some of this natural gas with green hydrogen could significantly reduce the plant's carbon emissions. In addition, the existing infrastructure and the NSW government's commitment to green hydrogen suggest considerable potential for the development of this industry in the region.

This section will review the most interesting equipment alternatives available on the market and justify the final selection considering technical, environmental and economic aspects.

3.1 PHOTOVOLTAIC PLANT

The new installation consists of a solar photovoltaic plant with an installed capacity of 500 MW.

3.1.1 PHOTOVOLTAIC PANELS

After a study of the panels on the market from the major manufacturers, several models that are of interest have been chosen due to their high efficiency. The following table shows 6 models and some of their most relevant characteristics, such as efficiency, power output or price per watt.

Manufacturer	Model	Efficiency	Power Output (W)	Price per Watt (AUD)	Warranty
Aiko Solar	Neostar 2P	23.80%	475	$0.32	25 years
SunPower	Maxeon 3	22.60%	400	$0.48	40 years
Jinko Solar	Tiger Neo	22.53%	440	$0.29	25 years
Canadian Solar	TOPHiKu6	22.50%	440	$0.30	25 years
LONGi Solar	Hi-MO 6 Scientist	22.50%	440	$0.30	25 years
Trina Solar	Vertex S+	22.00%	440	$0.30	25 years

Table 3.1. *Solar panel comparison table in 2025. Source: [92-97].*

The following conclusions are drawn from the analysis of the comparison table of the selected solar panel models:

- The Neostar 2P model from Aiko Solar presents a highly attractive option for photovoltaic installations due to its exceptional efficiency and high power output. Although its unit cost is relatively high, it remains competitive when compared to less efficient alternatives. Notably, the module exhibits low performance degradation over time and features an improved temperature coefficient of −0.26%/°C, indicating a reduced loss in power output under elevated temperature conditions.

- The Maxeon 3 model from SunPower offers notably high efficiency and an extended warranty of up to 40 years, exceeding standard panel warranties by approximately 15 years. However, despite these technical merits, the model's cost is approximately 50% higher than that of the higher-efficiency Neostar 2P module. Due to this significant cost differential, the Maxeon 3 is considered economically unviable for the current project and has therefore been excluded from the selection process.

- The models from Canadian Solar, LONGi Solar, and Trina Solar were discarded due to their lower efficiency and higher cost per watt compared to Jinko Solar's Tiger Neo model.

Therefore, a more detailed comparison between the two shortlisted panels will be conducted to evaluate whether the higher efficiency of the Neostar 2P model justifies its additional cost when compared to the Tiger Neo model. This analysis will assess the trade-off between performance gains and economic viability to determine the most cost-effective option for the project.

Manufacturer	Model	Efficiency	Power Output (W)	Price per Watt (AUD)	Warranty
Aiko Solar	Neostar 2P	23.80%	475	$0.32	25 years
Jinko Solar	Tiger Neo	22.53%	440	$0.29	25 years

Table 3.2. *Technical characteristics of the two selected models. Source: [92, 93].*

The additional capital expenditure (CAPEX) associated with the higher efficiency will be evaluated based on an installed capacity of 500 MW and an assumed operational lifetime of 25 years for the photovoltaic plant.

$$\Delta CAPEX = 500MW \times \frac{(0.32 - 0.29)AUD}{W} = 15 \times 10^{6} AUD$$

Considering the capacity factor of the PV plant (17.56%), the additional energy production due to the increased efficiency:

$$\Delta Energy = 25\ years \times 365.24 \frac{days}{year} \times \frac{24h}{day} \times 17.56\% \times 500MWp \times (23.8 - 22.53)\%$$
$$= 244.359\ GWh$$

Considering the average wholesale electricity prices in New South Wales (NSW), Australia, over the period 2022–2024, based on data published by the Australian Energy Market Operator (AEMO):

Financial Year	**NSW ($/MWh)**
2022-23	$144.96
2023-24	$101.57
2024-25	$116.48
Average Price	$121.00

Table 3.3. *Wholesale electricity prices in NSW (2022–2024). Source: [98].*

$$\Delta Profit = \Delta Energy\ (MWh) \times Price_{MWh}(\frac{AUD}{MWh})$$

$$\Delta Profit = 244359\ (MWh) \times 121 \left(\frac{AUD}{MWh}\right) = 29.57 \times 10^{6}\ AUD$$

The net economic balance resulting from the selection of Aiko Solar's more efficient Neostar 2P model over Canadian Solar's TOPHiKu6 model is as follows:

$$Balance = \Delta Profit - \Delta CAPEX = 14.57 \times 10^6 AUD$$

The increase in generation revenues due to improved efficiency is expected to outweigh the rise in capital expenditures (CAPEX). Therefore, the Aiko Solar Neostar 2P model is identified as the most technically and economically suitable option. This basic analysis does not consider factors such as panel degradation, humidity, pollution, or temperature effects, but it serves as a useful preliminary guide.

The specifications of Aiko Solar's Neostar 2P panel are as follows:

Electrical Characteristics (STC: AM1.5 1000W/m² 25°C NOCT: AM1.5 800W/m² 20°C 1m/s) Power Sorting Tolerance:0~ + 3%

Model	AIKO-A450-MAH54Mw		AIKO-A455-MAH54Mw		AIKO-A460-MAH54Mw		AIKO-A465-MAH54Mw		AIKO-A470-MAH54Mw		AIKO-A475-MAH54Mw	
Test Conditions	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
P_{max} [W]	450	339	455	343	460	346	465	350	470	354	475	358
V_{oc} [V]	40.94	38.66	41.00	38.72	41.06	38.77	41.12	38.83	41.18	38.89	41.24	38.94
V_{mp} [V]	34.50	32.58	34.56	32.64	34.62	32.69	34.68	32.75	34.74	32.81	34.80	32.86
I_{sc} [A]	14.12	11.42	14.22	11.50	14.25	11.61	14.29	11.55	14.32	11.58	14.35	11.60
I_{mp} [A]	13.05	10.41	13.17	10.51	13.29	10.41	13.41	10.71	13.54	10.80	13.66	10.90
Module Efficiency	**22.6%**		**22.8%**		**23.1%**		**23.3%**		**23.6%**		**23.8%**	

Figure 3.1. *Technical specifications of Neostar 2P panel. Source: [92].*

3.1.2 SIZING OF THE PHOTOVOLTAIC ARRAY

To determine the number of photovoltaic panels required for the solar power plant, a total peak capacity of 500 MWp was established as the design target. Solar panels with a rated output of 475 W have been selected based on current commercial availability and the preliminary study. The number of panels required is calculated by dividing the total plant capacity by the capacity of a single panel:

$$N_{panels} = \frac{500 \times 10^6 W}{475W/panel} \sim 1{,}052{,}632\ panels$$

This calculation provides a preliminary estimate of the total number of panels needed. It does not yet consider system losses, degradation, temperature coefficients, or spacing for maintenance and shading.

3.1.3 SOLAR MOUNTING SYSTEMS

In photovoltaic system design, the choice between fixed mounting structures and solar tracking systems has a significant impact on both capital expenditure (CAPEX) and energy yield.

- Fixed Mounting Structures

Fixed-tilt systems have lower upfront costs. They require little maintenance and have low operating costs, making them a good option for projects with limited budgets or areas with low direct normal irradiance (DNI). Their simple and reliable design makes them well suited for small to medium installations or places with mostly diffuse sunlight [99].

- Solar Tracking Systems

Solar tracking systems enhance energy generation by maximizing solar irradiance capture throughout the day [99]. There are two primary configurations:

- **Single-axis trackers**, which follow the sun's movement along one axis, are typically considered cost-effective in regions with high direct-normal irradiance (DNI) [100].

- **Dual-axis trackers**, which track both azimuth and elevation, are suitable for locations with more variable sun patterns [101].

Tracking systems involve increased CAPEX, as well as higher operation and maintenance (O&M) requirements. However, they are commonly deployed in large-scale solar farms and in high-irradiance regions where the resulting increase in energy production can economically justify the additional investment [99].

Given a direct normal irradiance (DNI) of 1,813.9 kWh/m²/year and a 500 MW PV plant, a single-axis tracking system is recommended. This level of irradiance is near the threshold where tracking systems become cost-effective. Although the capital expenditure (CAPEX) is higher than for fixed systems, the increased energy production improves the levelized cost of energy (LCOE), especially in large-scale projects. Thus, single-axis tracking is the most technically and economically efficient option for this project.

