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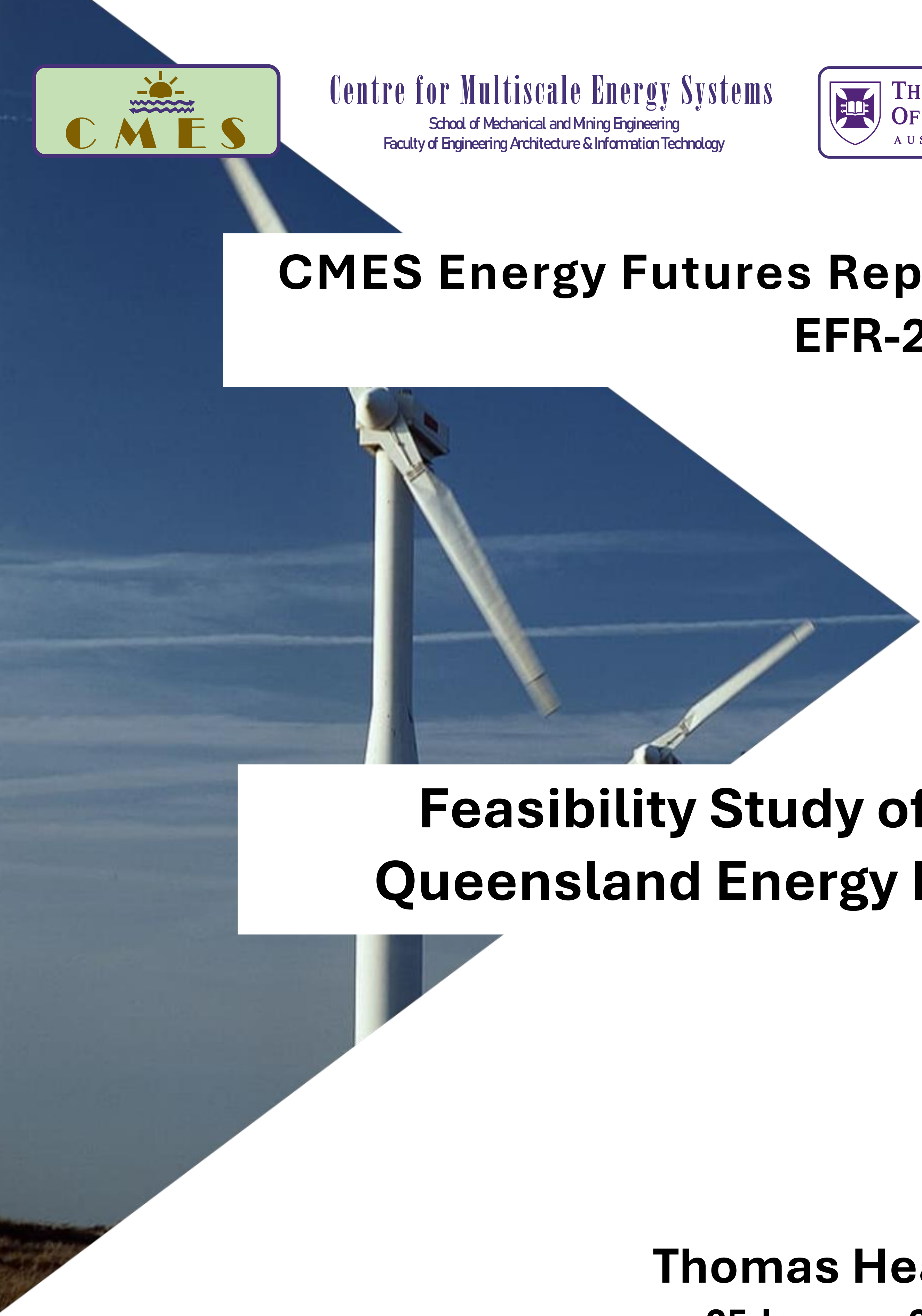

CMES Energy Futures Reports
EFR-24.02

Feasibility Study of the Queensland Energy Plan

Thomas Heath
25 January 2024

Foreword

We observe a new cycle of technological transformations unfolding in front of our eyes and changing the energy landscapes around the world. When faced with proactive action versus a wait-and-see approach, the Queensland Government has commendably chosen the former, adopting a forward-thinking strategy to transition towards a renewable economy. This decision is exceptionally meritorious as Queensland possesses the potential to emerge as a global frontrunner and exporter in the field of renewable energy. The critical importance of the government's initiative to transition away from coal power warrants independent evaluations that should carefully examine key factors such as the availability of resources, the reliability of the power grid and other infrastructure, and the capacity of energy storage systems in the wake of the planned phasing out coal-fired power stations.

While evaluating a major program is typically the domain of government departments or large consulting firms, this Herculean task was undertaken by Thomas Heath in his undergraduate thesis project[i] within CMES. Those who might become sceptical after reading these lines should remember that many significant civilisational breakthroughs, like the invention of the Internet, were initiated by individual talents. While this report simplifies or neglects certain aspects — a necessary approach in any complex analysis — it successfully integrates relevant information and provides reasonable and, most importantly, independent assessments of the feasibility of existing plans and trends. In his report, Tom demonstrates his capability for systemic thinking, navigating numerous uncertain and sometimes conflicting facts to construct and present a coherent picture of reality. Such capabilities are rare among young individuals.

What are the main findings of the report and their implications? First, the projected increases in renewable generation capacity are sufficient not only to compensate for phasing out coal-based generation but also to cover the expected growth in electricity consumption with a substantial safety margin. Second, the gradual loss of synchronous generation is projected to reduce the grid inertia. In the worst possible scenario of insufficient ongoing investments into grid inertia and unfavourable weather conditions, this may lead to blackouts such as the South Australian blackout in September 2016. Progressive installation of repurposed or original synchronous condensers is thus required. While this corresponds to the government plans, the current report points out that the planned measures may be insufficient. In any case, this problem and its solution are well understood by the government and the regulator and it does not represent any kind of unresolvable issue in the upcoming energy transition.

The third issue is energy storage and energy security. While Tom's analysis convincingly shows that the planned battery and pumped hydro energy storage facilities significantly exceed the requirements needed to offset daily fluctuations in electricity production and consumption, the situation is markedly different when it comes to renewable droughts — extended periods of reduced renewable energy generation and/or seasonal variations. The potential for unfavourable weather or disruptions caused by international crises underscores the necessity for long-term and seasonal energy storage solutions. Such critical issues seem to be mentioned but mostly overlooked in government documents. In contrast, Tom's report clearly illustrates that the planned storage capacity falls short of addressing critical or prolonged adverse scenarios. Tom correctly points out that the use of hydrogen (and other e-fuels) can be an essential pillar of energy security. In addition, preferences should be given to reversible conversions of coal-based generators to synchronous condensers, which can be reversed and used for generation in critical shortages.

The fourth problem investigated in the report is energy transmission. This problem is also profoundly important: slow development or inadequate planning in this area can easily stall technological progress anywhere, especially in regional Queensland. Due to large land areas with low populations, transmission is especially central in Australia. Analysing this problem is more problematic as it integrates production, consumption and storage at different localities. It requires global models to give way to more detailed and intricate multiscale analyses of network-based models. Tom’s work deploys LES-type multiscale methodology and makes a step in this direction by investigating the adequacy of transmission lines within and between Local Government Area (LGA) under evolving conditions between 2023 and 2040 and points out LGAs that require upgrades. It should also be noted that, if Queensland becomes a hub for renewable energy production and exports, the generated energy in the form of electricity, hydrogen and/or other e-fuels will need to be transmitted from the inland regions to the shores requiring massive upgrades of the transmission infrastructure.

In conclusion, I recommend studying this report to all people who wish to understand more about the emerging energy transition in Queensland, its challenges, opportunities, and broader implications. The Centre places this report into the public domain.

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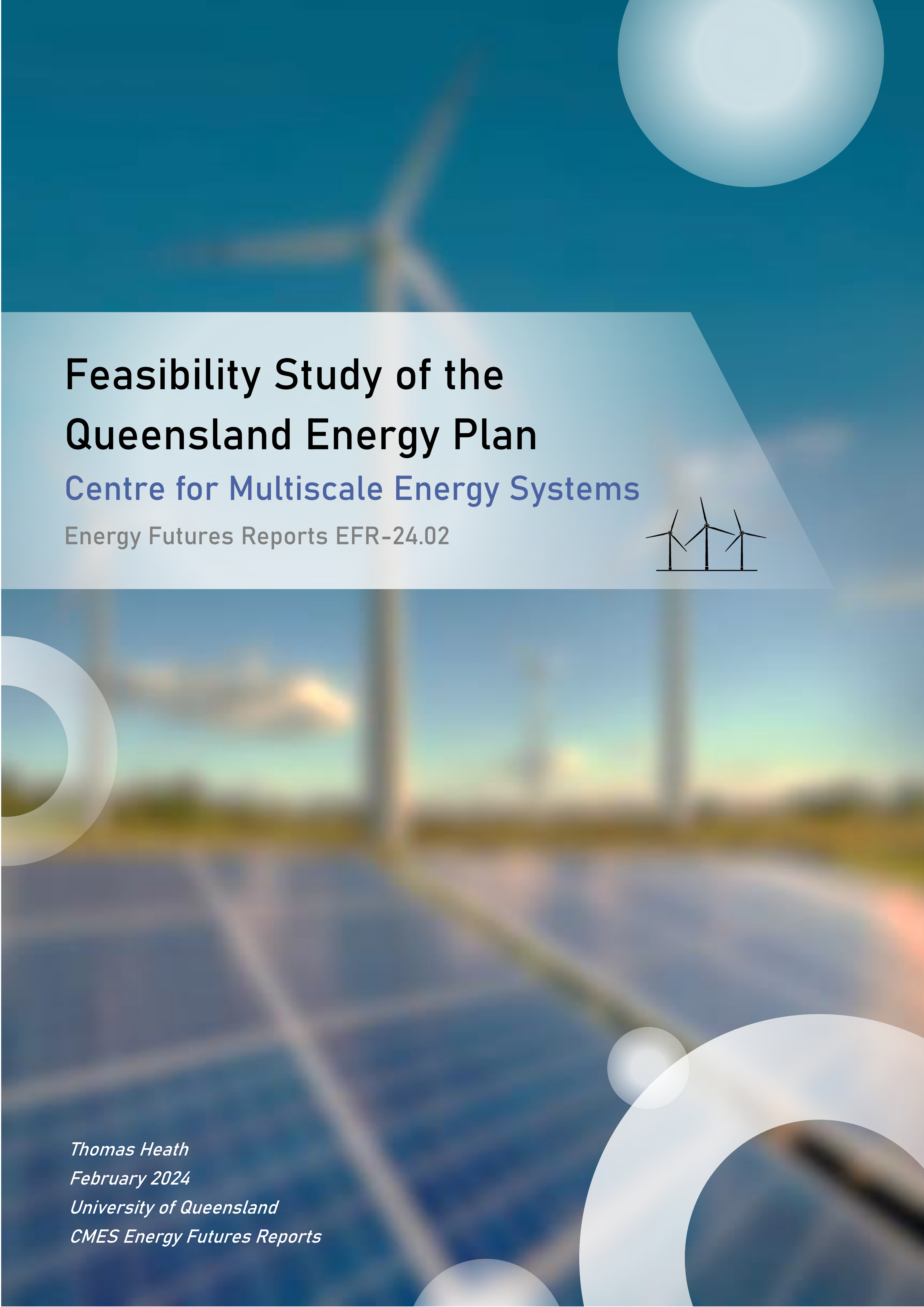
[i] *This report (EFR-24.02) is an edited version of the Bachelor of Engineering (BE) Thesis “The Critical Analysis of Queensland's Energy Plan” by Thomas, Heath, which was submitted to The University of Queensland on October 26, 2023 (Supervisor A.Y. Klimenko).*



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Energy Futures Reports EFR-24.02

Thomas Heath
February 2024
University of Queensland
CMES Energy Futures Reports

Abstract

Amidst the emergence of the renewable energy revolution, Queensland has published energy plans and policies to direct the energy sector through the dynamic transition from a fossil-fuelled generation base to a sustainable and renewable future. The aim of this report was to conduct a feasibility study of the Queensland Energy Plan through a feasibility study of the fundamental components from an engineering perspective, over the next two decades until 2040. This analysis provides an insight for stakeholders, investors, engineers, and the general population into the grid pathway, and outcomes, which is crucial for progression and awareness.

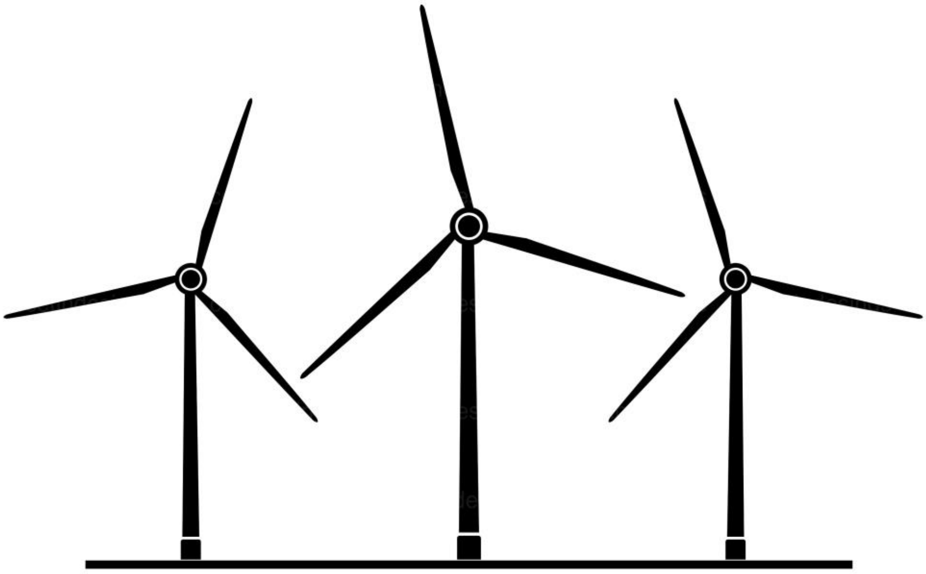
This structured analysis involved assessing the feasibility of the four critical aspects of the evolving Queensland energy system: generation, stability, storage, and transmission. The generation aspect refers to the changing energy production within the state in parallel with the consumption and operational demand. Stability is the resilience of the system to contingencies and the ability to maintain operating standards. Storage is an essential component in the new grid to ensure system security with the new fleet of variable generation resources. Finally, transmission interconnects these central components and must have the ability to support the dynamic new system.

The technique employed to examine the feasibility of each facet varied greatly throughout the analysis but followed a general approach of: research, model development, data collection, analysis, and refinement. Research involved studying the various aspects of the system from a quantitative perspective and data was collected from a variety of energy system stakeholders, providers, and regulators. The Excel models developed throughout the course of this report investigation are highly dynamic, interactive, and insightful to facilitate a comprehensive and detailed assessment.

The results from the various modelling and forecasting provided invaluable understanding of the progression of the energy system over the succeeding decades:

1. Energy Consumption and Generation: Despite the decline in coal generation, the government, and associated operators and providers, should deliver sufficient grid generation (with greater than 30% excess) during the energy transition period to meet the rising operational demand. The total annual generation and consumption are both estimated to rise by approximately 76% from current levels by 2040. Surplus production and generation management and control are essential to the development and success of this aspect of the grid.
2. Grid Stability: Considering the operational frequency and system inertia, approximations revealed the government, and associated operators and providers, have partially addressed the short-term inertia shortfall with yet unconfirmed development for the long-term. Approximately 20 standard-sized synchronous condensers will be required in the long-term to meet stability requirements. It is essential the system regulators monitor stakeholder interest and schedule the procurement and construction of synchronous condenser facilities.
3. Grid Energy Storage: Daily operational analysis revealed that sufficient attention and development has been directed towards short-term storage solutions. Contrarily, drought modelling revealed there has been limited resources directed towards long-term and seasonal storage with self-sustaining grid operation feasible for only 36 hours in the event of a complete renewable drought in 2040. Renewables must operate at greater than 70% of average production in order to sustain more than a week of operation. Hydrogen energy may provide a potential solution to the long-term storage but is dependent on the development of this industry and infrastructure in Queensland.
4. Grid Transmission: 14 local government areas within the transmission network were identified as requiring potential upgrades over the succeeding two decades. These requirements have been partially addressed by plans proposed by energy regulators and operators; however, plans for development are still in early stages with external stakeholder interest still required.

Overall, the energy plan is proceeding with various levels of progression; however, increased attention is required in a number of areas. The conclusion from section of analysis emphasised the importance of effective energy system planning, management, and monitoring; further government incentives and intervention will likely be required to meet the energy system requirements. Furthermore, hydrogen energy in the Queensland system (and developing industry) could provide potential benefits to the energy system and Queensland's energy outlook; further assessment should consider the compatibility and potential of this technology. Model refinement and improvement was recommended for each research question and the assessments of the procurement process, economic outcomes, and social and environmental impacts are essential to holistically address all aspects of the energy plan in Queensland.



"The energy transition:
impossible challenge or unique opportunity?"

- Amy Simpson (ICIS Energy, 2022) -

Figure 1: Wind Turbine
(Etsy, 2023)

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Report Reference:

Heath, T. (2024). *Feasibility Study of the Queensland Energy Plan.*
The University of Queensland, CMES energy Futures Reports,
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1.0 INTRODUCTION

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February 2024
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CMES Energy Futures Reports

1.1 Overview and Context

The increasing global demand for energy, coupled with shifts in policy and the escalating impacts of climate change, is driving the need for a transition of industries and countries from fossil fuelled industrialisation towards a decarbonised and renewable energy system that is environmentally sustainable and economically feasible. Significant progress has been made towards the adoption of renewable energy globally with various commitments emerging on localised business, to national government levels to ensure demand is met efficiently while environmental pledges are upheld.

In the wake of the emergence of the renewable energy scene, Australia and its respective states have recently published energy plans and policies to direct the energy sector through the first shift in energy production since the fossil-fuelled industrial revolution. Policies and associated strategies are paramount to the future prosperity of the Australian economy and livelihood, and the global environment (CSIRO, 2017). This highlights the cruciality of the compilation and critical analysis of information regarding the Queensland Energy Plan and this will form the foundation of this report. Through research and analysis, guided by the proposed questions and aims, a comprehensive examination will be performed on this pivotal topic.

The Queensland Department of Energy and Public Works and associated energy operators and stakeholders such as the Australian Energy Regulator, and Australian Energy Market Operator, have recently published various documents for the proposed energy pathway in Queensland for the subsequent two decades, until 2040 (EY, 2022). The modelling and forecasting of the Queensland energy system has been undertaken by various organisations and various resources for the plan including breakdowns and schedules have been released by the Queensland Government in parallel with the overarching energy plan including:

- Predictions on the electricity market demand, prices, and emission intensities
- Potential industry impacts under the plan, including economic output and employment
- Emerging resource mining, mineral refining, hydrogen, and battery manufacturing industries
- The broader economic impacts based on output, investment, and household incomes
- Details regarding the Queensland super-grid infrastructure pathway
- Procurement and development details and processes

These resources attempt to outline the various pathways and impacts of the energy plan

Overall, the Energy Plan has been defined as "*The rapid investment in both electricity network infrastructure and renewable generation over the succeeding 20 years to replace coal-fired generation, with Queensland achieving its 50% Renewable Energy Target before the 2030 objective*" (EY, 2022). This plan attempts to establish an approach to the energy transition instead of allowing the continuation of the status quo and leaving the energy transition to market forces which would result in an inefficient or unsuccessful transition. The energy system is essential for all aspects of the Queensland economy and livelihood, and thus this energy plan is critical to continual operation of the grid.

1.2 Research Gap and Relevance

Although the general direction of the plan is progressive and it provides an insight into the development of the state's energy system, there have been various issues identified in the proposed approach and available resources. Ultimately, there is no centralised approach to the development of the various aspects of the grid with the government relying on commercial contributions in many facets. Furthermore, the proposed plans are inconsistent, with various issues as outlined below:

- Limited and misleading data: The various documents and data bases provided by the government and grid operators are often out-of-date with various inconsistencies and limitations. This creates doubt regarding the accuracy and methods of the plan and questions proposed outcomes.
- Omission of essential components and requirements: While some aspects of the energy plan have been given significant attention, other components have been selectively or negligently omitted. This again poses issues into the feasibility of the plan, and demonstrates that the government and operators are addressing certain components but neglecting alternate areas.
- Idealised development and outcomes: It is common for government proposals to idealise projected development and success in attempt to gain support or political gain. This is evident in various aspects of the energy plan in the operational outcomes, emission reduction goals, and other aspects such as employment opportunities. This creates uncertainty regarding the actual outcomes of the energy plan and the associated impacts.

Overall, the details regarding the implementation of the plan are both limited and ambiguous, often omitting crucial details such as the reliability and durability of the system in the dynamic Queensland environment. This produces an inherent gap in the research as the feasibility of the energy plan is not directly addressed in full.

This research is highly relevant as nations and industries worldwide shift to a renewable pathway, having widespread economic and social impacts. Queensland has a unique opportunity in the renewable scene and the respective emerging industries due to its abundance of natural advantages and active economy. The various opportunities and impacts industrially, socially, and environmentally have not yet been realised but this research provides an insight for stakeholders, investors, engineers, and the general population into the grid pathway and outcomes which is critical for progression and awareness.

1.3 Aims and Scope

This report attempts to clarify the outcomes and feasibility of the proposed Queensland energy plan from a holistic, unbiased, and practical perspective. This involves undertaking an applied engineering analysis of the current and forecasted Queensland energy systems in order to perform a comparison to the plan proposals. This ascertains and clarifies the physical feasibility of the plan in regards to the capacity to meet the changing grid dynamics and operating conditions, in turn providing an insight into the ambitiousness and reasonability of the plan. Associated issues and opportunities are highlighted to provide additional information and background to the energy pathway.

The scope of this investigation is refined throughout the analysis process dependent on the specific research question being addressed; however, based on the research gap identified and the proposed aim, the general scope of analysis focusses on the quantitative feasibility of the various aspects of the energy system development until 2040 as a result of the energy plan.

The primary focus is the electricity grid system, with complementary energy systems (such as the gas storage and pipeline networks) being considered out of scope. Likewise, the economic, industrial, regulatory, social, and environmental implications of the energy plan including employment predictions and electricity pricing estimations are out of scope for this analysis as these aspects have low relevance to the practical feasibility of the system. Furthermore, the procurement of the plan has not been directly addressed.

Ultimately, the purpose of this report is to analyse and summarise in its entirety the proposed Queensland Energy plan to quantitatively assess its forecasted feasibility and explore the impacts and opportunities associated.

1.4 Report Research Questions

Aligning with the research gap, and the proposed aim and scope of investigation, the overarching research questions and associated outcomes are presented below to provide a structured framework for the feasibility analysis. Each research question corresponds to a fundamental aspect of the grid operation and thus conducting a feasibility assessment on each component provides an insight into the overall feasibility of the collective system and energy plan:

1. Energy Consumption and Generation: The first stage of research will attempt to analyse the current and forecasted energy demand and respective production in Queensland. This involves:
    - Assessment of the forecasted consumption to produce a benchmark comparison for generation requirements.
    - Investigation of the generation operators and providers in attempt to capture the developing commercial interest.
    - Identification of the major changes in the network generation mix and the implications of this shift in production.

    This will primarily focus on a quantitative engineering approach, to provide an insight into the feasibility of the proposed system from a generation perspective.

2. Grid Stability: The next phase will continue the feasibility assessment by exploring the stability conditions of the Queensland energy system and whether these requirements have been addressed in the proposed plan. This involves:
    - Estimation and forecasting of the Queensland grid requirements in terms of stability including summary of the current system and the expected changes.
    - Identification of the proposed solution and approach to ensure continued grid stability during the renewable transition and long-term operation.

    Again, this will entail a quantitative analysis of requirements and proposed solutions in the government energy plan from a stability perspective.

3. Grid Energy Storage: Continuing with the feasibility analysis, the existing and forecasted energy storage will be investigated to compare with the grid requirements. This involves the:
   - Summary the existing and forecasted storage facility projects and corresponding capacities and duration of storage.
   - Assessment of the grid operation considering the proposed storage facilities

   This quantitative analysis will provide an insight into the feasibility of the energy storage aspect of the grid operation.

4. Grid Transmission: The final component of the Queensland energy system to be assessed is the transmission and powerline network.
   - Ensure the grid can connect new projects and handle the energy loads and fluctuations of a renewably powered system.
   - Research and summarise the current infrastructure in place and the respective capacities.
   - Through prior research of the forecasted projects (from the research questions above), determine the new loads and requirements of the energy system.
   - Comment on the feasibility of the transmission aspect of the proposed energy system.

This segmented analysis of the various energy system components provides an insight into the overall feasibility of the proposed system resulting from the energy plan. The associated key issues encountered can be identified and mitigated with proposed solutions and recommendations; likewise, the effectiveness of the government involvement to facilitate the energy transition can be assessed. Finally, this analysis aims to highlight the optimal strategy to ensure the success of the given energy plan. Ultimately, this research will foreground the cruciality of a robust and feasible state plan to guide the state and nation as a whole towards a reliable, and feasible renewable energy future.

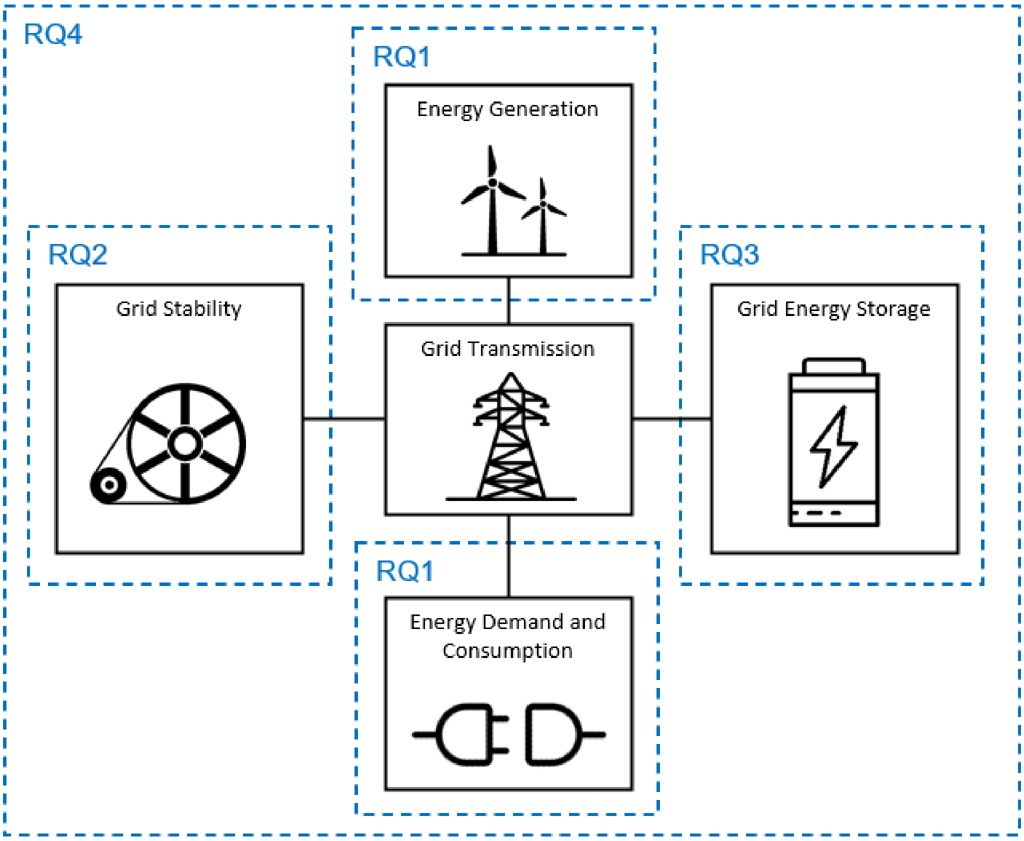

Figure 2: Research Question Interconnection

The selected research question corresponds to the underlying components of the energy system, all of which are interconnected and interdependent.

2.0 LITERATURE REVIEW

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CMES Energy Futures Reports

2.1 Energy Plan Primary Stakeholders and Resources

The Queensland Energy Plan consists of numerous documents and government policies, and the following acronyms describe the central bodies or processes involved with the implementation of the energy plan. These are used throughout the energy plan resources and will be used in this report. They have been summarised below in an order to explain the fundamental management of the energy system:

AEMC – Australian Energy Market Commission

AEMC was set up by the Australian Government and develops the rules by which the NEM must operate according to national energy laws (AEMC, 2023). The AEMC is guided by three legislated national energy objectives, the gas, energy, and retail objectives (NEO, NGO, NERO).

AEMO – Australian Energy Market Operator

AEMO is responsible for operating Australia's daily gas and electricity markets and power systems. They are pivotal in the implementation of the QLD Energy Plan and have published documents regarding the integration of the new plan. AEMO are focussed on delivering secure and reliable energy to consumers nationwide (AEMO, 2023).

AER – Australian Energy Regulator

AER enforce the rules developed by the AEMC and makes judgements on the regulatory proposals of monopoly network operators under national energy legislation and rules, ultimately ensuring a fair market is in operation for Australian consumers (AER, 2023).

EY – Ernst and Young

Various modelling and forecasting of the QLD Energy System was undertaken by Ernst and Young (EY) who compiled the Queensland Energy and Jobs Plan on behalf of the Queensland government. EY is an internationally recognised consultancy and strategy corporation with the insight to build confidence in capital markets and economies globally (EY, 2018). EY is based in London with an office in Brisbane.

ISP – Integrated System Plan

The integrated system plan provides an integrated pathway for the development of the NEM for the succeeding two decades and beyond. The ISP is published by the AEMO and is updated every 2 years, with the most recent being published in 2022. The documents regarding the ISP are crucial toward research for this report project (AEMO, 2022).

NEM – National Energy Market

Electricity in Australia is generated, bought, sold, and transported on the NEM to match supply and demand in real time. Spanning approximately 40,000 km of transmission lines and cables and serving about 9 million customers, the NEM is among the world's largest integrated electricity systems. It operates as a wholesale market in Australia, facilitating the trade of electricity between generators and retailers and accounts for approximately 80% of the country's total electricity consumption (AEMO, 2023). The NEM operates in QLD and is central to the research for this report.

NEMDE – National Energy Market Dispatch Engine

NEMDE computer systems used by AEMO to optimise the central dispatch process. Transmission network flows are controlled by the use of constraint equations in NEMDE (AEMC, 2008).

TNSP – Transmission Network Service Provider

Controlled by the AER (as monopoly market), TNSPs manage the high voltage lines transmitting electricity to consumers and across state borders within the interconnected jurisdictions of the NEM (AEMC, 2023).

2.2 Key Drivers for the Energy Transition

The previous definitions provide an insight into the legislation and processes of the energy system as Australia's energy outlook transitions to a renewable foundation. It is critical to understand the various motives that encourage this change to provide a background to the research being conducted. Although traditionally, generation and transmission development have been driven by load growth, AEMO now states that the energy system is more substantially influenced by the changing generation mix (refer Appendix 12) (AEMO, 2022). Six identified primary drivers of this transition have been summarised below.

1. Reductions in relative costs of generation technology

   Due to the continual innovation in wind and photovoltaic (PV) generation, they are now considered the cheapest form of new bulk energy generation globally (IEA, 2022). In Australia, wind energy is already the cheapest, and large-scale PV generation is expected to become more economic than gas-powered electricity generation (GPG) by 2021. Consequently, the majority of new generation projects in the NEM involve wind or PV generation. Almost 70% of new generation projects registered in the NEM since 2012 are wind or PV; furthermore, these projects consist of approximately 82% of new generation projects in development (AEMO, 2017). While emission reduction policy was the primary driver for development in these technologies, the decreasing relative costs of wind and PV generation are expected to drive the development to add generation capacity as aging plants are decommissioned. Furthermore, this cheaper production is opening opportunities in the hydrogen market with Australia setting a goal to produce $2/kg hydrogen (Arena, 2020). This pathway to the emerging hydrogen industry is being facilitated through the emergence of cheaper energy production.

2. Aging coal generation systems in the NEM

   By 2040, approximately 16 GW (70%) of the existing 23 GW coal generation in Australia will exceed 50 years of operation (AEMO, 2017). This indicates that the majority of the systems in operation are nearing the end their intended operating life. The coal withdrawal graph in Appendix 8 shows the Queensland coal generation fleet and the phase out of individual coal plants over the succeeding decades

   There are many considerations, which are not all be captured by predictions and market models, that need to be considered before the final commercial decision to terminate generation is made. These consider various portfolio optimisation and financial position factors including asset conditions, costs of rehabilitation, and company policies. Continuing operation may prove beneficial beyond 50 years; however, the revenue sufficiency of coal generation will be impacted by the sustained influx of PV and wind, likely leading to earlier withdrawal. Contrarily, coal generation may be favoured for a longer duration to provide grid stability. The details of the closing plants over the succeeding decades such as the location, scale, and timing of withdrawal will provide drivers for new generation and transmission development. The planning and development of new supply resources and transmission assets are crucial to ensure the continued reliability of the delivered power system during this transition.

3. Geographic diversity of generation

There are potential benefits and driving factors from an increased need of geographically varied renewable generation. Firstly, the diversification of generation across the state will smooth aggregate wind and PV production and reduce the need of higher marginal cost energy production such as gas-powered generation when there is low productivity of renewables in a specific region. Furthermore, variegated renewable locations will optimise the natural resources available; concentrating excessive renewables within a region can result in a diminishing return in that area. Utilising all of Australia's natural advantages will provide incentives for renewable growth throughout the state.

4. Emissions reduction policies

Government incentives and legislative requirements with the intention of reaching emission targets are also key drivers in the new generation development. The proposed ISP assumes the NEM will achieve at least the required contribution of the 2015 United Nations Climate Change Conference (COP21) commitment of 28% emissions reduction by 2030 (AEMO, 2022). Following 2030, AEMO is proposing a Fast Change emissions reduction pathway to align with the Australian Government obligation to the COP21 Paris agreement of preventing a mean global temperature rise of 2° Celsius (UNCC, 2015). According to the CSIRO Low Emissions Technology Roadmap, emissions in the energy sector must reduce by 52-70% by 2030 and 90% by 2050 to meet these respective requirements (CSIRO, 2017). The possible drivers of accelerated investment in generation and transmission are considered in this prediction to examine what new developments are required in the ISP.

5. Changing consumer behaviour

The previous drivers consider the large-scale transition incentives; however, the ISP also considers factors affecting the consumer aspect of the energy supply chain which in turn impacts state-wide development. Factors affecting the renewable transition from a consumer level include:

- The implementation of rooftop PV: more of these projects will reduce large scale PV facilities.
- Reducing efficiency and consumption due to response to energy prices: this will impact the need for new large-scale infrastructure.
- Controlled load shifting and demand management: incentivising consumers to shift demand away from peak periods or when there is a high PV penetration in the day will achieve higher efficiency of the resources in the energy.
- Distributed battery storages: aggregation software is in development that can control multiple systems to deliver a cumulative response for frequency control or in direct response to a network demand.
- Increasing Demand Side Participation (DSP): DSP typically involves industrial or large commercial consumers controlling their demand in response to electricity prices. Likewise, this also involves producers managing their supply in response to prices, which is known as Aggregated Distributed Demand Response (ADDR).
- Micro-grids and standalone power systems switch between functioning in parallel with the grid or to isolated operation (AEMO, 2017).

In addition to these drivers, AEMO, in collaboration with TNSP's and other key stakeholders, are encouraging input at all stages in the development of the ISP. Various collaborative workshops with key industry stakeholders identify possible points of external input and government incentives and education encourages individual investors. Ultimately, these factors are driving the transition that the Queensland Energy Plan is facilitating.

6. Meeting technical requirements of the power system

Various technical requirements of the power system must be maintained to ensure energy supply is reliable. The provision of these various services is an engineering necessity and is non-negotiable in all planning scenarios and is thus an essential future driver of the generation and transmission development. Synchronous generation and grid rigidity infrastructure to maintain consistent electricity frequency and voltage is vital as the penetration of non-synchronous variable generation is increased. Ultimately, as the NEM's technical requirements evolve with the operational pre-requisites of the power system, the necessary infrastructure will develop in parallel; the essential pre-requisites and attributes of the system are listed below (AEMO, 2017):

- Ability to measure the various outputs of the energy system in real time
- Ability to forecast power system requirements
- Ability to configure power system services to maintain power system reliability
- Ensure there is sufficient diversity in the energy portfolio to continuously achieve balancing of supply and demand
- Ability to set and maintain system frequency and voltage within acceptable limits
- Ability to restore system from a significant power system disruption

2.3 Relevant Technologies

In response to these drivers, the Queensland energy system is evolving and intensive research is being conducted into optimising the efficiency and output of the system by taking advantage of Queensland's natural and existing advantages which offers the state a unique competitive lead. The technologies and processes briefly described below are referenced throughout the various research documents and are highly relevant to the implemented Queensland energy plan:

BESS - Battery Energy Storage Systems

Batteries store electrical energy in the form of chemical potential energy between various metals and electrolytes. Batteries are the most scalable form of grid storage and store energy for short term use (usually a few hours). Lithium-ion are the are the most common type of batteries which typically have an efficiency of 80-90% for modern systems. Battery systems are expensive, require high maintenance and monitoring, and have a relatively short service life of 20 years compared to other short term storage systems such as pumped hydro (IEA, 2022). This technology is becoming more common in the QLD energy system as a short-term energy storage method for grid stability.

Figure 3: Rendering of Proposed Chinchilla BESS Project

The number BESS facilities in Queensland are expected to increase over the energy transition period. (Colthorpe, 2022)

DER – Distributed energy resources

Small scale power generation and storage that are commonly located at houses or businesses. These systems can be isolated from the grid and thus the influence they have on the grid is hard to predict. DER are growing in demand in Queensland and Australia abroad; by 2050 DER is predicted to contribute approximately 45% of the national electricity generation capacity (AREA, 2023). Designing the grid to accommodate these individual systems to ensure the overall grid remains stable is critical.

GPG – Gas Powered Generation

An existing high-energy density technology that has many applications in the emerging renewable scene is gas powered electricity generation. This is usually in the form of combined cycle gas turbines (CCGT) which has a thermal efficiency of approximately 60% are able to provide fast and reliable energy for grid stability when alternate production is low (Abdalla, 2022). Gas is considered a transition method of production and security between fossil fuels and renewable energy due to its relatively low carbon emissions and fast reaction times to peak demand.

Hydrogen Energy

Hydrogen energy refers to the energy stored in hydrogen compounds that can be used to transport, store, and generate energy. These very high energy dense compounds are made through various processes such as electrolysis and can be used to generate electricity in various forms such as in hydrogen fuel cells. The hydrogen industry is relatively new and has seen recent advancements and interest with the emergence of renewables. As a result, this market is an opportunity for Queensland industry as the state shifts to renewables (for storage requirements) and as demand for this product increases in neighbouring nations such as Japan.

PHES – Pumped Hydro Energy Storage

This involves pumping water into an elevated reservoir and extracting energy by running water back through a turbine when required. These low energy density storage systems are highly efficient at about 80% and typically provide a days' worth of high output storage capacity (Diawuo and Amanor, 2023). Pumped hydro storage requires large initial infrastructure but minimal ongoing costs and the lifespan of these facilities is considerable with approximately 40 years for the electro-mechanical equipment and over a century for the solid-state infrastructure. Additionally, closed loop pumped hydro has minimal environmental impact as it does not greatly disrupt existing water systems. Queensland does not have natural hydro potential as a form of energy generation; however, there are numerous potential sites for closed loop pumped hydro as an energy storage option (refer Appendix 5).

Figure 4: Existing Wivenhoe PHES Facility

The number PHES facilities in Queensland are expected to increase over the energy transition period. (Colthorpe, 2022)

PV – Photovoltaic Solar Energy

Also called solar cells, PV cells convert sunlight directly into DC electricity using the photovoltaic effect through semiconductors. Solar radiation is a unit of energy per area and commercial PV cells are approximately 20% (at a maximum) efficient at converting the input energy into output electricity (CER, 2023). Typically, an output of 200kW/m^2 is expected from commercial solar panels. The lifespan varies; however, PV cells are considered to be economically productive for the first 25 to 30 years of operation (Walker, 2022). Maintenance is limited due to the absence of dynamic mechanical components. Low energy density production through PV has a massive application in the QLD environment due to the high solar radiation exposure (refer Appendix 2).

Synchronous Condenser

A synchronous condenser consists of a large freely rotating synchronous motor whose shaft is not connected to anything. These large inertia systems (that operate at the frequency of the grid) are able to provide instant stability to variations in the grid conditions by dumping or increasing rotational kinetic energy in response to grid requirements. These facilities only offer intermediate stability (from the time of the disturbance for a short amount of time) until larger capacity energy backup generation can be utilised. The lifetime of these assets are typically 30-40 years (AER, 2017). This technology will have applications in the volatile renewable-based Queensland grid.

Wind Energy

Wind energy refers to converting wind into electricity via turbine generators. Land based turbines typically have an output of hundreds of kilowatts to a few megawatts (at 20% efficiency in converting wind to electricity). Efficient wind sites are often in remote locations and require large infrastructure. The lifespan of a turbine is relatively small at 20 years and the disposal of the composite materials is an issue due to difficulty recycling (USEPA, 2013). Wind generated electricity is utilised in the current QLD grid and is expected to grow (refer Appendix 3). The indicative area required for the development of both wind and solar generation facilities is compared in the appendix and concludes that PV is more energy dense for production (refer Appendix 4).

Figure 5: Macintyre Wind Farm Project

The primary forms of generation in the emerging energy system are forecasted to be wind and solar production. (Power Technology, 2020)

These current and emerging technologies are highly relevant in the QLD energy plan and will be referenced and explored in greater detail throughout the research and analysis of this report. These technologies are prevalent in the four major underlying components of the energy system which are explored below in section 5.0 Preliminary Results.

2.4 Energy System Components Overview

1. Energy Generation

The underlying concept of energy generation is that the grid requires a portfolio of controllable, diverse, and flexible resources to ensure a reliable and consistent energy supply. Although renewables are promising in terms of offering a solution to the changing energy dynamics, they are inherently different to the existing production methods in terms of reliability. This involves significant consideration to ensure demand is met throughout the year. Furthermore, implementing generation to capture Queensland's diverse weather systems will reduce the overall number of local reserves needed for a reliable supply and will minimise the cost and infrastructure of the system. Due to the current reliance on coal generated energy, these new supply resources need to be planned and developed in advance to coal withdrawal. The significant lead times of these facilities emphasises the aforementioned need for a coordinated plan to ascertain the locations and sequence of renewable generation sites and coal facility removals.

Both the output capacity of a plant and the required energy input of the grid are measured in watts. Nominal capacity refers to the maximum net electric power output of an energy facility based on standard conditions (Wenzyl, 2009). Renewable energy rarely operates at nominal capacity which must be considered whilst analysing the various contributions to the grid. Other terms for nominal capacity include nameplate, rated installed, maximum, or gross capacity. The operating capacity varies throughout the day for both wind and solar. In addition to daily variances, seasonal variances occur due to weather systems especially in northern Queensland; this links in with the stability and storage components of the system.

2. Grid Stability

Grid stability or strength refers to the ability of the power system to return to standard operation following a system failure or disturbance. This involves maintaining or restoring the required conditions of the grid such as voltage and frequency specifications. The Queensland grid operates at 50Hz AC and the system is considered in standard operation with "*no contingency event or load event*" when the frequency is contained within 49.85 to 50.15Hz 99% of the time (AEMC, 2012).

The grid stability is a measure of the inertia of the system which is provided by synchronous generation (from turbine and generator driven production) or synchronous condensers. Currently with the decommissioning of coal plants, the quantity of synchronous machines on the grid Is decreasing and consequently so too is the system strength and inertia. Appliances and generators that consume or generate DC power (through the means of an inverter) do not contribute to grid inertia which includes PV power. Thus, these resources require additional system inertia for stable operation. This involves an instant reaction to frequency variations and inertia shortfalls. Technologies such as synchronous condensers with flywheels provide these functions for an immediate variation until substantial backup and storage can provide reactive power and voltage control. DER and capacitor banks also provide services in this facet of the energy system.

3. Grid Energy Storage

Storage is an essential component of a renewable based power system where generation is dependent on external factors. Capacity is measured in Watthours (quantity of energy) and the dispatchable capacity is the rate of energy output from the storage facility in watts. An energy grid

requires various grades of storage from intraday to long duration and even seasonal storage. Intraday storage involves capturing excess energy (energy that would otherwise be spilled) from solar or wind generation during times when generation surpasses demand to store and discharge when required in a few-hour time frame. Batteries are ideal and highly competitive for this purpose and small-scale PHES assets (2-6 hours) are being developed in the private sector. Long duration storage typically involves over a day of storage, usually utilising large PHES facilities, to account for small periods of time of unfavourable weather systems during a wind and solar drought. These facilities also supplement intra-day storage requirements. Finally, seasonal storage which accounts for extended periods of renewable drought (weeks of storage) consists of very large PHES (such as the Snowy Hydro 2.0).

Furthermore, other considerations in storage involve dispatchable and peaking generation which refers to production methods that can be initiated for immediate response in support of the renewable generation. Gas generators (particularly CCGT) are ideal for these applications to provide on-peak support or during extended droughts as they are both more rapid in response and efficient than other traditional methods such as coal. They are also cheaper to implement and maintain than PHES, and are currently the lowest capital cost method of backup and peaking generation per megawatt to a renewable system (CSIRO, 2022). Retrofitting existing coal turbines into hydrogen fuelled systems is a possible pathway for future dispatchable generation. Finally, transmission interconnection with other states could provide additional support and firming capacity. This will further reduce the effect of weather systems in Queensland and can utilise excess energy produced state-wide.

4. Grid Transmission

Queensland's renewable generation, stability facilities, storage and dispatchable units will be located throughout the state and the electricity must be transported long distances to meet demand. Transmission development has previously been driven by load growth, but will now primarily be influenced by the changing generation base and their locations. Currently, the various powerline networks in QLD are designed for transmitting energy from traditional coal and gas generation facilities, thus this system must adapt to facilitate large scale non-synchronous generation.

Adjacent to new growth, certain existing infrastructure is becoming redundant with the decommissioning of various coal stations. The optimisation of these existing assets with the development of new infrastructure will ensure a low cost and efficient solution to the changing dynamics. The primary purposes of the QLD transmission network include:

- Sharing generation and facilitating the diversity of renewable generation across QLD regions
- Bolstering the power system through the interconnection of stability facilities to provide frequency and voltage support services
- Facilitating the changing dynamics of the system including retirements of existing generation and increased dependencies on DER
- Providing interconnection between states to allow regions to export power during a local generation surplus, and import power when required (AEMO, 2022)

Transmission assets typically have large capital costs and operational lives of in excess of 50 years; this highlights the importance of considering diverse scenarios and closely examining the entire energy supply chain.

2.5 Regional Energy Zones Overview

The plan divides Queensland into three QREZs which are key to enabling the coordinated and efficient connection of renewable generation in the Northern, Central and Southern regions. These overarching regions will be comprised of smaller sub regional energy zones (REZ) and will coordinate generation sources to ensure a stable state-wide energy grid. Each zone consists of various generation, stability, storage, and transmission resources (refer Figure 1). This design pathway will facilitate the development and connection of the renewably sourced energy by 2035 in three phases (AEMO, 2022):

Phase 1 (2022–2024): Utilising existing infrastructure and the current energy foundation, areas with available network capacity or that require minimal transmission development will provide early investment opportunities for initial generation projects.

Phase 2 (2024–2028): Scaling and expanding opportunities will arise to efficiently match emerging renewable generation to localised demand as the generation mix varies throughout Queensland. This will present new energy zones across the state for expanding renewable energy generation.

Phase 3 (2028–2035): Further network enhancements and growth of new non-synchronous generation will present large requirements in terms storage and stability as coal is phased out. Furthermore, emerging industries will present opportunities such as the hydrogen market.

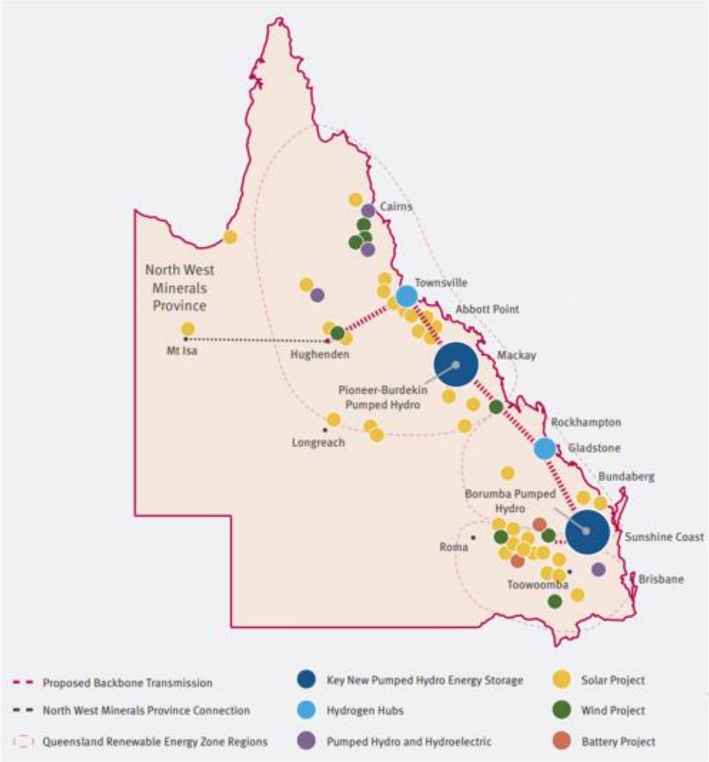


Figure 6: Queensland Renewable Energy Zones

Establishment of the QREZ will optimise the generation, storage, and transmission capabilities of the grid (Queensland Government, 2022)

2.6 General Approach of Analysis

As previously outlined, the four major components of focus in the analysis of Queensland's energy system are: energy generation, grid stability, energy storage, and energy transmission. These identified components are all interconnected to form the energy system, and thus have formed the basis of the research questions and provide a framework for the feasibility analysis of the plan.

The methodology for the assessment of each research question is highly specific to each individual topic. The general approach, in an order that best suits the flow of research, involves:

- The identification and justification of the scope and assumptions
- Research and summary of relevant theory
- Outline of the methodology of data collection and modelling
- Presentation of results and analysis
- Discussion and conclusions from the analysis

This facilitates the assessment of the feasibility of each individual component to form a conclusion regarding the overall direction and viability of the proposed plan. As previously emphasised, this report involves a 'Feasibility Study of the Queensland Energy Plan' and assesses the feasibility from an engineering and technological perspective including the requirements and execution.

An important approach followed and referenced throughout the report is the conservative approach (CA). This involves the selection of methods or values where applicable, to produce a conservative estimate. For example: the lower range of production capacity factors were selected for the calculation of generation forecasts. Thus, if the conclusions indicate that an aspect of the plan is feasible, it is likely to be accurate. Contrarily, if the result indicates an aspect is unfeasible, a further analysis is required, or a reasonable conclusion must be drawn.

2.7 Interactive Excel Model Overview

The analysis of the research questions required extensive data collection and analysis which was conducted on Excel. This forms the primary appendix for all results, tables, and graphs in this document (refer Appendix 1). Furthermore, the modelling conducted in Excel incorporated various parameters which can be varied to assess different scenarios and outcomes. All values coloured in green in the Excel model correspond to manually input parameters. The various sheets of the Excel document have been briefly described below; refer to these instructions to navigate to the results section of each sheet:

Note: All graphs and tables labelled as 'Table X' or 'Graph X' in this document were produced through personal modelling from this investigation; some graphs used data obtained directly from databases, while most considered various factors and calculations.

Sheet 1: Model Instructions

This sheet provides the summary instructions below for each sheet as well as additional information regarding the Excel document.

Sheet 2: Data Tables

This sheet provides the tables of all collected data for the existing and proposed generation and storage facilities across Queensland. This data formed the basis of the generation, storage, and transmission models. The table is interactive and data types can easily be sorted as required. Over 200 sources are sited from various operators and providers with various other sources used for corroboration.

Sheet 3: Capacity Factors

This provides the input platform for the average capacity factors for different renewable generation types. These values are used in the ‘Generation Prediction’, ‘Generation’, ‘Storage’, and ‘Transmission’ sheets. The values in green can be varied to observe the effects of different capacity factors. The values selected were based on research conducted in section 3.2.2.

Sheet 4: Consumption

The ‘Consumption’ sheet shows all data and analysis for the forecasted consumption until 2040 used in section 3.1.4. There are various tables showing annual consumption, consumption rates, and percentage breakdowns. The grey data was data imported from the AEMO data base but was not directly used in calculations. The resultant graphs are also evident.

Sheet 5: Generation Prediction

This sheet shows the generation prediction based on the analysis conducted in section 3.2.4. There are various scenarios listed and the calculations are based on the consumption results and the input capacity factors.

Sheet 6: Generation

The generation model was developed on this sheet according to section 3.2.6. The first 280 rows consist of the raw data analysis and calculations. The summary of results, graphs and input cells can be referred to at the bottom of the spreadsheet (approximately row 300). Calculations extend to column HR.

