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Why are solar microgrids not the norm in remote Central Australia? Exploring local perception on solar energy and health

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A R T I C L E I N F O

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A B S T R A C T

Australia has immense potential to harness solar energy. Despite this potential, the electricity sector still contributes to one-third of the country's greenhouse gas emissions. Solar projects are important in remote Aboriginal communities because remote residents regularly face energy poverty and energy insecurity. Frequent power disconnections affect people's health and daily life activities. This study explores the enablers and barriers to solar energy adoption and the benefits of having solar microgrids in remote Australia.

Three sets of data, which included researcher observations and two sets of qualitative data were triangulated for the purpose of this study. Qualitative data included – i) virtual semi-structured interviews with professional and policy experts with experience in promoting and implementing solar projects in Central Australia and ii) one-to-one 'yarns' or community 'yarning circles' with Aboriginal residents of very remote communities of central Australia. The collected qualitative data were coded deductively, whereby similar codes were placed into broader themes.

Seven renewable energy industry and policy experts participated in the interviews. Thirty community members from across three very remote locations in central Australia were engaged through one-to-one yarning and group yarning activities. There is clear evidence from all three communities that the environmental costs of using diesel-powered generators are largely unknown to residents. While power costs and energy poverty were discussed as issues in the three communities, industry expert opinion was that residents' economic motivation to switch from diesel to solar power was masked by the fact that power costs were not dependent on the source of power, but were provided at subsidised rates in remote Australia. In general, community yarns were mostly around the need for energy security in remote households, rather than the need to switch to clean energy sources.

The study concludes that small solar microgrids and rooftop solar technology have the potential to improve energy and climate resilience in remote Australia. However, to effectively promote such investments in very remote settings, there is a need to appropriately engage with local community members and evaluate and communicate the overall social, environmental, and economic benefits of transitioning to solar.

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1. Introduction

Australia has immense potential to harness solar energy for electricity generation. Despite this, the electricity sector still contributes to one-third of the country's greenhouse gas emissions (Department of Industry Science Energy, 2021). As temperatures rise due to climate change, the electricity demand for cooling will also escalate (Emodi et al., 2018).

The need for clean energy solutions, energy-efficient homes and devices is becoming increasingly important and many Australian residents have already adopted measures to maintain comfortable thermal conditions within houses during summer by installing air conditioners powered by rooftop solar panels (Zander et al., 2021). However, energy-intensive adaptation measures are often not viable for remote households in Central Australia as remote residents endure low household income, poor housing infrastructure, overcrowding issues (Memmott et al., 2022), poorer health (Australian Institute of Health and Welfare, 2016), geographical isolation, and limited access to services including renewable energy infrastructure (Quilty et al., 2022a; Race et al., 2016). Also, the residents of remote Australia are disproportionately affected by energy poverty and extreme temperatures (Race et al., 2016). While solar homes and solar microgrids could be considered as an adaptation/mitigation solution for remote communities, many of these communities have little choice but to rely on diesel generators for their energy needs (Australian PV Institute). High photovoltaic potential or use of solar energy does not guarantee sustainable energy consumption (Isabelle dos Santos et al., 2024). For sustainable energy consumption, energy systems should satisfy human energy needs (i.e. eradicate energy poverty and enhance energy capability within environmental limits), ensure energy justice (i.e. ensure fair processes in policies and projects and fair outcomes of benefits and burdens), and respect environmental limits (i.e. achieve climate mitigation requirements, ensure environmental preservation) (Holden et al., 2021).

1.1. Central Australian context

The Central Australian region within the jurisdiction of the Northern Territory (NT) has a surface area of 551218 km^2 and a population of 40543 people (Regional Development Australia, 2021), most of whom are concentrated in the major service town, Alice Springs, and a small proportion dispersed across several very remote communities surrounding the town (Northern Territory Public Health Network, 2020). Aboriginal people constitute more than a third of the Central Australian population (Regional Development Australia, 2021). The very remote communities surrounding the town of Alice Springs are predominantly inhabited by Aboriginal people who experience a high burden of disease and a high level of socioeconomic disadvantage (Australian Bureau of Statistics (ABS), 2033).

Central Australia has a desert climate and experienced on average 113 (92–137) days with maximum daily temperatures $\geq$35 °C, and 32 (10–57) days with maximum daily temperatures $\geq$40 °C in the past five years (Bureau of Meteorology (BoM), 2023). In recent years, there have been instances where the annual number of hot days has surpassed the climate projections for 2030, 2050 and even 2090 under a high-emission scenario (NESP Earth Systems and Climate Change Hub, 2020).

