Repurposing existing generators as synchronous condensers

Report on technical requirements

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Acknowledgements and disclaimer:

This report was commissioned by the Australian Renewable Energy Agency (ARENA). The report presents the findings of DIgSILENT Pacific Pty Ltd (hereafter referred to as DIgSILENT Pacific), which was prepared to inform industry regarding the potential opportunities and challenges with respect to repurposing existing generators as synchronous condensers.

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Executive summary

The need for system strength and inertia services in the power system

The reports published by the Australian Energy Market Operator (AEMO) in December 2022 [1] [2] highlight ongoing requirements for system strength and inertia services, which AEMO requires to manage power system security. Retirement of fossil-fuel generation, particularly large coal-fired power stations, is projected to reduce both system strength and inertia.

Synchronous condensers (SCs) are identified as providers of both system strength and inertia. The minimum requirements for these services, as identified by AEMO, could potentially be met by installing SCs around the National Electricity Market (NEM). However, the international energy transition and adoption of more inverter-based renewable generation is driving international demand for large SCs. The delivery times for large SCs (>100 MVA) are growing, making it more challenging to procure and install enough SCs in a timely manner to consistently provide the services needed by AEMO within the next five to ten years.

Alternative avenues for the provision of these services are thus being explored.

Repurposing existing generators as synchronous condensers

One possible solution is to convert existing fossil-fuelled generators, which are synchronous machines, into SCs. At face value, this should provide a cost-effective way of providing the required security services to the power system through an existing point of connection (PoC), which already has most of the required infrastructure to support the operation of the plant as a SC. The size of the larger generator units (upwards of 750 MVA) is several times that of a standard SC (around 125 MVA), meaning one conversion could substitute for up to five or more new SCs.

Hydro generators can, and are, also used for this purpose, with many already able to operate as SCs. Comparatively, the opportunity for fossil-fuelled generator repurposing is very much greater than that available from hydro. This report focusses more on the fossil-fuelled options.

Operation of a re-purposed generator as an SC will:

- Stabilise the voltage and thus provide system strength,
- Depending on how the conversion is implemented, contribute inertia at a significant, but possibly reduced, level when compared with the original generator,
- Provide a source of reactive power for voltage control,
- Contribute positively to fault levels.

Our analysis indicates that repurposing generators as SC can provide a viable solution for delivering the required security services. This approach can be used in combination with new SC investments to mitigate the risk of insufficient services.

Repurposing has benefits including:

- Faster implementation times than procuring new synchronous condensers in a tightening international market – repurposing could potentially be achieved in 12-24 months at some sites with new investments taking 30+ months,
- Larger scale, given that the existing generators typically have higher ratings than new SCs, and
- In most cases, lower costs than new synchronous condensers.

Repurposing appears feasible at some sites and more work is required to determine specific conversion options and costs, given that there is a significant variability in plant condition and power station arrangements.

Material supporting our findings

NER framework for procuring system strength and inertia services

From 2025 onwards, the relevant TNSP will be responsible for procuring the efficient level system strength and inertia services, taking account of projected requirements.

AEMO will define the ***minimum*** required service levels and the TNSPs must then procure an ***efficient*** level of each service so that it can reliably deliver the minimum service specified by AEMO, at the time defined by AEMO.

The individual TNSPs must determine the ***efficient*** levels of service, and this will be subject to regulation by the Australian Energy Regulator (AER). The ***efficient*** levels procured will need to be higher than the minimum levels to account for, among others, potential outages of service providers and to provide headroom such that new inverter-based generation can continue to be connected.

Large requirement for system strength and inertia services

In its report on system strength in December 2022 [1], AEMO indicates that around 5,000 MVA of SCs may be required to provide system strength services for a 100% renewables scenario. This can be quantified as 40 SCs with a rating of 125 MVA (similar rating to those installed in South Australia). The requirement is linked to the retirement of fossil generators and will be accelerated if faster retirements occur.

Transgrid released an expression of interest in December 2022 [3] indicating their assessment that 20 SCs (125 MVA) would be required by 2025 and a further seven by 2030.

In some states, such as South Australia, recent investments in four SCs with flywheels will reduce the services that the relevant TNSP needs to procure in the short- medium-term.

However, considering AEMO and Transgrid projections, there is a need to procure significant amounts of both system strength and inertia services.

Duration of the requirements

The size of the requirement and the delivery times and costs of new SCs make it increasingly likely that the need for these services from repurposed generators will exceed ten years. It is likely that contracts for repurposed SCs will also need to be at least ten years to underwrite the conversion and life-extension costs.

Emerging technologies, such as grid forming inverters on battery energy storage systems, may be able to provide similar services of synthetic inertia and system strength. In the longer term, there may be less reliance on SCs. As such, it is difficult to specify the long-term duration of the service requirements.

Technical and commercial considerations when repurposing existing generators

Discussions with asset owners and equipment manufacturers identified several technical and commercial challenges that must be dealt with as part of the conversion process.

The technical matters differ with technology and vary greatly across sites, as turbogenerators (gas, steam turbines) may have materially different designs. Many of the candidate generators for repurposing are near the end of their design life and plant condition may be an important factor in a decision to repurpose and extend the life by some ten years.

The commercial matters are less affected by the technologies but affected by the different operating and maintenance costs, for example.

Technical considerations

There are many technical issues to consider, and the materiality and significance of these issues varies greatly between power stations and the generator technology. Key issues include:

- Condition of the generator and its transformer,
- Starting the SC – addition of a motor or an electronic drive system,
- Feasibility of installing a clutch between the turbine and the generator,
- Condition of the foundations and the ability to modify/extend these,
- Cooling and lubrication of the repurposed generator,
- Losses associated with SC and its auxiliary systems,
- Control and protection systems, potential to automate,
- Operating and maintenance requirements, including requirements for skilled staff,
- Ability to retain inertia (for example, through de-blading of the turbine) or add inertia via a flywheel.

Generator technologies

The ease with which existing generators can be converted to SC operation varies with technology, as well as local site conditions. Key points are:

- **Hydro generators** are generally the easiest to convert and many existing hydro generators already have the capability to operate as SCs. Conversion is relatively simple and involves de-watering the turbine. An advantage of this process is the full inertia is retained.
- **Gas turbines** can be relatively easy to convert if it is possible to install a clutch between the turbine and the generator. Since gas turbines are typically located on ground-mounted foundations, extension of foundations is easier than for steam turbines. When operating as a SC, the turbine is disconnected, and the inertia is reduced.
- **Steam turbines** can be converted by either disconnecting the turbine, de-blading the turbine or fitting a clutch, in increasing level of difficulty. Shaft modifications are required, and this can be challenging on the elevated foundations. Cooling arrangements may also present challenges. Disconnecting the turbine reduces the inertia to about one third of the generator value.

Commercial challenges

A key issue noted in the discussions with service providers and procurers is the significant variation of repurposing costs because of the amount of work required to convert individual generators and prepare them for ten or more years of service as SCs. There are also substantial differences related to costs of operation and maintenance.

Key elements of the commercial arrangements that may need to be considered include:

- The requirement for significant feasibility works, costing around AUD $250-500k, to understand the conversion options, costs, and lead times, will need to be recovered. Because of differences between power stations, these costs are expected for each power station considering conversion works.
- The recovery of conversion costs over the contract term suggests longer contracts will be preferred.
- The procurement of efficient levels of service will mean that some plant may not be ‘dispatched’ until needed. To be financially attractive, contracts will likely need to include payments for both availability and usage.
- Operating losses and secondary equipment electrical energy consumption is around 1-2% of SC rating. Re-purposed SCs may have higher overall energy consumption because the secondary systems like cooling and lubrication may not be optimised for SC operation. The energy consumption may create market risk for the asset owner. Allocation of this cost and market exposure needs to be considered in the commercial arrangements. One option to manage this risk is to treat the repurposed SCs the same as TNSP-owned SCs, with losses and energy consumption recovered via marginal loss factors.
- The TNSP are expected to require rebates on availability payments to cover periods where the plant is unavailable for service. This will incentivise high availability.

Lead times to convert existing generators to SC operation

One of the critical factors in the repurposing of existing generators as SCs is the lead time, particularly when compared with the time taken to implement new SCs.

Table 0.1: Indicative lead times for conversions of existing generator types to SC operation

Technology	Leadtime (excluding connection)	Notes
New build SC	≥30months for delivery and installation.	May lengthen as demand increases; shorter timeframes may be possible with smaller SC unit sizes.
Hydro	Approximately 6-12 months for works, dependent on turbine type.	Dependent on ability to de-water the turbine and maintain cooling water flow.
Gas turbine (open cycle)	Clutch 6-8 months.	Clutch is longest lead-time item.
Gas turbine (combined cycle)	For separate steam turbine, add clutch 6-8 months. For operation with turbine connected, 1-2 months.	Clutch is main lead time. For windmilling turbine, protection modifications may be required (e.g., reverse power).
Steam 1: **Decouple turbine**	Around 18 months – site dependent.	Design and add thrust bearing; add starting system; revise lubrication and cooling.
Steam 2: **De-blade turbine**	18-24 months – site dependent.	Remove turbine blades and re-balance; starting system, revise lubrication and cooling.
Steam 3: **Add clutch**	Around 12-18 months – if no foundation modification.	Not suitable in all cases; clutch design, shaft modifications. Benefits from not need starting system, utilisation of existing cooling, lubrication etc.
Steam 4: **Add flywheel**	Up to 48 months for larger units (>300 MW).	Foundation modification (major time factor for suspended foundations), shaft modification; flywheel design and implementation, shaft dynamics assessment.

Approximate costs to convert an existing generator to SC operation

The costs to convert existing generators to SC operation is highly dependent on the original power station design and the condition of the generator and associated equipment. Obtaining accurate estimates form asset owners was not easy as this information is commercially sensitive. The following table provides indicative conversion costs:

Table 0.2: Indication of conversion costs

Type	Modifications (or notes)	Cost (or cost indication with respect to new SC)
Feasibility study	Approximately 6-12 months.	*Approx. AUD $250-500k*
New SC	Approx 125 MVA; including installation and commissioning.	*Approx. AUD $35-40M*
Hydro	Modification to controls; air compressor; cooling modification;	Small (with respect to new SC)
Gas	Clutch, foundations, modification to controls, lubrication system, starting;	Medium Approx 60% per MVA with respect to new SC
Steam	De-couple turbine (or de-blade the turbine), possible addition of clutch, modifications to bearings, lubrication system, cooling, foundations, controls, and new starting mechanism.	Medium – Large, say 60% to >100% per MVA with respect to new SC.

Type	Modifications (or notes)	Cost (or cost indication with respect to new SC)
		May well be significantly less if generator is higher capacity (>300 MVA).

Recommendations

There are no precedents for the conversion of large fossil fuelled generators to SCs in Australia[1] so the uncertainty around costs is a major factor for both asset owners, regulators, and policy makers. In addition, there can be significant variations in the conversion costs even between similar plant (same rating, same manufacturer), which points to the need to undertake site specific assessments and feasibility study before plant can be offered in a security service tendering process.

1 Recommendation 1 – funding for site-specific investigations

It is recommended that at least two and preferably three site-specific investigations are supported so that the industry can develop a better understanding of:

- Capital works and costs required to repurpose larger generators for SC operation.
- Operating costs, including losses, secondary system energy consumption, and maintenance costs.
- Plant age, life cycle and plant risks and, where appropriate, options to mitigate these risks.
- Lead times to undertake the conversion works.

Funding a large steam turbine project (>300 MVA), and a gas turbine conversion, would provide valuable learnings to the industry in general.

2 Recommendation 2 – urgency to commence repurposing projects.

This report highlights the lead times for both repurposing projects and for new SC investments. The Transgrid EOI [3] and the AEMO reports of December 2022 [2] [1] both have a sense of urgency because of the extent of the requirements and the deadline constraints. The AEMO report [1] encourages early interaction between the TNSP (as System Strength Service Providers - SSSP) and potential service providers. Generally, the 'efficient' service level defined by the SSSP is expected to be significantly higher than the minimum service levels defined by AEMO, and this drives the sense of urgency.

It is therefore strongly recommended that:

- SSSPs commence engagement with potential service providers at the earliest opportunity to assess which projects can be delivered quickly and efficiently.
- SSSPs commence procurement processes and regulatory approvals as soon as possible to avoid delays that result in AEMO having to constrain operations because of service deficiencies.

3 Recommendation 3 – form of contracts

It is recommended that TNSPs explore the term and form of the contracts used to procure security services from repurposed generators in association with asset owners and regulators to provide guidance on how cost recovery can occur, including for:

- Making plant available to provide security services (system strength, inertia, reactive power support).
- Recovery of losses and secondary system energy usage.

[1] The Swanbank A coal-fired generators were run as SCs in the [late 1980s] [16] with minimal cost and relatively easy re-configuration to generator operation. The units were rated at 60 MW. Also, some hydro generators have been converted.

- Maintenance and fixed costs.
- Risk allocation for unplanned outages.
- Cost allocation (including market exposure) for energy consumption.
- Other funding streams may be possible if governments, for example, seek to expedite the conversion process.

4 Recommendation 4 – value of inertia

It is recommended that TNSPs or AEMO provide asset owners with some indication of the value of inertia (in $/MWs) so that they can assess the potential benefit against the cost of making inertia available. This information could come from:

- Tasmanian contract values for inertia.
- OEM estimates of the cost of providing flywheels for purpose built SCs.
- Analysis, for example, of the trade-off between fast frequency response services (priced in a market) and inertia
- RIT-T assessments for the SCs in South Australia indicate a fairly low incremental cost for adding a flywheel. Specifically, a 1,100 MWs flywheel cost is around $1M, giving a modest cost of $91k/100 MWs. However, the cost of a comparatively scaled flywheel on a large generator (300-800 MVA) is likely to be significantly higher and include foundation modifications.
- A secondary recommendation is that all new-build SCs should be fitted with flywheels, given the relatively low cost per MWs.

5 Recommendation 5 – spare generators and transformers

In its reports of December 2022 [2] [1], AEMO recommended that the relevant TNSPs begin discussions with asset owners to explore options for providing system strength and inertial services. It is recommended that TNSPs explore the possibilities of using spares holdings to support the development of purpose-built SCs. The benefit of developing purpose built SCs from spares holdings is that delivery times could be shorter, given that critical assets would already be in the country.

This report

ARENA has engaged DIgSILENT Pacific Pty Ltd (DIgSILENT) to assist with the preparation of this report, which outlines the key technical and commercial issues associated with the repurposing of existing generators as synchronous condensers. A working group with ARENA, AEMO and DIgSILENT representation was established, and information was collated from:

- An international literature survey,
- Interviews and discussions with AEMO and some TNSPS,
- Discussions with asset owners and original equipment manufacturers (OEMs).

This report looks at the feasibility of converting existing generators, particularly gas and coal-fired, to enable operation as SCs. The feasibility assessment includes:

- Technical issues associated with the conversion processes,
- Indicative requirements and timeframes for the provision of services,
- Delivery timelines,
- High level commercial issues, including the nature of the payments and the contract terms.

This report is not a commentary on the National Electricity Rules frameworks that are in place to define service requirements and their procurement.

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GLOSSARY OF TERMS

AC	Alternating current, the most common form of electrical energy in power systems. Voltage and current oscillate sinusoidal at 50 or 60 cycles per second.
AEMO	Australian Energy Market Operator.
DC	Direct current, an alternative form of electrical energy in power systems. Usually used for transmission of power over long distances and within power electronics devices.
HV	High voltage, typically referring to voltage of 1kV and above.
Hz	Hertz, a measure of frequency, equivalent to s-1.
IBG	Inverter-based generator with a power electronic interface (static) with the power system
kV	Kilovolts, one thousand volts, a measure of electric potential.
LV	Low voltage.
MCR	Maximum continuous rating.
MVA	Megavolt Amperes, a unit for apparent power, the vectorial sum of real and reactive power.
Mvar	Megavolt Amperes Reactive, a unit for reactive power.
MW	Megawatts, a unit for real (active) power.
NEM	National electricity market; the inter-connected electricity grid of the Australia eastern states.
NER	National Electricity Rules, the rules that govern the planning and operation of the national electricity network of Australia.
NSP	Network Service Provider.
OEM	Original Equipment Manufacturer.
P	Signal representing the generator real (active) power output.
PoC	Point of connection – the physical location where a customer connects to the power system and where services are measured
pu	Per unit, an expression of system quantities as fractions of a defined base unit quantity.
Q	Signal representing the generator reactive power output.
SC	Synchronous condenser – a synchronous machine with no prime mover used to provide reactive power
SM	Synchronous machine – an electrical machine that operates in synchronism with its AC supply
TNSP	Transmission Network Service Provider.
V	Signal representing the terminal voltage.