3.2 GREEN HYDROGEN PRODUCTION

The water electrolysis process to produce green hydrogen is powered by the photovoltaic plant and the energy storage system. This CO2 emission-free process will enable the decarbonisation of Orica's ammonia plant on Kooragang Island.

As seen in section 2.4, Proton Exchange Membrane (PEM) technology is the most robust and efficient technology for hydrogen production and the most suitable for integration with renewables [67].

3.2.1 PEM ELECTROLYSER SELECTION

The following table shows the leading manufacturers of PEM electrolysers:

Manufacturer	Max Output (MW)	Efficiency (%)	Price Range ($/kW)	Warranty	Unique Feature
NEL Hydrogen	20+	68–75	900–1200	5–10 yrs	Modular Design
ITM Power	10–100+	75–80	950–1300	10 yrs	Scalable Modules
Plug Power	5–25	70–78	850–1100	7 yrs	Integrated H2 Infrastructure
Siemens Energy	50–500	74–80	1100–1500	10 yrs	Industrial Scale
Cummins	2.5–20	68–72	950–1250	8 yrs	Advanced AI Monitoring

Table 3.4. *Comparison of leading PEM electrolyser brands. Source: [102].*

After a thorough market analysis, three electrolyser models have been identified as the most suitable for large-scale hydrogen production, based on their efficiency, scalability, and compatibility with renewable energy sources. The following table summarizes their key characteristics:

Company	Model	Efficiency	Hydrogen Production	Water Consumption	Scalability	Key Features	Renewables Compatibility
Nel Hydrogen	**MC500**	55.2 kWh/kg	492 Nm3/h 1,062 kg/day	15.9 L/kg	Very high (multiple units can be grouped together for larger hydrogen output needs)	Load following mode automatically adjusts output to match demand	Strong (designed for variable input)
Plug Power	**EX-4250D**	49.9 kWh/kg	1,989 Nm3/h 4,250 kg/day	10.23 L/kg	Modular building blocks enable custom sizing to meet any demand	Instant load following, flexible and scalable	Perfect product for use with grid or renewable energy resources

Cummins	**HyLYZER® 4000-30**	48 kWh/kg	4000 Nm3/h 8630 kg/day	9 L/kg	Highly scalable for larger demands	Compact, ultrafast response to changes in power input, high output pressure without compressors, long and maintenance-free lifecycle	Perfectly suited to projects where dynamic operation is valuable, such as in combination with renewables

Table 3.5. *Comparison of leading PEM electrolysers. Source: [103-105].*

In the table, the hydrogen production is shown in Nm3/h (cubic metres of hydrogen per hour under normal conditions) and in kg/day.

Cummins' HyLYZER 4000-30 stands out for its exceptional energy efficiency, minimizing kilowatt-hours per kilogram of hydrogen, and its superior production capacity relative to competing models. Its modular architecture supports extensive scalability, while dynamic operation facilitates effective coupling with renewable power. Additionally, the unit's compact footprint delivers hydrogen at 30 bar without external compression and significantly lowers water usage, further optimizing system performance [103].

The following picture shows Cummins PEM technology at scale:

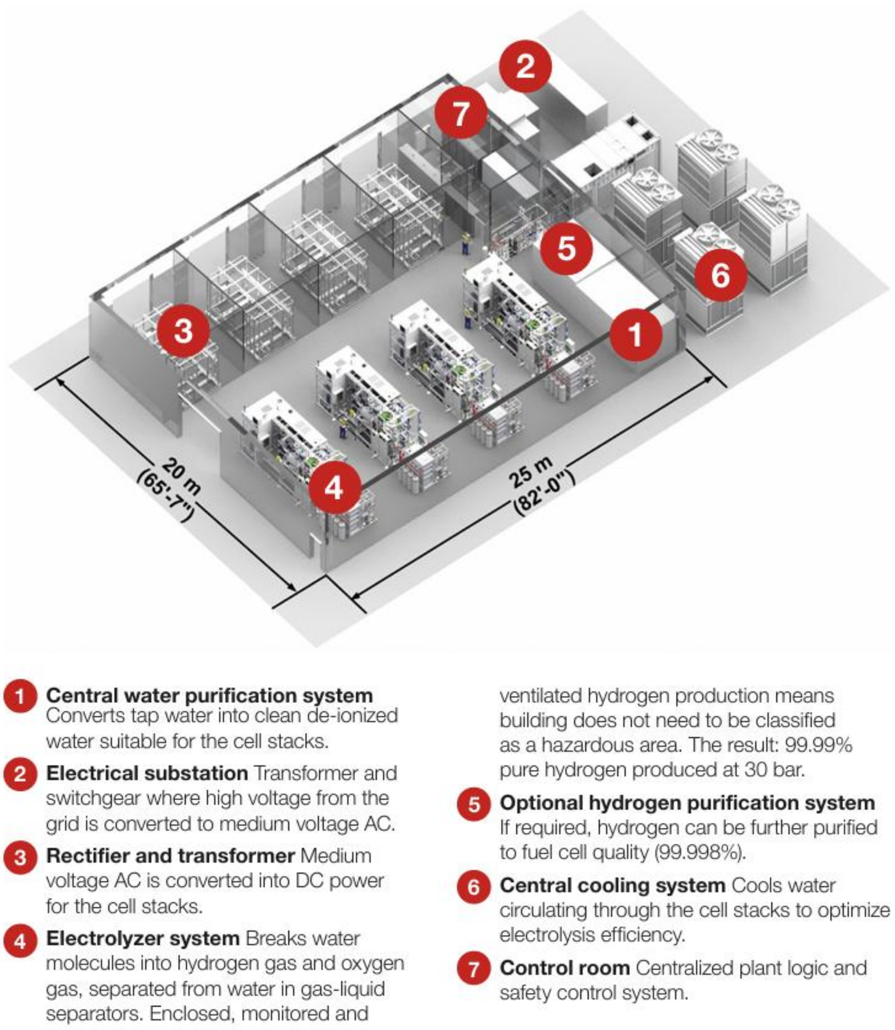

Figure 3.2. *Cummins PEM technology at scale. Source: [103].*

FEATURES

	HyLYZER® - 4000
Technology	PEM water electrolysis
Hydrogen production	4000 Nm^3/h (8630 kg/day)
H_2 delivery pressure	30 bar_g (435 psig) without a compressor
H_2 quality max impurities	99.99% dry basis, gas is fully saturated with water O_2 < 100 ppm Optional > 99.998% with hydrogen purification system

TECHNICAL SPECIFICATIONS

	HyLYZER® - 4000
Operating range	5-125%
DC power consumption at stack	40 to 50 kWh/kg, 48 at nominal load (3.6 to 4.5 kWh/Nm^3, 4.3 at nominal load)
System specific consumption*	≤ 51 kWh/kg
Utilities required to operate the plant	Electrical power, demineralized water, cooling water, HVAC, instrument air, nitrogen for purge
Rectifier specifications	4.1 to 30kV 50/60 Hz, 23 MVA 97% efficiency
Auxiliary installed power	150 kVA (estimated)
Demineralized Water Consumption and Recommended Water Quality	~0.8 L/Nm^3 of H_2 [9 L/kg of H_2] ASTM D1193 Type
Total footprint (including maintenance area)	Electrolyzer dimensions (estimated) = 10 m x 15 m (34 x 50 ft) Rectifier dimensions (estimated) = 10 x 15 m (34 x 50 ft)
Installation environment	Indoors 5°C to 40°C / 41°F to 104°F

Figure 3.3. *Technical specifications of Cummins HyLYZER 4000-30 model. Source: [103].*

3.2.2 SIZING OF A 20 MW HYDROGEN ELECTROLYSER SYSTEM

To design a 20 MW system, we determine the number of units required based on electrical input and hydrogen output:

Single HyLYZER® 4000 unit:

- Nominal power consumption per unit: 23 MVA (≈ 20 MW electrical at stack, considering 97% rectifier efficiency).
- **Daily hydrogen output**: 8630 kg/day.
- **Daily water demand:**

$$8630\,\frac{kg}{day} \times \frac{9L}{kg} = 77{,}670\,\frac{L}{day}$$

- **System Footprint**

- Electrolyser area: 10 m × 15 m = 150 m².

- Rectifier area: 10 m × 15 m = 150 m².
- Total estimated footprint: 300 m².

