



Energy insecurity during temperature extremes in remote Australia

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Indigenous communities in remote Australia face dangerous temperature extremes. These extremes are associated with increased risk of mortality and ill health. For many households, temperature extremes increase both their reliance on those services that energy provides, and the risk of those services being disconnected. Poor quality housing, low incomes, poor health and energy insecurity associated with prepayment all exacerbate the risk of temperature-related harm. Here we use daily smart meter data for 3,300 households and regression analysis to assess the relationship between temperature, electricity use and disconnection in 28 remote communities. We find that nearly all households (91%) experienced a disconnection from electricity during the 2018–2019 financial year. Almost three quarters of households (74%) were disconnected more than ten times. Households with high electricity use located in the central climate zones had a one in three chance of a same-day disconnection on very hot or very cold days. A broad suite of interrelated policy responses is required to reduce the frequency, duration and negative effects of disconnection from electricity for remote-living Indigenous residents.

Indigenous communities in remote Australia face temperature extremes that can increase their use of electricity and amplify their risk of being disconnected. Energy is a necessary resource for work, education, participation in social life and for maintaining healthy living practices at home^{1–6}. Energy insecurity remains a pressing issue globally, including in countries with an abundance of wealth and resources^{4,7–10}. It can be defined as ‘an inability to meet basic household energy needs’⁵ and is broadly synonymous with the concept of energy poverty^{11–13}. Insufficient access to energy has been linked to poor health (both mental and physical) as energy is required to maintain essential services, including food security, lighting, essential medical equipment and thermal comfort/safety during extreme weather^{4,5,14–22}.

There is a need to better understand the extent of energy insecurity experienced by Australia’s remote Indigenous communities, in particular the role that temperature plays in shaping energy insecurity. The vulnerabilities associated with energy insecurity vary spatially on the basis of underlying characteristics, which can be highly regionalized and locally specific²³. Socio-economic, demographic and behavioural factors, as well as occupancy and structural characteristics (including the size, type and quality of housing stock and appliances), are all key drivers of energy consumption; while the prevailing temperature can affect the security of electricity supply due to the cost of heating or cooling^{24,25}.

Temperature extremes are likely to act as a risk multiplier, worsening energy insecurity for those at greatest risk as ‘vulnerable households typically live in poorer quality housing, and have least resource or opportunity to invest in improvements to its efficiency and heating technology’⁶. The importance of access to energy has prompted governments worldwide to implement policies maintaining this access, many with special attention to reducing the health effects of heat and cold^{7,26,27}.

The climate of the Northern Territory (NT) ranges from equatorial and tropical regions in the north to hot dry grassland regions in Central Australia (Fig. 1a). Remote Indigenous communities in the NT are mostly off-grid and unregulated by the guidelines of the Australian Energy Regulator²⁸. In a situation unusual in Australia, remote living residents prepay for access to electricity and regularly experience disconnection on non-payment. Distant from Australia’s urban centres and major electricity grids, these communities have long relied on diesel and gas-fired generators. In recent years, there has been incremental integration of renewable energy into these isolated, high-cost electricity networks.

Australia’s remote Indigenous communities face some of the highest temperatures nationally and are vulnerable to the effects of a warming climate (Fig. 1b–d)²⁹. Exposure to extreme temperatures has been associated with a range of adverse health outcomes and death^{22,30–33}. In the three hottest climate zones in Australia, between 4.5 and 9.1% of all deaths were associated with heat-related mortality, which is an estimate that is much higher than in other Australian regions (2% nationally)³¹. The challenge of maintaining thermal comfort and safety during temperature extremes is a pressing issue for author N.F.J.: “We can’t do anything about climate change except turn the power up, but it costs a lot too, don’t forget that. Electricity, you’re using more power when you turn that air conditioner up!” Temperatures over 35 °C, and even over 40 °C, are increasingly common in the NT as the climate changes (Fig. 1d). There is a need to better understand how extreme temperatures already shape the experience of energy insecurity in remote Indigenous communities.