Remote community residents rely on prepaid electricity meters and thus experience high levels of power disruptions and energy insecurity, which worsens during extreme temperature days (Longden et al., 2022a). Household energy demand also varies due to overcrowding issues (Race et al., 2016) and poor housing infrastructure (Memmott et al., 2022). In the NT, houses are currently built to a 5-star rating, while all other jurisdictions in Australia require a 7-star rating (Health habitat, 2022).

Another challenge in Central Australia is the discrepancy in the region's climate zone classification allocated by the Australian Building Code Board (ABCB) as having hot dry summer and warm winter (Australian Building Codes Board) compared to the actual climate zones for Central Australia, which is hot dry summer and cold winter (Bureau of Meteorology). This discrepancy means current building codes do not consider the demand for both heating and cooling in Central Australia (see Fig. 1 for extreme hot and cold day projections for 2050). An inability to afford increased demand for electricity during summer and winter is evident through high number of disconnections (91% of households experiencing at least one disconnection) that were recorded in 28 remote communities across the NT during the 2018/2019 financial year (Longden et al., 2022b).

Central Australia receives the highest global horizontal irradiation (sum of direct and diffuse irradiation components received by a horizontal surface), which is around 6.2kWh/m^2 per day (Energy Sector Management Assistance Program, 2020), but still has many remote communities reliant on diesel generators. VRemote communities closer to Alice Springs (e.g. within around 100 km) are connected to the town's grid, while very remote communities further away from the town are powered by either diesel generators or a mix of solar and diesel generators (NESP Earth Systems and Climate Change Hub, 2020).

There are environmental, economic (greenhouse gas emissions, ongoing maintenance, part replacement, and diesel fuel costs) and health costs associated with the use of diesel generators (Farghali et al., 2023). Around 25 million litres of diesel is used yearly to power regional and remote Aboriginal communities in the NT (Infrastructure Australia). The diesel generator operating costs from purchasing and transporting diesel to remote communities are excessively high compared to that in urban centres ($3.00 per litre in remote locations such as Hermannsburg compared to $1.89 in urban centres such as Sydney) (FuelPrice Australia, 2024). The combustion of diesel, results in the emission of fine particles with a diameter of 2.5 μm or smaller (PM2.5) that have been linked to heart diseases, respiratory infections, cancers, preterm births, and a range of other illnesses (Thangavel et al., 2022). A study that compared emissions of different Australian thermal power generation technologies found that diesel fired power stations emit the largest amounts of particulate matter (Strezov and Cho, 2020), emissions of which could be categorised as poor air quality (NT Environment Protection Agency). In these contexts, the present study aims to understand the barriers, drivers to solar energy adoption, and the environmental, health related and other societal benefits of using solar energy to generate electricity for remote communities in Central Australia. Using qualitative research approaches, this study documents the perceptions of local experts and residents living in very remote communities in Central Australia.

2. Data and methods

Three data sets were used in this study: (i) general researcher observations to capture key differences between each community if any related to the communities' climate and energy use context, (ii) one-to-one 'yarns' or 'yarning circles' with residents of very remote communities in Central Australia to capture local resident perceptions, and (iii) semi-structured interviews with government and non-government industry stakeholders and policy experts to capture practical challenges and drivers related to adopting solar energy in Central Australia.

Firstly, general observations about the community's lifestyle and general use of the community's outdoor space were made by the research team. Secondly, one-to-one 'yarns' or 'yarning circles' were conducted with community residents ($\geq$18 years of age) from three remote communities in Central Australia. Yarning has been used as a decolonising qualitative data collection methodology to engage with Aboriginal participants in research projects safely (Kennedy et al., 2022). Through the yarning sessions, researchers and participants build rapport and trust prior to the sharing of stories relevant to the research from their lived experiences (Walker et al., 2014). The yarning sessions were facilitated by a Central Australian Aboriginal researcher (GB) with more than five years of experience engaging with communities in Central Australia for research purposes. In each community, a male and/or female local Aboriginal community cultural expert who spoke the local language, lived in the remote community and was a respected local community member was employed. The extended research team included two qualitative non-Aboriginal researchers who are long-term local resident researchers (SM (>12 years) and MB > 2 years). Non-local senior Aboriginal researchers (VM and LF) provided advisory support to the local qualitative research team.