The sizing of a 20 MW hydrogen electrolyser system using the Cummins HyLYZER® 4000 indicates that a single unit is sufficient to meet the power input and hydrogen production requirements. Each unit consumes approximately 20 MW of electrical power and produces around 8,630 kg of hydrogen per day at 30 bar, with a specific energy consumption of up to 51 kWh/kg. Water consumption is approximately 77,670 L/day, and the total system footprint, including the electrolyser and rectifier, is estimated at 300 m². The system is compact, efficient, and well-suited for industrial-scale, pressurized hydrogen production directly from renewable electricity.

3.2.3 HYDROGEN TANKS

The storage of green hydrogen is essential to ensure the stability of supply required by Orica's ammonia plant and to make efficient use of production.

Choice of H2 tanks

The following table shows the four types of hydrogen tanks available and their applications.

Types	Key Features	Pressure	Price	Applications
Type I	Strength and durability	Below 200 bar	1.000 €/kg	Stationary storage due to its high weight
Type II	High pressure withstand	Up to 1000 bar	1.500-2.000 €/kg	Stationary applications
Type III	Reduced weight	Up to 700 bar	2.000 €/kg	mobility applications, such as hydrogen vehicles

Type IV	Considerably more lightweight than types I and II	Up to 700 bar	4.000 €/kg	mobility applications, especially in cars and trucks

Table 3.6. *Comparison of four hydrogen storage tanks. Source: [106].*

Based on the analysis presented in the table, tank Types III and IV have been identified as the most suitable options to meet the requirements and objectives of the plant. The application is non-stationary, meaning that the weight and size of the tanks are critical factors in the selection process.

The storage will be done in tanks at 30 bar, as this is the outlet pressure of the chosen electrolyser. The following table shows the chosen models.

Manufacturer / Model	Tank Type	Storage Capacity	Mass of Empty Tank	Operating Temperature	Notes	Pressure	Datasheet
MAHYTEC – MHT-30bar 850L	Type IV	2.3 kg H_2	130 kg	-15°C to +65°C	Ideal solution to store H2 after electrolyzer	30 bar	MAHYTEC Datasheet
Hystorsys – Metal Hydride Module	Metal Hydride	21-252 kg H_2	2.3 - 27.6 ton	5-40°C	Modular scalable system consisting of multiple cylindrical vessels; suitable for stationary energy storage systems	10-30 bar	Hystorsys
Methydor – Hydor S 240	Metal Hydride	7.6 kg H_2	1100 kg	15-25°C	System can be directly coupled with electrolyser; modularity allows simple scalability	20-35 bar	Methydor

Table 3.7. *Comparison of hydrogen storage tanks. Source: [107-109].*

- The **Hystorsys Metal Hydride Module** and **Methydor Hydor S 240** models are noteworthy for their high storage capacity and scalable modular design. However, due to their substantial weight, they are more suitable for stationary applications such as energy storage systems. Consequently, these options are not considered appropriate for the current application.

- In contrast, the **MAHYTEC MHT-30bar 850L** model is deemed the most suitable choice for this application, primarily due to its low weight, its suitability for storing hydrogen post-electrolysis, and its appropriate operating pressure of 30 bar [107]. Therefore, this option has been selected.

3.2.4 Sizing of the Hydrogen Tanks

The second critical component in the design of the hydrogen production facility is the sizing of the storage tanks used to hold the green hydrogen produced on-site. The selected tank model has a storage capacity of 2.3 kg of hydrogen at 30 bar.

Given that the cummins hylyzer® 4000 electrolyser produces 8,630 kg of hydrogen per day, the total number of tanks required to store one full day of hydrogen production can be calculated as follows:

$$Number\ of\ tanks = \frac{8{,}630\ kg\ H_2}{2.3\ Kg\ H_2/tank} = 3752.17\ tanks$$

Therefore, a total of 3,753 tanks are required to store the entire daily production of green hydrogen at 30 bar. This configuration ensures sufficient capacity to supply the required quantity of hydrogen for daily delivery to Orica's Kooragang Island ammonia plant.

3.3 Battery Energy Storage System

3.3.1 Selection of the Vanadium Redox Flow Battery

The project incorporates a system of 20 MW and 80 MWh vanadium redox flow batteries in a solar photovoltaic plant with hydrogen production, with the aim of stabilising the electricity supply to the electrolyser, avoiding harmful transients and maintaining production in the absence of irradiation. In addition, the battery provides synthetic inertia by means of power converters and fast response control, compensating for the loss of natural inertia due to the disconnection of synchronous generators and improving the stability and resilience of the system in the face of frequency variations.

Unlike lithium-ion batteries, whose lifetime is limited to approximately 11 years, the selected technology allows continuous use for more than 25 years, making it compatible with the typical operating life of a solar PV plant [110].

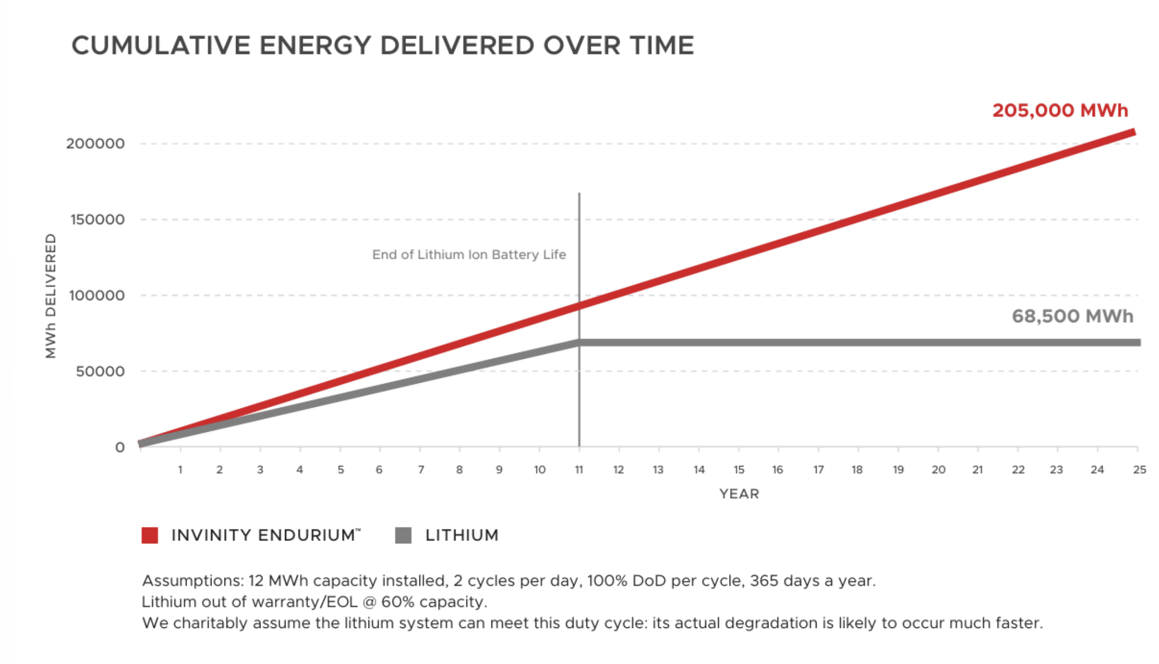

Figure 3.4. *Lithium-ion vs. Invinity Endurium redox flow battery lifespan comparison. Source: [111].*

Following an analysis of the vanadium redox flow battery market, Invinity's ENDURIUM™ model has been selected for its high modularity, scalability for long-term storage, high efficiency, lack of degradation with use, intrinsic safety and compact design with easy maintenance, making it an ideal choice for this study [111].

The following figure shows the technical characteristics of Invinity's ENDURIUM battery.

ENDURIUM™

PRODUCT DATA SHEET

STRING SPECIFICATION

COMPONENTS
4x Vanadium Flow Battery Modules, 1x String Control Unit, Inter-String cabling

PERFORMANCE[1]	2 Power Blocks	3 Power Blocks
Max DC Power	300 kW	375 kW
Max Usable Energy[2]	1310 kWh	1370 kWh
Discharge Durations at Constant Power	4h @300 kW 8h @160 kW 10h @130 kW 12h @110 kW	4h @310 kW 8h @170 kW 10h@ 140 kW 12h @120 kW
Max DC RTE Max Total RTE	74% 69%	75% 70%
DC Response Time	<15 ms from On; <1 min from Off	
Voltage Range	800–1280 VDC	
Max DC Current	406A	

OPERATING CAPABILITIES	
Duty Cycle	Continuous at Max Power. No rest period
Lifetime Cycles	Unlimited for 25 years
Depth of Discharge	0-100 %
Cooling System	Forced Air
Communications	Modbus TCP/IP
Annual Energy Degradation	<0.2%

Figure 3.5. *Technical characteristics of Invinity ENDURIUM battery. Source: [111].*

Figure 3.6. *Invinity ENDURIUM equipment. Source: [110].*

3.3.2 SIZING OF THE VANADIUM REDOX FLOW BATTERY

To maintain continuous operation of the 20 MW electrolyser for 4 hours, the required power of the battery is 20MW.