Sheet 7: Stability

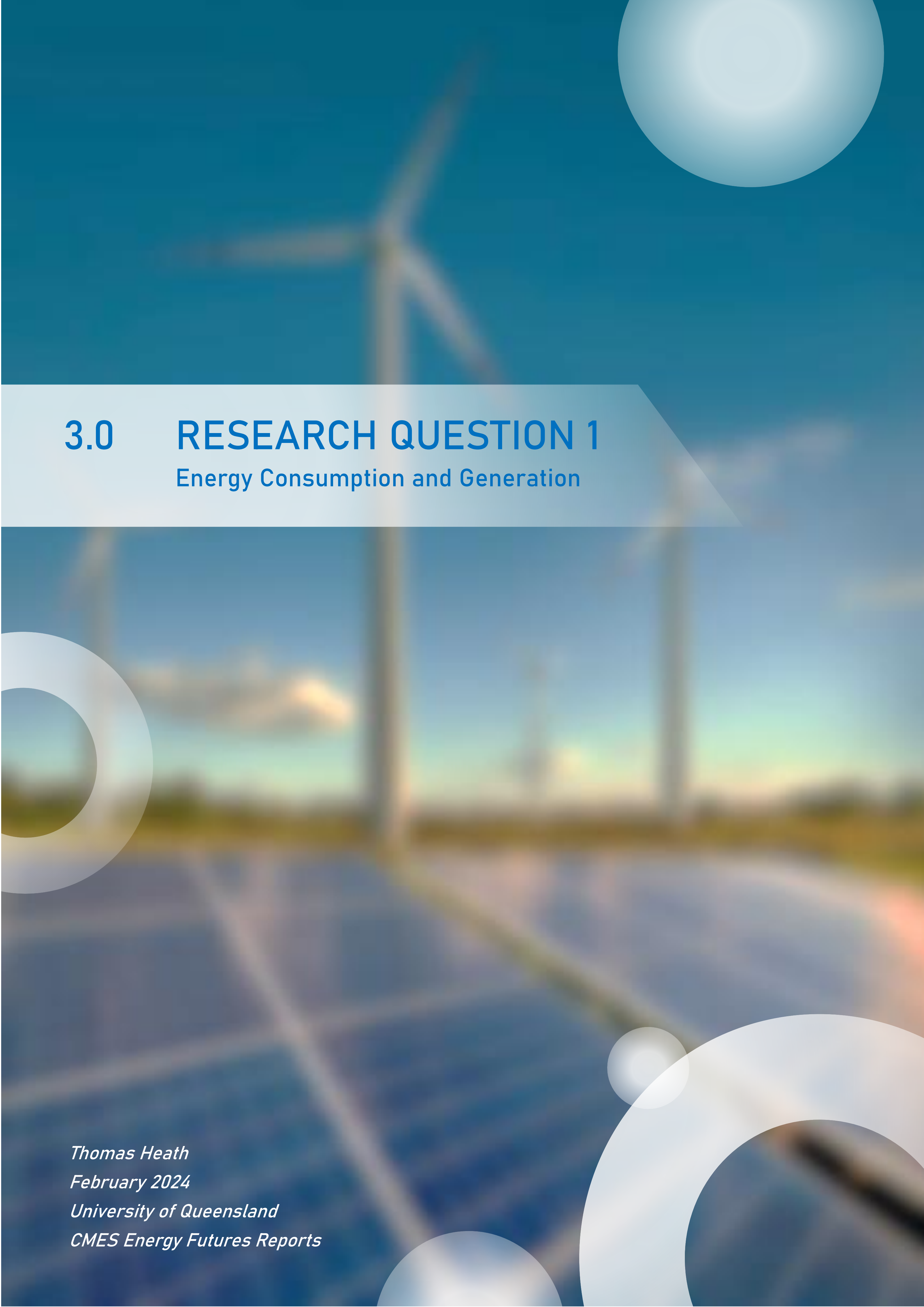
This sheet consists of all synchronous condenser calculations according to section 4.5. Again, the values in green can be varied to assess different parameters and specifications.

Sheet 8: Storage

The storage model was developed on this sheet according to section 5.3. The first 350 rows consist of the raw data analysis and calculations. The summary of results, graphs and input cells can be referred to at the bottom of the spreadsheet (approximately row 400). Calculations extend to column XR.

Sheet 9: Transmission

The transmission model was developed on this sheet according to section 6.3.3. The first 340 rows consist of the raw data analysis and calculations. The summary section of results, and input cells can be referred to at the bottom of the spreadsheet (approximately row 350). Calculations extend to column BG.



3.0

RESEARCH QUESTION 1

Energy Consumption and Generation

Thomas Heath
February 2024
University of Queensland
CMES Energy Futures Reports

3.1 Forecasted Energy Consumption and Requirements

In an attempt to analyse the current energy situation and the developing commercial interest, the current and forecasted annual grid electricity consumptions were summarised to form a comparison benchmark. This was the first step of analysis prior to all research questions as it provides a background reference for the grid requirements.

3.1.1 Forecasted Energy Consumption - Scope and Assumptions

In order to extract meaningful results from the analysis and avoid over-complication, the following scoping considerations were made for this section. This scope also ensures that this analysis complements other research questions.

Table 1: Energy Consumption Scope and Assumptions

Description	*Justification*
The energy requirements and forecasted consumption data was analysed with an annual outlook ranging from the 2023 consumption forecast through to 2040. As a result, the net energy requirements were considered in terms of total yearly average energy consumption (GWh) and an average power consumption (MW) (AEMO, 2021).	A year-by-year forecast for the succeeding two decades simplifies and narrows the scope of this research to provide an insight into the feasibility of the plan over the energy transition period whilst delivering a breakdown of major contributions and allowing certain short-term conclusions to be drawn. Furthermore, forecasts beyond this time period are increasingly inaccurate and is thus not worthwhile attempting to formulate predictions; according to the US energy consumption, energy consumption projections for more than years in the future have an average error of approximately 4% and typically underestimates energy consumption (O'Neill, 2005). Furthermore, beyond 2040, new energy plans will have been implemented.
Related to the selected range of data above, the intra-year variances (hourly, daily, and seasonal) are out of scope for this stage of research.	The consumption and generation analysis is the assessment of whether there is available production to meet demand from an average perspective. The smaller daily and seasonal variances will be assessed in later research questions when considering stability and storage requirements.
The consumption data collected from AEMO has already factored in the demand met by rooftop PV has already been factored into collected data. Furthermore, small-scale non-scheduled generation is excluded from this analysis.	Since the data collected already factors in the demand met by PV, the generation data for PV does not need to be considered in the generation forecasts. The PV generation forecasts will be discussed as they are vital components of the grid that contribute significant generation. Small-scale non-scheduled generation produces negligible energy generation relative to the scheduled generation in the grid and can thus be excluded.
Losses incurred from energy generation, transmission and usage have been excluded from the scope for this stage of research.	This refers to both distribution and transmission losses at a regional resolution and distribution losses at a connection point resolution. The consumption forecasts consider only direct consumption from demand, and thus losses must be factored in through the generation forecasts.

3.1.2 Forecasted Energy Consumption - Relevant Theory

The annual consumption for grid-supplied energy is referred to as operational consumption. This operational consumption refers to the electricity used by industrial, commercial, and residential consumers as supplied by scheduled, semi and non-scheduled generators. A detailed definition of more precisely what operational consumption is can be referred to in the appendix (refer Appendix 6). The individual components of operational consumption are defined below (AEMO, 2022):

Business - Refers to all industrial and commercial consumption.

Residential - All private consumption in residences such as homes and apartments.

Electrification - Forecasted consumption from technologies converting from traditional power systems to electrical processes such as gas to electric hot water systems (RF, 2022).

Electric vehicles - Consumption from the growing EV market including battery operated (BEV), plug in hybrid (PHEV) and fuel cell EVs (FCEV). At current, the AEMO has no visibility devices to detect electricity usage of these units but consumption has been forecasted.

Hydrogen production - Refers to the energy directed to the commercial production of Hydrogen, a growth industry in Queensland over the coming decades.

The energy losses from generation and transmission were omitted for this section of results as they are incorporated from the generation side of the analysis. Likewise, the energy generation from rooftop photovoltaics was subtracted from the residential consumption values and was thus excluded (refer section 3.2.6).

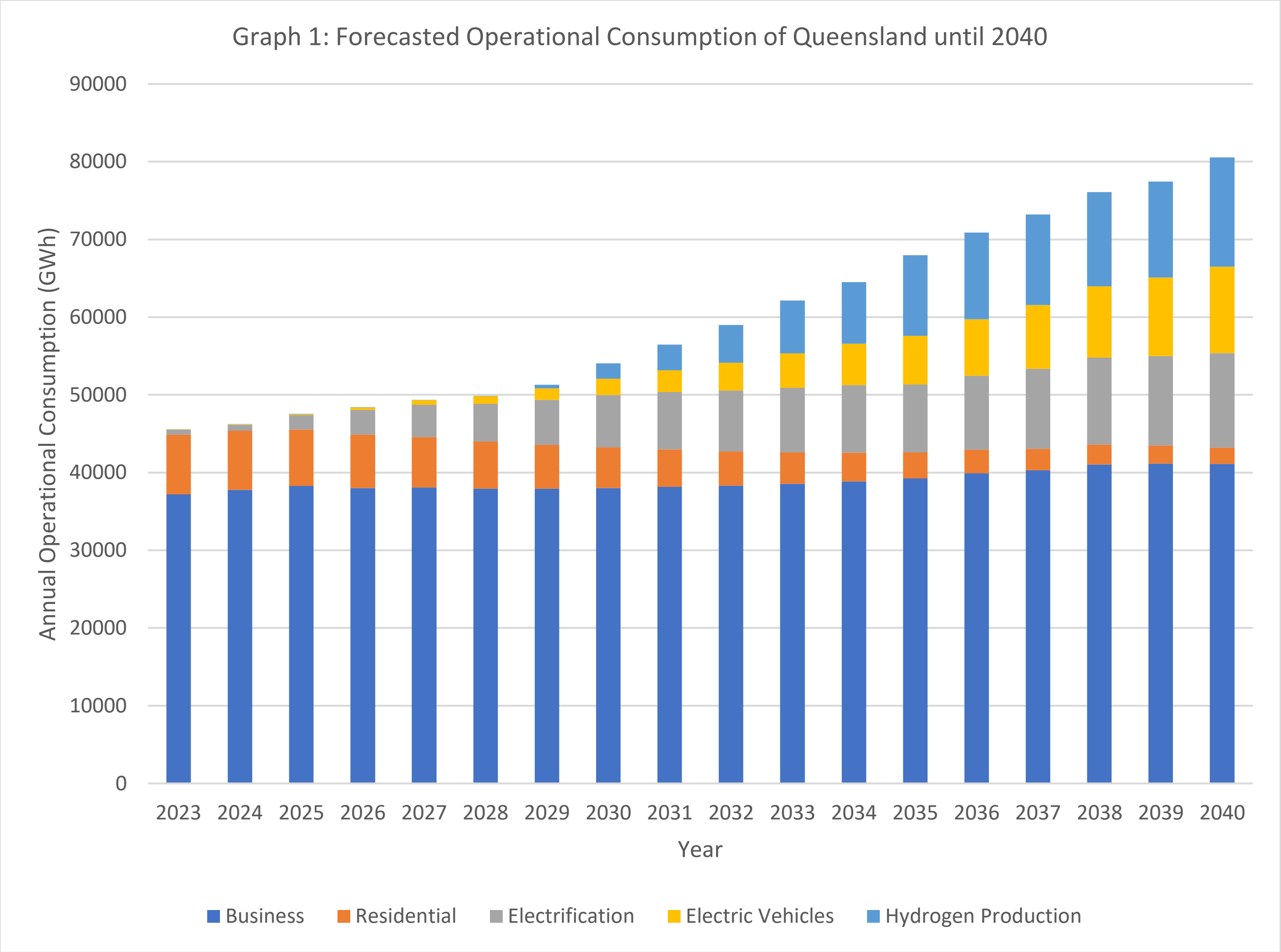
3.1.3 Forecasted Energy Consumption - Data Collection and Methodology

This operational consumption demand data was obtained from the AEMO National Electricity and Gas Forecasting Model which combines a multitude of resources and data sets to formulate a reasonable forecast for the annual electricity consumption for the coming years in Queensland. Initial analysis (in the interim report) involved the use of the ESOO 2022 publication which forecasted consumption as of 20-09-2022; however, large variances were observed between these publications and thus the data was updated to a of 31-08-2023 using the ESOO 2023 publication (AEMO, 2023).

The model uses AEMOs demand forecasting system and calculations performed by the NEMDE, which determines the total demand and is used as the launch point for the central dispatch; it also performs dispatch targets for generating units (AEMO, 2021). Furthermore, this data has been corroborated with various other data sets such as the AER and Powerlink (AER, 2023) (Powerlink, 2016). The data was collated on Excel and was reconfigured into a graphical form to clearly illustrate the individual yearly consumptions for later comparisons with generation figures. All specific data values can be referred to in the Excel 'Generation' sheet with respective calculations. This method of data collection was deemed sufficient for the consumption forecasts as this section of analysis does not provide an insight into the feasibility of the plan, rather it provides a benchmark for later comparisons.

3.1.4 Forecasted Energy Consumption - Results and Analysis

The results for the forecasted operational consumption have been summarised below in Graph 1. The tabulated data and calculations can be referred to in the 'Consumption' tab in the spreadsheet.



It is evident that the overall annual energy consumption is expected to rise in the following decades by 34,982 GWh (77%) from 45,585 GWh in 2023 to 80,567 in 2040 due to increased hydrogen production, electrification, electric vehicle usage. Business applications have the greatest share of energy consumption (82% in 2023 to 51% in 2040) which is expected from a state dominated by manufacturing, construction, and mining outputs which support approximate annual outputs of $140, $126, and $100 billion respectively (EDA, 2023). The overall consumption of this sector is expected to increase by 3928 GWh (11%) as the business sector in Queensland grows with the economy.

The largest growth occurs in the hydrogen production field which increased from negligible production in 2023 to 14,061 GWh of production in 2040. This is one of the primary reasons for the forecasted increases in annual consumption and by 2040 it is predicted that hydrogen production will contribute to nearly 18% of the state's total grid energy consumption. This is a critical field of expansion and a promising emerging industry for Queensland and Australia.

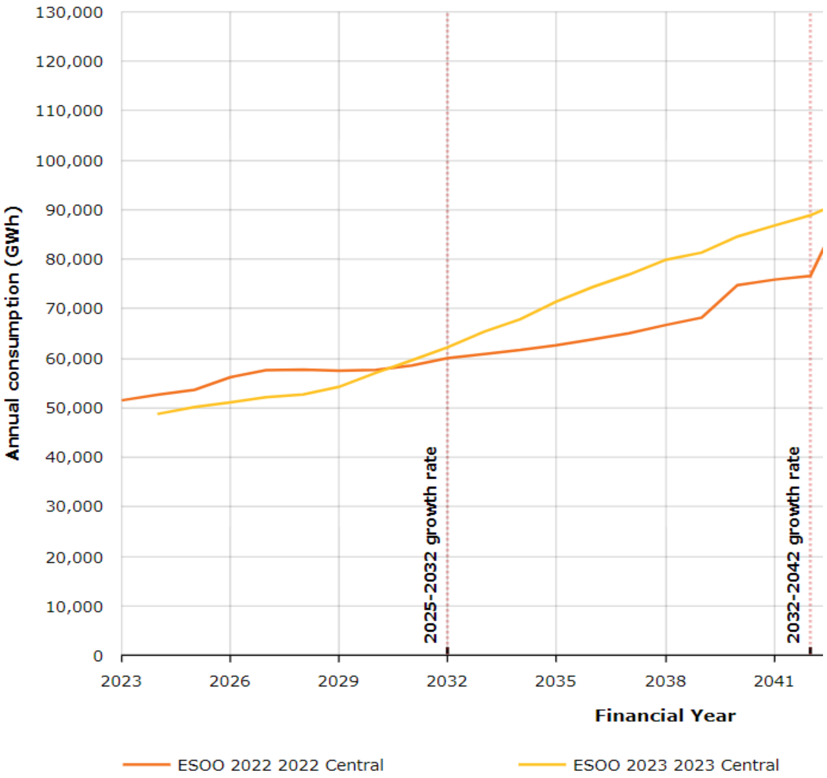
Large growth also occurs in the electrification category from 645 GWh (1.4%) in 2023 to 12,165 GWh (15.1%) in 2040. This is anticipated to occur in unison with the transition of the grid to renewables as many appliances and systems evolve to electrical counterparts. Electrification is influenced by similar factors to those that are driving the grid transition such as emission reduction policies and the phase out of traditional power systems as well as the availability of cheaper electricity. Likewise, significant growth occurs in the EV sector which grows from 43 GWh (0.1%) to 11,109 GWh (13.8%) by 2040. This growth comes with the influx of private EV for transport as well as public transport.

This consumption factors in the demand that is met by rooftop solar PV (refer scope). This explains the decrease in residential consumption as the increase in rooftop PV generation will reduce this consumption by 5,584 GWh (73%) from 7686 GWh (17%) in 2023 to 2,102 GWh (2.6%) in 2040. This is an important consideration for the next stage where the state-wide generation will be analysed and compared. Likewise, as stated in the scope, it is important to note that energy losses have been excluded in the consumption data which again must be accounted for in the next stage of data collation.

The accuracy of this data has a high uncertainty due to the dynamic and volatile nature of the energy system in the transition period over the following decades. The various factors affecting the predictions are complex ranging from the state of various economies and political relations, to technological advancements. Furthermore, as previously discussed, there were high variations in predictions between from the ESOO 2022 and 2023 publications which were both performed by AEMO. This demonstrates that the central governing body of the Australian energy market is publishing results disposed to change and updates. The variations between the data can be seen in Figure 7 below; note that this graph includes losses (and is thus not for analysis purposes), rather to highlight the uncertainty and variations in the predictions. As a result, a large uncertainty must be applied to maintain consistency with the CA (refer scope). This data provides the foundation of the comparison for Research Question 1.

Figure 7: Consumption Forecast Comparison of 2022 and 2023 Data

The difference between these plots highlights that an updated assessment was required using the latest data. It also demonstrates the high variability in data collection. (AEMO, 2023)



3.2 Forecasted Energy Generation

In an attempt to best assess the developing residential and commercial interest, a prediction of the electricity generation was formed to provide a benchmark for comparison to the actual development forecast. Within this prediction, the withdrawal of coal fired electricity generation from the NEM was considered to ensure the new installed facilities can provide the lost difference.

3.2.1 Forecasted Energy Generation - Scope and Assumptions

The scope considerations and assumptions made throughout the collection, processing and analysis of data have been summarised and justified below in Table 2. These considerations attempt to simplify the models used in order to produce meaningful results. All previously stated scopes and assumptions apply to where relevant in this section of analysis.

Table 2: Energy Generation Scope and Assumptions

Description	*Justification*
Similar to the consumption analysis, the generation forecast involved a year-by-year outlook from 2023 to 2040 in terms of an average yearly generation (GWh) and the nameplate capacity available for production (MW).	This was done to remain consistent with the consumption data for later comparisons. The annual average generation considers capacity factors of operation, transmission losses, and phase out periods of coal facilities. The nameplate capacities only consider the phase out period of coal facilities. It is important to note that beyond 30 years renewable plants will begin to reach the end of their financially viable life; however, this has been deemed out of scope and impractical to assess at the current time.
Average capacity factors were used to calculate the usable energy generated. The lower range of these factors were used for each facility generation type and joint coefficients were not considered but are discussed later.	The use of capacity factors is required to determine values for usable generated energy as the actual energy produced from facilities is significantly less than their nameplate capacities. These factors were researched for Queensland and it was assumed they apply to all facilities of the same generation type without consideration of joint capacity factors. This was done for model simplicity but as discussed in section 3.2.2, these factors depend on a number of factors. The possibility of renewable droughts or reduced production reinforced the use of the lower range of the capacity factor values to maintain consistency with the CA. The relevant theory regarding capacity factors and values used in the forecasts can be referred to in section 3.2.2.
Generation and transmission loss factors were applied to all generation facilities for the average annual usable generated energy results.	This was applied for similar reasons the capacity factor was applied. All resources were affected the same by transmission losses which may not be accurate as facilities with low output close to the location of consumption will have a lower loss factor. The relevant theory regarding the transmission and generation losses and the values used in the forecasts can be referred to in section 3.2.2.
The phase out of the coal facilities was considered in both the average annual production and the available nameplate capacity.	This consisted of another factor being applied to the generation data specifically for the coal generation fleet. This was done to best replicate the gradual withdrawal of coal facilities with the increasing renewable penetration. The phase out program for each facility is unique; however, for model simplicity reasons, a general phase out process was applied. The relevant theory and specific values used can be referred to in section 3.2.2.
As previously mentioned, at this stage of analysis, the daily, weekly, monthly, and seasonal variances are not considered.	These variances will be analysed in the stability and storage research questions. The justification for this exclusion is the same as the reasoning presented in Table 1.

The inclusion of leap years or the actual dates of commission or decommission was deemed an unnecessary level of precision.	The commission dates were assumed to be at end of the year and decommission dates at the start of the year to remain consistent with the conservative approach (this is the latest possible commissioning or earliest possible decommissioning of a facility).
Facilities with an unknown commission date were included in the forecast through a staggered phase in approach.	Unknown commission dates were common for facilities that were not planned to commence construction for significant time (typically more than 5 years). In an attempt to include these facilities in forecasts, it was assumed these facilities will be phased in from 2030 over a period of 10 years to full generation capacity. This accounted for facilities starting later than this date or for facilities that had a planned phase in procedure.
The model does not account for facilities that do not eventuate. As observed from historical data, a certain percentage of projects are expected to not proceed to fruition due to various factors.	An exact percentage of unsuccessful facilities could not be determined due to lack of historic data and high dependence on a range of unpredictable factors. This is partially accounted for through the staggered inclusion of facilities with unknown commission dates. Furthermore, the status of facilities is constantly changing; thus, the model is applicable for date the data was collected which is specified below.
Rooftop PV were not considered as they were accounted for in consumption forecast.	This was justified in Table 1. A brief overview of the rooftop PV outlook was discussed below in section 3.2.2.
In general, a phased commission or decommission of plants has not been considered.	This is discussed in previous assumptions. This does not apply for coal plants, facilities being constructed in multiple distinct components or phases, or facilities with unknown commission dates. Phase-in of renewable generation technology is uncommon with plants usually being fully operational upon the construction completion.

Note 1: All data was collected June 2023 and thus this model is susceptible to changes and requires updating for more recent predictions.

Note 2: Some proposed plants are exclusively for hydrogen production which have been included in the data spreadsheet but have not been included in generation forecasts.

3.2.2 Forecasted Energy Generation - Relevant Theory

There are three specific concepts relevant to the generation forecast predictions. These concepts are discussed below and appropriate values are suggested.

Usable Generation

Usable generation refers to the energy produced from all generation facilities that is immediately available for consumption in the grid system. This is an important concept for this analysis as the consumption data acquired in section 3.1.4 is the total energy required from production, thus the generation analysis must consider the actual produced energy incorporating efficiencies and losses.

Capacity Factor

Generation facilitates are characterised by their nameplate capacity power output. This is the theoretical rated capacity of the plant typically expressed in standardised units (MW); however, this installed capacity is rarely reached due to a variety of inhibiting factors including variabilities in efficiency, load factors, and productivity. For fossil-fuelled generation, the operating capacity primarily depends on the load requirements, while for renewable generation such as solar and wind, the operational capacity depends on environmental conditions.

The average operational capacity is characterised by the capacity factor which is expressed as a percentage and represents the ratio of the actual power output of the facility to its nameplate capacity. This factor is unique for every facility and depends on a number of factors including the facility type, location, requirements (demand), and time of operation. An average yearly capacity factor can be applied to similar plant types to best encapsulate the annual power generation. The capacity factors for the major fuel-type facilities in Queensland have been summarised below in Table 3.

Table 3: Queensland Facility Capacity Factors

Facility Type	*Average Capacity Factor in QLD*	*Explanation*
Coal	0.6 - 0.69	The capacity factor for coal generation facilities in Queensland in 2020 was 69% and this factor has been steadily declining. This factor likely to reach 60% by 2025. A capacity factor of 50% is a challenging financial threshold for aging coal plants (Tran, C) (Australia Institute, 2020).
Gas	0.3 - 0.35	The gas capacity factor is highly volatile and depends on various factors affecting the grid and is primarily controlled by demand and peak requirements. Typically, gas generation in Queensland has a capacity factor of around 30 to 35% (Tran, C) (ED, 2023).
Fuel Oil	0.1 - 0.3	Fuel oil facilities typically have a reduced capacity factor due to the nature of their operation. A general figure for these types of these facilities was used and will unlikely affect results as the total penetration of these plants in the generation mix is negligible (ED, 2023).
Hydro	0.3 - 0.36	Hydroelectricity capacity factors vary greatly depending on the type of facility and location. As of 2016, the factor in Queensland was 36%, but many facilities operate at an even lower capacity (Tran, C).
Bioenergy	0.5 - 0.6	Similar to the fuel oil capacity factor, a general bioenergy facility capacity factor range was used. This value is well corroborated (Aus Gov, 2023) (ED, 2023).
Thermal Solar	0.4 - 0.5	Thermal solar or concentrated solar power plants have a capacity factor range as specified. This heavily depends on whether these plants have significant heat storage (such as molten salt) which retain heat and production during periods of low sun (Denholm, P).
Solar	0.25 - 0.3	Queensland has the highest solar facility capacity factor range of all Australian states. Many facilities are above the national average and new records are being broken for regions such as the Rugby Run Solar Farm. Despite this, QLD is prone to environmental factors which can have prolonged effects on the capacity factors of solar plants. During periods of solar drought (widespread cloud), such as in early 2022 in Queensland, solar output had a capacity factor as low as 10% statewide (QLD Gov, 2022) (Aus Gov, 2023).
Wind	0.3 - 0.5	Wind generation facility capacity factors are highly dependent on environmental and locational factors. An average capacity factor for QLD wind plants can be applied for an overall analysis; however, the results will have a very high uncertainty (QLD Gov, 2022) (Aus Gov, 2023).

These capacity factor ranges are corroborated by numerous sources. Queensland specific data was used and supported where possible (QLD Gov, 2022)) (Aus Gov, 2023) (Tran, C) (AE, 2023), and international values were used for further support and background reading (PNAS, 2022), (ED, 2023) and (ONE, 2020). The various references can be referred to in the text in the table. For the purpose of this analysis, the lower range of capacity factors will be used (refer 'Capacity Factor' tab in the spreadsheet). This is justified in section and ensures a CA.

Energy Losses

Another concept relevant to this section of analysis is the quantification of energy losses. Energy losses were not considered in consumption, and thus it must be accounted for in the usable generated energy. There are two primary factors that contribute to energy losses in a grid system: generation losses (accounted for by the capacity factor) and transmission losses. The consumption associated losses are accounted for in operational consumption data.

Transmission losses depend on a number of factors; some general electrical relationships are specified below for fundamental concepts:

$$P = VI \qquad (1)$$

$$P_{loss} = I^2 R \qquad (2)$$

$$R = \frac{\rho D}{A} \qquad (3)$$

$$\therefore P_{loss} \propto I^2 D \qquad (4)$$

P_{loss}	Power lost (W)
I	Transmission current (A)
R	Resistance (Ω)
ρ	Resistivity at temperature K (Ω · m)
A	Cross sectional area (m^2)
D	Transmission distance (m)

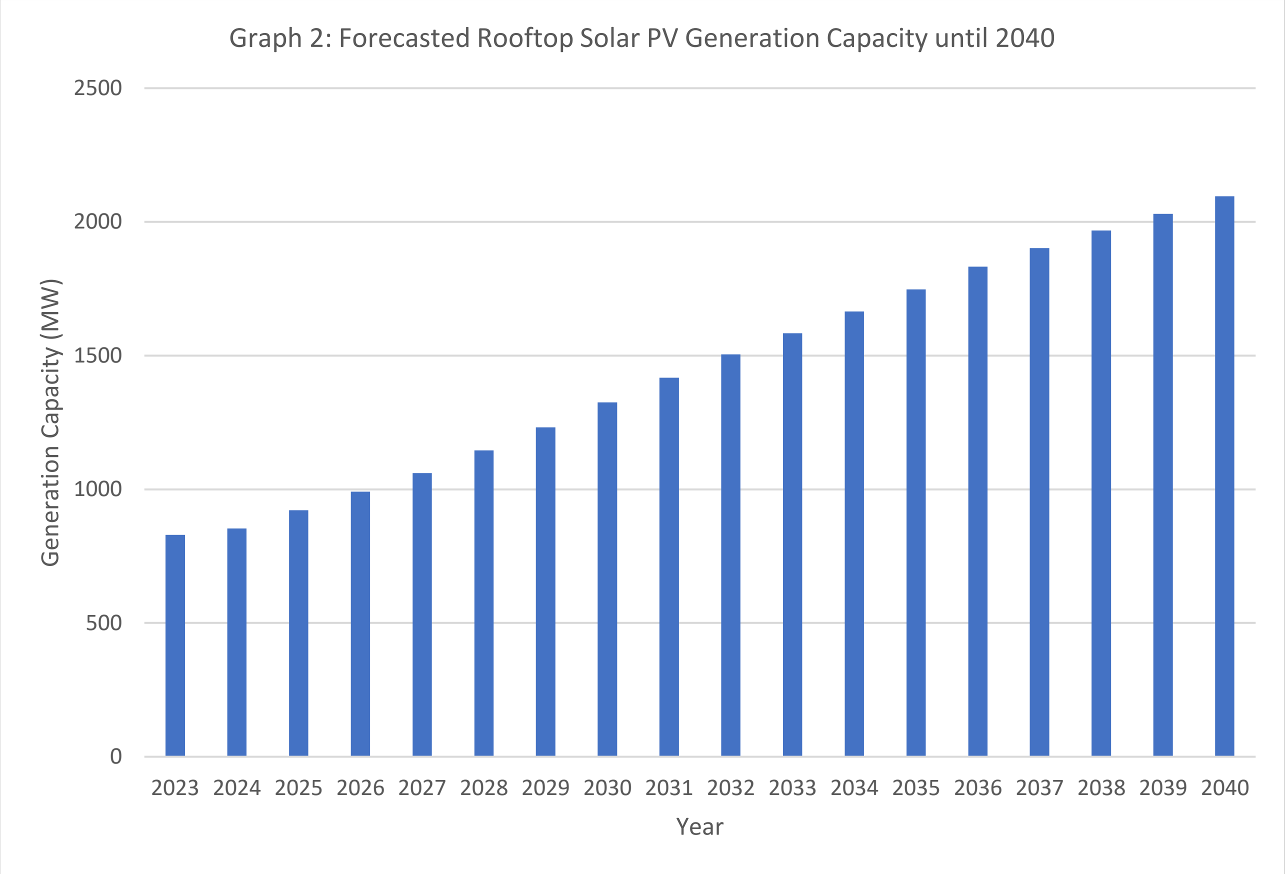
It is evident that if the transmission voltage and the transmission line properties are kept constant, losses increase quadratically with current, and linearly with transmission distance; this would require an increase in the transmission current to accommodate a higher power load. In reality, there are other factors affecting losses including temperature and the type of conductor (whether it is ohmic etc.) and the transmission voltage would typically be adjusted for higher loads. Other losses are incurred from inverters and transformers which have not been considered but will be accounted for in the overall transmission loss factor.

It is evident that with the emergence of more isolated power generation facilities, and a higher overall grid production, losses will increase if the transmission network is unchanged. Solar and wind facilities in particular often require a significant distance of transmission due to their location. This will be discussed further in the transmission research question (refer section 6.0); however, this provides reasoning for the inclusion of losses in the usable generation calculations.

Typically, the transmission loss factor is around 10% for the Queensland grid (AEMO, 2023); however, this is expected to rise during the transmission period. As a result, this loss factor was assumed to be between 10% and 15% and depended on the total annual energy production: the year with lowest forecasted production was assigned a loss factor of 10%, and the year with the highest forecasted production a factor of 15%. Although this may overestimate the losses, this maintains consistency with the CA. Note for the generation prediction mode, a standard 90% factor was applied until 2035 and then a factor of 85% was applied for this simplistic prediction.

Rooftop PV Overview

Rooftop PV systems are defined as a system of one or more PV panels installed on residential or business premises with an output of less than 100kW (AEMO, 2022). The number of these installations has seen significant increases in recent years from incentives and reduced installation costs. As of 2023, the cumulative capacity of rooftop PV surpassed 800 MW, and by 2040, the combined capacity is predicted to approach 4,100 MW. This cumulative capacity is far greater than the largest individual generation facility in Queensland (which is the Gladstone Power Station at 1,600 MW). The capacity and number of installed units can be seen in Graph 2.



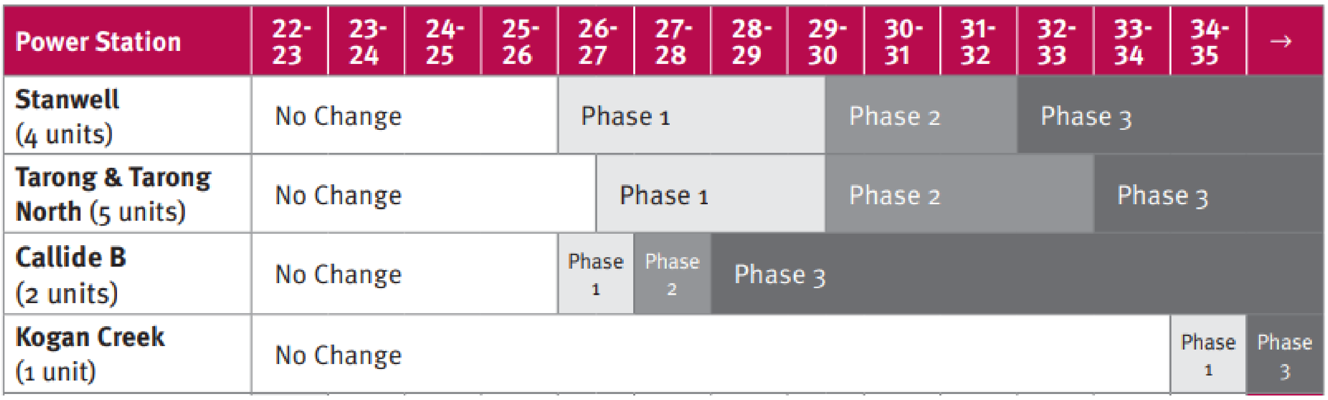
It is evident that the output capacity of the installed rooftop PV generation fleet is forecasted to have a steady linear increase from 2025 to 2040. This is likely due to increasing government incentives with many new buildings receiving rooftop PV installations with construction. This will occur in parallel with the increase in overall capacity of large scheduled generation plants.

Phase-Out of Coal Facilities

The gradual withdrawal of coal generation prior to decommissioning is a process being employed for many facilities. The Queensland Government is actively collaborating with individual Government-owned energy corporations to develop long term strategic plans for the gradual decommissioning of facilities to meet the State's renewable energy targets and ensure grid reliability.

The various phase schedules for some Queensland coal plants are shown below in Figure 8. The phases are defined as:

1. Phase 1 is the gradual shift to seasonal operation or reversible synchronous condenser conversion of 1 or more units. Phase 1 for most plants occurs from 2027 onwards and thus in this forecast model a reduced capacity factor of 50% was applied to the coal fleet from 2027 onwards.
2. Phase 2 involves the further conversion of units to seasonal operation and reversible synchronous condenser conversion. This typically occurs from 2031 onwards after the first PHES facilities become operational (such as Borumba Dam and Big T). For the forecast model, a further reduced capacity factor of 45% was applied for the coal fleet.
3. Phase 3 involves further progression of phase 2 with the reduced operation of more units. Further developments are expected to occur on site during this phase. For the forecast model, a final reduced capacity factor of 30% was applied to coal facilities from 2036 onwards.



Power Station	22-23	23-24	24-25	25-26	26-27	27-28	28-29	29-30	30-31	31-32	32-33	33-34	34-35	→
Stanwell (4 units)	No Change				Phase 1			Phase 2			Phase 3			
Tarong & Tarong North (5 units)	No Change				Phase 1			Phase 2				Phase 3		
Callide B (2 units)	No Change				Phase 1	Phase 2	Phase 3							
Kogan Creek (1 unit)	No Change												Phase 1	Phase 3

Figure 8: Decommissioning Phases of Coal Facilities Over the Following Decade
This figure highlights the timing of the different phase-out stages of certain coal plants in Queensland (QLD Gov, 2022).

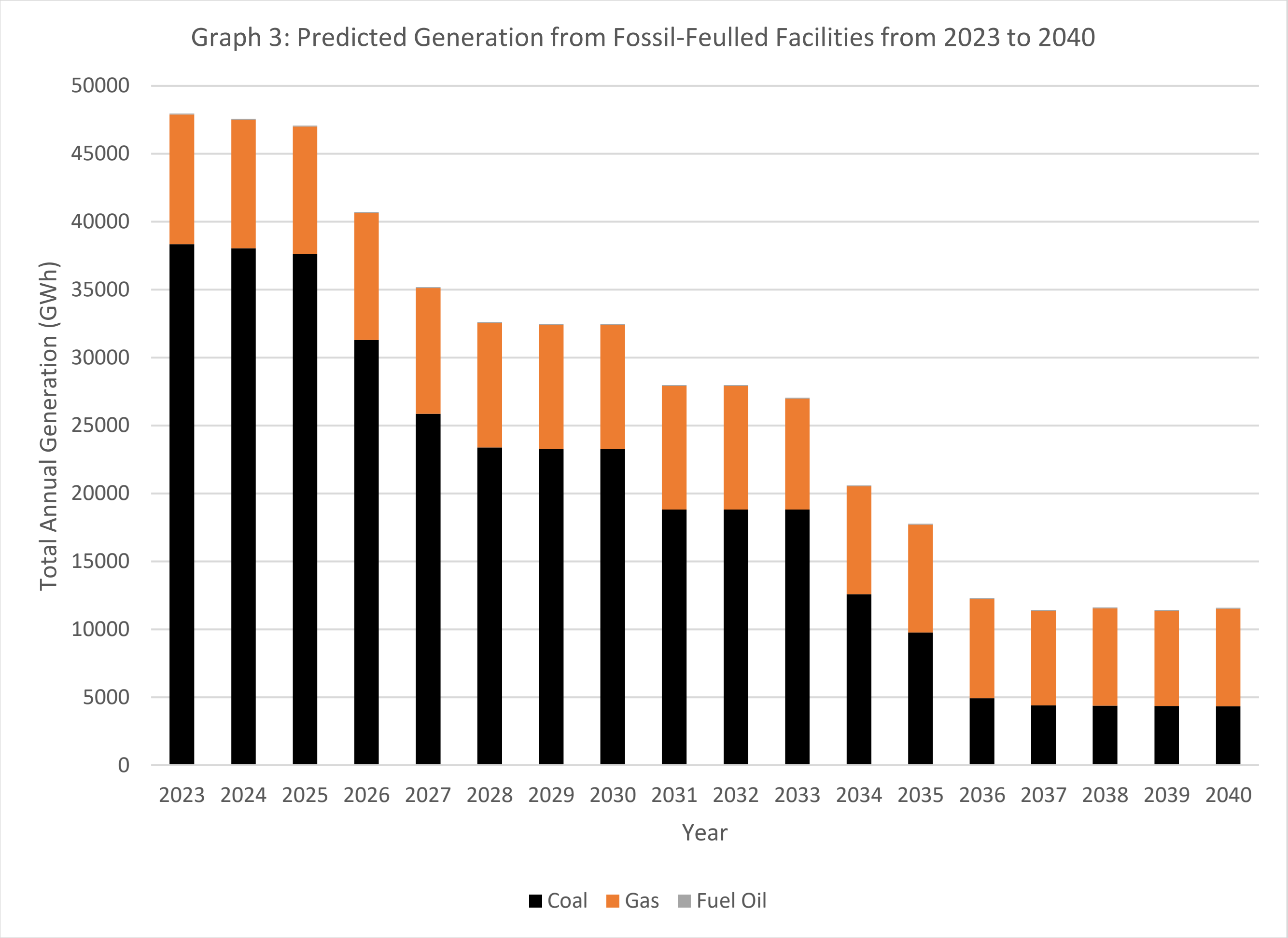
Note the Kogan Creek Power Station does not have the same phase program as typical plants as it is a different plant design consisting of a supercritical boiler that operates at much higher pressures and temperatures than conventional coal-fired power stations. This station was recently modernised in 2007.

3.2.3 Forecasted Energy Generation - Fossil Fuelled Plants

The withdrawal of Queensland's existing coal fired plants is expected to occur over the succeeding two decades due to both the aging of these facilities, and from the implemented direction of the energy plan. Many smaller gas and fuel-oil type facilities will also be phased out as they reach the conclusion of their intended operating lifespan; however, new CCGT turbines and reactive power generation facilities are being implemented as a part of the peak generation fleet according to the energy plan. The fluctuations caused from fossil-fuelled energy generation withdrawals was researched and summarised to incorporate in the predictions for the renewable generation. There were two sets of data considered:

1. Coal generation without a phase-out period to highlight the major coal withdrawals and determine the maximum generation output of the fossil-fuelled sector prior to the decommissioning of plants. The capacity factor of the coal plants is the lower range of the values presented in Table 3. The results from this analysis can be referred to in the Appendix 8.
2. Coal generation with a phase out period as specified in Figure 8. This represents a more realistic scenario as facility operations are reduced approaching the decommission date and as the renewable production penetration increases. The specific phase out programs are unique for each facility and thus, for simplification of the model, certain assumptions were made (refer Table 2).

As stated in the scope, the contributions from the facilities are expressed in terms of GWh to remain consistent with the consumption data. This prediction considers the average capacity factors of the respective facility types, transmission losses and the phase out programs for coal facilities. The general methodology is outlined in section 3.2.6 but was modified to include just the coal plants. The results can be seen below in the stacked column Graph 3 (refer 'Generation' tab in the spreadsheet) (Ludlow, M).

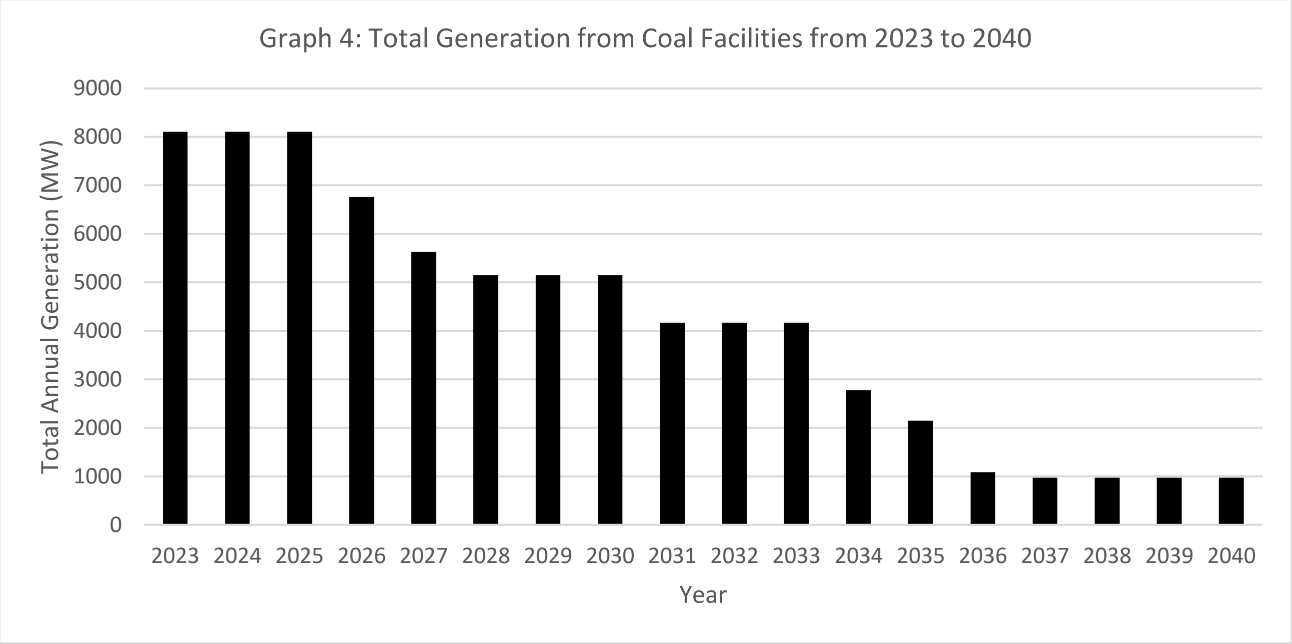


There are 4 major coal plant withdrawals planned over the following two decades including: Callide B in 2028, Gladstone Power Station in 2035, Tarong Power Station in 2036, and Tarong North Power Station in 2037. This amounts to a nameplate production decrease of 4,223 MW by 2040 and considering phase outs, the expected generation capacity in 2040 from coal facilities is just 970 MW. Considering capacity factors, losses, and the phase out, this is equivalent to an annual production decrease of 34,017 GWh per year by 2040. In terms of percent decrease in coal generation, there is a 39% decrease by 2030, 75% decrease by 2035 and 89% decrease in coal generation by 2040. Despite the apparent decrease, the coal fleet remains largely operational until half way through next decade where it approximately halves. Thus, if extra generation is required, these plants can provide essential backup.

There are 6 planned gas power plant withdrawals confirmed to occur by 2040 (from 2033 onwards) amounting to a total of 812 MW of withdrawn nameplate production. Considering average capacity factors and losses, this is an estimated reduction of 2,343 GWh per year of annual production by 2040. There is a proposed 1,000 MW gas-powered plant (consisting of 6 turbines) proposed as a part of the Lockyer Energy Project that has an unannounced commission date; this plant was incorporated according to the methodology outlined in section 3.2.1 (linearly from 2030 onwards over a 10-year period). Although there is no change in nameplate production until 2033, there was a decrease in the usable energy generated due to the transmission loss factors. In terms of percent, there was 4% decrease by 2030, 17% decrease by 2035, and 25% decrease by 2040. A considerable 3,220 MW of nameplate gas generation remains in use by 2040 compared to the 2023 production of 4,031 MW. This will likely be reserved for peak generation applications or renewable droughts. Note the fuel-oil type plants have relatively little contribution.

Overall, the total decrease in the annual fossil-fuelled generation from 2023 to 2040 is 36,363 GWh per year with a withdrawal of 7,949 MW of capacity. This is a relatively high estimate to ensure a CA; the selected capacity, loss and phase out factors were conservative to produce a rapid withdraw scenario. This is a reasonable assumption; however, during this renewable transition phase these various factors may vary significantly depending on grid requirements.

The following column Graph 4 was produced to highlight the coal facility capacity withdrawals for comparison with other sources. This graph does not consider the capacity factor or any losses incurred, but does consider the phase out period. The generation is expressed in terms of power output (MW) and this graph highlights the nameplate capacity withdrawals of the coal facilities.


Graph 4: Total Generation from Coal Facilities from 2023 to 2040

This can be compared to the forecast provided in the Supergrid Infrastructure Blueprint published by the Queensland Government (refer Figure 9). This source presents some inconsistencies with the results above which can be primarily attributed to the blanket phase out period applied to the model. The figure below likely considered specific phase programs for each plant to smooth the withdrawal of production (characterised by the more linear decline).

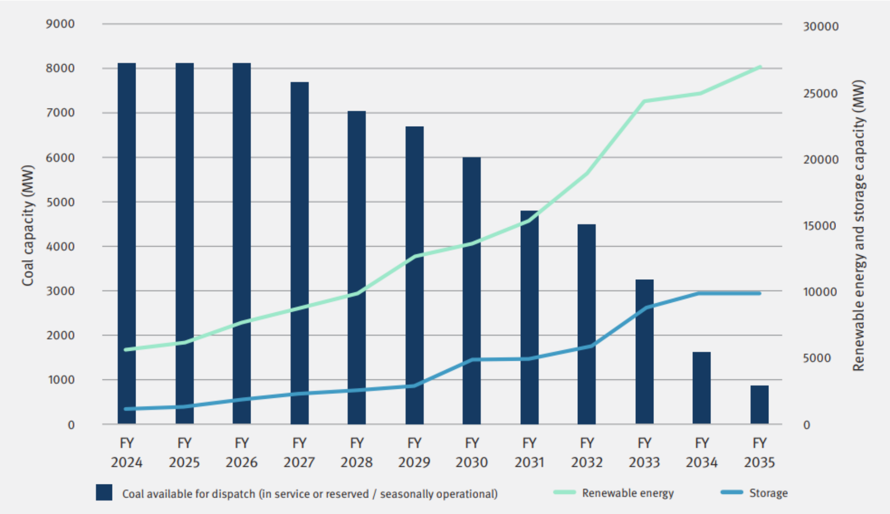


Figure 9: Decommissioning of Coal Facilities Over the Following Decade According to Government Model

This government model has a more regulated decline relative to the model developed (QLD Gov, 2022).

3.2.4 Forecasted Energy Generation - Preliminary Generation Prediction

Using the forecasted fossil fuel generation until 2040, as well as the expected annual consumption, the required renewable production can be calculated. Furthermore, the Energy Plan goals and renewable penetration estimates can be considered in the prediction: 50% renewable penetration in 2030, 70% in 2032, 80% 2035.

The minimum required annual renewable generation is the difference between the total consumption and the energy supplied from fossil-fuelled generation. It is important to note the actual renewable generation is likely larger in reality as a surplus production is necessary for grid stability and Queensland exports excess energy to other states. This model incorporates the previously acquired consumption data from section 3.1.4 which includes forecasted increases in certain fields, and the fossil-fuelled generation from section 3.2.3. Losses are also incorporated into the calculation. There is a high uncertainty in this prediction due to the omission of various factors which is discussed previously; however, the purpose of this prediction was to provide a benchmark value for later comparison. The required renewable energy production results are shown in the Excel 'Generation Prediction Sheet' with the respective percentage of renewable energy required to meet consumption (or refer to the 'Generation Prediction' tab in the spreadsheet); an extract has been provided below in Table 4.

It is evident the proposed renewable percentages are considerably higher than those calculated in this model: 7% below proposed 2030 value, 15% below the proposed 2032, and 3% below the proposed 2035 value. This was predicted as firstly, the energy plan consistently overestimates the rate of renewable energy development, and secondly as previously discussed, this is the absolute minimum production required.

Table 4: Generation Prediction Extract

Year	*Transmission Loss Factor*	*Consumption*	*Fossil Fuel Production*	*Required Renewable*	*Percent Renewable*	*Energy Plan Renewable Percent*
-	-	*GWh*	*GWh*	*GWh*	*%*	*%*
2030	0.9	54071.54	32454	24020	42.53	50
2031	0.9	56486.2	27973	31682	53.11	-
2032	0.9	59007.03	27973	34483	55.21	70
2033	0.9	62148.48	27044	39005	59.05	-
2034	0.9	64519.68	20577	48825	70.35	-
2035	0.85	67975.46	17778	59055	76.86	80

Utilising this minimum renewable production requirement, the required installed nameplate capacities renewable facilities was calculated. The prominent technologies being implemented are solar and wind, with a high ratio of solar to wind power relative to other grids; therefore, a scenario of 50:50 and 40:60 wind to solar contribution was applied to determine the required contribution from these technologies. The capacity factors identified previously were used, and at this stage of the analysis joint capacity factors were not considered to maintain consistency with the CA. The final results from the generation prediction can be seen in the Excel 'Generation Prediction Sheet'. It is evident that by 2040, approximately 38,000 - 41,000 MW of combined wind and solar generation is required to meet the demand not met by fossil-fuelled production. These values were used in later comparisons.

3.2.5 Forecasted Energy Generation - Data Collection

The model developed considers data from all past, current, and proposed energy generation facilities across Queensland. Firstly, the name and local government area (LGA) of all of the plants were obtained for later use in stability and transmission assessments. It became evident that the names of various projects can change throughout their respective progression pending company decisions, stakeholder handovers and other factors. These changes are poorly documented and are rarely updated by data providers such as AEMO resulting in the omission of certain projects or repeated inclusion of the same facility under different names.

The respective fuel types and categories of each facility were then identified. This consisted of either fossil or renewable fuel types and their respective technologies (coal, gas, fuel-oil, hydroelectric, bioenergy, wind, solar, and thermal solar. Note that hydroelectric does not refer to PHES, rather to energy produced from hydro-turbines that are not connected to a storage system. Next, the status of operation was determined to be either decommissioned, existing, proposed, under-construction, or cancelled. Again, there were inconsistencies in collected data as some projects that were listed as 'proposed' in some sources had already been cancelled upon further research. The respective commission and decommission dates were then included where appropriate; many facilities had uncertain or unknown dates, and some facilities had a commission or decommission period where the power output would slowly either increase or decrease (this was accounted for in the scope). Finally, the nameplate capacities of the facilities were included which were again susceptible to inconsistencies between sources. Any other specific and notable considerations were noted.

Significant difficulties were encountered gathering the data for this stage of analysis due to the identified inconsistencies and inaccuracies. All of these factors contribute to increased uncertainty in the data and respective results. This again highlights the uncertain nature and questionable management of the QLD energy plan and the various predictions proposed; the proposed actions are likely uninformed or misleading. In attempt to mitigate this uncertainty, the data was collected from a variety of sources, but was corroborated where possible to confirm various dates and nameplate capacities. All data was collected as of June 2023.

3.2.6 Forecasted Energy Generation - Methodology and Model

The developed model is a general approach to the feasibility assessment of the generation aspect of the Queensland energy plan. The scope of the model and its various assumptions result in the exclusion of certain implications; however, this model successfully determines whether the proposed and installed facilities are capable of meeting the energy requirements from an average annual perspective (refer scope and assumptions in section 3.2.1). As stated previously, a year-by-year forecast was deemed the most appropriate holistic approach to this feasibility assessment for the succeeding two decades. The model was implemented in Excel using primarily the ‘IF’, ‘AND’ and ‘OR’ functions.

Firstly, in the initial ‘Capacity Calculation’ columns, the average annual production of each facility (GWh) was obtained from its nameplate capacity (MW) which involved:

- Applying the respective capacity factor to the facility type through the use of an ‘IF’ function (refer Section 3.2.2 for capacity factor selection).
- Converting the MW power rate to a yearly production (GWh) through the multiplication of the factor $\left(\frac{1000}{24\times365}\right)$.

Facilities were then included in the forecast for a specific year (year of interest) if this year was between the facility’s commission and decommission dates. For example, if a facility was proposed to commence operations in 2030 and stop production in 2035, this facility was included in the forecast from 2031 to 2034. Various other factors were also considered for facilities with limited or unspecified data. This process is outlined below where the numbers represent the order actions were executed in the functions in the ‘Forecast Calculations’ columns:

1. If the status of the facility was ‘Decommissioned’ or ‘Cancelled’, then facility was not included in any calculations.
    - It was still necessary to ensure all facilities, past, present, and future were accounted for and included in the spreadsheet.

2. If the status of the facility was ‘Proposed’ or ‘Under Construction’, and the commission date was ‘Unknown’, the facility was assumed to finalise production in 2035 and begin production in 2036. Furthermore, to account for facilities commencing operation even later, the contribution of these facilities had a linear growth over the initial 10 years of production.
    - This was done as if a facility’s commission date was unknown, it is expected that it will either be cancelled or operation will not commence for a significant time. This is likely an overestimate but remains consistent with the CA.
    - An unknown commission date meant the projects were either in early stages of proposition or were securing clearance and still a few years from construction.
3. If the status of the facility was ‘Proposed’ or ‘Under Construction’, and the commission date was known, the facility was included in calculations from the year after its commission until the year prior to the decommission date (if known).
    - This avoids the inclusion of facilities that commence operation at the end of a year and stop operation at the beginning of a year to maintain consistency with the CA.
    - Note for all facilities either ‘Existing’, ‘Proposed’, or ‘Under Construction’, if the decommission date was unknown, it was assumed to be beyond the foreseeable future of 2040.

4. If the decommission date was unspecified, and the commission date was before the year of interest, the facility was included in calculations.
    - This applies to the ‘Existing’ facilities with unspecified decommission dates but were in operation.
    - If the commission date of an existing plant could not be found, a value of 1000 was input to remain consistent with formulas and ensure the facility was included.
5. If the decommission date was specified, the facility was included if the commission date was before the year of interest and the decommission date was after the year of interest.
    - This applies to the remaining ‘Existing’ facilities with specified commission and decommission dates. The phase out period was applied for only coal facilities.

Finally, to extract more information from the results, the annual data was sorted into respective energy types through the use of ‘IF’ functions in the ‘Fuel-Type Data Extraction’ Columns. This data was summed and collated at the bottom of the spreadsheet before respective transmission and generation loss factors were applied. Relevant values and percentages were then extracted from the results. The data obtained was also used in section 3.2.3.