1 Background

Australia's energy transition away from fossil fuels is already resulting in the closure of existing fossil-fuelled generators and further generators are scheduled to close in the coming years. These closures are happening as the number of inverter-based generators (IBGs) is rapidly increasing to supply renewable energy to the power system.

The decline in the number of synchronous machine (SM) based generators will have significant adverse impacts on the power system, including but not limited to:

- Reduction in fault levels, leading to protection related issues,
- Reduction in system strength, leading to system control and stability issues, and
- Reduction in system inertia, leading to frequency control issues.

Since the existing fossil fuelled generators are synchronous machines, one approach to mitigating these impacts is to convert these generators to synchronous condensers (SCs). At face value, this should provide a cost-effective way of providing security services to the power system through an existing point of connection (PoC), which already has most of the required infrastructure to support the operation of the plant as a SC. Operation of the re-purposed generator will:

- Contribute positively to fault levels,
- Stabilise the voltage and thus provide system strength,
- Provide a source of reactive power for voltage control,
- Depending on how the conversion is implemented, contribute inertia at a significant, but reduced, level when compared with the original generator.

These same services could be provided using other equipment, including:

- New, purpose-built synchronous condensers,
- Inverter-based generators using grid-forming technologies (still regarded as emerging technology at this stage).

There are many factors that must be assessed when considering the conversion of a generator to a SC. These relate to technical considerations, power system requirements, conversion costs and commercial arrangements with the plant owners.

1.1 Why are these services required?

The interest in converting or re-purposing existing fossil fuelled generators to operate as SCs is driven by the requirement to operate the power system in a secure manner and the long lead times for purpose built SCs. This means that, for a wide range of operating conditions, the power system must be able to tolerate the failure of a single network element anywhere on the power system. There are more details that specify what is meant by secure operation but, in essence:

- The voltage waveshape must remain robust to the changes caused by operation of the power electronic switches in inverter-based generators and loads. Insufficient system strength can result in distorted voltage waveshape, which can affect other plants in the power system and, in severe cases, result in incorrect operation of multiple inverter-based generators.
- The market and power system operator (here AEMO) must have sufficient reactive power to maintain voltages both during normal operation and during periods following faults or unpredicted power system conditions. If insufficient reactive power sources are available, power flows will be restricted, and constraints will be used to keep the power system secure. There are many ways of providing this reactive power and synchronous machines are not the lowest cost means. However, in conjunction with the other services that can be provided, the incremental costs may become competitive.

- The power system frequency must be maintained within a defined frequency operating standard (FOS) to avoid potential cascading events (i.e., tripping of load, generation, or network elements). The amount of inertia on the power system defines how the power system responds to events where the supply temporarily does not equal the demand. Having more inertia on the power system provides a longer period in which corrective actions can be applied.
- Maintaining fault levels means that protective systems, which are coordinated across the power system, must operate as designed and avoid cascading failures. Insufficient fault levels can compromise the coordination of protection and result in plant either not disconnecting when it should, or plant disconnecting when it should not.

Some of these services provide local support, such as reactive power, while others provide power system-wide support, such as inertia. However, even inertia can have localised effects and there may be requirements, for example, for sub-regions of the NEM to have a minimum amount of inertia to cover low probability events where they might be isolated from the rest of the power system.

The value of the services potentially provided by a repurposed generator will thus depend on where it is located relative to the power system needs.

1.2 Timelines driving the conversion of turbine generators to synchronous condensers

Some fossil fuelled generators have already retired, including Hazelwood Power Station in Victoria, Wallerawang Power Station in New South Wales. Many other coal-fired generators have signalled their intention to shut down over the next three to twenty years. Table 1.1 shows the coal-fired generators that have announced withdrawal within this decade.

Table 1.1: Expected withdrawals of coal-fired power stations in the NEM to 2030

Station	State	Expected closure year	Capacity (MW)
Liddell PS	NSW	2023	2,000
Eraring PS	NSW	2025	2,880
Callide B	QLD	2028	700
Yallourn W	VIC	2028	1,450
Vales Point B	NSW	2029	1,320

1.3 This report examines the issues associated with repurposing turbine generators as synchronous condensers

There are many detailed considerations associated with repurposing an existing generator as a synchronous condenser and these issues will vary with technology and fuel type. At a high level, the issues are expected to be:

- Operational:
  - Starting and synchronising the generator
  - Control and protection of the generator
  - Managing losses and auxiliary energy costs
- Electrical:
  - Suitability of location to provide services
  - Condition assessment of insulation and need for refurbishment
  - Excitation control

  - Static frequency converter or pony motor installation and control (for starting and synchronising the SC)
  - Start and stop sequence control
- Mechanical:
  - Disconnection of the turbine (if required) or de-blading
  - Lubrication and cooling
  - Vibration, torsional oscillations
  - Thrust bearing
  - Flywheel installation
- Civil:
  - Structural modifications to foundations
  - Condition assessment of foundations and structures
- Commercial:
  - Costs of repurposing and conversion
  - Operating costs
  - Basic elements of a commercial contract

Some technologies, like hydro, can be relatively easy to convert, while steam turbine generators require a case-by-case assessment and management of many actual and potential risks.

1.4 What this report does not deal with

This report delas with the conversion of existing generators to synchronous condensers and is not intended to deal with aspects relating to:

- National Electricity Rules framework (e.g., NER 5.3.9 process for changing GPS),
- AEMO requirements (e.g., modelling of the SC), or
- NSP procurement process.

2 Introduction

The energy transition is driving a rapid change in the make-up of the generation supplying energy in the NEM. Initial assessments of the consequences of the shut-down of existing fossil-fuelled generation by AEMO and others show that the impacts are severe and will require mitigation.

A key issue is the time frames in which this mitigation must occur. One practical solution is to use synchronous condensers, which can supply several security services, including fault level, system strength, reactive power, and inertia. Supplying large SC capacity in a timely manner is becoming more challenging as the transition to inverter-based generation is global and the demand for SCs is increasing rapidly, leading to longer delivery times. The current situation can be inferred from the fact that delivery time has been extended from 18 months to 30 months after the placement of the order, including the design phase.

Considering these issues, ARENA has engaged DIgSILENT to assist with the preparation of a report – this document – that outlines the key technical and commercial issues associated with the repurposing of existing generators as synchronous condensers.

2.1 Approach adopted in this project

In the NEM, AEMO has the accountability for power system security and is the body appropriate to define the requirements for the services that SCs can provide. Under the National Electricity Rules (NER), the transmission network service providers (TNSPs) have the accountability for procuring and providing these services from 2025 [4].

The input from both AEMO and the TNSPs is thus essential to define the scale and scope of the services that will be required as the energy transition proceeds.

The asset owners of existing generators that may be suitable for conversion or repurposing to operate as SCs have detailed knowledge of their plant and some have already actively analysed options in varying degrees of detail. Another critical factor is the age and condition of the plant.

Original Equipment Manufacturers (OEMs) with experience in building both the synchronous machines used in turbogenerators and the design of power stations have valuable knowledge on the scope of works and the feasibility of undertaking conversions to SC operation.

OEMs for alternative technologies that can provide some, or all, of the required services can potentially provide insights that will be important for selection of the most cost-efficient solutions. This aspect is not for consideration in this project as the focus is specifically on the re-purposing of turbo generators. The TNSPs, with the accountability of making security services available to AEMO, will need to consider the options to provide those services, their technical characteristics, and the costs of providing each service.

The approach in this project is to collect as much information on the repurposing or conversion for synchronous generators to allow them to be used as SCs, providing the services required by AEMO.

Based on the information gathered, a small number of illustrative examples are discussed in greater detail. These examples are based on the likely 'first movers' or where a higher level of certainty exists on technical issues and costs.

Different technologies, for example, a steam turbine and a gas turbine, are considered.

The overall objective is to provide technical, timing and cost information to support informed policy decisions about repurposing existing generators as SCs. This will, in turn, inform decision making on the relevant aspects of strategic management of power system security during the energy transition.

2.2 Work packages

This project is divided into several work packages as defined by:

1. Literature survey to review similar repurposing projects undertaken internationally.

2. Determine broadly the amount of service required, which indicates the extent of requirements.
3. Discussions with key stakeholders including AEMO, TNSPs, asset owners and OEMs to understand the key challenges and considerations relating repurposing generators as SCs. Identification of likely priority projects.
4. Summary of the feasibility of repurposing existing generators as synchronous condensers
5. Recommendations and next steps

Work packages 1 and 3 are reported in the Appendices. The remaining work packages are discussed in the following sections.

3 Service requirements – size of the market

In the following sections, the requirements for each service, as reported in AEMO publications, are presented to give an idea of how much of each service is required in the near term. These requirements are important for this study because they present an indication of how many synchronous condensers are required and how much inertia is required. These requirements will have a bearing on whether asset owners consider offering their plant and how this plant will be configured (for example, with or without a flywheel).

There is also a risk that some of the assumptions AEMO has made in relation to retirements need to be modified and updated because, for example, generators may retire earlier than planned. This would add further pressure on the size of the requirement and the delivery times. Although AEMO has specified minimum requirements, it is possible that these may increase, placing even greater emphasis on finding fast deliver options, such as repurposing of existing or retiring generators.

3.1 AEMO has power system security responsibility

AEMO has a non-delegable accountability to maintain and improve power system security[2], which means it must always operate and plan the power system in a secure manner. The need for security services such as system strength, inertia and reactive power are all inputs into the assessment of security. If insufficient services are available to underwrite security, constraints are put in place to reduce the need for those services to match the levels of service that are available. This can affect the reliability, which is the ability to meet the demand.

AEMO determines requirements – system strength, inertia

AEMO produces forecasts of what services will be required in the future and has defined locations for those services. For example, AEMO has defined system strength nodes where minimum levels of system strength must be achieved. This provides guidance for the transmission network service providers, who have the procurement responsibility, on what levels of service must be made available to AEMO from current day and into the future at each location.

AEMO published System Strength, Inertia and Network Support and Control Ancillary Services reports in December 2022 [2] [1] [5]. These reports, which are published annually, highlight inertia shortfalls and system security [service] shortfalls across the NEM. The reports also introduce system strength standards aligned to the amended framework for managing and procuring system security services.

3.2 Requirements by State / Region

System strength

AEMO applies the system strength rules framework [1] to the projected generation and transmission network outcomes. AEMO then declares system strength nodes across the NEM, and sets system strength standards at each node, considering critical planned outages. AEMO warns in their report that supply chain limitations present risks for infrastructure investments and encourages early engagement on system strength service options.

The AEMO report includes the results of a study of a 100% renewables scenario, under which the equivalent of up to 40 new synchronous condensers (with an assumed size of 125MVA each, giving a total of 5 GVA) could be needed to meet system strength requirements. This conclusion is part of the justification for this project assessing the feasibility and viability of converting existing generators to operate as SCs.

For each region / state, the AEMO report [1] identifies system strength nodes and the projected shortfalls. The details are in the AEMO report, but the total shortfall is summarised here by adding the shortfalls at the individual nodes.

[2] NER 4.1.1(b)

‘Minimum requirements’ and ‘efficient requirements’

Note that the above reports give the ***minimum*** **requirements.** The ***efficient*** requirements are determined by the TNSP in its role as System Strength Service Provider (SSSP). The efficient requirements will always be higher than the minimum requirements to allow for outages of system strength plant (like SCs) and other requirements the TNSP will have to consider to deliver with a high probability the minimum requirements for secure power system operation.

Minimum system strength requirements by region (summary to 2027-28)

Table 3.1: Minimum system strength requirements defined by AEMO [1] for the years 2026-27 and 2027-28

Region	2026-27 (MVA required)	2027-28 (MVA required)	AEMO report reference
Queensland	87	131	Table 17
New South Wales	305	699	Table 9
Victoria	710	899	Table 40
South Australia	0	0	Table 25
Tasmania	2,140	2,143	Table 33

To quantify this requirement in terms of the size of SC (or generator) that would need to be added at a system strength node, the following applies:

- Assume a 125 MVA SC with sub-transient reactance of 18%,
- Assume a step-up transformer with an impedance of 12% and a matching rating of 125 MVA,
- Fault level contribution (sub-transient time frame) would be 416 MVA.
- Note also in this table that the requirement in Tasmania arises because these services are currently provided under contracts between TasNetworks and Hydro Tasmania that will expire in 2024. Renegotiation of these contracts is expected to deliver the required minimum system strength services. TasNetworks is the SSSP for the Tasmanian region.

Inertia services

Inertia services can be provided by synchronous machines, which is physical inertia resulting from rotating masses [6]. This inertia can be provided by:

- Generators with their turbines
- Generators on their own
- Synchronous condensers with or without flywheels

Inverter based generating systems, like battery storage systems, are able to respond very quickly and deliver responses similar to the physical inertia of a synchronous machine and whatever is connected to it (turbine, flywheel, or just the stand-alone generator). This rapid response is sometimes referred to as synthetic inertia. Response times of the order of 150ms appear to be possible (roughly 1/6 of a second).

Synthetic inertia is not fully interchangeable with physical inertia but has other characteristics that are attractive.

There is a trade-off between the amount of physical inertia required and the amount of [very] fast frequency response available from plant such as batteries. This can be expressed simply as:

- If there is adequate physical inertia, less fast frequency response (or synthetic inertia) is required because the rate of change of frequency is lower and slower frequency response services are able to restore the frequency to nominal.

- If there is less physical inertia, the rate of change of frequency is higher and more fast frequency response services are required.

There can thus be an optimisation between the procurement of physical inertia and fast frequency response.

Because procurement of inertia is not market based, this optimisation must be considered as part of the RIT-T. According to the AEMO inertia report [2], very fast frequency control ancillary services markets will be introduced in 2023.

Sub-network requirements

A sub-network is any part of the power system that can be separated from the rest of the power system, thus forming a frequency island. AEMO determines where such sub-networks might credibly arise and determines whether there are likely to be shortfalls of inertia within those sub-networks over the next five years.

TNSPs, as 'Inertia Service Providers'[3], must then ensure that sufficient inertia network services are available to AEMO to manage the inertia requirements.

There are some regions where a reclassified non-credible contingency can separate the region from the rest of the NEM. Currently this applies to Queensland, South Australia, and Tasmania. South Australia should have a new interconnector (project EnergyConnect) in place by 2025, which will reduce the probability of isolated operation.

Where there is a non-negligible probability of a frequency island forming in a sub-network, the inertia requirement will be locational, even though frequency is a power system-wide phenomenon. The AEMO minimum inertia requirements report [2] thus provides requirement by region.

Inertia requirements by region

The following requirements are extracted from the AEMO inertia report [2] and broadly present the minimum requirements in each region.

Similar to the requirements for system strength, the efficient level of inertia is expected to be higher than the minimum level to account for factors such as outages and development of the power system in years ahead.

For Tasmania, the same comment applies as for system strength – the requirement in the AEMO report reflects the fact that these services are currently under contract, but the agreement is set to expire in 2024, necessitating renegotiation.

Table 3.2: Minimum inertia requirements defined by AEMO [2] for the years 2026-27 and 2027-28

Region	2026-27 (MWs required)	2027-28 (MWs required)	AEMO report reference
Queensland	0	10,352	Table 5
New South Wales	0	0	Table 4
Victoria	2,421	2,482	Table 8
South Australia	0	0	Table 6 – see note[4]
Tasmania	2,509	2,509	Table 7 – see note[5]

[3] NER 5.20B.4(a)

[4] For South Australia, there is an inertia shortfall if Victoria and South Australia are considered a sub-network. However, AEMO allocated this shortfall to Victoria.

[5] Tasmania is a frequency island. Contracts with existing generators are used to meet current inertia requirements.

As an illustration, the Tarong North plant in Queensland[6] has a generator nameplate rating of 615 MVA and an inertia time constant of 2.82s. If this one generator was converted to operate as a SC, the contribution in MWs could be estimated as:

- Inertial contribution when configured as a generator (i.e., current configuration):
  - 2.82s * 615 MVA = 1,734 MWs
- Assuming debladed operation and a 30% reduction in inertia:
  - 2.82s * 615 MVA * 0.7 = 1,214 MWs
- If the turbine is disconnected from the generator, leaving an (assumed) inertial time constant of 1 s:
  - 1.0s * 615 MVA = 615 MWs

The above example gives some insight into the extent of the requirement in each region. The 'heavier' the generator, the greater the inertial contribution will be and the greater the value will be if there is an inertial shortfall.

In some power stations there are multiple units and conversion of each unit would materially contribute to the service requirements.

If battery storage systems with fast response are configured to provide synthetic inertia, they can potentially contribute to meeting the shortfalls listed in the table.