- **Power requirement:**

From the data sheet, the string specifications are obtained. Each string is composed of 4 vanadium flow battery modules. Each string delivers 300 kW DC maximum power output [111].

The number of strings needed to achieve the desired output power (20MW):

$$N_{strings\ 20MW} = \frac{20{,}000\ kW}{300\ kW/string} = 66.67\ strings$$

Therefore, 67 strings are needed to achieve 20 MW of battery power output (rounding up to the nearest whole number).

- **Energy requirement**:

In order to maintain 20 MW operation for 4 hours, the battery energy required is:

$$20\ MW \times 4h = 80\ MWh$$

Considering that the energy provided by each string is 1.31 MWh [111], the number of battery strings required to meet 80 MWh energy capacity is:

$$N_{strings\ 80MWh} = \frac{80\ MWh}{1.31\ MWh/string} = 61.07\ strings$$

Consequently, in order to satisfy the energy demand, a total of 62 strings are required (rounding up to the nearest whole number).

To meet both energy and power requirements, we must size for the more demanding of the two. Therefore, the required number of strings is 67.

- Required number of strings = 67
- Total energy = 67 × 1.31 MWh = 87.77 MWh
- Total power = 67 × 300 kW = 20.1 MW
- Total footprint = 67 × 93.7 m² = 6,277.9 m² ≈ 0.63 hectares

Sizing of the Battery	String	Total (67 Strings)
Max DC Power	300 kW	20.1 MW
Max Usable Energy	1.31 MWh	87.77 MWh
Footprint (Area)	93.7 m^2	6,277.9 m^2

Table 3.8. *String and battery system specifications. Source: own elaboration.*

A battery system composed of 67 Invinity ENDURIUM™ strings is capable of supplying the 20 MW electrolyser with a stable power output for 4 continuous hours. This configuration provides a robust, long-life, and thermally safe energy storage solution, ideally suited for renewable-powered hydrogen production systems. The ENDURIUM technology ensures minimal degradation, high recyclability, and compatibility with large-scale infrastructure needs [111].

3.4 INVERTERS

Inverters are essential components in photovoltaic and battery energy storage systems, responsible for converting direct current (DC) produced by solar panels and stored in batteries into alternating current (AC) for grid integration [112]. In modern power systems, inverters are not only energy converters but also grid support devices capable of voltage regulation, frequency control, fault ride-through, synthetic inertia and grid-forming capabilities [113].

3.4.1 TYPES OF INVERTERS

Central Inverters vs String Inverters

Central inverters are used in large-scale PV installations due to their ability to handle high power ratings, typically greater than 1 MW per unit [114]. These inverters are installed at centralized locations and receive the combined output from multiple PV strings through combiner boxes [114]. Their design facilitates maintenance procedures and provides cost-effective solutions when deployed at scale [115].

String inverters have lower power capacities, generally ranging from approximately 10 kW to 250 kW. They are installed at the string level, offering a decentralized architecture [114]. This makes them suitable for commercial applications or distributed energy systems. However, their scalability is limited, and they are generally less efficient in terms of operation and maintenance for utility-scale projects [115].

Central inverters are commonly used in utility-scale projects due to their significant advantages over string inverters [115]. Beyond capital (CAPEX) and operational (OPEX) cost savings, they offer improved compliance with grid code requirements and higher overall system efficiency [114]. Their centralized topology also simplifies both system design and operation [114].

Grid-Following vs Grid-Forming Inverters

Grid-Following Inverters synchronize with the existing grid voltage and frequency, requiring a strong and stable grid to function [116].

Grid-Forming Inverters can autonomously regulate voltage and frequency, making them ideal for scenarios with high renewable penetration [117].

Grid-forming inverters enhance grid stability by controlling system voltage and frequency. Their ability to operate independently of a strong grid is crucial in renewable-dominated networks [117]. Moreover, synthetic inertia enables these inverters to emulate the inertial response of traditional synchronous machines, supporting frequency stability during disturbances [117].

Given the large scale of the project (500 MW PV), its hybrid nature (integration with battery energy storage systems), and the need for grid stability under high renewable penetration, the most suitable inverter solution is the central grid-forming inverter. This technology offers high power capacity, cost efficiency, and advanced capabilities for supporting grid stability.

3.4.2 INVERTER SELECTION

This section provides a technical and comparative analysis of advanced photovoltaic inverters suitable for large-scale applications, with a focus on grid-forming capabilities and the provision of synthetic inertia.

The table below compares 3 leading inverter models currently available for utility-scale deployment. All selected models include grid support functionalities.

Manufacturer	Model	AC Output Power	DC Voltage Range	AC Voltage Range	Efficiency	Cooling	Dimensions (mm)	Grid Support
Sungrow	**SG5000UD-MV**	5 MW	1300 - 1500 V	792 - 990 V	99.00%	Forced air cooling	6058 × 2896 × 2438	Fault ride-through, active and reactive power control, and voltage and frequency control.
Power Electronics	**HEMK FS4390K**	4.39 MW	891 - 1500 V	567 - 693 V	98.94%	Forced air cooling	3000 × 2000 × 2200	Advanced grid support. Combine solar and storage.
Gamesa Electric	**Proteus PCS 5150E**	5.477 MW	1202 - 1500 V	722.5 - 977.5 V	98.57%	Liquid and forced air	4325 × 2255 × 1022	Fast frequency response, synthetic inertia, grid forming in parallel operation with the grid.

Table 3.9. *Comparative analysis of utility-scale central inverters. Source: [118-120].*

Among the options considered, the Sungrow SG5000UD-MV is the most suitable inverter. It provides a high-power output (5 MW AC), reducing the number of units needed. It also offers full grid-forming capabilities, is fully compatible with battery energy storage systems

(BESS), and achieves high efficiency (99%). In addition, it meets international standards and has been widely used in projects around the world.

3.4.3 INVERTER SIZING

PV Inverter Sizing

The selected inverter model for this project is the Sungrow SG5000UD-MV, which has a rated AC power output of 5.0 MW. The total DC capacity of the photovoltaic (PV) system is 500 MWp. A typical AC to DC ratio (oversizing factor) of 1.1 is assumed, which is commonly used in large-scale PV systems to increase inverter utilization. Based on this ratio, the required AC capacity is:

$$AC\ Capacity = \frac{500\ MWp}{1.1} = 454.55\ MWAC$$

The number of PV inverters required, calculated by dividing the total AC capacity by the power rating of each inverter:

$$N_{PV\ inverters} = \frac{454.55\ MWAC}{5\ MW/inverter} = 90.91 \rightarrow 91\ inverters$$

This means that 91 PV inverters are needed.

BESS Inverter Sizing

The number of BESS inverters required, calculated by dividing the BESS rated power (20 MW) by the power rating of each inverter:

$$N_{BESS\ inverters} = \frac{20\ MW}{5\ MW/inverter} = 4\ inverters$$

For the battery energy storage system (BESS), with a rated power of 20 MW, four inverters are required, based on the same 5 MW unit size. In total, the project will require 95 inverters.

3.5 DC-DC CONVERTERS

In large-scale renewable energy systems that combine photovoltaic (PV) generation with battery energy storage systems (BESS), DC-DC converters are essential for efficient energy transfer and voltage control [121]. This project, located in Eraring, New South Wales (Australia), includes a 500 MWp solar PV installation and a 20 MW BESS. The PV system is designed to operate at a nominal voltage of around 1000 V, while the BESS operates between 800 and 1280 V. Because these voltage levels do not match, a power electronic interface is needed to manage the energy flow between them.

3.5.1 DC-DC CONVERTER TYPES

DC-DC converters are used to adjust voltage levels between components in a hybrid energy system. There are three main types:

- Buck converters reduce the input voltage.
- Boost converters increase the input voltage.
- Buck-boost converters can both increase and decrease voltage.

In this project, the PV array operates at around 1000 VDC, while the BESS has a voltage range of 800–1280 V. Because the battery voltage can be higher or lower than the PV voltage, a converter that can handle both directions is required.

