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Potential for farm-scale hybrid renewable energy supply options in the Victoria and Southern Gulf catchments

A technical report from the CSIRO Victoria and Southern Gulf Water Resource Assessments for the National Water Grid

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Important disclaimer

CSIRO Victoria and Southern Gulf Water Resource Assessments acknowledgements

This report was funded through the National Water Grid's Science Program, which sits within the Australian Government's Department of Climate Change, Energy, the Environment and Water.

Aspects of the Assessments have been undertaken in conjunction with the Northern Territory and Queensland governments.

The Assessments were guided by three committees:

i. The Governance Committee: CRC for Northern Australia/James Cook University; CSIRO; National Water Grid (Department of Climate Change, Energy, the Environment and Water); Northern Land Council; NT Department of Environment, Parks and Water Security; NT Department of Industry, Tourism and Trade; Office of Northern Australia; Queensland Department of Agriculture and Fisheries; Queensland Department of Regional Development, Manufacturing and Water

ii. The joint Roper and Victoria River catchments Steering Committee: Amateur Fishermen's Association of the NT; Austrade; Centrefarm; CSIRO; National Water Grid (Department of Climate Change, Energy, the Environment and Water); Northern Land Council; NT Cattlemen's Association; NT Department of Environment, Parks and Water Security; NT Department of Industry, Tourism and Trade; NT Farmers; NT Seafood Council; Office of Northern Australia; Parks Australia; Regional Development Australia; Roper Gulf Regional Council Shire; Watertrust

iii. The Southern Gulf catchments Steering Committee: Amateur Fishermen's Association of the NT; Austral Fisheries; Burketown Shire; Carpentaria Land Council Aboriginal Corporation; Health and Wellbeing Queensland; National Water Grid (Department of Climate Change, Energy, the Environment and Water); Northern Prawn Fisheries; Queensland Department of Agriculture and Fisheries; NT Department of Environment, Parks and Water Security; NT Department of Industry, Tourism and Trade; Office of Northern Australia; Queensland Department of Regional Development, Manufacturing and Water; Southern Gulf NRM

Responsibility for the Assessments' content lies with CSIRO. The Assessments' committees did not have an opportunity to review the Assessments' results or outputs prior to their release.

This report was reviewed by Daivd Green and Cuan Petheram (CSIRO). Cuan Petheram helped conceptualise the analysis and finalise the report. Cuan Petheram and Seonaid Philip prepared the maps.

Photo

Hybrid electricity generation systems for some remote communities in northern Australia are powered by off-grid diesel generators and supplemented with solar systems as seen here at Timber Creek in the Northern Territory. Source: CSIRO – Nathan Dyer

Director’s foreword

Sustainable development and regional economic prosperity are priorities for the Australian, Queensland and Northern Territory (NT) governments. However, more comprehensive information on land and water resources across northern Australia is required to complement local information held by Indigenous Peoples and other landholders.

Knowledge of the scale, nature, location and distribution of likely environmental, social, cultural and economic opportunities and the risks of any proposed developments is critical to sustainable development. Especially where resource use is contested, this knowledge informs the consultation and planning that underpin the resource security required to unlock investment, while at the same time protecting the environment and cultural values.

In 2021, the Australian Government commissioned CSIRO to complete the Victoria River Water Resource Assessment and the Southern Gulf Water Resource Assessment. In response, CSIRO accessed expertise and collaborations from across Australia to generate data and provide insight to support consideration of the use of land and water resources in the Victoria and Southern Gulf catchments. The Assessments focus mainly on the potential for agricultural development, and the opportunities and constraints that development could experience. They also consider climate change impacts and a range of future development pathways without being prescriptive of what they might be. The detailed information provided on land and water resources, their potential uses and the consequences of those uses are carefully designed to be relevant to a wide range of regional-scale planning considerations by Indigenous Peoples, landholders, citizens, investors, local government, and the Australian, Queensland and NT governments. By fostering shared understanding of the opportunities and the risks among this wide array of stakeholders and decision makers, better informed conversations about future options will be possible.

Importantly, the Assessments do not recommend one development over another, nor assume any particular development pathway, nor even assume that water resource development will occur. They provide a range of possibilities and the information required to interpret them (including risks that may attend any opportunities), consistent with regional values and aspirations.

All data and reports produced by the Assessments will be publicly available.

C. Chilcott

Chris Chilcott

Project Director

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Note: Assessment team as at September, 2024. All contributors are affiliated with CSIRO unless indicated otherwise. Activity Leaders are underlined. For the Indigenous water values, rights, interests and development goals activity (Victoria catchment), Marcus Barber was Activity Leader for the project duration except August 2022 – July 2023 when Kirsty Wissing (a CSIRO employee at the time) undertook this role.

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Shortened forms

SHORT FORM	FULL FORM
FIT	feed in tariff
HOMER	hybrid optimisation of multiple energy resources
LCOE	levelised cost of electricity
NEM	national electricity market
NPC	net present cost
NT	Northern Territory
NWPS	North West Power System
PV	photovoltaics
RSC	relative system cost

Units

UNIT	DESCRIPTION
kV	kilovolt, one thousand volts, which is an SI unit
kW	kilowatt, a unit of power
kWh	Kilowatt-hours, a unit of energy
L	litre, a unit of volume
MW	megawatt, a unit of power
MWh	Megawatt-hour, a unit of energy
m/s	metres per second, a unit of velocity

Preface

Sustainable development and regional economic prosperity are priorities for the Australian, NT and Queensland governments. In the Queensland Water Strategy, for example, the Queensland Government (2023) looks to enable regional economic prosperity through a vision which states ‘Sustainable and secure water resources are central to Queensland’s economic transformation and the legacy we pass on to future generations.’ Acknowledging the need for continued research, the NT Government (2023) announced a Territory Water Plan priority action to accelerate the existing water science program ‘to support best practice water resource management and sustainable development.’

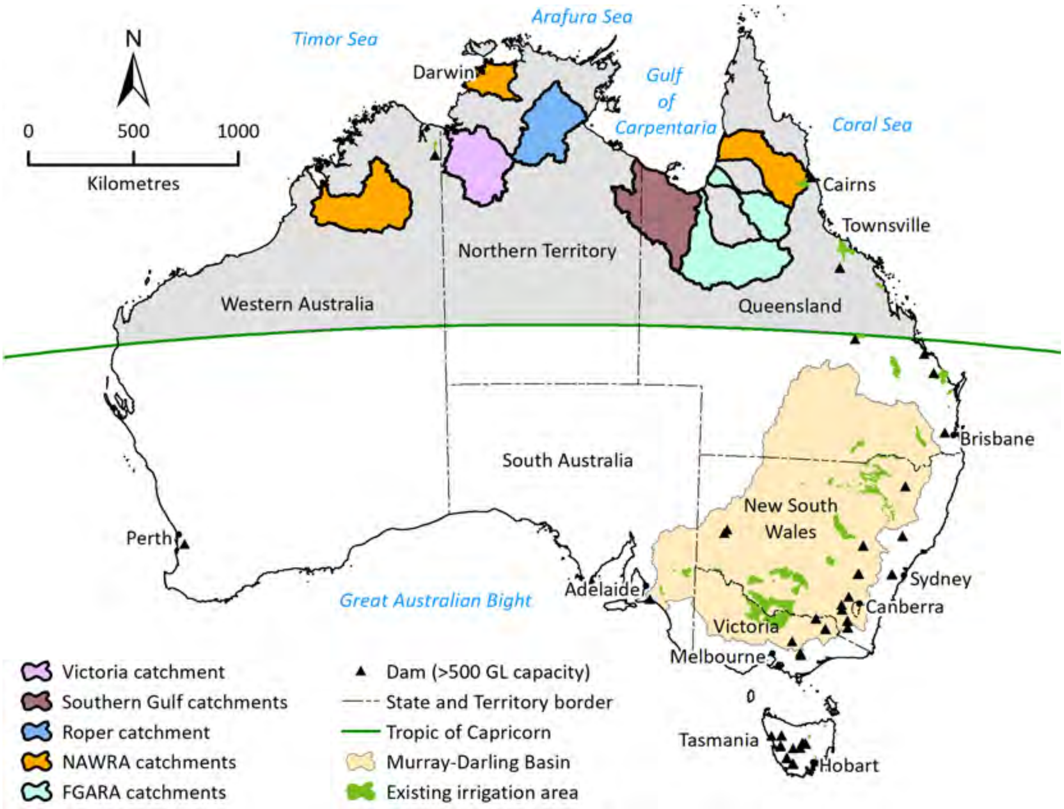
Governments are actively seeking to diversify regional economies, considering a range of factors, including Australia’s energy transformation. The Queensland Government’s economic diversification strategy for north west Queensland (Department of State Development, Manufacturing, Infrastructure and Planning, 2019) includes mining and mineral processing; beef cattle production, cropping and commercial fishing; tourism with an outback focus; and small business, supply chains and emerging industry sectors. In its 2024–25 Budget, the Australian Government announced large investment in renewable hydrogen, low-carbon liquid fuels, critical minerals processing and clean energy processing (Budget Strategy and Outlook, 2024). This includes investing in regions that have ‘traditionally powered Australia’ – as the North West Minerals Province, situated mostly within the Southern Gulf catchments, has done.