3.3 Transmission Network Service Providers procure the service

For system strength, fault level, inertia and reactive power, there are currently no markets, and a separate non-market procurement process is required. Transmission Network Service Providers in each state are responsible for delivering system strength, inertia, and other security services in response to the shortfalls and standards declared in the AEMO reports.

The process can be illustrated by the regulatory process Transgrid is undertaking, which commenced with the publication of Expression of Interest document in December 2022 [3].

Following the AEMO reports in 2022 [2] [1], AEMO gave notice[7] to Transgrid of projected shortfalls. Under the amended frameworks, the TNSPs must make system strength services available to address the expected system strength shortfalls identified by AEMO in its notices[8].

Transgrid has indicated that other factors are considered, such as the need to meet a minimum fault level for protection system coordination requirements [3]. Fault level and system strength have some similar characteristics (system strength is generally improved with increasing fault level) so this minimum fault level may be an additional indicator of the required quantity of services to be procured.

Transgrid has determined [3] "that the installation of synchronous condensers is the most credible short- to medium-term network solution to contribute to meeting NSW's system strength needs, comprising:

- From 1 July 2025 to 1 December 2025, four synchronous condensers to address the system strength Shortfall declared by AEMO, and
- From 2 December 2025, approximately 20 synchronous condensers (assumed at 125 MVA rating) in total to meet the entire minimum and efficient levels of system strength required by AEMO's forecast, growing to 29 synchronous condensers in 2032-33 as more inverter-based renewables connect".

This gives a perspective of the extent of the requirement as calculated by Transgrid. It also illustrates the application of minimum requirements and efficient levels that the TNSP determines to manage long run pricing stability.

[6] There is no suggestion in this report that the Tarong North plant will retire prematurely – it is used as an example to demonstrate the effectiveness of repurposed generators in meeting inertia requirements.
[7] NER11.143.14
[8] NER 11.143.15

3.4 Requirement duration

An important consideration in the procurement process is the term of any contracts for security services. As technologies change and new services are offered (for example, synthetic inertia, very fast frequency response), the AEMO defined requirements may change. Similarly, as in the case of protection systems, the implementation of different protection technologies or a review of the minimum fault level requirements, has the potential to change the service requirements.

There is thus a tension between the need to provide certainty to service providers with longer duration contract and the risk of over-procurement should requirements be reduced through technology advances or the development of alternative services or service providers with lower costs.

The requirements for system strength and inertia services listed in Table 3.1 and Table 3.2 are for the next five years. As more coal and gas-fired generators retire, these requirements are likely to increase. It is probably fair to say that significant gaps in security services are likely for at least the next ten years and some service providers have indicated that this is potentially the length of contract that could be contemplated.

3.5 State perceptions on procurement

Since there is a TNSP in each state, it is possible that their procurement approach for security services may differ, subject to overall regulation by the Australian Energy Regulator (AER). There are differences in requirements for each state as defined by AEMO [2] [1]. While these are minimum service requirements, the relevant TNSPs must assess what the efficient level of service procurement is required to reliably deliver this minimum requirement.

For example, there is a need to consider both availability and efficient levels of system strength when evaluating the capacity of a power system. The efficient level of system strength provides headroom above the minimum levels, allowing for easier connection of new generators over time. This is important for TNSPs, who deal with connection applications and must ensure that service levels are sufficient to meet the demand for new connections. Connection applicants may also be required to pay for system strength services consumed by their plant. Prudent planning for service levels available for new connections can help to achieve the desired 'efficient' level of system strength and avoid delays or constraints due to inadequate levels of service.

There are thus likely to be differences in the procurement strategies in each state, which may introduce some complexity for asset owners with portfolios that cross state boundaries.

Another observation is that some services in one state may be most efficiently procured in another state. Near-border services may thus result in a TNSP in one state contracting with a service provider in another state. This is not an issue and may improve the asset owner’s bargaining position where it has multiple buyers.

4 Considerations when repurposing an existing generator as a synchronous condenser

The following subsections report on information collected during the literature review and the stakeholder consultations.

Information is not attributed to any specific organisation unless, in some cases, reference made to information published by a stakeholder or via stakeholder consultation.

It is clear that not all issues will apply to all plants. The design of individual power stations is often bespoke, especially for coal-fired plant. As many of the coal-fired power plants have been operating for a significant period, it is probable that they have undergone several retrofits and refurbishments. This means that even power stations built by the same OEM at a similar time may now have some significantly different issues.

Similarly, the condition of the generators, turbines and other primary equipment may also differ across power stations with similar equipment, depending on how they have been operated, for example.

4.1 Technical considerations – steam turbines

Steam turbine driven generators are generally related to coal fired power station, although some gas fuelled steam generators exist in the NEM (e.g., Newport, Torrens Island). The technology and issues are likely to be very similar and the following topics will require consideration:

Design studies

With very few exceptions, each power station is different and, after a couple of decades operating, the condition and secondary equipment upgrades may result in significant differences between otherwise similar power stations.

The net result is that when consideration is given to re-purposing, each site will require its own detailed investigation to understand whether repurposing is viable or not and, if so, what work is required and how much this will cost.

A feasibility investigation that collects enough data for a design stage may have a cost in the multiple $100k and have a duration of six or more months.

An example of the type of data to be collected for the feasibility study is shown below [7]:

- Single line diagram,
- Generator and transformer datasheet,
- General arrangement drawing,
- Test certificates indicating losses,
- Operational data and history of generator,
- Shaft train outline, generator cross section with dimensions,
- Turbine generator foundation drawings,
- Rotor weight and inertia,
- Auxiliary system schemes,
- Details of the excitation and protection system,
- Phase isolated bus-bar arrangement layout (if applicable),
- Equipment layout of main plant,
- Residual life analysis for generator stator insulation.

Detailed condition assessments will be required for all electrical, civil, and mechanical components of the plant to assess whether a life extension of 10+ years is possible.

Starting and synchronising

In steam turbines, the start-up and acceleration to synchronous speed is achieved by admitting steam to the turbine. For a SC, there is no turbine, and some other means of starting is required. There are two main means of doing this:

- A motor (of several MW, say 5 MW for a 400 MW generator) is permanently attached to the shaft and is used to accelerate the shaft to synchronous speed, or slightly above synchronous speed. Normal synchronisation once the speed and phase of the synchronous machine and the power system are aligned.
- With appropriate connections, a static frequency converter (SFC) can be connected to the stator of the generator. Varying the frequency and voltage applied to the generator, the SM can be accelerated to super synchronous speed. The SFC is then disconnected, the SM is excited and then synchronised when the speed declines to synchronous speed. A single switched SFC can be used to run up more than one generator.

The motor option is simple but requires shaft modification, footing changes or adjustments and switching arrangements.

*Figure 4.1: Synchronous condenser arrangement with pony motor on **right** and synchronous machine on **left** [7]*

The SFC option does not require shaft connections or footing modifications but does require suitable switching arrangements that need to be interlocked to prevent inadvertent paralleling of supplies. The process can be automated. A single switched SFC can be used to run up more than one generator if the connection infrastructure is designed to allow the SFC output to be switched between units. The reliability of an installation is reduced where multiple machines are dependent on a single SFC.

The choice between using a pony motor or a SFC is essentially one of economic cost. Both methods are likely to be viable for most potential repurposing options. It is concluded that the starting arrangements are unlikely to be a significant obstacle to a repurposing project.

Voltage / reactive power control

As with a generator, the voltage control or reactive power control, when configured as an SC, is achieved through an automatic voltage regulator (AVR), which acts on the current in the rotor field winding. The AVR is referred to as an excitation system and excitation supply can either be from a transformer connected to the supply or the generator terminals, with various other combinations also possible. It may be possible to re-use the excitation system fitted when operating as a generator. Replacing the excitation system is also a feasible path with many commercial offerings available.

Achieving satisfactory voltage control is unlikely to be a technical obstacle in a repurposing project but the costs are not trivial, with an excitation system upgrade costing around $2M for equipment and labour[9]. Lower cost options that use existing equipment (e.g., thyristor bridges, excitation transformers) would also be available.

If an SFC is used to start the SC, it may be desirable to coordinate any upgrades or works on the excitation system to be compatible with the SFC and the proposed starting sequence.

Inertia

The inertia of a generating system depends on the spinning mass. With a turbine connected, the inertia is the sum of the generator inertia and the turbine inertia.

Disconnecting the turbine, the inertia of the generator alone is likely to be about one third of the combined generator and turbine. For example, a turbo generator might have an inertia time constant of 4.5s of which the generator component is 1.5s. Disconnecting the turbine thus has a significant impact on the inertia.

Leaving the turbine unchanged is unlikely to be a viable option because of the windage losses and the need to evacuate the turbine casings.

A more realistic option is to de-blade the turbines and leave the shaft spinning with relatively low windage losses. This preserves most of the inertia. There will still be a reduction in inertia as the mass of the blades is removed. The blade mass is also located some distance (radially) from the shaft, which increases the inertia. The net reduction in inertia from de-blading is thought to be of the order of 30%. So, in the example previously, the generator inertia is around 1.5s, the turbine with blades is around 3s, and debladed about 2s. The net inertia would reduce from 4.5s to about 3.5s.

An interesting observation during industry consultations was that, when debladed, the spinning shaft may produce higher noise levels (because of turbulent airflows), which may require treatment if they exceed acceptable health standards.

Depending on the value of inertia (i.e., how much the NEM is prepared to pay for inertia), it may be commercially viable to add a flywheel to the shaft of an existing generator. This is not a trivial task as it will require modification of the foundations, removal of the turbines, new or modified bearings and a new or modified shaft. Theoretically, this would only be justified if the contract price for inertia was significant, and the presence of alternatives such as synthetic inertia may mitigate against this. Note that adding a flywheel to a new SC is relatively low cost (less than $100k/100MWs), whereas adding it to an existing generator is expected to be higher cost because of bespoke design and the need to potentially modify foundations. As a common-sense approach, all new SCs should be fitted with flywheels because of this relatively cost for inertia contribution.

[9] This excludes the cost for connection study and due diligence studies by AEMO and the TNSPs as per the NER connection requirements.

*Figure 4.2: Example of a Siemens flywheel installation between a purpose-built SC (**left**) and the pony motor (**right**) [8]*

Synthetic inertia is available from inverter-based generators on energy systems like batteries. The inverter controls essentially mimic the inertial response of a rotating SM by providing a rapid response that is proportional to the rate of change of frequency. Spinning plant inertia is superior as it is instantaneous in its response, but synthetic inertia can be configured to have additional benefits, such as not needing to recover energy as the frequency rises. There is not much experience with synthetic inertia in the NEM and this should be regarded as an emerging technology. At this stage, it may be premature to rely on synthetic inertia and prudent operation would be, in the absence of actual operational data, not to do so.

Round rotor vs salient pole

Synchronous machines used as generators are typically classified as round rotor or salient pole.

- Round rotor SMs are usually high speed with two poles (and in some cases four) that are embedded in slots in an otherwise cylindrical rotor.
- Salient pole SMs are required in applications that require high torque at low speed (such as hydro generators) and the poles on the rotor are distinct, forming alternative poles (North and South) in a N*pole pair configuration, where N is an integer > 2. Slow speed hydro turbines may have N≥8.

The significance of the rotor construction is that the reactive capability can vary between a round rotor (more) and a salient pole (less) configuration. This is only an issue if reactive power is an important service from the unit.

The inertia of a salient pole generator is generally greater than an equivalently rated round rotor machine. Depending on construction, there may be little opportunity to add inertia (via a flywheel) in a vertical shaft salient pole machine, such as hydro generators using Francis turbines.

Cooling – plant rating requirement, air, water, or hydrogen cooling

Manufacturers advise that the largest air-cooled synchronous condensers (i.e., purpose built) are around 250 MVA in rating. Many of the NEM generators that are candidates for refurbishment are larger than this rating (for example, Eraring, Bayswater, and Mt Piper are all around 770-800 MVA rating per generating unit).

Large SMs require specialised cooling in the form of liquid cooling or hydrogen cooling or both. The losses incurred by current flowing in the stator and rotor produce heat and this needs to be removed from the generator. Normally this is done by having heat exchangers external to the generator that cool the circulating liquid or hydrogen.

Lubricants also require cooling and heat exchangers must be provided to keep temperatures within design specifications.

A generator will typically have losses of around 1-2% due to electrical losses and windage. The net draw from the power system for a 770 MVA synchronous condenser could thus be around 7-14 MW. To dissipate this amount of energy, some power stations utilise heat exchangers cooled using wet cooling towers. Since the cooling towers are sized for the steam cycle as well, they are likely to be very much larger than that the requirements for the losses when operating as a SC. Nevertheless, part of the repurposing costs will be associated with the arrangements required to manage the heat losses incurred by the electrical and mechanical systems.

The fault level, inertia, and system strength services only require a transient output from an SC. It may thus be possible to significantly reduce the requirements for the cooling arrangements if the repurposed SC is restricted in its continuous rating. This would be a viable approach if the NEM requirement for reactive power at the power station location was low.

Lubrication and bearings

The lubrication and bearing requirements will vary according to the configuration of the re-purposed generator. There are two principal options:

- Decoupled turbine: If the turbine is decoupled from the generators, it is necessary to provide a new thrust bearing for the generator. This is because there is only one thrust bearing in a turbine generator and is usually between the HP and LP turbines. Decoupling the turbine requires the addition of a new thrust bearing to locate in the new drivetrain arrangement, in the rotor correctly within the stator.
- Retained turbine: If the turbines are debladed, the existing thrust bearing can be utilised.

In both cases, the pumps providing the lubrication oil will require supplies, including back up supplies, should there be a loss of power. This may require some rearrangement of existing lubrication systems, including their supplies. Note that the back-up supplies (batteries) will also need to be retained and maintained. The lube system may also require a standby generator.

The lubrication system needs cooling to dissipate heat and although this is likely to be less demanding than when the turbine is operating with high temperature steam, it still requires consideration and may require some redesign.

The lubrication system is likely to be relatively straight forward to manage and resolve and is unlikely to be a potential blocker for a repurposing project.

Foundations – elevated -condition assessment

Turbo generators of high rating are typically on raised foundations designed specifically for the generator and each turbine. If any modifications are required to install a flywheel or a thrust bearing, a detailed assessment of the foundations is necessary. If the turbine is decoupled, the addition of a thrust bearing is unlikely to require any significant foundation modification.

The foundations and underpinnings of numerous current turbo generators are over 30 years old, and it is crucial to evaluate their status to ensure they are fit for purpose for at least another decade.

The cost of repairs or alterations to elevated foundations may have high associated costs and the time required to assess and design the changes may be critical path in a re-purposing project.

Reversible process – can it be restored as a generator?

A perceived advantage in repurposing a turbo generator in situ is that it is theoretically possible to restore the turbine and recommence generation at some point in the future. Concepts such as seasonal generation contemplate having generating systems available at peak demands periods such as summer or winter.

While there are options available for implementing this concept, the scope of work and complexity involved suggest that these options may not be commercially viable. Nonetheless, we include them here for the sake of completeness. The options include:

- In the case of a debladed steam turbine, the blades could be restored, and the unit recommissioned and returned to generator status.
- If a turbine is left rotating but the turbine cases are evacuated (with additional equipment to draw the vacuum), the return to service may be significantly faster.
- If a turbine is decoupled and the issues associated with a thrust bearing are resolved in a way that the turbine can be reconnected directly, this would again be a significantly faster process.

During the consultations, the realities of a reversible process were found to include:

- Time taken to re-blade a turbine is not trivial because:
  - Specialist OEM staff are required to undertake the work (e.g., turbine casing removal, blade re-insertion, steam path conditioning, balancing/vibration mitigation)
- Thrust bearing arrangements may need to be revised to original configurations (if changed)
- Recommissioning of mothballed steam plant (boilers etc) after months of inactivity will take time.
  - Safety tests and certifications are likely to be required generally (e.g., boilers, steam pipes etc)
  - Cleaning of all steam/condensate paths is required.
  - Fuel systems (conveyors, mills etc) have to be recommissioned.
- Need to recruit staff with power station operational experience and train sufficient people with specialist skills to operate the plant for the ‘seasons’ required.

The above issues become more acute for longer elapsed time between de-commissioning and re-commissioning. One estimate suggested approximately 5+ months for works associated with the first dot point only (i.e., blade restoration), assuming plant had been carefully mothballed.

Control and protection

It is likely that the controls and protection arrangements will need to be reviewed and modified, including:

- Making provision for the start sequence (whether pony motor or SFC)
- Synchronisation and switching automation with interlocks.
  - Additional control and logic would be required if a Clutch is installed for operation (i.e., engage and disengage),
- Modification of the voltage control arrangements to meet with AEMO requirements of point of connection voltage control.
- Confirmation of requirements for all NER technical standard compliance
- Cooling arrangements to suit SC operation.
- Protection philosophy to reflect SC operation (e.g., revise reverse power protection, reactive power limiters, PSS settings (if used))
- Automation of most functions to reduce operating and maintenance costs.