Some sample functions used in the Excel model are shown below in Table 5 (refer ‘Generation’ sheet on the Excel Document). The entire spreadsheet is automated (can easily vary capacity factors or transmission losses), and the results are collated at the bottom of the sheet.

Table 5: Sample Functions Used in Excel Model

Sample Function	*Sample Cell*	*Description*
`=IF(D4="Coal",'Capacity Factors'!$C$5,IF(D4="Gas",'Capacity Factors'!$C$6,IF(D4="Fuel Oil",'Capacity Factors'!$C$8,IF(D4="Hydro",'Capacity Factors'!$C$9,IF(D4="Bioenergy",'Capacity Factors'!$C$10,IF(D4="Solar",'Capacity Factors'!$C$12,IF(D4="Wind",'Capacity Factors'!$C$13,IF(D4="Thermal Solar",'Capacity Factors'!$C$11,"ERROR"))))))))`	L4	This function was used in the ‘Capacity Calculations’ section to apply the appropriate capacity factor to the generation type. This meant the capacity factors could be easily changed in the ‘Capacity Factor’ sheet to experiment with various values and combinations.
`=IF(OR($G4="Decommissioned",$G4="Cancelled"),0,IF(AND(OR($G4="Proposed",$G4="Under Construction"),$H4="Unknown",$S$291="Y",P$1>$S$297),((P$1-$S$297)*$N4/$S$294),IF($I4="",IF(P$1>$H4,$N4,0),IF(AND(P$1>=$H4,P$1<$I4,$D4<>"Coal"),$N4,IF(AND(P$1>=$H4,P$1<$I4),IF(P$1<'Capacity Factors'!$G$6,$N4,IF(P$1<'Capacity Factors'!$G$7,($N4/'Capacity Factors'!$C$5)*'Capacity Factors'!$H$6,IF(P$1<'Capacity Factors'!$G$8,($N4/'Capacity Factors'!$C$5)*'Capacity Factors'!$H$7,($N4/'Capacity Factors'!$C$5)*'Capacity Factors'!$H$8))),0)))))`	P4	This function was used in the ‘Forecast Calculations’ section to apply the appropriate generation contribution according to the rules specified above.
`=IF($D4="Coal",$P4,"")`	AI4	This simple function was used in the ‘Fuel-Type Data Extraction’ section to extract the individual fuel type contributions for further analysis.
`=IF($J4<100,IF(OR($G4="Decommissioned",$G4="Cancelled"),"",IF(AND(OR($G4="Proposed",$G4="Under Construction"),$H4="Unknown",GO$1>2030),1,IF($I4="",IF(GO$1>$H4,1,""),IF(AND(GO$1>=$H4,GO$1<$I4),1,""))))),"")`	GO4	This function was used in the ‘Facility Size Extraction’ column to extract and sort each of the individual facility sizes in their respective years.

3.2.7 Forecasted Energy Generation - Results and Analysis

The results from the model have been provided below and corresponding tabulated data can be referred to in the 'Generation' tab of the spreadsheet. Graph 5 shows a stacked column representation of the forecasted annual generation of usable energy for consumption (GWh) and the break-down of generation types. All data can be referred to in the Excel 'Generation' sheet, and an extract of final results can be seen in Table 6 below. All the critical observations are discussed below.

Graph 5: Forecasted Annual Generation Breakdown from 2023 to 2040

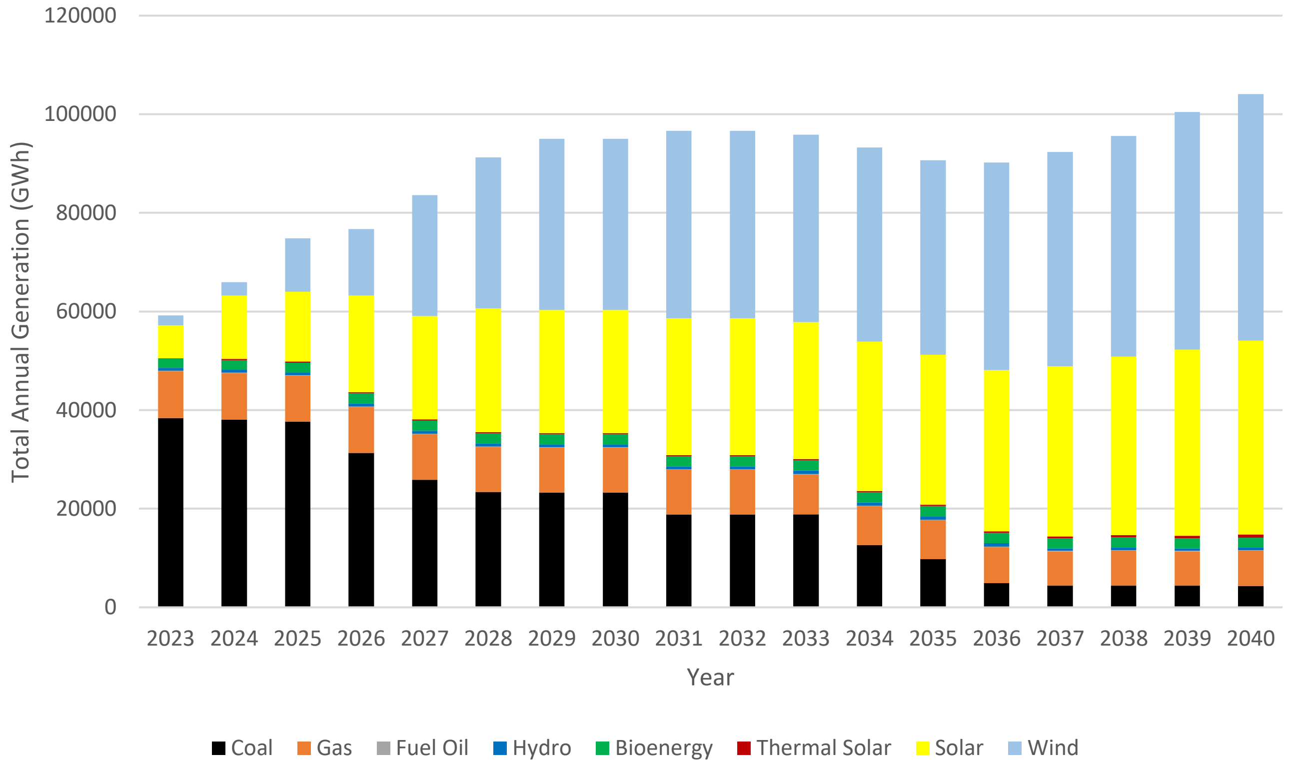


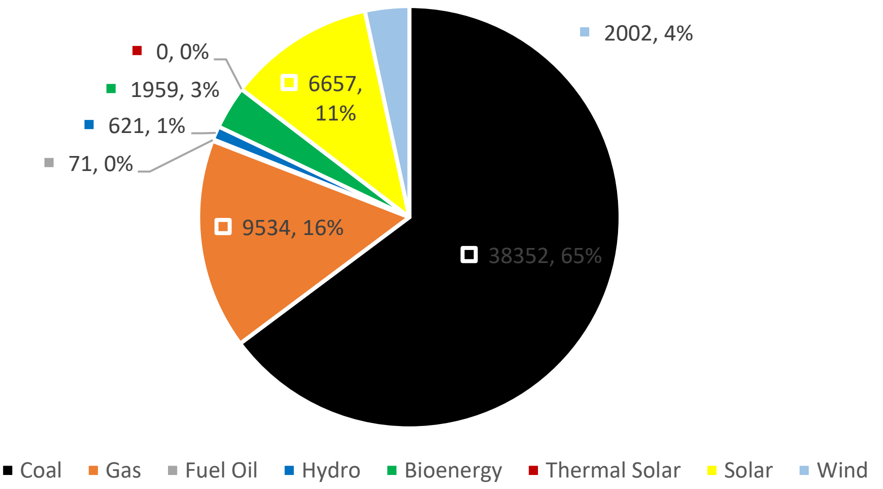
Table 6: Average Annual Generation Data Summary

Year	*Loss Factor*	*Coal*	*Gas*	*Fuel Oil*	*Hydro*	*Bioenergy*	*Thermal Solar*	*Solar*	*Wind*	*Fossil*	*Renewable*	*TOTAL*
-	*-*	*GWh*	*GWh*	*GWh*	*GWh*	*GWh*	*GWh*	*GWh*	*GWh*	*GWh*	*GWh*	*GWh*
Total change (GWh)		-34017	-2343	-4	-119	77	611	32691	48028	-36363	81288	44925
Change by 2025 (%)		-2	-2	-2	-2	-2	-	112	443	-2	147	26
Change by 2028 (%)		-39	-4	-4	-4	6	-	277	1430	-32	422	54
Change by 2030 (%)		-39	-4	-4	-4	5	-	275	1634	-32	457	61
Change by 2035 (%)		-75	-17	-4	15	6	-	357	1871	-63	549	53
Total Change 2040 (%)		-89	-25	-6	-19	4	-	491	2399	-76	723	76

Recall this graph represents the energy produced from all existing, and proposed scheduled and semi-scheduled generation facilities across Queensland after accounting for the capacity factor of each generation type and transmission losses. This can thus be directly compared to the forecasted consumption to determine if production is able to meet demand requirements (refer Graph 9). It is evident that despite the decline in fossil-fuelled generation discussed in section 3.2.3, there is a general trend of increasing total annual generation. An interesting observation is the decline in total annual production from 2032 to 2036. Although this trend is not reflected in the available capacity of the grid generation (refer Graph 10), incorporation of the capacity and loss factors highlight a potential overall decrease during the phase out of coal. The effect of this decline relative to consumption is discussed later.

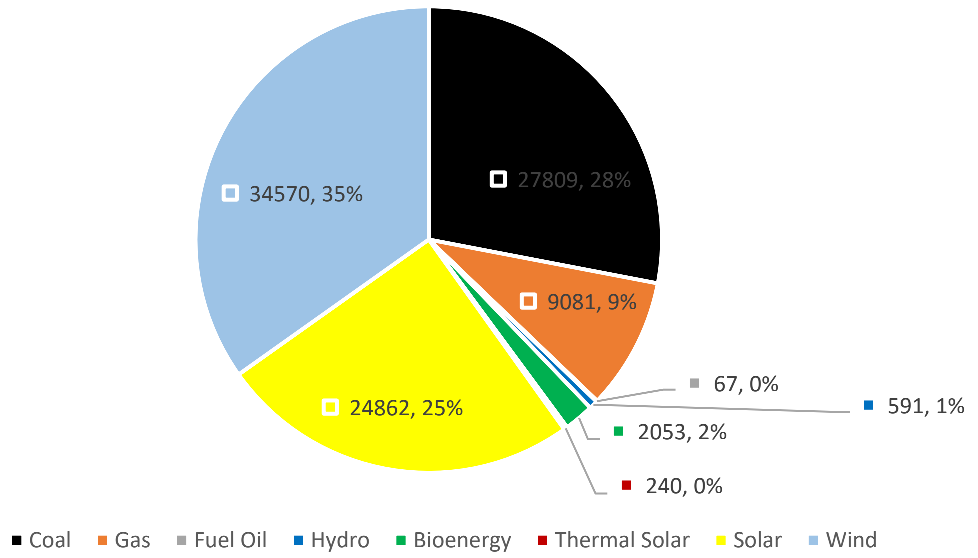
In terms of the increases in annual generation over the following two decades from the current 59,196 GWh in 2023, there is a 26% increase by 2025 (74,857 GWh), 61% increase by 2030 (95,024 GWh), and total 76% increase by 2040 (104,121 GWh). Between 2023 and 2040, there is an 89% decline in coal generation, 25% decline in gas and small declines in both fuel oil and hydro (less than 20%). Contrarily, there is 4% increase in bioenergy generation, a factor 5.9 increase in solar generation, and a factor of 25 increase in installed wind generation. The highest rate of growth occurs over the following 5 years to 2028 with an approximate average rate of increase of 7,000 GWh/year of additional available generated energy. This is highly ambitious considering the current 2023 annual renewable generation of 11,239 GWh (19% penetration) is expected to rise by a factor of 5.2 by 2028, to 58,632 GWh (64% penetration).

In regards to the Energy Plan goal of 50% renewables in 2030, 70% in 2032, and 80% in 2035, it is evident in Table 6 that according to this forecast, this goal will likely be achieved with expected values of 66% in 2030, 71% in 2032, and 80% in 2035. This is a surprising result considering the government is well renown for exaggerating development for political favour. A critical disclaimer regarding this prediction is that this model has not considered facilities that are cancelled, significantly delayed, or downsized prior to construction. This was not considered as this model provides a forecast according to the current outlook; this is discussed further in improvements. A breakdown of the generation penetrations for 2023, 2030, and 2040 have been provided below in the pie charts to highlight change in generation types.

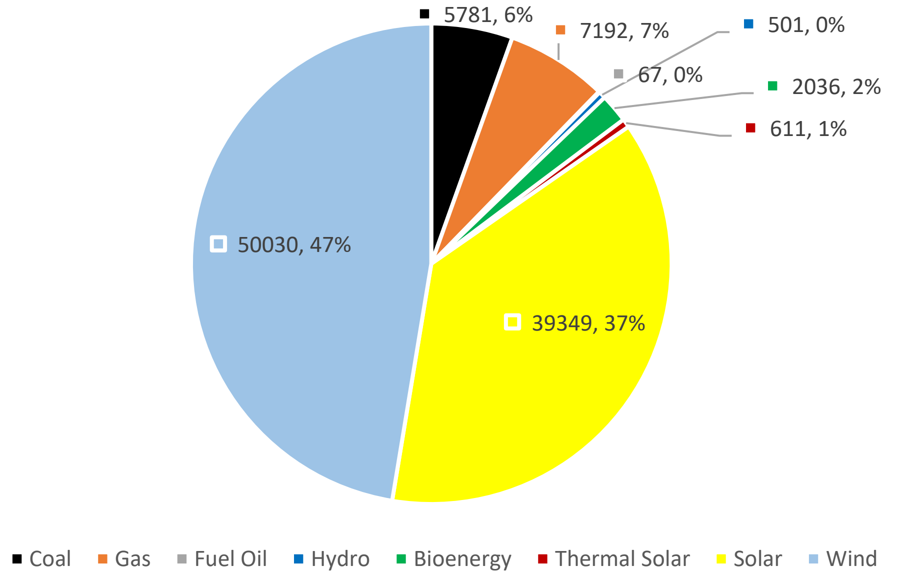


Graph 6: Annual Contribution of Energy Generation by Facility Types in 2023 (GWh, %)

Graph 7: Annual Contribution of Energy Generation by Facility Types in 2030 (GWh, %)



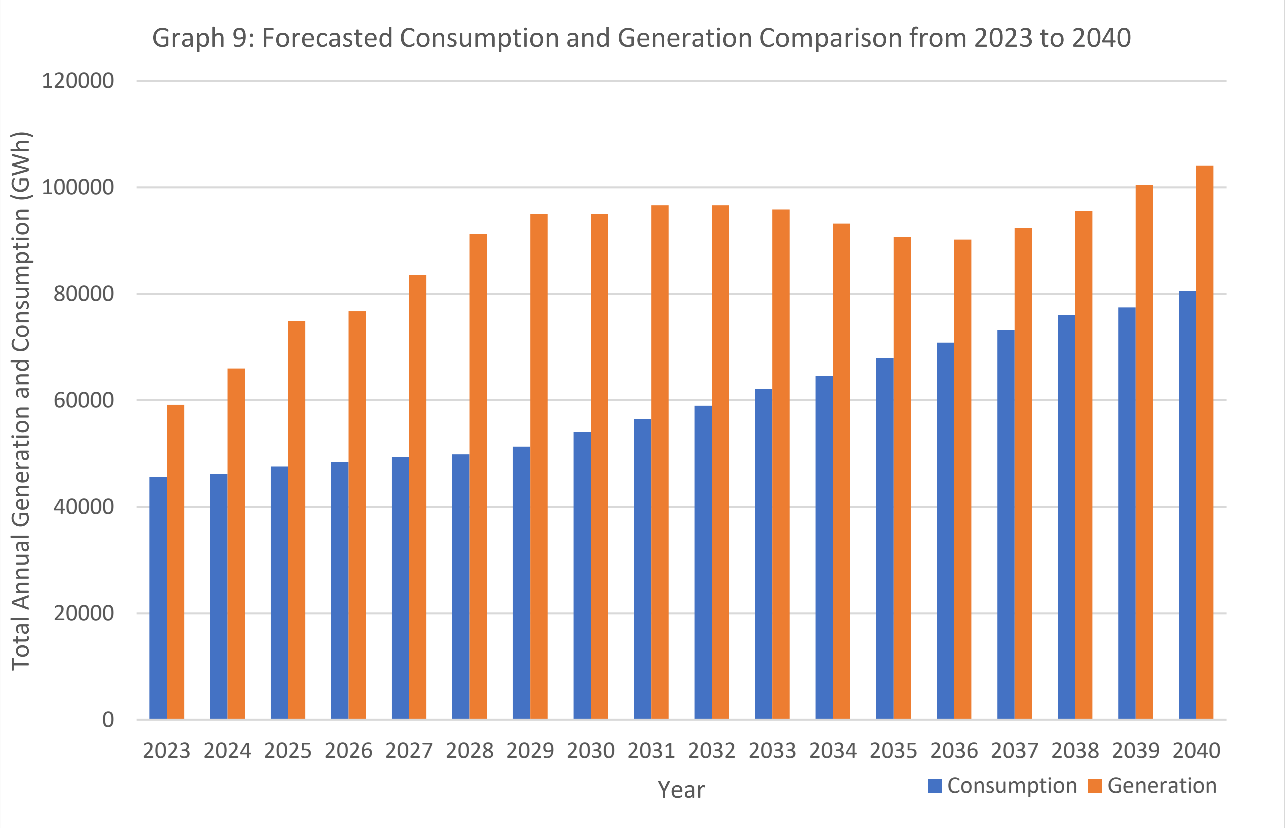
Graph 8: Annual Contribution of Energy Generation by Facility Types in 2040 (GWh, %)



It is evident that coal penetration reduces from 65% in 2023 to 6% by 2040. Gas penetration roughly halves from 16% to 7%. Contrarily, solar increases from a current penetration of 11% to 37% by 2040. Wind generation has the largest penetration percent increase from 4% in 2023 to 47% in 2024; by 2040 this is the largest generation contribution to the grid. This was unexpected as there is significant focus on solar in Queensland and thus it was expected that solar would have the largest contribution. This penetration can be compared to the prediction values for the 50:50 wind to solar scenario (refer Excel 'Generation Prediction' sheet). The prediction required approximately 39,800 GWh of both solar and wind generation which was a valid approximation (relative to the forecasted values above) considering it only factored the generation deficit to consumption (without excess generation as seen in Graph 9). The overall renewable penetration in 2040 is 88%.

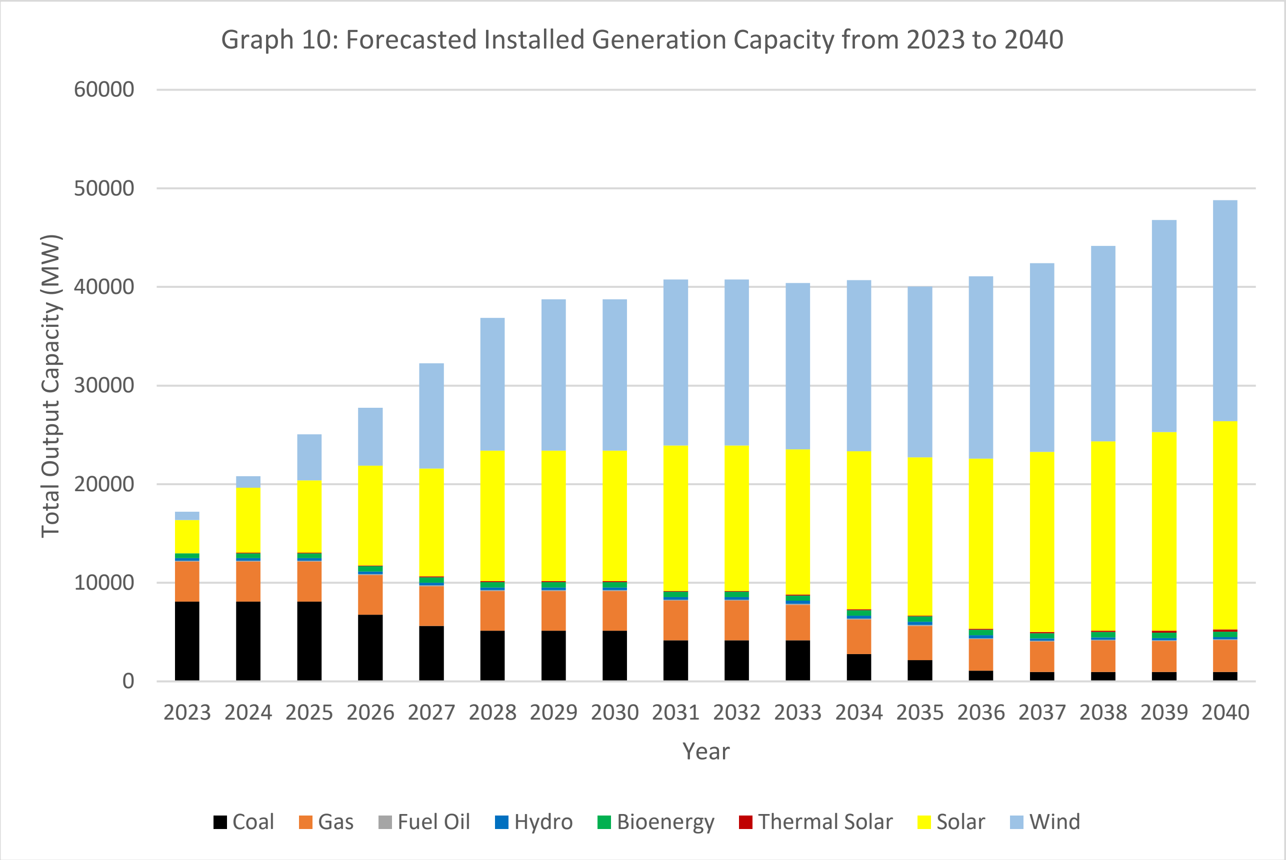
3.3 RQ1 Discussion

The annual generation forecast can be compared against the previously conducted annual consumption forecast to assess the feasibility of the generation aspect of the grid. The results for this comparison can be seen below in the clustered column Graph 9 below.



It is evident that over the following two decades, the predicted annual generation is significantly greater than the consumption data; this is a positive result indicating sufficient forecasted generation. By 2040, both consumption and generation have a comparable forecasted increase of approximately 76%. At current, there is an estimated 13,611 GWh excess production (30% excess). The short-term rapid development of generation results in a very large annual excess relative to consumption until 2035. During this period, the largest excess reaches 85% in 2029. Beyond 2035 the percent excess returns to approximately 30% which is reasonable. This excess must be managed through limiting generation to ensure production meets consumption. The management of fossil-fuelled generation involves powering off or disconnecting units within coal and gas facilities; however, managing renewable based production is much more difficult as these facilities rely on external conditions. This large excess could provide an incentive for the earlier development of hydrogen production technology as this would provide an effective means of productively utilising excess energy production (and would smooth the spot price curve for electricity). The large excess values indicate again that the generation forecast is likely an overestimation of actual levels.

For additional observations, the forecasted cumulative nameplate capacities (MW) of generation facilities are provided below in the stacked column Graph 10. This considers all existing and proposed scheduled and semi-scheduled generation in Queensland without factoring in capacity factors and transmission losses. The phase out of process of coal facilities has still been included in this analysis for comparison purposes.



This form of data presentation is not an accurate reflection of the actual average generation (as is displayed in Graph 5), rather this data presents the cumulative maximum capacity of all operational facilities for a year-by-year outlook until 2040. The increasing trend in capacity above is logically similar to the previously observed increasing average annual generation trend in Graph 5; however, the decline in nameplate capacity (MW) between 2030 and 2035 is not as pronounced as the decline in average annual generation (GWh) which is attributable to the omission of the efficiency factors in this analysis. The current installed capacity is estimated to be 17,212 MW while the forecasted capacities for 2030 and 2040 are 39,774 MW and 49,114 MW respectively. Other specific data values can be referred to in the attached spreadsheet, but the average annual generation data has greater value in terms of analysis. Despite this, Graph 10 provides a valuable comparison to the Queensland Government's prediction of dispatchable generation capacity in Figure 10 below (QLD Gov, 2022). The date of source publishment was September 2022.

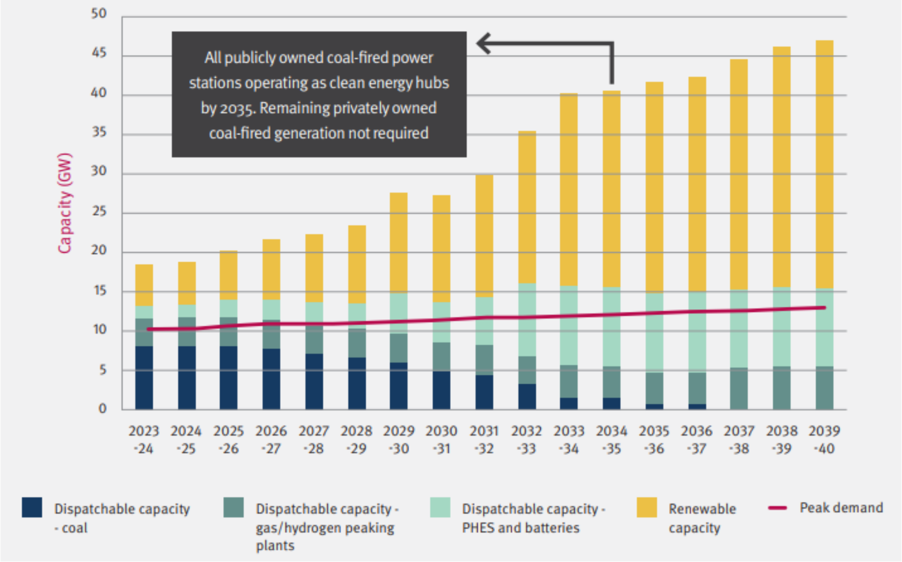


Figure 10: Forecasted Energy Generation Capacity of Queensland According to Government Model

This government model has a slightly lower estimate for the forecasted increase in generation capacity (QLD Gov, 2022).

The actual data for the Government's prediction was unavailable and the methodology used in formulating this forecast was not specified meaning only a rough comparison can be conducted for some general observations. The significant observations between these data sets include:

- The current dispatchable capacity value of 17,212 MW approximately agrees with the Government's forecast above (16 GW without storage).
- The final forecasted dispatchable capacity of 48,791 MW in 2040 differs significantly by approximately 12 GW to the Government's prediction above (24% reduction).
- The general increasing trend is still observed and if storage capacities are omitted from Figure 10, there is a similar plateau between 2029 and 2035 of installed generation capacity.

This brief comparison indicates again that the model used in this report likely overestimates the generation capabilities of the grid over the succeeding two decades. This is not attributable to a flaw in the model, rather the data supplied by AEMO and online sources regarding the generation facilities is not up-to-date or is overly optimistic (as previously discussed). The individual facility numbers and capacity sizes are summarised below in Table 7. This data provides additional background information and insight into the types of facilities.

Table 7: Installed Facility Sizes

Facility Size	*Number of Facilities in Specified Year*				
(MW)	2023	2025	2030	2035	2040
< 100	92	104	116	127	127
100 - 499	29	44	70	90	90
500 - 999	6	8	12	16	16
1000 - 1999	3	4	6	11	10
> 2000	0	0	0	1	1
TOTAL	130	160	204	245	244

It is evident that the total number of facilities is expected to increase by nearly double over the following two decades from 130 to 244 individual plants. Some of the largest proposed plants are provided below:

- Bulli Creek Solar Farm (Stage 1 at 475 MW and Stage 2 at 1,500 MW)
- Collinsville Green Energy Hub (wind and solar facility of 1,500 MW each)
- Flavian Super Hybrid Wind Project (1,800 MW)
- Harlin Solar Farm (1,500 MW)
- Pacific Solar Hydrogen facility (3,600 MW)

These facilities are very large considering the current largest individual generation facility in Queensland is the Gladstone Power Station with an output of 1,680 MW.

It is evident that the number of plants forecasted for installation between 2023 and 2040 is very significant resulting in an over-optimistic generation forecast. There is a high probability that many of the proposed plants will not come to fruition as: changes may occur in the market dynamics, government incentives may be retracted, policies and laws may be altered, grid requirements constantly change, certain companies may lose funding or pull out of construction. Regardless, as of July 2023, the results produced are confidently the current outlook on generation forecasts.

3.3.1 RQ1 Sensitivity Analysis

This sensitivity analysis primarily applies to the annual generation results. The data collected for the consumption forecasts was directly from AEMO, and there were no applied parameters or variables and thus a sensitivity assessment cannot be performed on these results. It is important to note however that the data provided by AEMO is still susceptible to high uncertainty as discussed with the change in results from 2022 to 2023 (refer Figure 7). A closer inspection of the model is required but is considered out of scope.

There is a high uncertainty in the annual generation results as the prediction is highly dependent on a number of factors and variables which have been outlined below in Table 8. The assumed baseline (values used in the results) and proposed variance (range of values possible) for each parameter has been provided in the table; recall all parameters in the results were selected based on the CA. A quantitative explanation of the sensitivity of each variable and effect on results was provided by conducting a one-at-a-time (OAT) analysis. Note the qualitative effects of each variable in green can be easily assessed by using the Excel model provided and manually changing these inputs (also coloured green in the Excel document).

Table 8: RQ1 Sensitivity Analysis

Variable or Parameter	*Assumed Baseline*	*Proposed Variance*	*Sensitivity and Effect on Results*
Capacity factor	The capacity factor for each generation facility type was selected from the lower range of the researched limits.	The variance is specified in section 3.1.2 for each plant type. Recall that these capacity factors refer to the yearly production not the daily variance.	Overall, if the capacity factor is increased, the generation contribution for the respective facility type increases accordingly. This relationship is linear as it is a multiplication factor. At the maximum range of values, there is an approximate increase of 16% in forecasted average annual generation; however, this varies for each year based on the generation mix.
Lower (current) Transmission loss factor	The transmission loss factor considered 10% losses at current which was considered to be the lower baseline with the losses expected to rise with increased generation.	The variance of this factor depends heavily on the capabilities of the transmission infrastructure and ranges from minimal losses to the 10% standard value researched.	The effect of increasing or decreasing the lower transmission loss factor has a proportional effect on the average annual generation results as again, this is a multiplication factor. Without considering a transmission loss factor, the results are 11% higher (1/9) which is logical and expected.
Upper Transmission loss factor	As the overall annual generation increases (the peak generation will have an even higher increase), and as transmission distances are increased, the transmission loss was considered to rise to 15%.	Again, the variance of this factor depends heavily on the capabilities of the transmission infrastructure and it expected to range from 5% to 15% depending on distance and transmission load.	The effect of increasing or decreasing the lower transmission loss factor has the same effect outlined above. The magnitude of effect varies for each year (due to the nature of the model used) as the applied transmission loss factor is greater for the years of high generation (linearly from the lower to upper factor).
Year of inclusion for facility with unknown commission date	The year of inclusion for these facilities was assumed to be 2035. It was assumed it would take a minimum 12 years for these facilities to go from an unknown status to development	This could change greatly as it may take even longer for some facilities t come to fruition, and some facilities may never be developed at all. Hence this could range from 10 to 15 years.	This simply changed the time that the unknown facilities were included in the generation forecast. An earlier year would see the sharp rise observed from 2035 onwards in Graph 5 moved to the left.

Inclusion of facility with unknown commission date	Facilities were included even if their commission date was not known. This can be changed in the model.	The variance is difficult to evaluate as the facility may be commissioned at any time beyond an assumed 10-year period.	Excluding the 'unknown commission date facilities' changes the results from 2035 onwards as this was assumed to the start date of the phased inclusion. The change in average annual production by 2040 is a 17% decrease if excluded.
Linear phase in time of facility with unknown commission date	The current baseline value was 10 years as this was considered reasonable to the time required for a facility to go from planning to finish construction.	The phase in period is highly arbitrary. A longer phase in period provides a more conservative approach. The period could range from 5 to 15 years.	This is linked to the parameter above, a shorter phase in time results in a sharper increase in the average annual generation from the year of inclusion. This has an inverse relationship due to the nature of the model used.
Number of generation facilities	The total number of generation facilities was used regardless of known commission dates. The number of facilities is outlined in Table 7.	This could vary significantly as plants are delayed or cancelled. The actual number that may not come to fruition is highly arbitrary.	The effect of this parameter is unknown as it was not included in the model due to the lack of information surrounding the number of facilities that go from proposal to construction and commission. This was included in the limitations.

It is evident that the variables with the greatest sensitivity in terms of the final results produced are the parameters associated with the inclusion of facilities with unknown commission dates. This has been managed with a confident approximation for the gradual inclusion of these facilities starting from 2035. The primary variance that should be remeasured is the transmission loss variance as this could have an even greater range with the changing generation mix. Despite the presence of these variances, the model developed is highly robust and has justified the use of the selected variables through extensive research. Therefore, although the results cannot be used as a verbatim prediction, they serve as a reliable forecast from which overarching conclusions can be made.

Unlike the annual generation forecasts (GWh), there is low uncertainty in the nameplate capacity generation forecasts (GW) as there are less parameters, fewer assumptions and the results are a pure representation of all data collected; however, there are still uncertainties associated with the collected data such as inaccurate, misleading, or out-of-date information. Both models do not consider factors such as unexpected closures, elongated operation of the coal facilities, delayed commissioning, phased commissioning, or cancelled projects. The effect of these parameters is highly variable and cannot effectively be incorporated into the model.

3.3.2 RQ1 Limitations and Recommendations

There are various limitations within the model developed and the associated results produced. Based on these limitations, the recommendations suggested below could be employed in future models and analysis to reduce the effect of these limitations and mitigate uncertainty in the results:

1. The individual phase out programs planned for each coal facility could be applied for a more accurate forecast. A more general approach was adopted for the model used in this analysis to assess the effects of varying the phase out parameters, also the phase out schedules are prone to change and applying an exact decommission program was deemed excessive.

2. The application of location-based capacity factors could be applied for a more accurate approximation of the generation values. This would involve incorporating data from the national map which provides capacity factors throughout Queensland for different generation types. The method of incorporation would likely require macro visual basic

coding in the Excel model to interact with the webpage and call data elements into the model. Furthermore, the national map source also provides joint capacity factors for regions with a certain generation mix. The joint capacity factor can have a significant impact on the region's generation productivity, especially at wind to solar ratios of 50:50 (refer Appendix 13). The reason for this is because the daily generation profiles of these technologies complement each other by reducing the overall variation in energy output resulting in a more consistent and predictable supply. It also diversifies the resource base and mitigates the effects of renewable drought. Incorporating location based and joint capacity factors would greatly improve the accuracy of the model and provide insights into the regions of highest productivity and the transmission requirements of certain areas.

3. Another limitation of the model was the arbitrary application of transmission loss factors. Although the value applied in the model (10%) was obtained and corroborated by various reliable sources and was considered reasonable for Queensland, the transmission loss factor varies greatly with changes in generation and distribution. As previously discussed, the renewable generation mix by 2040 results in not only a larger overall generation (GWh), but also periods of proportionally greater output (MW) during peak production times. This results in significantly larger loads than currently experienced (over double the capacity during certain periods, refer 'Storage' sheet in Excel Model). Furthermore, the overall transmission distance of the grid is expected to increase as the number of generation plants increases from the current 130, to 244 by 2040; these plants are distributed throughout the state and in remote locations. It is therefore evident that the transmission loss is a complex function of the varying generation load, transmission distance, and transmission infrastructure (load ratings of lines). An individual model would be required to account for these factors and was deemed excessive for the scope of this report; however, it is recommended a model is developed (again using data from the national map for transmission information) for greater accuracy in results.

4. As previously discussed in the sensitivity analysis, there is a large sensitivity in the model to the inclusion of facilities which may not come to fruition. It is unknown what facilities are likely to be dismissed before development and the constant updating of data is required for the most updated conclusions; many facilities are cancelled, delayed, or downsized prior to construction. It is recommended that over the following years, the number of facilities that are withdrawn before development are recorded and analysed to observe a potential trend. This trend could be extrapolated and incorporated in the model through the use of 'cancellation factor' that simply reduces the generation forecast according to the forecasted withdrawals of plants before development.

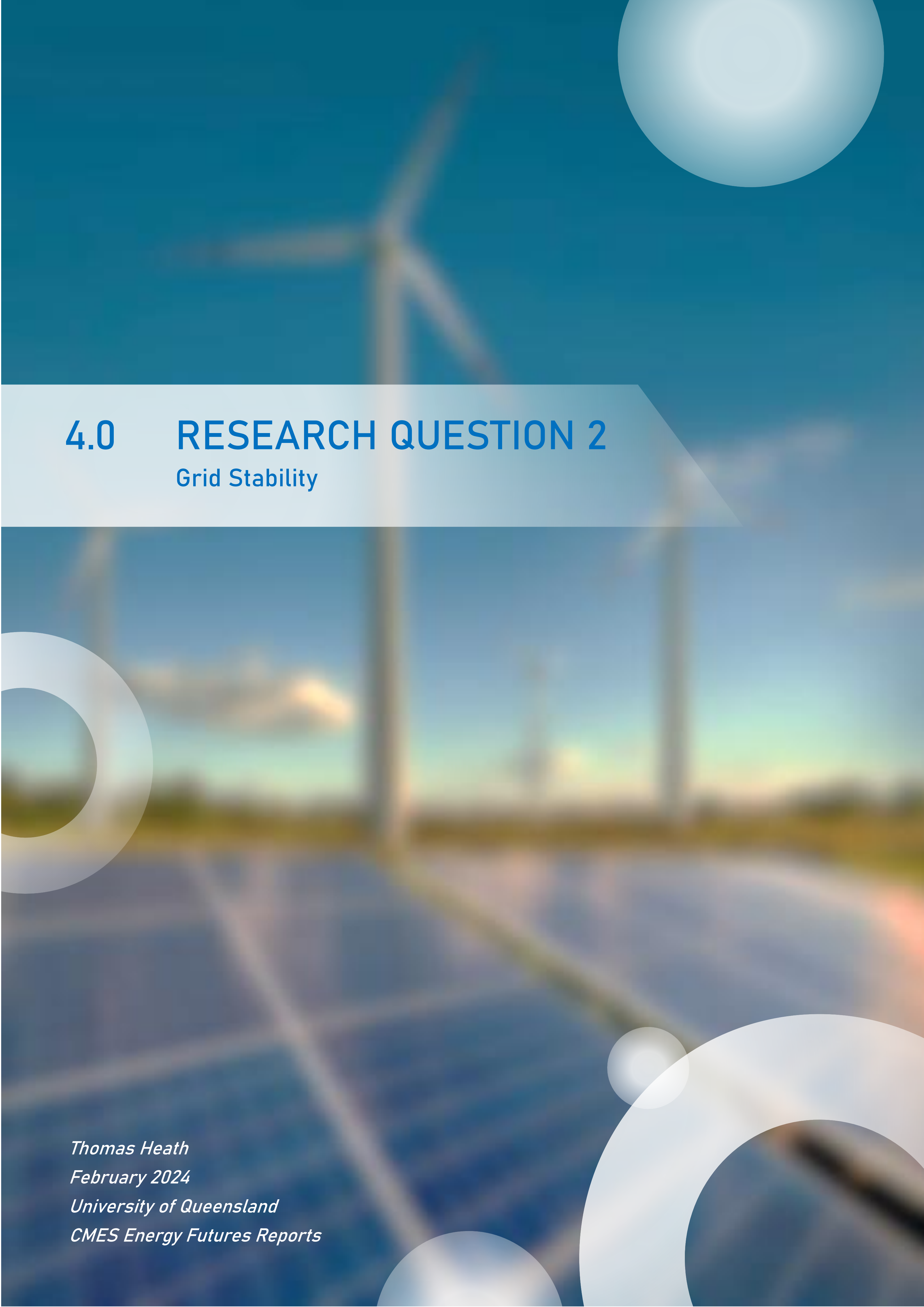
5. Finally, a major limitation of the model developed is the omission of all costing and procurement processes. A separate analysis to determine the effects of markets, policies, and supply chains are all necessary for a holistic analysis of the Queensland energy plan. AEMO has stated that, "*state governments and TNSPs will rightfully have a focus on driving new developments within their regions to ensure the required emission and reliability outcomes for consumers in that jurisdiction at the lowest possible cost*" (AEMO, 2017). There are also broad opportunities at a national level, with improved outcomes possible at an even lower cost. An economic approach to the analysis of energy plan will greatly affect the outcome and development of the new grid system and is thus recommended for a complete review.

3.6 RQ1 Summary

The aim of this first research question was to thoroughly assess the consumption and generation forecasts of Queensland's energy system to gain information regarding the processes, breakdowns, implications, and overall feasibility of operation of the grid from a generation perspective. The scope of this analysis involved a year-by-year breakdown of the consumption (including areas of consumption), and generation (including generation mix) from 2023 to 2040. Data was obtained from over 130 individual sources from various providers, stakeholders, and grid management operators and was corroborated with additional sources such as news articles, and procurement plans where possible. An interactive and dynamic model was developed on Excel that enabled the input of various parameters to assist with the data analysis. The major findings and conclusions have been summarised below:

- Consumption: Queensland's grid electricity consumption is forecasted to increase by 77% over the following 2 decades with the largest increase occurring in the hydrogen industry which contributes to 18% of the total energy consumption in 2040. There is also significant growth in EV and electrification applications.
- Generation: In terms of generation, the current coal-fired average annual generation contribution is expected to decline by 90% by 2040 while the renewable penetration is forecasted to rise from 19% at current, to 89% by 2040. This equates to an overall increase of 55% in average annual generation by 2040. The current installed capacity is approximately 17,000 MW and is expected to increase to over 45,000 MW by 2040.
- Overall Feasibility: Comparisons from the generation and consumption forecasts revealed that there is predicted excess energy generation relative to consumption for the following two decades. The smallest excess of 29% occurs in 2040 while the greatest excess occurs of 90% occurs in 2029. This demonstrates that the proposed facilities will sufficiently meet demand and the generation aspect of the grid is feasible (as of July 2023). While this excess is necessary for grid security and could pose as an incentive for developing hydrogen production technology, there is a notable challenge in terms of management, transmission, and potential energy wastage of this excess. These larger than expected values also raise questions about the accuracy of the data provided.
- Government Actions: The energy generation is primarily provided by individual producers and stakeholders. It is essential that the government regulates the development of generation facilities to not only ensure demand is met, but to mitigate excess energy production which is the main issue identified. This may be done by incentivising the development of energy consumption to reduce excess (e.g., through the hydrogen industry), or through stalling development and declining proposals if the excess is too significant. Proactive and constant analysis of accurate generation data is required. The grid is in early stages of transition and thus this has not yet been observed.
- Data Collection: As discussed throughout this analysis, much of the collected data was highly inconsistent, out-of-date, misleading, and poorly managed. This was mitigated through extensive research but it is evident that the public data is poorly managed.

Overall, from a generation perspective, the energy plan exhibits a positive trajectory toward a sustainably powered grid and reduced emissions. The government, and associated operators and providers, should deliver sufficient grid generation during the energy transition period to meet operational demand. Effective management and control are essential to the development and success of this aspect of the grid. Procurement and costing models should be considered for further analysis.



4.0 RESEARCH QUESTION 2

Grid Stability

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February 2024
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CMES Energy Futures Reports

4.1 Grid Stability Requirements

In an attempt to analyse the stability aspect of the Queensland grid system during the transmission period (Research Question 2), the grid stability requirements and forecasted security considerations were summarised. This was the second step of analysis as a part of the critical analysis of the Queensland Energy Plan.

4.1.1 Grid Stability - Background

AEMO maintains the power system security and ensures the grid operating parameters remain within the required technical limits by constantly balancing the supply and demand of electricity. AEMO accesses real-time data on the status of critical operating components in generation and transmission to control the central dispatch process; this dispatch process operates on 5-minute cycles and includes various forecasts on scheduled and non-scheduled generation. Forecasting information regarding customer demand is factored into the management and the various limitations of the system are constantly reviewed to predict effect and impact of unexpected events. The shift to a less centralised generation mix of largely renewable-based facilitates is introducing many challenges to the maintenance of the grid operational parameters (AEMO, 2023).

These operational parameters include voltage, network flow and frequency management. AEMO manages voltage control by ensuring the power flow through the grid is within the required technical limits; this involves constraining generation in the market, and maintaining a constant voltage profile across the grid. This management is largely dependent on generation and transmission infrastructure and will be explored further in section 6.0, and has thus been excluded from the scope of this section of investigation (AEMO, 2022). The other important parameter is frequency control which will be the primary focus of the stability feasibility assessment.

4.1.2 Grid Stability - Operational Frequency

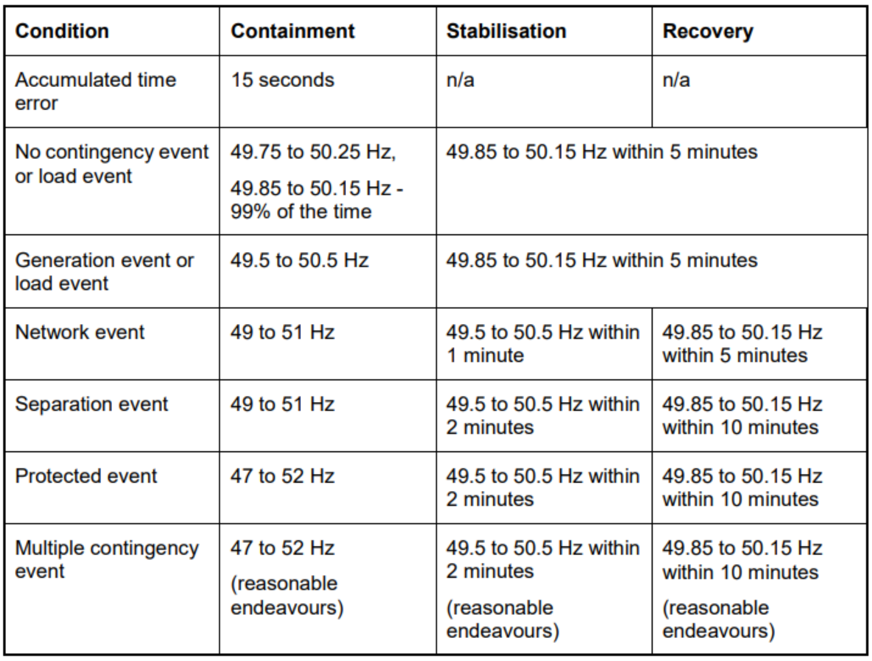
The standard operating frequency of the Australian grid is 50Hz alternating current. All production and transmission facilities are designed to specific standards to accommodate this frequency; likewise, consumption appliances connected to the grid are designed to operate according to this frequency. Thus, variations in this frequency can have detrimental effects on the grid performance, electrical infrastructure, and connected appliances. Risks associated with abnormal operating outside the technical limits of the grid range from disruption of the electricity market, through to disconnection of power facilities, separation of networks, blackouts to segments of the system and, if abnormal operation persists for extended periods of time, potential damage to the plant (AEMC, 2020). Furthermore, the efficiency of the grid will reduce as losses are incurred. This has huge implications involving costs from damages and safety concerns.

Variations in frequency are caused from contingency events which are major events that affect the grid operation and stability. These events include:

- Generation or load event: A generation or load event refers to the strain introduced on grid parameters from a variation in generation or consumption within the power grid. This may include the sudden shutdown of a power facility or a sudden increase in demand in a certain region of the grid.

- Network events: Network events are disruptions within the electricity transmission and distribution network that affects the grid operational parameters. This encompasses equipment failures, line faults, or other issues regarding the physical infrastructure.
- Separation events: A separation event refers to a situation where sections of the power grid become disconnected from each other causing an electrical separation. This typically involves equipment failures from weather events or operational errors.
- Protected events: A protected event is a low likelihood but high consequence non-credible contingency event. Following the occurrence of the event, AEMO must maintain high power system security standards including frequency operating standards.
- Multiple contingency events: These events involve the loss of multiple power system transmission or generation elements. There are schemes in place to deal with these events such as the MARNET scheme.
- Non credible contingency events: AEMO considers these events to have a low probability of occurrence such as busbar contingencies (electrical junction used for carrying and distributing electricity) or multiple transmission element trip. These events will be re-classified depending on likelihood of occurrence based operational environmental factors (such as bushfires or storms).

There are strict regulations and management of the grid to ensure that when these events occur, there is infrastructure and procedures in place to support the grids operation and stabilise the frequency with minimal risk. AEMO procures Frequency Control Ancillary Services (FCAS) from market participants which is historically provided by scheduled synchronous generation. The NEM Mainland frequency operating standards (which applies to the QLD grid) are outlined in the figure below. This applies to any part of the mainland power system during a period of supply scarcity or during load restoration. Note these standards do not apply to island networks; however, for the purpose of this investigation, small self-sustained grids are out of scope (AEMC, 2020).



Condition	**Containment**	**Stabilisation**	**Recovery**
Accumulated time error	15 seconds	n/a	n/a
No contingency event or load event	49.75 to 50.25 Hz, 49.85 to 50.15 Hz - 99% of the time	49.85 to 50.15 Hz within 5 minutes	
Generation event or load event	49.5 to 50.5 Hz	49.85 to 50.15 Hz within 5 minutes	
Network event	49 to 51 Hz	49.5 to 50.5 Hz within 1 minute	49.85 to 50.15 Hz within 5 minutes
Separation event	49 to 51 Hz	49.5 to 50.5 Hz within 2 minutes	49.85 to 50.15 Hz within 10 minutes
Protected event	47 to 52 Hz	49.5 to 50.5 Hz within 2 minutes	49.85 to 50.15 Hz within 10 minutes
Multiple contingency event	47 to 52 Hz (reasonable endeavours)	49.5 to 50.5 Hz within 2 minutes (reasonable endeavours)	49.85 to 50.15 Hz within 10 minutes (reasonable endeavours)

Figure 11: Operational Frequency Requirements for the NEM

This table shows the three stages of response to contingency events and the associated operating frequency levels. The scope of this analysis focuses on the containment window (AEMC, 2020).

It is evident that the standard range of operation for the Australian grid is 50Hz ± 0.15Hz for 99% of the time; frequency variations within 50 Hz ± 0.25 Hz are considered a fluctuation in operations not caused from a contingency event. Furthermore, it is apparent there is a much smaller tolerance in the time permitted for operation at increasingly higher or lower frequencies from the standard 50Hz. The table parameters are explained below:

- The condition refers to the various events that may cause frequency variations and strain on the network. The containment value corresponds to the frequency range that the grid can operate at for 15 seconds after the respective event occurs
- The stabilisation period is the time permitted to stabilise the grid to a certain operating range
- Similarly, the recovery period is the time allowed for the grid to return to the standard operating conditions

There are additional requirements to this table of standard operations such as how often these events or operation within certain bands can occur in a 30-day period. For more information on specific standards (AEMC, 2020). Thus, there are three stages of frequency control to consider: containment, stabilisation, and recovery, each requiring a method of mitigation.

4.2 Grid Stability Scope

The scope of this assessment has been summarised below in Table 9. Note the assumptions are discussed before calculations in section 4.

Table 9: Grid Stability Scope

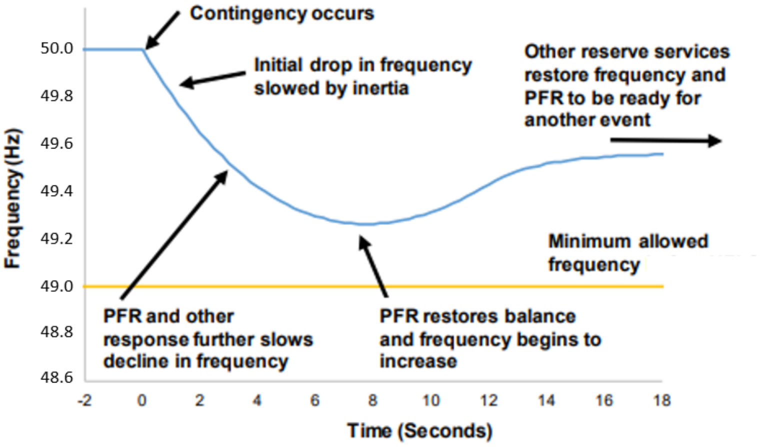
Description	*Justification*
Grid stability refers to the control of various parameters. The scope of this analysis considers only the operational frequency aspect of grid stability.	Although all stability parameters are essential to an operational grid, the operational frequency is the focus of this analysis as it is the parameter that will be most affected by the transition in generation mix. Parameters such as voltage control linked to frequency control and are thus partially addressed in this assessment (AEMO, 2022).
Stabilisation and recovery periods are only briefly discussed as the primary focus is on the containment window.	The primary reason for this focus is because the changing generation mix will not greatly affect the stabilisation and recovery windows. It is well documented that IBR can help manage frequency control beyond the immediate instantaneous response window (containment). Therefore, there will be sufficient resources to supply these windows with support.
The containment window will only focus on the effects of inertia.	Linked to the row above, IBR are not included in the inertial response for the containment window control. Thus, only synchronous based technologies are considered as there is limited practical evidence of IBR supplying system inertia effects.
Small scale island networks not connected to the NEM are out of scope.	These small-scale isolated networks typically rely on back-up generators that can provide support following contingency events. This was considered out of scope as the failure of these networks is not as essential as the NEM, and separate analysis are required for the individual systems.
The scope of the grid stability forecast and analysis extends to 2035	Due to limited forecast data, the grid stability analysis was conducted for the current decade until 2035. Beyond this scope, there is likely large margins of error as technologies change and IBR are tested more for FFR containment.
Similar to RQ1, the costing, procurement, and locational aspects are out of scope for the purpose of this feasibility assessment.	Although these aspects are crucial to a holistic feasibility assessment, this report is applying an engineering analysis to the feasibility which applies to the mechanics of the system rather than assessing the economic and political factors.

4.3 Operational Frequency Containment Control - Relevant Theory

Containment involves the immediate response of the grid within 15 seconds to a frequency disturbance. System inertia, historically provided by synchronous power generation, delivers instantaneous support in this immediate containment window following a contingency event. Inertial response refers to the immediate and inherent electrical power exchange from a device directly connected to the power grid in response to a frequency disturbance. A general frequency containment scenario can be seen in Figure 12 below (NREL, 2020); the initial drop in frequency is slowed by the system inertia before primary frequency response (PFR) mechanisms are implemented.

Figure 12: Containment Window Following Contingency Event

The effects of system inertia can be seen by the slowed rate of change of frequency following the contingency event. (NREL, 2020)



In the NEM, the power system inertia is measured as the combined inertia of synchronous machines on the generation side while any inertial load on the demand side, such as large induction motors, are omitted as their influence on the overall inertia is not well understood. AEMO is declaring inertial shortfalls in QLD over the next five years (AEMO, 2022) and there is now a large focus on the reducing levels of synchronous inertia levels of the grid as they are replaced with inverter-based resources (IBR) which do not contribute the same inertial response; however, inertial response capabilities from advanced inverter technologies are emerging.