For very remote areas like the Victoria and Southern Gulf catchments, the land (Preface Figure 1-1), water and other environmental resources or assets will be key in determining how sustainable regional development might occur. Primary questions in any consideration of sustainable regional development relate to the nature and the scale of opportunities, and their risks.

How people perceive those risks is critical, especially in the context of areas such as the Victoria and Southern Gulf catchments, where approximately 75% and 27% of the population (respectively) is Indigenous (compared to 3.2% for Australia as a whole) and where many Indigenous Peoples still live on the same lands they have inhabited for tens of thousands of years. About 31% of the Victoria catchment and 12% of the Southern Gulf catchments are owned by Indigenous Peoples as inalienable freehold.

Access to reliable information about resources enables informed discussion and good decision making. Such information includes the amount and type of a resource or asset, where it is found (including in relation to complementary resources), what commercial uses it might have, how the resource changes within a year and across years, the underlying socio-economic context and the possible impacts of development.

Most of northern Australia’s land and water resources have not been mapped in sufficient detail to provide the level of information required for reliable resource allocation, to mitigate investment or environmental risks, or to build policy settings that can support good judgments. The Victoria and Southern Gulf Water Resource Assessments aim to partly address this gap by providing data to better inform decisions on private investment and government expenditure, to account for intersections between existing and potential resource users, and to ensure that net development benefits are maximised.



Preface Figure 1-1 Map of Australia showing Assessment areas (Victoria and Southern Gulf catchments) and other recent CSIRO Assessments

FGARA = Flinders and Gilbert Agricultural Resource Assessment; NAWRA = Northern Australia Water Resource Assessment.

The Assessments differ somewhat from many resource assessments in that they consider a wide range of resources or assets, rather than being single mapping exercises of, say, soils. They provide a lot of contextual information about the socio-economic profile of the catchments, and the economic possibilities and environmental impacts of development. Further, they consider many of the different resource and asset types in an integrated way, rather than separately.

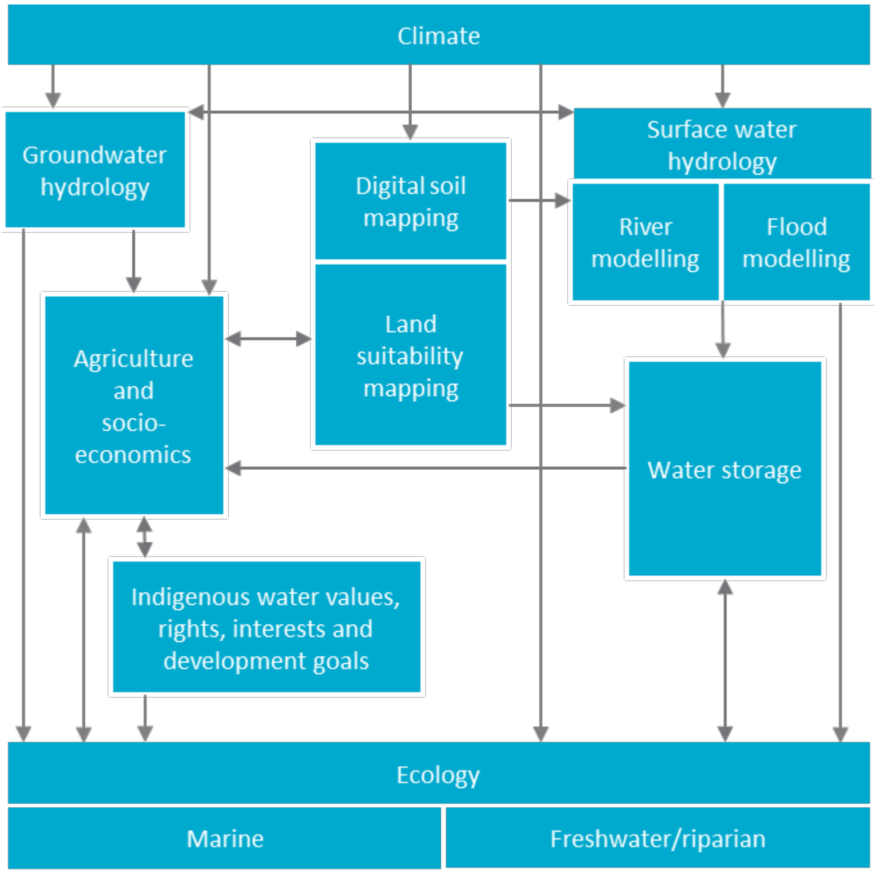
The Assessments have agricultural developments as their primary focus, but they also consider opportunities for and intersections between other types of water-dependent development. For example, the Assessments explore the nature, scale, location and impacts of developments relating to industrial, urban and aquaculture development, in relevant locations. The outcome of no change in land use or water resource development is also valid.

The Assessments were designed to inform consideration of development, not to enable any particular development to occur. As such, the Assessments inform – but do not seek to replace – existing planning, regulatory or approval processes. Importantly, the Assessments do not assume a given policy or regulatory environment. Policy and regulations can change, so this flexibility enables the results to be applied to the widest range of uses for the longest possible time frame.

It was not the intention of – and nor was it possible for – the Assessments to generate new information on all topics related to water and irrigation development in northern Australia. Topics not directly examined in the Assessments are discussed with reference to and in the context of the existing literature.

CSIRO has strong organisational commitments to Indigenous reconciliation and to conducting ethical research with the free, prior and informed consent of human participants. The Assessments allocated significant time to consulting with Indigenous representative organisations and Traditional Owner groups from the catchments to aid their understanding and potential engagement with their requirements. The Assessments did not conduct significant fieldwork without the consent of Traditional Owners.

Functionally, the Assessments adopted an activities-based approach (reflected in the content and structure of the outputs and products), comprising activity groups, each contributing its part to create a cohesive picture of regional development opportunities, costs and benefits, but also risks. Preface Figure 1-2 illustrates the high-level links between the activities and the general flow of information in the Assessments.



Preface Figure 1-2 Schematic of the high-level linkages between the eight activity groups and the general flow of information in the Assessments

Assessment reporting structure

Development opportunities and their impacts are frequently highly interdependent and, consequently, so is the research undertaken through these Assessments. While each report may be read as a stand-alone document, the suite of reports for each Assessment most reliably informs discussion and decisions concerning regional development when read as a whole.

Executive summary

This report examines the potential for hybrid renewable energy options (i.e. combinations of diesel, solar, wind and battery) to supply electricity to remote agricultural enterprises in the catchment of the Victoria River (NT) and the catchments of the Southern Gulf rivers (NT and Queensland). Two indicative locations in each study area were examined: Timber Creek and Kalkarindji in the Victoria catchment and Doomadgee and Kajabbi in the Southern Gulf catchments.