Three remote Aboriginal community sites were chosen for yarning and have been referred to as sites 1, 2 and 3 to ensure participants who live in communities with a small population size aren't identified. The three sites were selected to explore the diversity of energy provision models that exist in Central Australia and to understand whether community views converged or diverged based on their mode of energy supply. Site 1 was connected to the power grid of the service town, site 2 used a hybrid of diesel and solar powered energy, and site 3 was solely reliant on diesel power.

A topic guide related to the research objective was used for the yarning process. The topic guide aimed to cover Aboriginal community member's perceptions of outdoor temperature changes, effects of hot weather on Aboriginal people's health and daily activities, access to adaptation infrastructure such as cooling devices, enablers and barriers to clean energy adoption such as solar, and perceived benefits of clean energy. Before data collection, the research team conducted a workshop to ensure the local cultural expert was familiar with the research project and its objectives. The local cultural expert assisted the research team with the recruitment of community participants. The research team also recruited participants through the local shop and local art centre. Further to this, a snowball sampling approach (Etikan et al., 2016), where community members who participated in the interviews introduced the research team to other family and community members who they believed would be interested in participating in the research project was used. Community participants were provided a $20 prepaid power card voucher as a token of appreciation for their time participating in the project.

In each site, the local cultural expert sought consent for participating in the project and then initiated the data collection process through social yarning to establish connection with the participant (Burke et al., 2022). During the yarning sessions, the Aboriginal researcher respectfully oriented the conversation towards the research topic, while the two non-Aboriginal researchers who live and work in Central Australia took notes and prompted the Aboriginal researcher for any clarifications in the stories.

The third source of data used in this study was semi-structured virtual interviews conducted with government and non-government industry stakeholder and policy experts. The experts had expertise in renewable energy installations in remote Australia or worked in policy/advocacy roles related to the transition to renewable energy. These interviews aimed to understand the environmental, economic, health and other societal benefits of solar energy transition and enablers and barriers to solar energy adoption in Central Australian remote communities from an energy provider/policy maker perspective. The expert interviews were used to clarify or explore further some of the issues discussed by community members (von, 2023), as the expert interviews were conducted after community data collection.

The two qualitative data sets were analysed separately using a deductive approach against the topic guides. Connections and relationships between codes were studied and similar codes were placed under the major themes for both data sets (Azungah, 2018).

Human research ethical clearance was obtained from the Central Australian Human Research Ethics Committee (CAHREC) CA-22-4303.

3. Results

3.1. Researcher observations across study sites

The data collection was during the months of March, April and May 2023, which are not the hottest months in Central Australia. All visits were during weekdays or school days. Diesel or solar power plants were typically around 500 m away from community houses. Most outdoor areas within the communities, such as playgrounds or barbecue spots had limited vegetation or shading structures and were empty during the day. Local stores appeared to be busier after 10 a.m., while air-conditioned art centres seemed to be well used by female members of the communities throughout the day.

In terms of positive adaptation measures to hot weather, we (research team) observed that male residents had the habit of wearing hats. Considering local adaptation infrastructure, we observed that most old houses across sites had at least one large tree. We found elderly people sitting under shaded trees or on outdoor beds which were placed under tree shades. In terms of potentially maladaptive behaviour, we noted that residents wore dark coloured clothes. We observed community members purchasing readily available hot food and carbonated beverages from the local stores in the morning. We observed several families, including small children purchasing cold beverages from the store during the data collection period.

3.2. Community one-to-one yarns and yarning circles

In total, 30 remote community residents participated in the study (Table 1). This included 29 Aboriginal participants and one non-Aboriginal participant. The sample size in site 1 was small compared

Table 1
Research participates across the three research sites.

Site 1	Site 2	Site 3
3 women 3 men	5 women 4 men	12 women 3 men

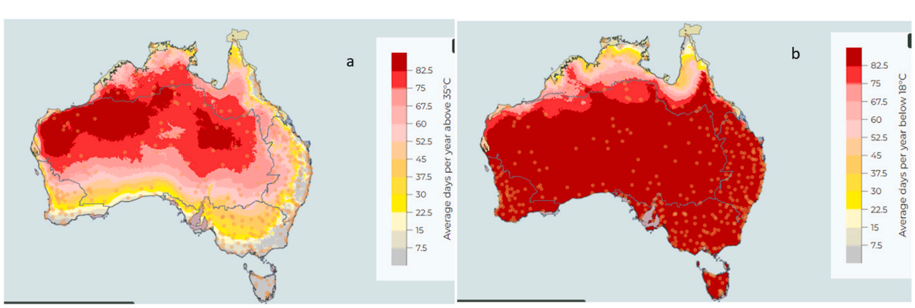

Fig. 1. Projected number of days with a) maximum temperature >35 °C and b) minimum temperature <18 °C under RCP 8.5 emissions scenario by 2050 during summer and winter periods respectively
Source: CSIRO and BoM thresholds calculator (CSIRO and Bureau of Meteorology).

to other sites as data collection in site 1 coincided with a major sports event in a neighboring community. Despite the low sample size, information saturation was achieved.