4.3.1 Synchronous Inertia Response

Synchronous inertial response is the electromechanical inertial response from stored kinetic energy (KE) in a rotating mass that is directly electro-magnetically coupled to the power system's voltage waveform at 50Hz (AEMO, 2023). This typically involves large coal, gas and hydroelectric turbines that consist of rotating masses (typically of hundreds of tonnes); it also includes synchronous condensers which are machines designed exclusively to provide an inertial response. In an attempt to resist the electromagnetic forces applied on a synchronous machine by the grid during a disturbance, stored KE is exchanged with the power system through a directly proportional reduction in the angular velocity of rotation. Although synchronous inertia is quantified by megawatt-seconds (MWs) or megajoules (MJ) of KE, synchronous machines can be compared by their inertia constant which is the ratio of KE stored at nominal speed to the size of the generator (MVA) and is measured in seconds:

$$H = \frac{\frac{1}{2}J\omega^2}{S} \qquad (5)$$

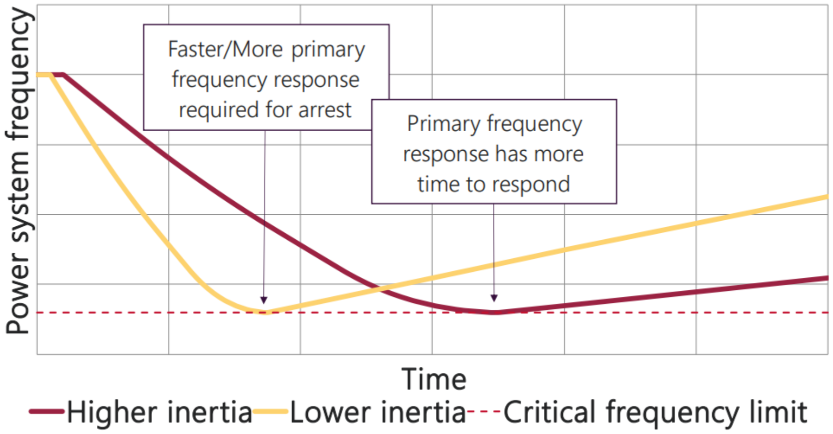
H	Inertia constant (s)
J	Machine inertia $(kg \cdot m^2)$
ω	Angular velocity (rad/s)
S	Generator rating (MVA)

This value is indicative of the duration a machine can inject energy at its rated electrical output (solely from its KE) and is typically around 2-8 seconds meaning synchronous condensers provide an immediate response to frequency changes and can provide this support for typically around 5 seconds from the stored KE.

The power system inertia is closely associated with the system's ability to control the rate of change of frequency (RoCoF). If all factors remain constant, a system that possesses greater inertia will demonstrate a slower initial RoCoF in response to a frequency disturbance. High inertia (slow RoCoF) allows more time for frequency arrest mechanisms to work effectively (but more energy to recover to nominal frequency); however, the same effect can be achieved from a faster and/or greater magnitude of primary frequency response (which poses potential for IBR to form a part of the PFR). The effect of high and low inertia systems is displayed below in Figure 13 (AEMO, 2023).

Figure 13: Effects of High and Low Inertia Systems

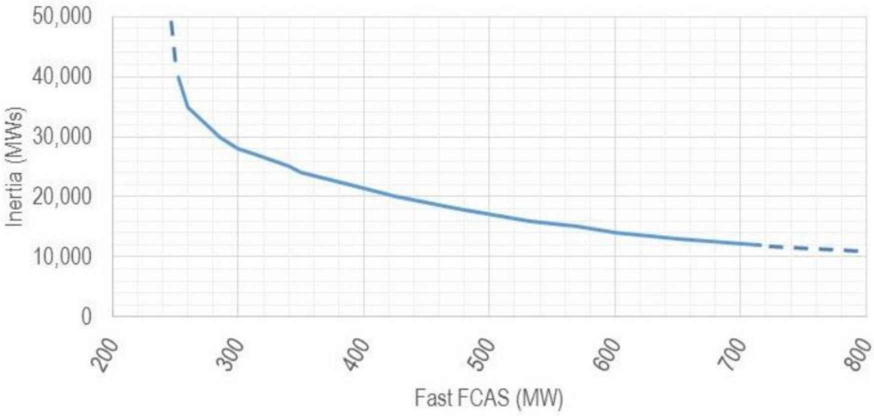
A larger system inertia slows the RoCoF but requires greater energy to restore to standard operation. (AEMO, 2023)



This forms the basis of the NEM frequency control mechanisms including the FCAS and emergency frequency control schemes (EFCS), and introduces the concept of Fast FCAS its relationships with inertia. Ultimately, a power system with high inertia has a lower requirement for the amount of Fast FCAS to maintain within an acceptable frequency following a contingency event; likewise, a power system with low inertia requires a larger amount of Fast FCAS. The exact relationship between these factors is developed from a complex array of factors and variables. AEMO uses a model of the power system inertia sub-network to assess the frequency trajectory following contingency events which can be used to establish this relationship. For a system of fixed demand and contingency size, the relationship between the Fast FCAS requirement and inertia is a typical inverse as below in Figure 14 (AEMO, 2018). It is evident that high levels of inertia correspond to lower levels of required Fast FCAS.

Figure 14: Relationship Between Inertia and Fast FCAS

A system with lower inertia requires a large Fast FCAS response. The inertia shortfalls consider minimal Fast FCAS response (AEMO, 2018).



There are other factors to consider with synchronous technology including:

1. *Location and transmission:* Stabilisation from synchronous support is facilitated through a capable transmission network and thus the network capacity for power transfer is an important consideration especially for large sparce networks such as the NEM. If the frequency disturbance occurs in a region of the network with insufficient capacity to transmit resultant power flows to the remainder of the system, the exceedance of the transfer limit and flow-on effects must be considered. A geographically diverse distribution of power system inertia is thus critical for a stable grid which introduces the concept of islanding.
2. *Rotor angle stability:* Another important consideration is the effect of clustering synchronous machines in a network. Following a disturbance, synchronous inertia sources may proceed to rotate out-of-sync which can amplify frequency oscillation over connecting powerlines causing damage if strengthened damping requirements are neglected.

Synchronous inertia in the renewable based grid will be provided by both purpose-built synchronous condensers (refer Figure 15) and re-purposed synchronous generation facilities (refer Figure 16). The re-purposing of generation facilities into synchronous condensers involves the utilisation of existing generators by maintaining their electro-mechanical coupling with the grid, often with the addition of a flywheel for additional inertia. Some plants will remain in use for energy production during this conversion with the option of disconnecting from generation via a modified clutch to provide exclusively inertia control. The conversion depends on various factors including:

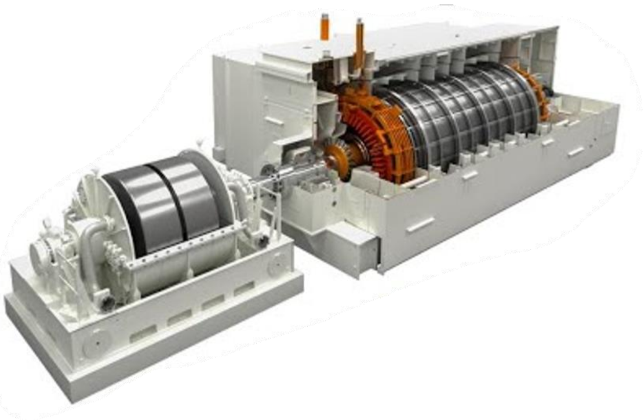
- The types of generators and their compatibilities including the structural foundations and mechanical integrity (fatigue and structural assessments are required)
- Availability of space in facilities including the room between the turbine, generator, and grid connection. The installed components are unique for each scenario (refer Figure 16).
- Cooling and lubrication systems configurations as there is energy loss (converted into heat)
- Starting options such as the requirements of a small starter pony motor
- Commercial terms and conditions according to asset owners.

This is a separate analysis but refer to the DigSILENT report for further reading (DigSILENT, 2023). There have been some proposals for projects involving the conversion of decommissioned coal turbines into synchronous condensers in the short term; however, most facilities have unconfirmed schedules.

The withdrawal of synchronous technology cannot be looked at from an inertial perspective alone as these forms of power sources have various effects on the general power system that cannot easily be differentiated or considered independently (AEMO, 2023). AEMO thus "*considers it prudent*" to ideally maintain substantial levels of synchronous inertia for stability during this transition; however as previously outlined, for the purpose of this analysis, the scope has been refined to exclusively the operational frequency control through inertial response.

Figure 15: Diagram of a Purpose-Built Synchronous Condenser

The synchronous condenser generator (right component) and fly wheel (left component) are evident in this schematic. (EWOA, 2022)



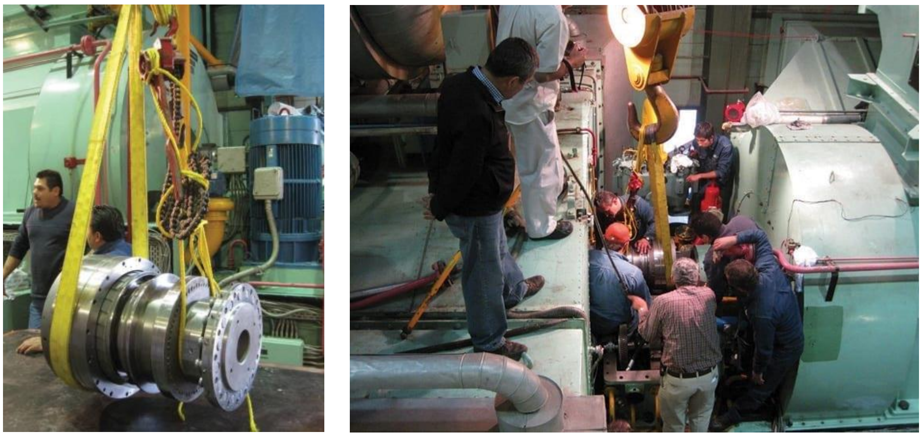


Figure 16: Repurposing of Coal-Fired Steam Turbine into a Synchronous Condenser

The installed clutch used between the turbine and generator is seen in the left image. The installation process and minimal space available is displayed in the right image (POWER, 2020).

4.3.2 Synthetic Inertia Response

A synthetic inertial response involves the emulated response from an IBR that is sufficiently fast and large enough to be purposefully initiated in response to a frequency disturbance to manage RoCoF. These are often referred to as fast frequency response (FRR) providers. This technology is interfaced with the power system through an inverter and do not have rotating mass and thus do not possess synchronous inertia; however, they can provide an emulated response through "*appropriate design of inverter controls*" (AEMO, 2023). An example an emerging IBR technology with frequency control capabilities is the energy storage solution called SEA-Power (SEAP). SEAP is a patented lithium battery power storage and management technology system that responds within milliseconds to frequency fluctuations by releasing or absorbing power from the electricity grid and the solar farm (PT, 2021). This synthetic inertia response is largely untested but AEMO recommends the implementation of this response in the new grid and is an important area of innovation in the future.

A substantial source of energy buffer and power headroom is required to facilitate this synthetic response. This can be achieved from a sufficiently high output capacity storage fleet, or from the curtailed output of generation facilities where possible (this is only applicable when there are sufficient resources for energy production) (AEMO, 2023). Note that wind turbines are typically a synthetic source of inertia as although they consist of rotating components with substantial stored KE in turbine blades, due to the variable nature of wind, many wind turbine facilities are fully inverter-based and are not directly electro-magnetically coupled to the grid. This also applies to variable speed drive hydro units that are inverter interfaced to the electrical network.

It is important to also note that IBR typically have their output current limited to significantly lower levels than what synchronous facilities can provide which limits the synthetic inertial response when the inverter is operating near capacity. Thus, the inertia capacity of these non-synchronous technologies depends on their current operating points. This is difficult to manage and it may be necessary to implement backup storage facilities with unloaded inverters. Furthermore, IBR do not have fixed inertia constants comparable to traditional facilities which makes comparisons, modelling, and implementation harder.

In summary, the combination of the limited understanding of the effects of synthetic inertial responses, as well as the lack of a standardised approach to the implementation and quantification of their responses, increases the difficulty and risk of reliance on these technologies. Therefore, it is likely that the RoCoF in the NEM will be managed by a combination of electro-mechanical and synthetic inertial responses.

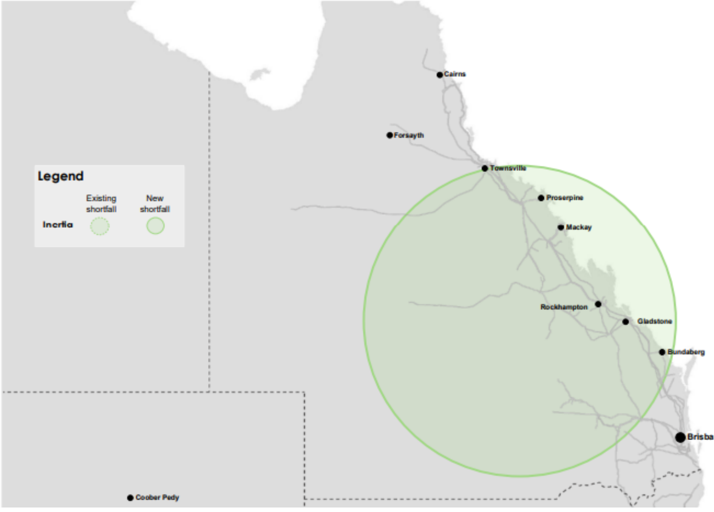
4.4 Grid Inertia Decline

4.4.1 Grid Inertia Decline - Overview

Ultimately, there is a decrease in synchronous based generation and an increased IBR penetration in the NEM; in Queensland, the rate of utility scale IBR installation is the greatest it has ever been and is still expected to rise (AEMO, 2022). Step Change modelling completed for the 2022 Integrated System Plan (ISP) suggests that 14 gigawatts (GW) of synchronous generation resources will withdraw from the NEM by 2030 (AEMO, 2022). According to section 3.2, there is an expected withdrawal of approximately 700 MW of synchronous powered generation in Queensland.

Figure 17: A Map of the NEM Showing the Current and Forecasted Inertia Shortfalls in Queensland

This map provides a qualitative insight into the regions of inertia deficits. This is primarily due to the decommissioning of synchronous based generation such as coal facilities (AEMO, 2022).



As outlined in the theory above, the combination of inertial responses includes existing synchronous generation, synchronous condensers, synthetic inertial responses. AEMO is facilitating the procurement of these plants by establishing an FCAS markets which is expected to be introduced in late 2023. There are various other ongoing regulatory reforms affecting progression. The impact of FFR providers has not been studied in detail for regions outside of South Australia.

4.4.2 Grid Inertia Decline - Model

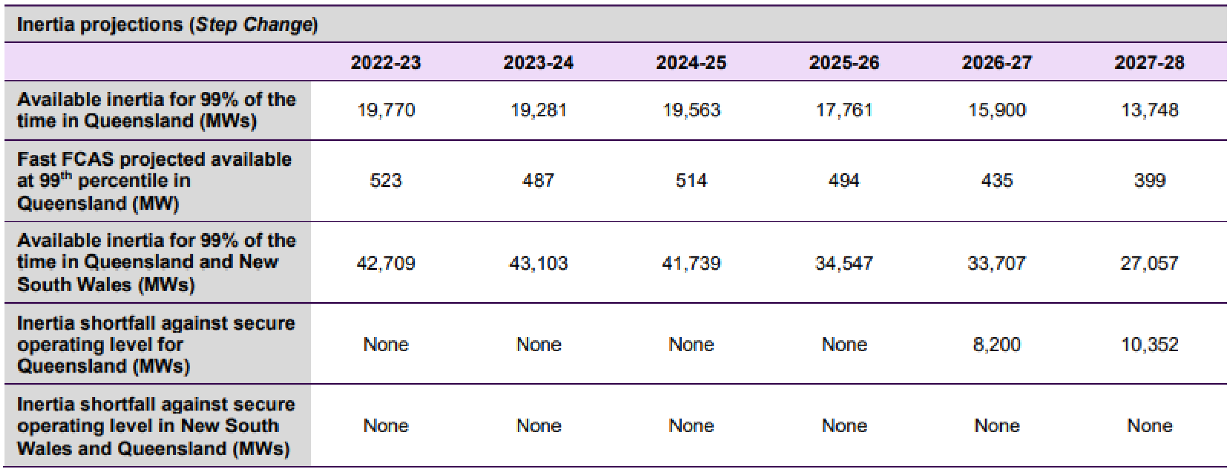
Initially, formulating a model of the state's available inertia was considered which required the compilation and analysis of a range of data. This would involve a complex model considering the inertial contributions of all production units in active synchronous generation facilities across Queensland. Furthermore, it would require the inclusion of re-purposed coal facility synchronous condensers which necessitates an in-depth analysis of the timelines of various projects including specific data. Due to the potential complexity of this model, this method was deemed impractical for this feasibility assessment.

An alternate approach involved analysing the forecasted data provided by AEMO for Queensland's inertial overview for the current decade. Although this approach is not as thorough as an entirely separate model (due to the reliance on the transparency and accuracy of AEMO's results), this method was deemed sufficient for the stability analysis of this report. Following this, the inertia contributions from an average purpose-built synchronous condenser and repurposed synchronous condenser were calculated. Then, from the collated information, the number of synchronous condenser units was calculated. Overall, this method is a simplistic approach to obtain a valuable insight into the inertia requirements of the grid.

4.4.3 Grid Inertia Decline - Data Collection

According to the 2022 inertia report published by AEMO, the secure inertial operating levels in Queensland over the following 5 years is predicted to be in the range of [24100MWs at 390MW Fast FCAS] to [16,600MWs at 455MW Fast FCAS] (AEMO, 2022). It is interesting to note that this required inertial operating level remains constant from 2021 to 2028 despite the expected increase in total electricity generation (as evident from the generation analysis in section 3.2.7) which introduces doubt regarding AEMO's proposed requirements.

The available inertia in the Queensland grid was supplied in the inertia report for the coming years until 2028, beyond which a regression was applied (refer below). The corresponding inertial shortfalls are also provided below in Figure 18 (AEMO, 2022).



Inertia projections (*Step Change*)						
	2022-23	**2023-24**	**2024-25**	**2025-26**	**2026-27**	**2027-28**
Available inertia for 99% of the time in Queensland (MWs)	19,770	19,281	19,563	17,761	15,900	13,748
Fast FCAS projected available at 99th percentile in Queensland (MW)	523	487	514	494	435	399
Available inertia for 99% of the time in Queensland and New South Wales (MWs)	42,709	43,103	41,739	34,547	33,707	27,057
Inertia shortfall against secure operating level for Queensland (MWs)	None	None	None	None	8,200	10,352
Inertia shortfall against secure operating level in New South Wales and Queensland (MWs)	None	None	None	None	None	None

Figure 18: Inertia Shortfalls in Queensland (and NSW) until 2028 According to AEMO

This table provides the data that forms the basis of the inertia shortfall forecasts. Although this data was not obtained from a separate model or analysis, for simplicity, this data was deemed sufficient (AEMO, 2022).

It is evident that the shortfall ranges from 8,200 MWs against the secure operating level in 1 July 2026 to 10,352 MWs from 1 July 2027. There were contradictions with these values with other sources such as the DigSILENT Report on repurposing existing generators as existing synchronous condensers which stated there was no shortfall in 2026 but an identical shortfall to the value above in 2027 which further increases the uncertainty regarding results (DigSILENT, 2023).

It is evident that there is little correlation between the decreases in inertia and the decommissioning of synchronous production as the system inertia decreases do not align with the withdrawals of any synchronous facilities (refer Graph 4); likewise, the magnitude of inertial decreases has little explanation. It was not specified whether re-purposed generators or purpose-built synchronous condenser facilities were factored into AEMO's data (there was no mention of these inclusions in the respective reports). Figure 19 is a plot of this data with the Inertia/Fast FCAS relationship curve to visually highlight the inertia shortfall from 1 July 2026 (AEMO, 2022).

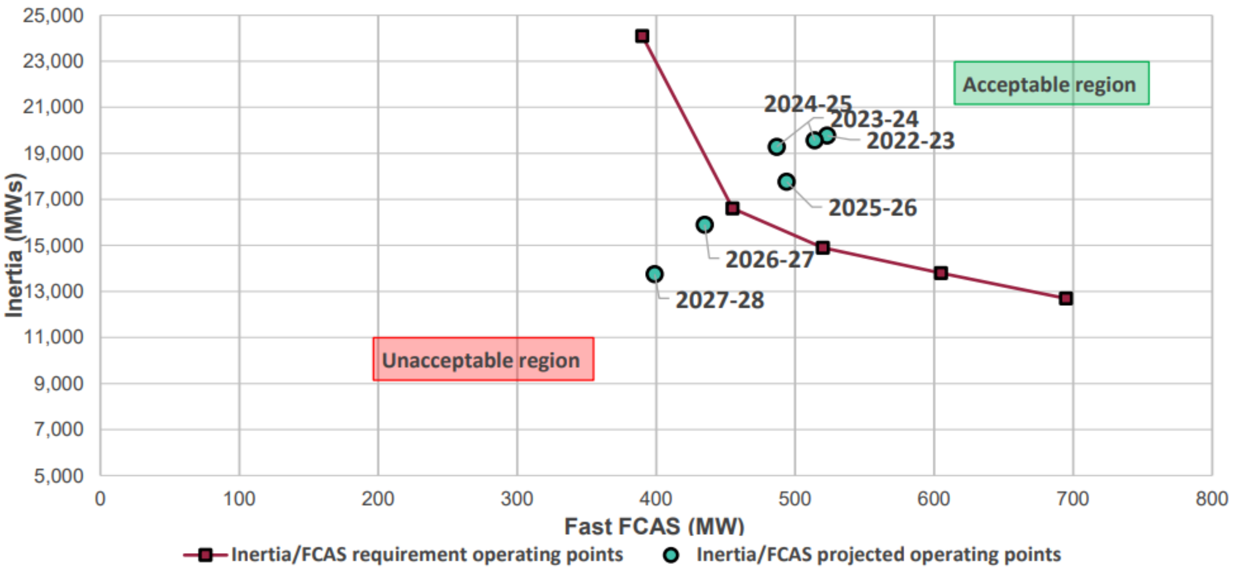
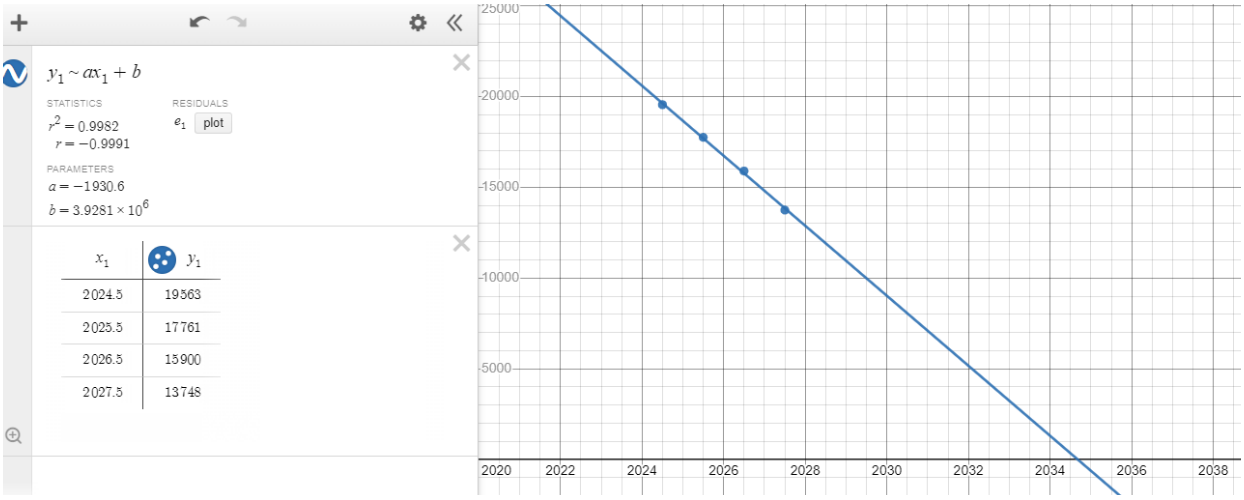


Figure 19: Plot of Secure Operating Levels of Inertia until 2028 with the Fast FCAS Curve

This is a plot of the corresponding data from Figure 15 and applies to the 99th percentile of operation standards (AEMO, 2022).

It is important to note the magnitude of the inertial shortfall is not the inertia deficit between the respective data point and the Inertia/Fast FCAS relationship curve, rather, it is the inertia deficit to the upper range threshold limit (24,100 MWs). This overestimates the inertia shortfalls as the values will be less in reality if there is greater Fast FCAS response; however, this maintains consistency with the CA. The decline in the supplied grid inertia levels was relatively linear and a regression analysis was run from the 2025 data onwards to provide a prediction on future shortfalls. As evident in Graph 11, the relationship was linear with an R^2 value 0.998 (Desmos, 2023).

Graph 11: Regression Plot of Inertia Shortfalls Using AEMO Data



$y_1 \sim ax_1 + b$

STATISTICS

$r^2 = 0.9982$

$r = -0.9991$

RESIDUALS

e_1 plot

PARAMETERS

$a = -1930.6$

$b = 3.9281 \times 10^6$

x_1	y_1
2024.5	19563
2025.5	17761
2026.5	15900
2027.5	13748

From this regression, and assuming this declining relationship supplied by AEMO is continued beyond the supplied data for 2027, it is predicted that there is negligible remaining grid inertia by 1 July 2034. This demonstrates that there is a steady decline in grid inertia levels that again does not correspond with withdrawals of synchronous generation. Applying the previous assumption of excluding IBR from the containment window inertia control, this deficit must be accounted for through the implementation of synchronous inertia from both repurposed coal plants and purpose-built synchronous condensers.

AEMO provides a forecast of the decommissioning of coal plants and associated conversion to synchronous condensers as seen in Figure 20 (QLD Gov, 2022). This is an unconfirmed forecast as many facilities have not specified plans for conversion. Note this figure is inherently inaccurate due a number of contradicting observations with the generation analysis in terms of dates and magnitudes of withdrawals (refer section 3.2.3); however, this figure does loosely agree with the regression analysis in Graph 11 in terms of the linear decline of system inertia to 2034 - 2035 assuming that the decommissioning facilities have a similar contribution to system inertia response.

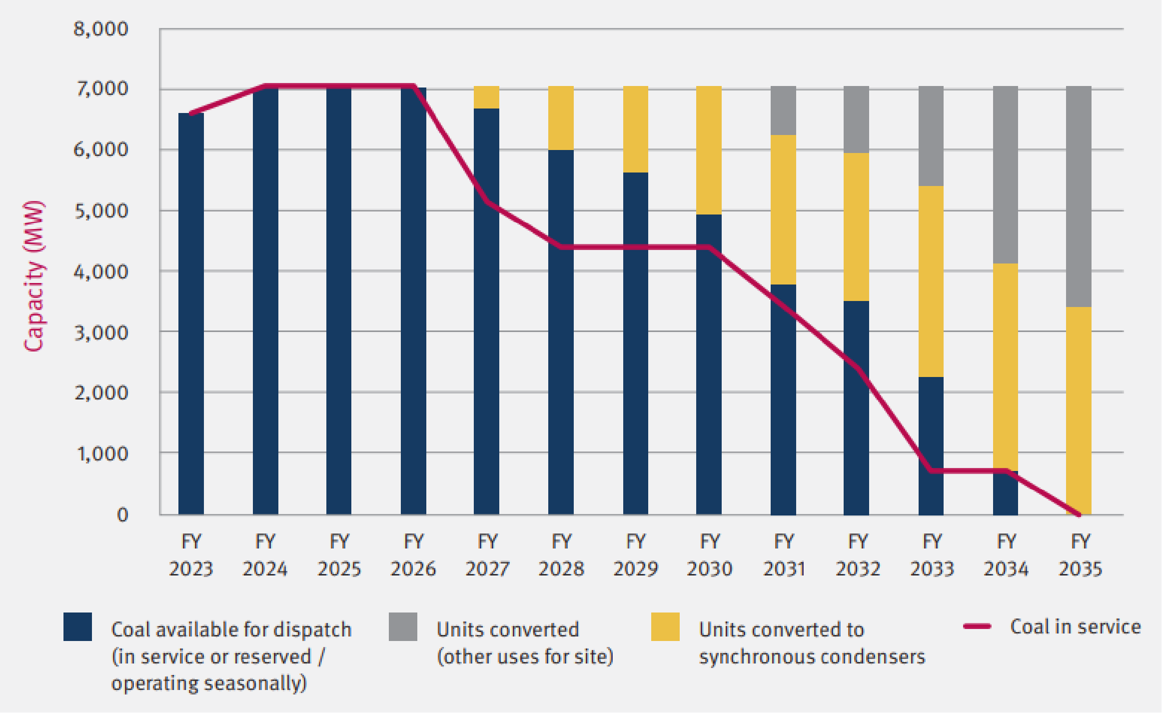


Figure 20: Plot of Coal Generation Decline Conversion of Turbines to Synchronous Condensers

The government believe that coal repurposing is a secondary consideration to energy security and depends on the timing of PHES assets. MW capacities on the vertical axis refers to nameplate capacity (QLD Gov, 2022).

Despite the lack of confirmation from online sources, AEMO has assumed in this forecast that nearly half of the generators, in terms of nameplate capacity, will be converted into synchronous condensers. This does not provide the contribution of these facilities to the containment frequency response as although a generator's power production may be high, the stability response is a function of the stored KE in the generator and possible flywheel (refer section 4.3.1). Thus, although it is evident that this analysis is not thorough, an approximation can be formed on the number of required repurposed generation facilities and purpose-built synchronous condensers.

4.5 Grid Inertia Forecasted Requirements

4.5.1 Purpose-Built Synchronous Condenser Contribution

At present, there are no purpose-built synchronous condensers; however, Powerlink have a number of planned facilities with one currently under construction. A standard purpose-built small scale synchronous condenser facility has the following approximate specifications outline in Table 10. These figures were selected based on a range of data from Powerlink, Andritz and DigSILENT and are in the lower range of specs to maintain consistency with the CA (Powerlink, 2021) (DigSILENT, 2023) (Andritz, 2023):

Table 10: Standard Purpose-Built Synchronous Condenser Specifications

Specification	*Symbol*	*Value*	*Unit*
Generator rating	S	200	MVA
Time constant of generator	H_g	2	s
Time constant of flywheel	H_w	4	s
Time constant of generator and flywheel	H_{g+w}	6	s

Assuming the use of this standard size synchronous condenser with a flywheel to produce an equivalent inertia time constant of $6s$, the inertial contribution of this plant is given by:

$$200MVA \times 6s = 1200MWs$$

∴ Each purpose-built synchronous condenser produces 1,200 MWs of inertia.

4.5.2 Repurposed Synchronous Condenser Contribution

As previously discussed, there is limited data regarding the re-purposing of the Queensland synchronous generation facilities into synchronous condensers. It is important to note that the majority of generation units in Queensland's coal facilities are similar in design and thus share similar properties as seen below in Table 11. The decommission date data is obtained from section 3.0.

Note the nameplate capacity is often larger than the cumulative contributions of the generation units as this is the advertised capacity. It is evident that there are a total of 22 generation units across the state including:

- 10 units of standard steam turbines with capacities of approximately 350 MW at Callide B, Stanwell and Tarong power stations.
- 6 units of smaller turbogenerator turbines with capacities of approximately 280 MW all at the Gladstone power station.
- 5 units of advanced cycle steam turbines with capacities of approximately 400 MW at Callide C, Millmerran, and Tarong North power stations
- 1 unit of a larger scale boiler turbine with a capacity of 750MW at Kogan Creek power station

Table 11: Summary of Queensland Coal Generation Units

Facility Name	*Nameplate Output Capacity*	*Number of Generation Units*	*Capacity of Individual Generation Units*	*Type of Generation Unit*	*Source*	*Decommission Date*
Callide B	700	2	350	Hitachi Standard steam turbines	(CSE, 2022)	2028
Callide C	825	2	405	Toshiba Advanced Cycle Steam Turbines	(CSE, 2022)	-
Gladstone	1680	6	280	Turbogenerator Steam Turbines	(NRG, 2022)	2035
Kogan Creek	744	1	750	Boiler Turbine Generator unit	(CSE, 2022)	2042
Millmerran	850	2	425	Advanced Cycle Steam Turbines	(Wilcox, 2023)	2051
Stanwell	1460	4	350	Standard Steam Turbines	(Stanwell, 2023)	2046
Tarong	1400	4	350	Standard Steam Turbines	(Stanwell, 2023)	2036
Tarong North	443	1	443	Advanced Cycle Steam Turbines	(Stanwell, 2023)	2037

Assuming similar property generators are used for like generating units, there are three primary categories of possible re-purposed synchronous condensers (excluding Kogan Creek). As such, the specifications for a standard plant were based on the Tarong power plant generation fleet as there are the greatest number of units in this category - 10 units in total amounting to 3,560 MW of nameplate generation capacity. The specifications for these units are outlined below in Table 12.

Table 12: Standard Re-Purposed Synchronous Condenser Specifications

Specification	*Symbol*	*Value*	*Unit*
Generator rating	S	615	MVA
Time constant of generator	H_g	1	s
Time constant of generator and turbine shaft	H_{g+t}	2.82	s
Time constant of turbine shaft	H_t	1.82	s
Time constant of de-bladed turbine shaft	H_{dt}	1.274	s
Time constant of de-bladed turbine shaft and generator	H_{g+dt}	2.274	s

As specified in the assumptions, the time constant of the generator alone is typically around one third of the combined generator and turbine and de-blading reduces the inertia of the turbine system by approximately 30% (DigSILENT, 2023). Thus, according to the time constant equation in section 4.3.1, the time constant of the de-bladed system reduces by this factor of 0.3 (assuming a constant rotational speed and generator rating). This is a relatively small unit in terms of its inertia constant which can range up to 6 - 8 seconds for larger bladed systems or 4 seconds for larger generators (DigSILENT, 2023); however, this underestimation maintains consistency with the CA. Assuming the re-purposed facility uses the de-bladed turbine configuration, the inertia provided by the new unit is given by:

$$615MVA \times 2.274s = 1398.5MWs \approx 1400MWs$$

$\therefore$ Each repurposed synchronous condenser produces 1,400 MWs of inertia.

It is also important to note that generators have a typical loss factor of 1-2% due to electrical losses and windage; for example, a power system of 700MVA will withdraw 7-14MW in losses. This necessitates the need for cooling systems to dissipate generated heat and possible energy supply considerations.

4.5.3 Synchronous Condenser Predictions

The model used to obtain a prediction on the number of required synchronous condensers is discussed below. SC refers to a purpose-built synchronous condensers and RSC refers to repurposed synchronous condensers from coal facilities. In general, the model involves a year-by-year forecast consisting of the inertia deficit (either obtained from data or predicted), and the number of SC and RSC required to stabilise this deficit. The calculations are based on a very specific scenario and is for a general reference. The assumptions and metho is outlined below in Table 13.

Table 13: Synchronous Condenser Prediction Model

Process	*Method, Assumptions and Justification*
Yearly predicted inertia shortfall values	The inertia shortfall predictions beyond the supplied 2027 - 2028 data were obtained from the regression analysis in Appendix 9 assuming the linear trend of declining inertia is maintained and that the net inertial requirement of 24100MWs remains constant. The linear trend is a valid assumption as multiple sources indicate this linear decline (refer Figure 18 and 19). The validity of the assumption that the maximum inertial requirement will remain constant beyond the provided data for 2028 is unknown; the inertial requirement may increase due to an increased generation production in the grid or may be maintained by inertial effects from an increase in IBR on the grid. For the purpose of this general prediction, these assumptions are valid.
SC and RSC specifications	Standard SC specifications were used according to various SC facility providers (refer section 4.5.1). These values reflected a medium-sized SC with a flywheel which is a valid assumption for this general prediction. Likewise, the RSC specifications were based off values from the Tarong Power Station generation units. This was justified in section 4.5.2 as a large number of power stations across QLD have similar generation units and this was the most common size of unit. This includes assumptions used in section 4.5.2 regarding the de-blading reduction in inertia and the proportion of the generator time constant. Both of the SC and RSC units being considered are of intermediate size. These generalised assumptions are deemed valid for this prediction model.

Operational dates of RSC in short term (before 2028).	In regards to the short-term outlook, there is only one scheduled decommissioning before 2030 (Callide B in 2028); it is therefore unlikely that there will be any operational RSC facilities before this time. This is validated by research suggesting that there have been no confirmed plans for commencing the repurposing facilities in Queensland until 2027 (QLD Gov, 2022); furthermore, according to DigSILENT, there is an anticipated lead-time of 30 months for delivery and installation which will likely increase in the future as the backorder list grows (Stanwell, 2023).
Operational dates of RSC in long term (beyond 2028).	Before the closure of Callide B in 2028, it is assumed all inertia shortfall is provided by installed SC, and then beyond 2028 RSC become optional. This required the assumption that RSC conversion occurs before the closure of facilities beyond 2029. This would require a special conversion with clutch mechanisms to allow the facility to switch between energy production (generation) and synchronous condenser (stability) modes. Specifically, this would require at least 1 unit from the Stanwell or Tarong plants to commence synchronous operation beyond 2029 assuming both units at Callide B are converted to RSC.
Predicted numbers of RSC in the long-term	As previously discussed, approximately half of the units (in terms of nameplate capacities) are predicted to be converted to synchronous condensers. If the 10 similar generator units from Callide B, Stanwell and Tarong are converted, this amounts to 3506MW of the cumulative 8100MW nameplate capacity of Queensland's coal fleet (44%). This entails various assumptions such as all of these units are compatible for conversion and can begin conversion before their decommission dates. Alternately, other units from different plants may be converted or more SC are required.

Based on these assumptions and methodology, the following calculations determine the number of SC and RSC facilities to maintain stability in the QLD grid. Due to the specific assumptions outlined, this model only provides an estimate for general reference and comparisons.

Table 14: Short-Term Synchronous Condenser Requirements

Time Period (1 July of year)	*Inertia Shortfall (MWs)*	*SC Calculation (1 SC = 1200 MWs)*	*Number of SC*	*RSC Calculation (1 RSC = 1400 MWs)*	*Number of RSC*
Before 2026	-	-	0	-	0
2026 - 2027	8200	$\frac{8200}{1200} = 6.8$	7	-	0
2027 - 2028	10352	$\frac{10352}{1200} = 8.6$	9	-	0
2028 - 2029	12184	-	9	$\frac{12184-(1200\times9)}{1400} = 0.99$	1
2029 - 2030	14114	-	9	$\frac{14114-(1200\times9)}{1400} = 2.4$	3
2030 - 2031	16045	-	9	$\frac{12184-(1200\times9)}{1400} = 3.7$	4
2031 - 2032	17975	-	9	$\frac{12184-(1200\times9)}{1400} = 5.1$	6
2032 - 2033	19906	-	9	$\frac{12184-(1200\times9)}{1400} = 6.5$	7
2033 - 2034	21837	-	9	$\frac{12184-(1200\times9)}{1400} = 7.9$	8
2034 - 2035	23767	-	9	$\frac{12184-(1200\times9)}{1400} = 9.3$	10
Beyond 2035	24100	-	9	$\frac{12184-(1200\times9)}{1400} = 9.5$	10

As previously discussed, these calculations are an overestimation of the number of required units as the shortfall quantity is based on the inertia deficit to the upper range threshold limit (24,100 MWs). Furthermore, the long-term inertia shortfall is likely much less than 24,100 MWs due to possible inertial effects from IBR. As a result, the short-term results are more meaningful.

Although the above year-by-year scenario is ideal considering existing resources, in attempt to broaden the analysis a range of scenarios have been provided below in Table 15 for possible long-term SC and RSC configurations. The year-by-year development of these scenarios has not been considered and these results serve as reference values for general analysis.

Table 15: Possible Long-Term SC and RSC Configurations (Beyond 2035)

Number of SC	*Number of RSC*
9	10
12	7
15	5
17	3
20	0

Note, the minimum number of SC (of the specified size) required for installation is 9 as RSC will not have commenced construction before 2027. It is evident that as a general figure, there are approximately 20 total synchronous condenser units required in Queensland in the long-term to supply the grid with operational frequency control.

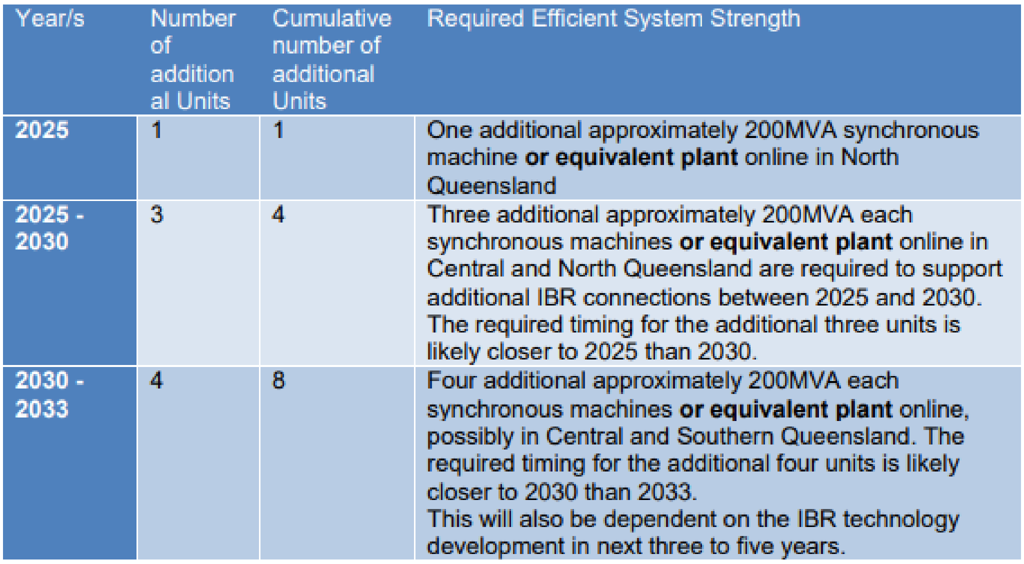
4.6 RQ2 Discussion

The approach to managing the stability of the Queensland energy grid system is changing dramatically during the energy transition period to of the emerging renewable-based grid. AEMO has stated that "*significant industry effort is needed to deliver system strength*" and there have been recent reforms and re-structuring of systems to facilitate a new approach (AEMO, 2021). In 2022, following stakeholder feedback suggesting that, "*addressing missing system services cannot wait until 2025*", the AEMC consulted on rule change requests concerning the valuing, procuring, and scheduling of system security services (AEMC, 2022). Following the publication of new rules in the National Electricity Rules, AEMO amended the market ancillary service specification to accommodate two new markets for very fast frequency control ancillary services (very fast FCAS). From the analysis in the above sections, it is crucial these reforms have taken place as inertia shortfalls are predicted from 2026 onwards, and it requires 30 months (nearly 3 years) for the construction of SC facilities. In order to avoid future system failures, it is evident that this issue must be given immediate attention. This has been addressed by AEMO as evident in their statement, "*planning for provision of system strength services across the NEM will be one of the highest priority matters in the Australian electricity sector for the next few years. AEMO looks forward to working with SSSPs and other industry stakeholders on this matter to ensure power system security in the NEM*" (AEMO, 2022).

Ultimately, AEMO is shifting stability management to new ancillary service markets opening in October 2023; a detailed description of each kind of market ancillary service can be referred to in AEMO's Market Ancillary Service Specification document effective 9 October 2023. This involves the development of an inertia spot market for applicants to provide stability services for the grid and AEMO has stated that it will, "*allow for the market to evolve as it matures*" (AEMO, 2021). The outcomes of this method are relatively unknown due to the nature of this emerging approach; the profitability and interest of stakeholders in this market is also largely unknown.

In terms of inertia support, AEMO has specifically requested that, "*Powerlink make inertia network activities (or inertia support services) available to address an inertia shortfall in Queensland, against the secure operating level, ranging from 8,200 to 10,352MWs*" (Powerlink, 2021). AEMO has requested that the services are made available from 1 July 2026 until at least 30 June 2028 which corresponds to previous analysis. In terms of RSC, conversion of 1 or more units is expected commence from 2027 which was considered in the analysis above. Note if conversion does not commence until later, more SC will be required (refer Table 15).

In terms of scheduled SC there are no facilities yet available, but there is one under construction in north Queensland. As evident in Figure 21, there 8 units planned for implementation over the next decade until 2033, with 1 unit in operation by 2025, 4 units by 2030, and 8 units by 2033. These units are rated at 200MVA (which was the value used in the calculations).



Year/s	Number of additional Units	Cumulative number of additional Units	Required Efficient System Strength
2025	1	1	One additional approximately 200MVA synchronous machine **or equivalent plant** online in North Queensland
2025 - 2030	3	4	Three additional approximately 200MVA each synchronous machines **or equivalent plant** online in Central and North Queensland are required to support additional IBR connections between 2025 and 2030. The required timing for the additional three units is likely closer to 2025 than 2030.
2030 - 2033	4	8	Four additional approximately 200MVA each synchronous machines **or equivalent plant** online, possibly in Central and Southern Queensland. The required timing for the additional four units is likely closer to 2030 than 2033. This will also be dependent on the IBR technology development in next three to five years.

Figure 21: Synchronous Condenser Units in Queensland Provided by Powerlink

This table outlines the forecasted implementation of purpose-built synchronous condenser units in Queensland provided by Powerlink (Powerlink, 2023).

It is evident from comparison with Table 15, these units will not suffice the inertial shortfall requirements; however, as previously discussed, the calculations were an overestimation as they used the shortfall to the higher range requirement and assumed a linear decline according to the regression. In reality, if this decline is not linear and if there is significant Fast FCAS response, the number of units required will be significantly less. It can thus be stated that the immediate short-term requirements have been considered by AEMO and are likely managed depending on Powerlink's analysis; however, this cannot be concluded without further modelling and assessment. In terms of stability requirements for the entire NEM (QLD, NSW, VIC, SA, ACT, TAS) under a 100% renewables scenario, AEMO has specified the requirement of, "*the equivalent of up to 40 new synchronous condensers to meet system strength requirements*" (AEMO, 2022). It is also interesting to note that SA has a number of synchronous condensers already built following system failures in the previous decade.

Finally, although the stabilisation and recovery windows have been considered out of scope for this report, a general assessment can be made. These periods require frequency support following the containment of the contingency event (which was provided by the inertial response). In the future renewable-based grid, new storage facilities (and existing gas plants) will provide a pivotal role in this support as renewable generation cannot provide reliable support (due to the reliance on environmental conditions). BESS can respond within a fraction of a second which is faster than any other energy storage or generation technologies (Aus Gov: AREA, 2023). This makes this technology ideal for short term reliability services in the PFR (NREL, 2019).

Standard PHES facilities can ramp up from 50% to 100% capacity in about 15 seconds, or from 0% to 100% capacity within less than two minutes (EERA, 2019). This varies depending on facility, for example, the South Australian Cultana PHES facility can provide, "*black start capability and a significant contribution to inertia as a synchronous generator, and fast system response capable of responding to major load and generation imbalances including in the 60 second and 5-minute FCAS markets*" (Aus Gov: AREA, 2017). Open-cycle gas turbine facilities provide a slightly fast response than these PHES plants but are more expensive at fast start generation (AEMO, 2020).

It can therefore be concluded that stabilisation and recovery periods in the new renewable based grid can be supported through the careful management of BESS, PHES and gas-powered facilities managed. The availability of these resources over the following two decades, the installed locations, and respective transmission capabilities all influence the PFR and recovery responses of these technologies and would require a separate analysis.

4.6.1 RQ2 Sensitivity Analysis

The data for the inertia shortfall forecasts was obtained directly from AEMO. The applied regression was linear which was deemed reasonable based on the data provided. It is important to note that the data provided by AEMO is still susceptible to uncertainties and a closer inspection of their model is worthwhile but is considered out of scope for this sensitivity analysis. The assumed baseline (values used in the results) and proposed variance (range of values possible) for each parameter has been provided in the table; recall all parameters in the results were selected based on the most probable sized unit. A qualitative explanation of the sensitivity of each variable and effect on results was provided by conducting an OAT analysis. Note the quantitative effects of each variable in green can be easily assessed by using the Excel model provided (refer 'Stability' sheet) and manually changing these inputs (also coloured green in the Excel document).

Despite the presence of these variances, the model developed is highly robust and has justified the use of the selected variables through extensive research. Therefore, although the results cannot be used with high certainty, they serve as a reliable prediction from which overarching comparisons and conclusions can be made.

Table 16: RQ2 Sensitivity Analysis

Variable or Parameter	*Assumed Baseline*	*Proposed Variance*	*Sensitivity and Effect on Results*
Generator ratings	The generator ratings for the SC and RSC were set as standard sized units that would likely be implemented in QLD based on existing units. The SC rating was 200MVA and RSC rating was 615MVA.	The variance of these units is very high depending on the size and type of units implemented. For the SC, this value can vary from 100MVA to 400MVA for common sizes. For the RSC, it is based on turbine generator ratings of QLD coal facilities.	Due to the large variances in generator ratings, the effect on the predictions for the number of units is significant. The relationship is inversely proportional, with a doubling of the generator capacity resulting in a halving of the number of units required (before rounding up). This demonstrates that the forecasted number of synchronous condensers required is highly dependent on the specified values and can thus only used as a reference value.
Generator time constants	The generator time constants for the SC and RSC were set as standard sized units that would likely be implemented in QLD based on existing units. The SC constant was 2s and RSC constant was 1s.	The variance of these units is high depending on the size and type of units implemented. For both the SC and RSC, this value can vary from 1s to 4s for common sizes.	This has a similar effect to the generator rating; however, the attached mass time constant must also be considered. The sum of the time constants is inversely proportional to the predicted number of units. As the time constant of the generator is typically less than the attached mass, it has a lower effect on the results than the mass time constant.
Flywheel and turbine shaft time constants	The flywheel time constant was based off an arbitrary standard of 4s. The turbine shaft was assigned the value from the Tarong Power Station units of 1.82s.	Again, the variance of this factor depends heavily on the type of unit and size of attached mass. A larger flywheel or turbine system results in larger time constants. The range of values for the fly wheel are 2s to 6s.	The sensitivity of this parameter is explained in the row above; the sum of the time constants is inversely proportional to the predicted number of units. This time constant generally has a larger effect on results as it typically larger.
Net reduction in inertia from de-blading	The baseline value for the net reduction in inertia from turbine de-blading was 30%. This was the general value obtained from research.	It is largely unknown the variance of this parameter. As most turbines have a similar design, the net reduction would likely be between 20% to 40%.	This value has a relatively small effect on the results produced. This is simply because it scales the time constant of the turbine shaft by a small factor and thus has a small effect on the cumulative time constant and overall results. For example, a value of 50% increases the required number of RSC by 2 in the ideal development scenario.
Year of re-purposed synchronous condenser deployment	The year of inclusion for these facilities was assumed to be earliest at 2028 as it was assumed it would take a minimum 3 years for these facilities to undergo construction and would only be operational once the coal facility is decommissioned.	The variance is difficult to evaluate it is highly dependent on the individual schedules for re-purposing synchronous condensers. The value assumed is likely early, and assumes the continual commissioning of RSC.	Delaying the year for RSC commissioning results in greater number of SC units being required. The actual sensitivity is dependent on the inertia shortfall for the corresponding years. Typically, a delay of the RSC commissioning by 1 year, results in the requirement of an additional 1 to 2 SC.
Linear regression of inertia shortfall data	The linear regression of the obtained data was applied. The equation of this regression can be referred to in Graph 11.	This model has a high variance as it is largely unknown how the inertia shortfalls will vary beyond the data provided. It is likely that the inertia shortfall will occur at a slower rate than the regression as some coal facilities will remain functional beyond 2035 which provide an inertia response.	Varying the rate of the inertia shortfall will greatly affect the results obtained. A higher rate of decline will result in a much larger number of SC units and less long-term RSC. Contrarily, a slower rate will mean less SC are required, and more RSC can be used; however, more than 10 RSC will be required meaning different sized units (to the Tarong unit) will have to be used.

It is evident that there are numerous variables with high sensitivity in terms of the final results produced in particularly: the generator ratings, time constants, and the RSC year of commissioning. The variable that is likely the source of greatest inaccuracy is the RSC year of commissioning as this is highly dependent on the conversion possibilities and schedules of coal facilities across QLD.

4.6.2 RQ2 Limitations and Recommendations

There are various limitations within the model developed and the associated results produced. Based on these limitations, the recommendations suggested below could be employed in future models and analysis to reduce the effect of these limitations and mitigate uncertainty in the results:

- As previously discussed, a model of the inertia levels in the Queensland grid system should be developed. This would utilise data from all synchronous generation units across Queensland as well as the inertia requirements to determine a forecast for the inertia shortfalls over the following two decades as synchronous (coal and gas) generation is withdrawn. This would not only verify the data obtained from AEMO, but would provide a more robust prediction of inertia shortfalls beyond 2028 rather than relying on the linear regression approach. This model would require extensive research into the phase-out programs of each individual coal facility as well as the specifications of all generation units within these plants; due to this complexity, the development of this model was out of scope for this report.

- In addition to the number of facilities and provided inertia, the location of these facilities is important factor to consider. Although this has been considered out of scope for the purpose of this assessment, locational stability is a crucial factor to consider. Locational factors depend on numerous factors such as transmission capabilities, local generation and synchronous inertia levels and the local effects of contingency events. According to AEMO and Powerlink, synchronous condensers will be required in Central and Southern Queensland near the critical transmission nodes of Gin-Gin, Greenbank, and Western Downs; this also depends on the timing of RSC units (AEMO, 2021) (Powerlink, 2021). The timing and management of this process is a complex task that is crucial to the provision of Queensland's grid stability.

- The conversion process of steam turbines to repurposed synchronous condensers was only briefly touched on in this analysis. A case study of the conversion process including the timeframes and resources required would provide a further insight into the development of a synchronous condenser fleet in Queensland.

- The effects of IBR on grid frequency management would be a highly valuable and relevant area of study as electricity grids throughout the world transition from a synchronous generation to renewable-based resources that are connected via inverters. There have been little known practical uses of IBR in frequency control applications; further research into this area would improve coverage of this report and pose additional solutions for grid stability.

- Other grid stability parameters such as voltage management were only briefly referenced in this document. There are many aspects to a stable and secure grid and this analysis only touched on one specific time window of one stability parameter. Although the operational frequency is likely to be a primary component affected by the changing generation mix, extending this analysis to include all aspects of grid stability would add greater depth.

- Similar to RQ1, the costing and procurement of these synchronous unit systems and the integration process should be considered from an economic and political perspective.