Operating staff

Consultations indicated that once a generator is repurposed as a SC, the number of staff and their skill sets required for ongoing operation is very different to an operating power station. Staff are expected to be redeployed or moved to other roles.

This is not an issue while the plant is being used as a SC, but it may become a constraining issue if the SC is being reconfigured as a generator, where turbine and steam side operations are once again required.

Since the SCs are located in an existing or partly decommissioned power station, the underlying maintenance is expected to be significantly higher than for a purpose built, fully automated SC. The staff required for this will need to be suitably skilled to work safely in a power station environment.

A re-purposed SC will still require more intensive monitoring and maintenance due to the age of the plant, more than a bespoke SC due, for example to:

- On-going inspections of rotor and stator
- Transformer maintenance
- Brush replacements
- Oil systems
- Bearing conditions
- Relay and control system calibration/maintenance (unless these are new and fully automated)

The extent of the ongoing monitoring and maintenance will dictate the size of the required workforce. The key point is the workforce needed to maintain and operate a repurposed SC will be significantly larger and require a broader skill base that a purpose-built SC, which is likely to be fully automated with no full-time O&M staff.

Connection studies

Repurposing an existing generator as a SC will trigger some review of the existing Generator Performance Standard. Precisely which clauses are used to trigger the review and which standards apply is not clear as the repurposed SC is technically no longer a generator, although its dynamics remain very similar to that of a generator. It is believed that as a minimum, Clauses relating to frequency and active power control (i.e., S5.2.5.11 and S5.2.5.14) are not relevant to SC.

While the regulatory framework for new SCs or a repurposed existing generator may not be clear at present, it is expected that a full review of the GPS will be required, and compliance will be expected for the relevant technical standards. The resulting connection process is likely to costly and time-consuming (estimates of AUD $1M+ and take 3-6 months) if one assumes the current processes for new generator connections as a guide.

Service life

A turbo generator has a design life of around 40 years. Many of the existing generators are close to the end of their design life. There are many components of a turbo generator that are subject to ageing, including:

- Primary plant:
  - Stator and rotor insulation, winding integrity, cooling system,
  - Turbine shaft, which can age (an example of actual ageing issues was presented during the consultations),
  - Generator transformer, secondary supplies transformers,
  - Generator circuit breaker,
  - Foundations (generator and turbine if it remains connected).
- Secondary plant:

  - Excitation control system (may have been upgraded already),
  - Protection systems (typically have a life of up to 15 years and may have been updated several times),
  - Battery backup systems,
  - Cooling systems for generator, lubrication oil.

During consultations, respondents identified many components that had already been upgraded, including generator stators, rotors, transformers. The plant condition is thus likely to be very much dependent on how much heavy primary and secondary maintenance has already been carried out during service.

During the design phase, the condition of all re-used equipment must be assessed to identify what additional maintenance, upgrades and replacements are required. This will affect both the time and the cost of the conversion and is likely to drive quite significant differences in project costs, even between similar plant.

Lead times

The lead times discussed during consultation varied between six months and four years and is obviously dependent on the scope of works. Options with shorter lead times would likely be prioritised to fill emerging gaps, whole longer lead time projects could either be deferred or developed to target later requirements.

The shorter lead times, which are assumed to apply AFTER the initial plant assessment and conversion design, would apply to:

- Minimal changes to the generator,
- Decoupling the turbine and adding a thrust bearing,
- Compatibility of existing equipment with a SFC starting arrangement,
- Scalability of cooling systems or de-rating of generator to simplify cooling requirements, and
- Accelerated connection process.

The longer lead times would apply for an extended scope of work, which may include:

- Civil works on foundations,
- De-blading the turbine, or provision of systems to evacuate the turbine casings,
- Addition of a flywheel or pony motor,
- Switchgear rearrangements to support start up using an SFC,
- Replacement of any capital plant – rotor or stator replacement/refurbishment, new generator transformer, new GCB etc.,
- Replacement of secondary system – protection, controllers, and
- Complicated connection process.

Realistically, the lead time that can be expected for most turbo generator repurposing projects would be:

- Initial assessment of condition and development of options – three to six months,
- Project design, costing and approval – three months,
- Equipment lead time (assumed only controllers, SFC, excitation equipment, thrust bearing etc) – three to six months,
- Shutdown for implementation – two to four months,
- Recommissioning and compliance tests – two to four months.

The above gives a fast-track lead time of just over one year and a more realistic lead time of around 20 months for the assumptions discussed.

4.2 Technical considerations – gas turbines

Gas turbines are likely to continue to serve as backup power sources and have longer generating lifetimes compared to most steam generators. Therefore, the capability to switch from energy storage (SC operation) back to power generation (generator operation) is crucial. The comparatively straightforward design of gas turbines makes it more feasible to fulfill this dual role, with the condition of meeting some technical prerequisites.

Gas turbines are much more compact that steam turbines but share many of the considerations discussed for steam, including:

- Round rotor vs salient pole
- Control and protection
- Operating staff
- Service life
- Site requirements
- Connection studies

However, there are some differences, which are discussed in the following subsections.

Scope of work and design studies

A gas turbine conversion that will enable the generator to operate, additionally, as a SC generally requires less work than a steam turbine driven generator. The typical scope of work would involve:

- Adding a clutch between the generator and the turbine,
- Modifying the foundations to provide for the extra shaft length required by the clutch, and
- Some modification to the control and protection systems (minor).

The simplifications over a steam turbine include:

- The foundations are at ground level as opposed to being elevated and are thus more readily modified.
- The turbine can continue to be used to start the generator.
- Synchronisation is unchanged and no extra equipment is likely to be required.
- Cooling modifications are likely to be minimal as generator and lubrication oil cooling systems are likely to be unchanged.

These aspects are discussed in more detail below.

Starting and synchronising

A gas turbine will have some form of starting mechanism to get the turbine and generator up to a speed where the turbine can be fired and accelerate the generator up to synchronous speed. Generally, this starting mechanism is an SFC. The starting SFC is not usually designed to get the generator up to synchronous speed but to get the turbine to a speed where it can commence firing and continue to drive the turbine speed up to a point where the generator can be synchronised.

Starting and synchronising is thus identical to the normal starting procedure for a generator. The only difference is that once started and synchronised, the turbine is shut down and de-couples from the shaft using a synchro-self-synchronising (SSS) clutch.

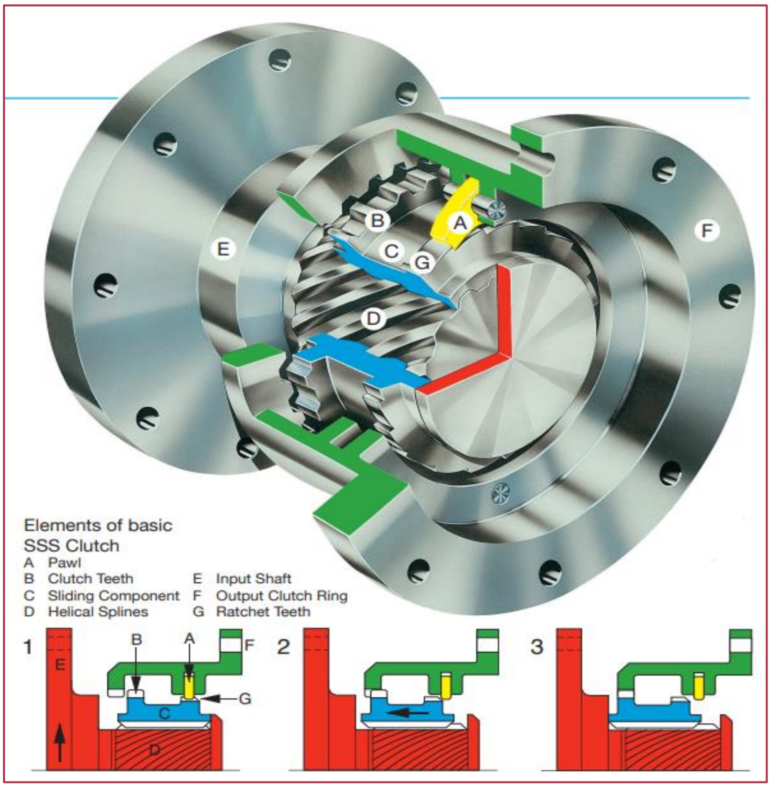

Figure 4.3: Elements of a SSS (synchro self-synchronising) clutch [9]

Changing modes

A gas turbine with a clutch can operate in two modes:

- Generator mode, where the turbine remains connected to the generator and energy is converted, and
- SC mode, where the turbine is decoupled.

The starting process describes how the SC mode is established, with the turbine being disconnected and running down to stationary.

If the plant is operating as an SC, it can only be changed back to generator mode if the SC is disconnected and allowed to slow down and stop. Once stationary, the normal generator start procedure can be initiated. The key issue is the time taken to stop SC mode and restart in generator model. This time will be plant dependent but is typically around 30 minutes.

Voltage / reactive power control

Voltage and reactive power control uses the same equipment as the generator and only minor settings changes are likely to be required.

Inertia

When a generator is synchronised and the turbine is decoupled, the remaining inertia is that of the generator only. As previously discussed, this may give an inertial time constant of some 1-2 seconds. It may be possible to add a flywheel, but this may not be practical if there is an exciter or slip ring on the non-turbine end of the generator shaft.

If inertia is at a premium, it would still be possible to run up the turbine and leave it synchronised at minimum load. The fuel cost might be justified in circumstances where low inertia was driving high prices in frequency control ancillary services. Ideally, the cost of the very fast FCAS (or all FCAS) should be co-optimised with the cost of providing inertia but the key point here is that with a gas turbine it is possible to:

- Decouple the turbine and provide fault level, system strength and reactive power services but only have a small inertial contribution.
- Leave the turbine coupled and operate at minimum load to provide all the above services as well as inertia if the service is appropriately valued.

The advantage of the gas turbine SC is that the option exists to, at a cost, use the additional inertia of the turbine.

Assuming there is enough space and no need for the turbine to operate as a generator, it may be feasible to disconnect the turbine, install a flywheel, a starting system, and establish a SC like a purpose-built device.

During consultation, a further option was described with an aero-derivative gas turbine whereby the turbine was left connected when operating in SC mode. The windmilling turbine absorbs about 10% of the plant rating as windage losses. It is thus a high-cost option but potentially lower cost than running the turbine at minimum output and burning gas or liquid fuels.

Cooling and lubrication

Without the steam cycle, the cooling requirements for an open cycle gas turbine are straightforward and can be achieved without cooling towers. Even for a combined cycle plant, the generator and lubrication oil cooling are separated from the steam cycle cooling requirements.

The consequence is that it is unlikely that the cooling and lubrication system will need any material modification to run as a SC.

Foundations – ground level, condition assessment

The foundations of a gas turbine are usually on ground level and therefore easier to modify or extend, subject to other space limitations. The condition of the foundations will also need to be assessed to determine whether a life extension of, say, ten years, is achievable.

An extension of the foundation is required to accommodate the clutch mechanism, with an extension of 1-2m being indicated in consultation discussions. Some services may need to be relocated but these are generally above ground anyway and therefore less complex.

Lead times

The lead time for converting a gas turbine to enable SC operation is shorter than a steam turbine because less work is required and the civil works required to extend the foundations are simpler, typically being at the ground level.

Once the initial assessment and engineering design are completed, the time taken to implement the modifications may only be three to six months, with most of that time being for the manufacture of the clutch.

The lead time that can be expected for typical gas turbine repurposing projects would be:

- Initial assessment of condition and development of options – one to two months,
- Project design, costing and approval – two to three months,
- Equipment lead time (assumed only SSS clutch, controllers, etc) – three to six months,
- Shutdown for implementation – two to three months, and
- Recommissioning and compliance tests – two to four months.

The above gives a fast-track lead time of around nine months and a more realistic lead time of around 17 months for the assumptions discussed.

4.3 Purpose built synchronous condensers

One of the key drivers for considering the conversion of existing generators is that it provides a faster option with potentially lower costs than new-build SCs of equivalent rating. For completeness, the characteristics of new, purpose-built SCs are provided here.

Purpose built SCs are optimised for their function and have advantages of lower losses, can be erected in desired locations, and the ability to fully automate the site. This section provides some basic information on purpose built SCs for purposes of comparing them with the re-purposed generator options.

Components of a purpose-build synchronous condenser

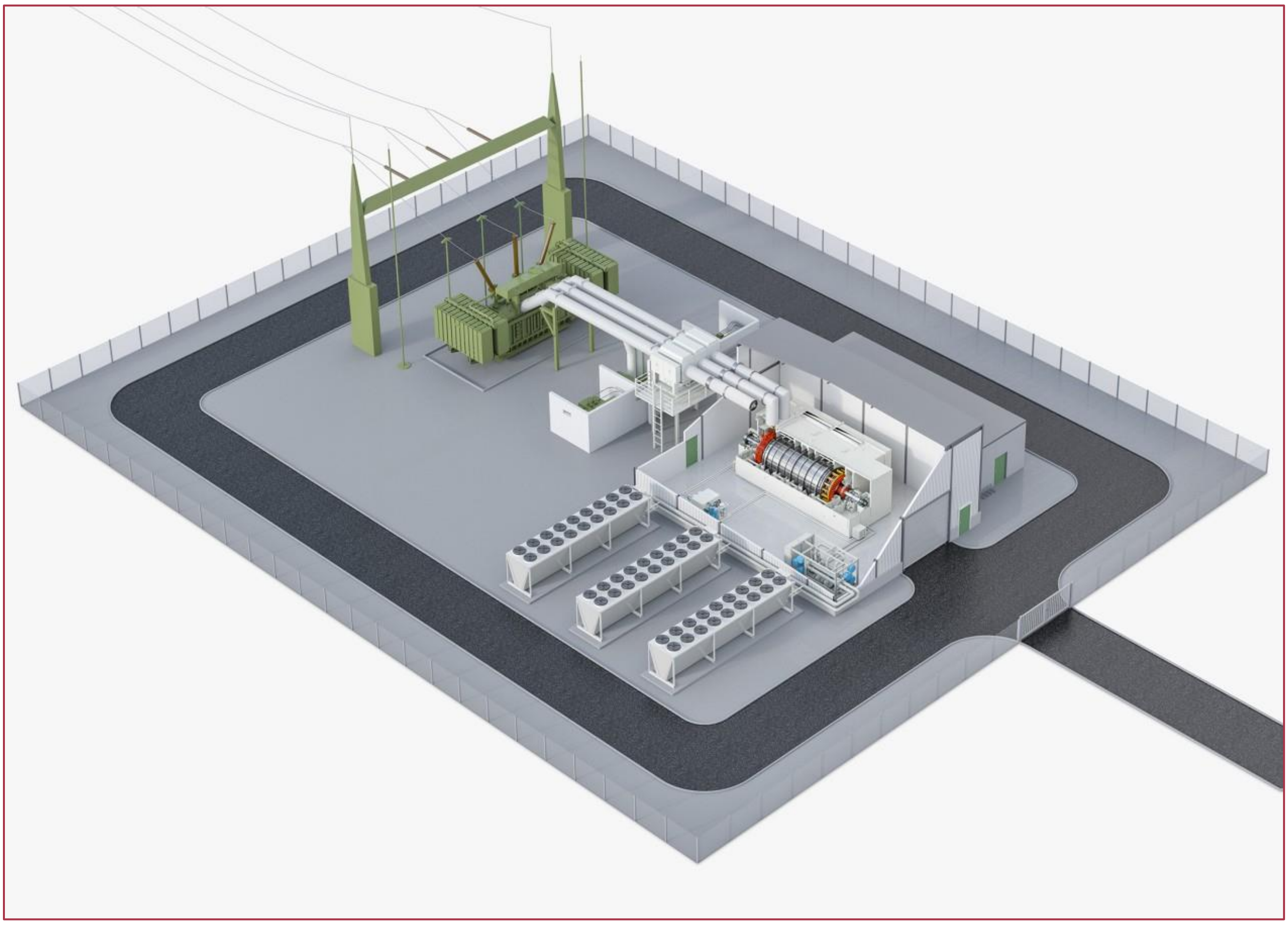

Figure 4.4: Modern synchronous condenser installation with a fully automated site (courtesy Siemens-energy.com)

As shown in Figure 4.4, the key components are:

- The connection to the grid via a transformer (green),
- The building (noise-proofed) containing the synchronous condenser,
- The cooling systems (three banks of fan cooled radiators to the left of the SC building), and
- The control room housing protection, communications, and control facilities (to the right of the SC building).