A bidirectional buck-boost converter is the best choice. It allows energy to flow from the PV system to the battery (charging) and from the battery to the grid (discharging). It also adjusts voltage in both directions, ensuring compatibility between the PV and BESS.

3.5.2 DC-DC CONVERTERS SELECTION

A comparative analysis of commercially available bidirectional buck-boost converters was conducted, considering key performance parameters such as power rating, input/output voltage range, efficiency, and scalability.

Manufacturer	Model	Type	Power Rating	Input Voltage Range (VDC)	Output Voltage Range (VDC)	Efficiency	Datasheet
Power Electronics	DC/DC	Bidirectional, Buck-Boost	1.2 MW	850 - 1500 V	850 - 1500 V	99.18%	DS-DCDC-WEB-EN-01.pdf
SMA	SMA DC-DC CONVERTER	Bidirectional, Buck-Boost	500 kW	550 – 1500	550-1500	98.2%	SMA DC-DC Converter - Greater efficiency for large PV power plants
Sungrow	SD125HV	Bidirectional, Buck-Boost	125 kW	0-1500	500-1500	99%	EN DS SD125HV Datasheet.pdf
Dynapower	DPS-500	Bidirectional, Buck-Boost	500 kW	100-1500	100-1500	99%	DPS-500_Datasheet_Nov22.pdf

Table 3.10. *Comparison of available utility-scale DC-DC converters. Source: [122-125].*

The Power Electronics DC/DC converter offers a power rating of 1.2 MW, with an input and output voltage range of 850–1500 V, and a high efficiency of 99.18%. This makes it an excellent match for the voltage levels of both the PV array and the BESS. Its high-power capacity also means fewer units are required (only around 17), simplifying system design and reducing installation and maintenance efforts.

In comparison, the SMA DC-DC converter, rated at 500 kW, has a suitable voltage range (550–1500 V) but a lower efficiency of 98.2%. Its smaller power rating would require over 40 units, increasing system complexity. Similarly, the Sungrow SD125HV provides wide voltage flexibility (0–1500 V) and 99% efficiency, but with only 125 kW capacity per unit, it would require 160 units, making it impractical for large-scale deployment. The Dynapower DPS-500 matches the SMA in power rating (500 kW) but lacks advanced MPPT (Maximum Power Point Tracking) functions and still requires a higher number of units compared to the Power Electronics option.

Considering all factors, the Power Electronics DC/DC converter is the most suitable choice for this project. It meets the voltage compatibility requirements, offers superior efficiency, minimizes the number of units required, and supports modular, utility-scale implementation.

3.5.3 Technical Requirements and Sizing

For the 20 MW battery storage system, the converters only need to manage energy between the BESS and the DC bus shared with the PV plant. To determine the number of converter units needed, we consider two common sizes: 500 kW and 1.2 MW. Using 500 kW converters would require about 40 units, while 1.2 MW converters would require only about 17 units. Fewer units means simpler installation, lower costs, and easier control, making the 1.2 MW option more attractive.

PV Array Configuration and DC-DC Converter Integration

The photovoltaic (PV) system in this project uses high-efficiency Neostar 475 W monocrystalline panels, which have a module efficiency of 23.8%. Each panel operates at a voltage of 34.8 V at its maximum power point (Vmp). To match the PV array with the DC bus and the selected DC-DC converters, the configuration of the strings must be carefully designed.

To reach the target system voltage of approximately 1000 VDC, the number of panels per string is calculated by dividing 1000 V by the Vmp of one panel:

$$N_{panels\ per\ string} = \frac{1000 \frac{V}{string}}{34.8 \frac{V}{panel}} \sim 28.7 \frac{panels}{string}$$

Therefore, each string will include 29 panels, resulting in a string voltage of:

$$V_{string} = 29 \frac{panels}{string} \times 34.8 \frac{V}{panel} = 1009.2 \frac{V}{string}$$

This value fits well within the input voltage range (850–1500 V) of the selected Power Electronics DC-DC converters, ensuring proper operation and voltage matching with the battery system (which operates between 800 and 1280 V).

The power output of one string at its maximum power point is:

$$P_{string} = 29\,\frac{panels}{string} \times 475\,\frac{W}{panel} = 13.775\,\frac{kW}{string}$$

To supply one DC-DC converter unit with a rated capacity of 1.2 MW, the number of required strings is:

$$N_{strings\ per\ block} = \frac{1200\,\frac{kW}{block}}{13.775\,\frac{kW}{string}} \sim 87.1\,\frac{strings}{block}$$

Thus, 87 strings will be connected per converter block to fully utilize the converter capacity. This modular approach simplifies the field layout and makes it easier to operate and maintain the system.

By using this configuration, the PV array operates close to its optimal voltage, and the DC-DC converter ensures efficient energy transfer to the BESS. Since the selected converters are bidirectional and include MPPT (Maximum Power Point Tracking), they can adapt to changing solar conditions and always draw the maximum available power from the PV modules.

This setup guarantees compatibility between the PV generation system and the battery storage, while also offering high performance, flexibility, and scalability for utility-scale applications.

To summarize the main electrical characteristics of the subsystems involved in the PV-BESS integration, Table 3.11 presents the voltage ranges and nominal power ratings for each configuration level, from individual panels to full system blocks.

Subsystem	Voltage Range (VDC)	Nominal Power	Notes
PV Panel (1 unit)	34.8	475 W	Vmp used for power calculations
PV String (29 panels)	1009.2	13.775 kW	Vmp=29×34.8=1009.2 V
Block of 87 Strings	1009.2	1.2 MW	Each block consists of 87 strings in parallel
BESS (Redox flow)	800-1280	20 MW	Suitable for direct connection to PV via DC-DC boost converter

Table 3.11. *Summary of electrical specifications for PV and BESS subsystems. Source: own elaboration.*

CHAPTER 4. ECONOMIC ANALYSIS

This chapter provides a comprehensive economic and financial evaluation of the Eraring Renewable Energy Project, which proposes the transformation of an existing coal-fired power station into a hybrid renewable energy facility. The redesigned project integrates three core components: a 500 MW photovoltaic (PV) solar plant, a 20 MW vanadium redox flow battery energy storage system (BESS), and a 20 MW proton exchange membrane (PEM) electrolyser for the production of green hydrogen.

The assessment spans a 25-year project horizon and includes a detailed analysis of capital expenditures (CAPEX), operational expenditures (OPEX), revenue generation, and key financial performance metrics such as Net Present Value (NPV) and Internal Rate of Return (IRR).

The hybrid system is designed to fulfill multiple functions: supplying electricity to the grid, offering ancillary services via battery storage, and generating green hydrogen for commercial distribution. The project adheres to contemporary industry standards and employs data from the National Renewable Energy Laboratory's (NREL) 2024 Annual Technology Baseline (ATB), ensuring that all financial projections are grounded in current, reliable, and conservative assumptions.

4.1 ASSUMPTIONS

This analysis is based on realistic and conservative assumptions that reflect current conditions in Australia's economy and renewable energy market. The assumptions draw on publicly available data from key sources such as the Australian Energy Market Operator (AEMO), the Reserve Bank of Australia (RBA), and the National Renewable Energy Laboratory (NREL).

Project Characteristics

- Project Lifespan: 25 years.
- Technology Configuration: Utility-scale photovoltaic (PV) system integrated with 4-hour vanadium redox flow battery storage.
- PV Capacity Factor: 17.56%.
- PV Degradation Rate: 0.25% per year.
- Battery Technology: Invinity Endurium vanadium flow battery, offering unlimited cycle life over the project duration [111].

Financial Parameters

- Inflation Rate: 2.5% (based on the RBA's long-term target) [126].
- Corporate Tax Rate: 30% (standard rate for large Australian companies) [127].
- Discount Rate (WACC): 7.0% (commonly used for utility-scale renewable projects) [128].
- OPEX Growth Rate: 1.0% annually (to reflect inflation and maintenance cost increases).
- Depreciation Method: Straight-line.

Market Prices and Revenue Assumptions

- Electricity Price: A$116.63/MWh (average wholesale price in NSW for 2024–2025, from AEMO) [129].
- Hydrogen Selling Price: A$6.00/kg (based on current market rates in Australia) [130].
- Battery Services Revenue: A$148,000 per MW per year (average for battery storage in the NEM in 2024) [131].