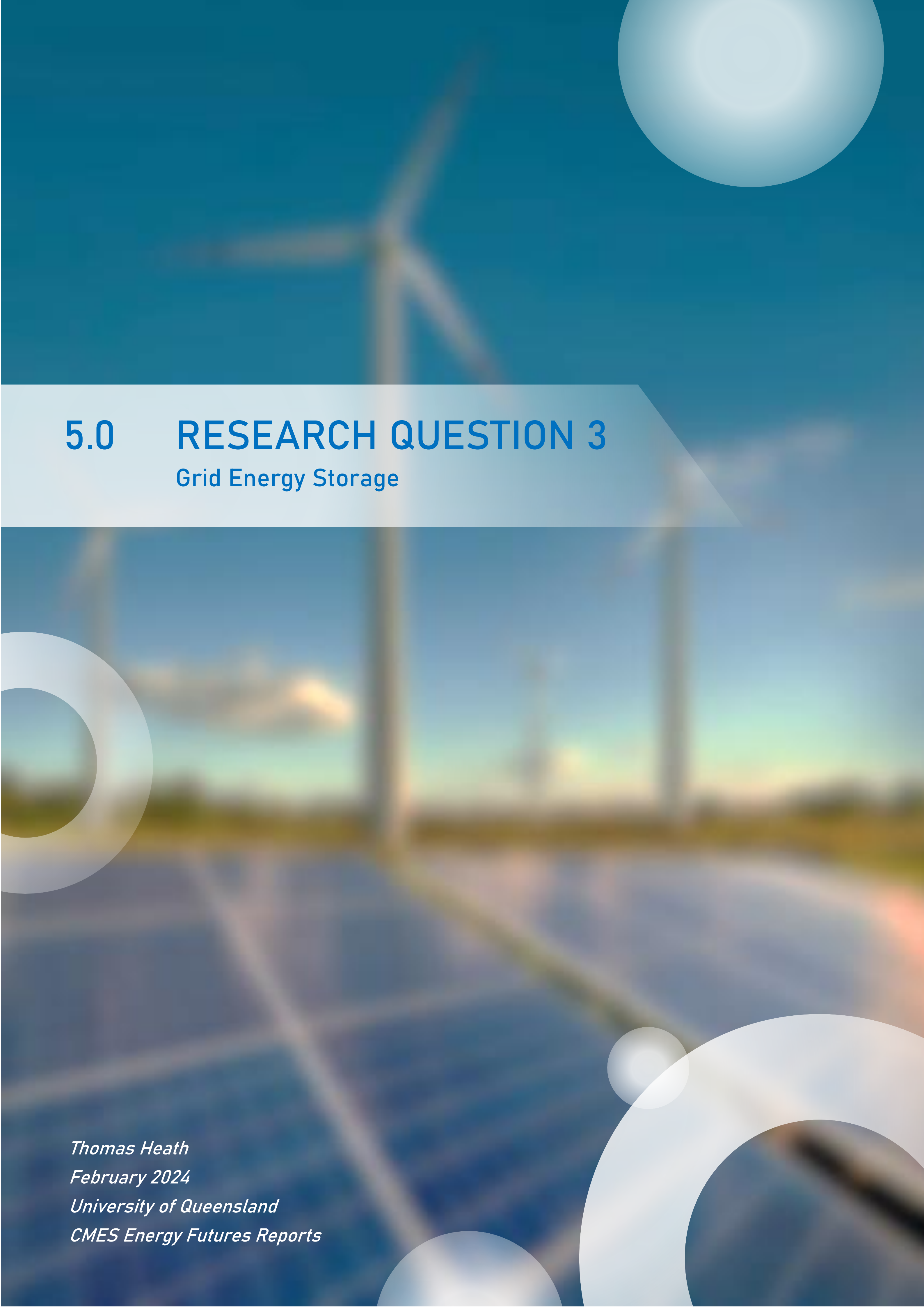
It is evident that there is significant improvement possible to expand the scope of this analysis and provide a more holistic analysis of the grid stability.

4.7 RQ2 Summary

The aim of this second research question was to thoroughly assess the grid stability forecasts of Queensland's energy system, in particular, the operational frequency and the effects of reducing inertia levels. The inertia requirements, development and overall feasibility outlook were considered from a physical engineering perspective. The scope of this analysis involved a year-by-year breakdown of the inertia shortfalls from 2023 to 2035 using data collected from the NEM inertia regulators (primarily AEMO and AER). Following this, standardised purpose-built and repurposed synchronous condenser units were developed using data from various synchronous condenser providers. With these two sets of data, predictions on the commissioning of synchronous units were formulated involving dates and numbers of units. An interactive and dynamic model was developed on Excel that enabled the input of various parameters to assist with the data analysis. The major findings and conclusions have been summarised below:

- Inertia Shortfalls: Queensland's inertia levels are expected to decrease linearly from 2024 onwards, with shortfalls predicted to occur from 2026 onwards. This is primarily due to the decommissioning of synchronous generation facilities; however, the inertia data obtained did not directly align with specific inertia withdrawals which is likely a result of the AEMO model. Using a linear regression analysis, the inertia levels are expected to reduce to complete deficit by 2035.
- Purpose-built synchronous condensers: SC specifications were based on a standard Powerlink facility (which are currently planned for QLD); the individual inertial contribution of a single SC unit is 1,200 MWs. In the ideal development scenario (where RSC development is prioritised), it was forecasted that a significant 9 SC units are required by 2027 and this number will remain constant beyond 2035.
- Repurposed synchronous condensers: RSC provide advantages through the utilisation of existing infrastructure such generators, turbine masses and transmission systems. It is expected that approximately half of the generation units in Queensland (in terms of generation capacity) will be converted to RSC. RSC specifications were based on the Tarong Power Station turbine (as this was the most common turbine unit size in QLD); the individual inertial contribution of a single RSC unit is 1,400 MWs. In the ideal development scenario, it was forecasted that a total 10 of these units are required by 2035 and into the long-term.
- Government and Stakeholder Actions: Inertia response is soon to be provided by individual stakeholders with the opening of the recent ancillary service markets. The Queensland government and AEMO have both stressed that the planning of system strength in the NEM over the next few years is of utmost importance. Powerlink is to provide short-term inertia response units which consists of SC 8 units by 2033. This demonstrated that the inertia shortfall (at least in the short-term) has been partially to fully addressed depending on the model developed in this analysis.

Overall, from an operational frequency and system inertia perspective, the energy plan exhibits a positive trajectory toward a secure and reliable grid and showcases proactiveness and urgency. At current approximations, the government, and associated operators and providers, have partially addressed the short-term inertia shortfall with yet unconfirmed progress for the long-term. It is critical that the energy market and system regulators (primarily AEMO): maintain consistent and accurate modelling of the stability requirements in Queensland; monitor stakeholder interest through the profitability and incentives for operators to join the new markets (government funding and regulations may be necessary); schedule the procurement and construction of SC and RSC facilities; and successfully manage any change in the current dynamic transition period. A system inertia model should be developed for greater accuracy and further analysis.



5.0 RESEARCH QUESTION 3

Grid Energy Storage

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February 2024
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CMES Energy Futures Reports

5.1 Grid Storage Overview, Assumptions and Scope

In an attempt to analyse the energy storage aspect of the Queensland grid system, the forecasted storage outlook was assessed in detail. This was the third step of analysis as a part of the feasibility study of the Queensland Energy Plan. Energy storage is an essential component for a variable-generation based grid system and requires various aspects to work effectively. The major components of focus in this analysis involve the requirement for adequate output capacity (MW) and duration of output (total storage MWh). Both aspects form the basis of this energy storage assessment of the Queensland energy system for the following to two decades.

The scope considerations and assumptions made throughout the collection, processing and analysis of data have been summarised and justified below in Table 17. These considerations attempt to simplify the models used in order to produce meaningful results. All previously stated scopes and assumptions apply to where relevant in this section of analysis.

Table 17: Energy Storage Scope and Assumptions

Description	*Justification*
Similar to the generation and stability components of analysis, this section does not consider locational or transmission aspects.	This section focusses solely on the fundamental generation capabilities of the state without considering the implementation or other logistical parameters. This is the first stage of analysis for a general insight into the feasibility; there are many other components essential to effective grid operation.
The costing and procurement are out of scope for this analysis.	Although these aspects are crucial to a holistic feasibility assessment, this report is applying an engineering analysis to the feasibility which applies to the mechanics of the system rather than assessing the economic and political factors.
For the purpose of this assessment, inter-state grid connection has been considered out of scope. In reality, the NEM operates with multiple small sub-systems that are all connected and interdependent.	Although Queensland is connected with multiple other states in the NEM, for this analysis, only the QLD-based consumption and facilities are considered to narrow the scope. It is important to note AEMO has stated that there are benefits in increasing interconnection between New South Wales and Queensland. Despite this, QLD is considered as an individual system for this analysis.
The only storage facilities being considered within this analysis are BESS and PHES plants being implemented in Queensland.	Emerging storage types such as underground gas reservoir or compressed air storage are still in their technological development stages, and there are no significant storage facilities planned within the state in the near future. Furthermore, gas storage has not been directly considered in terms of infrastructure; however, non-variable generation sources such as gas turbines have been included in calculations.
This storage section of analysis has considered only the intra-day variances, while the inter-day variances have been omitted.	The weekly, monthly, and seasonal variances have not been considered, rather an average daily analysis has been conducted. This was to consider an average daily outlook with variable rates applied to the consumption, as well as wind and solar production. Based on the findings from the daily assessment, the storage capabilities of the grid can be summarised and the effects of seasonal variances can be deduced.

The daily assessment was conducted in increments of 0.2h for the current scenario in 2023 followed by 5-year outlooks for 2025, 2030, 2035, 2040.	The researched and calculated storage facility durations of output were often provided to within an hour; however, the smallest duration increment obtained was to a precision of 0.2 hours (12 minutes). Thus, this was decided as the increment for the 24-hour model as this would provide the highest degree of accuracy based on the precision of the acquired data.
The various scenarios modelled were only applicable for certain years within the scope.	The current 2023, and 2025 outlooks, were not considered in the renewable drought scenario model as there was still significant contribution of non-renewable generation. Similarly, the 2023 daily operation outlook was not assessed as the grid is currently operational.
If the output capacity and overall storage capacity of a storage facility were not specified, it was omitted from calculations.	Facilities that were in the very early stages of proposal had unspecified storage and output capacities, or unknown commission dates. This meant their inclusion in the analysis was not practical; however, they were still listed in the tables to track their development over succeeding years.
If the plant's commission date was unknown, the facility output was incorporated from a specified year with a specified phase in factor.	The incorporation of facilities with unknown commission dates is investigated in the discussion. The manual inclusion of these plants with an optional phase in factor allowed the variance of this unknown variable to be assessed.
Decommission dates were not included as the lifetime of the plants is likely to be beyond the scope of analysis (beyond 2040).	The decommission year was not considered for the storage facilities as this data was not provided and was likely beyond the foreseeable future and scope of the model. The lifetime of facilities is discussed in section 5.5.
An average battery time was applied to batteries with unknown lifetimes.	This assumption enabled facilities with only partially supplied information to be incorporated. The average lifetime of the batteries was calculated from the plants with fully specified information; there was little variance in overall lifetime and thus it was deemed a valid assumption to apply this value plants with unknown durations.
This model does not include the potential decline in performance that occurs at end of a storage facility's lifetime.	The output capacity (MW) and overall storage (MWh) of storage facilities may decline depending on the age, condition, maintenance, and usage history. This is discussed further in the discussion; however, as the scope of this analysis only applies to 2040, it was assumed based on the associated theory, that there would be no notable decline in storage performance during the first 20 years of operation.
The models developed do not include losses from charging and discharging of the storage facilities.	Although the efficiency of storage facilities is an important factor to consider and emphasises why excess production is required, this factor was excluded from the models. This was deemed acceptable as the daily operation and drought scenario outcomes were largely unaffected by this parameter. Storage type efficiencies are assessed briefly in the discussion in section 5.5.
The transmission loss factor applies only to the generation facilities and not the storage plants.	The same transmission assumptions from the generation analysis apply to this section. It was assumed that there was lower to negligible transmission losses for generation facilities as these plants are situated much closer to consumption locations.

5.2 Grid Storage Relevant Theory

5.2.1 Storage Duration Definition

For the purpose of this report, the various lengths of storage are defined as below. The time frames of duration refer to the length of duration at maximum output capacity. For example, a 500MWh storage facility with a nominal 100MW output capacity has a storage of 5 hours.

1. Short-term storage (STS): 1 - 6 hours
2. Medium-term storage (MTS): 6 - 24 hours
3. Long term storage (LTS): 1 - 7 days
4. Seasonal storage (SS): Greater than 7 days of storage

All four types of storage are essential for an effective, durable, and stable electricity grid. The importance of each storage is explained in the three-stage assessment below. Stage 1 forms the basis of the forecasting model.

1. The first stage considers the immediate timeframe which entails all intraday storage (consisting of STS and MTS). If the intra-day storage is inadequate, the variable-generation based grid will be unable to operate at all. Thus, this is the initial and most immediate scope of storage assessment. Technologies. BESS and small-scale PHES facilities are ideal for this management and peak-time gas turbines provide support. The collected data consists exclusively of these technologies.

2. The second stage of analysis and priority is the inter-day storage (consisting of LTS); however, from a simple inspection of the data acquired, this stage has not been given significant attention in the Queensland plan with only two facilities in the entire state having a proposed maximum output storage of 24 hours (Pioneer-Burdekin and Borumba Dam PHES). There are no facilities with a longer storage duration than this. Large scale pumped-hydro facilities can aid in long duration storage; however, QLD lacks the natural advantage of significant elevation regions. An example of LTS is the Snowy Hydro 2.0 facility proposed in NSW. This plant will have an output capacity of 2,200 MW and a storage capacity of 350,000 MWh resulting in an operational duration of nearly 7 days (160 hours). In Queensland, current gas turbine and coal facilities will aid the long duration storage requirement over the next two decades during the adaption to the renewable grid.

3. The third stage is the seasonal outlook (consisting of SS) which is the final stage of a stable and well-supported grid in terms of storage. Over the following two decades during the energy transition, the existing coal facilities will aid in this sector. During terms of extended renewable drought, facilities in phase 1 or 2 of decommission can provide support through the start-up of additional turbine units. A long-term renewable solution to seasonal storage is hydrogen energy storage and generation facilities. This technology effectively capitalises on the variable energy production of renewable-based grids by increasing hydrogen production during periods of excess energy production (and low electricity spot prices) and generating energy from hydrogen when required during periods of insufficient production (and high electricity spot prices). This also forms an effective means of converting excess energy produced from the grid to a productive cause to stabilises the grid, mediates electricity prices, and provide potential export options. As the coal facilities are decommissioned, the inter-day and seasonal storage must be given much more attention, in particular the hydrogen industry.

5.2.2 Energy and Power

Calculating the total energy production from multiple variable power sources was necessary for the analysis of the section. The time integral of power is the total energy, thus the area under a power output curve is the total energy for the integral period (UCF, 2016). This was used for the 24-hour period considered in the calculations:

$$W = \int_{t_2}^{t_1} P \ dt$$

$$Energy\ (J) = \int_{t_2}^{t_1} Power\ (W)\ dt$$

$$Energy\ (MWh) = \int_{t_2(hours)}^{t_1(hours)} Power\ (MW)\ dt$$

5.2.3 Consumption Variation

Previously, average capacity factors were used for an average annual analysis; however, to accurately assess the storage requirements of the grid, an inter-hourly assessment is required. As a result, average consumption rates and capacity factors do not provide an accurate approximation for this time scope. It is thus worthwhile considering the consumption and production variations through a 24-hour period.

From the previous consumption forecast analysis (refer section 3.1), the average annual energy requirement was predicted for every year until 2040. This annual consumption (GWh) can be converted to an approximate average daily consumption (MWh); however, the actual rate of consumption at any specific time during the day varies greatly. Applying the theory from above, it can be concluded that the integral of the instantaneous consumption (MW) throughout the day should be equal to the known daily consumption (MWh). Thus, using this concept, a variable consumption curve can be applied to the model.

The way in which consumption varies throughout the day depends on numerous factors and follows a general trend (Torriti, 2017):

- The consumption is lowest at 3am and increases to a peak just after 6am as the population wakes and prepares for the day.
- The rate of energy consumption slightly declines from this initial peak throughout the day as people are at work and away from home.
- As people arrive home at around 6pm and appliances are turned on for entertainment, comfort, and cooking, the power consumption peaks.
- This is followed by a gradual decline throughout the night as people go to bed.

Note this approach considers an average daily consumption, but in reality, will vary depending on:

- The day of the week (weekends and weekdays have different variations)
- Possible events (social behaviours and holidays affect daily consumption)
- Time of the year (seasonal factors can cause variations such as heating)
- Location (energy usage is highly locational specific such as the higher use of cooling appliances year-round in North QLD)

The average demand for the NEM in Queensland is shown below in Figure 22 and is referred to as a Duck Curve. The actual values for the rate of consumption will be obtained from the consumption forecast in section 3.1, and the general shape and trend of the figure below will also be used in the model (LEE, 2023).

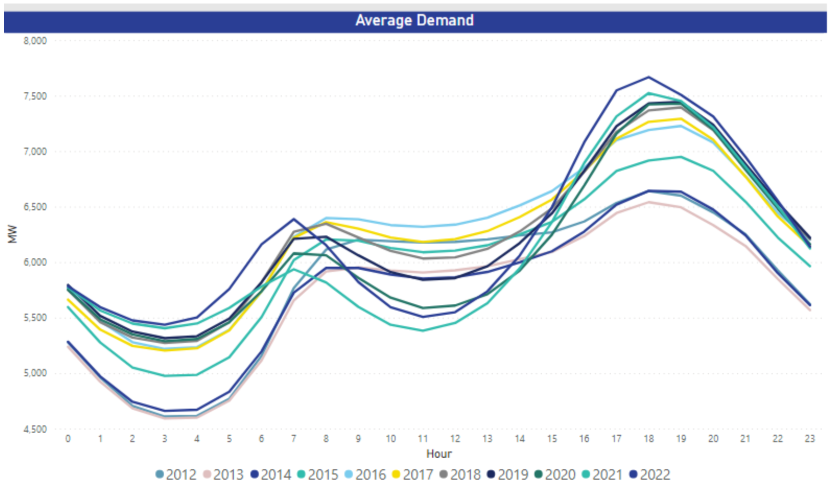
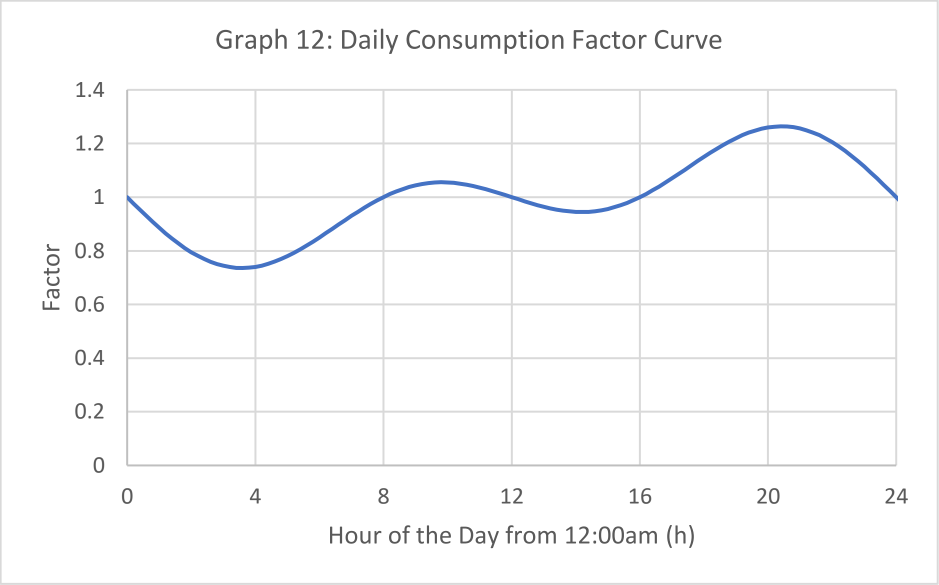


Figure 22: Variable Energy Consumption in Queensland

This plot shows the varying average consumption throughout the day from 12am for 24 hours. The data was obtained from the NEMDE. (LEE, 2023)

In attempt to replicate this shape, without unnecessarily over complicating the model, a series of trigonometric curves were superimposed and manipulated to produce the 'consumption factor curve' below in Graph 12:


Graph 12: Daily Consumption Factor Curve

The respective equation for this curve is below and was used in the spreadsheet model:

$$y = -0.15 \sin\left(\frac{\pi}{12}x\right) - 0.15 \sin\left(\frac{\pi}{6}x\right) + 1$$

This produces a variable consumption rate factor curve. The integral of this curve is strategically 24, and thus can be applied, through multiplication, directly to the average daily consumption rate (MW) for each time interval of the day. For example, at midnight the consumption rate factor is 1, and thus apply a multiplication factor of 1 is applied to the average daily consumption rate. The integral of the curve will then be the exact average daily consumption over the 24-hour period (MWh).

5.2.4 Production Variation

The same variable approach was applied to the variable production facilities, primarily wind and solar. Coal facilities do not vary greatly due to their inherent design; coal boiler and turbine unit are very inefficient to start and stop production and thus production remains relatively constant. Gas turbines are much more efficient to vary output according to demand requirements and as previously discussed, there are some new turbine facilities are under construction for peak demand application. Figure 23 below shows some historical data from Queensland demonstrating the varying capacities of different facilities relative to their maximum output (note this maximum output is not the nominal capacity as coal facilities do not operate at 100% capacity, rather it refers to the facility's average maximum output).

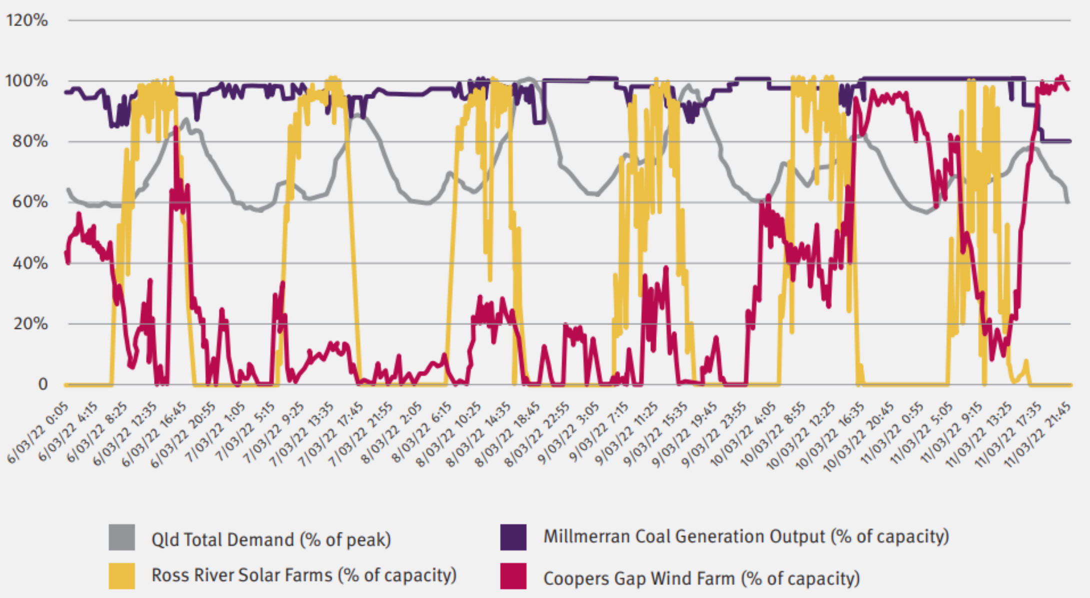


Figure 23: Variable Energy Production Sample from Queensland Facilities

This plot shows the varying production of a sample wind, solar and coal facility in Queensland over 6 days in March 2022. The consumption can also be seen for this sample week. The data was obtained from the Queensland Government (QLD Gov, 2022).

Solar Production

Solar production varies throughout the day due to the change in exposure from solar radiation and due to other factors including:

- Daily and seasonal weather patterns
- Rare weather events including extended periods of cloud cover
- Location which is connected to weather patterns and overall sun exposure (latitude)
- Type of facility including inverter capabilities, cooling systems, battery connections

Fortunately, Queensland's solar capacity remains relatively consistent throughout the state and year due to the natural conditions of the state (AEMO, 2022).

Applying the same justification that was used for the average demand curve, an average solar capacity curve was used for a general day in Queensland. Figure 24 provides a reference curve for this varying capacity factor which was averaged over 6 months to account for cloudy days and seasonal changes (Parkinson, 2022). Note this figure also demonstrated the effects of weather patterns on long-term productivity. For this analysis, to maintain consistency with the CA, the 2022 January to June curve was used as this was considered an unproductive solar term.

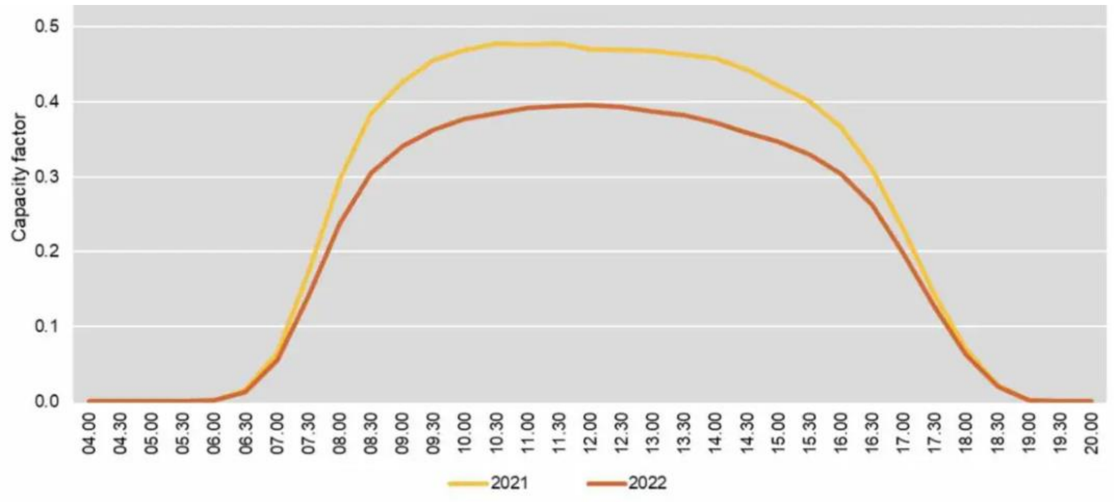
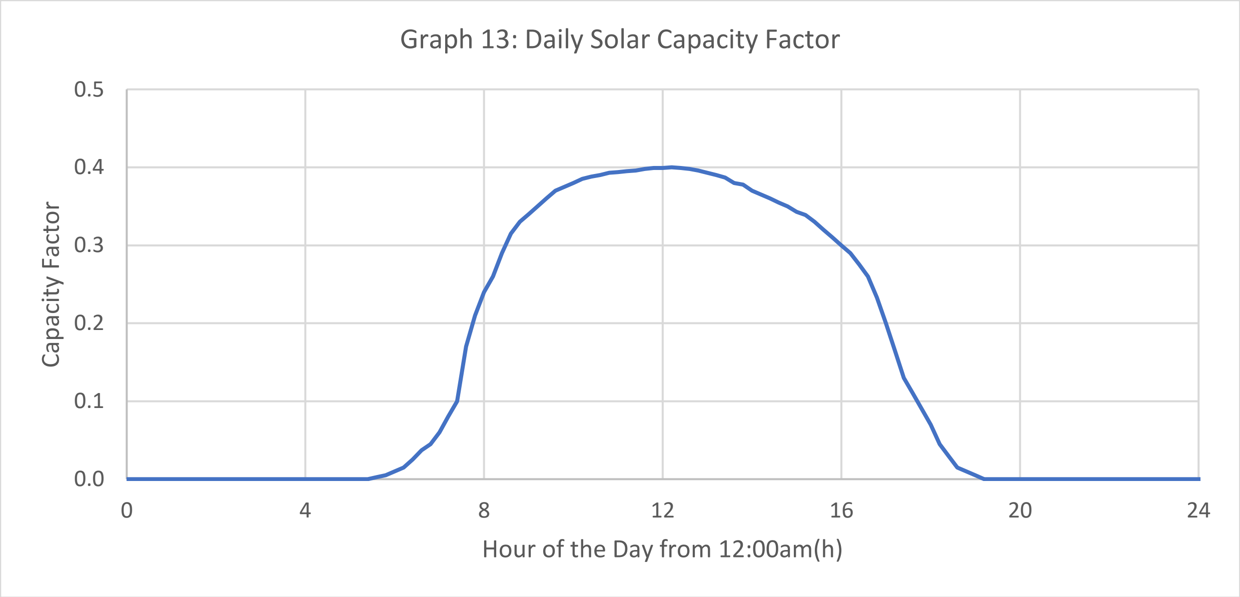


Figure 24: Queensland Average Daily Solar Production

This plot shows the varying production of solar facilities in Queensland throughout the day from 4am to 8pm in the months of January to June. The 2021 and 2022 data sets are shown to display the effects of renewable drought. The data was obtained from the AER using NEM data (Parkinson, 2022).

It is evident that the capacity rises rapidly from 0 at around 6am to a capacity factor of 0.3 by 8:30am. It continues to rise at a slower rate and peaks at 0.4 at midday and then very gradually declines back to 0.3 at 4pm before falling sharply back to 0 over the final 2.5 hours. As shown in Graph 13, this pattern was replicated for a data set of 0.2h intervals to be compatible with the existing model.


Graph 13: Daily Solar Capacity Factor

An important final note is that the peak capacity factor utilised (0.4) is relatively low relative to nominal capacity. Despite this, it will not significantly affect daily operational results due to the timing profile. This will become evident in the analysis in section 5.4.2; the main value affected is the calculated daily excess production (in the daily operation analysis). The 100% renewable drought scenario will not be affected by the selection of this capacity profile while the critical drought factor will only be marginally affected.

Wind Production

The daily wind generation capacity is very difficult to model due to the very high dependence on location and other factors such as weather events and seasonal changes (which are inherently affected by the location). As a result, an average wind energy production curve for wind facilities in Queensland was used as a basic approximation to capture the general trend for the purpose of this model. Figure 25 below provides the general wind production profile for Queensland plants (refer green dashed line); it is interesting to note that this 'dip' profile means wind facilities have efficient compatibility with solar to take advantage of high prices that occur on the solar shoulder period (Engel, 2021). Furthermore, this figure corroborates the solar and consumption capacity curve profiles (noting again that the maximum output is not the nominal capacity, rather it refers to the facility's average maximum output).

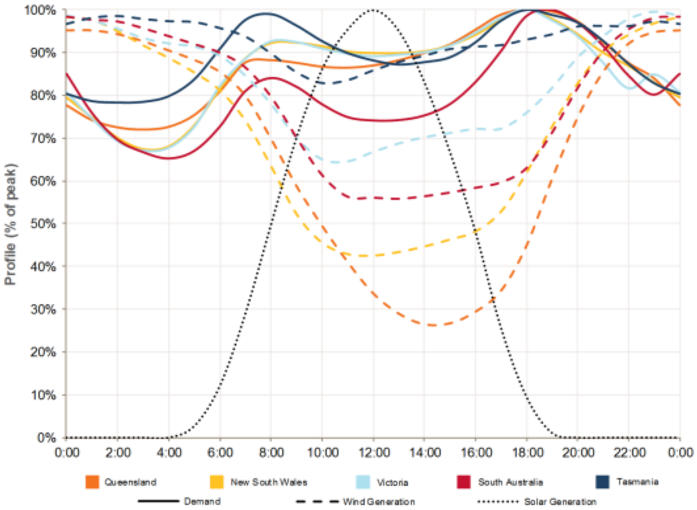
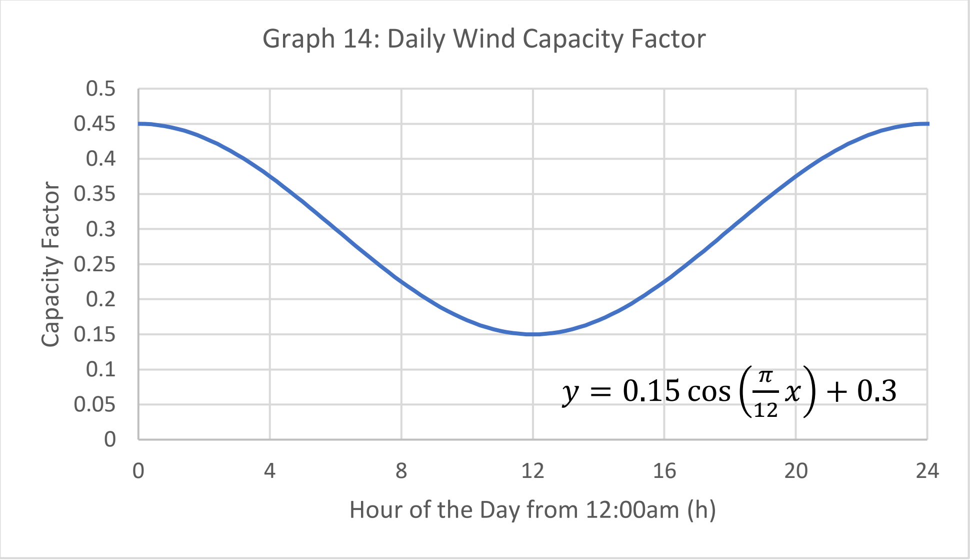


Figure 25: Production and Consumption Profiles in the NEM

This plot shows the varying production of wind and solar plants, and the varying consumption in states within the NEM over a 24-hour period from 12am. The data was obtained from the NEMDE (QLD Gov, 2022).

Using the annual average capacity factor of wind plants (30% as applied in the generation model), the wind capacity factor was modelled according to the profile provided by Figure 25. The associated equation used in the Excel spreadsheet is also supplied with Graph 14 below:


Graph 14: Daily Wind Capacity Factor

It is evident that wind generation follows a generally periodic curve and is more productive at night-time; the lowest production occurs during the middle of the day. Although this creates a high compatibility with solar facilities, this profile has an inefficient alignment with the consumption curve as there is little demand for energy at night.

5.3 Grid Storage Data Collection and Methodology

The model developed considers all existing and proposed energy storage facilities across Queensland from 2023 until 2040. Similar to the generation facility data collection process (refer section 3.1.3), the name and local government area (LGA) of all of the plants were obtained. The respective storage type; either BESS or PHES was listed; emerging storage types such as underground gas reservoir or compressed air storage are still in the development stages of their technology in QLD and there are no major planned storage facilities. The status of operation was then noted as: proposed, under-construction, existing or cancelled, and the respective commission dates were researched and included where necessary. If the commission was not yet specified, the facility was omitted from calculations. Decommission dates were not included as not specified and lifetime is likely to be greater than scope of analysis (beyond 2040). Finally, the nameplate capacities were included which involved recording:

- The maximum output capacity of the facility to the grid (MW).
- The overall storage capacity of the facility (MWh).
- If output or storage capacity was not provided, but the operating time at maximum output (hours) was available, this was recorded to back-calculate the required information.
- If the nameplate capacity was not yet specified, the facility was omitted from calculations.

The same issues noted during the generation data collection were encountered during this process. These issues primarily included:

- Repeated inclusion of facilities under different project names
- Poorly managed or sources or out-of-date information. Some projects were cancelled, modified, moved or name changed without being updated on data bases
- Contradicting sources in terms of commission dates or capacities

5.3.1 Grid Storage Forecasting Model

The collected data was analysed to produce a current outlook, and forecasts in 5-year increments from 2025 (2025, 2030, 2035 and 2040). This was deemed a sufficient scope to provide an insight into the storage outlook of the grid. As previously outlined, there are four types of storage (STS, MTS, LTS, SS) which are all essential for an effective, durable, and stable electricity grid; however, from the data collection there is only STS and MTS in development and thus, only the first stage (intra-day storage) was assessed as the technologies to support storage longer than this are not yet a focus in Queensland development which will be discussed later and this stage is the immediate concern. Linked to the previous point, and as outlined in the variable capacity factor assessment, the weekly, monthly, and seasonal variances have not been considered, rather an average daily analysis has been conducted.

For battery facilities with specified nameplate output capacities (MW) and storage capacities (MWh), the average battery operating time (at maximum capacity) was calculated to be 2.4 hours (considering 45 BESS plants across QLD). This value was then applied to batteries with specified output capacities but unknown overall storage capacities. This was deemed reasonable as most battery facilities are similar in nature. Note the output and storage of all PHES facilities was obtained. This produced the corrected generation capacity and corrected storage capacity columns in the spreadsheet which accounted for the battery facilities with unknown data.

Using a similar approach to the generation data extraction, the spreadsheet model ran off the following criteria in Excel primarily the 'IF', 'AND' and 'OR' functions:

1. If the status of the facility was 'Decommissioned' or 'Cancelled', the facility was not included in any calculations. These facilities were still included in the spreadsheet to account for all facilities, past, present, and future.

2. If the status of the facility was 'Proposed' or 'Under Construction', and the commission date was 'Unknown', the facility was not included in calculations. Although they could have been incorporated after a certain period, as was done for the generation facilities with unknown commission dates, there were only 8 facilities with unknown commission dates. Furthermore, the storage capacity and duration of operation for the majority of these facilities were unknown and thus could not be included regardless.

3. If the status of the facility was 'Proposed' or 'Under Construction', and the commission date was known, the facility was included in calculations from the year after its commission. Again, this avoids inclusion of facilities that would start at the end of a year (CA). Note the decommission year was not considered for the storage facilities (refer section 5.1).

4. The model then extracts the relevant data and presents the storage breakdown over a 24-hour period for the outlined years of interest to assess the first stage of immediate intra-day storage as this is the initial focus of the grid operators and regulators.

5. Various graphs were produced to assess different aspects of the storage outlook including drought scenarios and total storage availability. These are summarised below:

Result Set 1: Storage Capacity Forecast

- The first set of results outlines the installed storage capacity forecast. This includes the type and number of facilities and their respective total storage capacities (GWh). The forecasted maximum output capacity profiles for the storage fleet were then graphed to visualise supplying potential.

Result Set 2: Daily Storage Operation Outlook

- This consisted of an investigation of the grid performance from a daily perspective. This utilises the variable capacity factors introduced above in section 5.2 to plot the daily energy generation against the daily consumption. From this analysis, the excess energy production or deficit throughout the day could be obtained to determine the capacity and duration of daily storage required.

Result Set 3: Renewable Drought Outlook

- Combining result sets 1 and 2, a forecasted renewable drought scenario was developed. This involved applying a drought capacity factor to the existing renewable production. For example, a drought capacity factor of 0.5 corresponds to 50% renewable production relative to its normal daily production. This produced the corresponding daily drought production which was combined with the battery storage available to determine the time-period for which the grid can sustain itself. A corresponding plot was produced to help visualise this outlook. This process is described in greater detail in section 5.4.3.

Various other equations and processes were applied for each method utilising the relevant theory. Some sample functions used in the Excel model are shown below in Table 18 (refer ‘Storage’ sheet on the Excel Document). The entire spreadsheet is automated (can easily vary capacity factors or transmission losses), and the results are collated at the bottom of the sheet.

Table 18: Sample Functions Used in Excel Model

Sample Function	*Sample Cell*	*Description*
`=IF($F5="Cancelled",0,IF($G5="Unknown",IF($I$395<=$R$2,IF($O5>=R$4,IF($R$2-$I$395>=$K$395,$M5,$M5*($R$2-$I$395)/$K$395)),0),IF($R$2>$G5,IF($O5>=R$4,$M5,0),0)))`	R5	This function was used for the incorporation of applicable BESS and PHESS storage facilities based on the year of interest and the input factors for the inclusion of facilities with unknown commission dates. This meant various scenarios could be considered for a broader analysis.
`=IF(OR($F90="Cancelled",$F90="Decommissioned"),0,IF($G90="Unknown",0,IF(AND($G90<$JH$2,OR($H90="",$H90>$JH$2)),IF(($O90-JH$4)>=0,($M90/'Capacity Factors'!$C$5)*'Capacity Factors'!$H$6,0),0)))`	JH92	This function was used for the incorporation of coal facilities in the generation aspect of the model. This equation applied the theory from the generation analysis in section 3.2.6 in regards to the phase out of coal facilities.
`=-0.15*SIN((PI()/12)*R4)-0.15*SIN((PI()/6)*R4)+1`	R354	This superposition sinusoidal equation was used for the consumption factor profile. The relevant theory foregrounding this equation can be referred to in section 5.2.3.
`=IF((SUM(R363:R368))<R369,(R369-SUM(R363:R368))*0.2,0)`	R377	This equation was one function in the process to determine the daily storage requirement in the daily operational outlook. It considers the deficit between the generation and consumption levels throughout an average day of operation.
`=(SUM(R363:R368)-R369)*0.2`	R373	Similar to the equation above, this function was one of many in determining the storage requirements of the daily operation. This particular equation determines the net excess for the respective time segment of the day.
`=IF((R382-SUM(R383:R388))>0,R382-SUM(R383:R388),0)`	R392	This was the modified consumption calculation used for the duration of drought survival. This formula removed the periods of time during the consumption cycle where consumption was less than generation.
`=IF($F5="Cancelled",0,IF($G5="Unknown",0,IF(($R$2-$G5)>0,1,0)))`	XS5	This equation simply extracted information to determine what facilities were implemented by certain years. This was used in the ‘number of facilities’ column.

5.4 Grid Storage Results and Analysis

5.4.1 Storage Capacity Forecast

The BESS and PHES storage data are summarised below in Table 19 and displayed in the stacked column Graph 15 to highlight the individual contributions of the facility type and the cumulative sum of both storage types over a 24-hour period. As previously discussed, this was applied for the current scenario (2023) and forecasts for 5-year intervals from 2025 to 2040. The facilities with unknown commission dates were factored in from 2036 onwards and were assumed fully operational by 2040 (this can be adjusted in the model).

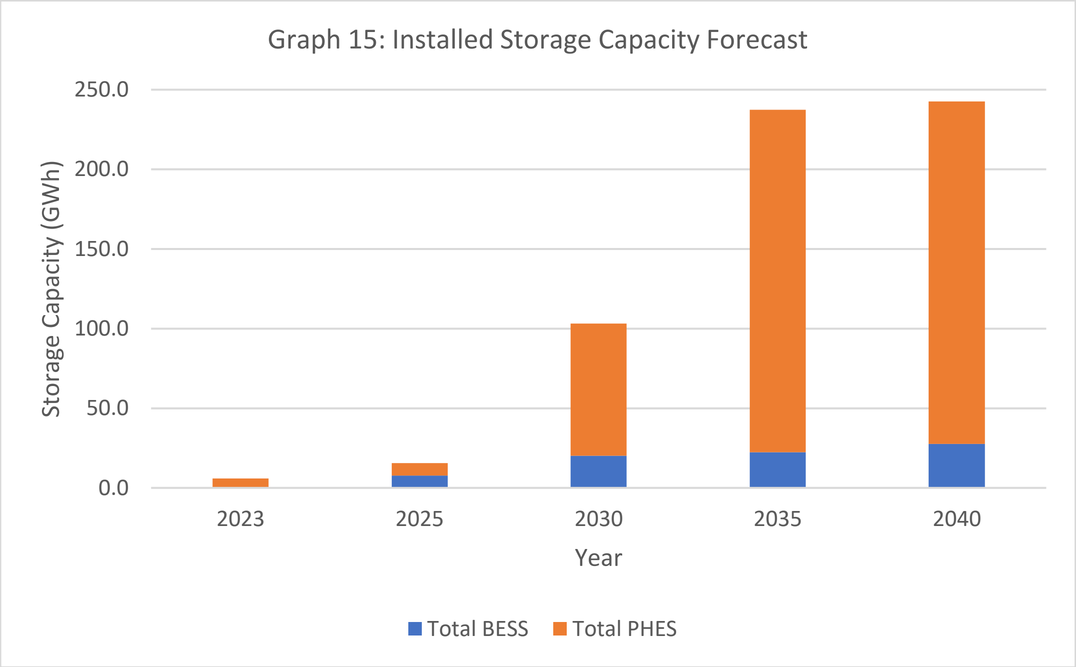


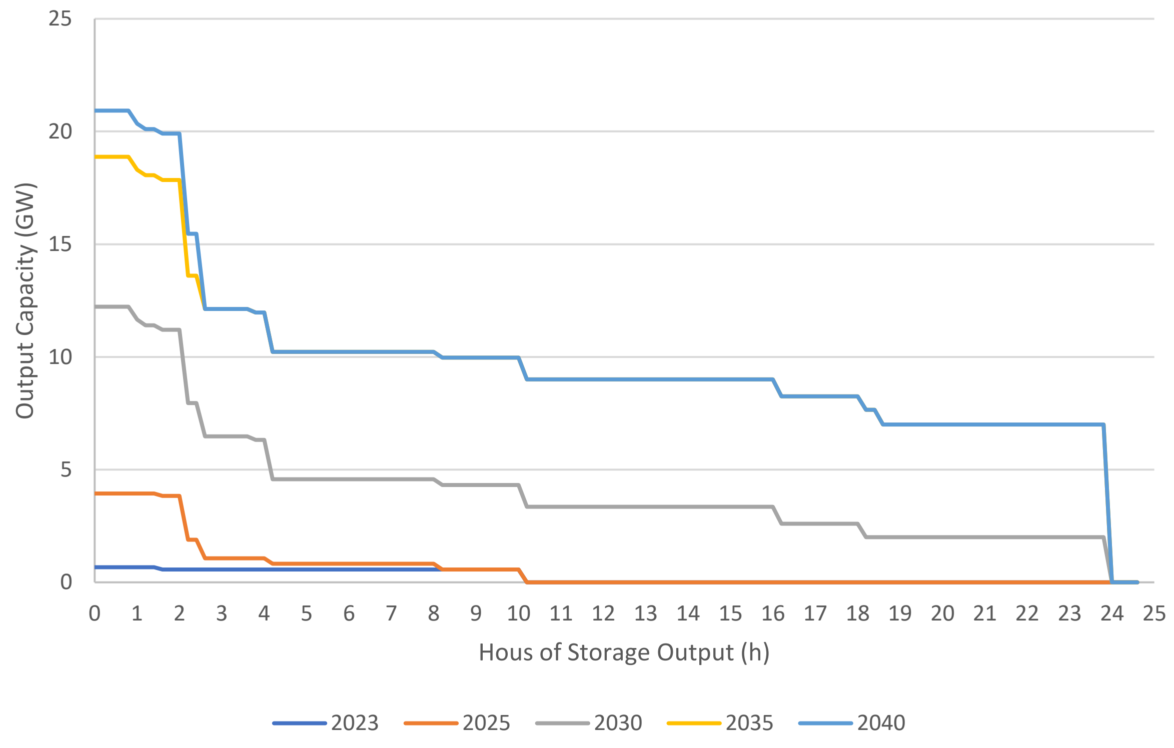
Table 19: Storage Capacity Forecast Data

Data Type	*Unit*	*2023*	*2025*	*2030*	*2035*	*2040*
Number of BESS	-	1	12	33	34	35
Total BESS	*GWh*	0.2	7.6	20.1	22.3	27.5
Percent of Total	*%*	2.7	49.3	19.5	9.4	11.3
Number of PHES	-	1	2	6	8	8
Total PHES	*GWh*	5.8	7.9	83.0	215.1	215.1
Percent of Total	*%*	97.3	50.7	80.5	90.6	88.7
Total Storage	*GWh*	6.0	15.5	103.2	237.4	242.6
Growth from Previous Period	*GWh*	-	9.5	87.7	134.3	5.2

It is evident that the current storage of 6 GWh is expected to increase to approximately 240 GWh by 2040. The only existing substantial storage facilities in Queensland are Wivenhoe Dam and the Wandoan Battery Energy Storage. The Borumba dam contributes 24 hours of 2 GW capacity (48 GWh) between 2025 and 2030 and the largest growth occurs between 2030 and 2035 with the commissioning of the Pioneer Burdekin PHES which contributes 24 hours of 5 GW capacity storage (120 GWh). There is little additional growth forecasted to occur between 2035 and 2040 (even with the inclusion of facilities with unknown commission dates) and by 2040 there are 35 BESS and 8 PHES operational.

The cumulative output maximum output capacity profiles of these facilities are displayed below in Graph 16; this is the combined output of BESS and PHESS facilities. Although this is not a realistic forecast of output, this data shows the output potential of the storage fleet and allows for the comparison of different forecasted profiles. Applying the theory from above, the integral of these curves corresponds to the total storage (GWh) over the 24-hour period expressed in Table 19. Furthermore, as outlined in the assumptions, this data does not incorporate charging/discharging or transmission inefficiencies.

Graph 16: Output Capacity Profile of Storage Facilities (at Maximum Output)



The initial value of each profile is the cumulative instantaneous output of all storage facilities operational in Queensland for the specified year (GW). The declines correspond to the end of the storage duration of individual facilities assuming maximum output.

As previously discussed, although consumption remains relatively consistent from day-to-day, some periods may have abnormally large consumption for short periods. Furthermore, contingency event recovery and PFR requires an excess supply of output capacity. The maximum height of the profiles is reflective of the storage network's ability to accommodate for these sudden spikes in consumption. It is evident that there is significant output capacity potential when the BESS and PHES plants are available. Currently, there is only 0.67 GW of instantaneous storage output from BESS and PHES facilities. By 2040 there is a predicted 20.91 GW of instantaneous output capacity with a duration of 1 hour before decline. This is discussed further with comparisons to peak consumption later analysis.

The width of the profiles is reflective of the storage network's duration of support. At maximum capacity, there is only 24 hours of support available; however, storage is managed with generation to efficiently handle durations of low production (refer section 5.4.3).

Again, the commissioning of the Borumba and Pioneer-Burdekin PHES facilities can be seen by the large increases in longer duration capacities from 2025 - 2030 and 2030 - 2035 respectively. This graph also highlights the differences between the BESS and PHES technologies. The BESS facilities provide have a very high output (GW) for a short duration, resulting in a lower overall total storage (GWh), as visualised by the integral under the BESS output curve. Contrarily, the PHES plants have a cumulatively lower output capacity (GW) but a much longer net duration of storage (GWh).

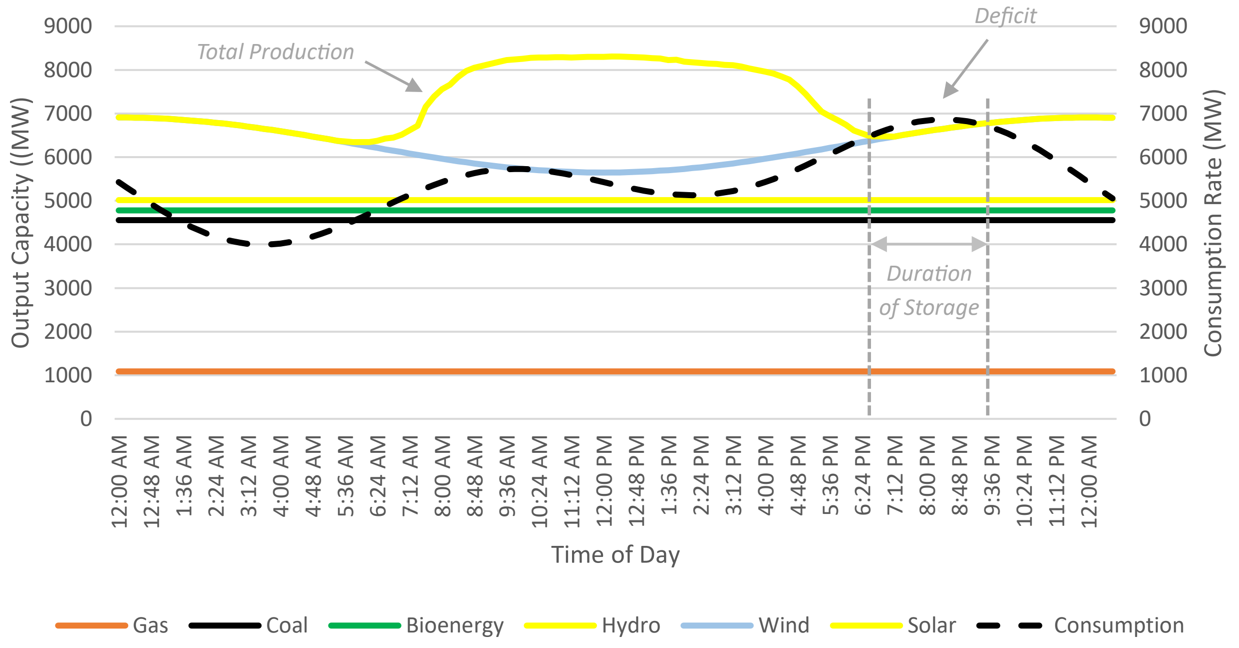
5.4.2 Daily Storage Operational Outlook

In attempt to analyse the storage requirements, the average daily grid operation was assessed in terms of consumption and generation for an average production scenario; this was conducted for 2025, 2030, 2035, 2040.

A stacked line graph was used to visualise the individual contributions and cumulative sum of all production types. The topmost profile corresponds to the total generation while the vertical difference between two solid lines is the contribution of respective generation types. Average capacity factors were used for non-renewable sources such as coal and gas while the variable capacity factors introduced in section 5.2 were used for the renewable plants. The daily consumption profile (dashed line) was superimposed on the same graph on a separate axis (with the same scale and units). From this analysis, the excess energy production or deficit throughout the day was obtained to determine the capacity and duration of daily storage required. Transmission losses were also incorporated for generation plants (the same transmission loss factors and assumptions from the generation assessment were applied).

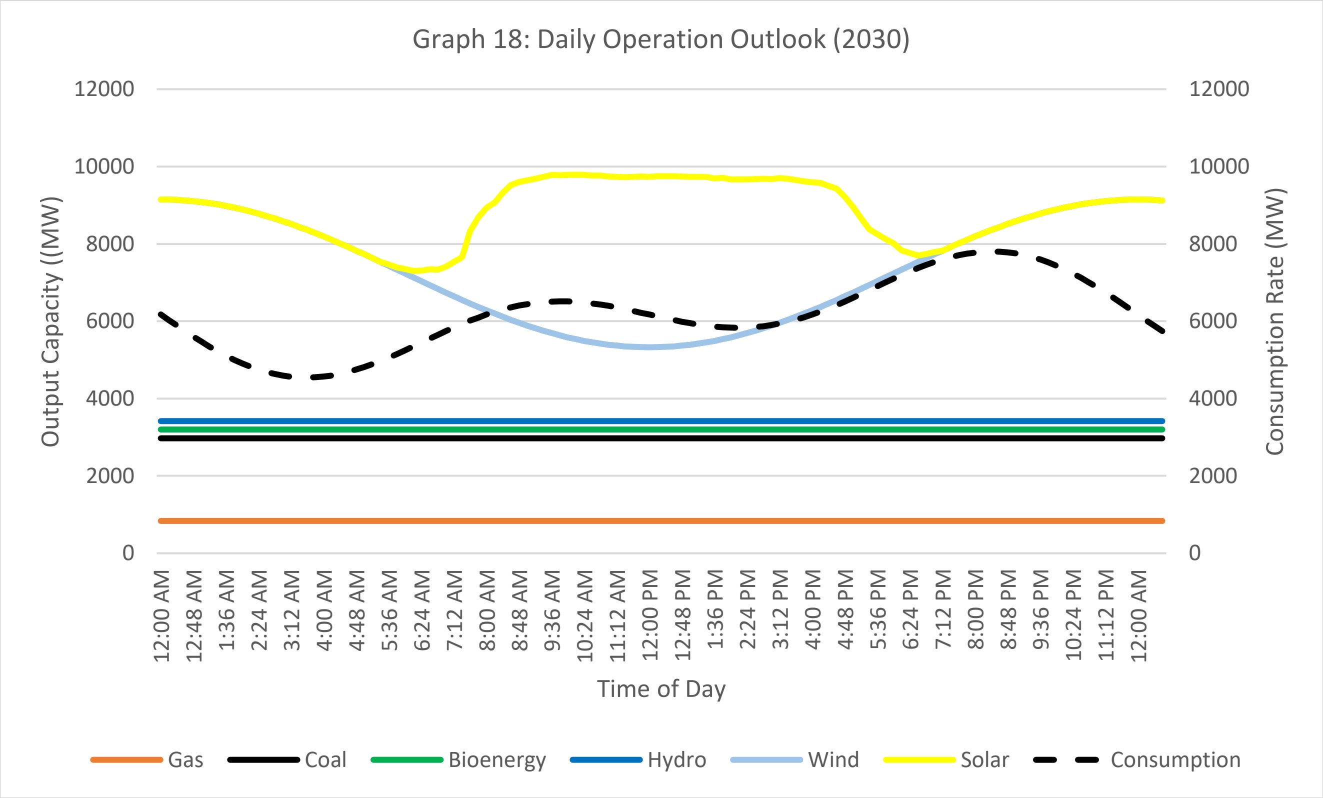
In the graphs below, the total excess or deficit energy (GWh) is the integral of the difference between the dashed consumption profile and the topmost cumulative generation profile. All specific values can be referred to in the Excel 'Storage' sheet. This can be compared to the available storage values for the relevant year (refer Table 19). The duration of required storage is the time period during which the dashed consumption curve is above the cumulative generation. The areas of interest have been annotated on Graph 17 below.