Not shown in the figure is a flywheel. If fitted, a flywheel would require a shaft extension and space for the flywheel. Flywheels have considerable stored energy, and the design must include safety systems to prevent hazards in the event of a catastrophic failure of the flywheel.

Optimising performance

When investing in a new SC, it is possible to optimise the performance by:

- Designing the synchronous machine with a low sub-transient reactance,
- Minimising losses,
- Using a lower impedance transformer to connect to the grid,
- Optimising the cooling system for the installation site.

Note that the ability to minimise losses is quite small, given that there is likely to be no material difference between the synchronous machine used in a generator and that used in a SC. However, the cooling, lubrication and secondary loads are likely to be lower as they would be designed specifically for SC operation. This might reduce the standing losses by 10-15%, depending on the arrangements at the repurposed generator site.

Automation

Once commissioned, the SC can be fully automated with remote start and stop facilities and no requirement for continuous attendance by site personnel, other than for routine checks and maintenance.

The OEM can thus support and service many SCs with a relatively small team of specialists, producing O&M cost savings. This is facilitated where several of a one type/class of SC are installed. By comparison, a repurposed generator may have many site-specific systems that require more specialised maintenance. An example would be hydrogen cooling, or a more complicated lubrication system, originally designed for a large steam turbine.

Lead times

Discussions with OEMs indicated that, due to a global demand of SC, there is a 2-to-2.5-year lead time on the delivery of new, large SCs (i.e., after order is placed). Smaller SCs in the sub-100 MW range potentially have faster delivery of around 18 months. OEMs also now recommend that every new gas-fired project is either installed with or designed to allow space for a clutch to future-proof for SC conversion.

It is also reasonable to assume that if the NEM generally required 30 or more SCs, the supply chain pressure would increase, and delivery times would grow even more.

Size

The size of purpose built SCs is limited by the air-cooling capability and sizes of up to 200-250 MVA are possible. Smaller units in the 70-125 MVA are common. Once the SC size exceeds the air-cooling limit, the step up in complexity becomes significant with, for example, gas and liquid cooling.

Comparing these sizes with the larger retiring generators, which may have ratings of 750 MVA or more, means that several purpose-built SCs would be required to deliver like-for like services.

Location

Installing new SCs gives the ability to optimise the location and deliver services where they may be most needed. For example, SCs might be more efficiently located in a renewable energy zone (REZ) than at the site of an existing power station.

4.4 Spare generators and transformers

Some NEM power stations carry extensive spares, including generator components and transformers. It may be possible to use these spares to create new SC systems.

For example, one asset owner indicated they have a complete spare generator and a spare transformer on site. It is likely that other power stations may have spares for generators, but it is not known whether complete SCs can be constructed.

Some issues are:

- Construction lead times may be long because the projects will require full designs of:
  - Foundations,
  - Secondary services (cooling, lubrication),
  - New connections.
- The asset owner may wish to have access to the plant in the event of a failure of their generator or transformer.

Advantages are:

- The assets are built and, in the country, avoiding long lead-times.
- It may be possible to expedite consenting as it is a similar use of the site.

It is an opportunity worth further examination.

4.5 Commercial issues for asset owners and procurement bodies (TNSPs)

Consultations confirm uncertainty around how asset owners could monetise the services. Other concerns include a lack of information on the size of the market and the magnitude of initial costs and time required to develop a proposal to a point where a commercial deal can be struck. In addition, there are significant issues with market risks and losses incurred in both standby and operating modes.

This section discusses some of the issues raised in more detail.

Competing uses of site

Existing generators have a connection point to the NEM and a site permitted for generation activities. There are at least three NEM relevant development options that asset owners may consider at an existing generation site:

- Development of energy storage facilities
- Addition of purpose built, modular SCs
- Development of firming generation (gas turbines, hydrogen powered generation etc)

As an example, there is evidence (media articles and public announcements) of large BESS projects at the Wallerawang PS and Liddell PS sites.

Similarly, if there is a long-term requirement for services provided by a SC, asset owners may be attracted to an alternative to repurposing existing generators, which would be to invest in new, purpose-built SCs. The higher capital cost could be offset by:

- Reduced operating expenditures as operation can be automated.
- Better reliability and availability as the plant would be new.
- Reduced land area required as the SC is self-contained.
- More efficient investment as the SCs can be installed in modules, matching size with requirements.

There would also be options for firming generation at these sites, potentially gas turbines or other generation that can operate on lower carbon fuels.

Feasibility study – who pays

Because of the individuality of each power station, a bespoke feasibility study is required to assess the options available for repurposing as a SC. These studies will include assessments of plant condition and defining the works required to achieve the conversion.

The cost of a site-specific feasibility study of this nature is likely to be significant and in the range of $250-500k (based on discussions with asset owners). However, it is quite conceivable that at some sites, this preliminary work could be higher than this range, given the specialised nature of the work. For purposes of this report, a cost of $375k is assumed for the feasibility studies.

The feasibility studies are required before any offers can be made for services in response to an expression of interest (EOI) or a request for proposals (RFP). It is also possible that the feasibility studies will indicate that the costs are prohibitive or that there are some good reasons why repurposing is not a realistic option.

The question was raised during consultations as to who should pay for these feasibility studies. The studies can be regarded as a business development cost for plant with comparatively very much higher operating and capital costs or they can be seen as response to request by regulators for a service that would not normally be offered.

Subsidising or funding for at least some projects would help inform the industry of the cost magnitudes and the likely scope of work for conversion processes.

Shut down period, opportunity cost

Plant such as gas turbines may continue to operate as generators after the SC conversion works are completed. During the conversion works (for example, installation of a clutch), the plant is unavailable for service as a generator. There is thus an opportunity cost for the shutdown period.

The opportunity cost for a steam turbine generator is probably small if it is going to be shut down anyway. However, if it is being shut down well ahead of its commercial shutdown date (for example, to facilitate the conversion works) there will be some opportunity costs.

Procurement method – contract basis

Asset owners will only offer services if there is a reasonable return on investment. The costs of the conversion of existing generators for SC operation may be reasonably well understood but there are several new risks that may affect the viability of such works.

Key issues include:

- Term of contracts – the costs of repurposing a generator to operate as a SC may be similar to the cost of a new SC. The period over which these costs are recovered is important if reasonably priced services are to be offered from plant that may have a limited service-life.
- Fixed and variable charges – as the procurement process is not a market but contract based, the asset owner will need a minimum payment to support the capital and standing costs of making the service available and then a usage charge to recoup any variable costs associated with operation as an SC.
- Procurement and construction risk – under a contract-based procurement for availability and usage, there is substantial risk of not winning a contract, which could render feasibility/design costs stranded. Similarly, there may be construction risks that cause over-runs above the expected delivery costs.
- Performance risk – contracts for services can reasonably be expected to include performance requirements and reductions in payments if targets (such as availability) are not met. This risk is heightened by the fact that plant that is close to its design life is more likely to have reliability problems that new, purpose-built equipment. The prospect also exists for rewarding better than contract availability, providing a two-way incentive / disincentive for performance.
- Indemnities – these are critical services with potentially large ramifications if the service fails or is otherwise unavailable when required. Asset owners may thus seek appropriate indemnities.

- Losses and auxiliary loads – During SC operation and even when in standby mode, the plant will consume energy and have an exposure to NEM prices. The operational losses are in the order of 1-2% of the plant rating, so for a 600 MVA generator, the losses could be 6-12 MW and some additional auxiliary load (lubrication pumps, cooling system, etc) possibly adding a further [1-2] MW. The exposure to high NEM prices has a risk that say 10 MW of load could be priced at around $15k per hour, giving $150k per hour of operation at Market Pricing Cap. The normal operation, assuming 24-hour operation and NEM prices of $100/MWh and an average loss of, say, 7 MW, gives an indicative annual loss cost of around $6M.
- Ownership – potentially, the TNSP (as SSSP) could lease or own the plant (as it does with purpose-built SCs), and the asset owner maintains it and operates it under direction from the SSSP.

Operational requirements for SC and site generally – cyber security, IT, rates

Aside from losses, other normal business costs will continue to accrue.

A coal fired power station site is large because it accommodates fuel handling and the boiler system. Coal is a bulky fuel that needs to be stored in large quantities on-site, and it requires specialised equipment for handling and processing. The rates are proportionate. Partial demolition and remediation may occur in parallel with synchronous condenser operation, potentially complicating site management.

The existing control rooms, security and IT facilities may continue to be used. Overall, it is likely that the site will be substantially larger than a purpose-built SC. Most services will be higher cost because of the size and cyber-risks may be elevated if old IT systems are being re-used.

In any event, these costs are expected to be small in comparison with the operating cost of the SC itself and it is also highly unlikely that these matters will become a deciding factor in any decision to convert an existing generator to a SC.

Specialist staff – hydrogen cooling, secondary systems, turbine, generator (compare with power station and purpose-built SC)

Purpose-built SCs will generally have low maintenance and staffing requirements. By comparison, a repurposed generator operating as an SC will require specialist staff on site as well as specialist equipment and maintenance for:

- Cooling systems, particularly where hydrogen cooling or cooling towers are required,
- Turbine shafts (if debladed or flywheel modifications are made),
- Site maintenance, including WH&S,
- Starting and synchronising (this can also be automated).

5 Case studies for different technologies

The following section is dedicated to case studies of example sites located in the NEM. Selection was based on consultations with relevant stakeholders and considering at least one of each generation type discussed in this report (steam and gas turbines). There are no known major conversion examples completed for coal-fired generators in Australia, although there are examples internationally. Whilst the data and plant specifics pertaining to each generator is confidential, the discussion in each case study is based primarily on consultations and literature review.

5.1 Callide B

Callide B PS is a coal power station, located near Biloela in QLD. The station is owned and operated by CS Energy, a Queensland government-owned corporation, and comprises two Hitachi 350 MW coal fired generating units (Units B1 and B2), that connect to the Powerlink transmission network at the 275 kV voltage level.

Callide B was commissioned in 1988, and it is accepted to be approaching "end-of-life". The Queensland government has notified the market that it plans to retire Callide B PS in 2028.

High-level procedure

Due to the age and condition of plant, converting Callide B may be a complex process. The most likely approach to repurposing Callide B is to disconnect the turbine; in addition, DIgSILENT have assumed for this case study that CS Energy would consider adding a flywheel in place of the turbine to retain and offer inertia. Therefore, the general steps that may be involved are:

1. Disconnect and remove the steam turbine rotor. This can be a complex process that requires specialised equipment and OEM expertise.
2. Inspect the rotor and stator windings. Considering the rewind of the generators was undertaken in 2010, a subsequent rewind is not anticipated. However, the actual need can only be accurately assessed after inspecting the machine. In case a rewind becomes necessary, it would entail refurbishing the stator and rotor windings according to the machine's specifications. This process includes dismantling the existing windings, insulating the core, and applying new copper wires onto the core.
3. Install a flywheel. Once the steam turbine rotor is removed, the flywheel may be installed in its place. The flywheel should be designed to match the specifications of the existing shaft, including its size and rating. Furthermore, according to supplier discussions, both the flywheel and casing are proposed to be brand new, complying with the most recent standards and specifications. The foundations may require strengthening.
4. Modify the turbine casing. If the existing turbine casing is to be used, it may need to be modified to fit the new flywheel. This can involve cutting or welding the casing to ensure a proper fit. The foundations may require strengthening.
5. Install a new starting mechanism at the exciter end, which is necessary to spin the synchronous condenser (SC) and flywheel to their operating speed. The starting mechanism must be specifically designed to meet the specifications of the new or revised shaft, which includes the flywheel and existing machine.
6. Install a new thrust bearing. The new thrust bearing will be necessary to support the weight of the flywheel. The thrust bearing must be designed to match the specifications of the flywheel and the existing machine.
7. Install a new excitation system (and excitation transformer). Due to the age of the existing excitation system and transformer, a replacement is required to extend the life of the plant. The new excitation system must be accompanied with suitable connection studies that consider changes to the plant (e.g., change in inertia due to removal of turbine and addition of the flywheel).
8. Commission the repurposed SC and new systems.

Challenges

Generator rotor and stator

Considering the generators were rewound as recently as 2010, a subsequent rewind might not be required, contrary to what might be expected due to the age and condition of the plant. The necessity for a rewind can only be confirmed after inspecting the windings during a plant outage or upon retirement of the plant. While a rewind is not a minor task and may present significant challenges and costs, the recent rewinding done in 2010 should ideally prolong the need for such an operation.

In the unlikely event a rewind is required, the stator and rotor will require disassembly and reassembly. Disassembling the stator and rotor from the generator can be difficult, as these components are often large, heavy, and complex. Reassembling the components after rewinding requires extreme care to ensure that everything is aligned and balanced correctly.

The winding process itself is complex and requires specialized knowledge and expertise. It involves removing the old windings, preparing the core for new windings, winding the new copper wires onto the core, and insulating the windings. The new windings must be precisely matched to the specifications of the original windings to ensure that the generator operates correctly. Any errors, defects, or deviations in the winding process or from specification can result in reduced efficiency, increased maintenance costs, and reduced lifespan of the generator.

Costs of a rewind can vary significantly depending on the size and design of the generator (as well as overall condition), but it is expected to be more than AUD $20M. It is unknown if CS Energy are in possession of spares that may be used, which may reduce the cost of the project.

Flywheel

The benefits of adding a flywheel have already been presented in this report. A flywheel can easily be included in a purpose-built SC at a green field site. However, retrofitting a flywheel to an existing plant may present some challenges.

1. Design compatibility - the flywheel must be designed to work with existing generator and must be carefully integrated into the system to ensure that it operates safely and efficiently. This requires significant engineering expertise and a thorough understanding of both the flywheel and the driveshaft.
2. The size and weight of the flywheel must be carefully considered in relation to the existing shaft and foundation. The weight of the flywheel, although it will vary based on requirements and manufacturer, is assumed to be in the range of 60 to 100 tonnes (excluding the vacuum pump which can add several tonnes as well). The addition of the flywheel (and vacuum) could result in increased stress on the shaft and foundation, which could potentially cause damage or failure if not properly addressed.
3. The installation of the flywheel could also present challenges related to space constraints. There may not be enough room in the existing system to accommodate the flywheel, which could require significant modifications to the system.
4. The addition of a flywheel could also require significant balancing of the system. The flywheel must be precisely balanced to ensure that it operates smoothly and does not cause undue stress or vibration on the system. Upon return to service, vibration monitoring would be required and if an issue presents itself, further balancing may be required.

The addition of a flywheel can place additional stress on the synchronous condenser. This is because the flywheel adds additional weight and inertia to the system (see above), which can cause increased wear and tear on bearings and other components. To avoid reducing the lifetime of a synchronous condenser, it is important to properly design and install a flywheel. The system should be carefully balanced and aligned to minimize vibrations, and components should be properly maintained to ensure that they operate within their designed parameters. Regular maintenance and monitoring of the system can help to identify and address any potential issues before they cause significant damage or shorten the lifespan of the synchronous condenser.

The cost of adding a flywheel to an existing driveshaft can be significant, as it requires significant OEM engineering, design, and installation expertise. The cost could vary depending on the size and complexity of the project, as well as the specific challenges involved in integrating the flywheel into the existing system.

Starting system

After consulting with CS Energy, it was determined that the starting mechanism could involve either connecting and adding a pony motor (with a capacity of approximately 5MW) or using an SFC. No technical difficulties were identified for the implementation of either option. Consideration should be given to the space required and placement; it is generally considered that this would occur at the exciter end of the driveshaft.

Excitation system

The existing excitation system comprises of the legacy system installed when the site was initially commissioned in 1988. The system is no longer supported by the OEM and spare parts are scarce. A complete refurbishment of the excitation system, including the excitation transformer, is required. The requirements for a new system are likely to be similar as stated in the previous case study and cost up-to AUD $2-2.5M.

There are no obvious technical issues with replacing the excitation system. The new system should be designed to integrate and interface with the existing plant, whilst ensuring it can operate in SC mode.

Schedule and costs

The time it takes to design, procure components (including lead times and shipping), and repurpose Callide B for SC operation will depend on several factors, such as the complexity of the project, the availability of the required components (e.g., flywheel), and the experience and expertise of the design and installation team (both locally on-site and from the OEM). Here are some general estimates of the time it might take:

- The design phase can take 6 to 12 months as an estimate. During this phase, the design team will assess the feasibility of the project, determine the required modifications to the steam turbine, and develop a detailed design plan.
- The procurement and shipping of components can also take several months, depending on the availability of the factory and required components and any customization required. This may be further delayed if it is required to book slots in factory for manufacturing. CS Energy will need to identify and source the required components, negotiate contracts, and ensure that the components meet the required specifications.
- The repurposing phase can take several months on-site, depending on the complexity of the modifications required. The installation team will need to carefully dismantle and modify the steam turbine, install the new components, and test to ensure that it is working as intended.