Because of the health implications of energy disconnection and the subsequent loss of essential services, there are questions around how strongly disconnection events relate to temperature and whether disconnections occur more frequently during extreme

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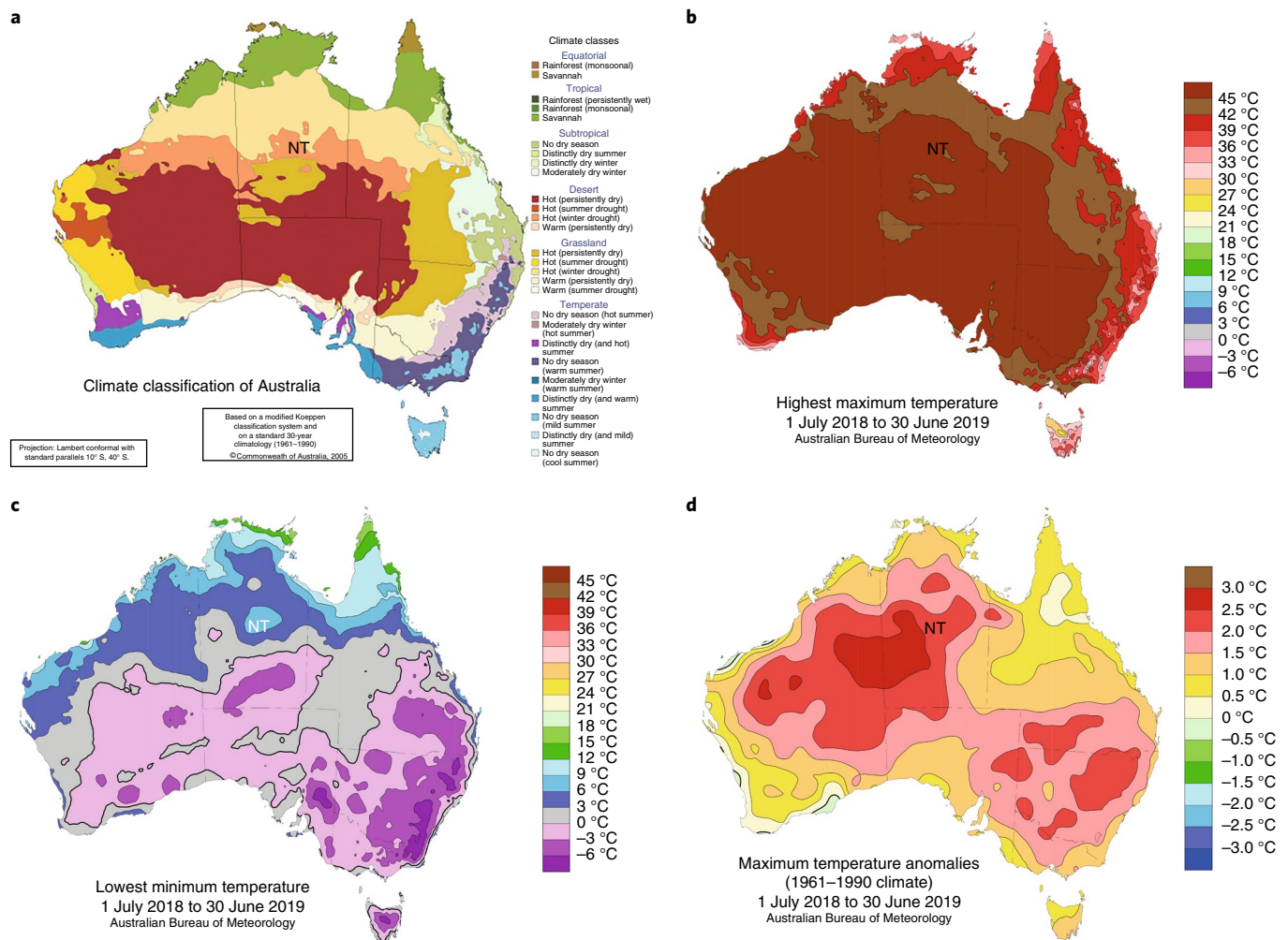


Fig. 1 | NT compared with other Australian regions. **a**, Climate zones. **b**, Highest maximum temperatures. **c**, Lowest minimum temperatures. **d**, The 12-monthly mean maximum temperature anomaly for Australia compared with 1961 to 1990. Panels reproduced with permission from the Australian Government Bureau of Meteorology under [Creative Commons license CC-BY 3.0 AU](#): **a**, ref. ⁷³; **b**, ref. ⁷²; **c**, ref. ⁷⁴; **d**, ref. ⁷⁵.

temperatures. In this paper, we assess the relationship between temperature, electricity use and disconnection using daily smart meter data for 28 remote Indigenous communities in the NT, all of which are using prepayment metering. We then present how many disconnection events occur during example temperatures to indicate the extent and severity of energy insecurity attributable to temperature extremes. Quantification of energy insecurity and how it is related to temperature thresholds could support future policy responses.