Graph 17: Daily Operation Outlook (2025)

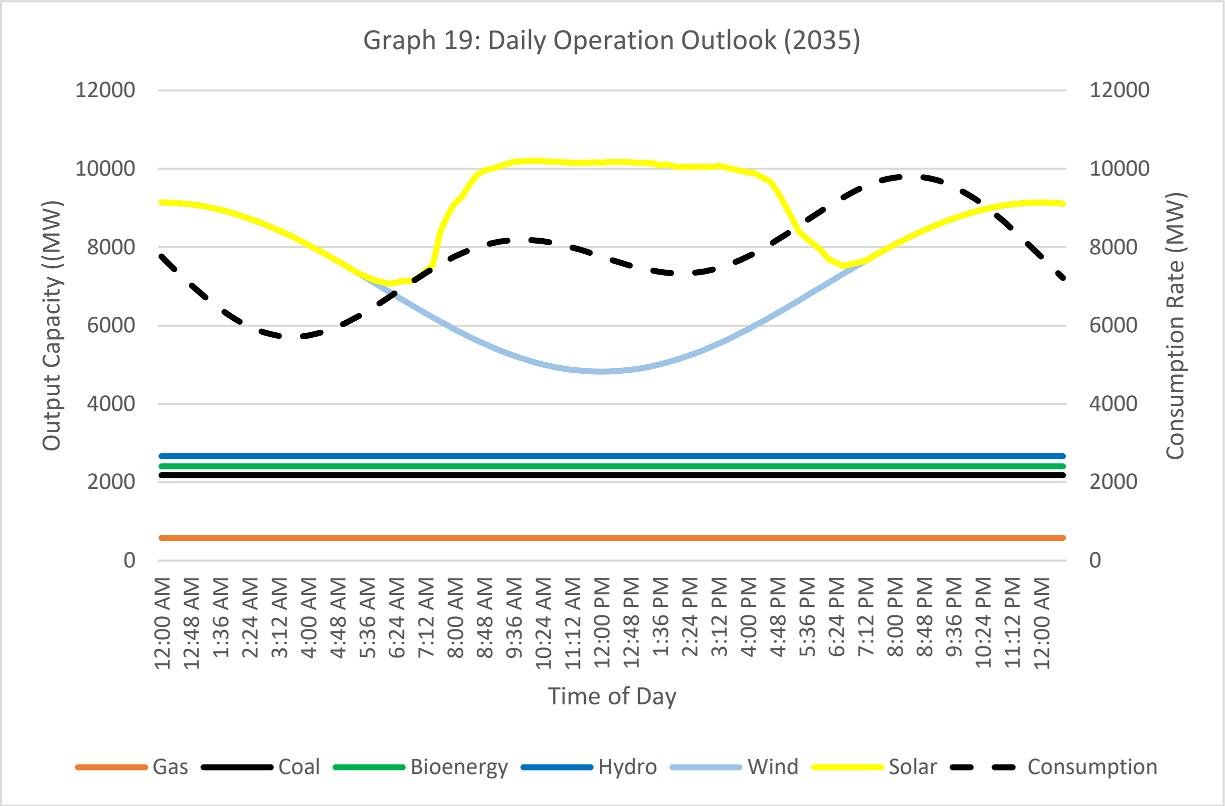


Graph 17 provides a general insight into the daily operation of the grid in 2025. Although this information is accurate, it omits peaking gas generation which would account for the small deficit that occurs at around 6:30pm; the grid system will unlikely be reliant on BESS and PHES storage in 2025. Regardless, the total excess energy produced relative to consumption is positive 44.1 GWh and thus indicates that the grid is self-sustainable; this is a significant excess that must be managed to avoid energy wastage and to regulate spot prices. The effective required daily storage of 1.7 GWh is easily covered by the installed 15.5 GWh, or peaking gas storage. It is interesting to note the time at which this storage is required is at the shoulder of the solar production as the consumption reaches its peak for the day.

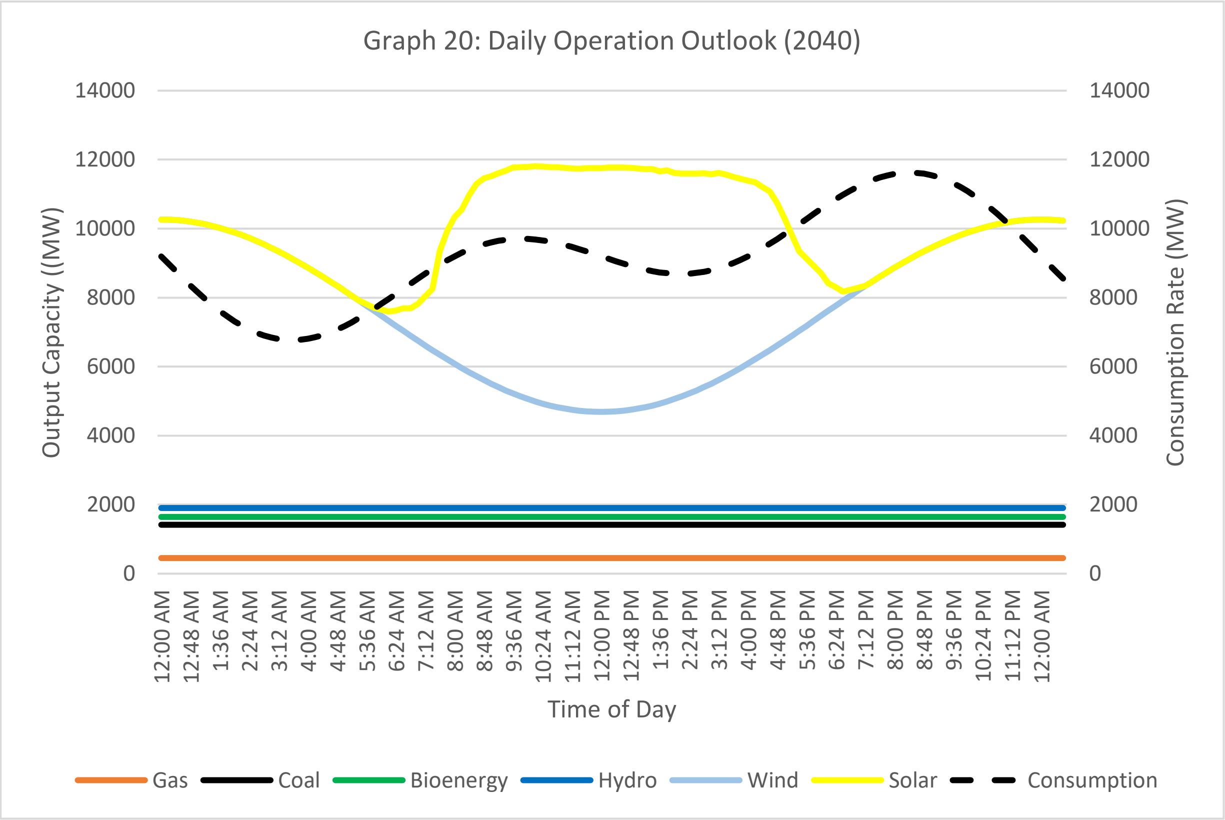
Graph 18 provides the daily operational outlook for 2030. This graph demonstrates the magnitude of excess energy relative to consumption which was previously identified in section 3.3. According to this model (which as previously discussed likely overestimates generation forecasts), daily storage is not required for the average day-to-day operation of the grid system in 2030. In total, an excess of positive 64.2 GWh is produced daily which must be managed if the generation fleet follows the current development forecast.


Graph 18: Daily Operation Outlook (2030)

The 2035 Queensland grid daily operational outlook is displayed in Graph 19 below. It is evident that by 2035, that storage is required for daily operational requirements. The total energy excess produced is a substantial decline from 2030 at a positive 34.4 GWh, indicating again that the daily grid operation is self-sustainable. The total daily storage required is 6.3 GWh over a period of 5.2 hours from approximately 5:00pm to 10:30pm at night. Compared to the available grid storage by 2035 of 237.4 GWh, this storage requirement is easily fulfilled with the forecasted infrastructure. The proximity of the consumption curve to the cumulative generation profile suggests that soon beyond 2030, as coal declines and consumption increases, the consumption will surpass generation on the solar production shoulder. Thus, storage is required soon beyond 2030.


Graph 19: Daily Operation Outlook (2035)

Finally, Graph 20 below displays the daily operation of the Queensland grid in 2040. It is immediately evident that daily storage solutions are required at multiple times during the day, the first of which occurs at the beginning of the first consumption peak at 5:30am to 7:00am before solar production increases. Storage is then required again between 5:00pm and 11:00pm when solar production reduces and the second consumption peak occurs. The total duration of storage is 7.6 hours, requiring a net 12 GWh of storage; this storage requirement is accounted for by the forecasted grid storage level of 242.6 GWh (refer Table 19).


Graph 20: Daily Operation Outlook (2040)

The graphical results have been summarised in Table 20 below. Excluding the 2025 anomaly accounted for by peak gas generation, it is again evident that grid storage will be required from around 2030 onwards. The total excess energy production must be effectively managed to mitigate inefficiencies and control the electricity spot market. The forecasted implemented storage should suffice the storage requirements from the daily operational perspective of the Queensland grid.

Table 20: Daily Storage Operation Outlook

Data Type	*Unit*	*2023*	*2025*	*2030*	*2035*	*2040*
Total Excess Energy Produced	*GWh*	-	44.1	64.2	34.4	32.6
Total Deficit Energy Required	*GWh*	-	0.5	0.0	6.3	12.0
Net Excess Energy Produced	*GWh*	-	43.6	64.2	28.1	20.6
Daily Storage Required	*GWh*	-	0.5	0.0	6.3	12.0
Duration of Storage Required	*h*	-	2.8	0.0	5.2	7.6

It is important to note that these results are based on an average production and consumption forecast. These parameters vary significantly depending on various factors such as the time of year and weather conditions.

5.4.3 Renewable Drought Outlook

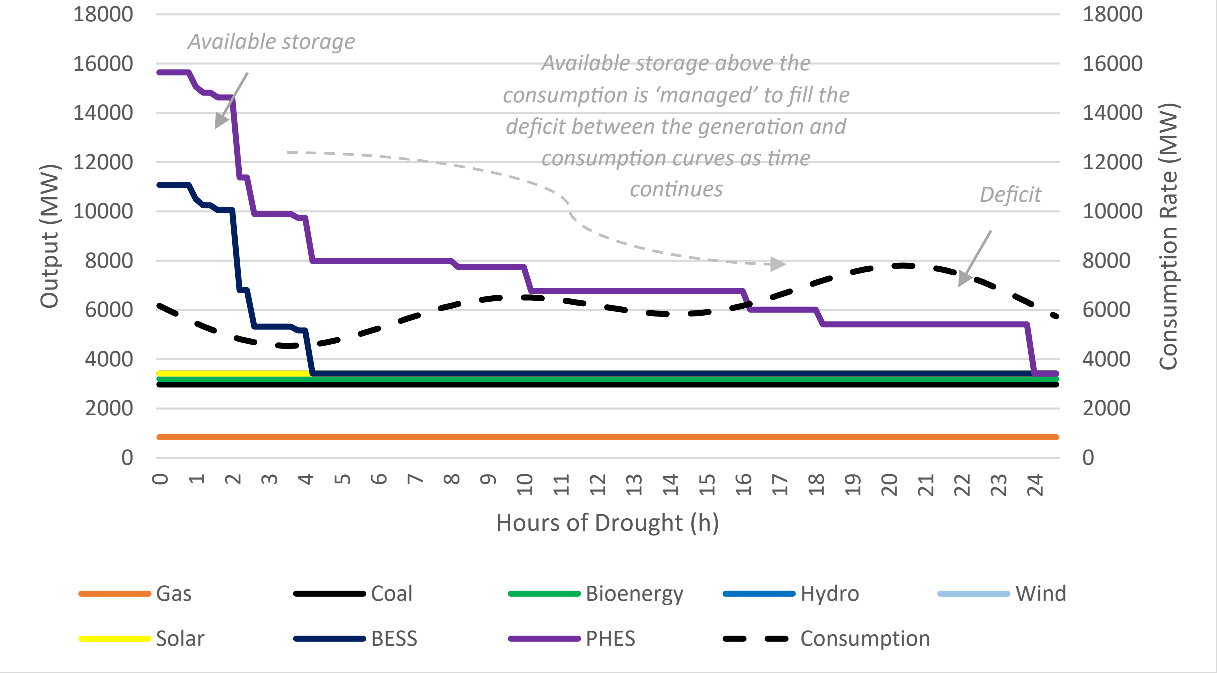
The renewable drought outlook involved a similar approach to the daily operation outlook; however, the drought model applied a ‘drought factor’ to wind and solar generation facilities. This was done to simulate a reduction in renewable generation from external factors, primarily unfavourable weather conditions (cloud cover and lack of wind). Furthermore, the storage facility contributions were added onto the ‘drought’ generation (total generated energy with applied drought factor) to extract information regarding the grids ability to handle extended periods of minimal renewable production.

Initially, the renewable drought scenarios considered a renewable factor of 0% for both wind and solar production in attempt to assess the baseline capabilities of the installed storage in the Queensland grid. The transmission loss factor and phase in factors for plants with unknown commission dates were kept consistent with the previous daily operational model (all unspecified facilities were assumed to be fully operational from 2040 onwards).

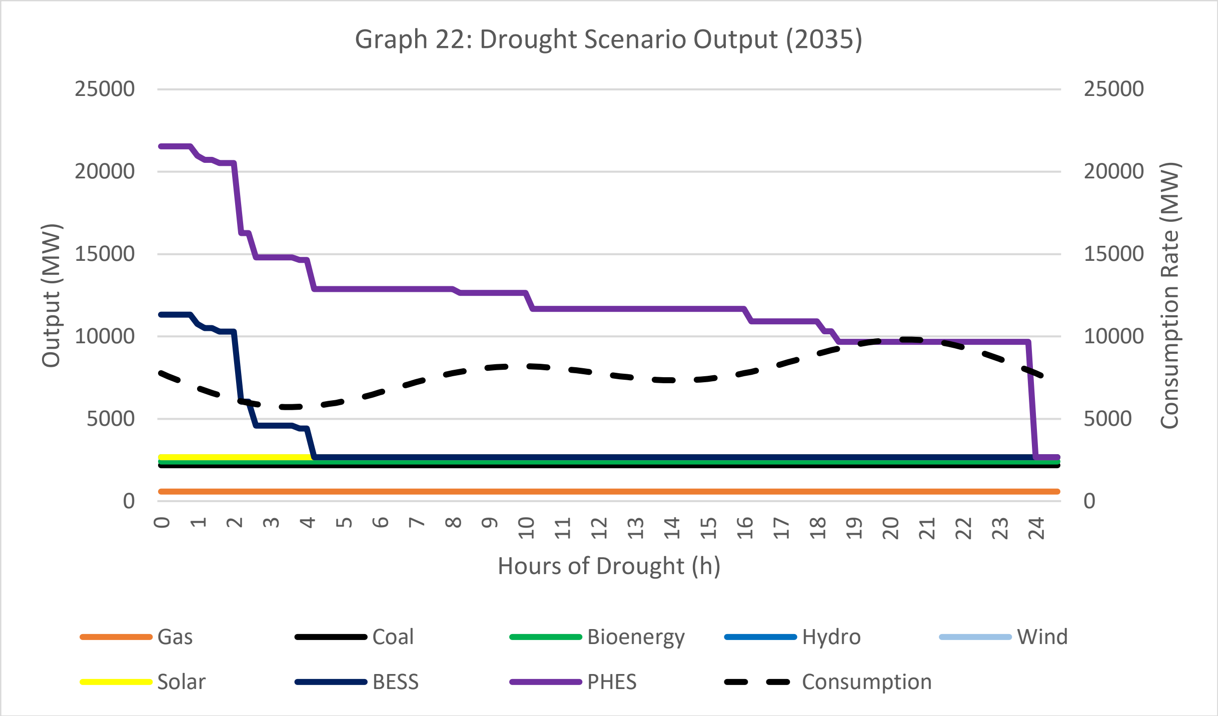
A stacked line graph was used to visualise the individual contributions and cumulative sum of all output types during the drought. The topmost profile corresponds to the total potential output while the vertical difference between two solid lines is the contribution of respective output types (either generation or storage facilities). Average capacity factors were used for non-renewable sources such as coal and gas while the variable capacity factors introduced in section 5.2 were used for the renewable plants (not applicable for the 0% renewable scenario). The daily consumption profile (dashed line) was superimposed on the same graph on a separate axis (with the same scale and units). The horizontal axis represents the hours from the commencement of the drought.

It is important to note that the graphs show the maximum storage output from 0 hours (refer Graph 16). This is for visualisation purposes only as the Excel model calculates the amount of storage required to meet the consumption curve and removes this from the total amount of available storage above the curve (only if the consumption is greater than generation, refer to the modified consumption formula in Table 18). Then, once the storage has run out, the model records the duration that the grid remained operational. The recharging of storage facilities during periods when the consumption was less than generation was not considered as this did not occur in the years considered (for the 0% renewable scenario).

From this hour-by hour analysis, information was obtained regarding the daily drought production, and the duration of feasible grid operation during the drought. Graph 21 below shows the drought scenario for 2030 considering 0% renewable production. It is evident that as the consumption continues beyond the shown 24 hours, the consumption will require additional support from the available storage reservoir (as annotated on the graph). The daily drought production at 0% renewables in 2030 is 82 GWh and the time the Queensland grid can remain operational is 36.3 hours (1.5 days).


Graph 21: Drought Scenario Output (2030)

Graph 22 on the following page is the drought scenario for 2035. This scenario has a similar outlook; however, as the majority of the state's storage facilities have been implemented by 2035 (refer Table 19), there is a large quantity of storage available relative to consumption. As a result, the duration of self-sustained operation is greater at 45.2 hours (nearly 2 days). The drought production in 2035 is 63.9 GWh per day of usable energy (after considering transmission losses).


Graph 22: Drought Scenario Output (2035)

Finally, Graph 23 shows the 2040 drought outlook, again at 0% renewable production. The storage and generation profile is similar to 2035; however, the consumption has increased according to the analysis in section 3.1.4. The daily drought production is 45.7 GWh per day of usable energy (after transmission) and the drought support duration is 32.2 hours (1.3 days). All results from the drought analysis have been summarised below in Table 21.

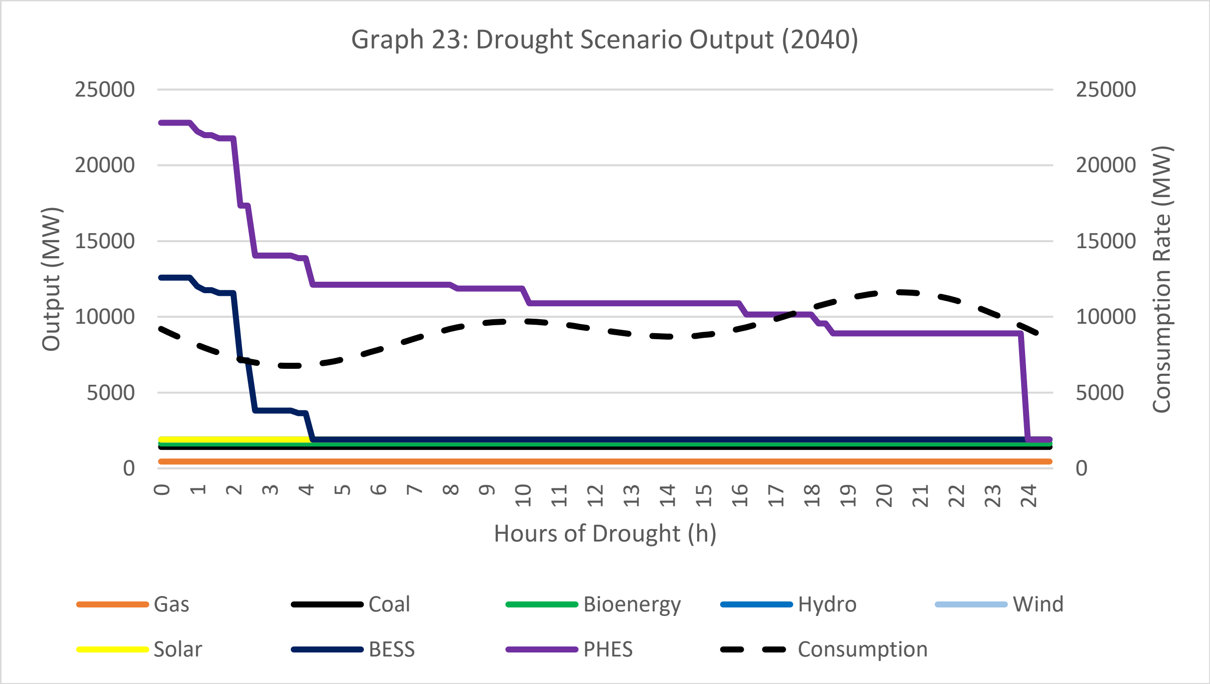
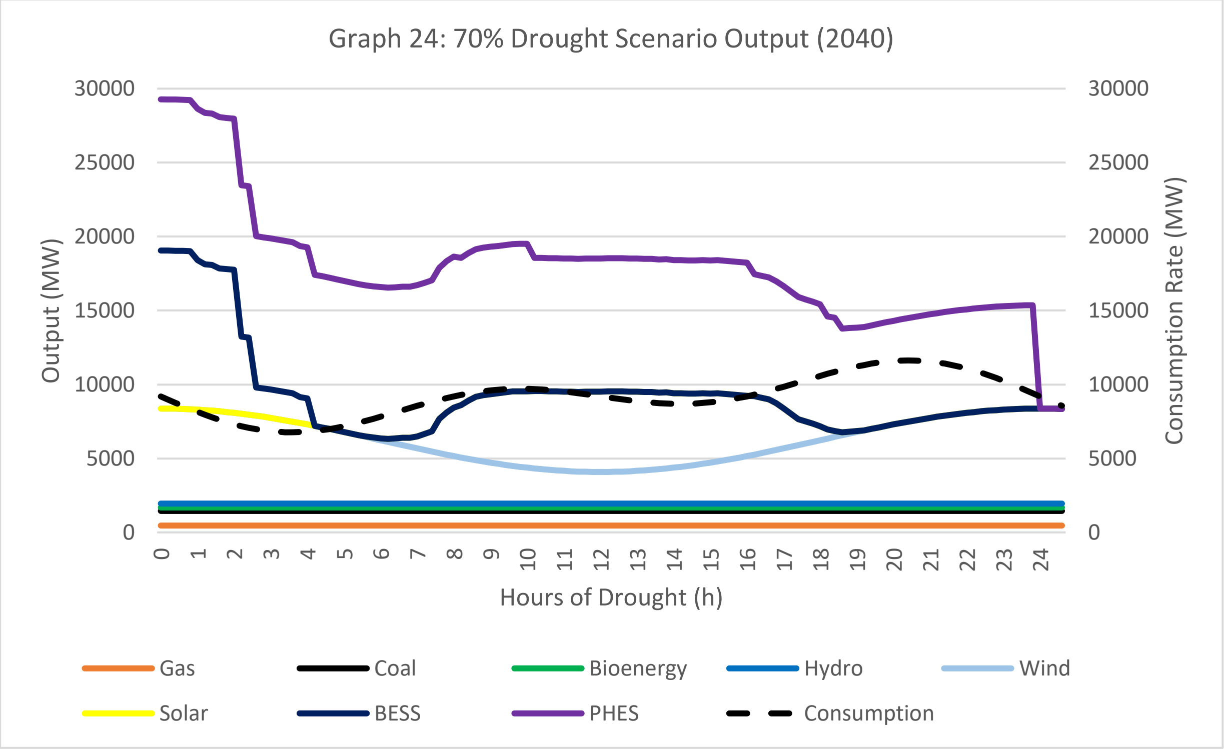

Graph 23: Drought Scenario Output (2040)

Table 21: Renewable Drought Outlook Results Summary

Data Type	*Unit*	*2023*	*2025*	*2030*	*2035*	*2040*
Daily Drought Production	*GWh*	120.4	118.0	82.0	63.9	45.7
Battery Storage Available	*GWh*	6.0	15.5	103.2	237.4	242.6
Daily Consumption	*GWh*	124.9	100.6	148.1	186.2	220.7
Drought Support Duration	*h*	-	-	36.3	45.2	32.2

Using this drought outlook model, an iterative approach was adopted to assess different scenarios for the long-term grid system (beyond 2040). The drought factors were varied to determine the minimum renewable generation required for the grid to sustain a week of operation. Following the iterations, it was determined that a drought factor of 70% would support the grid operation for approximately one week. The corresponding Graph 24 below displays this scenario; the graph is difficult to conceptualise as it is a stacked line curve of various different storage and generation profiles but the same theory applies.



From this analysis it is evident that at the 70% drought factor (renewable production at 70% of their respective average productions), there are periods of time where the generation is greater than consumption. This significantly increases the duration of operation as the storage 'reservoir' is not required during these periods. Additionally, the storage facilities are able to partially recharge during these periods further extending the self-sustained duration; however, as previously discussed, recharging has not been considered in this model. This will not greatly affect the results of this particular 70% scenario as there are only very brief periods of possible re-charging.

Applying the same process, the drought factor was iterated to determine the 'critical drought factor', or the minimum renewable energy generation (relative to the average), required to completely self-sustain the grid indefinitely. This value was determined to be approximately 80%. Thus, if the state-wide renewable wind and solar generation operates at approximately 80% of their average production, the grid should be self-sustainable. It is important to note that excluding storage recharging in this analysis significantly affected the determination of this critical drought factor, and thus the value obtained is very approximate; this is discussed further in 5.5.1.

5.5 RQ3 Discussion

There were various findings from the implemented analysis and models from which an assessment can be made regarding the feasibility of the grid storage system. This analysis primarily focussed on the short-term, (STS) and medium-term storage (MTS) which extended to 24 hours of operation. As evident from the daily operational outlooks, this is the first crucial scope of energy storage as without STS, the grid is unable to operate on a day-to-day basis. Beyond this time-frame, it was evident from the drought modelling that there has been little consideration towards long-term (LTS) or seasonal storage options (SS). This is a major issue in terms of grid operation during reduced renewable production and forms the major conclusion of this investigation.

The Queensland Energy plan states that long duration assets have significant development and deployment time with greater capital costs and significant approval requirements and uncertainty; therefore, these facilities are, "*unlikely to be developed by the private sector on a merchant basis*" (QLD Gov, 2022). Furthermore, it was stated that these assets are of high strategic importance to the Queensland energy system and support of Queensland's macro-economic strategy; however, despite significant research, there has been no significant government or commercial attention directed to storage solutions beyond a 24-hour duration for the following decades; this is a significant omission in the energy plan and provides doubt surrounding the current long-term outlook of the feasibility of the energy plan.

Aside from fossil-fuel generation, PHES facilities are currently the most common form of LTS and SS with over 95% of global storage being attributable to these facilities (NYSERDA, 2023). Unfortunately, Queensland has limited options for long duration (greater than 24-hour) PHES plants due to the lack of natural advantages in terms of elevation and mountain ranges. Other LTS options may include compressed air or gravitational storage; however, these technologies are still highly experimental and are not in common practice.

Perhaps the most viable option for LTS and SS in Queensland is hydrogen energy. This aligns with the potential development of the Queensland hydrogen industry which is expected to grow with increased renewable penetration and possible foreign markets (EY, 2022). As of 2022, Australia had over 100 hydrogen projects in the pipeline and the world's second highest planned capacity of electrolysers to be online by 2030. Furthermore, Australia became the first nation globally to export Hydrogen during a trial export to Japan in 2022. Australia is expected to export 3 million tonnes annually by 2040 making it a $10 billion economy. Other countries interested in hydrogen energy are Germany, UK, Netherlands, South Korea, India, Singapore, and the USA. South Korea, Singapore and Japan provide the greatest locational advantage for the export of hydrogen from Queensland (Aus Gov, 2023). Thus, this momentum towards hydrogen production provides an ideal foundation for the implementation of an LTS and SS solution.

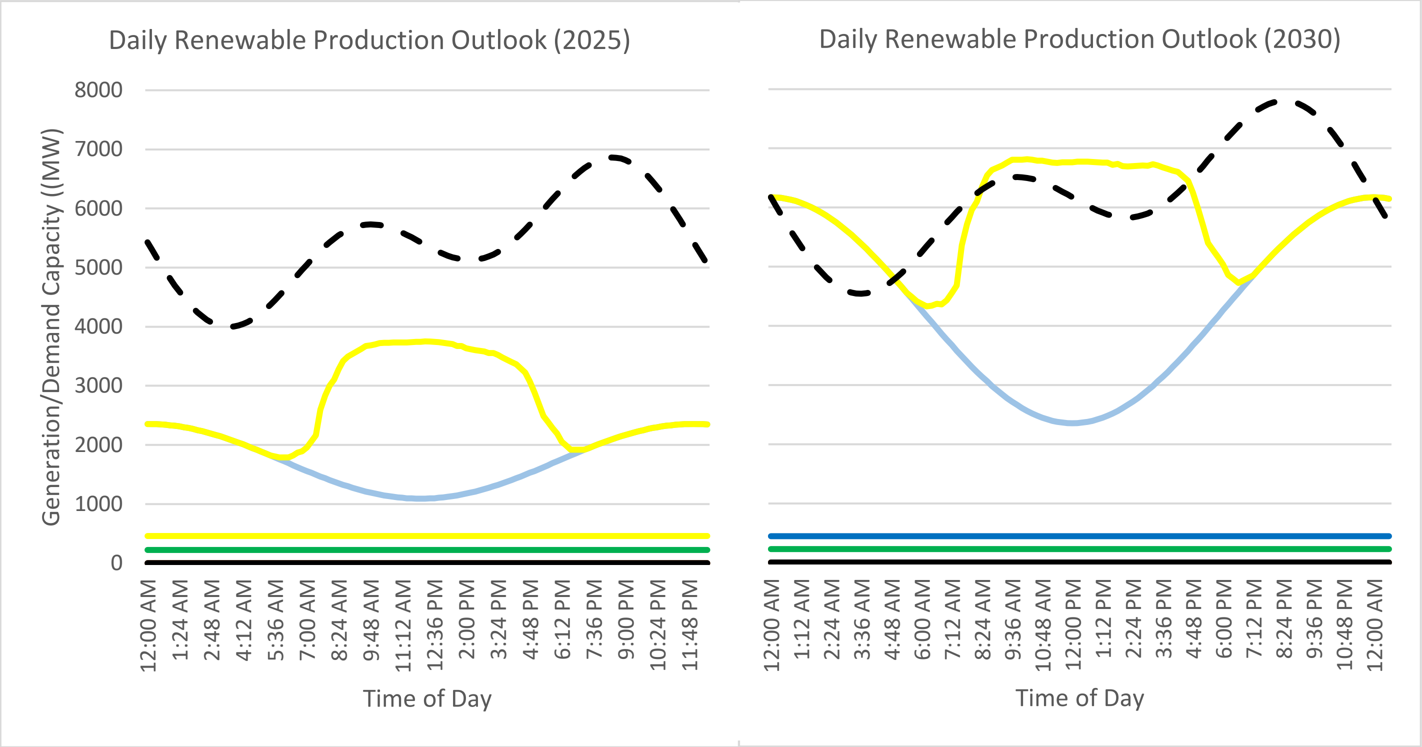
Another issue surrounding LTS is the lack of profitability for investors to supply this service. As evident in the drought scenario model, extended periods of low renewable production must occur before LTS is required. As a result, there is high uncertainty for return on investment for LTS providers. Government incentives may be essential to attract additional stakeholder interest or government owned LTS facilities may be required. If the hydrogen industry and associated infrastructure grows, utilising stored hydrogen as an LTS option alongside export opportunities would provide a profitable option. Hydrogen producers can either export hydrogen abroad, or sell it domestically during periods of high demand (renewable droughts). This increases business opportunities and reduces the economic risks for these suppliers. It is important to note that the infrastructure requirements for hydrogen energy are extensive, and the risks of transport, storage and generation are also very high which must be managed with use of this technology.

Interconnection with other states will also provide Queensland with additional LTS support as different states have different geographical features, storage options and generation profiles. AEMO has stated that they will, "*consider benefits of increased interconnection between New South Wales and Queensland, and recommends that Powerlink and TransGrid initiate a regulatory investment test for transmission (RIT-T) to increase interconnector capacity and reduce the likelihood of reserve deficit in either region*" (AEMO, 2019). This interconnection was considered out of scope for this analysis but would provide support during renewable droughts in Queensland.

In terms of the output capacity of the storage facilities across QLD, AEMO believes that according their current Queensland demand forecasts and energy market modelling, the state is expected to need, "*at least 6,000 MW of long duration storage for a highly renewable system, complemented by up to 3,000 MW of grid-scale storage, and up to 3,000 MW of new low-to-zero emission gas-fuelled generation and the existing interconnection to New South Wales to meet demand*" (QLD Gov, 2022). Although this statement does not specify the actual duration of storage required (MWh), the minimum cumulative capacity output of the gas generation, and storage facilities is outlined to be 12,000 MW (AEMO's definition of long-term storage is less than 24 hours, again indicating the omission of LTS and SS storage in the proposed system). Referring to Graph 20 for the highly-renewable system in 2040, it is evident that at maximum demand approximately 12,000 MW of output capacity is required without the contribution of renewables. Thus, this statement is correct in terms of the minimum requirement; however, the operation of the grid depends on the duration of this storage which again, has not been provided in detail.

Furthermore, AEMO has also stated that, "*from 2025, there are forecast to be times when the NEM will have enough renewable energy resources to meet 100% of its demand*" (AEMO, 2022). The daily operational model can be used to assess the validity of this claim in Queensland. The non-renewable generation capacity factors (coal, gas) were set to 0% and the daily renewable production in 2025 and 2030 have been provided on the following page in Graph 25. It is evident that the renewable production will not be close to exceeding consumption during normal operation in 2025; however, by 2030, renewable production will meet 100% demand during certain hours of the day (during the peak of the solar production and the midday dip in consumption). Thus, the modified statement according to this analysis should read, "between 2025 and 2030, there are forecasted to be times when the Queensland grid will have enough renewable energy resources to meet 100% of its demand".

Graph 25: Renewable Production Comparisons



A brief assessment of various other parameters for the different storage types has been conducted below in Table 22. Many of these parameters were considered out of scope for this analysis, and thus this summary provides a brief insight into these factors.

Table 22: Storage Facility Additional Information

Parameter	*BESS*	*PHES*
Energy Density	Batteries have a very high energy density relative to PHES. The various battery type energy densities can be referred to in Appendix 11 (EPEC, 2023).	PHES energy density depends heavily on the plant specifications and reservoir heights; however, PHES have a relatively low specific energy density which is countered by the large volume of stored energy in the reservoirs.
Recharging Time	The rate of recharging is much higher for batteries when they are fully discharged. Battery recharge time depends on numerous factors including inverter and transmission connections, and power supply; however, recharge typically takes less than 12 hours for most systems. For average systems in optimal conditions, it takes 5 to 8 hours to recharge a battery using solar generation (Bolt, 2023).	A pumped hydro recharge duration is typically longer than the discharge duration. This again depends on various factors including turbine and pump specifications. In terms of reservoir filling, an initial flow of water is required. For example, Pioneer will take 2 wet seasons to fill the pumping reservoir (QLD Hydro, 2022). The same applies to the Borumba PHES plant (QLD Hydro, 2023). Note that water lost from evaporation is minimal and is accounted for by general rainfall.

Cycle Efficiency	Battery cycle efficiency generally declines with the aging of the facility. Typically, a BESS plant full cycle efficiency is around 80% with lithium-ion batteries having an efficiency closer to 90% (59).	PHES facilities are typically, around 70 - 85% efficient through a full cycle. This efficiency remains relatively consistent regardless of the age of facility or extent of discharge (59).
Response Time	Battery response time is almost instant (Origin, 2023). Although batteries do not provide system inertia as there is no electromechanical coupling, BESS plants are thought to contribute synthetic inertia (refer section 4.3.2). This makes batteries an ideal technology for PFR and grid regulation. Batteries are also able to provide black start services where they do not require energy to start in the event of a blackout.	Depending on the plant configuration, PHES facilities can ramp up output generation from stationary to maximum pumping capacity within less than five minutes (EERA, 2019). This is faster than most turbine-driven generation technologies which makes PHES plants an option for energy regulation control.
Energy capital cost	Lithium-ion battery costs have seen a 70% decline in from 2010-2016 and are projected to decline further (NREL, 2019). Overall, batteries are most cost effective for delivering small amounts of stored energy at high power levels.	PHES plants are much cheaper for long term storage; however, the initial capital costs are more significant, requiring the construction of large reservoirs and generation facilities (Stocks, 2021). PHES facilities generally have a longer lifetime to offset this initial cost.
Lifecycle	The cycle life of batteries depends heavily on the depth of discharge. For lithium-ion batteries, this relationship can be seen in Appendix 10. Typically, batteries can last around 10,000 cycles depending on intensity of use (ScienceDirect, 2021).	The lifetime of the generation aspect of a PHES plant is typically between 30 to 60 years depending on the facility type. The dam reservoir infrastructure typically lasts much longer (EESI, 2019).

It is evident that BESS and PHES facilities provide unique contributions to the grid storage system. Both technologies are essential to a diverse and reliable grid; however, neither technology provide LTS or SS solutions.

5.5.1 RQ3 Sensitivity Analysis

This sensitivity analysis applies to the respective outcomes of the various storage forecasts developed. The data for the storage facilities was obtained from AEMO and various other websites and government documents amounting to 53 individual sources (refer 'Sources' column in the Excel spreadsheet). There is a low uncertainty in data collected as most facilities, especially large plants, have significant documentation and many are in early stages of proposal. The results obtained from analysis are highly dependent on a number of factors and variables which have been outlined below in Table 23. The assumed baseline (values used in the results) and proposed variance (range of values possible) for each parameter has been provided in the table; recall all parameters in the results were selected based on the CA. A quantitative explanation of the sensitivity of each variable and effect on results was provided through an OAT analysis. Note the qualitative effects of each variable in green can be easily assessed by using the Excel model provided and manually changing these inputs (also coloured green in the Excel document).

Table 23: RQ3 Sensitivity Analysis

Variable or Parameter	*Assumed Baseline*	*Proposed Variance*	*Sensitivity and Effect on Results*
BESS average storage time	The assumed baseline for the average storage time of battery plants was 2.4 hours. This was based on the calculation performed using 53 BESS plants with specified duration times.	Due to the nature of BESS facilities, this parameter likely has minimal variance. In terms of the BESS facilities with known duration times, the variance was 0.9 hours to 4 hours.	This parameter has a relatively low effect on the results as the proposed variance is low. If the assumed storage time was increased to 4 hours, the effect on the daily operational outlook is negligible, and the effect on the drought scenario is a slightly extended support duration (in the order of a few percent). Note this average value can be varied through manual override of the formula in cell I399.
Inclusion date for facilities with unknown commission dates	8 BESS facilities had unknown commission dates, seven of which amount to 429MW of output capacity. The Bulli-creek solar farm has the potential development rights for a further 1,600MW. Thus, at a maximum, there is 2,029MW of BESS facilities not included.	All of these facilities had the assumed average BESS storage time of 2.4 hours. The total variance of this parameter involves the degree of inclusion of these facilities. Thus, the total variance is the complete exclusion to complete inclusion of these facilities.	This parameter has a relatively little effect on results. If these facilities are not included at all, the 2035 and 2040 storage forecasts are the same. The flow-on effect in the other models is also relatively little with changes in the fundamental results (in the order of a few percent).
Phase in period for facilities with unknown commission dates	The model utilised assumed all facilities were fully operational from 2040 onwards (phased in from 2036 onwards). This was the latest year of inclusions possible.	This parameter has a very large variance. The facilities may never eventuate or commence development after beyond the scope of this model. Alternately, the facilities may begin immediate development and be operational by 2025 or 2030.	This phase in parameter effectively scales the effect of the inclusion year parameter in the row above. The model considered an instantaneous phase in period (value of 1), larger values will reduce the immediate effect of the inclusion of the facilities with unknown commission dates.
Renewable drought capacity factors	For the renewable drought modelling, the baseline for this parameter was 0%; however, multiple values were considered throughout the analysis.	The renewable drought capacity factor has a variance from 0% (no renewable production) to 100% (average production). The factor could realistically exceed 100% for greater than average production.	This parameter has a very significant effect on the renewable drought model. This was the intended purpose of this parameter as analysis involved varying the drought capacity to achieve the desired forecasted drought support duration. The various effects on results can be referred to in section 5.4.3.
Applied wind, solar and consumption profiles	The baselines for each respective variable profile can be referred to in section 5.2. These were based on average scenarios in Queensland.	These profiles can vary greatly in terms of shape and magnitude. The wind profile is the most inconsistent profile across Queensland while the solar profile remains relatively constant.	These profiles significantly affect the daily operation outlook models and drought scenario models. The effects depend on the shape and magnitude, both of which will affect the results regarding the total storage required, duration of storage required, and duration of drought support possible.
Non-variable coal and gas generation	The coal and gas had a constant contribution to the generation aspect of the storage model based on the facilities available and the capacity factor.	While coal remains relatively constant in practice, gas generation varies significantly based on demand response. Only few gas facilities run at a constant output rate.	A variable gas factor would have produced more accurate results in section 5.4.3. The magnitude of effect of this parameter diminishes for more distant forecasts as the gas contribution also declines.
Factors associated with the generation aspect of the model	Parameters outlined in the RQ1 sensitivity analysis in section 3.3.1 also apply for this model. This includes non-variable generation capacity factors, transmission losses, and the phase out parameters of coal plants. The variances of these parameters will affect the generation as discussed previously; however, their effect on the storage forecasts is high specific based on the parameter and section of results. Overall, these factors all contribute varying levels of uncertainty and variance to the results which can be assessed through varying the respective parameters on the Excel model.		

5.5.2 RQ3 Limitations and Recommendations

There are various limitations within the model developed and the associated results produced. Based on these limitations, the recommendations suggested below could be employed in future models and analysis to reduce the effect of these limitations and mitigate uncertainty in the results:

- The first and foremost limitation in this model was the absence of LTS and SS analysis. The model revealed the requirement for LTS but did not quantitively address potential solutions. Longer duration storage models using the discussed hydrogen solution could be developed to assess the requirements of this technology. This would involve an assessment of the developing hydrogen infrastructure in Queensland and the feasibility of this storage solution.
- A major limitation, particularly in the drought scenario modelling, was the omission of storage recharging and discharging parameters. Modifying the model to include parameters such as cycle efficiencies, recharging rates, and life-span efficiency declines would provide a more accurate insight into the long-term operation of the grid storage system. This would require a complex model that would apply various relationships dependent on storage technology type and specifications, grid connection, and extent of charging and discharging.
- The model used did not consider the management of storage facilities and only utilised information regarding the energy output and duration of BESS and PHES facilities without differentiating their operation. Thus, modelling the operation of BESS and PHES facilities to ensure optimal outcomes would provide valuable insights. This would involve discharging certain storage facilities for the most efficient outcome based on facility specifications.
- Another limitation discussed was the exclusion of inter-state grid connection. Improving the model to assess interconnection would provide insights into the compatibility of the Queensland grid with other state grid systems within the NEM. This would involve the diversification of generation profiles and possible reliance on storage facilities such as the planned Snowy Hydro 2 which would provide critical LTS support. This was out of scope for this analysis to conduct a feasibility of the Queensland system alone.
- Gas generation was included in the analysis as a constant generation source even though these facilities are typically peak-time operators. This was deemed appropriate for the scope of this model to assess the renewable technology contribution; however, this introduced limitations to the model. Firstly, this overestimated the excess energy generation results as gas facilities would not typically operate when production is greater than consumption. This could be improved by considering a variable gas factor only during peak consumption; this would involve matching the gas output curve with the consumption curve to produce the same average contribution.
- This model did not consider alternate forms of energy storage not directly coupled with the grid such gas storage. Further analysis should assess all forms of storage in terms of infrastructure and usage. Finally, the procurement, costing and locational aspects of storage facilities should be considered for diversified insight into the feasibility of the energy plan.

Note that if the provided model in the Excel file is used to replicate results, the appropriate figures must be input for the various parameters discussed in the sensitivity analysis. With the improved model suggested, further analysis could involve the assessment of different drought factor scenarios considering historic renewable droughts. Furthermore, more accurate results regarding the major findings such as the critical drought factor could be obtained. It is evident that there is significant improvement possible to expand the scope of this analysis and provide a more holistic analysis of the grid storage system.

5.6 RQ3 Summary

The aim of this third research question was to thoroughly assess the storage forecasts and requirements of Queensland's energy system to gain information regarding the technology types, breakdowns, and overall feasibility of operation of the grid from a storage perspective. The scope of this analysis involved the assessment of three aspects of the grid storage outlook for 5-year intervals until 2040: the state-wide forecasted storage output capacity and duration; the daily operational outlook and storage requirements; and the effects of renewable drought on grid operation. Storage data was obtained from over 50 individual sources from various providers, stakeholders, and grid management operators and was corroborated with additional sources such as news articles, and procurement plans where possible. An interactive and dynamic model was developed on Excel that enabled the input of various parameters to assist with the data analysis. The major findings and conclusions have been summarised below:

- Storage Capacity Forecast: Queensland's grid storage capacity is expected to significantly increase with the implementation of 34 BESS and 7 PHES facilities amounting to 242.6 GWh of installed capacity by 2040. The majority of this growth will occur between 2025 to 2035. The output capacity profiles revealed that combined BESS and PHES storage will provide an instantaneous response of more than 20 GW maximum output in 2040 that declines over the course of 24 hours. There were no storage facilities planned with a maximum output storage greater than 24 hours.

- Daily Storage Operational Outlook: In terms of the daily operational outlook, it was determined that daily grid storage was not required until beyond 2030 assuming average generation contributions from traditional and renewable sources. By 2040, 7.6 hours of daily storage was required on the solar production shoulders during demand peaks, amounting to 12 GWh. It was concluded that the forecasted storage installations will suffice average daily operational requirements.

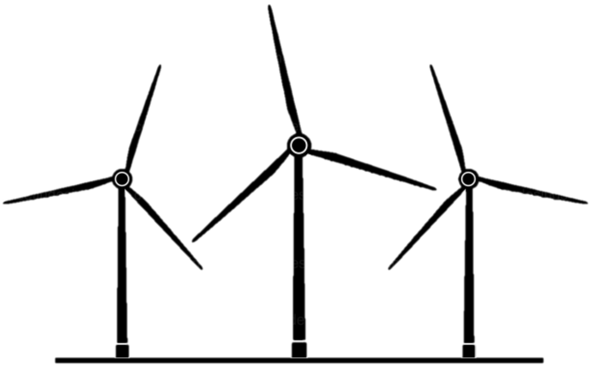
- Renewable Drought Outlook: Considering reduced renewable production, it was determined that with a complete blackout of state-wide renewable production, the 2040 Queensland grid would only remain operational for 32 hours. At 30% reduced renewable capacity (from the average generation level), the 2040 grid would self-sustain operation for approximately 1 week. The critical drought factor to ensure continued self-sustainable operation in 2040 was determined to be approximately 80% of average renewable capacity.

- Overall Feasibility: This analysis revealed that the immediate scope of the storage outlook has been considered by the energy plan; the STS and MTS levels are forecasted to provide sufficient storage services to facilitate daily operation beyond 2040. The broader scope regarding LTS and SS had not been addressed in Queensland by the government or the commercial sector. Thus, this is a major issue for long term operation; however, AEMO has considered interconnection possibilities with other states which will mitigate this issue.

- Solution: The proposed solution for LTS was the use of hydrogen energy technology. This would provide an effective, high-energy density, long-term storage and would ideally align with the developing hydrogen industry in Queensland. This would also mitigate issues surrounding uncertainty in investment attraction such as profitability.

- Data Collection: The storage data collected for the model proved to be more consistent and updated than the collected generation data. As a result of this more available information and resources, the produced results have lower uncertainty than previous models. Despite this, there are still various limitations and variables within the models that result in potential uncertainty and high sensitivity to inputs.

Overall, from a storage perspective, the energy plan demonstrates that sufficient attention and development has been directed towards the STS and MTS solutions; resultantly, the daily operation of the renewable-based grid beyond is forecasted to be feasible beyond 2040. Contrarily, there has been limited resources directed towards LTS and SS from the government or associated operators and providers; thus, the drought modelling revealed significant issues in the sustained operation of the grid during reduced renewable generation. Hydrogen energy provides a potential solution to the long-term storage but is dependent on the development of this industry and infrastructure in Queensland. LTS solutions should be modelled in future analysis and storage management parameters such recharging and discharging factors should also be incorporated. Effective planning and potential government incentives may be required to holistically address all aspects of storage operation in the Queensland energy system.



6.0 RESEARCH QUESTION 4

Grid Transmission

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February 2024
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CMES Energy Futures Reports

6.1 Grid Transmission Overview, Assumptions and Scope

In an attempt to analyse the transmission aspect of the Queensland grid system, the proposed transmission network was assessed in detail. This was the final step of analysis as a part of the feasibility study of the Queensland Energy Plan and forms the connection between all previously analysed components. Transmission connects all aspects of the grid and thus is a critical focus during the transition to variable-generation based grid system. The major component of focus will be the statewide transmission rather than small distribution networks.

The scope considerations and assumptions made throughout the collection, processing and analysis of data have been summarised and justified below in Table 24. These considerations attempt to simplify the models used in order to produce meaningful results. All previously stated scopes and assumptions apply to where relevant in this section of analysis.

Table 24: Energy Generation Scope and Assumptions

Description	*Justification*
The transmission assessment was conducted considering the changing generation load.	This section primarily focusses on the transmission feasibility outlook as a result of the changing generation mix and load. This was done to maintain consistency with previous research, and to simplify the scope of analysis; this will provide an insight into the feasibility of the system with overcomplication.
The costing and procurement are out of scope for this analysis.	Although these aspects are crucial to a holistic feasibility assessment, this report is applying an engineering analysis to the feasibility which applies to the mechanics of the system rather than assessing the economic and political factors.
For the purpose of this assessment, inter-state grid connection has been considered out of scope. In reality, the NEM operates with multiple small sub-systems that are all connected and interdependent.	Although Queensland is connected with multiple other states in the NEM, for this analysis, only the QLD-based consumption and facilities are considered to narrow the scope. It is important to note AEMO has stated that there are benefits in increasing interconnection between New South Wales and Queensland. Despite this, QLD is considered as an individual system for this analysis.
This transmission assessment considers average peak operation without the analysis of contingency events and abnormal load spikes.	The weekly, monthly, and seasonal variances have not been considered, rather an average peak operation was conducted. This was to best capture the average performance aspects of the transmission network.
This model does not include the potential decline in performance that occurs with varying conditions from environmental aspects or aging equipment.	This was out-of-scope for this general feasibility assessment to avoid excessive complications. Weather conditions are an important factor to consider to mitigate risks and increase the reliability of the transmission network. In terms of aging equipment, the transmission network is currently in the infant stages of a large scale upgrade and construction and thus aging factors have minimal application.
All assumptions applied to the generation and storage facilities also apply	The same transmission assumptions from the generation analysis apply to this section. It was assumed that there was lower to negligible transmission losses for generation facilities as these plants are situated much closer to consumption locations.
Modelling simplifications and assumptions can be referred to in section 6.3.	This includes the narrowing of the scope so the only aspect of the transmission network being assessed was the transmission lines. Substations, inverters, transformers, and other aspects of the grid have not been included.

6.2 Grid Transmission Relevant Theory

The primary purpose of the transmission network is to provide the most efficient means of interconnection between generation and load centres whilst facilitating system support. Section 3.1.2 provides previously researched theory regarding transmission losses which is partially relevant to this research question. The current Queensland system consists of an expansive 275kV transmission network that has been incrementally developed with the growth of Queensland's energy requirements. Energy is transmitted via an alternating current of 50Hz (refer section 4.1).

6.2.1 Transmission Network Specifications

There are numerous aspects that form an effective transmission network. As outlined in the scope, the primary focus of this investigation are transmission lines, in particular the capacity and load bearing capabilities of the network. Powerlines are characterised by various properties, all of which affect the performance and applications of the line including:

1. Transmission distance: The transmission distance of powerlines is determined by the factors listed below, ultimately the transmission distance is optimised to reduce capital costs of construction, and operational cost such as maintenance and transmission losses:
    - Locational aspects of connected facilities including generation, storage, and stability plants.
    - Location of load centres which are primarily situated in densely populated areas or industrial zones that require large energy consumption. In Queensland the primary load centres are along the east coast and in South-East Queensland.
    - Geographic features can affect the transmission distances of power lines. Mountainous terrain, river systems and deserts must be accounted for when constructing powerlines and thus these aspects affect the overall distance and location of powerlines.
    - Existing infrastructure, and accessibility also affect the location of powerlines and their transmission distances. Network infrastructure must be easily accessible for maintenance and repair, and thus most lines follow amin roads and transport routes.

2. Foundation and support infrastructure: The type of infrastructure that supports powerlines affects the performance and capabilities of the network. These aspects include substations, transformers, connections, regulators, inverters, power-pole construction (pole design, pole material, pole height, insulator design etc.). Some standard power-pole constructions in the NEM can be seen below.