Overall, the entire process of designing, procuring components, and repurposing Callide B to a SC could take anywhere from 2-3 years, depending on the specific details of the project. Note that this is an estimated schedule, and further information from CS Energy would be required to improve the accuracy of the estimate.

Likewise, specific costs for the conversion are unknown. It is likely that the repurposing of a Callide B unit will exceed AUD $30M. There are significant costs associated with the inspection and rewind of the stator and rotor (if required), as well as the flywheel and refurbishment of the excitation system.

5.2 Liddell PS

Liddell was a coal fired power station in the Hunter region of New South Wales. It comprised four units of 500 MW and was shut down in April 2023.

Liddell was of interest because AGL was in the process of shutting it down and works were underway to demolish the power station completely. It was thus a prospective site for a conversion.

A Battery Energy Storage System is proposed for the site but is not dependent on the power station (i.e., separate land), although it is proposed to use the same connection point.

AGL advise the main reason for shutting down the plant is the condition of the boiler and turbine. The generator and connection asset condition has not been accurately assessed but it is thought to be satisfactory.

Around the time the shutdown was announced, AGL undertook feasibility studies on the conversion to a SC. These studies were relatively high level and considered technical and costing issues.

Turbine

The option examined was for a disconnection of the turbine and possible fitment of a thrust bearing.

Starting

Both the Pony motor and the SFC starting options were considered. No specific technical issues were identified for the addition and connection of a pony motor.

Cooling and lubrication

Modification of the interfaces to the generator to provide both cooling and lubrication would be required. This was identified as a cost and risk area.

Demolition

The site is being demolished. If a conversion is required some demolition would continue (boilers etc) but the foundations, control and cooling facilities for the generator would need to be left. This would make the demolition process more complicated and costly.

Losses and auxiliary supplies

The exposure to energy costs and losses over long periods is seen as a risk area - a common issue for asset owners. Losses were estimated at over 1% per machine (i.e., 5 MW). It is not clear if these losses included auxiliary energy consumption.

Costs- capex and opex

The feasibility study did not investigate costs with a high degree of accuracy. No quotes were requested. However, it was estimated that the cost of converting one unit would be 'more than $20M'. Given the potential for unforeseen issues and associated costs during the conversion process, this figure is expected to rise.

In contrast, a small 50 MVA SC (for a different project) was quoted as $30M, indicating that the **capex costs** for conversion may be lower than those for constructing a new purpose-built SC. This is higher cost than the ‘standard’ 125 MVA SC used elsewhere in this report.

The **opex costs,** excluding the energy costs, are expected to be significantly higher than a purpose-built SC because:

- The auxiliaries require greater intervention on an old power station,
- More staff is required to maintain and support the older auxiliary equipment, and
- The site will be larger with associated higher costs.

The above issues are generally applicable for all conversions. Some of the opex costs could probably be reduced by expending more capex to automate the plant.

Lead time

The time for a conversion, bar any unforeseen issues, was estimated to be around 18 months. This time could be affected by the ongoing demolition works on the site and any unforeseen issues.

No allowance was made for the connection process and associated commissioning.

Summary for Liddell conversion (as at May 2023)

AGL engaged a consultant to investigate converting Liddell to a SC several years ago. At the time it was considered not to be commercial as there was no clear revenue stream for the services the SC would provide, including losses and auxiliary energy consumption. AGL then decided to demolish the power station, and this is underway.

Following release of the Transgrid's system strength EOI [3], AGL is reviewing this decision. AGL indicated that the demolition progress is now progressing, and this reduces the willingness to consider the project. For the right commercial terms, AGL indicated it will take another look at the option.

Key features of the option, as investigated, include:

- Disconnection of the turbine,
- Addition of a pony motor,
- Modification of interfaces with the generator for cooling, lubrication etc.,
- Demolition of the rest of the plant,
- Lead time >18 months (from approval, assuming design work is done),
- Estimated capex cost – at least $20M,
- Losses – expected to be >1%.

5.3 Mortlake PS

Mortlake PS is an open-cycle natural gas-fired power station owned and operated by Origin located in the south-west of Victoria, approximately 12km west of the town of Mortlake. The station comprises of two Siemens SGTS 4000F-type gas turbines (Unit 11 and 12) rated for 333 MVA each. It connects to the southern 500kV AusNet transmission circuit between Heywood and Moorabool, ideally located in the proposed south-west Victorian renewable energy zone (see Figure 5.1).

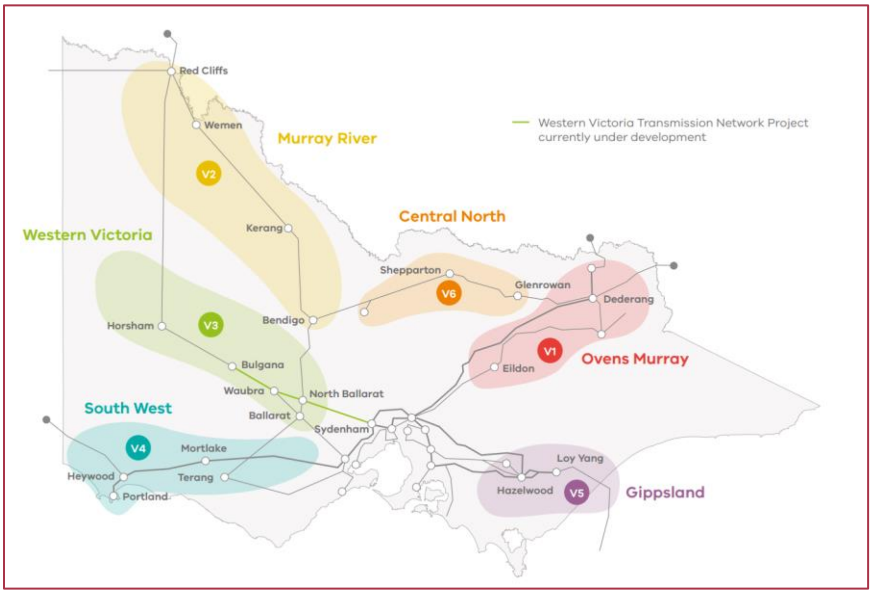

Figure 5.1: Victoria's Renewable Energy Zones (courtesy of Victorian state government)

Following consultation with Origin, the following high-level notes are presented:

- Conversion of Mortlake possible with a SSS clutch. Successful integration of a SSS clutch would require detailed engineering in partnership with the generator OEM.
- It is also possible to operate in SC mode with the gas turbine coupled. When the gas turbine is coupled, the turbine is freewheeling (essentially acting as a compressor), and it is not generating electricity, and can still absorb or generate reactive power as needed to help regulate voltage levels on the grid. However, the losses would increase (approximately 10% per unit, i.e., 33 MW) due to the mechanical (and electrical) losses attributed to additional friction and windage in the turbine.
- The Mortlake generating system can start in 20 minutes as SC from idle; however, a period of 30 minutes is required to run-down to then be able to re-engage clutch and run as a generator.
- Conversion costs for Mortlake PS are approximately 50-60% of a new greenfield SC.
- The losses to operate as SC for Mortlake are estimated to be 1% (with the gas turbine disengaged) per generating unit.

The SSS clutch allows for the turbine to be disconnected for SC operation (i.e., generator only). This means that the rotating inertia when operating as an SC will be approximately 25-30% of the overall figure for each Mortlake unit (note that the existing inertia constant of the complete rotating mass is 6.33 seconds).

High-level procedure

The existing Mortlake gas turbines can be converted to a SC by incorporating a SSS clutch into the existing driveshaft to disconnect the turbine when operating as a condenser. At a high level, the SSS clutch will be placed between the generator and the turbine, as shown in Figure 5.2. The clutch acts to disengage the prime mover (i.e., the gas turbine) for SC operation.

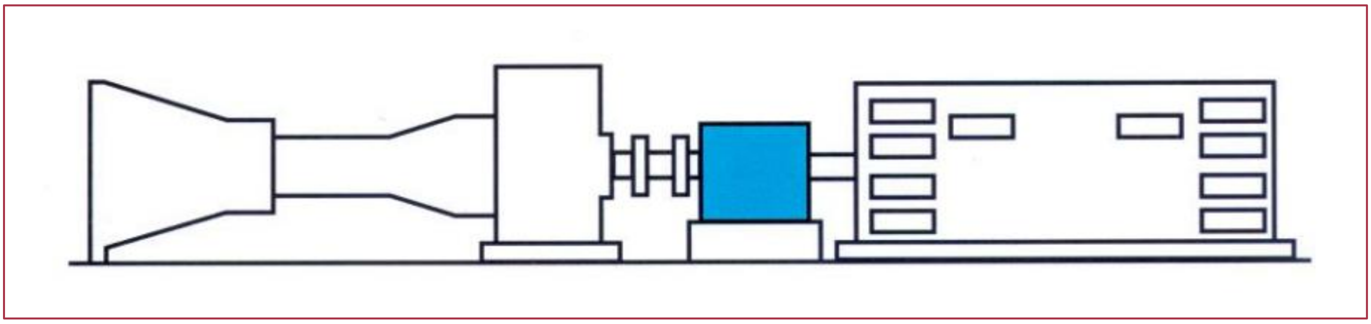

Figure 5.2: Placement of clutch between generator and turbine

The general steps involved are:

1. Evaluate the existing site and gas turbine – this is in the form of an engineering feasibility study and preliminary design. The study will need to evaluate whether the turbine has a shaft and foundations that can accommodate a clutch.
2. Design the clutch system. This will include clutch components, plate, flywheel, pressure plate, and determination of how it will be mounted to existing shaft. The duration of operation should be considered and factored into the design to ensure the clutch can handle the added stress and thermal loads.
3. Modify the gas turbine – adding the clutch will require modifications to the foundations, shaft, turbine to make room for mounting the clutch.
4. Modify the turbine controls – adding the clutch will require modifications to the control system of the gas turbine. The controls will need to be able to engage and disengage the Clutch as required.
5. Installation and commissioning. Once the clutch system is designed, a major outage is required to perform all installation works on site and then test to ensure it functions properly.

Challenges

Clutch

An SSS clutch is required to be retrofitted between the turbine and the generator to allow for the turbine to be decoupled from the generator for SC operation. The clutch will need to be encased and require a footprint of approximately 3-5m (with respect to the length of shaft). This will mean the drive train, and subsequent foundations (i.e., plinth), will need to be extended to accommodate for the footprint of the clutch.

The retrofit will require both mechanical and civil works to be performed on site during a major outage. The general steps that are likely to be involved in extending the driveshaft and foundations of the gas turbine to accommodate a clutch are:

1. Determine the new length of the driveshaft – this will require existing knowledge of the current length and diameter of the shaft, and the type of coupling used to connect the shaft to the load. The length of the extension required to accommodate the clutch is required, considering the new coupling and other factors such as added weight and torque loads.
2. Assess the foundation design. Determine the existing foundation design and determine whether it can accommodate additional length of the driveshaft and the added weight and torque loads generated by the clutch.
3. Design the extension and foundation modifications. The extension and foundation modifications must be designed to match the existing shaft's specifications and be able to handle the additional loads and stresses generated by the clutch. This will require careful consideration of the ground (and soil), materials, dimensions, and manufacturing techniques used for the extension and foundation modifications. New footings and an extension to the plinth will be required to create the space needed for the clutch.

4. Fabricate the extension and foundation modifications: Once the design is complete, the extension and foundation modifications can be fabricated.
5. Install the extension and foundation modifications – the modifications must be installed with precision to ensure alignment and balance. This may require disassembly of the turbine.

Modifications to the turbine's foundation can have significant impact on its overall stability and reliability, so careful analysis and design is essential to ensure that the turbine can operate safely and effectively with the added clutch.

Starting the SC

The starting of Mortlake PS as a SC should be relatively straight-forward; the turbine will bring the generator up to speed. Once the generator is synchronised, the turbine and can be disconnected from the generator and shut down. The generator will continue to remain online in SC operation.

Turbine controls

As discussed earlier, the turbine controls need to be modified to accommodate a new clutch retrofitted into an existing system. This will involve:

- Determination of the Clutch control requirements, including engagement and disengagement process, and the required torque and speed limits.
- Modification to the control software. This may involve updating the control loops and algorithm, which may require specialised OEM support and design.
- Modification to the control hardware. This may involve adding new sensors or actuators, modifying existing components, or installing new controller modules.
- Installation and commissioning of the modified control system. The entire control system should be thoroughly tested to ensure it is operating correctly and safely.

Excitation system

Mortlake PS comprises of a Siemens Semipol static excitation system. The exciter is shunt supplied, i.e., it is fed from an excitation transformer connected to the terminals of the synchronous generator and assembled with a three-phase thyristor bridge. The excitation system was installed when the plant was commissioned (circa 2012), and hence it is approximately 10 years old. Assuming it has been maintained correctly, it is likely that Origin can expect a further 10-15 years from the current system before a refurbishment is required.

Schedule and costs

Origin advises during consultation that the cost of converting a Mortlake generator for SC operation is approximately 50-60% the cost of a purpose-built SC. This would include:

- Detailed engineering,
- Design, procurement, and shipping of the clutch,
- Modifications to the drive shaft to accommodate the new clutch,
- Modifications to foundations (i.e., civil works),
- Modifications to the turbine controls,
- Installation and commissioning.

We understand that the cost of a new 125 MVA SC is in the region of AUD $35-40M (or $320k/MVA); hence conservatively the estimate to convert Mortlake is roughly AUD $24M per unit (or $192k/MVA).

Cost of a SSS Clutch

The cost of a clutch for a gas turbine can vary widely depending on several factors, including the manufacturer, the size and rating of the clutch, and project specific requirements. We estimate the cost of a large clutch suitable for a turbine the size of Mortlake to be in the order of AUD $1+ M.

6 Summary and findings

6.1 The emerging issues

Retirement of existing coal fired plant will reduce the available security services dramatically over the next five to ten years. AEMO, with the accountability for power system security, must manage the power system with whatever services are available. If the services are not provided, there is potential for significant restrictions on power supply or the need to add supplementary controls and systems to preserve security.

The key services where shortfalls might occur are:

- System strength
- Fault level
- Reactive power supply and voltage control
- Inertia.

The conclusion by AEMO [2] that "… the results of a study of a 100% renewables scenario, under which the equivalent of up to 40 new [125 MVA][10] synchronous condensers could be needed to meet system strength requirements" indicates that there will be pressure on nearly all retiring coal and gas-fired generators to convert to SC operation. Alternatively, considerable investment in new, purpose built SCs will be required with the associated risks of long lead times (particularly as global demand for SCs accelerates and a resultant supply shortage emerges).

There is thus a very important nexus emerging - the power system needs many SCs but the availability of new purpose-built SCs is being pressured by increasing demands, leading to unacceptably long delivery times.

Transgrid recently advised [3] that its initial estimates have indicated a need for 20 SCs in NSW by 2025 and 27 SCs by 2030 (each SC assumed to be 125 MVA). Estimates for other states / regions are not available but the requirement for NSW alone is very significant.

Not all regions are expected to see serious shortfalls similar to those in NSW in the near term (i.e., next five years).

- Tasmania has many hydro units that can be used as SCs already and investigations into the use of some gas plant are also underway but will only proceed if commercial. Surplus services cannot be exported to the mainland via the HVDC link.
- South Australia has commissioned four large SCs with flywheels. The local TNSP is thus unlikely to need to contract with further service providers in the short- to medium-term term.
- Queensland has five supercritical coal fired power stations that are likely to be among the last coal plants to retire. In the mid- to long-terms these could also be considered for seasonal operation and periodic application as SCs. The state plans for energy transition include pumped storage stations that would have the capability to operate as SCs. Some requirement for additional services is indicated but this is less extensive than NSW.
- The shutdown of brown coal power stations in the Latrobe Valley will create shortfalls in the required services and additional services will be required to compensate. In the short- to medium-term, some of the requirements could be met by modifying additional Victorian Hydro generation or implementing seasonal operation of some coal-fired units.

Considering the downsides of having insufficient security services available for power system operation, it is expected that the efficient levels of services, as assessed by the TNSPs, will include procurement of services in all NEM regions in the short- and medium- terms.

[10] AEMO have used a standard size SC in [2]

6.2 Options to address the emerging issues

Adding, or retaining, synchronous machines on the power system will help to compensate for the retiring fossil generation and provide at least some of the security services that AEMO needs to operate the power system securely.