4.2 CAPITAL EXPENDITURE (CAPEX)

The capital expenditure (CAPEX) for the Eraring Renewable Energy Project has been estimated based on detailed cost breakdowns for each system component. The estimates incorporate 2024 market data and reputable sources, including the National Renewable Energy Laboratory (NREL) and other relevant industry publications. The total CAPEX includes the utility-scale photovoltaic system, vanadium flow battery energy storage, hydrogen electrolyser, and hydrogen storage tanks. The PV system represents the largest share of the investment, accounting for A$830 million out of the total A$1,005.463 million. All cost components have been calculated using standard unit prices per watt, kilowatt-hour, or kilogram as appropriate for each technology.

Component	Capacity	Unit Cost ($/W)	Total Cost ($ million)	Reference
Photovoltaic Modules	500 MW	0.50	250	Utility-Scale PV | Electricity | 2024 | ATB | NREL
Inverters	500 MW	0.06	30	Utility-Scale PV | Electricity | 2024 | ATB | NREL
Single-axis solar tracking system	500 MW	0.10	50	High-availability 220V/110V single Axis Solar Tracker Energy System By Suzhou Jsolar Incorporated,
Balance of System (BOS)	500 MW	0.39	195	Utility-Scale PV | Electricity | 2024 | ATB | NREL
Installation labor	500 MW	0.30	150	Utility-Scale PV | Electricity | 2024 | ATB | NREL
Installer margin & overhead	500 MW	0.13	65	Utility-Scale PV | Electricity | 2024 | ATB | NREL
Contingency	500 MW	0.02	10	Utility-Scale PV | Electricity | 2024 | ATB | NREL

Engineering & developer overhead	500 MW	0.02	10	Utility-Scale PV | Electricity | 2024 | ATB | NREL
Grid interconnection	500 MW	0.04	20	Utility-Scale PV | Electricity | 2024 | ATB | NREL
Land prep & transmission	500 MW	0.02	10	Utility-Scale PV | Electricity | 2024 | ATB | NREL
Permitting & environmental studies	500 MW	0.02	10	Utility-Scale PV | Electricity | 2024 | ATB | NREL
Sales Tax	500 MW	0.06	30	Utility-Scale PV | Electricity | 2024 | ATB | NREL
Total PV System	500 MW	1.66	830	Utility-Scale PV | Electricity | 2024 | ATB | NREL
Vanadium Flow Battery Energy Storage System	20 MW / 80 MWh	1500 $/kWh	120	Another Vanadium redox flow battery to be installed in Australia – pv magazine International
Hydrogen Electrolyser (PEM)	20 MW	2500 $/kW	50	CSIRO GenCost 2023–24
Hydrogen Storage Tanks (Type IV)	8,630 kg/day capacity	633 $/kg H2	5.463	NenPower
Total CAPEX			**1,005.463 $ million**	

Table 4.1. *Breakdown of capital expenditure (CAPEX) by component for the Eraring Renewable Energy Project. Source: own elaboration.*

4.3 OPERATIONAL EXPENDITURE (OPEX)

The annual operational expenditure (OPEX) for the Eraring Renewable Energy Project is estimated at A$24.515 million. This includes operation and maintenance costs for the 500 MW PV system, 20 MW vanadium redox flow battery, and 20 MW PEM electrolyser, as well as site-related services such as inverter maintenance, electrical inspections, and security. Cost estimates are derived from industry reports, technical publications, and data from recognised organisations to ensure accuracy and relevance.

Component	Capacity	Annual Unit OPEX ($/MW)	Annual OPEX ($)	References
PV Operation & Maintenance	500 MW	30,000	15 million	ARENA – Large Scale Solar Operations
Redox Flow Battery (Invinity) Operation & Maintenance	20 MW / 80 MWh	11 $/MWh	880	Invinity Energy Systems
PEM Electrolyser Operation & Maintenance	20 MW	88,210	1.7642 million	ScienceDirect – Cost of Alkaline and PEM Electrolyser Stacks
Inverter Maintenance	500 MW	7,500	3.75 million	(PDF) BUDGETING FOR SOLAR PV PLANT OPERATIONS & MAINTENANCE: PRACTICES AND PRICING Budgeting for Solar PV Plant O&M: Practices & Pricing
Wiring/Electrical Inspection	500 MW	5,000	2.5 million	(PDF) BUDGETING FOR SOLAR PV PLANT OPERATIONS & MAINTENANCE: PRACTICES AND PRICING Budgeting for Solar PV Plant O&M: Practices & Pricing
Site Maintenance & Security	500 MW	3,000	1.5 million	(PDF) BUDGETING FOR SOLAR PV PLANT OPERATIONS & MAINTENANCE: PRACTICES AND PRICING Budgeting for Solar PV Plant O&M: Practices & Pricing
Total OPEX			**24.515 $ million**	-

Table 4.2. *Breakdown of operational expenditure (OPEX) by component for the Eraring Renewable Energy Project. Source: own elaboration.*

4.4 REVENUE STREAMS

The project will generate revenue from three main sources: electricity sales, hydrogen sales, and ancillary services from battery storage. These estimates are based on current market prices and industry forecasts.

a. Electricity Sales

A 500 MW solar PV plant in New South Wales (NSW), Australia, operating at a capacity factor of 17.56%, will produce:

Annual Energy Production:

$$Annual\ Energy\ Production = 500\ MW \times 0.1756 \times 365\ days \times 24\ hours$$
$$= 769{,}128 \frac{MWh}{year}$$

A 20 MW electrolyser running continuously consumes:

$$Energy\ Used\ by\ Electrolyser = 20\ MW \times 365\ days \times 24\ hours = 175{,}200 \frac{MWh}{year}$$

Therefore, the net energy available for sale is calculated as the total annual electricity production minus the energy consumed by the electrolyser:

$$Net\ Energy\ for\ Sale = 769{,}128 \frac{MWh}{year} - 175{,}200 \frac{MWh}{year} = 593{,}928 \frac{MWh}{year}$$

Using the NSW average wholesale price of AUD \$116.63/MWh, the revenue is:

$$Annual\ Revenue\ from\ Electricity\ Sales = 593{,}928 \frac{MWh}{year} \times 116.63 \frac{AUD}{MWh}$$
$$= AUD\ 69.27 \frac{million}{year}$$

This revenue excludes income from hydrogen or grid services.

b. Hydrogen Sales

The 20 MW PEM electrolyser will produce 8,630 kg of green hydrogen per day.

Therefore, the annual hydrogen production is estimated as:

$$Annual\ Hydrogen\ Production = 8{,}630\,\frac{kg}{day} \times 365\,\frac{days}{year} = 3{,}149{,}950\,\frac{kg}{year}$$

Annual revenue from hydrogen sales at AUD $6 per kg is [130]:

$$Annual\ Revenue\ from\ Hydrogen = 3{,}149{,}950\,\frac{kg}{year} \times 6\,\frac{AUD}{kg} = 18.9\ million\,\frac{AUD}{year}$$

c. Grid Support Services

A 20 MW battery energy storage system (BESS) provides grid support services such as frequency control and energy trading.

Based on an average revenue of AUD $148,000 per MW in 2024 [131]:

$$Annual\ Revenue\ from\ Grid\ Support\ Services = 148{,}000\,\frac{AUD}{MW} \times 20\ MW$$
$$= 2.96\ million\,\frac{AUD}{year}$$

The following table provides a summary of the three main revenue streams for the Eraring renewable energy project in Year 1. The values are expressed in millions of Australian dollars (AUD) and include revenues from electricity sales, hydrogen production, and grid support services.

Revenue Stream	Annual Value (A$ million)
Electricity Sales (PV surplus)	69.27

Hydrogen Sales	18.9
Battery Grid Services (BESS)	2.96
Total Annual Revenue (Year 1)	91.13

Table 4.3. *Annual revenue breakdown for Year 1 of the Eraring project (in AUD million). Source: own elaboration.*

4.5 Cash Flow Model

The table below outlines the 25-year cash flow model for the Eraring renewable energy project. It includes annual estimates of energy production, revenues, operating expenses, depreciation, tax, net income, and cash flow. Discounted cash flows are also calculated using a 7.0% discount rate to evaluate the financial performance of the project over its lifetime.