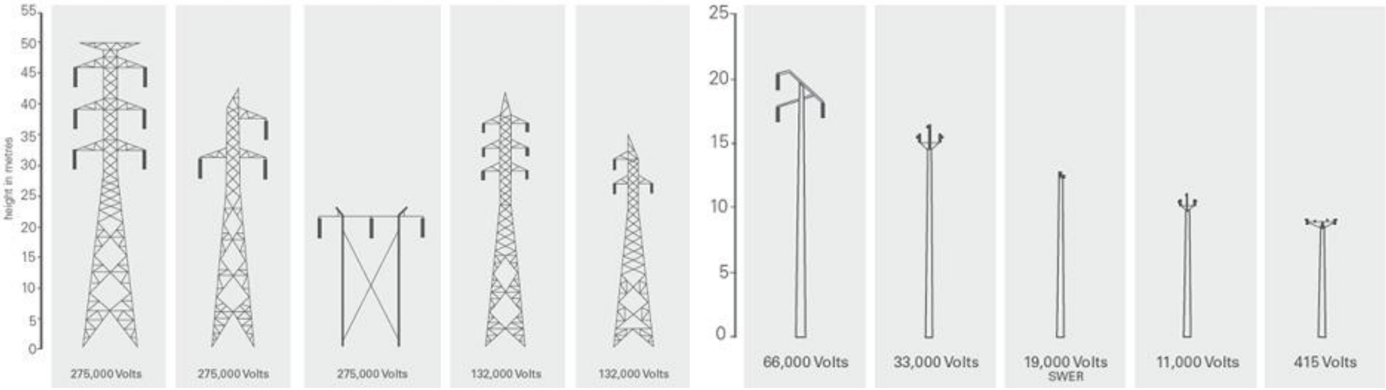


Figure 26: Common Powerline Pole Infrastructure Configurations in the NEM

This figure shows the design of some power pole structures commonly used in Queensland. An interesting observation is the increasing height with higher voltages (Gov of SA, 2023).

3. Line Specifications: This is the primary factor that determines the capabilities of a powerline. This includes the physical design, parameters, and material of the conductor used. The design of the transmission line including material and cross section are out-of-scope of analysis.

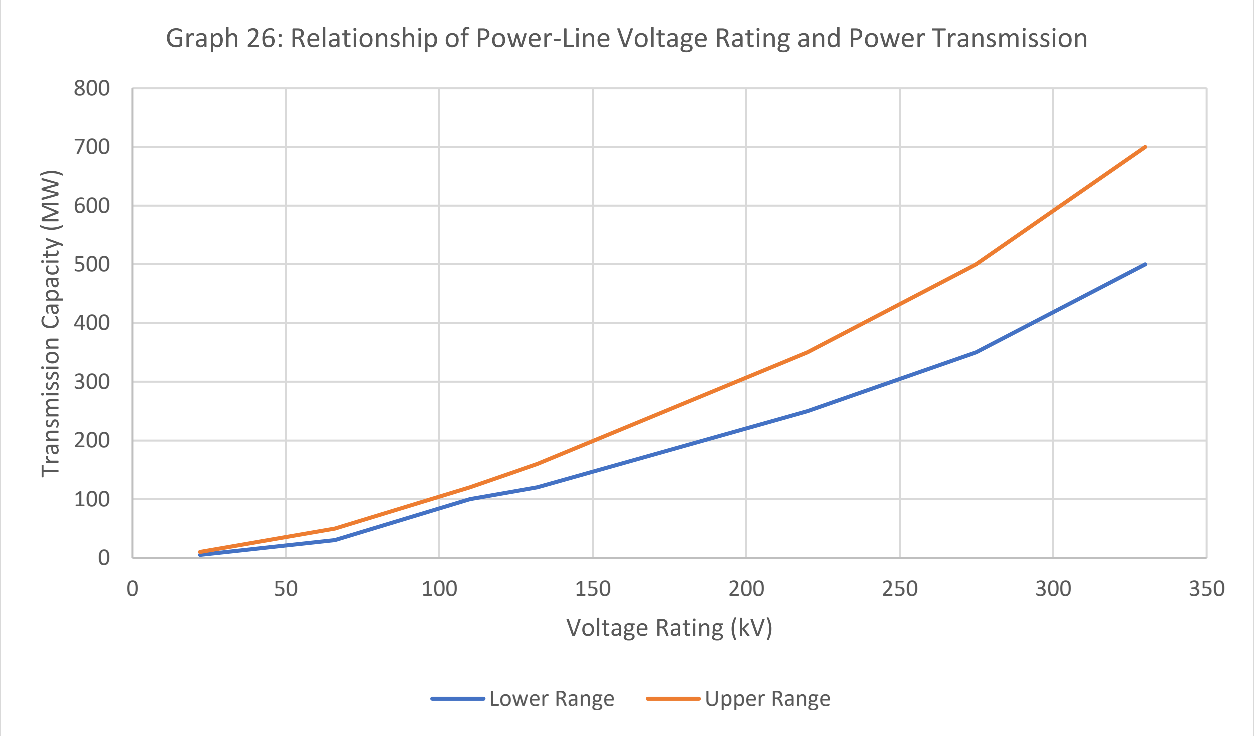
All parameters are interconnected and aim to produce the most efficient network attainable. Due to the various relationships involved with transmission networks, it is evidently difficult to assess all aspects; considering the approach to the previous research questions, the scope was narrowed to the feasibility of energy transmission based on the changes forecasted in the NEM. Thus, the primary parameter of focus is the voltage rating of power lines which indicates the transmission capabilities. Fundamentally, the power transmitted by an electrical conductor is given by the previously stated equation (1).

Powerlines are rated according to their transmission voltages (V) which remain relatively constant during operation and thus current (I) and power (P) fluctuate in proportion. Although the actual relationship is far more complicated due to the dependence on numerous conditions and parameters, this equation demonstrates that powerlines have a range of power transmission capacities for a fixed voltage specification. Powerlines typically operate within a certain range of power transmission rates (again based on various parameters such as loss reductions and resistor properties) which were researched and summarised for use in the calculations; this provided a means of simplification as determining specific power line power rate would require an extensive model. The standard transmission lines used in the current and planned Queensland grid system have been summarised below in Table 25 with their associated power ratings (USDI, 2019) (EMFs, 2019) (DehliSLDC, 2023) (Enerdata, 2022). Various sources were used to corroborate these values; for example, AEMO states that, "*a 500kV line has around three times the power capacity of a 275kV*" (AEMO, 2022).

Table 25: Power Line Transmission Capacities

Line Voltage Rating (kV)	*Transmission Capability Lower Range (MW)*	*Transmission Capability Upper Range (MW)*
22	5	10
66	30	50
110	100	120
132	120	160
220	250	350
275	350	500
330	500	700
500	1000	1500

It is evident that the relationship between voltage rating and power transmitted is not linear due to the range of operational currents and other parameters previously discussed. The actual relationship for the values selected has been displayed in Graph 26.



It is evident that this voltage-power relationship is not linear, with higher voltage lines being capable of transmitting increasingly higher loads. The region between the plots represents the range of values used for calculations (both curves have a similar relationship and general shape).

It is also important to note that higher voltage lines typically have lower proportional transmission losses due to a variety of factors (equation (2) from section 3.2.2 does not directly apply) which is supported by AEMO who stated that a 500kV line has approximately one-third the loss rate of a 275kV line despite having significantly larger power transmission capacities (AEMO, 2022).

Ultimately, the transmission network is a highly complex dynamic system that depends on a multitude of parameters. The approach used for this analysis attempts to bypass the various variables involved by using this range of power transmission values.

6.2.2 Key Drivers for Transmission Network Development

Although transmission development is primarily driven by load growth, it is now predominantly driven by the changing generation mix and the location of new generation (AEMO, 2017). Modification is required for the existing transmission network, originally designed for transporting generated energy from coal and gas facilities, to support the significant and diversified development non-synchronous generation in new areas. The underlying factors that necessitate this higher voltage system are explored further below:

1. Increase in Power Transfer Capacity

- As evident in section 3.2.7, there is a large increase in the overall generated power output over the succeeding decades (76% increase from current levels). Furthermore, due to the nature of renewable production, the peak generation is greater again at approximately 12,000 MW by 2040 (refer section 5.4.2). This power must be transported to the existing load centres in south, central and north Queensland to meet the forecasted increasing demand.
- In addition to increased generation, the operational shift to a system with storage facilities requires additional transmission from these facilities, most notably the Borumba and Pioneer-Burdekin PHES sites. As previously assessed in section 5.4.3, the grid will rely on these storage installations during periods of renewable drought to meet demand; resultantly, concentrated transmission will be required from these facilities to capitalise on their proposed power outputs. This peak energy load would be difficult to transmit with the existing 275kV system due to inadequate capacity and high inefficacies incurred over this distance and voltage.

2. Changing Generation Mix

- In conjunction with the net increase in power load, there is also a dramatic shift in the generation mix and number of individual generation facilities. Thus, the network coverage must be expanded to connect all components resulting in a greater cumulative transmission network distance.
- Furthermore, due to the nature of the availability solar and wind resources, these new facilities are more locationally diverse. Regions of high wind or solar radiation exposure can be seen in Appendix 2 and 3. It is evident that the solar radiation exposure is more intense further west in Queensland as indicated by the red region. Wind resources are more abundant along the coast (due to the weather dynamics provided by the Great Dividing Range); this distribution of wind is beneficial in terms of proximity to existing load centres along the east coast (refer Appendix 3).
- Likewise, PHES facility implementation is locational dependent; these facilities capitalise on the natural elevation changes in the geographic domain. As evident in Appendix 5, the optimal locations for PHES facilities again lie along the major range systems in Queensland.

While initial capital investments in transmission infrastructure are substantial due to the magnitude construction, transmission solutions typically asset lifecycles in excess of 50 years. The benefits of a successfully implemented transmission development pathway include:

- Greater load bearing efficiency and capabilities between the QREZs.
- Increased supply competition causing reductions in electricity costs and market fluctuations.
- Effective management of the diverse variable generation across the state.
- Improved diversity and compatibility with changes in supply resources, including decommissions and growing dependency on DER
- Improved power system resilience through a more inter-connected network.
- Optimised system security and support services for frequency and voltage control.

This emphasises the importance of considering diverse scenarios and examining the entire energy system. Ultimately, this system should facilitate Queensland's projected energy pathway and enable the management of all facets of the energy system.

6.3 Grid Transmission Data Collection and Methodology

As evident in the relevant theory, the transmission network is highly dependent on a number of factors. Detailed modelling of this system was thus deemed excessive due to the complexity, high sensitivity on parameters, and extensive required information and data; therefore, a highly simplified and general approach was adopted to gain an insight into the transmission development and feasibility.

As with all previous models, this model was developed individually and is independent of existing models; as a result, this model is highly unique and provides and provides an alternate insight into the feasibility of the plan. This increases the uncertainty of this model.

6.3.1 Transmission Network Scope

The model applies to the large-scale, state-wide, intermediate transmission infrastructure considering powerlines greater than 22kV (refer Figure 27). This is the primary component of the transmission pathway under development. The other components have been defined below:

- Primary transmission involves the energy transmission from generation, storage or stability facilities to a connection point for intermediate transmission. These powerline specifications vary depending on the capacity of the associated facility; for example, Pioneer Burdekin will require a substantial system that can transmit the proposed 5,000 MW to the intermediate transmission network. It is assumed this component of the transmission pathway will be developed in parallel with the construction of the associated generation or storage facility and thus has not been considered in analysis.
- Substations refer to the infrastructure in place to connect the primary and distribution networks to the intermediate network. Whilst these facilities are essential to the transmission network, they will be developed according to the requirements of the intermediate transmission network; as a result, substation requirements and development have been excluded from this initial scope.
- Distribution transmission refers to the localised small-scale energy distribution utilising powerlines operating at lower than 22kV. This load centre distribution is out of scope as these systems will not see substantial change with the changing generation mix, rather they will develop as per usual with increasing consumption requirements.

Although this is a highly simplified model of the transmission network, it provides an insight into the scope of this analysis and the justification for scope decisions.

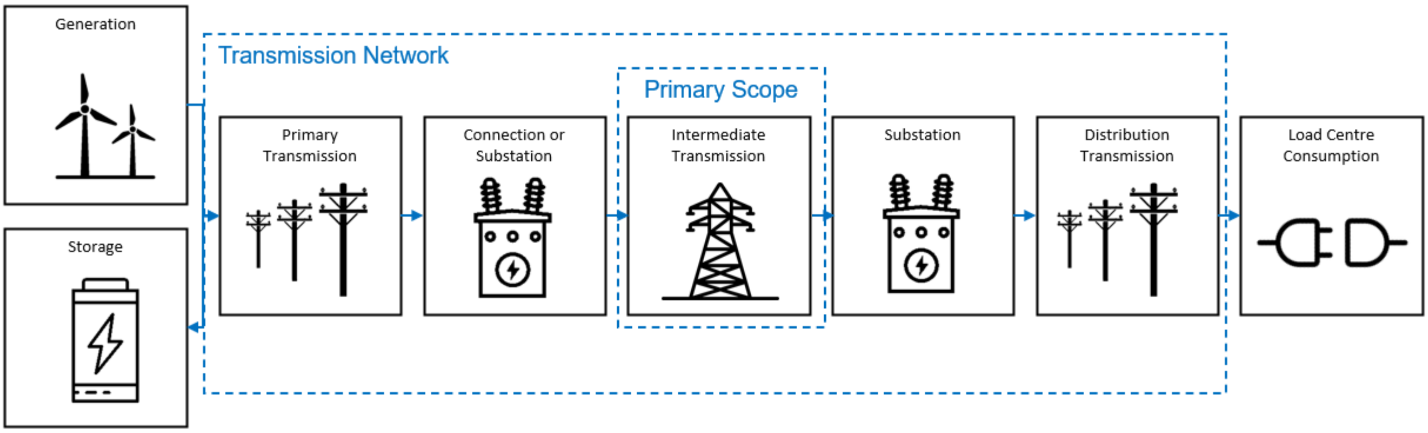


Figure 27: Transmission Pathway and Primary Scope of Model

This figure shows the transmission pathway from generation and storage facilities to consumption load centres. The primary focus of the model is the intermediate transmission.

6.3.2 Methodology and Data Collection

The fundamental method of this analysis involved assessing the intermediate transmission infrastructure in certain individual regions across Queensland to determine what areas require attention or development. This segmentation of the transmission network was based on regions defined by the local government area (LGA) which was conducted due to various reasons:

- Segmentation was deemed the optimal approach instead of modelling the entire system to reduce the complexity and uncertainty of a large integrated model.
- There are 77 LGAs across Queensland and thus this method provides a highly localised insight into the transmission outlook for different regions.
- The LGA of each generation and storage facility was previously researched in RQ1 and RQ3 respectively, and thus is an efficient use of existing modelling.

The data bases used to determine transmission infrastructure information with respect to LGA regions were through the National Map resource provided by the Australian Government (Aus Gov, 2023). The LGA data was provided by the Australian Bureau of Statistics while the existing transmission data was provided by the Geoscience Australia data bases (ABS, 2023) (Geo Science, 2023). The map visualisation of the data be seen in Figure 28.

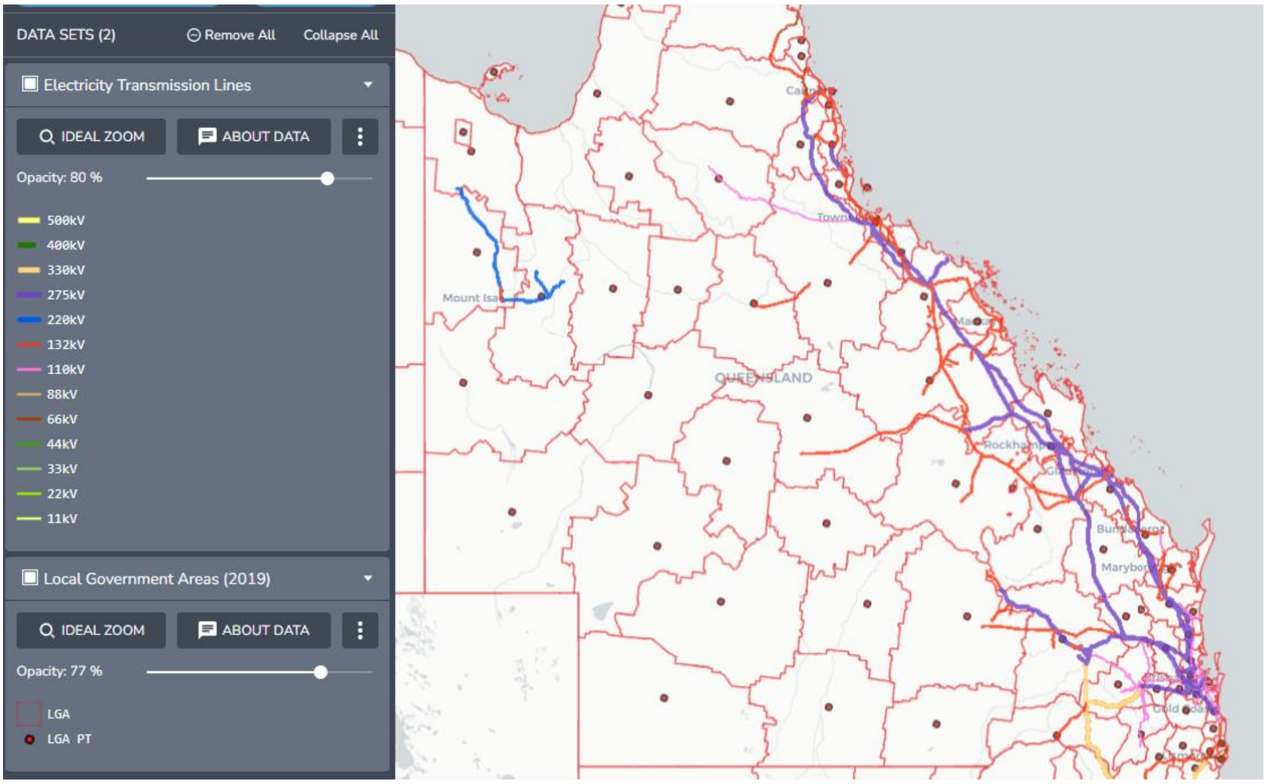


Figure 28: Transmission Network and LGA Regions

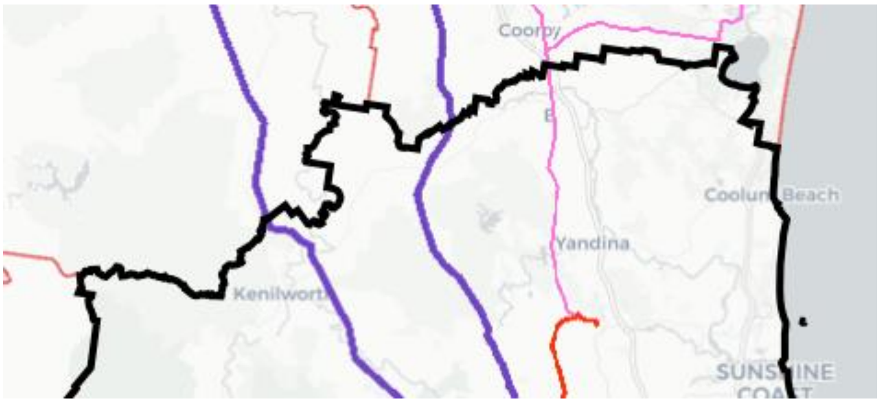
This figure shows the current transmission network throughout Queensland with the LGA regions also specified (Aus Gov, 2023).

The methodology used for the evaluation of the grid transmission capacity in this work resembles the classical methodology of Large Eddy Simulations (LES) in modelling of turbulent flows (Rogallo and Moin, 1984). The grid connections between different LGAs are resolved and explicitly accounted for, while grid operation within each LGA is not resolved and modelled either as a provider or a consumer of electricity. Ultimately, the data represented the number of individual transmission line 'border crossings' based on the powerline rating (refer 'Transmission' sheet on the Excel model).

A brief example of the data collection is provided below in Figure 29.

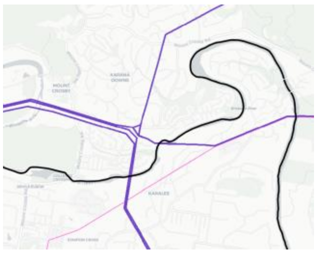
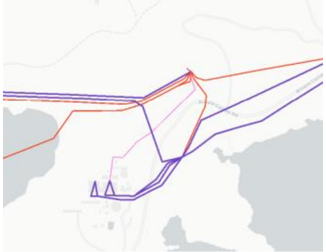
Figure 29: Transmission Data Collection Example

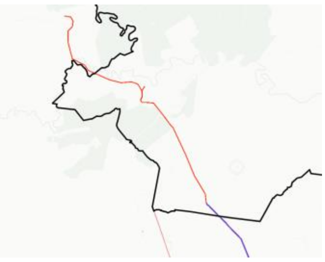
Using the developed methodology, it is evident that for this section of the Sunshine Coast LGA border, there are two 275kV line crossings and one 110kV line crossing. (Aus Gov, 2023).



From this analysis, there were various limitations and potential sources of error identified which have been briefly explained in Table 26 below with corresponding diagrams (Aus Gov, 2023). The associated simplifications of the model have also been summarised.

Table 26: Limitations and Simplifications of Transmission Model

LGA	*Limitation Description*	*Diagram*
Moreton Bay Regional Council	As evident in the diagram, the left vertical 275kV line crosses in and out of the LGA without change. This line still provides the same service despite the multiple crossings, and thus it is only countered as a single border crossing. As a result, a rule was noted that if a transmission line crossed a border and did not undergo any 'change' (connection or modification), it was countered as a single border crossing.	
Ipswich City	As evident in the diagram, a double set of 275kV lines cross the border vertically into a connection system, from which one 275kV crosses back into the LGA. This is still counted as 3 border crossings as the line experienced a 'change'. This means that the line is a separate component of the system and is transmitting a different load, thus offering a potential transmission avenue.	
Toowoomba Regional Council	This diagram shows a complex array of powerlines and connections that occurs on the boarder of the LGA. It is evident that the 330kV line only briefly enters into the left LGA before undergoing 'change' at a connection; despite this, it is still included as a border crossing as it still facilitates energy transmission in or out of the LGA.	
Banana Shire	This diagram does not present issues regarding an LGA border, rather it demonstrates that this model does not consider the internal workings of the system. This diagram shows the Callide Power Station and the powerlines that transmit energy from directly from this site out of the LGA. This presents a limitation that is discussed below regarding the assumption of 'continuation'.	

Banana Shire	This diagram outlines two important observations. Firstly, it is evident that the 132kV line is directly upgraded to (or downgraded from) a 275kV line; as a result, this is counted as one crossing of both a 132kV and 275kV line (as this model assumes transmission in either direction). This demonstrates again that directionality of the energy flow is again ignored.	

This analysis led to the refinement of the model and resulted in the identification of the three distinct requirements of the intermediate transmission network in each LGA:

1. Origination: Transmit locally generated energy out of the LGA
    - 'Origination' estimates involve using existing generation and storage data and extracting output information based on the location.
2. Continuation: Transmit incoming energy from other regions across and out of the LGA
    - Formulating reasonable estimates for 'continuation' would require a model that considers the entire transmission network (region segmentation does not provide this information without extensive modelling).
3. Termination: Transmit incoming energy to a load centre within the LGA
    - Formulating reasonable estimates for 'termination' would require extensive data regarding consumption and load centres

These requirements are approximately interconnected according to the equation below. This relationship is highly dynamic and would vary constantly depending on real-time generation and consumption profiles and requirements.

$$Continuation = Origination - Termination$$

$Continuation > 0$	The LGA network must be able to facilitate the transmission of locally generated energy and energy from other regions.
$Continuation = 0$	The LGA has an effective zero net energy flow across the border; the generation is equal to consumption in this local area.
$Continuation < 0$	The LGA relies on incoming energy flow from other regions to meet internal demand.

Using this concept, the model initially assumed all transmission infrastructure within a LGA is developed for continuation; this means no powerlines 'originate' or 'terminate' in the LGA. Although this is not practical as energy experiences a flow from generation to consumption, this assumption meant that the model assesses a LGA ability to export generated energy assuming the infrastructure is designed for 'continuation' - providing an insight into the LGAs that may require upgrading.

Following this, the model was adjusted to assume all transmission infrastructure within a LGA is designed for origination or termination; this means all powerlines 'originate' or 'terminate' in the LGA. Again, this is not practical as many LGA solely transmit energy generated from other areas; however, by using this approach, if it was determined that an LGA is unable to export the locally generated energy (assuming infrastructure designed for origination), it can be concluded with high certainty that infrastructure development is required.

This avoids the necessitation to formulate estimates for 'continuation' or 'termination' as if the LGA can export its own generation (with a network that is designed for continuation), it not only guarantees the LGA can definitively export its own energy (regardless of network configuration), but it provides the potential ability for the LGA to offer 'continuation' support. This also maintains consistency with the CA.

In order to implement the first approach in the model, the number of border crossings for each powerline type was divided by '2' prior to calculations. This assumed that absolutely no power line originates or terminates in the LGA. Note this would produce a decimal of 0.5 for power line types with an odd number of crossings; however, the directionality of the power lines was not known (without further extensive modelling), and thus this decimal would produce an effective halved contribution assuming it would transmit in either direction (again providing a conservative approach to the results). The value of this division can be modified in the Excel model (refer to the sensitivity analysis in section 6.5.1). Dividing by any factor less than 2 means assumed there is excess energy originating or terminating in each LGA which was then utilised for the second approach.

6.3.3 Excel Model

Applying the methodology and concepts outlined above, an Excel model was developed to assist with calculations (refer 'Transmission' sheet). The following steps were applied:

1. The generation and storage data were imported into the sheet. This included the name, local government area, fuel type, status of operation, commission and decommission dates, and nominal generation capacity.
2. An 'IF' function was used to apply respective capacity factors to each generation type. The wind and solar capacity factors were based on the maximum daily values (to simulate a maximum scenario), and thus were imported from the 'Storage' sheet (from row 435).
3. The corrected generation capacities were calculated noting that the storage outputs were the maximum nameplate output capacities; both steps 2 and 3 assume maximum output scenarios in the LGAs to maintain consistency with the CA.
4. The data was extracted according to a similar process and formula used in the 'Generation' sheet; therefore, the same inputs apply and can be varied to simulate different scenarios. The results were based on a specific input 'Year of Interest', which can be varied to observe the outlooks for different years.
5. The cumulative maximum output of each LGA was summed (for the year of interest) and compared to the current 2023 outlook.
6. The transmission aspect was then considered through the analysis of the collected data. The range of power transmission capacities for each line type were averaged (as the lines should not continually operate at the upper range); again, the range can be varied to assess different scenarios.
7. The total power transmission capacity for the LGA was then calculated using the average transmission capacity, powerline border crossings, and 'Directivity Factor' (which can also be adjusted).
8. The required LGA output was compared to the transmission capabilities to produce the 'Capacity Available for Continuation'.
9. Conditional formatting was used to highlight the feasibility of transmission in each LGA based on the inputs and year of interest. Data was collected for every year until 2040 to produce the plot shown in Excel. Light colouring indicated feasibility while dark colouring indicates attention is required and potential upgrades are necessary.

It is evident that the modelling uses a quantitative approach to produce a largely qualitative outcome. This was because the values produced are highly sensitive to the inputs selected, and thus this model was designed to provide a general insight into LGA transmission feasibilities. Quantitative results are provided for the capacity available for continuation which corresponds to the difference between the generation output and transmission capacities and is indicative of a LGA's ability to transport energy from other LGAs. The respective 'Percent Available for Continuation' is a percentage value from 0% to 100% corresponding to the proportion of the LGA transmission capacity that can be used for continuation. Conditional formatting was used to identify percentages less than 20% as these are the LGAs with higher proportion of generation to transmission.

Note: There was a special case for LGAs with very small production (less than 20MW) that had no substantial transmission infrastructure (greater than 22kV). This occurred in highly isolated areas:

- Bulloo Shire (far south west QLD)
- Carpentaria Shire (far north west QLD)
- Longreach Regional (central west QLD)
- McKinlay Shire (central west QLD)
- Torres Shire (far north QLD)
- Weipa Town (far north QLD)

The model would flag these LGAs as having insufficient transmission capacity; however, this was a false positive as for small, isolated production, smaller networks are used to distribute power to the small load centres. As a result, if the LGA production was less than 20 MW and it had no substantial transmission network, it was excluded from the final feasibility assessment.

Table 27: Sample Functions Used in Excel Model

Sample Function	*Sample Cell*	*Description*
`=IF(D3="Coal",'Capacity Factors'!$C$4,IF(D3="Gas",'Capacity Factors'!$C$5,IF(D3="Fuel Oil",'Capacity Factors'!$C$7,IF(D3="Hydro",'Capacity Factors'!$C$8,IF(D3="Bioenergy",'Capacity Factors'!$C$9,IF(D3="Solar",Storage!$L$434,IF(D3="Wind",Storage!$L$435,IF(D3="Thermal Solar",'Capacity Factors'!$C$10,"ERROR"))))))))`	I3	This function was used for applying the appropriate capacity factor to respective technology types. A similar approach was used previously; however, this formula also uses to 'peak' productions of wind and solar according to the storage feasibility assessment.
`=IF($C3=L$2,IF(OR($E3="Decommissioned",$E3="Cancelled"),0,IF(AND(OR($E3="Proposed",$E3="Under Construction"),$F3="Unknown",Generation!$S$304="Y",$G$343>Generation!$S$310),(($G$343-Generation!$S$310)*$J3/Generation!$S$307),IF($G3="",IF($G$343>$F3,$J3,0),IF(AND($G$343>=$F3,$G$343<$G3,$D3<>"Coal"),$J3,IF(AND($G$343>=$F3,$G$343<$G3),IF($G$343<'Capacity Factors'!$G$5,$J3,IF($G$343<'Capacity Factors'!$G$6,($J3/'Capacity Factors'!$C$4)*'Capacity Factors'!$H$5,IF($G$343<'Capacity Factors'!$G$7,($J3/'Capacity Factors'!$C$4)*'Capacity Factors'!$H$6,($J3/'Capacity Factors'!$C$4)*'Capacity Factors'!$H$7))),0))))),0)`	L3	This function is very similar to the 'Generation' extraction formula used to determine the inclusion of certain facilities given the input conditions. The primary modification to this formula is the inclusion of the LGA extraction which is the outermost 'IF' function. The inputs from other sheets can be used to adjust this formula as done in the generation model.
`=IF(AND(SUM(L348:L354)=0,L338<20),0,IF((L338-L356)>0,1,0))`	L365	This formula applies the special consideration discussed above and a binary result for the transmission feasibility of the LGA (1 for unfeasible, and 0 for feasible). This forms the basis of the conditional formatting which used the result to colour the cells light or dark.

6.4 Grid Transmission Results and Analysis

Using the model developed, various scenarios were considered to gain an insight into the feasibility of the transmission network in respective LGAs, and Queensland as a collective system. As previously discussed, there were various input parameters required; the parameters used in this analysis have been outlined throughout the methodology and relevant theory sections with respective justifications and the parameters used from other research questions were kept constant with previous analysis. The various parameters include (and are discussed in section 6.5.1):

- Lower and upper ranges for transmission line power capacity
- Directivity Factor
- Capacity factors for generation facilities
- Phase out parameters for coal generation facilities
- Phase in factors for generation facilities

As a result of the specific selection of parameters, the results produced are a highly conservative and overestimate transmission requirements (the model is more likely to flag a LGA as requiring transmission attention); thus, the results provide an insight only. In total, there were 47 applicable LGAs with proposed generation or storage. These have been listed in Appendix 14 for reference (each LGA was assigned a value 1 to 47 for presentation purposes).

6.4.1 Continuation Transmission Assessment (Directivity = 2)

The primary results from the analysis can be seen in Table 29 which shows the years for which the transmission in a LGA will likely require potential upgrades or support assuming the transmission network is designed for continuation. The data has been summarised below in Table 28 and the quantitative data can be referred to in the 'Transmission' sheet on the Excel model (from row 400).

Table 28: Flagged LGA (Directivity = 2)

Local Government Area	*Number*	*Year*	
Banana Shire Council	1	2025	-
Cook Shire Council	13	2036	-
Etheridge Shire Council	15	2024	-
Flinders Shire Council	16	2028	-
Gladstone Regional	18	2029	-
Goondiwindi Regional Council	20	2028	-
Gympie Regional	21	2030	-
Mackay Regional	28	2033	-
Rockhampton Regional Council	35	2025	-
Somerset Regional	37	2025	-
South Burnett Regional	38	2028	2031
Toowoomba Regional Council	42	2028	-
Western Downs Regional Council	46	2023	-
Whitsunday Regional Council	47	2029	-

There were a number of interesting observations from this analysis. Firstly, it was evident that the Western Downs LGA (46) requires immediate attention; however, this was an overestimation due to the directivity factor as this LGA primarily exports energy with little continuation requirements (similar to the limitation identified in the Banana Shire LGA in Table 26). The Braemar, Kogan Creek and Condamine Power Stations are all situated in this LGA, and thus the transmission lines export significant power (which was not considered with a directivity factor of 2). This demonstrates that in reality, some of the flagged LGA may not require attention from the specified date.

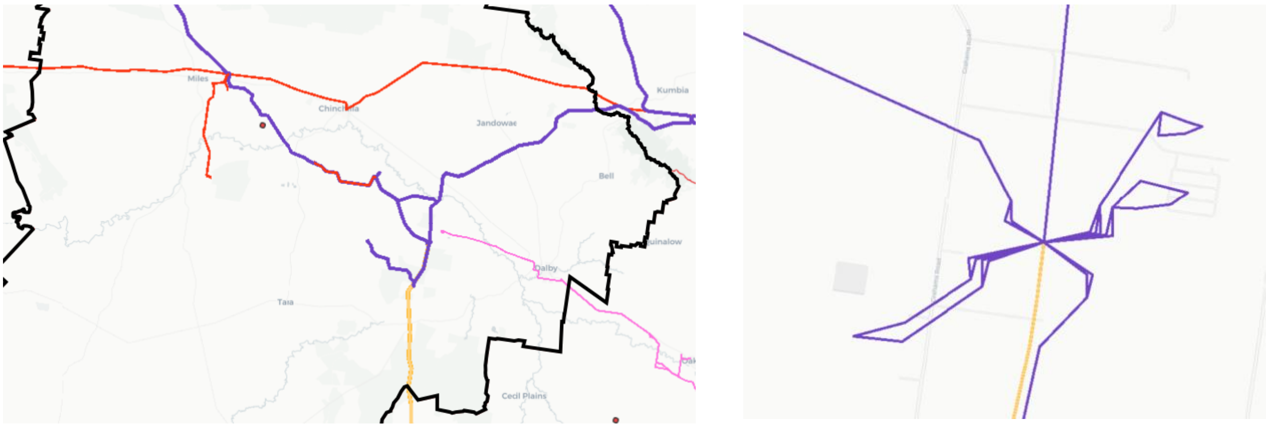


Figure 30: Western Downs LGA and Braemar Power Station

The Western Downs LGA has a high internal generation; however, the model does not consider directionality and assumes all LGA transmission is built for 'Continuation' (Aus Gov, 2023).

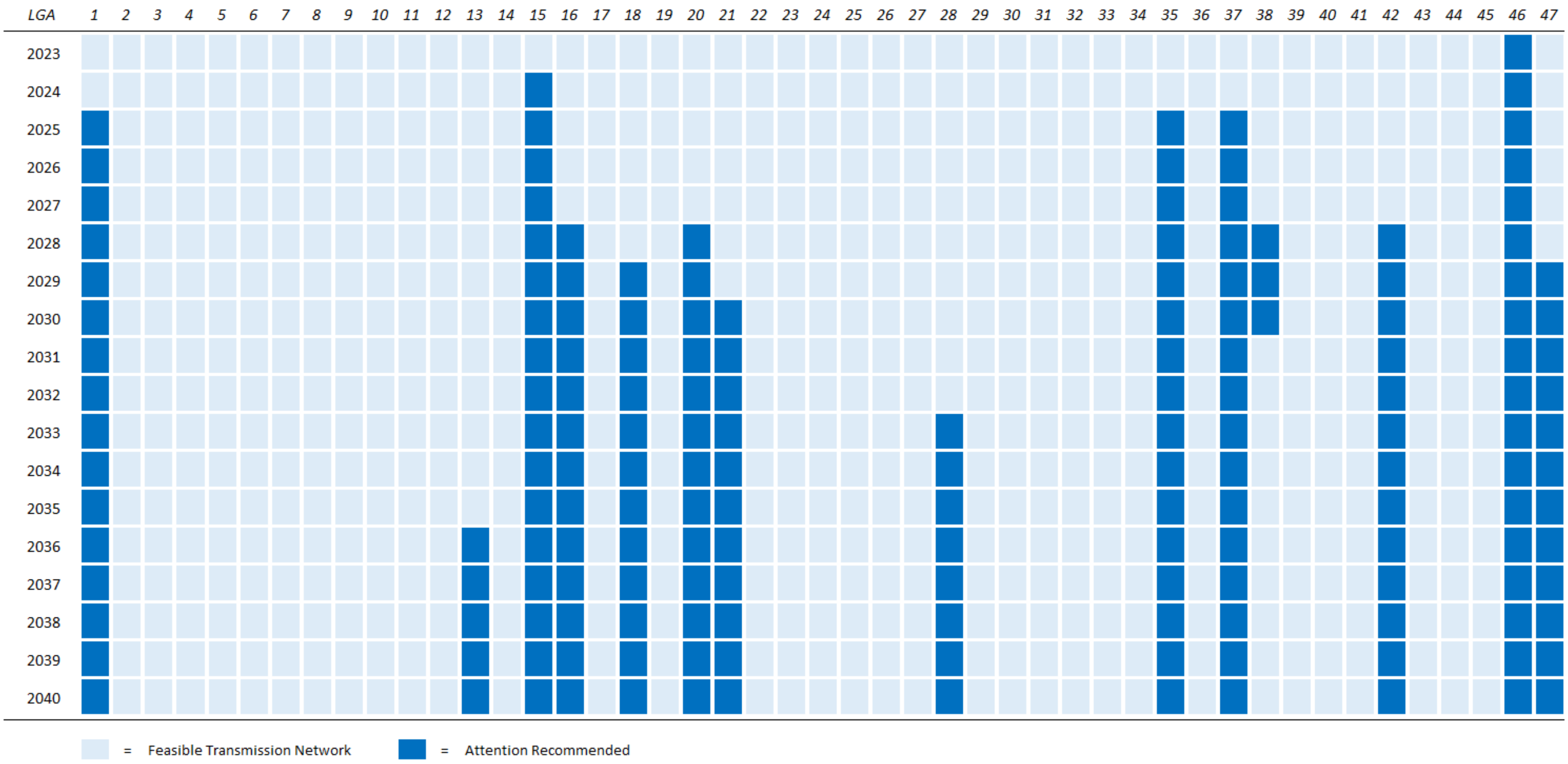
It is evident from Table 29, that attention is recommended in some LGAs from 2024 onwards coinciding with the commissioning of certain generation and storage facilities. The particular generation facilities causing the potential overload can be acquired from the 'Data Tables' in the Excel document but is not the primary focus of this assessment.

Another interesting observation occurred in the South Burnett Region (Aus Gov: AREA. 2017) as it recommends attention from 2028 but then the existing infrastructure should be sufficient from 2031 onwards. The initial upgrade recommendation is due to the commissioning off the Tumuruu Solar Farm from 2028 onwards while the downgrade status back to sufficient transmission in 2031 is attributable to the transition of the Tarong Power Station to phase 2 of the decommissioning program (refer Figure 8). This pattern was observed for a number of region whilst trialling different inputs.

From inspection of the quantitative values (refer from row 413 on 'Transmission' sheet), it is evident that an additional 3 LGA are forecasted to operate with less than 20% transmission capacity available for continuation (by 2040): Hinchinbrook Shire (22), Tablelands Regional (41), and Townsville City (44). This assessment reveals the LGAs that should be given attention but may not necessarily require upgrading depending on further analysis.

Table 29 below shows a visual representation of the first stage of transmission feasibility results. Light colouring corresponds to a feasible transmission system within the LGA network for the specified year, while dark colouring indicates attention is recommended towards the transmission infrastructure in the LGA.

Table 29: Transmission Network Feasibility Forecast in Queensland Local Government Areas (Directivity Factor = 2)



LGA	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
2023	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜
2024	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜
2025	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜
2026	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜
2027	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜
2028	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	🟦	⬜	⬜	⬜	🟦	⬜
2029	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	🟦	⬜	⬜	⬜	🟦	🟦
2030	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	🟦	⬜	⬜	⬜	🟦	🟦
2031	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	🟦	🟦
2032	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	🟦	🟦
2033	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	🟦	🟦
2034	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	🟦	🟦
2035	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	🟦	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	🟦	🟦
2036	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	🟦	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	🟦	🟦
2037	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	🟦	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	🟦	🟦
2038	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	🟦	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	🟦	🟦
2039	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	🟦	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	🟦	🟦
2040	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	🟦	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	🟦	🟦

⬜ = Feasible Transmission Network 🟦 = Attention Recommended

6.4.2 Origination Transmission Assessment (Directivity = 1)

The results from this second stage of analysis can be seen in Table 31 which shows the years for which the transmission in a LGA will likely require potential upgrades or support assuming the transmission network is designed for origination. The data has been summarised below in Table 30 (the model can be used to acquire the quantitative data).

TABLE 30: Flagged LGA (Directivity = 1)

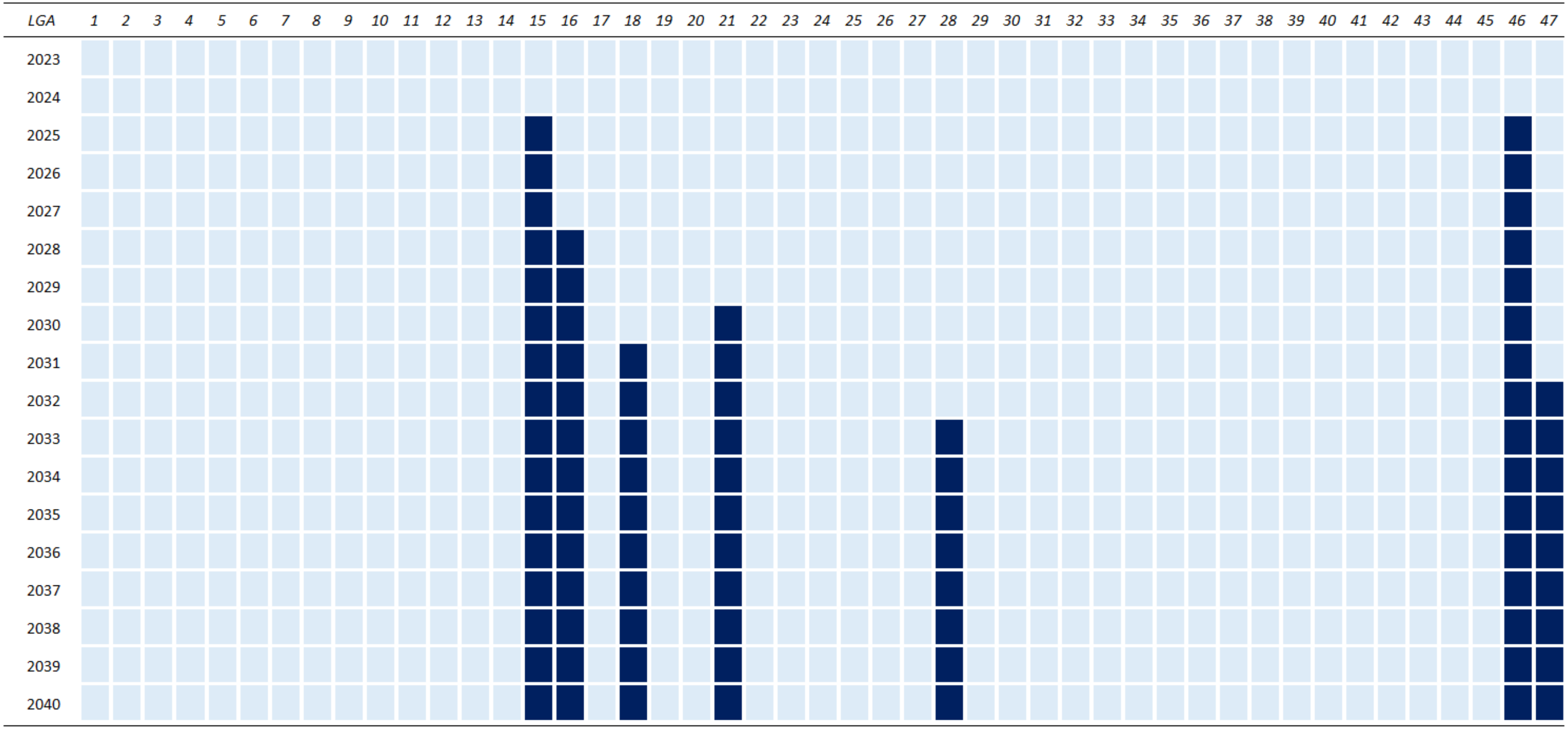
Local Government Area	*Number*	*Year*	
Etheridge Shire Council	15	2025	-
Flinders Shire Council	16	2028	-
Gladstone Regional	18	2031	-
Gympie Regional	21	2030	-
Mackay Regional	28	2033	-
Western Downs Regional Council	46	2025	-
Whitsunday Regional Council	47	2032	-

It is evident from Table 31, that attention is required in some LGAs from 2025 onwards coinciding with the commissioning of certain generation and storage facilities. This table shows regions with a very high likelihood of requiring upgrades as even with the transmission network assumed to be developed for maximum energy export, the LGA cannot export its internally generated energy (there is a limitation associated with this statement discussed in section 26).

Finally, the results from Table 29 and Table 31 have been displayed in Table 32 to show the LGAs with recommended and required upgrades. It is evident that many LGAs have a period of recommended upgrade before certain upgrade is required, while other LGA have an immediate status of requiring an upgrade (from the implementation of a very large generation or storage facility). Overall, there a 7 LGAs requiring an upgrade or load shift by 2033 (as early as 2025), with an additional 7 LGAs likely requiring support throughout various periods over following two decades (as early as 2024).

Table 31 below shows a visual representation of the second stage of transmission feasibility results. Light colouring corresponds to a feasible transmission system within the LGA network for the specified year, while dark colouring indicates attention is required towards the transmission infrastructure in the LGA.

Table 31: Transmission Network Feasibility Forecast in Queensland Local Government Areas (Directivity Factor = 1)



LGA	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*	*32*	*33*	*34*	*35*	*36*	*37*	*38*	*39*	*40*	*41*	*42*	*43*	*44*	*45*	*46*	*47*
2023	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
2024	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
2025	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	□
2026	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	□
2027	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	□
2028	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	□
2029	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	□
2030	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■	□	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	□
2031	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■	□	■	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	□
2032	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■	□	■	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■
2033	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■	□	■	□	□	■	□	□	□	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■
2034	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■	□	■	□	□	■	□	□	□	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■
2035	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■	□	■	□	□	■	□	□	□	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■
2036	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■	□	■	□	□	■	□	□	□	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■
2037	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■	□	■	□	□	■	□	□	□	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■
2038	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■	□	■	□	□	■	□	□	□	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■
2039	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■	□	■	□	□	■	□	□	□	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■
2040	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■	□	■	□	□	■	□	□	□	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■

□ = Feasible Transmission Network ■ = Attention Required

Table 32 below is a combination of Table 29 and Table 31, to demonstrate the various recommendations and requirements of the LGA transmission networks.

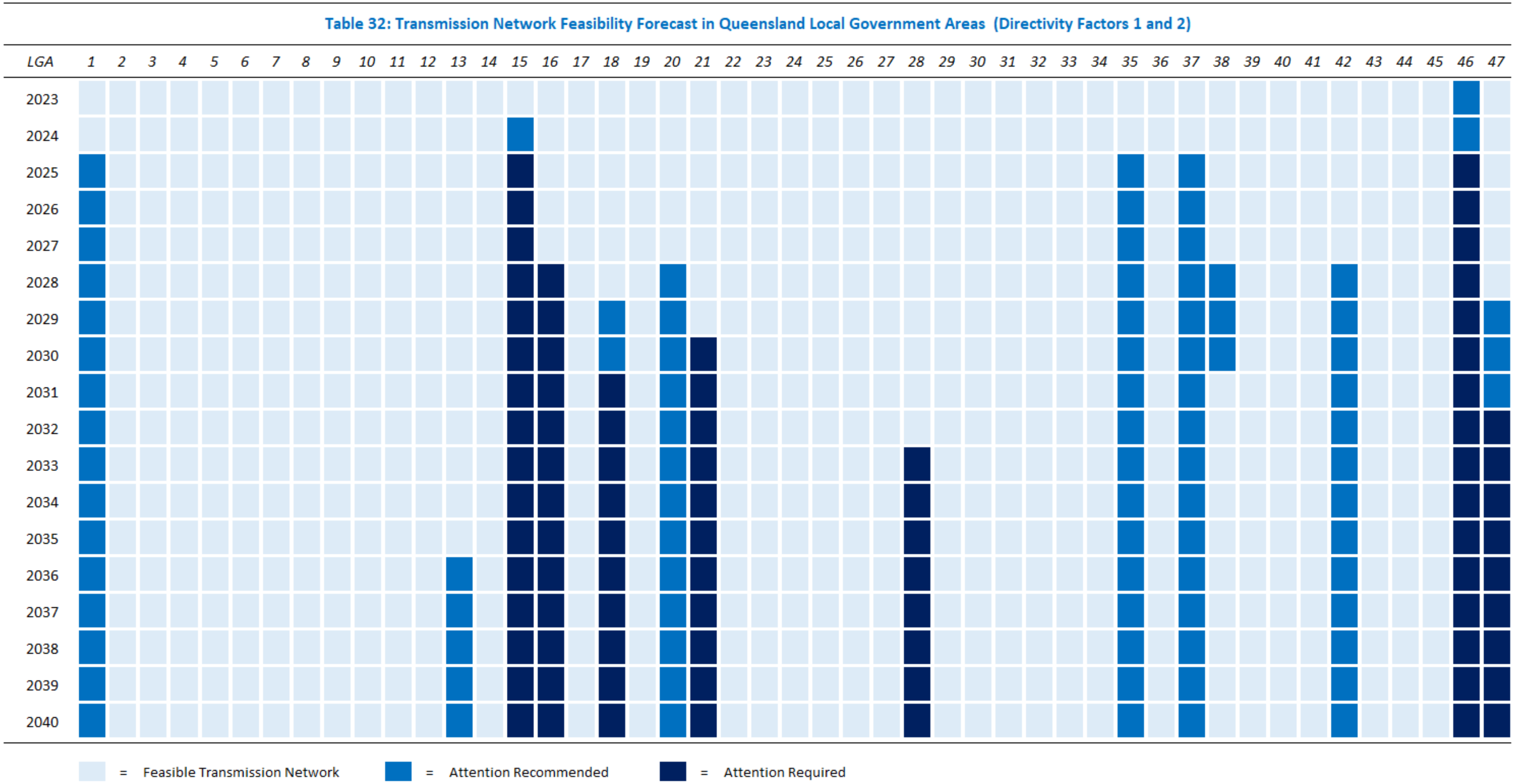


Table 32: Transmission Network Feasibility Forecast in Queensland Local Government Areas (Directivity Factors 1 and 2)

LGA	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*	*32*	*33*	*34*	*35*	*36*	*37*	*38*	*39*	*40*	*41*	*42*	*43*	*44*	*45*	*46*	*47*
2023	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜
2024	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜
2025	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬜
2026	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬜
2027	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬜
2028	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬛	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬛	⬜
2029	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬛	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬛	🟦
2030	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬛	⬜	🟦	⬜	🟦	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	🟦	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬛	🟦
2031	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬛	⬜	⬛	⬜	🟦	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬛	🟦
2032	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬛	⬜	⬛	⬜	🟦	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬛	⬛
2033	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬛	⬜	⬛	⬜	🟦	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬛	⬛
2034	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬛	⬜	⬛	⬜	🟦	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬛	⬛
2035	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬛	⬜	⬛	⬜	🟦	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬛	⬛
2036	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬛	⬛	⬜	⬛	⬜	🟦	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬛	⬛
2037	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬛	⬛	⬜	⬛	⬜	🟦	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬛	⬛
2038	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬛	⬛	⬜	⬛	⬜	🟦	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬛	⬛
2039	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬛	⬛	⬜	⬛	⬜	🟦	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬛	⬛
2040	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	⬛	⬛	⬜	⬛	⬜	🟦	⬛	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬜	⬜	⬜	⬜	⬜	⬜	🟦	⬜	🟦	⬜	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬛	⬛

⬜ = Feasible Transmission Network 🟦 = Attention Recommended ⬛ = Attention Required

6.5 RQ4 Discussion

From the results and analysis, it is evident that there are various upgrades or new developments required to support the existing infrastructure. The recommendation periods identified should be used to conduct respective RIT-Ts (Regulated Investment Test Transmission) which is the necessary evaluation process to justify a proposed upgrade or new transmission development.

According to AEMO, throughout the network development, the existing 275kV network will remain operational and provide support and system security, subsequently being leveraged to transmit renewably produced energy to storage and load centres. Upon completion of the new high-voltage system, the existing infrastructure will provide continued support for the new high-voltage central system; some powerlines in the new system are proposed to have voltage ratings of 500kV. It is important to note that there will be possible reductions in transmission requirements of existing infrastructure following the decommissioning of large-scale power stations (particularly coal plants). Transmission operators and service providers should remain conscious of this in order to optimise the utilisation of current assets to achieve more efficient and lower-cost solutions.

It is also interesting to note that AEMO is considering an alternative option of reinforcing the network with a High Voltage Direct Current (HVDC) system which can be seen in Table 33. This is a long-term option as the high-voltage AC network is more flexible and requires lower cost for intermediate substations and overall, more closely aligned with the immediate technical requirements of the system. Furthermore, AEMO is also considering a strengthened connection with NSW as according to the national transmission network development plan (NTNDP) modelling, "*new and upgraded interconnection between adjacent NEM regions may be economic over the next 20 years*" (AEMO, 2018).

There are a number of resources that highlight specific forecasted network upgrades; however, as these plans are in early stages of research and development, the descriptions are often general with ambiguity regarding the capacity of support in terms of MW. Research involved attaining information on transmission network upgrades that addressed the region of intended support and provided approximate support capacity values. AEMO's 2021 Transmission Cost Report provides this detailed insight into the proposed transmission upgrades and thus all relevant information from this resource has been directly summarised in Table 33 (AEMO,2021).

There were various options and scenarios provided, the ones selected were the optimal short-term and long-term support strategies. A description of the upgrade and the LGAs affected have been listed; the LGAs highlighted in green correspond to the regions identified in the results and analysis that require a potential upgrade. The transmission capacity upgrade has also been provided; however, as this is a largely qualitative assessment, these values are indicative only (they are also prone to change with as the development plan evolves). The proposed cost of the upgrades has also been provided for additional information.