The responses were coded against four main themes: i) community perceptions of temperature changes; ii) adaptation to hot weather – challenges and solutions; iii) barriers and enablers to solar energy adoption; and iv) benefits of adopting clean energy.

3.2.1. Community perceptions of temperature changes

Majority of the remote residents highlighted that they had observed changes to recent weather patterns. In general, participants perceived the weather to be getting hotter. Specifically, the months of March to May, during which data was collected, were perceived to be warmer compared to the past weather ('olden days').

> "This time of the year, it should be cold with [people wearing] jumpers. It is really getting warmer. In the 60s and 70,s it was nice and cool [at this time of the year]" Site 1.1 (Site 1, participant 1)

3.2.2. Adaptation to hot weather – challenges and solutions

3.2.2.1. Adaptation practices for hot weather. In terms of adaptation measures, remote community residents adopted a range of strategies which included reliance on electric fans and air conditioners to cool houses, opening windows to moderate indoor temperatures, sleeping in the courtyard under tree shades at night, sitting under tree shades during the day, hosing down the ground with water, filling inflatable pools for children and visiting cooler public centres, such as the art centre or the local shop. Air conditioner use within homes was quoted as the most common adaptation strategy.

3.2.2.2. Challenges of depending on energy intensive adaptation practices. Some participants living in new tranisitonal homes thought that air conditioners were essential in every room as people not only used the lounge, but also used other rooms in a house.

> *"Air conditioners and fans only in the lounge, not in the rooms" Site 3.1*

Participants also referred to poorly maintained air conditioners that could not regulate the indoor temperature. During summer – *"Air conditioners do not work, no pressure, pushes hot air in [to the house]" Site 2.2.*

There were mixed responses concerning community-level power outages. Some participants recalled power outages (blackouts). Participants were aware of battery backups being used during unforeseen disruptions causing outages. Mostly, participants thought that if there was any power generation and supply issue, energy service providers fixed it quickly (within a few hours). A minority of Aboriginal respondents recalled power outages due to cyclones or the energy provider conducting uninformed maintenance works (even during summer).

> "*They (energy providers) don't update people, no notices" Site 2.1*

Across the sites, participants believed they paid too much for electricity, around \$200-\$600 a month. Electricity is purchased through prepaid 'power cards' at the local store and thus power cards have to be purchased within store opening hours. Some remote community stores were closed for half days on Saturdays and completely closed on Sundays, affecting power card purchases. For site 1, participants who worked in the nearby town mentioned that their households' power was mainly used by other family members while they were away, but they were able to top up power while at work in the service town.

> *We pay \$20 (\$20 power card) a day for power". Site 3.1*

> *"\$30 power card is for 3–4 days" Site 2.2*

Household sizes varied. At the time of the research visit, some 3-bedroom houses accommodated six adults and three kids, including infants. Participants highlighted that they have had instances where around 17 family members lived in a 3-bedroom house. Overcrowding in houses and the use of power by visitors were discussed as critical issues –*"some visitors come and go, they don't pay for power" site 2.1*

> *"More people in the house means more power … TV in each room, separate fridge, fan in each room, but one person paying for power" Site 2.2*

The need for uninterrupted power was highlighted as many households had infants, elderly people and even children reliant on electronics. Specific examples raised were a child with autism needing video game equipment charged all the time and another sick child who needed a continuous power supply for medical reasons.

> *"We have old sick people in our house, we try to keep the power going for them" Site 2.2*

High rental costs (about \$70-\$100 for a bedroom for a week) and high costs associated with running many energy-consuming devices such as air conditioners and fans in every room to maintain habitable indoor temperatures meant limited disposable income for community members. Some participants could not understand why they had to pay for both rent and power separately.

> *"We are paying for rent, why should we pay for power?" Site 2.2*

Participants felt that air conditioners stopped working frequently and people often had to wait a long time (weeks to months) to get them repaired. Participants were unsure who was responsible for fixing the air conditioners.