A techno-economic analysis, optimising for least-cost of supply of electricity to meet a wide range of hypothetical demands, has been undertaken using current costs and future cost projections to the year 2040. Given the variety in potential enterprises, and hence variety in types of demand patterns, the analysis went beyond simply determining the least-cost solution: a metric that compares the least-cost renewable and fossil fuel solutions (whether diesel generators or grid electricity) has been calculated, noting that the least-cost renewable solution may be a hybrid of solar PV with diesel generators. The value of this metric, the Relative System Cost, highlights to what extent the renewable solution is cheaper than the full fossil fuel solution. The share of renewable electricity supply in the least-cost renewable solution is also shown.

General findings

The largest driver of the uptake of renewable energy as the least-cost solution was found to be the technology capital cost. This was followed by the cost of diesel fuel or grid electricity and then the cost of the renewable energy resource at each location.

In terms of meeting electricity demand of remote agricultural enterprises, it was found that the share of renewable electricity supply in the least-cost solutions increased as the number of days of demand increased and was higher when demand occurred over fewer hours in each day. Hybrid renewable electricity with fossil fuels were the most common least-cost solution across all levels of electricity demand.

Renewable energy potential in the Victoria and Southern Gulf catchments

The Victoria and Southern Gulf catchments have some of the best solar resources in Australia and have low to modest wind resource relative to other locations in Australia. A convenient metric for comparing renewable energy technologies is using the capacity factor of an energy plant, which is the ratio of electricity generated over one year relative to the nameplate capacity of the solar or wind farm. For example, for a capacity factor of 0.25, each 1 MW of a solar or wind farm will generate about 2190 MWh of electricity per year. In the Victoria and Southern Gulf catchments solar photovoltaic capacity factors are uniformly high, ranging from 0.24 to 0.25 in the Victoria catchment and from 0.23 to 0.25 in the Southern Gulf catchments. In contrast, the capacity factor can be as low as 0.12 in southern Australia and along the east coast.

Wind resources for the Victoria and Southern Gulf catchments are reported as a capacity factor at a turbine hub height of 150 m, which is a typical height for a commercial wind turbine. Although wind capacity factors in the Victoria and Southern Gulf catchments are comparable to solar capacity factors, wind farms have a higher capital cost, which can result in a higher cost of electricity production. This is particularly the case for smaller wind turbines than examined here, whose generation capacity is more likely to be commensurate with the energy requirements of a farm-scale irrigation enterprise. Furthermore solar is modular and scalable and easier to maintain in remote locations than wind turbines. Wind energy is also a relatively mature technology, and projections of the levelised cost of wind in 2040 suggest that its cost is plateauing. Solar photovoltaic is projected to still be steadily decreasing, so the levelised cost of solar photovoltaic by 2040 would be 26% to 34% lower than wind on average.

Hence, solar photovoltaic is the most viable renewable technology in the Victoria catchment. Solar photovoltaic is also the most viable renewable technology across most of the Southern Gulf catchments. The exception is Kajabbi, one of the few locations with soils potentially suitable for irrigated agriculture and a grid connection in the Southern Gulf catchments. Having a grid connection at Kajabbi may enable excess renewable electricity to be sold to the grid, potentially changing the economic viability of wind turbines.

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1 Electricity system analysis

A techno-economic analysis of electricity system options for supplying electricity to remote off-grid enterprises in the Victoria catchment in the NT and the Southern Gulf catchments, which span Queensland and the NT, has been performed using the Hybrid Optimisation of Multiple Energy Resources (HOMER) software[1] and Graham et al. (2023) technology cost assumption data for 2023 and projected out to the year 2040. The costs have been adjusted to reflect the remote location AEMO (2023). While the emphasis of the analysis is on the provision of energy for the operation of different infrastructure (e.g. water pumps, refrigerated sheds, irrigators) on potential agricultural enterprises with a variety of demand patterns, the results of the analysis are applicable to any enterprises or infrastructure requiring electricity. Two indicative locations in each study area were examined: Timber Creek and Kalkarindji in the Victoria catchment and Doomadgee and Kajabbi in the Southern Gulf catchments.

1.1 Study area description

The Victoria catchment is in a remote part of the NT which does not have access to major electricity networks. The largest electricity network in the NT is the Darwin-Katherine Interconnected System, which connects the capital of Darwin to Katherine further south by a 132 kV transmission line. Power and Water in the NT provides electricity to Timber Creek using diesel generators (NT Emergency Service 2023a) which are not connected to any regulated electricity network[2]. Kalkarindji is powered by a hybrid of diesel and solar (408 kW)[3]. It is also not connected to any electricity network (NT Emergency Service 2023b).

The Southern Gulf catchments are also in a remote part of northern Australia. Doomadgee is serviced by Ergon Energy, and it contains its own diesel power station with a 4.5 MW solar PV (photovoltaics) farm to provide power to the community. There are also plans to install 4 MWh of energy storage, to save on diesel consumption and reduce emissions[4]. Doomadgee is not connected to the National Electricity Market (NEM), which is the electricity network that connects the eastern states of Australia, including Tasmania and South Australia. The NEM is Australia's largest electricity network. The other major network in Queensland is the North West Power System (NWPS) which is a shared network centred in Mount Isa. Gas-fired generation is responsible for the majority of power in the NWPS. Kajabbi is connected to the NWPS via a distribution network in the township. Kajabbi is also serviced by Ergon Energy and Diamantina Power Station in Mount Isa is the closest to Kajabbi (Butterworth 2021).

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[1] https://www.homerenergy.com/

[2] https://www.powerwater.com.au/about/what-we-do/power-networks-and-supply

[3] https://arkenergy.com.au/solar/tkln-solar-kalkarindji/

[4] https://statements.qld.gov.au/statements/98544

1.2 Techno-economic optimisation

HOMER microgrid modelling tool, developed by the National Renewable Energy Laboratory, has been used to optimise the electrical system designs at each location.

HOMER requires input in the form of electrical demand/load, which needs to be provided for one year and it can be down to one-minute intervals. It features various generation and energy storage components, such as diesel generators, solar PV, wind, fly wheels and batteries. The size, costs, performance and emissions from each device can be adjusted by the user. Renewable resource from the NASA resource databases is used by default.

Many different variations of technology size, scale, resource and load exist in HOMER and the optimiser works through all of these variations to find the optimal solution and explore the sensitivity space. The results show the cost of energy, net present cost, capital, capital replacement and operating costs for each system configuration.

HOMER is a simple optimisation tool and does not take into account all of the equipment required for a microgrid and the physical layout. For instance, cabling and wiring, water and other requirements are not included although it is possible to include an additional cost for a grid connection.

1.3 Electricity demand

Since agricultural enterprises and other potential energy uses in remote areas of Australia (e.g. mining, residential) have a wide variety energy demand patterns. Even within a single enterprise different infrastructure may have very different energy demand patterns. For example, within an agricultural enterprise there may be large water pumps which are required to pump large volumes of water in a short period of time and/or large refrigerated processing and storage sheds. With such a wide range of potential energy demand patterns the Assessment undertook a generic analysis to better understand the potential viability of hybrid renewable energy options for supplying electricity to meet the needs of different infrastructure and enterprises.

Given that future electricity demand in the catchments is unknown, we have decided to explore all levels of potential electricity demand. The overarching assumptions are as follows:

- We have assumed the same hypothetical quantity of electricity (10 MWh) is required over a year, however, when it is required varies. This means that when electricity demand occurs more frequently, electrical load/power (MW) will be lower. If electricity demand occurs less frequently, then the power required will be higher.
- Electricity demand has been assumed to be the same for each year of operation.
- The load is constant when being used.

Demand has been split into hourly and daily operations. Over the year, electrical demand is assumed to occur over either 10%, 30%, 50%, 80% and 100% of days. Of those days, demand has been assumed to occur over either 4, 8, 12 or 24 hours. This results in a variety of electrical demand regimes with different power requirements. This is shown in Table 1-1.

Electrical demand has been assumed to begin in January. This means that for example, under a 10% (37 days) share of the year demand regime, electrical demand occurs over the first 37 days of the year.

A refrigerated shed may be indicative of the demand scenario that requires a load of 24 hours per day for a several months, while particular equipment at a mining enterprise may be more indicative of a demand scenario that has a demand of 12 hours a day over 365 days per year.