Year	Energy (MWh)	Revenue (M AUD)	OPEX (M AUD)	Depreciation (M AUD)2	EBIT (M AUD)	Tax (M AUD)	Net Income (M AUD)	Cash Flow (M AUD)	Discounted CF (M AUD
0	0	0.000	0.000	0	0	0.000	0.000	-1005.46	-1005.4600
1	593928	91.130	24515.000	40.218	26	7.919	18.478	58.696	54.8564
2	592443	90.957	24.760	40.218	25.978	7.793	18.185	58.403	51.0115
3	590962	90.784	25.008	40.218	25.558	7.667	17.890	58.109	47.4341
4	589485	90.612	25.258	40.218	25.135	7.541	17.595	57.813	44.1054
5	588011	90.440	25.510	40.218	24.711	7.413	17.298	57.516	41.0081
6	586541	90.268	25.766	40.218	24.284	7.285	16.999	57.217	38.1264
7	585075	90.097	26.023	40.218	23.856	7.157	16.699	56.917	35.4453
8	583612	89.927	26.283	40.218	23.425	7.027	16.397	56.616	32.9509
9	582153	89.756	26.546	40.218	22.992	6.898	16.094	56.313	30.6304
10	580697	89.587	26.812	40.218	22.557	6.767	15.790	56.008	28.4717
11	579246	89.417	27.080	40.218	22.119	6.636	15.483	55.702	26.4635
12	577798	89.249	27.351	40.218	21.680	6.504	15.176	55.394	24.5956
13	576353	89.080	27.624	40.218	21.238	6.371	14.866	55.085	22.8582
14	574912	88.912	27.900	40.218	20.793	6.238	14.555	54.774	21.2422
15	573475	88.744	28.179	40.218	20.347	6.104	14.243	54.461	19.7392
16	572041	88.577	28.461	40.218	19.898	5.969	13.928	54.147	18.3414
17	570611	88.410	28.746	40.218	19.446	5.834	13.612	53.831	17.0414
18	569185	88.244	29.033	40.218	18.992	5.698	13.295	53.513	15.8326
19	567762	88.078	29.324	40.218	18.536	5.561	12.975	53.194	14.7085
20	566342	87.912	29.617	40.218	18.077	5.423	12.654	52.873	13.6633
21	564926	87.747	29.913	40.218	17.616	5.285	12.331	52.550	12.6914
22	563514	87.583	30.212	40.218	17.152	5.146	12.007	52.225	11.7879
23	562105	87.418	30.514	40.218	16.686	5.006	11.680	51.898	10.9478
24	560700	87.254	30.819	40.218	16.217	4.865	11.352	51.570	10.1669
25	559298	87.091	31.128	40.218	15.745	4.724	11.022	51.240	9.4409

Table 4.4. *Annual and discounted cash flows for the Eraring renewable energy project over a 25-year period (AUD million). Source: own elaboration.*

4.6 FINANCIAL METRICS

NPV	-351.8991
IRR	2.642%

Table 4.5. *Net Present Value (NPV) and Internal Rate of Return (IRR) of the Eraring renewable energy project, based on a 25-year cash flow model and a 7.0% discount rate. Source: own elaboration.*

The project, under the current assumptions and cash flows, is not financially attractive:

- The NPV is negative, indicating a loss in present value terms.
- The IRR (2.64%) is significantly below the WACC (7.0%), which means the project does not meet the required rate of return for investors.

The financial analysis of the Eraring renewable energy project shows a Net Present Value of negative A$351.90 million and an Internal Rate of Return of 2.64 percent, which is significantly below the assumed Weighted Average Cost of Capital of 7.0 percent. Under these conservative assumptions, the project does not currently appear to be financially viable.

Nevertheless, this assessment is based on cautious projections and does not take into account the growing availability of public support and financial incentives that could strengthen the project's economic case. For example, green hydrogen initiatives in Australia may benefit from government programs such as the Hydrogen Headstart initiative, designed to provide funding for early-stage projects. Likewise, battery energy storage systems may qualify for support through various national and state initiatives, including the Capacity Investment Scheme and the New South Wales Electricity Infrastructure Roadmap, both aimed at encouraging investment in reliable low-emission energy solutions.

As public policies continue to evolve and technology costs decline over time, the financial outlook for integrated renewable projects like Eraring could improve considerably. This highlights the importance of considering both financial projections and future policy developments when evaluating the long-term potential of clean energy investments.

CHAPTER 5. SUSTAINABLE DEVELOPMENT GOALS

In 2015, the United Nations adopted the Sustainable Development Goals (SDGs) as a global call to eradicate poverty, safeguard the environment, and ensure that all people can enjoy peace and prosperity by 2030 [132]. These goals serve as a strategic framework to address climate change and promote sustainable development [132]. This project is closely aligned with several of these goals, particularly in the following areas:

Goal 1. No Poverty

This project seeks to boost regional economic development by creating high-quality employment opportunities, particularly for workers and families affected by the planned closure of the Eraring coal-fired power station in 2027. The construction, operation, and maintenance of the 500 MW photovoltaic solar plant, the 20 MW battery energy storage system using redox flow technology, and the green hydrogen production facility will generate direct and indirect jobs, support local businesses, and promote workforce training in clean energy sectors. By enabling a fair transition from fossil-based to renewable energy systems, the project aims to reduce economic vulnerability and strengthen community resilience.

Goal 7. Affordable and Clean Energy

The deployment of a large-scale photovoltaic solar plant, integrated with a 20 MW redox flow battery storage system, will significantly expand the supply of clean and renewable electricity in New South Wales. This infrastructure enhances grid stability, reduces reliance on fossil fuels, and supports long-term affordability in the energy sector. Additionally, the project includes a green hydrogen production system powered entirely by renewable energy through a Cummins HyLYZER electrolyser, capable of generating up to 8,630 kilograms of hydrogen per day. While the hydrogen produced will not fully replace the natural gas currently used at Orica's Kooragang Island ammonia facility, it represents a critical initial step toward lowering the carbon footprint of ammonia production and industrial energy consumption.

Goal 11. Sustainable Cities and Communities

This project contributes to sustainable industrial development by supplying renewable electricity and low-carbon hydrogen for decarbonizing ammonia production. The integration of solar energy and green hydrogen into the ammonia supply chain supports emissions reduction not only at the point of production but also across downstream sectors such as fertilizers, mining, and chemical manufacturing. These industries, which depend heavily on ammonia, will benefit from cleaner inputs, thereby advancing the transition to more sustainable practices.

Furthermore, replacing coal-fired electricity generation with solar energy and battery storage will lead to a substantial improvement in regional air quality. The reduction in emissions of sulphur dioxide, nitrogen oxides, particulate matter, and heavy metals will enhance environmental health and reduce risks associated with air pollution. These changes will have a direct, positive impact on the well-being of nearby communities, particularly those historically exposed to pollution from coal combustion.

Goal 13. Climate Action

A central goal of the project is to accelerate the reduction of greenhouse gas emissions across both the energy and industrial sectors. Transitioning from coal-based electricity generation (which is among the most polluting sources of energy) to solar power with integrated energy storage will significantly cut carbon dioxide emissions. In parallel, the green hydrogen produced will support the partial decarbonization of ammonia manufacturing and contribute to lowering emissions in other industries reliant on ammonia-derived products.

The project's combined effects (phasing out coal, scaling up renewable electricity, incorporating long-duration energy storage, and introducing green hydrogen into industrial processes) represent a comprehensive strategy for emissions reduction. These actions align with national and global climate goals, including those of the Paris Agreement, and reinforce Australia's broader efforts to transition toward a low-carbon and environmentally responsible economy.

CHAPTER 6. EMISSIONS

The transformation of the Eraring Power Station from a coal-fired thermal plant into a renewable energy facility will significantly reduce greenhouse gas emissions and other pollutants. The new installation will consist of a 500 MW solar photovoltaic plant, an 80 MWh Vanadium Flow Battery system, and a 20 MW hydrogen production system using electrolysis powered by renewable energy.

Greenhouse Gas Emissions

Eraring Power Station, with an annual electricity output of 13,151,237 MWh in 2021 [25], has been one of Australia's largest sources of carbon dioxide. Based on a carbon dioxide emissions factor of 340.56 kilograms of CO_2 per MWh [133], the facility emits approximately 4.48 million tonnes of CO_2 per year.