> *"We sleep outside during the summer if air conditioners break". Site 3.1*

> *"We make a bit of fire and sit near a fire during winter" Site 3.2*

*3.2.3. **Enablers and barriers to solar energy** adoption*

3.2.3.1. Community knowledge of solar projects. Participants in site 1 recollected a time when the community was powered by a solar power station. Some participants thought that the authorities may have stopped relying on power from the solar station due to low power generation, more cloudy days, the need for battery storage or the need to maintain the solar plants. None of the participants engaged in site 1 were aware of the actual reasons for solar power ceasing and did not recollect being consulted at any stage about it. One participant in the community also raised the issue of environmental waste related to the dumping of old solar panels from the community.

> *"Solar was here. We don't know what happened" Site 1.2*

> *"Solar doesn't charge as quickly as we need it to, there were two weeks of rain out here" Site 2.1*

3.2.3.2. Maintenance challenges in remote settings. Maintenance issues were discussed as barriers to implementing solar projects across sites. Some people also drew from their experiences visiting nearby outstation communities and highlighted that training was provided to local people to ensure on-going maintenance of the solar plants, but this was presented as insufficient.

> *"More support is required for maintenance of solar powered plants" Site 2.1*

3.2.3.3. Rooftop PV panels and their use. Across sites, most household hot water systems were powered by rooftop photovoltaic panels. At times, power from the main power system was accidentally used to heat water. Instances where kids played with the booster switches, consuming the entire power charge were reported.

"We tell the kids not to play with the switch [booster switch] … but they do to see the numbers and play [with the switches] and then [we have] no power in the house". Site 1.3

Participants believed that the time taken to heat water using solar was a barrier to its promotion by community members. Hot water requirements varied and depended on how many people lived in the house. Participants said -

"Someone washing their dishes, someone in the shower, then the water goes cold". Site 3.1

3.2.4. Benefits

Most respondents had seen operational solar plants in outstations or other communities. In general, there was consensus that solar systems were good for outstations and some wanted it in their community. Most participants did not directly link their responses specifically to the need for solar powered energy, but highlighted that it would be most beneficial to have power sources that enable uninterrupted power supply. There were no discussions around the environmental benefits of clean energy, despite prompting by the researchers.

"Solar is good for outstations. We are close to the town, so we are fine" Site 1.4

"Solar is great for outstations, that's what I want". Site 2.1

3.2.4.1. Power to keep homes thermally comfortable and refrigerators operational. Participants highlighted the need to maintain thermally comfortable homes and operational refrigerators as necessities. During power disconnections, food and medicines stored in the fridge had to be thrown out, adding to the overall household costs.

"Some people keep medicine in someone else's house when there is no power in their house". Site 3.2

3.2.4.2. Disruption to daily activities. Participants also spoke about the disruption caused by outdoor cooking within the community (e.g. smoke, dogs barking etc) when power cards ran out. Participants said –

"*On the weekend, when the power goes off, some people don't have power, they sit outside and build a fire and cook food". Site 3.2.*

"Cooking outside creates smoke from firewood and dogs barking cause disturbance in the community". Site 3.1

School-going kids were affected as they stayed up late at night waiting for cooked meals. Participants also talked about how power disruptions affected their family's sleep, daily activities, including participation in workforce activities as well as the ability to cook nutritional breakfast for their kids.

"If kids didn't get enough sleep, they go to school tired". Site 3.2

"[People] wake late in the morning and can't cook breakfast … we go to the local store to feed the kids.. get a hot pie" Site 3.2

These information from the community also validates some of the general researcher observations in terms of store use and local store purchases.

3.2.4.3. Economic benefits. A minority of participants preferred to have solar powered energy in the hope that it would save costs to purchase power cards. Generally, community members perceived solar hot water systems to be reducing their power related costs.

"Solar is good, saves dollars" Site 2.2

3.3. Industry expert interviews

A total of seven industry experts based in Central Australia were interviewed. The expert responses were placed under two major themes: (a) enablers and barriers to clean energy adoption and (b) benefits of clean energy in remote Central Australia.

3.3.1. Enablers and barriers to clean energy adoption in central Australia

Experts talked about a range of enablers to solar energy transition in the Northern Territory. A major enabler was the Northern Territory government's commitment to reach net zero emissions by 2050 and a target to source 50% of the Territory's electricity and 70% of remote community's electricity from renewable energy by 2030 (Northern Territory Government). This commitment from the government meant that energy providers and house owners were offered incentives for small to large scale solar projects and rooftop solar panels. The expert respondents acknowledged that the incentives for rooftop solar panels were not targeted at community residents living in social housing.