Energy injustice and a history of policy exceptionalism

Similar to Indigenous peoples worldwide, communities in the remote NT have long been at greater risk across the three dimensions of energy injustice. Energy justice is concerned with the distribution of costs, benefits and risks in energy transitions and is a principle that arises from theories of distributional justice^{2,6,9,34–37}. Distributional injustices in energy systems can be produced by systemic inequalities that arise from ongoing procedural injustices (which is a concept rooted in the failure to accord some groups of people equal rights and respect)³⁸ and recognition injustices (when certain groups face a lack of cultural respect and are excluded from decision-making)³⁹. Procedural injustices extend to differences in legal rights; distributional injustices are reflected in differences in the quality of housing that affects energy use; and injustices in recognition include a lack of acknowledgement of the unique needs

of specific communities, including those associated with energy access, use and practices¹⁶. Some groups, such as remote Australian Indigenous communities, consistently have less access to energy efficient housing, less ability to shape the electricity systems that they are connected to and less ability to pay for higher electricity costs that may result from certain systems^{6,9}. These aspects tend to be intertwined.

For author V.N.D., who works on issues related to energy, housing and social justice in Central Australia, maintaining access to electricity during temperature extremes represents a complex suite of interrelated challenges: “Older houses had solar hot water and pot belly stoves for the winter. We could collect wood and the sun heated the water. The new houses built by the Government since the Intervention (in 2007) have electric hot water heaters and no pot belly stoves. When the old houses were upgraded, pot belly stoves were removed. Our houses don’t have heating anymore. Most residents don’t have much money, so residents buy cheap fan heaters and air-cons. The problem with these is that they are expensive to run. Our houses have become expensive to heat and expensive to cool and we run out of money for electricity. When the power goes off it is bad for our health, the food gets spoiled, we can’t wash our clothes and we can’t wash our kids.”

Residents of remote communities live in extremely challenging socio-economic circumstances and in housing that can be extremely

crowded (see Supplementary Table 1 for example statistics from the 2016 census). Housing quality is often poor across these remote communities. Approximately half of Indigenous households in the NT fall below the poverty line. The National Indigenous Reform Agreement (Closing the Gap), the core of the Australian Government's agenda to address social and health inequities facing Indigenous Australians, identifies 'healthy homes' as a key priority for healthy living practices^{40,41}. Nine priorities are identified, with six pertaining to electricity systems, which are power connection, electrical safety, heating for showering, facilities to wash children, laundry facilities and facilities to store food and prepare food (including refrigeration)⁴¹.

Moreover, Aboriginal and Torres Strait Islander peoples have experienced frequent changes in the policy environment regulating their lives and lands, via a non-Indigenous regime of law. Many communities in the NT have been subject to frequent changes in regulatory practices for electricity and regressive changes in procedural and recognition justice aspects, such as cycles of gain then subsequent loss of representation in governing bodies³⁷. Some of this complex regulatory and legislative history is summarized in a non-exhaustive timeline of key developments in policy affecting Indigenous peoples in the Territory between 1967 and 2021 (Fig. 2). This includes the unilateral introduction of a 'user-pays' model for energy provision in 1992. Author and Warumungu elder N.F.J. has lived experience of these deep structural imbalances that impact, too-often detrimentally, on the lives and livelihoods of Indigenous communities in the NT: "I reckon the Government doesn't want to listen to Wumpurrarni (Indigenous) people because I reckon they've had enough and they're just ignoring us now, they think we get everything for free but we struggle for that. Policy is like a bible, for Government, it tells them how they run things, how they can do things. If they don't have a policy, they don't know how things run. And if they have a policy they can jam you and that's what happens to us, they jam us all the time."

Limited protections and prepaying for power in the remote NT

Prepayment for electricity is uncommon in urban Australia. It is heavily regulated in most jurisdictions on the basis of concerns for wellbeing^{42–45}. It remains disproportionately common in small and widely dispersed remote communities across the NT, Queensland, Western Australia and South Australia. In the NT prepayment is not limited to urban town camps and remote communities. It is also used in urban and regional settings, including Darwin, Palmerston, Nhulunbuy, Katherine, Tennant Creek and Alice Springs. Many of these communities have prepaid electricity services as their only option for service provision⁴⁶. There is considerable variation in the operation of services and available protections for prepayment consumers subnationally. As an example, in other parts of Australia where consumers are protected by the Australian Energy Regulator guidelines, people cannot be disconnected from electricity when life support medical equipment is being used⁴³. This protection is not comprehensively applied in remote NT communities^{47,48}.