Table 33: Proposed Transmission Network Upgrades in Queensland (AEMO, 2021)

Description	*LGA Support*	*Additional Network Capacity*	*Lead Time and Completion*	*Expected Cost*
North to Central Queensland - New 275 kV double-circuit line between Calvale and Calliope River - Rebuild Calliope River to Larcom Creek 275 kV double-circuit line. - Rebuild Larcom Creek to Bouldercombe 275 kV double-circuit line with one line tapped at Raglan	- Gladstone - Rockhampton - Banana Shire - Bundaberg - North Burnett - Central Highlands - Isaac - Mackay (possibly)	North to Central: 550 MW Central to North: 500 MW	5 years from project approval (October 2030)	$408 million
North and Central to South Queensland - A new 275 kV double-circuit line between Calvale and South West of Queensland. - 275 kV line shunt reactors at both ends of Calvale - South West of Queensland 275 circuits.	- Banana Shire - Maranoa - Western Downs - North Burnett - South Burnett	North to South: 900 MW South to North: 900 MW	5 years from project approval (December 2028)	$476 million
North and Central to South Queensland - A 1,500 MW HVDC bi-pole overhead transmission line from Calvale and South West Queensland. - A new 1,500 HVDC bipole converter station in locality of Calvale. - A new 1,500 HVDC bipole converter station in South West Queensland. - AC network connection between HVDC converter station and 275 kV substation in Calvale. - AC network connection between HVDC converter station and 275	- Banana Shire - Maranoa - Western Downs - North Burnett - South Burnett	North to South: 1,500 MW South to North: 1,500 MW Central to South: 1,500 MW	Long-term (unspecified)	$1,615 million
South Queensland to North New South Wales - A 2,000 MW HVDC bi-pole overhead transmission between a new substation in North West New South Wales REZ and Western Downs. - A new 2,000 HVDC bipole converter station in North West New South Wales. - A new 2,000 HVDC bipole converter station in locality of Western Downs. - AC network connection between HVDC converter station and 275 kV substation in Western Downs. - AC network connection between HVDC converter station and ac network in in NWNSW REZ. - A new 330 kV line between NWNSW REZ and Tamworth.	- Western Downs - Goondiwindi - Toowoomba	North to South: 1,800 MW South to North: 2,000 MW	Long-term (unspecified)	$3,125 million

There is an additional planned upgrade for the Kaban Green Power Hub involving a 320km upgrade of the 132kV line that runs from Townsville to Carins to a 275kV line, providing support to Townsville, Hinchinbrook, Tablelands, Cassowary Coast, and Carins (Neoen, 2023).

Tables 28 and 30 and were combined below in Table 34; the LGAs that were addressed in AEMOs transmission upgrade proposals were coloured green, while the regions that were not considered are coloured red.

TABLE 34: LGAs Considered in AEMO Transmission Upgrades

Local Government Area	*Number*	*Recommend*		*Require*
Banana Shire Council	1	2025	-	-
Cook Shire Council	13	2036	-	-
Etheridge Shire Council	15	2024	-	2025
Flinders Shire Council	16	2028	-	2028
Gladstone Regional	18	2029	-	2031
Goondiwindi Regional Council	20	2028	-	-
Gympie Regional	21	2030	-	2030
Mackay Regional	28	2033	-	2033
Rockhampton Regional Council	35	2025	-	-
Somerset Regional	37	2025	-	-
South Burnett Regional	38	2028	2031	-
Toowoomba Regional Council	42	2028	-	-
Western Downs Regional Council	46	2023	-	2025
Whitsunday Regional Council	47	2029	-	2032

It is evident that the majority of the regions expected to incur transmission overloads have been considered in AEMOs development proposal. The LGAs that were omitted are summarised below with potential reasonings:

- Cook (far north QLD): Isolated community with upgrades not considered until 2036
- Etheridge (central north QLD): Isolated community with minimal existing infrastructure, the new infrastructure will likely be developed with associated generation plants.
- Flinders (central north QLD): The same reasoning as the Etheridge LGA applies.
- Somerset (south east QLD): This LGA is between two regions with forecasted development and thus may be interconnected in the future.
- Whitsunday (central east QLD): The same reasoning as the Somerset LGA applies.

The date from which attention is required is not crucial provided there is effective generation management and load sharing with other LGAs. Furthermore, as previously discussed, this transmission feasibility assessment has not considered the quantitative aspects in detail as the data provided by AEMO is reflective of early stages of planning, and the model developed primarily provides a qualitative outlook to indicate potential issues in LGAs.

AEMO has stated that the upgrades are to be facilitated by Powerlink (upon AEMO request) or, "*to be provided by interested parties*" (AEMO, 2021). Thus, the stakeholder interest must also be monitored over the following years to ensure interest is developed or government intervention is provided. Overall, this analysis demonstrates that the transmission network is actively being assessed by AEMO and indicates that with further adjustments and continued progression, the transmission network will develop in parallel with the growing and changing generation and storage mix.

6.5.1 RQ4 Sensitivity Analysis

This sensitivity analysis applies to the respective outcomes of the transmission feasibility forecasts developed. The results obtained from analysis are highly sensitive to the various input which have been outlined below in Table 35. The assumed baseline (values used in the results) and proposed variance (range of values possible) for each parameter has been provided in the table; recall all parameters in the results were selected based on the CA. A quantitative explanation of the sensitivity of each variable and effect on results was provided through an OAT analysis. Note the quantitative effects of each variable in green can be easily assessed by using the Excel model provided and manually changing these inputs (also coloured green in the Excel document). The data acquired regarding the transition infrastructure is up-to-date with low uncertainty.

Table 35: RQ4 Sensitivity Analysis

Variable or Parameter	*Assumed Baseline*	*Proposed Variance*	*Sensitivity and Effect on Results*
Lower and upper ranges for transmission line power capacity	The assumed baseline was the average between the lower and upper ranges. This was based on extensive research and the suggestion that powerlines do not continually operate at their maximum capacity.	The variance is demonstrated by the range of values presented. The value used in calculations can be anywhere within this range.	This parameter has a direct effect on the results. Assigning a higher operational transmission capacity to powerlines results in less LGA being flagged as requiring upgrades as the network used in calculations can sustain a greater load. Thus, the results are highly sensitive to this input.
Directivity Factor	The directivity factors used were 1 and 2 to assess transmission networks designed for origination and continuation respectively.	The range of values is between 1 and 2 as this represents the scenarios where all powerlines either start (or end) in the LGA or, no powerlines start (or end) in the LGA. A value closer to 2 represents greater continuation.	The sensitivity of varying this parameter was observed in the results of this analysis in Table 32. A directivity factor of 1, results in a more certain result as the flagged LGAs cannot handle internal generation with optimal export design. A value of 2 is more conservative approach and flags potential issues in transmission networks.
Capacity factors for generation facilities	The capacity factors used for constant generation facilities were the same as in previous calculations. The variable solar and wind generation capacity factors were based off maximum production from the storage analysis.	As previously discussed, these values vary greatly depending on a range of factors. Each facility has a unique capacity factor with its own fluctuations.	Higher capacity factors results in a more conservative approach as the model will assume higher transmission loads, thus a higher proportion of LGAs would fail to meet requirements and be flagged as requiring potential upgrades.
Factors associated with the generation aspect of the model	Parameters outlined in the RQ1 and RQ3 sensitivity analysis also apply for this model such as the phase out parameters of coal plants or phase in factors of generation facilities. The variances of these parameters will affect the transmission feasibility assessment in various ways. Overall, these factors all contribute varying levels of uncertainty and variance to the results which can be assessed through varying the respective parameters on the Excel model.		

Note: Transmission losses were not considered in this analysis which differs from previous research questions. This was because the losses are incurred as a result of the transmission process, and thus transmission networks must support loads directly from generation or storage facilities (before the application of a transmission loss factor).

6.5.2 RQ4 Limitations and Recommendations

There are various limitations within the model developed and the associated results produced. Based on these limitations, the recommendations suggested below could be employed in future models and analysis to reduce the effect of these limitations and mitigate uncertainty in the results. Various limitations have already been assessed in section 6.3 as the model is explained.

- The first and foremost limitation in this model was the segmentation approach. Although this provided an effective means of performing a fundamental analysis, the nature of segmenting the transmission network into LGAs results in the loss of information regarding the flow of energy across the state. This limits the conclusions that can be drawn and reduces the meaning of quantitative results. This can be improved through the development of a more complex model that considers the entire system as a collective network which would require extensive research but provide more insightful conclusions. It would also address issues regarding the directionality of flow.

- Generation that occurs near the boundary of an LGA may use transmission infrastructure in neighbouring LGAs. This was a major limitation within the model and reduces the accuracy of the concluding claims. This can be improved with additional research into the connection points of various facilities; thus, this locational information would be used instead of the location of the actual facility.

- Assumes maximum generation and maximum storage output are occurring in parallel which is a very unlikely scenario and results in false positive results. Implementing a component in the model that more accurately forecasts generation and storage outputs would reduce the effect of this limitation.

- Another limitation is the lack of detail in regards to transmission network systems within LGAs; this was briefly discussed in the development of the methodology. This can be improved with additional research and the inclusion of substations and smaller distribution networks. Furthermore, this would provide insights into the feasibility of the substation facilities and highlight the potential requirement of upgrades.

- Another limitation discussed was the exclusion of inter-state grid connection. Improving the model to assess interconnection would provide insights into the compatibility of the Queensland transmission network with other state grid systems within the NEM. This would involve the ability for the Queensland powerlines to facilitate energy flow NSW generation and storage which would in turn provide critical diversification to the Queensland generation mix.

Note that if the provided model in the Excel file is used to replicate results, the appropriate figures must be input for the various parameters discussed in the sensitivity analysis. With the improved model suggested, further analysis could involve an enhanced assessment of the transmission network. It is evident that there is significant improvement possible to expand the scope of this analysis and provide a more holistic analysis of the transmission system.

6.6 RQ4 Summary

The aim of this final research question was to thoroughly assess the transmission network capabilities during transition of the energy grid over the following decades to provide an insight into the potential requirements of the grid development. The scope of this analysis involved the assessment of the transmission network through the segmentation of the Queensland powerline system into local government areas; this applied from the current system to the 2040 outlook. Transmission data was collected from the Australian Government, Geoscience Australia, AEMO and individual stakeholders. An interactive and dynamic model was developed on Excel that enabled the input of various parameters to assist with the data analysis. The major findings and conclusions have been summarised below:

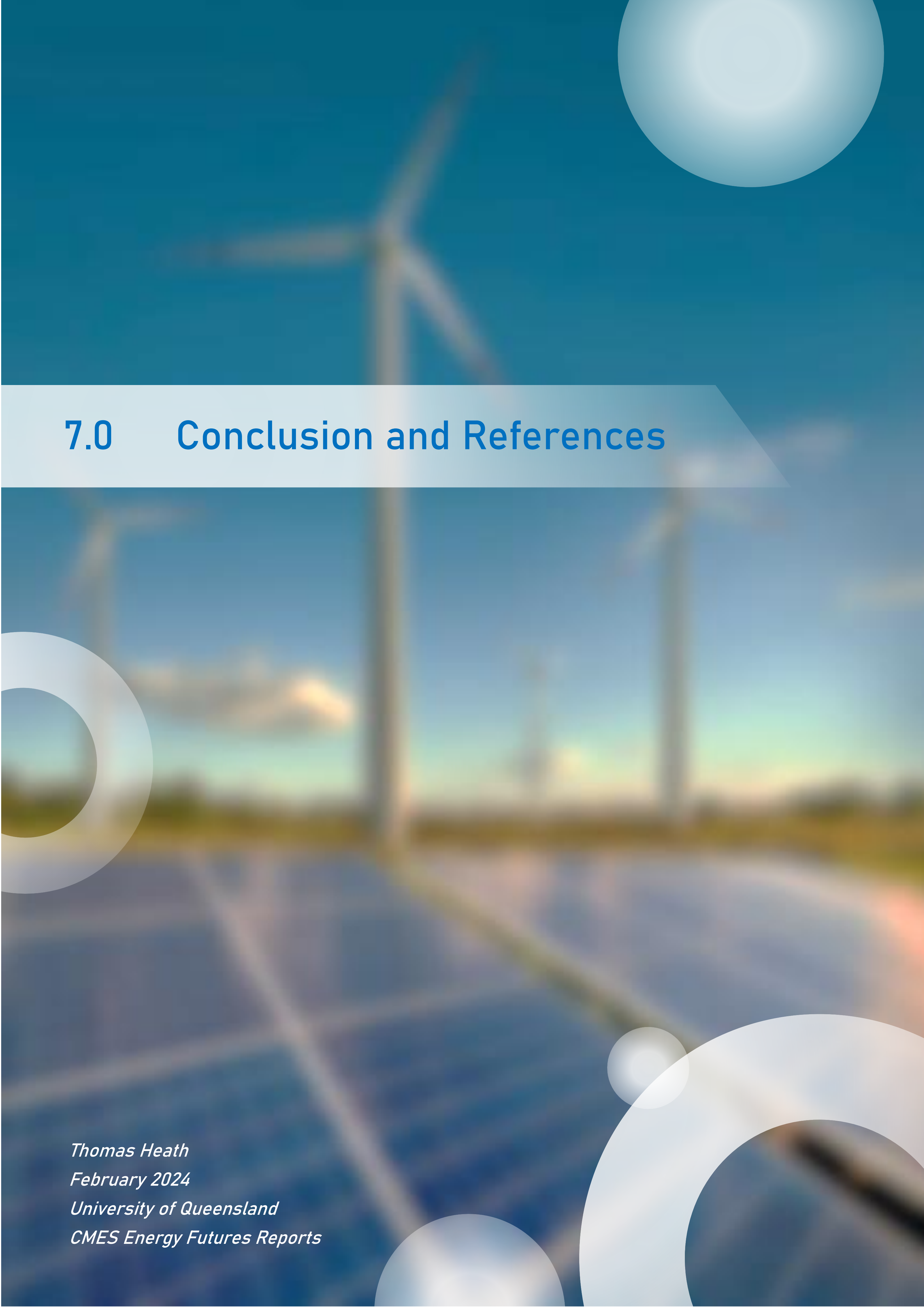
- Forecasted Transmission Network Feasibility: The developed model provided an insight into the feasibility of the transmission network within local government areas. The results demonstrated that over the following two decades, the transmission network within various LGAs will require either an enquiry for potential upgrade or immediate attention and support. Management will be required from 2024 onwards to ensure loads are managed between various LGAs, and by 2033, 7 LGAs will require an upgrade based on their current internal network capacity and generation forecasts. It is recommended that the performance of an additional 7 LGAs be assessed over the course of the grid transition.

- Projected Transmission Network Development: In terms of the planned progression of the transmission network, according to AEMO there is substantial development planned over the following 20 years; however, many of these developments are in very early stages of progression and some proposals still require interest from external stakeholders and there is no certain pathway yet anticipated. From the information provided in the plans, 9 of the LGAs identified as requiring attention were addressed with potential upgrades, while 5 of the LGAs had not been addressed; the omitted LGA networks are either very isolated systems or are close to developing regions.

- Overall Feasibility and Solution: This analysis revealed that there is immediate attention required for the load management of the transmission network in various regions. Provided AEMO continue to monitor the various changes within the system, and facilitate region upgrades of the network accordingly, the transmission network will remain operational through the energy transition and will be able to support new generation growth across Queensland.

- Data Collection: The transmission data collection process was simple and structured with the transmission network information being well documented and easily available. Despite this, there are still various limitations and variables within the models that result in potential uncertainty and high sensitivity to inputs.

Overall, from a transmission perspective, the energy plan demonstrates that substantial attention has been directed towards the development of the powerline network over the following two decades. There were numerous regions within the transmission network identified as requiring potential upgrades with the change in state-wide generation. These requirements have been partially addressed; however, plans for development are still in early stages with external stakeholder interest still required. Effective planning and potential government incentives may be required to holistically address all aspects of the transmission network across Queensland.



7.0 Conclusion and References

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February 2024
University of Queensland
CMES Energy Futures Reports

7.1 Conclusion

It is evident that the feasibility assessment of the Queensland Energy Plan is a multifaceted topic that involves a plethora of considerations and assumptions, and that the requirement for accurate and reliable modelling is pivotal to a valuable and discerning investigation. There has been significant research, modelling, analysis, and refinement throughout this feasibility study.

The aim of this report was to conduct a feasibility assessment on the four underlying cornerstones of the Queensland energy system; the resultant conclusions from this thorough examination provide a clear and comprehensive insight. Overall, the energy plan is proceeding with various levels of progression and the fundamental conclusions have been briefly outlined below:

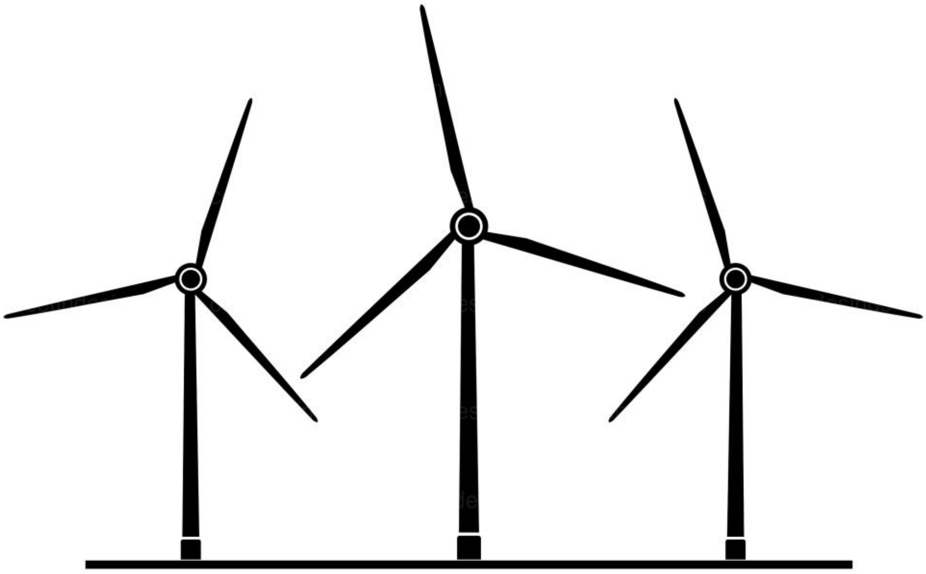
1. Energy Consumption and Generation: From the developed models, the government, and associated operators and providers, should deliver sufficient grid generation during the energy transition period to meet operational demand. Excess production and generation management and control are essential to the development and success of this aspect of the grid.

2. Grid Stability: Considering the operational frequency and system inertia, approximations revealed the government, and associated operators and providers, have partially addressed the short-term inertia shortfall with yet unconfirmed development for the long-term. It is essential the system regulators monitor stakeholder interest and schedule the procurement and construction of synchronous condenser facilities.

3. Grid Energy Storage: Daily operational analysis revealed that sufficient attention and development has been directed towards short-term solutions. Contrarily, drought modelling revealed there has been limited resources directed towards long-term and seasonal storage. It was suggested hydrogen energy may provide a potential solution to the long-term storage but is dependent on the development of this industry and infrastructure in Queensland.

4. Grid Transmission: Numerous regions within the transmission network were identified as requiring potential upgrades over the succeeding two decades. These requirements have been partially addressed; however, plans for development are still in early stages with external stakeholder interest still required.

Each component emphasised the importance of effective planning, management, and monitoring. Government incentives and intervention will likely be required to meet requirements. The prospective benefits of hydrogen energy in the Queensland system (and developing industry) were also revealed to be promising and future assessment should consider the compatibility and potential of this technology. Model refinement and improvement was recommended for each research question and the assessments of the procurement process, economic outcomes, and social and environmental impacts are essential to holistically address all aspects of the energy plan in Queensland. This analysis provides an insight for stakeholders, investors, engineers, and the general population into the grid pathway and outcomes which is critical for progression and awareness. This concludes the critical analysis and *Feasibility Study of the Queensland Energy Plan*.



“The energy transition…
a unique opportunity”

- Thomas Heath -

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Note: The various reference sources used in the Excel model have been provided in the 'Data Tables' sheet as URLs if required.

8.0 Appendix

Thomas Heath
February 2024
University of Queensland
CMES Energy Futures Reports

8.0 Appendix

Appendix 1 – Excel Data and Modelling

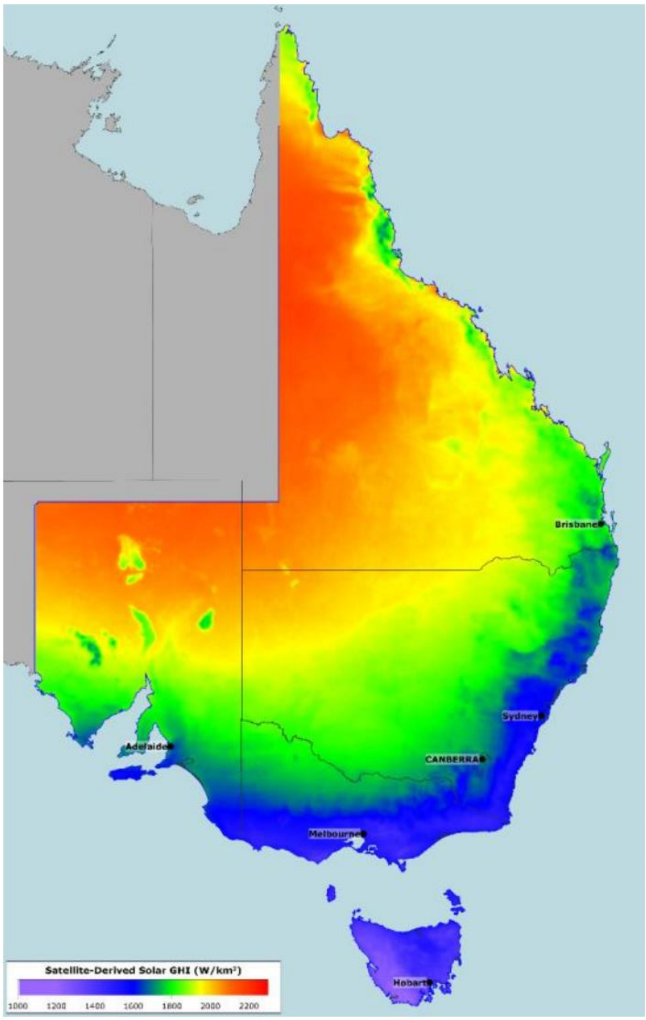
All modelling and data collection is available in this primary appendix. In order to attain link access; please contact *tomheath28@gmail.com*

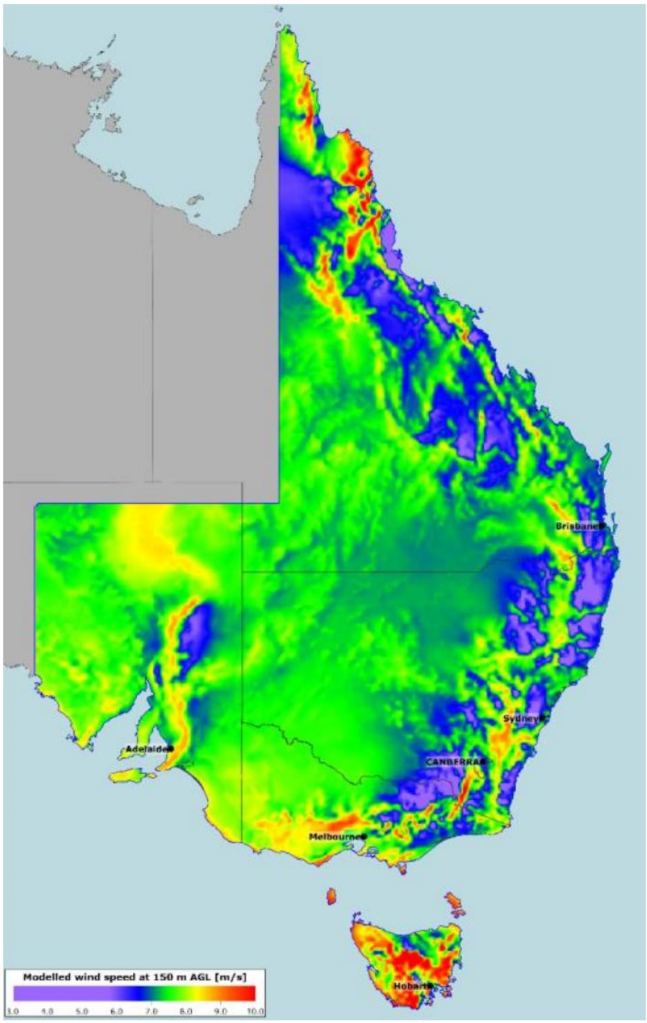
https://drive.google.com/drive/folders/1Btx0xzjM5FXJCP7Bl3s2VfKuFs2JcftA

Appendix 2 and 3 – Queensland Solar Radiation and Queensland Wind Conditions

PV energy production has a massive application in the QLD environment due to the high solar radiation exposure (below left). It is evident that solar radiation is higher in North and West QLD.

Wind generated electricity is in the current QLD grid and is also expected to grow; there are regions of moderate wind conditions throughout Queensland and on the coasts (below right) (GEM, 2018).





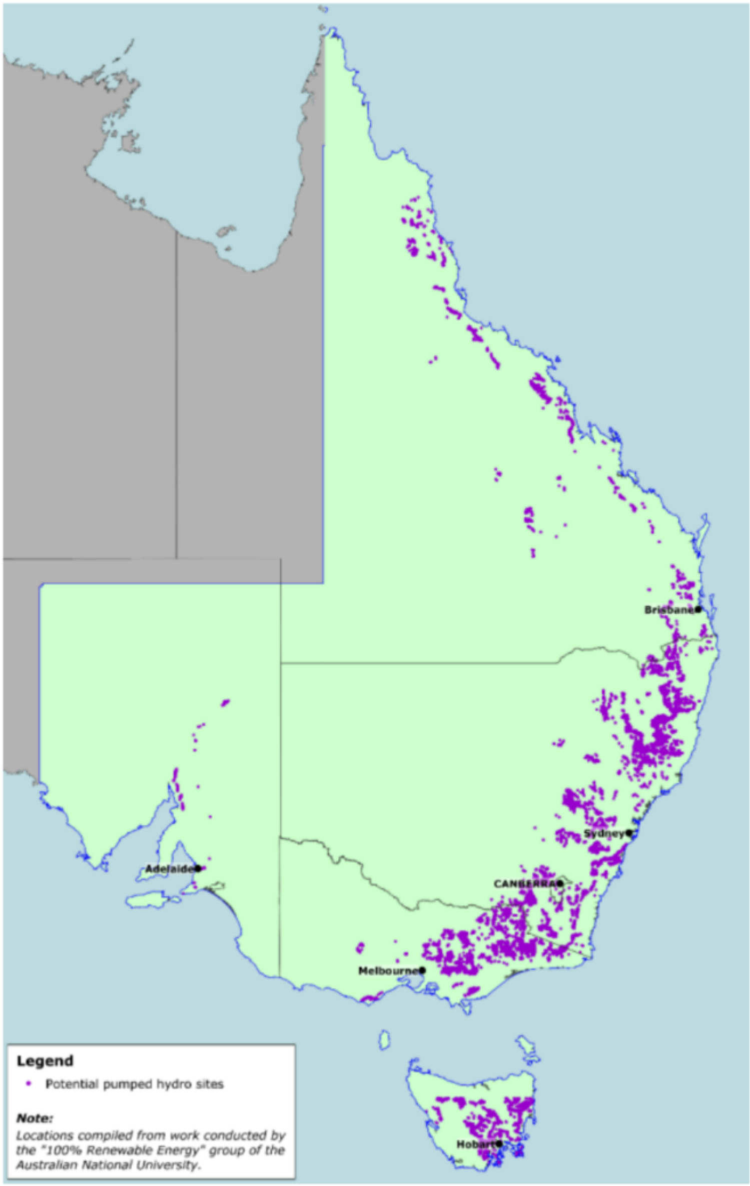
Appendix 4 – Indicative Area for Development of 15 GW Wind and PV generation

This is relevant to research question 1 and provides additional information for these facilities (AEMO, 2017).

Resource	Capacity density (MW/km^2)	Example capacity / MW	Area required / km^2	Proportion of top 10% scoring area	Proportion of farm land in NSW, QLD, VIC	Proportion of crop land in NSW, QLD, VIC
Wind	2 - 5	15,000	3,000 - 7,500	~1.1% - 2.7%	~0.13% - 0.39%	~1.8% - 4.6%
Solar	25 - 75	15,000	200 - 600	~0.0% - 0.2%	~0.01% - 0.03%	~0.1% - 0.4%

Appendix 5 – PHES Locations in Queensland

Queensland does not have natural hydro potential as a form of energy generation; however, there are numerous potential sites for closed loop pumped hydro as an energy storage option. These possible locations are shown below and primarily exist on the Great Dividing Range along the east coast (GEM, 2018).



Appendix 6 – Operational Consumption Definitions

Scheduled generation

A constant output system with an aggregate production of over 30MW (AEMO, N.A.) that is offered for dispatch and supplies live data to the AEMO to be controlled if required for system security; it is currently primarily comprised of coal and gas generation.

Semi-scheduled generation

An intermittent output system with an aggregate production of over 30MW. AEMO receives live data and forecasts production of these plants to include in the dispatch process and can be controlled if required for system security; this is comprised of renewables such as wind and solar.

Non-scheduled generation

Various systems that have an aggregate production of 5-30MW and are not a part of the dispatch process. They are independent units that are not constantly monitored but are forecasted by the AEMO to ensure melange larger production. Note generation is not required to register with AEMO if production is less than 5MW

Transmission connection point (TCP)

A TCP is the physical point of connection where facilities owned by TNSP interconnect with facilities provided by distribution network service providers (DNSP) (AEMO, 2021). The provide a reference point in the calculation and forecasting of operational consumption.

Auxiliary loads

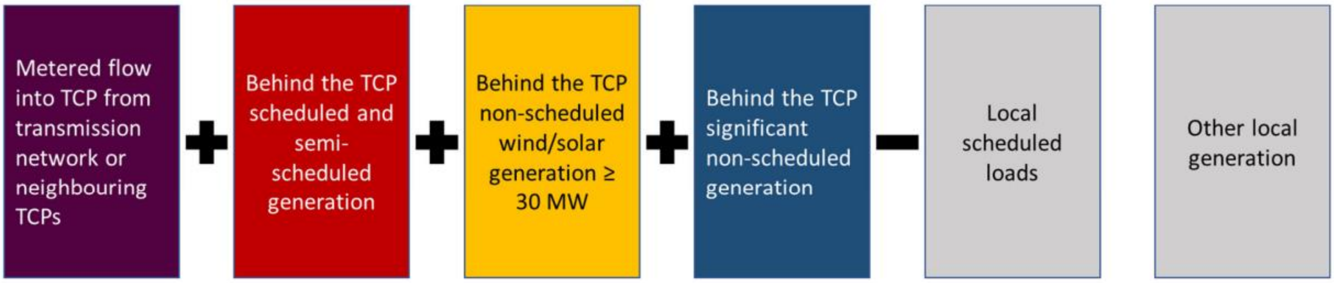
Refers to energy generated for specific use within power stations and is not considered in operational consumption. Note energy used to charge battery facilities is a consumption and is treated as a market load rather than an auxiliary load.

Operational consumption

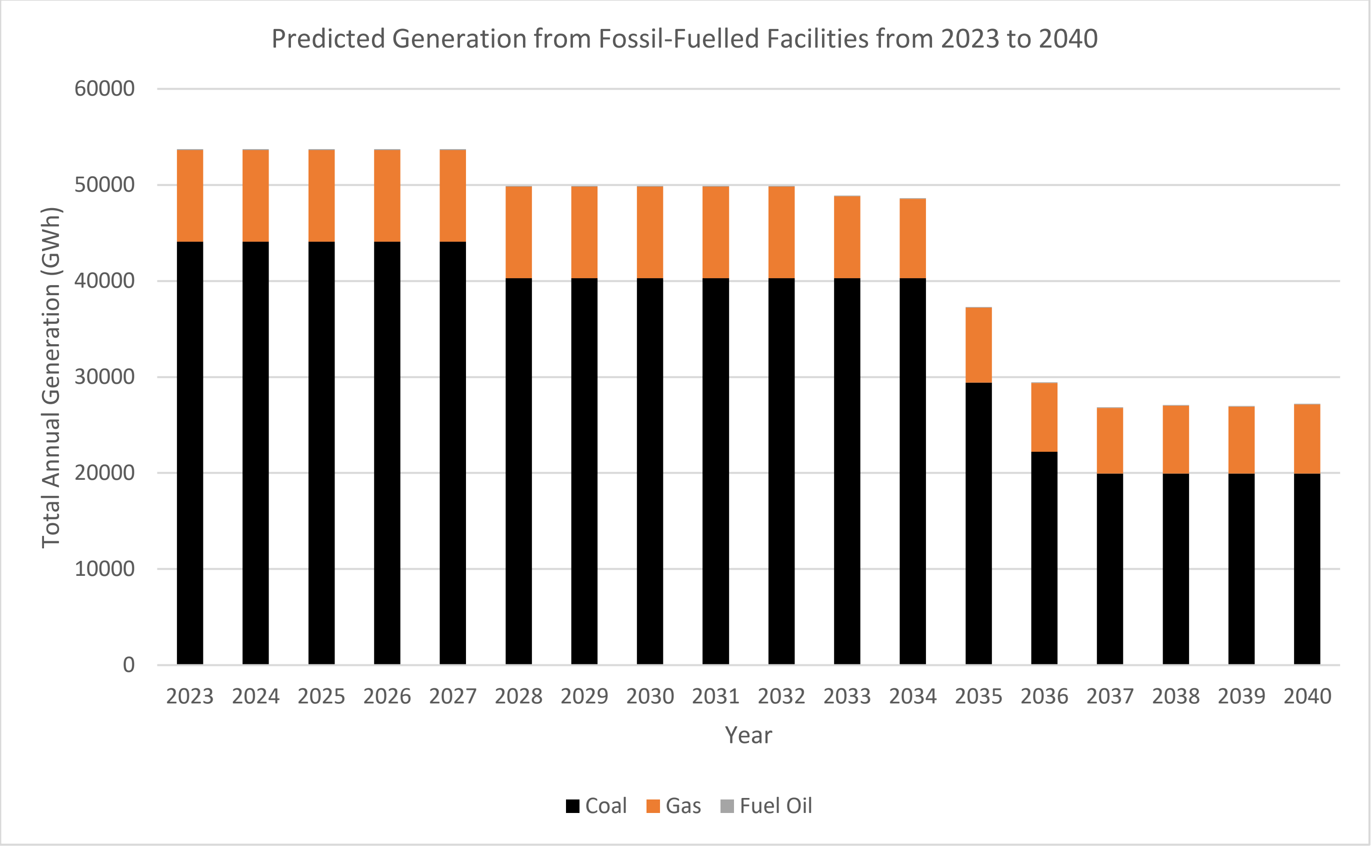
At the TCP reference point, operational consumption includes:

- Measured flow from the transmission network entering a TCP
- Measured flow from neighbouring TCPs within the same region (if applicable) into a TCP
- Any flow from generators embedded within the TCP including locally scheduled, semi-scheduled and non-scheduled generation
- Deduction of any local scheduled loads

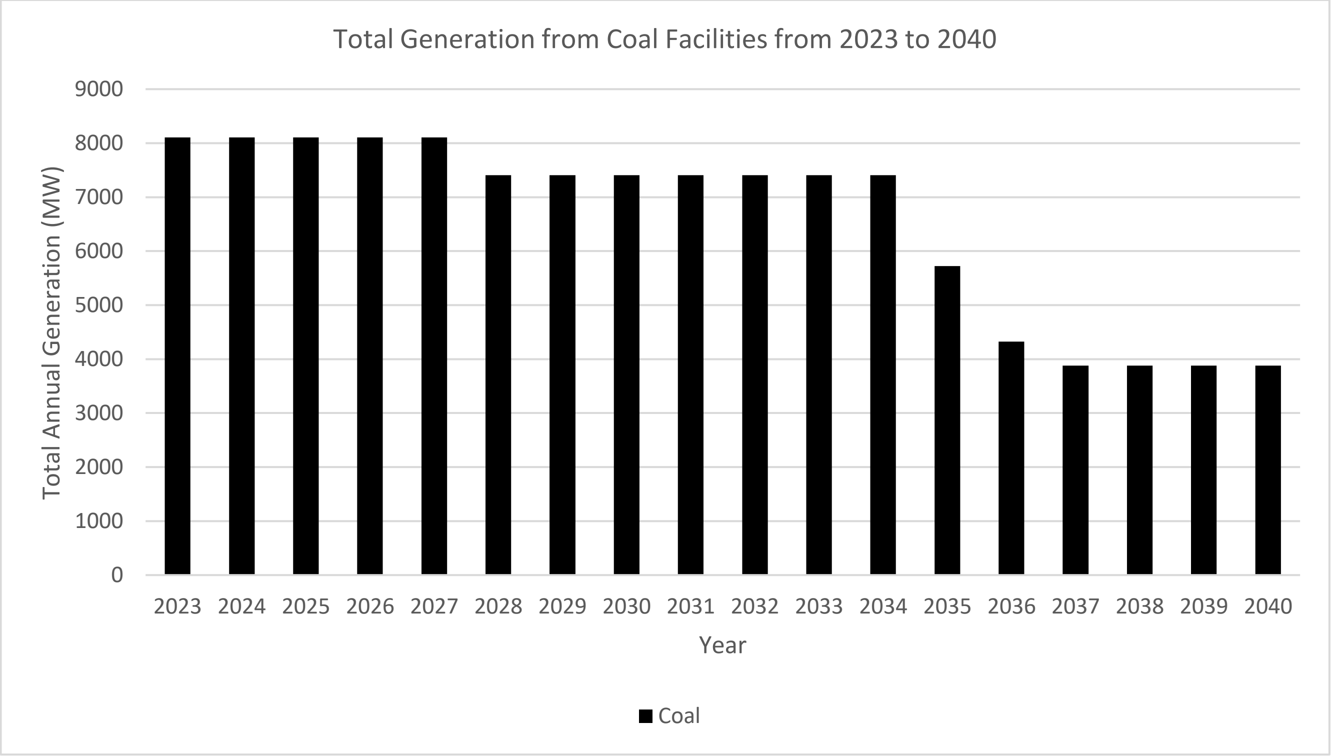
When these flows are combined over all TCPs, the ‘as consumed’ operational consumption is obtained which excludes transmission losses and auxiliary loads. Operational consumption includes the coloured boxes on the LHS of the diagram below while the grey boxes on the RHS are excluded (AEMO, 2021):



Appendix 7 – Forecasted Decline in Annual Generation from Fossil-Fuelled Facilities

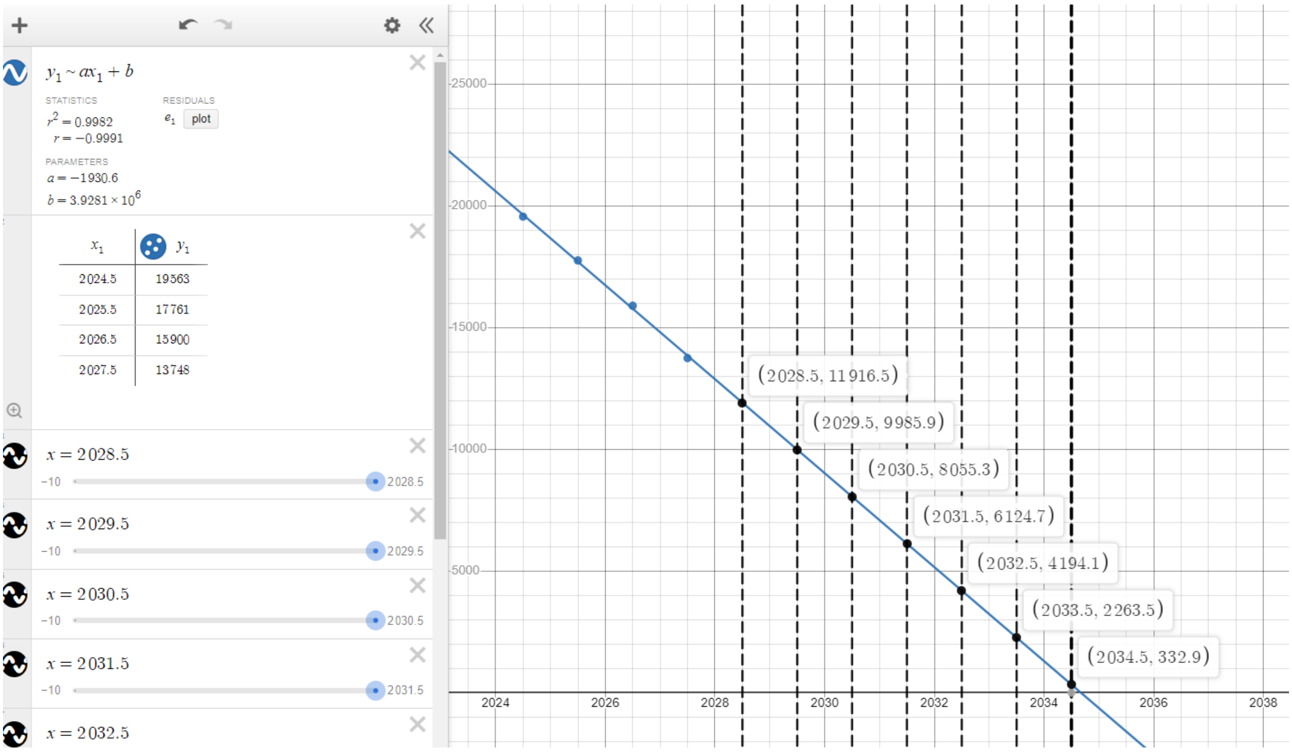


Appendix 8 – Forecasted Decline in Capacity of Coal Facilities



Appendix 9 – Inertia Forecast Regression Data Points

Desmos was sued to extrapolate the data provided by AEMO (Desmos, 2023).



$y_1 \sim ax_1 + b$

STATISTICS

$r^2 = 0.9982$

$r = -0.9991$

RESIDUALS

e_1 plot

PARAMETERS

$a = -1930.6$

$b = 3.9281 \times 10^6$

x_1	y_1
2024.5	19563
2025.5	17761
2026.5	15900
2027.5	13748

$x = 2028.5$

−10 2028.5

$x = 2029.5$

−10 2029.5

$x = 2030.5$

−10 2030.5

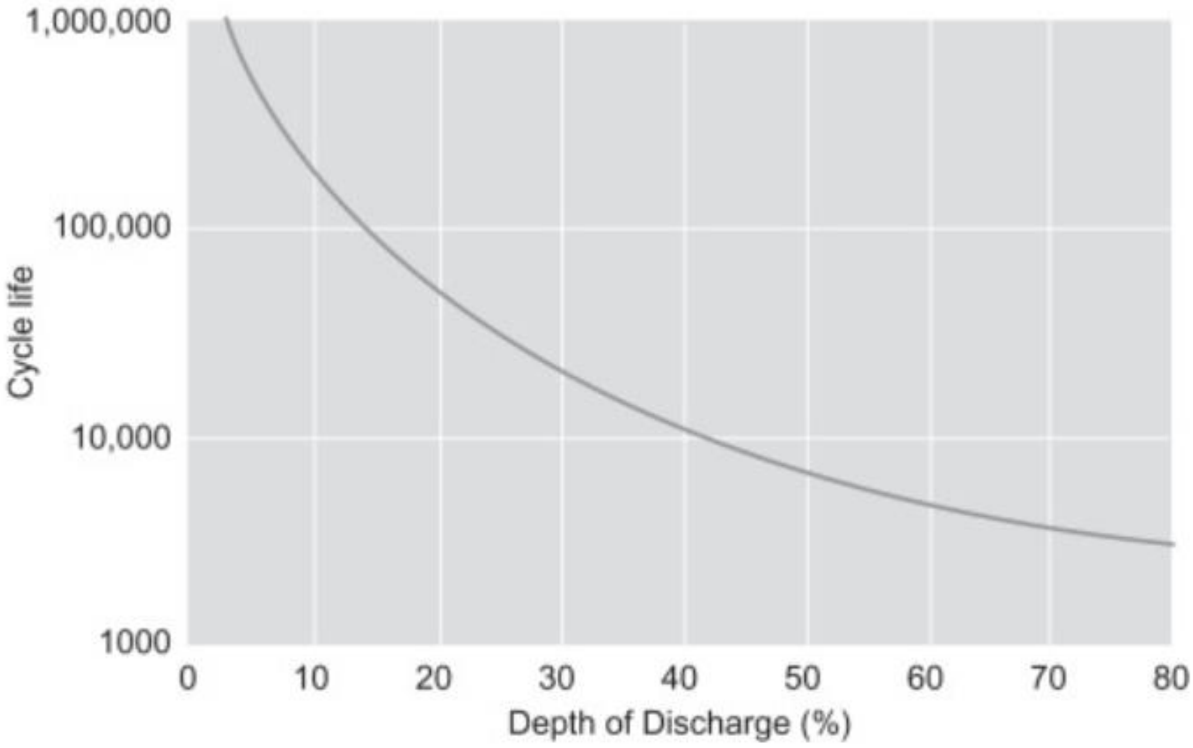
$x = 2031.5$

−10 2031.5

$x = 2032.5$

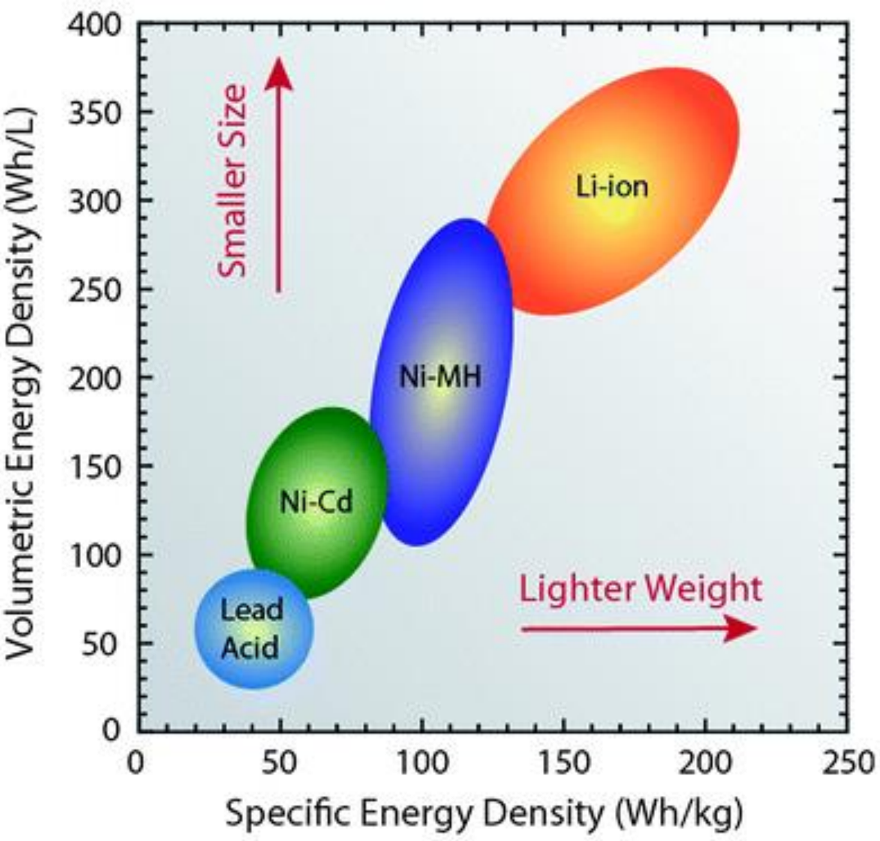
Appendix 10 – Lifetime of Lithium-Ion Battery

The relationship between the depth of discharge and number of cycles of a Li-Ion Battery (ScienceDirect, 2021).



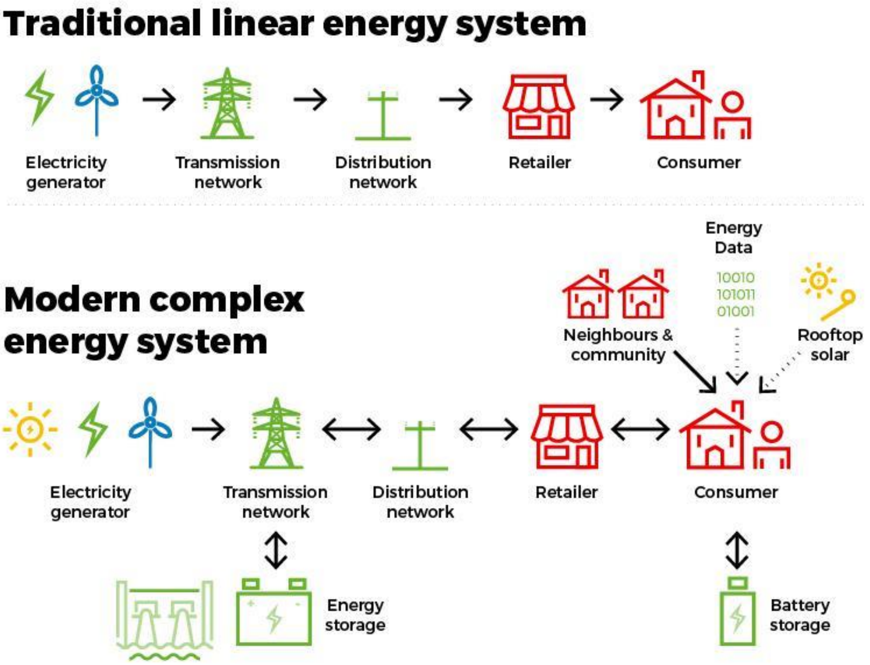
Appendix 11 – Battery Energy Densities

The energy densities of different battery types (EPEC, 2023)



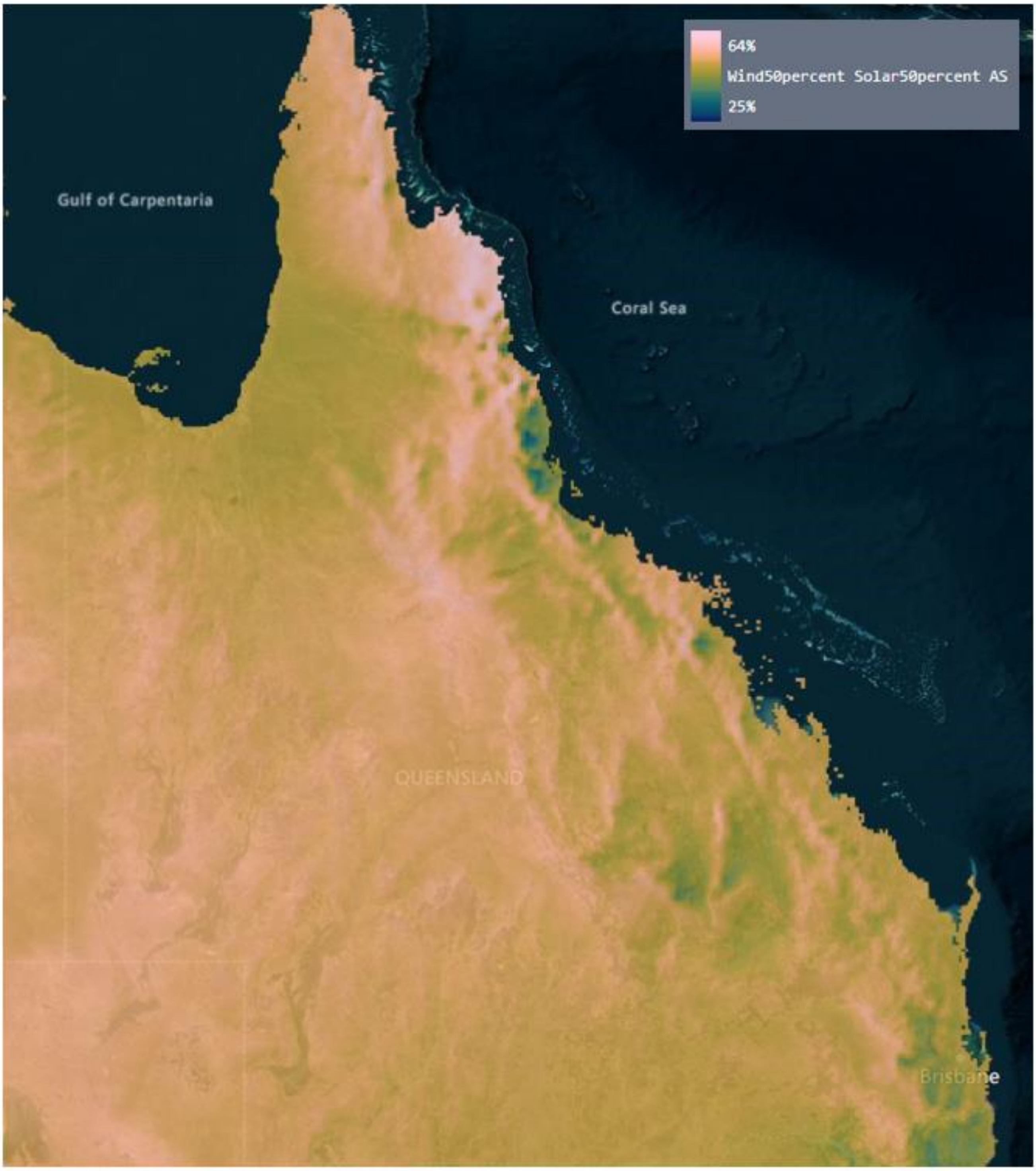
Appendix 12 – The Changing Generation Mix:

A simple infographic showing the changing generation mix (NSW Gov, 2022)



Appendix 13 - Joint Capacity Factor Map

This map shows the joint capacity factor map for a ratio of 50:50 wind to solar generation (Aus Gov, 2023).



Appendix 14 – Queensland Local Government Area Number Assignment

Local Government Number Assignment			
Banana Shire Council	1	Lockyer Valley Regional	25
Barcaldine Regional Council	2	Logan City	26
Brisbane City Council	3	Longreach Regional Council	27
Bulloo Shire	4	Mackay Regional	28
Bundaberg Regional	5	Maranoa Regional	29
Burdekin Shire	6	Mareeba Shire	30
Cairns Regional Council	7	McKinlay Shire	31
Carpentaria Shire Council	8	Moreton Bay Regional Council	32
Cassowary Coast Regional	9	Mount Isa City	33
Central Highlands Regional	10	North Burnett	34
Charters Towers	11	Rockhampton Regional Council	35
Cloncurry Shire	12	Scenic Rim Regional	36
Cook Shire Council	13	Somerset Regional	37
Douglas Shire	14	South Burnett Regional	38
Etheridge Shire Council	15	Southern Downs Regional	39
Flinders Shire Council	16	Sunshine Coast Council	40
Fraser Coast Regional	17	Tablelands Regional	41
Gladstone Regional	18	Toowoomba Regional Council	42
Gold Coast City	19	Torres Shire	43
Goondiwindi Regional Council	20	Townsville City	44
Gympie Regional	21	Weipa Town	45
Hinchinbrook Shire Council	22	Western Downs Regional Council	46
Ipswich City	23	Whitsunday Regional Council	47
Isaac Regional Council	24