Aboriginal ownership of solar installations and investments were considered to enable the on-going sustainability of solar projects in remote communities. Specific examples where communities took pride in being part of modern technological installations and were keen to take ownership of clean energy projects were discussed. Experts thought that mostly Aboriginal community members and traditional Aboriginal landowners were aware that the benefits of solar projects would be in the longer term rather than immediate. Experts perceived some remote Aboriginal communities to be more receptive to renewable technology, particularly if neighboring remote communities had already adopted such technologies. Experts also perceived some communities to be influenced by the 'Not In My Backyard' (NIMBY) phenomenon (Devine-Wright, 2009; Petrova, 2013; Larson and Kranich, 2016) as Aboriginal members of specific communities did not disagree on the need or the benefits of having solar projects, but showed aversion towards having large external infrastructure in their communities.

Regarding motivation to switch from diesel powered generators to solar powered plants, experts thought that financial benefits were not a driver for Aboriginal community members. This was perceived to be because the net costs of power did not vary between diesel versus solar powered plants for remote residents. While diesel-powered electricity was expensive, power costs were heavily subsidised by the government due to the tariff equalization policy, which ensures that both town and remote residents in the Northern Territory pay the same rates per kilowatt hour. In general, expert participants thought that Aboriginal community members could be '*oblivious to the actual costs of power generation and thus may not see any financial benefits in switching to renewable energy' [x1]*.

High capital costs required for the initial infrastructure and transportation costs required for installations in remote Aboriginal communities were pointed out as the main implementation barriers as quoted by an expert participant

"Partly dollars in terms of people are more likely to have operational budgets rather than capital expenditure budgets. … those making the decisions are able to ask for operational budgets, you know, up and down based on cost increases and all that sort of stuff, than a capital expenditure budget to install renewables". [x5]

The potential role of philanthropic organisations, community-controlled organisations and private agencies as investors or co-investors was discussed as a potential way forward for solar project investments in remote communities.

Administrative and bureaucratic complexities related to the lengthy approval processes required for large scale installations, gaining access to land tenures and finalising Traditional Aboriginal Owners Land Use Agreements with Land Councils time and resources for environmental impact assessments and local community consultations meant medium to large scale solar projects were less attractive for many investors.

Limited availability of infrastructure (e.g. additional transmission lines) in remote Aboriginal locations, operations and maintenance challenges (e.g. absence of adequate knowledge to operate and maintain systems; time to get spare parts for maintenance and technical complexities (e.g. energy storage, ability to connect to existing grids without affecting the reliability of power supply)) were considered to be technical barriers. All experts resonated with the importance of local workforce development in remote communities, training and empowering local Aboriginal people to manage solar assets. The highly mobile nature of remote Aboriginal populations meant training was to be offered to multiple community members to ensure well-trained staff are available all year round.

> *"workforce development's been a lot more kind of importing labour from interstate and internationally to come and do this work, and then that knowledge and that capability just leaves when the project is finished and then it just becomes a drive in, drive out or a fly in, fly out maintenance of process with professionals who are trained as opposed to actually trying to really grow". [x5]*

3.3.2. Benefits of clean energy in remote Australia

Experts perceived reduced provider costs (cost of diesel and the cost of transporting diesel through unsealed roads) as the main benefit of switching completely or partially to solar. The *"vulnerability of the [diesel] supply systems and service systems to [extreme weather events such as] floods" [x3]* was also highlighted by an expert. The reduction in noise and air pollution associated with running diesel generators in communities was pointed out. The need for an uninterrupted power supply to meet the high health needs was highlighted by all expert participants. Key benefits for remote Aboriginal community members were highlighted as access to thermally comfortable houses, storage of food and medical supplies and the ability to stay within the community for treatment. The environmental benefits of switching to solar through reduced carbon emissions and reduced air pollution were also mentioned.

One of the expert participants highlighted the need to consider and plan effectively for the future solar waste likely to be generated by current and future solar installations in remote communities as in other locations. Experts perceived that community members had limited information on the environmental (e.g. air pollution and greenhouse gas emissions) and health (e.g. respiratory illnesses) costs associated with relying on diesel generators in remote Aboriginal community settings. All respondents agreed that there was a need to promote successful examples of solar project investments and highlight it's environmental and health benefits among Aboriginal community members residing in very remote Australia.