In previous international studies, rates of disconnection among prepayment households ranged from 10% to 53% for the UK, Germany and New Zealand^{49–52}. Prepayment disconnection numbers for Australia are not systematically collected or reported by regulators or providers and estimates are scarce. Previous analysis in the NT found prepayment disconnection rates between 59% and 91% (ref. ⁵³). In comparison, the rate of 'raised disconnections' for postpayment households in other Australian regions that are most at risk of disconnection ranged from 3% to 30% with large variation in disconnection rates associated with local and regional socio-economic characteristics and whether smart meters were commonly used⁵⁴. The St Vincent de Paul Society and Alviss Consulting report defines a 'raised disconnection' as the case when

a 'retailer raises a service order with the relevant network business'. These raised disconnections may be rejected, cancelled or completed. They may be rejected on the basis of an invalid address or when disconnection is prohibited for medical reasons. And the disconnection request can be cancelled by the retailer when the payment issue has been resolved. This can be a full payment or the establishment of a payment plan⁵⁴. These rates of disconnections are the higher end of estimates as they are those that were found for the top 30 postcode regions from four Australian areas (that is, New South Wales, Victoria, South East Queensland and South Australia). Across the eastern (and most populous) parts of Australia, the rate of completed disconnections for postpayment households was 1% (ref. ⁵⁵).

While data are scarce, issues with prepayment and disconnection in other regions of Australia have been noted by key organizations, including the Essential Services Commission of South Australia⁴⁴, Energy and Water Ombudsman New South Wales⁴⁵, the Queensland Council of Social Service⁵⁶ and Bushlight⁴⁶. The last two raised these concerns specifically in relation to remote Indigenous communities.

Disconnection as an indicator of energy insecurity

While energy insecurity describes more than disconnection rates alone, having an electricity connection is the first part of being able to access electricity to meet household energy needs. Here we assess disconnection rates as a proxy for energy insecurity, while noting that other factors also contribute to the disconnection rates observed. This may include housing design, construction and insulation; sociodemographic factors such as income and health; and entrenched regulatory structures.

When the households in our dataset run out of credit, they face immediate disconnection between 10:00 and 14:00. Outside these hours, credit is extended and the accumulated debt is automatically deducted from the subsequent purchase of energy credit. Energy services are not recommenced until the accrued debt is paid⁵⁷.

For the houses in our study with complete data for the 2018–2019 financial year (July 2018 to June 2019), 91% of households experienced a disconnection. Most disconnections were same-day disconnections (92% of the total) where the meter was reconnected when credit was restored on the same day. A total of 71% of households experienced a same-day disconnection more than ten times in a 12-month period. These rates of disconnection are much higher than Australian and international examples (mentioned above). On average, a same-day disconnection lasted for almost 3 h. Multi-day disconnections were less common (0.9% of days), but two thirds of households experienced this type of disconnection, which lasted overnight or longer. Of all households, 7% experienced a multi-day disconnection more than ten times in 1 year. These disconnections could last for many days (the all-region average was almost 4 days). Table 1 shows how these disconnections differed by climate zones.

Electricity use during temperature extremes

To confirm our expectation that temperature affects electricity use, we used linear regression with panel-corrected standard errors to provide estimates for seven daily temperature ranges. These temperature ranges are specified in the regressions as the daily average temperature for the same day as electricity use and the daily average temperature for the 2 days before. We estimate these regressions for all climate regions pooled together, and for each climate region separately. The regressions were also estimated for all houses and then re-estimated for different levels of the average daily use of electricity. Our data did not include any information on household characteristics, so we have used the average level of daily electricity use to group the households. Determinants of the average daily load include occupancy and the use of appliances. For more information, refer to the methods section for more details on the grouping of households with high/low electricity use.