Table 1-1 Division of power and electricity demand over hours per day and days per year

DAYS AND SHARE PER YEAR	DAILY ELECTRICITY DEMAND (KWH/DAY)	LOAD OVER 24 HOURS (KW)	LOAD OVER 12 HOURS (KW)	LOAD OVER 8 HOURS (KW)	LOAD OVER 4 HOURS (KW)
37 (10%)	274	11	23	34	68
110 (30%)	91	4	8	11	23
183 (50%)	55	2	5	7	14
292 (80%)	34	1	3	4	9
365 (100%)	27	1	2	3	7

1.4 Technology and modelling assumptions

The Victoria and Southern Gulf catchments have among the best solar resources in Australia, with just about the highest capacity factors for solar photovoltaics (PV) as shown in Figure 1-1 and Figure 1-2 respectively, indicated by the red region of the smaller maps of Australia. In the southern areas and along the eastern coastlines of Australia, the capacity factor is lower, down to a minimum of 0.11. Within the catchments themselves there is some variability, but only at the top end of the range of capacity factors from 0.24 to 0.25 in the Victoria catchment and 0.23 to 0.25 in the Southern Gulf catchments.

Capacity factor is the ratio of electricity generated over one year to the capacity of a solar PV farm. The maximum capacity factor is 0.253, which means that for each 1 MW of a solar PV farm, 2,216 MWh of electricity are generated over a year[5]. It can be possible to increase the capacity factor of solar PV by using single axis or dual axis tracking farms, where the sun is tracked throughout the day.

Wind resources in both catchments are shown in Figure 1-3 and Figure 1-4 as capacity factor at a hub height of 150 metres, which is a typical height for a wind turbine. Wind resources vary across Australia and are highest along the southern coastline, Tasmania, eastern Australia long the Great Dividing Range, higher areas of central Australia, the Atherton Tablelands and Cape York. Wind speeds in Tasmania can reach a top of 13 m/s, which corresponds to a capacity factor 0.4, but this can vary depending on the size of the wind turbine. In the Victoria catchment, capacity factors vary from 0.17 to 0.31 and in the Southern Gulf catchments from 0.23 to 0.33.

[5] 0.253 (capacity factor) x 8760 (number of hours per year)

While capacity factors can be higher for wind compared to solar PV, wind farms have a higher capital cost which can offset the advantage posed by having a higher capacity factor and result in a higher cost of electricity production.

Currently, the typical wind turbine size being installed in Australia are 6 MW, with proposals for projects with 7-8 MW turbines. 4 MW turbines were used in 70% of global projects in 2022. These turbines are basically too large for hypothetical modelled electricity demand. It would be impractical for a site to have only one wind turbine as it would mean higher specific operating and maintenance costs and the only backup would be a diesel generator, in the case of a hybrid system, should the wind turbine fail. Solar PV is very modular and scalable and is easier to maintain than wind turbines. It is a more practical solution for an off-grid and remote location. For these reasons wind turbines were not modelled in the Victoria catchment and Doomadgee. Kajabbi is grid-connected and therefore excess renewable electricity can be sold to the grid. Given this, wind turbines have been included as an option in the modelling of Kajabbi.