4. Discussion

The energy requirements of Aboriginal households in small off grid communities in Central Australia are exacerbated by the demand for both heating and cooling (Quilty et al., 2022a). People living in very remote communities of Central Australia are at risk of temperature extremes due to poor housing stock, poor housing maintenance, housing designs that do not match the local climate characteristics, overcrowding and a high burden of diseases (Memmott et al., 2022; Australian Institute of Health and Welfare, 2019). In addition to these, the dependence on prepaid power cards places remote households at risk of extended periods of power disconnection (Quilty et al., 2022b), unlike the postpaid system which is prevalent in regional and urban Australia. This study re-iterates all these issues and interestingly, the opinions of remote community members did not differ between communities powered by solar, diesel or connected through the town grid.

Despite Central Australia having a high PV potential, several reasons were listed on why diesel-powered generators continue to be one of the main sources of power in many remote Aboriginal communities. In line with other studies (Akinyele et al., 2018; Streimikiene et al., 2021), the remoteness of locations and large geographical distances from service towns, high capital set-up costs of solar infrastructure, its ongoing maintenance requirements, lack of skilled technicians and lack of community engagement and ownership were considered as barriers to the roll-out of solar microgrids in remote Australia. Limited awareness of the economic, environmental and health benefits of switching to solar was identified as another key barrier.

The discussions around health effects were not directly linked to switching from diesel to solar but were linked to energy insecurity. As noted in other studies (Quilty et al., 2022b), the health benefits of having a continuous supply of energy were linked to access to refrigerated food and medical supplies and thermally comfortable housing, which was highlighted as most important for the elderly, infants, people with medical conditions, particularly for those who prefer to stay in the community for treatment.

Disruptive sleep was quoted as an issue caused by poor thermal comfort within houses and is increasingly being reported as an issue globally (Minor et al., 2022; Zander et al., 2024). In this study, poor sleep was discussed to have wider socio-economic implications, including the inability of adults to contribute effectively to the local workforce and for school students to participate effectively in school activities. This is of significant public policy relevance, given there is low Aboriginal participation among working-age Australian population (48% of the Aboriginal and Torres Strait Islander population were unemployed, with higher rates reported in more remote areas (Australian Institute of Health and Welfare, 2023)) and low school attendance among Aboriginal students in remote Australia (just above 60% for Aboriginal students enrolled in primary and secondary schools in remote Australia (Australian Government, 2020)). Delayed start to morning routines also meant reliance on quick unhealthy choices for breakfast usually purchased from the local store, which has longer term health implications, particularly on chronic medical conditions (Australian Institute of Health and Welfare, 2019) such as diabetes and obesity. Post western colonisation, traditional food (high in protein, fibre and micronutrients) habits which were prevalent among Aboriginal people were forcefully replaced by Western diets (high in sugar, starch, fatty meat and salt) (Christidis et al., 2021). This study indicates that energy insecurity will further influence dependence on store bought readymade food and Western diets. There was a lack of vegetation in all three study sites. Greening of cities has been at the forefront of urban planning and has been found to reduce local urban temperatures and promotion of active lifestyles (Chong et al., 2019), but there seems to be limited focus on the use of culturally appropriate biophilic designs in remote communities.

Well-established health issues, such as the effects of air pollution caused by diesel generators were not raised as an issue by community members. This might be because air pollutants such as particulate matter are invisible to community members. There are no studies that have estimated the health effects of air pollution exposure on remote Aboriginal populations due to limited environmental monitoring in remote Australia (Mathew et al., 2023). This is evident in the study area as there has been no air quality monitoring in any of the three remote sites.

Experts highlighted the longer term economic and environmental benefits of transitioning to solar energy systems, but there was no mention of this by community members. While community members were concerned about the power costs, it wasn't discussed in the context of the actual economic costs of diesel-powered energy in remote communities. It is important to also note that most remote community members are not eligible for the NT government concessions for electricity (Northern Territory Council of Social Service, 2023). Experts perceived that while remote communities would prefer to reduce household power consumption and costs, there may be little financial incentive for community members to switch to solar unless solar power is distributed at much cheaper rates than diesel-generated power.

Currently, power costs are independent of power sources and heavily subsidised by the government to account for the equal tariff policy.

Regarding the environmental costs of diesel-generated power, there was no reference to greenhouse gas emissions, only a mention of the waste left in communities from abandoned solar projects or faulty rooftop solar panels. Solar waster is also an important factor to consider as if solar panels are not properly disposed of, old solar panels could disintegrate releasing harmful chemicals that could leach into the ground contaminating soil and water (Frischknecht et al., 2016), potentially affecting the availability of potable water in remote communities. While, disposal of solar e-waste is a growing challenge globally, with costs for recycling (excluding transportation costs) estimated in the United States to be $15-$45 per module (US Department of Energy, 2022). These costs are likely to be much higher in a remote Australian context due to the large distances to recycling facilities.