The problems could be solved using purpose built SCs. There are two reasons why this option is problematic:

- New SCs cost around $35-40M per 125 MVA to install and connect, based on recent experience in South Australia.
- International demand is affecting delivery of new SCs. Delivery times more than two years from order placement are expected and these times are likely to increase further. Note also that the delivery time from order placement and the planning and design process, as explained in this report, can also take 12-18 months. This would make AEMO's position as System Operator extremely difficult from a security perspective.

The standard sizes of purpose-built SCs tends to be smaller than the larger generators that are retiring, which means that multiple new-build SC units would be required to compensate for the retirement of a single coal fired generator.

Grid forming inverters on battery energy storage systems (BESSs) have the potential to provide some of the services. The project install rates of these BESSs is significant and it is likely that at least some of the services can be met with this technology. However, there is limited experience in the NEM with this grid forming technology and it is understood that AEMO is treating it as an emerging technology, rather than a proven technology. As such it is unlikely that the shortfall in services will be met to AEMO’s satisfaction with grid forming inverters in the short term. However, it may well be a perfectly acceptable solution in the future (say, ten years out).

Hydro generators, generally, have the ability to operate as SCs if the turbines can be de-watered. Most hydro units in the NEM already have this capability and some of the remaining units could be modified to operate as a SC. The location of hydro units and the overall capacity is insufficient to meet the projected shortfalls.

Gas turbines can operate as SCs if a clutch is fitted between the turbine and the generator. This is a cost-effective modification for some plant. However, gas turbines are often not ideally located for provision of the required services.

6.3 The opportunity to use existing generators

The option to repurposing existing generators as SCs presents a credible and attractive opportunity to meet AEMO's security requirements because:

- It is technically feasible and, in most cases cheaper, to convert existing generators for use SCs,
- The scale is such that one big existing generator (say 750 MVA) could obviate the need for five or more smaller SCs (say 125 MVA), and
- Conversion times are expected to be quicker than implementation of new SCs.

These conclusions make a convincing case to pursue the re-purposing possibilities, recognising that there is a significant variation across sites.

Converting existing generators to SC operation requires careful coordination of closure dates, favourable site and equipment conditions, and timely procurement through TNSP processes. While this approach can yield positive outcomes, it may not be feasible for all existing generators, as not all sites are suitable for providing the required services. Additionally, repurposing existing generators may be only a partial solution, and may not be able to fully provide all the services needed.

A significant benefit arising from re-purposing is that it takes the pressure off the need to rapidly implement many new purpose-built SC, pumped storage systems, and grid-forming batteries, effectively buying time for the orderly implementation of longer-term solutions (which may include repurposed generators).

6.4 High level assessment of the repurposing opportunity

The review and consultation undertaken in this project indicate that there are indeed effective and efficient opportunities to repurpose some generators as SCs. In all cases, significant investment is required to repurpose a retiring coal- or gas-fired generator. Despite this, the capex and delivery timeframes appear to be more favourable than new build SCs for many existing generating systems.

Repurposing presents realistic opportunities to fill gaps left by retiring generators

Technically, retaining retiring generators on the system will provide significant security services and support AEMOs power system security accountabilities. The technical modifications required may result in a reduction of the available services when compared with generator operation, but the larger size of some units means that significant services will still be made available to AEMO.

Based on the high-level assessment and consultations, we believe there is merit in pursuing the opportunity of converting retiring generators to SCs. There are caveats and some generators are likely to be less economic to repurpose in this way. However, the attraction of being able to convert even some of the large (retiring) coal fired generators to SC operation remains high because of the large quantity of services that they will provide and the faster timeframe in which they can be provided.

Which technologies are most suited to repurposing?

Some technologies are easier to repurpose than others. The following discussion lists those technologies that are easiest to convert to those that are more difficult. This cannot be taken as a bounded conclusion as there is significant variation across individual power stations, let alone technologies. In the main:

- Hydro power stations are easiest to convert as they require minimal modification. Essentially, compressed air is used to push the water below the turbine[11], which reduces losses. Since the turbine remains connected to the generator, the inertia is unchanged. Cooling and lubrication will likely require minimal modification.
- Gas turbines – open cycle – can be fitted with a clutch between the turbine and the generator. This may require modifications to the foundations to provide space for the clutch, however, this is usually achievable at modest cost. Cooling and lubrication may require some modification, likely to be minimal.
- Gas turbines – combined cycle – may be suitable, especially if the steam turbine and generator is on a separate shaft. Adding a clutch may be complicated by the plant layout and the heat recovery steam generator. Operating CCGTs as SCs is far less common that for OCGTs.
- Steam turbines can be decoupled from their generator, or they can be debladed. The easiest approach is to decouple the turbine and fit a thrust bearing to the generator shaft. However, this reduces the inertia. De-blading requires no bearing modification and has a smaller reduction in inertia. Starting the SC requires installation of an electronic frequency converter or the fitting of a motor to the shaft of the generator (pony motor). Cooling and lubrication may require moderate to extensive modifications.

Potential risks

The repurposing of retiring generators as SCs is not without risk and may not be ‘efficient’ in some cases. The key issues that can affect ***some*** plant, particularly coal-fired generators, include:

- The capital investment required, particularly for coal-fired generating systems, to convert to SC operation is likely to be substantial – bearing re-design, shaft modifications, adaptation of cooling and lubrication systems, modification of foundations, life extension of primary and secondary of plant that is approaching the end of its design life – any or all of these can be technically challenging and potentially unworkable. These works have the potential to be:
  - Costly - significant redesign, modification and refurbishment of brownfields plant can be costly.
  - Time consuming - Conversions, modifications and refurbishments may take many months to plan, approve, and implement. OEM or specialist services may be required that are seldom available on call.

[11] For example, in a Francis turbine. A Pelton turbine may not even require special measures to de-water the turbine.

- For some sites, the cost of conversion works may surpass the cost of a greenfield investment. In these scenarios, the brownfield option would need to be able to be deployed significantly faster than a greenfield option to justify the investment.
- The reliability (or availability) of repurposed generators is expected to be lower than a greenfield development given that the rotating plant and connection assets will all be at or near end of life (typically around 30-40 years).
- The existing connection points for retiring generators may have alternative development options and thus opportunity costs. Examples include publicised plans to develop BESS systems at locations of already retired coal plant (example is Wallerawang).
- Operating costs may be materially higher than a purpose-built SC because of the losses and energy consumption of secondary plant (pumps, fans, etc). The cost of specialist staff to operate the plant may also be material. The net present value of these operating costs, when compared with a purpose-built and fully automated SC, maybe a significant contributor to the latter appearing as a lower cost, and therefore more efficient, investment.

Advantages and disadvantages for repurposing existing generators as synchronous condensers

All things considered, there will be some existing generators (all technologies) that are suitable and cost effective for conversion to SC operation and others not so suitable. As far the advantages and disadvantages of repurposing existing generators as SCs are concerned, some are listed in Table 6.1.

Table 6.1: Summary of advantages and disadvantages for repurposing existing generators as SCs

Topic	Advantage	Disadvantage
Cost of conversion	For existing generators suitable for low-cost conversion, the overall cost can be less than a purpose-built SC	If major conversions works are required, the costs may exceed a greenfield development
Timeliness	All major equipment is already on site so conversion time could be materially faster than a new development with factory lead times.	Heavy engineering (e.g., shaft modifications) may take significant design, manufacture, and installation time. Supply constraints are expected to lead to even longer lead times as global demand for SCs ramps up, resulting in even longer lead times.
Efficiency	Provided the full capacity is required, one large unit may be more efficient than several smaller units.	Purpose-built SCs are designed for low losses and 'right-sizing' may further reduce operating costs.
Reliability	Service duty operating as a SC is less stressful than as a generator and fewer turbine or boiler trips are expected. Reliability can be expected to be higher than a generator.	Plant may be approaching end of life. There is increased risk of major failure (e.g., stator, transformer, excitation system) that may then have a long repair time. Provision will need to be made of potential forced outage of repurposed generators.
Location	Having SCs at locations of existing generators will deliver similar fault levels and require fewer protection changes.	For some important services like system strength and even inertia, location is important. Some power stations (particularly GTs) may not be located at optimal locations, and this may result in a need to over-procure services.
Connection	Having an existing connection point may provide faster access as grid impacts are already understood.	Changes to existing plant will likely require full assessment and demonstration of compliance with current technical standards, incurring both cost and time requirements.
Re-configuring to switch between generator and SC modes	If generators are expected to operate intermittently (including seasonally), they may be well-suited to operating as a SC when not generating electricity. This can help the system benefit from both the system security services and the potential availability of the additional generation capacity.	Re-configuring may be expensive and require specialist OEM support. The need to retain turbine/fuel/boiler specialists for seasonal utilisation may not be viable.

6.5 Findings in relation to repurposing of generators as synchronous condensers

The importance of moving quickly

While SC conversions can provide material cost savings, the real value of this model is likely to be through faster delivery of systems services. Slow delivery of these services could constrain operation of existing generators and also delay connection of new generators resulting in a supply shortage and higher wholesale prices. The costs and lead time for conversion works are critical. Projects that can be delivered quickly will be favoured. It may even eventuate that less cost-effective conversions may still be highly beneficial if they have fast conversion times.

Plant variations make it difficult to generalise

The feasibility of converting an existing generator for operation as a SC is very dependent on individual power stations. There is a wide range of technical issues that must be managed, and the solutions may differ considerably from power station to power station. Even power stations using similar plant – for example, the Toshiba 660 MW units NSW or the Hitachi 350 MW units in Queensland – can have materially different issues requiring management. These issues include (but are not limited to):

- Plant condition (generator and transformer insulation, shaft integrity, foundation integrity)
- Space to implement changes to foundations.
- Cooling and lubrication systems configuration
- Starting options (for example, space/capability to add a pony motor)
- Commercial terms and conditions required by asset owners.

It is thus difficult to generalise and place a cost on a conversion (or a cost/MVA) as each retiring generator will likely need a site-specific assessment to check technical and commercial feasibility.

Significant pre-work may be required to develop options

Before an offer can be made to a TNSP procurement initiative, the asset owner needs to assess the feasibility and budget cost of the conversion / repurposing. These feasibility studies are then followed by design studies to firm up the costs and develop the delivery and implementation timeline.

The work associated with these studies is expected to be considerable, including condition assessment of all plant that will be used in the repurposed plant, required rearrangement of existing services like lubrication and cooling systems, provision of new equipment for starting etc.

The cost of these studies is commensurate for the effort and detail, and it remains possible the conclusion may be that the plant cannot be converted efficiently.

Lead times for conversion process

The lead time for a conversion of a generator to having the ability to operate as a SC depends on the technology. The lead time is a critical factor in the conversion process because the AEMO requirements may arise before it is possible to procure new SCs in a tight international market.

Table 6.2: Indicative lead times for conversions of existing generator types to SC operation

Technology	Leadtime (excluding connection)	Notes
New build SC	≥30months for delivery and installation.	May lengthen as global demand increases; shorter timeframes may be possible with smaller SC unit sizes.
Hydro	Approximately 6-12 months for works, dependent on turbine type,	Dependent on ability to de-water the turbine and maintain cooling water flow.
Gas turbine (open cycle)	Clutch 6-8 months.	Clutch is longest lead-time item.
Gas turbine (combined cycle)	For separate steam turbine, add clutch 6-8 months. For operation with turbine connected, 1-2 months.	Clutch is main lead time. For windmilling turbine, protection modifications may be required (e.g., reverse power).
Gas	Clutch, foundations, modification to controls, lubrication system, starting;	Medium Approx 60% (with respect to new SC)
Steam 1: **Decouple turbine**	Around 18 months – site dependent.	Design and add thrust bearing; add starting system; revise lubrication and cooling.
Steam 2: **De-blade turbine**	18-24 months – site dependent	Remove turbine blades and re-balance, starting system, revise lubrication and cooling
Steam 3: **Add clutch**	Around 12-18 months – if no foundation modification	Not suitable in all cases; clutch design, shaft modifications;
Steam 4: **Add flywheel**	Up to 48 months for larger units (>300 MW)	Foundation modification, shaft modification; flywheel design and implementation, shaft dynamics assessment.

High level costs and comparison with new purpose-built synchronous condensers

In general, the costs of re-purposing an existing synchronous generator are relatively unknown and highly dependent on the generation type and condition of the plant and site. Accurate capital expenditure may not be determined until a detailed feasibility study is undertaken by both the asset owner and the OEM.

Table 6.3 provides a high-level indication of costs from a bespoke SC to each generation type. An indication of the feasibility costs is also provided for reference.

Table 6.3: Indication of costs

Type	Modifications (or notes)	Cost (or cost indication with respect to new SC)
Feasibility study	Approximately 6-12 months.	*Approx. AUD $350-500k*
New SC	Approx 125 MVA; including installation and commissioning.	*Approx. AUD $35-40M*
Hydro	Modification to controls; air compressor; cooling modification;	Small (with respect to new SC)
Gas	Clutch, foundations, modification to controls, lubrication system, starting;	Medium Approx 60% (with respect to new SC)
Steam	De-couple turbine (or de-blade the turbine), possible addition of clutch, modifications to bearings, lubrication system, cooling, foundations, controls, and new starting mechanism.	Medium – Large but may well be significantly less per MVA if generator is higher capacity.

A cost analysis study compared the life-cycle cost of a purpose-built SC with the conversion of a thermal unit and concluded that the costs are lower from the transformed thermal unit if the remaining life is 15 or more years [10].

This means that the total cost of ownership, including the initial investment, construction, and ongoing maintenance costs, is lower for the converted thermal unit.

However, it is important to note that this conclusion is specific to the context of the study in [10] and may not be applicable to all situations. Other factors, such as the specific requirements of the SC and the availability of suitable thermal units for conversion, may also need to be considered.

There are potential trade-offs of converting a thermal unit versus building a purpose-built SC, such as differences in performance, energy efficiency, and environmental impact. These factors may have an impact on the long-term costs and benefits of each option.

Ultimately, the decision to convert a thermal unit or build a purpose-built SC will depend on a range of factors specific to the individual case and should be based on a comprehensive cost-benefit analysis that considers all relevant factors. In this context, however, there is an urgency that is likely to favour faster implementation times over lower long-term operating costs, because the downside of not having the services is expected to significantly outweigh any inefficiencies in the converted plant.

6.6 Commercial arrangements

Asset owners considering options to convert retiring generators to SCs will require some certainty on their investment return. In nearly all cases, the capital cost of the conversion can be a significant fraction (more than 50%) of investment in new purpose-built SCs. The operating costs are also likely to be significant and, because the plant is older and not purpose-built, higher than a new SC.

This section does not propose to specify a form of contracting but rather highlights issues brought to our attention during the consultations. The asset owners are less likely to offer their plant if the contract terms include high levels of commercial risk.

Risk assessment and expected costs of failure events

Because the plant is approaching end of life (in most cases), the risks of major failures are expected to be high and the outage and repair times longer.

In some cases, and depending on the term of potential contracts and the penalties for non-delivery of services, it may be desirable to pre-emptively replace or refurbish ageing plant components. If a whole power station is retiring, it may be economical to carry common spares and improve overall availability.

A detailed risk assessment should enable an expected cost of failure to be estimated. This will then form part of the business case to undertake a conversion.

Contract term – needs to be long enough to recover investment costs

During consultations, the required terms of contracts was generally thought to be around ten years, allowing capital costs to be recovered as well as allow for a reasonable return on investments. Any shorter than this and the cost recovery would need to be accelerated and annualised costs would therefore escalate.

Contracts for services and availability

Asset owner considerations

The framework for the provision of security services implies that the TNSPs will require a range of services, with some margin above the minimum requirement (‘the efficient level’). Indeed, AEMO indicated that anything above the minimum requirement would add to resilience of the power system.

There is thus no guarantee that a contracted SC will be required 100% of the time and AEMO/TNSPs may opt against ‘dispatching’ the SC if the services are excess to needs. This indicates that for financial security, it would be necessary for asset owners to receive some form of availability payment.

TNSP considerations

The TNSP may contract for system strength, inertia, reactive power, or fault level, depending on requirements. The SC can then be requested to operate should any of these services be required.

As previously discussed, the use of generators that are close to end of life may result in higher-than-normal forced outage rates and service providers need incentives to make sure plant is maintained and fit for service, The TNSPs are expected to require contracted service providers to have a reasonable level of availability to allow them to deliver, with a high probability, the required services to AEMO.

Assuming an availability payment is negotiated, it is reasonable that the TNSP will suspend these payments and possibly have some form of clawback if a service provider is unavailable or found to have been unable to deliver the contracted service.