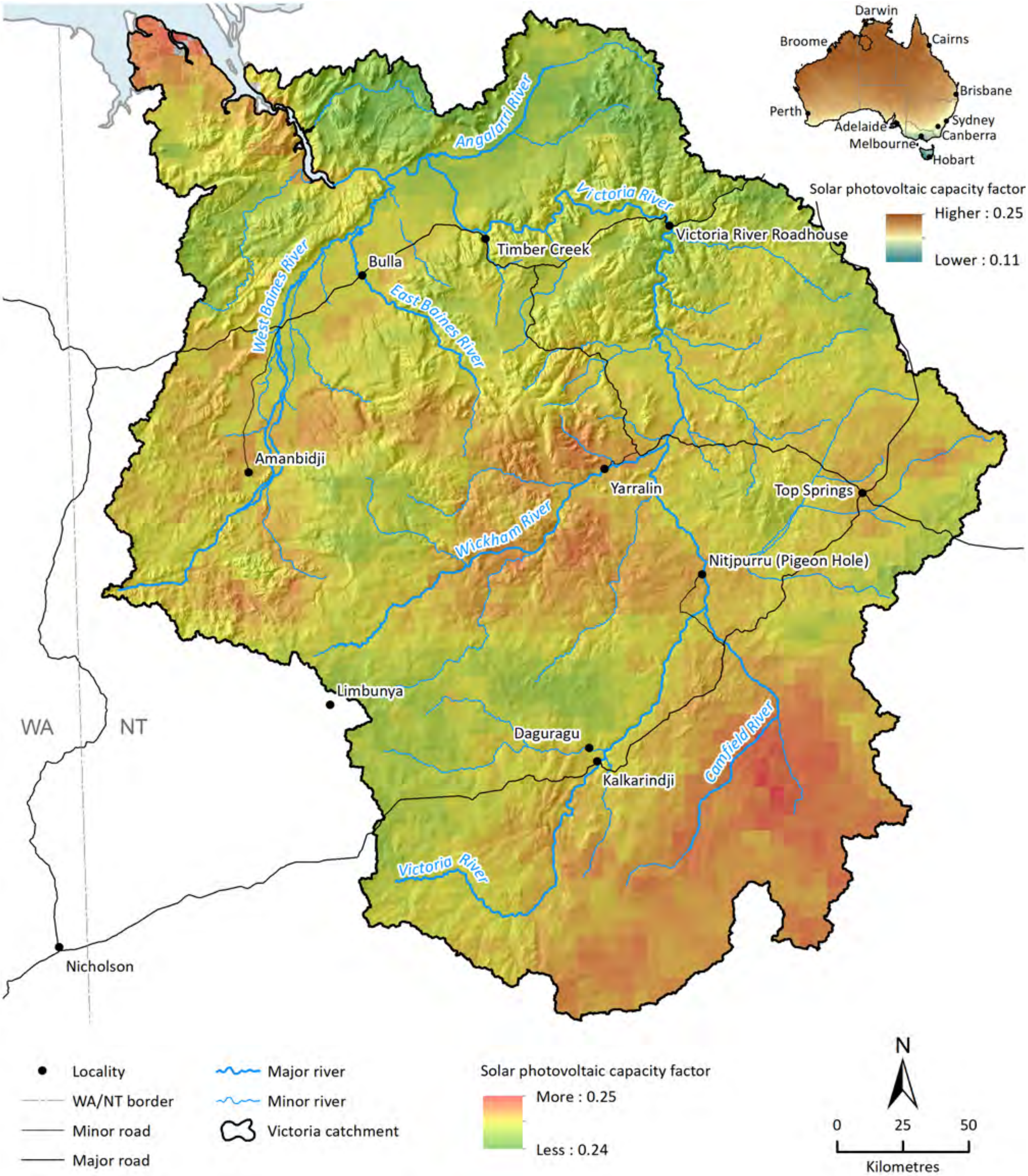

Figure 1-1 Solar PV capacity factors in the Victorian River catchment

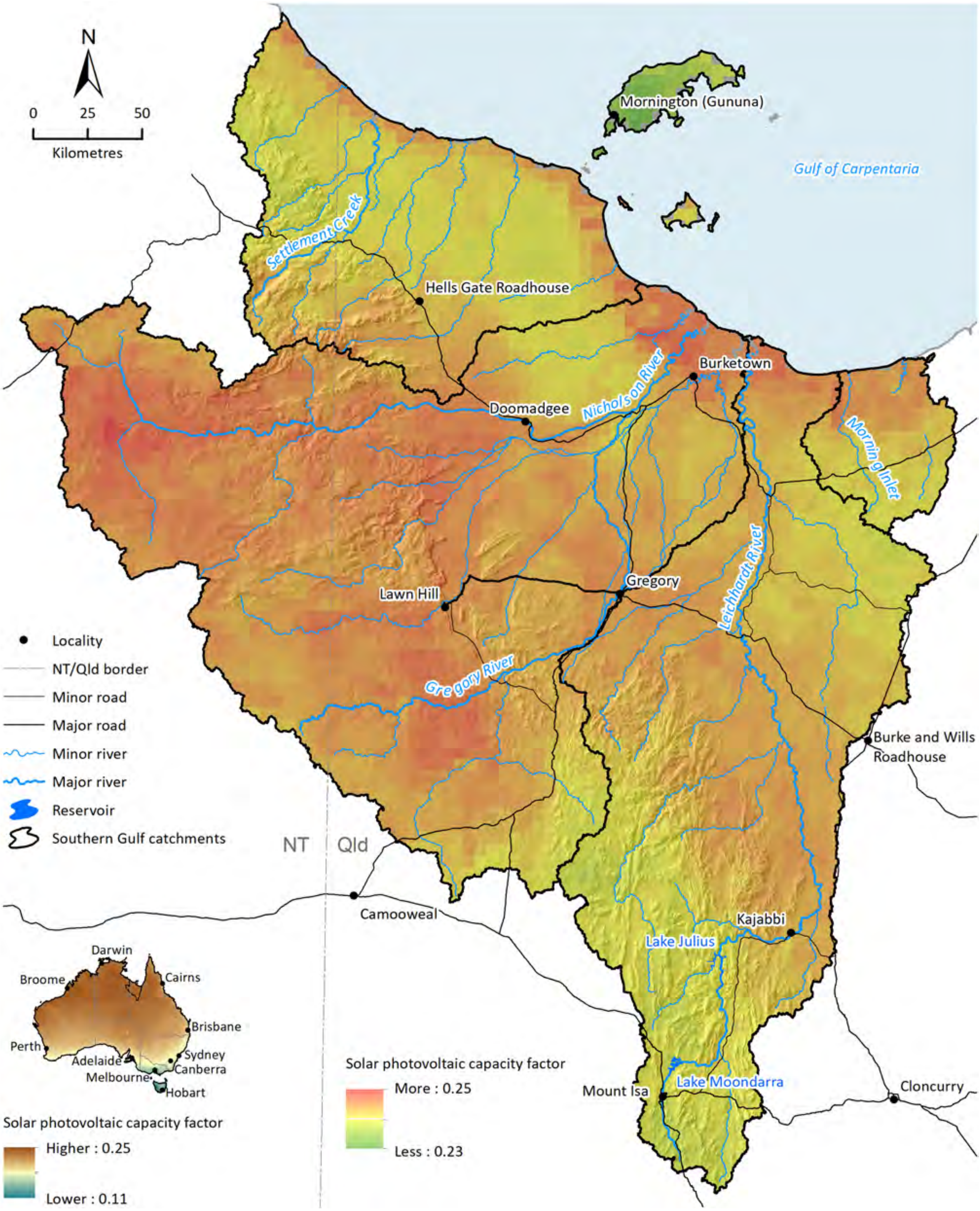

Figure 1-2 Solar PV capacity factors in the Southern Gulf catchments

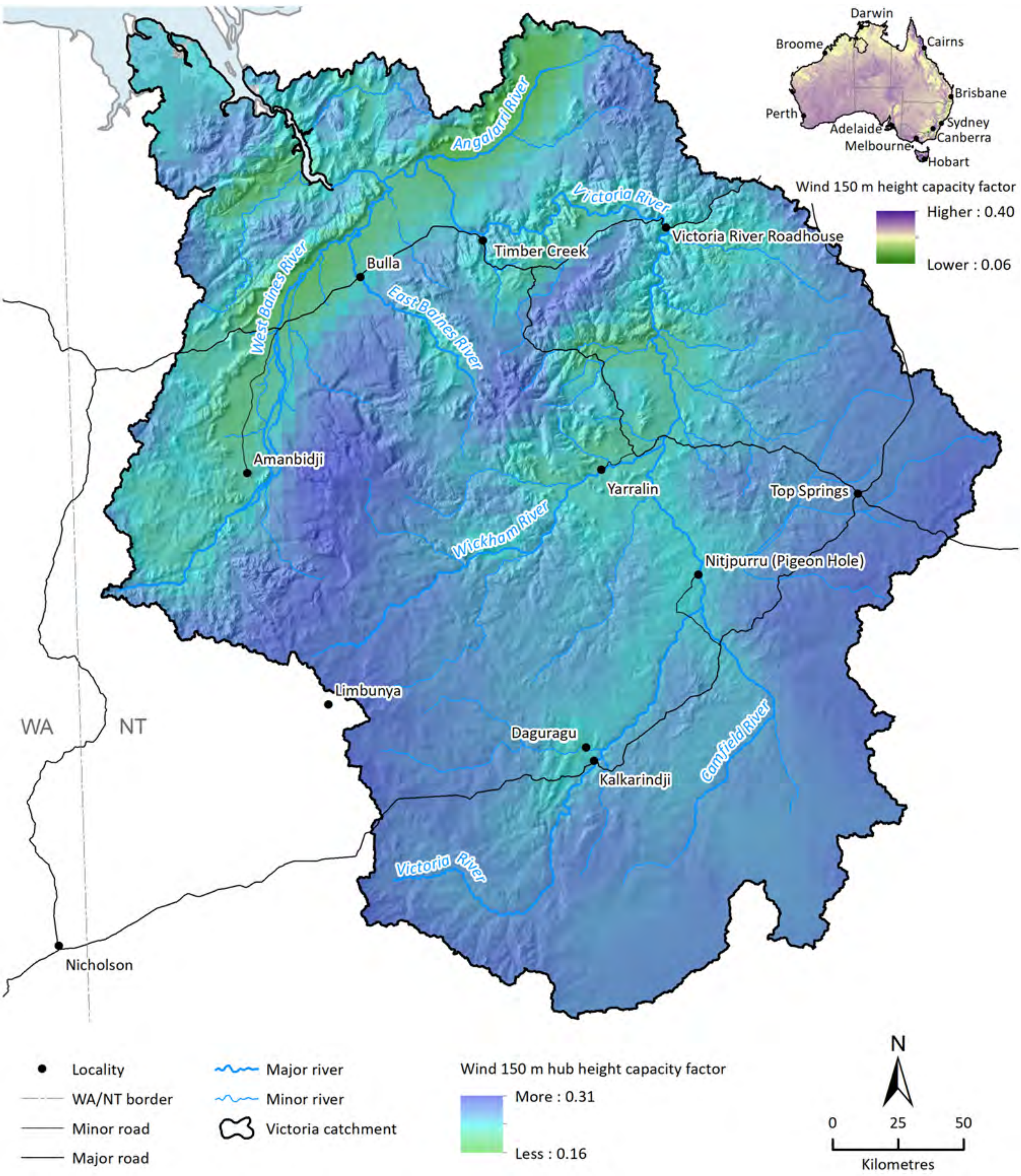

Figure 1-3 Wind capacity factors in the Victorian River catchment

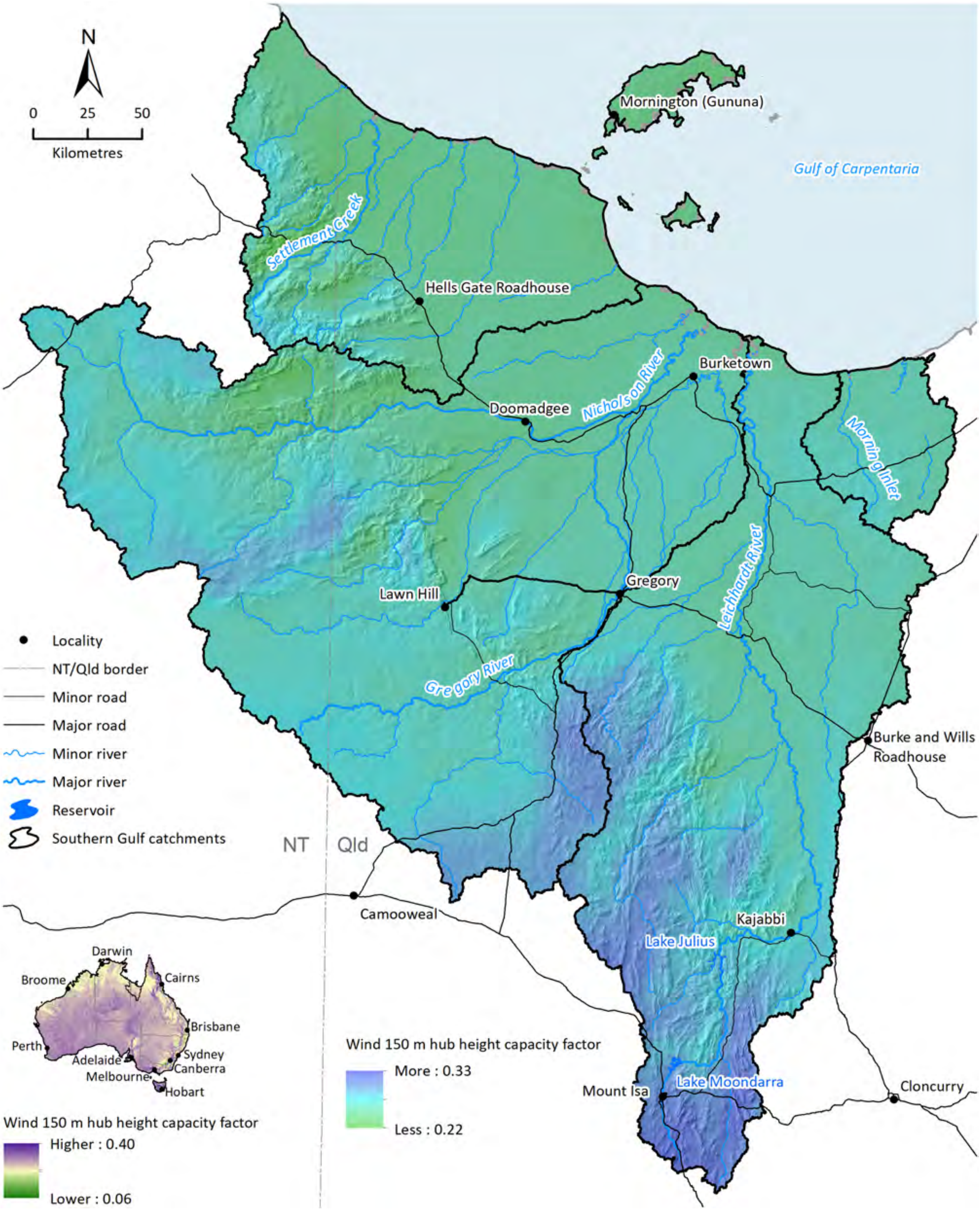

Figure 1-4 Wind capacity factors in the Southern Gulf catchments

Key technology cost and performance assumptions including regional cost adjustment factors are shown in Table 1-2 for 2023 and in Table 1-3 for 2040.

Table 1-2 2023 modelled technology cost and performance assumptions

TECHNOLOGY	CAPITAL COST ($/KW)	FIXED O&M COST ($/KW/YEAR)	VARIABLE O&M COST ($/KWH)	BATTERY REPLACEMENT COST ($/KWH)	LIFETIME (YEARS)
PV	1791	16	-	-	25
Wind	3490	33	-	-	25
Reciprocating engine	2230	32	0.01	-	25
Battery (1 hour)	1129	12	-	474	20
Battery (2 hours)	1648	18	-	460	20
Battery (4 hours)	2690	28	-	452	20
Battery (8+ hours)	4779	49	-	444	20

Table 1-3 2040 modelled technology cost and performance assumptions

TECHNOLOGY	CAPITAL COST ($/KW)	FIXED O&M COST ($/KW/YEAR)	VARIABLE O&M COST ($/KWH)	BATTERY REPLACEMENT COST ($/KWH)	LIFETIME (YEARS)
PV	755	16	-	-	25
Wind	2046	33	-	-	25
Reciprocating engine	2086	32	0.01	-	25
Battery (1 hour)	445	12	-	105	20
Battery (2 hours)	554	18	-	100	20
Battery (4 hours)	768	28	-	97	20
Battery (8+ hours)	1204	49	-	95	20

Two diesel fuel prices were modelled: $1.50/L and $2.50/L.

In this energy assessment a discount rate of 5.9% is assumed as this is consistent with CSIRO energy modelling and longer-term trends in discount rates (e.g. Graham et al., 2023). The total project lifetime was assumed to be 20 years.

1.4.1 Optimising electrical systems for Timber Creek, Kalkarindji and Doomadgee

The technologies included in HOMER for the optimisation of electricity solutions in the Victoria catchment and Doomadgee are solar PV, lithium battery storage and diesel generators. Current costs and projected costs for the year 2040 were modelled. As can be seen in Table 1-2 and Table 1-3, battery costs vary depending on the number of hours of storage. These different battery system sizes and costs were included in HOMER, which results in a curve of cost versus hours of storage. This allows HOMER to choose any sized battery system, rather than discrete hourly intervals of storage.

Timber Creek, Kalkarindji and Doomadgee are not grid connected and therefore the systems were modelled to meet all of the electrical demand themselves.

1.4.2 Optimising electricity systems for Kajabbi

Kajabbi is grid connected and therefore the HOMER optimisation has included solar PV and wind with the grid connection. Batteries and diesel generators were not modelled because the grid can provide electricity when there is no wind or solar generation.

Kajabbi has power supplied by Ergon Energy. An Ergon Energy small business tariff, Tariff 22C, was assumed as the cost of grid electricity (Ergon Energy 2023). This was the least-cost small business tariff and is shown in Table 1-4. In addition to the time of use charges there is also a daily supply charge for annual energy usage from 0-20 MWh of $1.54308. HOMER allows for the inclusion of an annual charge; therefore the daily charge was converted to an annual charge for the modelling.