Aboriginal populations care for the environment and maintain strong connections with the environment, which also directly influences a community's health and well-being (Verbunt et al., 2021) This study highlights procedural injustice as local community members weren't aware how different sources of power affect the environment or weren't across decisions regarding sources of power for their community. Socio-economic inequality has also been shown to affect access to low-carbon options (Kukowski and Garnett, 2024). While, top-down governance approaches (e.g. government commitment to reduce carbon emissions, funding from various government levels) could drive investments in remote Australia, bottom-up approaches that include adequate community consultations, co-financing of solar projects with local community-controlled organisations, group training of local community members to enable on-going maintenance of solar projects and promotion of the actual range of benefits of having solar microgrids are equally important. Such initiatives are underway in the NT, with the establishment of the First Nations Clean Energy Network, its advocacy and support for prototype projects showing the benefit of rooftop solar on remote community housing (First Nations Clean Energy Network). For very remote communities, the feasibility of expanding the use of rooftop solar beyond powering hot water systems needs to be explored.

The use of diesel generators is justifiable as an emergency backup for remote communities, but complete dependence on diesel presents a significant public health concern as it presents energy insecurity issues and exposure to combustion fumes, which remains unmonitored in remote communities.

Resilient clean energy systems, such as solar microgrids, have the potential to improve the health and well-being of Aboriginal people, including reduced exposure to heat and air pollution, and providing opportunities for increased participation in education, employment, and ability to stay on Country for medical care. Ensuring clean energy power costs are minimal to remote households is essential for health and wellbeing and proper socio-economic participation of remote Australian residents. The study findings align with the concept of sustainable energy consumption (Isabelle dos Santos et al., 2024) and highlights complementing the use of renewable energy sources with other functional aspects, including costs, consumer attitudes, and energy efficiency.

4.1. Strengths and limitations of the study

The strength of the study is that it includes perceptions of community members as well as local experts (renewable energy experts and policy makers). The limitation of the study is that it is mainly based on the perceptions of the respondents and does not include local quantitative evidence of costs (e.g. economic costs of solar vs diesel power in remote Australian contexts) or air pollution caused by diesel generators (e.g. PM emissions from diesel plants as opposed to solar plants).

In terms of future research, the social, environmental and economic costs and benefits of diesel versus solar microgrid systems versus hybrid systems need to be compared, explored and quantified for remote Aboriginal Australians using a life cycle approach. Local environmental data should be publicly available for everyone, independent of whether people reside in remote or urban locations. The overall costs and benefits of solar microgrid systems vs diesel-fired energy generation need to be researched and communicated to remote Aboriginal communities as advocacy for the right energy sources should be led by well-informed community members.

5. Conclusion

Solar microgrids and rooftop solar panels have the potential to improve climate resilience by improving energy security and reducing off-grid communities' reliance on diesel-powered generators. The study points towards a range of direct and indirect social, environmental and economic costs and benefits of transitioning to solar energy. The overall costs and benefits of clean energy need to be communicated to local residents, which will empower off-grid communities and organisations to make informed decisions and participate in the most suitable clean energy supply arrangements. The health and well-being of people, particularly Aboriginal and Torres Strait Islander people are interlinked to the local environment and thus local residents should be involved in all policy decisions affecting their communities and the local environment.

We recommend environmental monitoring, pre and post-implementation evaluation studies of existing solar projects or immediate trials of new projects, comparing the environmental, societal and health costs and benefits of switching to clean energy in off-grid settings across the globe, adequate community engagement and dissemination of the findings.

CRediT authorship contribution statement

Supriya Mathew: Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Manoj Bhatta:** Writing – review & editing, Investigation, Data curation. **Gloria Baliva:** Writing – review & editing, Investigation, Data curation. **Veronica Matthews:** Writing – review & editing, Funding acquisition, Data curation, Conceptualization. **Kerstin K. Zander:** Writing – review & editing, Funding acquisition, Conceptualization. **Amelia L. Joshy:** Writing – review & editing, Investigation. **Rishu Thakur:** Writing – review & editing, Investigation. **Catherine Joyce:** Writing – review & editing, Investigation. **Linda Ford:** Writing – review & editing, Funding acquisition, Conceptualization. **Shiva Nagendra:** Writing – review & editing, Funding acquisition, Conceptualization. **Krishna Vasudevan:** Writing – review & editing, Funding acquisition, Conceptualization. **Jimmy Cocking:** Writing – review & editing. **Sotiris Vardoulakis:** Writing – review & editing, Project administration, Investigation, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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