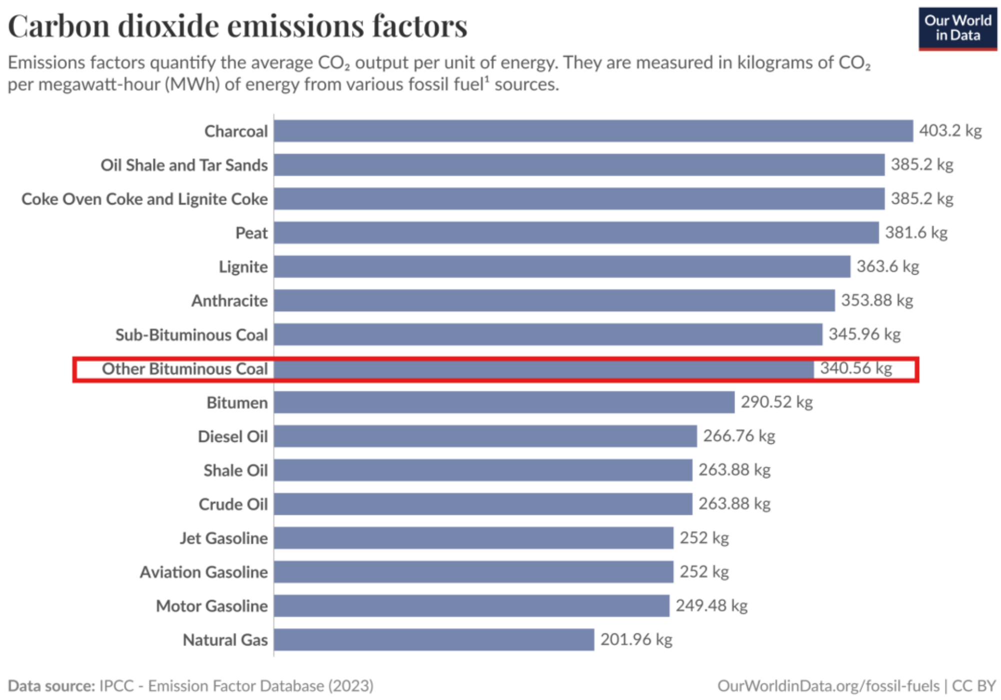

Figure 6.1. *CO_2 emissions (kg/MWh) from various fossil fuel sources. Source: [133].*

$$13{,}151{,}237\ MWh\ \times 340.56 \frac{kg\ CO_2}{MWh} = 4{,}478{,}785{,}272\ kg\ CO_2$$
$$= 4.48 \frac{million\ tonnes\ of\ CO_2}{year}$$

The solar photovoltaic plant is expected to generate about 769,128 MWh annually. This estimate is based on a capacity factor of 17.56 percent, which reflects the average solar radiation in the region (Project Data). Replacing coal-fired generation with solar power of this magnitude will avoid the emission of roughly 262,000 tonnes of carbon dioxide every year, assuming the same emissions factor of 340.56 kilograms of CO_2 per MWh.

$$769{,}128\ MWh\ \times 340.56 \frac{kg\ CO_2}{MWh} = 261{,}934{,}232\ kg\ CO_2 = 261{,}934 \frac{tonnes\ of\ CO_2}{year}$$

In addition, the hydrogen produced by the 20 MW electrolyser, about 3.15 million kilograms per year, will partially substitute natural gas in ammonia production. This substitution avoids approximately 31,500 tonnes of CO_2 emissions per year, based on typical emissions from hydrogen production via natural gas, which emits 10 to 12 kilograms of CO_2 per kilogram of hydrogen [134]. Using the average factor of 10 kilograms of CO_2 per kilogram of hydrogen:

$$3{,}150{,}000\ kg\ H_2 \times 10 \frac{kg\ CO_2}{kg\ H_2} = 31{,}500{,}000\ kg\ CO_2 = 31{,}500 \frac{tonnes\ of\ CO_2}{year}$$

The Vanadium Flow Battery system will store renewable energy without producing additional emissions. This storage capacity improves the reliability and dispatchability of solar power, contributing indirectly to further emission reductions by reducing the need for fossil-fuel backup generation [135].

Air Pollutants Eliminated

Coal-fired power stations remain the dominant source of Australia's fine particle pollution PM2.5, contributing 25 percent of the national total from all sources, oxides of nitrogen NOx at 25 percent, and sulphur dioxide SO_2 at 49 percent, some of the air pollutants most toxic to human health [136].

Beyond CO_2, coal-fired plants emit substantial amounts of other harmful substances.

The table presents the air emissions from Eraring Power Station for the year 2018 to 2019, as reported by the National Pollution Inventory. Mercury and its compounds were emitted in a quantity of 36 kilograms [137]. Oxides of nitrogen were released in significantly higher amounts, totaling 23,062,000 kilograms [137]. Particulate matter PM2.5 emissions reached 123,100 kilograms [137]. Finally, sulfur dioxide was the most emitted pollutant, with 45,000,048 kilograms recorded [137]. These data reflect the scale of air pollution caused by the power station and underline the need for a cleaner and more sustainable energy transition.

Power station emissions to air 2018-19 (kg)	Eraring	Reference
Mercury & compounds (kg)	36	National-Pollution-Inventory-NPI-analysis-2018-19-1.xlsx
Oxides of Nitrogen (kg)	23.062.000	
Particulate Matter 2.5µm (kg)	123.100	
Sulfur dioxide (kg)	45.000.048	

Table 6.1. *Air pollutant emissions from Eraring Power Station for 2018–2019 (kg). Source: [137].*

Overall, the project will achieve a substantial reduction in emissions by eliminating coal combustion and replacing it with clean energy generation and green hydrogen production. This transition supports Australia's climate commitments and contributes meaningfully to global efforts to mitigate climate change.

The table below presents the estimated annual CO_2 emissions avoided by each system component. Calculations are based on expected annual energy production and standard emission factors for equivalent fossil fuel sources.

Source	Annual Production	Emission Factor	Estimated CO_2 Emissions Avoided Annually
Eraring Power Station (coal)	13,151,237 MWh	340.56 kg CO_2 / MWh	4.48 million tonnes CO_2 avoided
Solar PV Plant	769,128 MWh	340.56 kg CO_2 / MWh	262,000 tonnes CO_2 avoided
Hydrogen Production (Electrolyser)	3.15 million kg H_2	10 kg CO_2 / kg H_2 (natural gas-based)	31,500 tonnes CO_2 avoided
Vanadium Flow Battery	80 MWh storage capacity	0 kg CO_2 / MWh (no direct emissions)	Indirect emission reductions by reducing fossil backup

Table 6.2. *Estimated annual CO_2 emissions avoided by system components, based on production values and emission factors. Source: own elaboration.*

CHAPTER 7. CONCLUSIONS

The proposed hybrid renewable energy system at the Eraring site integrates a 500 MWp photovoltaic solar plant, a 20 MW PEM electrolyser, and an 80 MWh vanadium redox-flow battery. The selected PV configuration, using over one million Aiko Neostar 2P panels with single-axis tracking, is projected to generate 769 GWh annually. This design maximises solar resource capture while maintaining operational simplicity and cost-efficiency.

The green hydrogen production system, based on a 20 MW Cummins HyLYZER 4000 PEM electrolyser, is estimated to produce 8,630 kg of hydrogen per day (3.15 million kg/year), supplied with treated water from Lake Macquarie. The hydrogen will replace natural gas at Orica's ammonia plant on Kooragang Island, enabling substantial emissions reductions in an industrial sector with high carbon intensity.

The Invinity ENDURIUM 80 MWh redox-flow battery was selected due to its high safety, long lifespan, and grid support functionalities such as frequency regulation, reactive power control and backup power. It allows the electrolyser to operate continuously during periods of low solar irradiance, enhancing system reliability and decarbonisation potential.

The full system enables an estimated annual avoidance of 293,500 tonnes of CO_2 emissions: 262,000 tonnes from solar electricity generation, 31,500 tonnes from hydrogen replacing natural gas, and indirect benefits from the BESS by mitigating fossil-fuel backup and improving renewable energy integration.

The project directly supports Sustainable Development Goals (SDGs) 7, 9, 11, and 13. It contributes to the availability of clean energy, promotes sustainable industrial transformation, and supports climate action through emissions reduction and infrastructure reuse.

From an economic standpoint, the project involves an initial investment (CAPEX) of AUD 1.005 billion and an annual OPEX of AUD 24 million. The base case financial analysis, under conservative assumptions, yields a Net Present Value (NPV) of –351.9 million AUD and an Internal Rate of Return (IRR) of 2.64%, which is below the WACC of 7%. Despite its current lack of profitability, the project's strategic value remains high. Public financing instruments such as Hydrogen Headstart and the Capacity Investment Scheme, as well as future revenues from green hydrogen certificates and grid services, could enhance its financial feasibility.

In conclusion, the conversion of the Eraring coal power station into a hybrid renewable hub is technically sound, environmentally impactful, and strategically aligned with national and international decarbonisation goals. While its financial success may rely on external support, the project offers a strong and practical example of how to repurpose coal-fired power plants and integrate renewable energy at scale.

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