Table 1-4 Ergon Energy Tariff 22C time of use charges

DAILY PERIOD	HOURS	COST ($/KWH)
Peak	4pm to 9pm weekdays	0.70221
Night (shoulder)	9pm to 9am weekdays and 4pm to 9am weekends	0.28195
Day (off-peak)	9am to 4pm daily	0.11963

Ergon Energy currently has a feed-in-tariff (FiT) for household/small business renewable energy generation of 13.441 c/kWh. When this was included in the modelling, very large solar PV and wind farms were the least-cost optimised solution because the FiT is greater than the cost of electricity from solar PV and wind, which means significant revenue could hypothetically be generated, though energy market dynamics mean this is unlikely in reality. A large-scale solar PV and wind farm would participate in the wholesale market and thus would not receive such a generous FiT but rather be subjected to a variable market price, which would resemble the cost of electricity production i.e. the levelised cost of electricity (LCOE).

This assessment is not focused on generating a large revenue from electricity exports but rather understanding the potential to use renewables to reduce the cost of electricity in remote parts of northern Australia. Therefore, the maximum size of solar PV and wind farms was constrained to be no more than 25% of the electrical load. Setting the size of the renewable energy farms to be 25% more than load is based on a rule of thumb (Hayward et al., 2015) which aims to reduce short term variability in renewable energy output by slightly oversizing the system. Export revenue was included, but only equal to the LCOE. This further ensures that revenue is not the driver of the size of the renewable energy farms. This method was used for the energy analysis in Petheram et al. (2021).

Kajabbi was also modelled as an off-grid system, the same as the other locations, but with wind included as well. As already discussed, from a practical point of view wind turbines are too large but to explore the impact their higher capacity factor can have on the system optimisation they were included for just this location. Therefore, the technology options for the off-grid modelling of Kajabbi were solar PV, wind, batteries and diesel generators.

1.5 Relative System Cost

HOMER optimises the electricity system configurations to ensure that electricity demand is met and at the same time determines the overall least-cost system as well as the least-cost system of different configurations that meet electricity demand. This includes the least-cost diesel system (least-cost grid system in the case of Kajabbi), least-cost hybrid system and the least-cost system with batteries. Results for each system configuration include the LCOE, the share of electricity generation from renewables, greenhouse gas emissions, fuel consumption, annual system cost, net present cost (NPC) etc

The LCOE is the cost that electricity would need to be sold at to recover all system costs. It does not include profit, revenue etc.