Energy consumption – losses and secondary systems

When the SC is dispatched, there are losses and secondary system energy consumption. For the large generators – for example, a Toshiba 660 MW (say 780 MVA), the basic losses of the synchronous machine would be around 8-16 MW, depending on what level of reactive power is required. Secondary plant energy consumption could be another 2-4 MW. Perhaps the average energy consumption when online could be around 14 MW.

There is market cost and risk associated with this energy consumption. SCs can be expected to run for extended periods. For an average market price of $100/MWh, the annual energy consumption is around $13M. However, at times when prices are approaching the market cap, the exposure could rise to around, $190k per hour.

Asset owners will not want to have exposure to market prices, given they are unable to manage them. Similarly, they may elect to turn the SC off if the commercial incentives are unfavourable.

There are several ways to manage the market price risks. These include:

- Pass-through of energy costs to the TNSP
- TNSP ownership (i.e., through sale of the asset)
- Incorporation of SC energy consumption into marginal loss factors

It is noted that TNSP-owned assets like SVCs and, in the case of South Australia, SCs typically allocate energy consumption from similar TNSP-owned equipment (e.g., SVCs) into marginal loss factors.

7 Recommendations

There are no precedents for the conversion of large fossil fuelled generators to SCs in Australia[12] so the uncertainty around costs is a major factor for both asset owners, regulators, and policy makers. In addition, there can be significant variations in the conversion costs even between similar plant (same rating, same manufacturer), which points to the need to undertake site specific assessments and feasibility study before plant can be offered in a security service tendering process.

1 Recommendation 1 – funding for site-specific investigations

It is recommended that at least two and preferably three site-specific investigations are part- or fully funded so that the industry can develop a better understanding of:

- Capital works and costs required to repurpose larger generators for SC operation.
- Operating costs, including losses, secondary system energy consumption, and maintenance costs.
- Plant age, life cycle and plant risks and, where appropriate, options to mitigate these risks.
- Lead times to undertake the conversion works.

Funding a large steam turbine project (>300 MVA), and a gas turbine conversion, would provide valuable learnings to the industry in general.

2 Recommendation 2 – urgency to commence repurposing projects.

This report highlights the lead times for both repurposing projects and for new SC investments. The Transgrid EOI [3] and the AEMO reports of December 2022 [2] [1] both have a sense of urgency because of the extent of the requirements and the deadline constraints. The AEMO report [1] encourages early interaction between the TNSP (as System Strength Service Providers - SSSP) and potential service providers. The difference between the minimum service levels defined by AEMO and the 'efficient' levels defined by the SSSP may not be well understood but is likely to require the procurement of significantly higher level of service than those published by AEMO.

It is therefore strongly recommended that:

- SSSPs commence engagement with potential service providers at the earliest opportunity to assess which projects can be delivered quickly and efficiently.
- SSSPs commence procurement processes and regulatory approvals as soon as possible to avoid delays that result in AEMO having to constrain operations because of service deficiencies.

3 Recommendation 3 – form of contracts

It is recommended that the term and form of the contracts used to procure security services from repurposed generators is explored in association with asset owners and regulators to provide guidance on how cost recovery can occur, including for:

- Making plant available to provide security services (system strength, inertia, reactive power support).
- Recovery of losses and secondary system energy usage.
- Maintenance and fixed costs.
- Risk allocation for unplanned outages.
- Cost allocation (including market exposure) for energy consumption.
- Other funding streams may be possible if governments, for example, seek to expedite the conversion process.

[12] The Swanbank A coal-fired generators were run as SCs in the [late 1980s] [16] with minimal cost and relatively easy re-configuration to generator operation. The units were rated at 60 MW. Also, some hydro generators have been converted.

4 Recommendation 4 – value of inertia

It is recommended that TNSPs or AEMO provide asset owners with some indication of the value of inertia (in $/MWs) so that they can assess the potential benefit against the cost of making inertia available. This information could come from:

- Tasmanian contract values for inertia.
- OEM estimates of the cost of providing flywheels for purpose built SCs.
- Analysis, for example, of the trade-off between fast frequency response services (priced in a market) and inertia
- RIT-T assessments for the SCs in South Australia indicate a fairly low incremental cost for adding a flywheel. Specifically, a 1,100 MWs flywheel cost is around $1M, giving a modest cost of $91k/100 MWs. However, the cost of a comparatively scaled flywheel on a large generator (300-800 MVA) is likely to be significantly higher and include foundation modifications.
- A secondary recommendation is that all new-build SCs should be fitted with flywheels, given the relatively low cost per MWs.

5 Recommendation 5 – spare generators and transformers

In its reports of December 2022 [2] [1], AEMO recommended that the relevant TNSPs begin discussions with asset owners to explore options for providing system strength and inertial services. It is recommended that TNSPs explore the possibilities of using spares holdings to support the development of purpose-built SCs. The benefit of developing purpose built SCs from spares holdings is that delivery times could be shorter, given that critical assets would already be in the country.

8 References

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Appendix A Literature survey

The first phase of the desktop study is to review existing public literature that is available with respect to SC and the conversion of existing generators to SC operation.

Table 8.1: High-level summary of public literature reviewed

Literature	Type
Conversion of retired coal-fired plant to synchronous condenser to support weak AC grid [11]	IEEE paper
Guide on the assessment, specification, and design of synchronous condenser for power system with predominance of low or zero inertia generators [7]	CIGRE
Synchronous condensers – information, conversion, costs, and consideration for the NEM	AEMO technical note (confidential)[13]
Converting a synchronous generator for operation as a synchronous condenser [12]	EPRI technical update report
AEMO costs and technical parameter review [13]	GHD
Queensland supergrid infrastructure blueprint [14]	QLD Government
2022 System Strength Report [1]	AEMO
2022 Inertia Report [2]	AEMO

A.1 Key discussion points

Key technical considerations are presented below.

A.1.1 Technical considerations

- Cooling: air/hydrogen/water
    - A cooling system is required in generators to remove heat generating in the windings (I^2R losses) of the generator. The inability to remove heat results in damage to the insulation and can reduce the life span of the generator.
    - For generators above ~60 MVA (approximately), air cooling may be insufficient to cool the generator.
    - Emergency cooling and braking
- Pole type (round rotor or salient) – a round rotor (i.e., a two-pole machine) will have a lower rotating inertia, which may result in reduced starting requirements; however, a salient pole (i.e., a multi-pole machine) will have a larger rotating inertia.
- Flywheel – rotating disk connected to shaft. Increase capital costs and footprint, as well as losses. The primary benefit however is that the rotating inertia is increased and improved [7].
- Clutch – conversion of GT to clutch option possible but difficult; requires mechanical modifications to shaft. Used when power production is required [7].
- Consider losses. Cost of energy and expected operating range of SC. Auxiliary losses.
    - For example, a steam-turbine generator, energized by grid and at rated speed, will draw approximately 1% of full load current with turbine removed. This represents windage and friction losses [12].

[13] Not included in references due to confidentiality.

A.1.2 Starting of SC

The two main types of starting methods discussed are a Static Frequency Converter (SFC) and a Starting Motor (also known as a pony motor or auxiliary motor) controlled by a Variable Frequency Drive (VFD).

- A SFC can be used to start a SC by providing a controlled, variable frequency power supply to the rotor.
- A SFC is similar to a VFD and connected between the SC and the GCB. The SFC will bring the condenser to overrated speed without the turbine and is protected by a current limiter. Once this is achieved, the SFC is switched off. During this free rotating condition, synchronisation occurs when the machine voltage, speed and phase are matched to that of the network [7].
- A starting motor can be used to start a SC by providing a temporary power source and the required torque to the rotor to rotate.
- The starting motor (either an AC induction motor or a synchronous motor) is coupled to shaft and may require clutch to de-couple (or can free wheel), and a gearbox. The pony motor is soft start using a VFD [7].
- It is imperative to check with the manufacturer if the shaft (usually the end the exciter is connected to) can cope with starting torque.
- Gas turbines can use either a starting motor or static start (LCI) to get the turbine to a speed where is can be fired. The turbine then accelerates the generator to synchronous speed.
- It may be possible to use one static start system for more than one condenser (see also [15]). This requires ability to switch the SFC between machines.
- For static starts, rotating exciters will need to be replaced and converted as a static excitation system. Estimates for a new static exciter could cost up-to AUD $2M+ for ratings up-to 5,000A.
- Depending on design of start-up drive, some bearings associated with turbine thrust bearing may be reused or modified. In some cases, entirely new thrust bearing must be installed for condenser operation[14] [12] – see further below.

5.1 Thrust bearing

The principal function of a thrust bearing is to resist the axial thrust unbalance developed within the working elements of a turbine and to maintain the rotor position within tolerable limits. If a turbine is disconnected from its generator, it may be necessary to add a thrust bearing. After an accurate analysis has been made of the thrust load, the thrust bearing should be sized to support this load in the most efficient method possible [16].

A.1.3 Basic conversion steps

When implementing a retrofit solution (i.e., conversion) consider the following major steps [7] [12]:

6. Decoupling turbine – remove the turbine at the turbine-end of the generator [12]
7. Overhauling windings [7],
    a. Condition of stator/rotor – is a rewind or repair required, including a cost analysis of overhauling versus gains in operating lifetime [7],
8. Setting up a starting system:
    a. Motor coupled to shaft driven by VSD – may include modifications such as thrust bearings, turning gear, and starting motor with coupling [7].
    b. Replace the decoupled turbine with a start-up drive system capable of accelerating the SC to speed [12].
9. Consider and install thrust bearing to accommodate the axial thrust [12].

[14] Axial thrust developed by large generator range from 320-1500 kg (700-3300lbs) [3].

10. Lubrication system may need to be evaluated (and modified) for flow requirements if the same system is used for turbine, generator, exciter and back up oil for seal oil system [12].
11. Evaluate and modify the generator auxiliaries to provide reliable lubrication and cooling.
12. Evaluate if the start-up drive system (if employed) will be de-energized, disconnected or allowed to free wheel when the SC is online.
13. Evaluate and modify where required the excitation system – including if the excitation system will employ a brushless exciter (i.e., rotating exciter) versus a static excitation system, and the voltage control strategy.
14. Other concerns:
    a. Balancing of the shaft once the turbine is de-coupled or debladed
    b. Analysis of the shaft torsional frequencies (only if the turbine is left coupled to the generator).
    c. Turning gear (which is usually assembled on turbine shaft),
    d. Civil works such as foundations.

A.1.4 Power system requirements considerations

- Criteria for sizing/placement:
    - Rotational inertia.
    - Short-circuit support.
    - System strength.
    - Reactive power support.
- Placing criteria (for new SC) should include [7]:
    - Remote area where inverter-based resources are located (but far from existing generators)
    - Area where reactive components are located – fault level critical to ensure voltage deviation limited
    - Remote end of line due to voltage compensation

A.1.5 Queensland supergrid infrastructure blueprint

The aim of the document is to present a plan to implement infrastructure to enable QLD to decarbonise the existing electricity system and load in QLD.

The plan includes repurposing existing publicly owned coal fired power stations into clean energy hubs. The clean energy hubs will include converted units to SC – for purposes of **system strength** and **inertia** - which will be reversible to avoid possible energy security risks.

The blueprints target is to repurpose approximately 3,500 MW of existing coal-fired generation to SC.

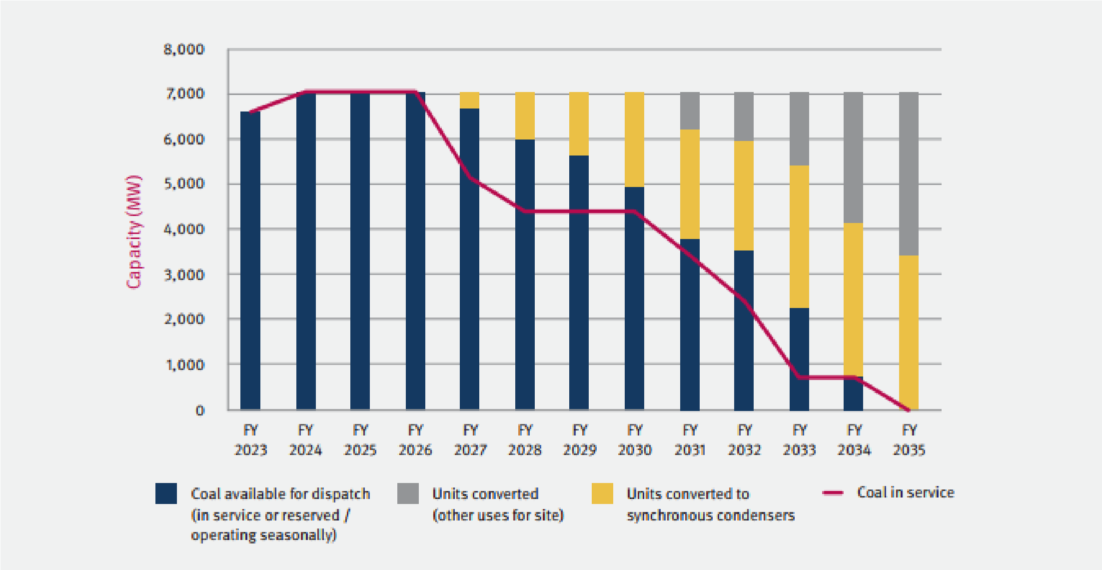

Figure 12: Publicly-owned coal portfolios will progressively transform to clean energy hubs. Coal repurposing is a secondary consideration to energy security, which is dependent on the timing of the PHES assets. MW capacities refer to nameplate capacity.

Figure 8.1: Re-purposing of coal portfolios in QLD [14]

A.1.6 Other considerations

The report in [13] on behalf of AEMO estimates that the fixed operating cost is $800/MW/year (publicly sourced (from "Cost implication and reactive power generating potential of the synchronous condenser" CTU).

GHD also estimates that a new SC cost $9M (equipment), with a further $1M in installation costs (estimates based on a 100 MVA rating).

A.2 Example case studies

Table 8.2: Example case studies from literature

Site	Country	Technology	Notes	Reference
City of Columbus "Waste to Energy Facility"	USA	3 x 38.4 MVA air-cooled turbogenerators	Turbine rotor replaced with bladeless shaft; AC induction motor attached to end of shaft with a variable frequency supply for start-up; existing bearings, lubrication system and thrust bearing utilised.	[12]
Eastlake Units 4 and 5	USA	2 x 240 MW steam turbines	Direct AFD start-up drive	[12]
Zion Nuclear Plant	USA	2 x 1,040 MW	Decoupled from turbine. Large induction motor and torque converter/clutch used to accelerate rotor. Thrust bearing added.	[12]
Bibles A Nuclear	Germany	1,200 MW	A 14 MW medium-voltage startup converter was set up for generator startup. This was connected to a new 18.3 MVA transformer, which subsequently transforms its output voltage to the generator terminal voltage of 27 kV via a further 17 MVA transformer. With a gas-insulated 30 kV medium voltage switchgear, the new system was	[12] [17]

Site	Country	Technology	Notes	Reference
			connected to the generator via the generator terminal lead.	
Huntington Beach 3 & 4	USA	2 x 225 MVA cross compound steam turbines	Turbines uncoupled. Two generators electrically tied at low speed. Pony motor attached to one shaft; AFD used to accelerate the pony motor and both shafts to speed.	[12]
Deeside Power Station	UK (Wales)	498 MW CCGT (2 by 166 MW Alstom GT13E2 and a 176 MW steam turbine)	Two GTs repurposed. Six-year contract for inertia and reactive power awarded 2020. Service as SC from June 2021. Implementation time 15 months approximately. New turbine blocks installed for inertia (no blades). Several new staff to manage operations. Expected to save GBP £128M over six years (about AUD $38M per year).	[18]

Appendix B Consultation with stakeholders

B.1 Consultations with stakeholders

The project team consulted regulators, NSPs, OEMs and asset owners. The full list of organisations consulted is given below:

- AEMO
- TransGrid
- Powerlink Queensland
- Origin
- CS Energy
- Siemens
- ABB
- Hydro Tasmania
- AGL
- Alinta – Loy Yang B

B.1.1 Summary

DIgSILENT thanks the parties for their contributions and the information they provided on this broad topic.

Melbourne
(Head Office)
Level 13,
484 St Kilda Rd
Melbourne
VIC 3004

+61 3 8582 0200

Perth

Suite 11, Level 2,
189 St Georges Terrace
Perth
WA 6000

+61 8 6220 6700

Brisbane

Level 5,
82 Eagle Street
Brisbane
QLD 4000

+61 7 3144 6400

Sydney

Suite 28.03,
31 Market Street,
Sydney
NSW 2000

+61 400 339 416

Project Team

Tim George
Tony Bertes

@digsilent-pacific

info@digsilent.com.au

digsilent.com.au