NPC is the present cost of all costs occurred over the systems lifetime minus any revenues, which in this case is the salvage value of equipment at the end of system life.

Given the large number of modelling runs, the results have been summarised as a Relative System Cost (RSC) to highlight the key takeaways: i.e. during what electricity demand regimes are:

- diesel operations alone more cost-effective
- hybrid systems of renewables and diesel cost-effective
- hybrid systems of renewables, batteries and diesel cost-effective
- different penetrations of renewables cost effective.

In the case of Kajabbi, where both grid connected and off-grid systems were modelled, cases were also explored where:

- grid operations alone are more cost-effective
- hybrid systems of PV, wind and the grid are cost-effective

The formula for calculating the RSC is:

RSC = NPC diesel or grid system / NPC least-cost system

A value of 1 means the diesel-only/grid-only system is the least-cost option. Higher RSCs indicate that the least-cost system is lower in cost than a diesel-only or grid-only system. Therefore, it could be expected that with high diesel fuel prices and lower renewable technology costs in 2040, least-cost renewable/battery/hybrid systems will be much lower in cost, leading to higher RSCs. The higher the RSC the greater the cost savins compared to diesel-only and grid-only systems.

2 Results

2.1 Timber Creek (Victoria catchment)

2.1.1 Current costs

The RSCs projected using current costs are shown in Table 2-1 for diesel at $1.50/L and diesel at $2.50/L in Table 2-2.

Table 2-1 Projected Timber Creek RSCs using current costs and where diesel is modelled as $1.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	1.0	1.0	1.0	1.0
30%	1.0	1.1	1.0	1.0
50%	1.1	1.2	1.2	1.0
80%	1.2	1.4	**1.4**	1.2
100%	1.2	**1.4**	1.5	**1.4**

Table 2-2 Projected Timber Creek RSCs using current costs and where diesel is modelled as $2.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	1.0	1.0	1.0	1.0
30%	1.1	1.2	1.2	1.0
50%	1.2	1.4	1.4	1.2
80%	**1.4**	**1.8**	**1.8**	**1.6**
100%	**1.7**	**2.1**	**2.2**	**2.0**

It can be seen from all tables that diesel-only systems are the preferred option when there is electricity demand for 10% of days of the year. If there is electricity demand for at least 30% of days of the year some fractional renewable energy hybrid systems are lower in cost. It is expected that with higher diesel prices at $2.50/L renewable energy systems with batteries would be more favoured. This is particularly the case when the systems are assumed to operate for 80% and 100% of days of the year. This constant operation provides more hours over the year over which the solar PV and battery systems can have their upfront capital cost amortised. This is reflected in the fact that a 100% renewable energy system was the least-cost option under a $2.50/L diesel price and when electricity demand occurs over 80% and 100% of the days of the year.

2.1.2 2040 costs

The RSCs projected using 2040 costs are shown in Table 2-3 for diesel at $1.50/L and diesel at $2.50/L in Table 2-4.

Table 2-3 Projected Timber Creek RSCs using 2040 costs and where diesel is modelled as $1.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	1.0	1.0	1.0	**1.0**
30%	**1.4**	**1.6**	**1.5**	**1.6**
50%	**2.2**	**2.4**	**2.2**	**2.4**
80%	**3.3**	**3.6**	**3.4**	**3.4**
100%	**3.9**	**4.1**	**4.2**	**4.1**

Table 2-4 Projected Timber Creek RSCs using 2040 costs and where diesel is modelled as $2.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	**1.1**	1.1	**1.1**	**1.2**
30%	**1.9**	**2.2**	**2.1**	**2.2**
50%	**3.1**	**3.3**	**3.2**	**3.3**
80%	**4.7**	**5.1**	**5.0**	**4.9**
100%	**5.7**	**6.2**	**6.2**	**5.9**

Lower renewable energy costs result in higher fractions of renewable energy penetration, as can be seen in Table 2-3 and Table 2-4 where systems operating for more than 30% of days per year have more than 90% renewable energy and the vast majority of systems which operate during daylight hours are 100% renewable.

2.2 Kalkarindji (Victoria catchment)

2.2.1 Current costs

The RSCs for each modelled power and electricity demand are shown in Table 2-5 where diesel is $1.50/L and Table 2-6 where diesel is $2.50/L.

Table 2-5 Projected Kalkarindji RSCs using current cost information and where diesel is modelled as $1.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	1.0	1.0	1.0	1.0
30%	1.0	1.1	1.0	1.0
50%	1.1	1.2	1.2	1.0
80%	1.2	1.4	**1.4**	**1.2**
100%	**1.2**	**1.6**	**1.6**	**1.5**

Table 2-6 Projected Kalkarindji RSCs using current cost information and where diesel is modelled as $2.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	1.0	1.0	1.0	1.0
30%	1.1	1.2	1.2	1.0
50%	**1.2**	1.4	1.5	1.2
80%	**1.5**	**1.9**	**1.8**	**1.8**
100%	**1.9**	**2.3**	**2.4**	**2.1**

As with Timber Creek, when the systems are only assumed to operate over 10% of days of the year then diesel-only systems are the lowest-cost option. With higher diesel prices, hybrid systems are the preferred option where electricity demand is expected to occur over at least 30% of days of the year and when demand is for more than 80% of days of the year 100% renewable energy systems are the least-cost option.

2.2.2 2040 costs

The RSCs projected using 2040 costs are shown in Table 2-7 for diesel at $1.50/L and Table 2-8 for diesel at $2.50/L.

Table 2-7 Projected Kalkarindji RSCs using 2040 cost information and where diesel is modelled as $1.50/.

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	1.0	1.0	1.0	**1.1**
30%	**1.5**	**1.7**	**1.6**	**1.8**
50%	**2.3**	**2.5**	**2.4**	**2.5**
80%	**3.4**	**3.7**	**3.7**	**3.6**
100%	**3.8**	**4.5**	**4.5**	**4.3**

Table 2-8 Projected Kalkarindji RSCs using 2040 cost information and where diesel is modelled as $2.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90% pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	**1.1**	1.1	**1.1**	**1.2**
30%	**2.1**	**2.3**	**2.2**	**2.3**
50%	**3.2**	**3.5**	**3.5**	**3.5**
80%	**4.9**	**5.4**	**5.4**	**5.8**
100%	**5.8**	**6.8**	**6.6**	**6.3**

The 2040 results for Kalkarindji follow the same trends as those of Timber Creek except the RSCs are slightly higher, which indicates a slightly higher solar PV resource.

2.3 Doomadgee (Southern Gulf catchments)

2.3.1 Current costs

The RSCs for each modelled power and electricity demand are shown in Table 2-9 where diesel is $1.50/L and Table 2-10 where diesel is $2.50/L.

Table 2-9 Projected Doomadgee RSCs using current cost information and where diesel is modelled as $1.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	1.0	1.0	1.0	1.0
30%	1.0	1.1	1.0	1.0
50%	1.1	1.2	1.2	1.0
80%	1.2	1.4	**1.4**	**1.2**
100%	1.2	**1.4**	1.5	**1.3**

Table 2-10 Projected Doomadgee RSCs using current cost information and where diesel is modelled as $2.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	1.0	1.0	1.0	1.0
30%	1.1	1.2	1.2	1.0
50%	1.2	1.4	1.4	1.2
80%	**1.3**	**1.7**	**1.7**	**1.6**
100%	**1.7**	**2.1**	**2.1**	**1.9**

The results for Doomadgee modelled using current costs are very similar to those of Timber Creek, except the RSCs are slightly lower. This means the solar resource is greater in Timber Creek than Doomadgee. A 100% renewable system is the preferred option when demand occurs for 80% of days of the year or more and diesel is $2.50/L.

2.3.2 2040 costs

The RSCs projected using 2040 costs are shown in Table 2-11 for diesel at $1.50/L and Table 2-12 for diesel at $2.50/L.

Table 2-11 Projected Doomadgee RSCs using 2040 cost information and where diesel is modelled as $1.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	1.0	1.0	1.0	1.0
30%	**1.4**	**1.5**	**1.5**	**1.6**
50%	**2.3**	**2.3**	**2.1**	**2.3**
80%	**3.2**	**3.5**	**3.3**	**3.2**
100%	**3.9**	**4.0**	**4.0**	**4.0**

Table 2-12 Projected Doomadgee RSCs using 2040 cost information and where diesel is modelled as $2.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90% pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	**1.1**	1.1	**1.1**	**1.2**
30%	**1.9**	**2.1**	**2.0**	**2.1**
50%	**3.2**	**3.2**	**3.1**	**3.1**
80%	**4.6**	**5.0**	**4.8**	**5.2**
100%	**5.6**	**5.9**	**5.9**	**5.7**

The 2040 results are also very similar to those of Timber Creek, again with slightly lower RSCs. 100% renewable energy solutions are the least-cost option for the majority of operating regimes.

2.4 Kajabbi (Southern Gulf catchments)

2.4.1 Grid-connected

The RSCs for each modelled power and electricity demand are shown Table 2-13 in for the grid-connected system using current costs and future costs are in Table 2-14.

Table 2-13 Projected Kajabbi RSCs using current cost information for a grid-connected system

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Italics indicate a system with wind.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	1.2	1.5	1.7	1.7
30%	*2.1*	*2.3*	2.0	1.5
50%	*1.9*	*2.7*	*2.1*	1.5
80%	*1.8*	*3.0*	*2.2*	1.6
100%	*2.0*	*3.1*	*2.2*	1.6

Table 2-14 Projected Kajabbi RSCs using 2040 cost information for a grid-connected system

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Italics indicate a system with wind.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	*1.2*	1.5	1.7	1.7
30%	*2.1*	*2.3*	2.0	1.5
50%	*1.9*	*2.7*	*2.1*	1.5
80%	*1.8*	*3.0*	*2.2*	1.6
100%	*2.0*	*3.1*	*2.2*	1.6

There is a high degree of similarity between the current cost and 2040 cost results. The RSCs are identical, but the renewable share can vary. Under current costs, operating for 30% of days of the year, 24 hours per day has a higher renewable penetration than using 2040 costs. However, operating for 24 hours per day over 10% of days has a higher renewable penetration under 2040 costs. The LCOEs are lower in 2040 and consequently the FiT is lower. This has led to slight differences in results.

2.4.2 Off-grid

Current costs

The RSCs for each modelled power and electricity demand are shown in Table 2-15 where diesel is $1.50/L and Table 2-16 where diesel is $2.50/L.

Table 2-15 Projected Kajabbi RSCs using current cost information and where diesel is modelled as $1.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries and italics indicate wind.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	1.0	1.0	1.0	1.0
30%	1.0	1.1	1.0	1.0
50%	*1.2*	1.2	1.2	1.0
80%	***1.3***	***1.4***	***1.5***	**1.4**
100%	***1.5***	***1.8***	**1.8**	**1.6**

Table 2-16 Projected Kajabbi RSCs using current cost information and where diesel is modelled as $2.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries and italics indicate wind.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	1.0	1.0	1.0	1.0
30%	*1.1*	1.2	1.2	1.0
50%	***1.7***	1.4	1.5	***1.3***
80%	***1.7***	***2.2***	***2.2***	**1.9**
100%	***2.2***	***2.7***	**2.6**	**2.1**

The results show that 100% renewable energy solutions are favourable, particularly when the systems are operating for more than 80% of days of the year. This is similar to the other locations, except that with the inclusion of wind energy the impact diesel costs have on the share of renewable energy is reduced.

2040 costs

The RSCs projected using 2040 costs are shown in Table 2-17 for diesel at $1.50/L and Table 2-18 for diesel at $2.50/L.

Table 2-17 Projected Kajabbi RSCs using 2040 cost information and where diesel is modelled as $1.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90%, pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries. Italics indicate a system with wind.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	1.0	1.0	***1.0***	***1.3***
30%	***1.5***	**1.7**	**1.7**	***1.8***
50%	***2.3***	**2.5**	**2.6**	**2.6**
80%	***3.4***	**3.9**	**3.9**	**3.8**
100%	**4.1**	**4.9**	**4.9**	**4.6**

Table 2-18 Projected Kajabbi RSCs using 2040 cost information and where diesel is modelled as $2.50/L

Legend: purple indicates a renewable fraction between 50 and 75%, teal indicates a renewable fraction between 75 and 90% pink indicates a renewable fraction greater than 90% and blue indicates a 100% renewable system. Bold text indicates least-cost systems with batteries. Italics indicate a system with wind.

	HOURS PER DAY WHEN OPERATING			
Percentage of days of the year when operating	**24**	**12**	**8**	**4**
10%	**1.1**	***1.3***	***1.3***	***1.5***
30%	***2.1***	**2.4**	**2.4**	***2.4***
50%	***3.4***	**3.7**	**3.8**	**3.6**
80%	***5.2***	**5.8**	**5.8**	**6.2**
100%	***4.1***	**7.3**	**7.2**	**6.6**

The inclusion of even lower cost renewables has resulted in 100% renewable energy solutions being least-cost except when operating for 24 hours per day. In these cases, renewable penetration is 96% or greater and the small diesel generators make up the remaining 4%. The load is lower when operating over 24 hours per day, which means a smaller generator can be used compared to operating for 4 hours per day (see Table 1-1 for loads).

3 Summary

The key assumptions that are driving the results are: renewable energy technology capital costs, diesel price and the renewable energy resources.

Comparing the 2040 and current cost results by diesel price and location reveals that under 2040 costs electricity demand regimes with more than 90% renewables are the dominant least-cost system and that the number of 100% renewable energy systems has more than doubled. By 2040, solar PV costs are projected to reduce by 58% compared to the current costs and projected battery cost reductions range from 61% to 75%, where the larger cost reductions are for the larger systems. To have a high share of renewable energy in an electricity system, long duration battery storage is required to replace diesel generators. Consequently, there is a much greater uptake of long duration battery storage when the capital cost is low.

The impact of diesel price is greater in terms of the share of renewable energy when modelling current costs but the differences in RSC values between systems with diesel at $1.50/L and diesel at $2.50/L are greater when modelling with 2040 cost projections. The reason for this is that the 2040 cost projections are so low that renewable energy systems are the least-cost option no matter what the diesel price, and because of this the main component of the NPC is the diesel price, which results in a higher RSC. When technology capital costs are higher, hybrid systems are the least-cost option to offset some of the cost of diesel. This is particularly the case for electricity demand regimes with operations over 4 and 8 hours per day as these systems can rely on solar PV during the day when they are assumed to be demanding electricity.

In terms of the impact of renewable energy resources, the results are slightly better for Kalkarindji as it has a higher penetration of renewable energy followed by Doomadgee and then Timber Creek. Solar PV resources are shown in Figure 1-1 for Timber Creek and Kalkarindji and Figure 1-2 for Doomadgee and Kajabbi. By comparing the figures it can be seen that Kalkarindji has the highest solar PV capacity factor of the four modelled locations.

Kajabbi has the highest renewable penetration overall when it is grid-connected and the least-cost option always includes some form of behind-the-meter renewable energy with a share of at least 50%. The Kajabbi off-grid modelling using 2040 capital costs has more 100% renewable systems when operating for 10% of days of the year compared to other locations. These systems include wind energy. Wind farms can operate at all hours of the day unlike solar, which means a shorter duration battery may be sufficient. This makes it more cost-effective to have a 100% renewable energy system.

If electricity demand is assumed to occur over only 10% of days of the year, which may be the case for pumping water during the wet season for example, then installing a diesel-only system is the overall least-cost option using current costs, but a hybrid system would be favourable in 2040 and with high diesel prices. If electricity demand is assumed to occur over 80% and 100% of days of the year, which may be case with a community power supply or mining operations, then the most cost-effective option would be either a 100% renewable energy system or at least a hybrid with more than 90% renewable energy. For electricity demand regimes of 30% and 50% of days of the year, hybrid systems are the preferred option, with a higher share of renewable energy using 2040 costs and with higher diesel prices. For a grid-connected system it is always preferable to include renewable energy and consume that energy but also export to the grid.

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