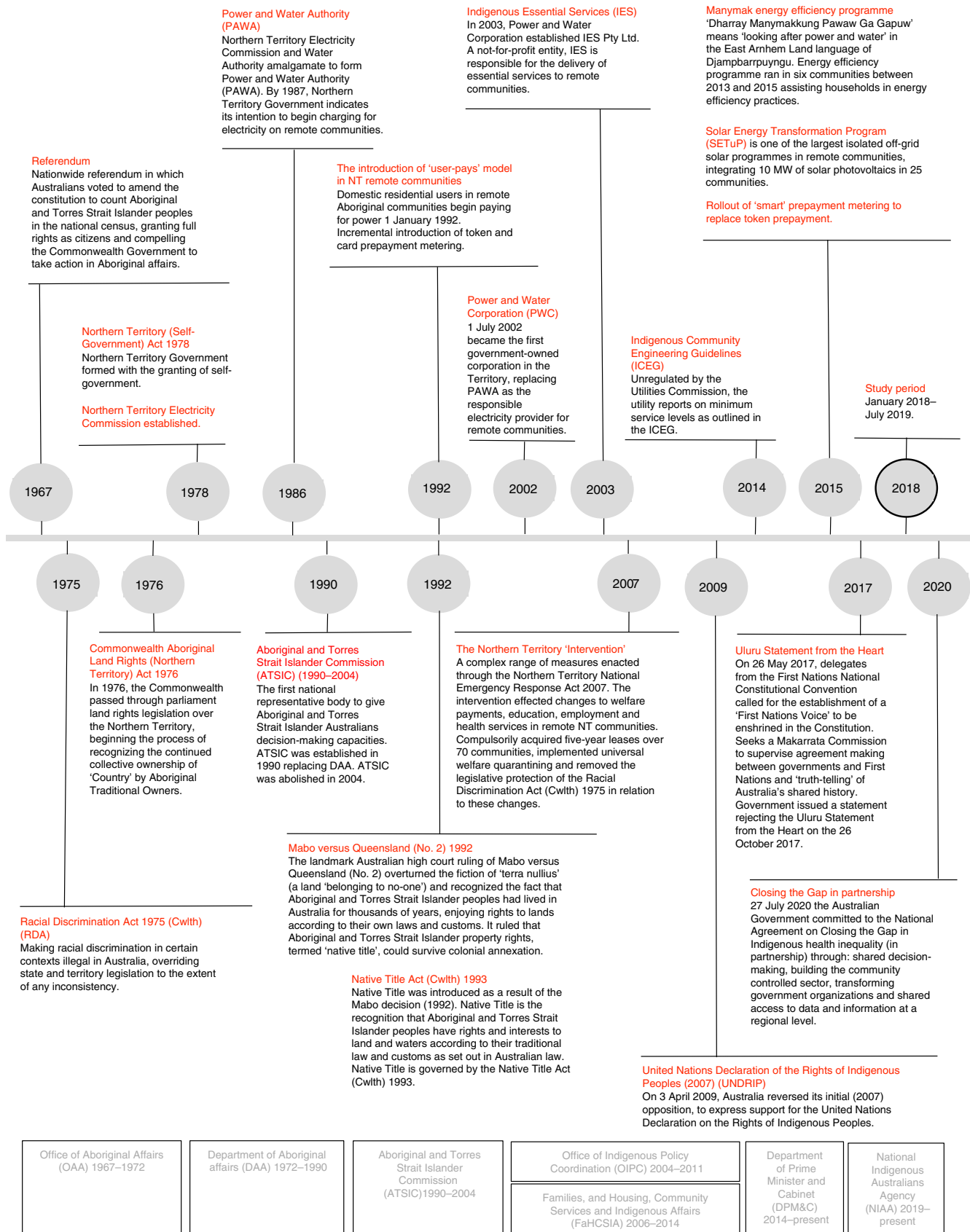


Fig. 2 | Timeline of the complex history of Indigenous policy in Australia. Key developments in Indigenous policy, including remote community energy policy, between 1967 and 2021. Boxes at the bottom are the federal departments or agencies responsible for Indigenous policy.

Table 1 | Disconnection rates by climate zone between July 2018 and June 2019 (*n* = 1,045,725)

	Equatorial climate zone (most northern)	Coastal tropical climate zone	Savannah tropical climate zone	Hot persistently dry grassland climate zone (most southern)	All regions
Same-day disconnections					
Percentage of households experiencing a same-day disconnection at least once	85	94	90	90	89
Percentage of households experiencing a same-day disconnection at least ten times	60	77	75	75	71
Percentage of days in the sample with a disconnection	7	11	11	10	10
Average length of disconnection (hours)	2.92	2.89	2.69	2.19	2.67
Multi-day disconnections					
Percentage of households experiencing multi-day disconnection at least once	47	68	71	83	66
Percentage of households experiencing multi-day disconnection at least ten times	2	4	9	16	7
Percentage of days in the sample with a disconnection	<1	1	1	2	1
Average length of disconnection (hours)	102.23	87.82	73.29	125.49	98.48
Any type of disconnection					
Percentage of households experiencing any type of disconnection at least once	87	95	91	92	91
Percentage of households experiencing any type of disconnection at least ten times	63	80	78	78	74
Percentage of days in the sample with a disconnection	7	11	12	12	10
Average length of disconnection (hours)	8.60	8.46	8.39	17.66	10.62
Daily electricity use and expenditure					
Daily electricity use (kWh) (s.d.)	21.25 (16.46)	23.29 (15.24)	25.73 (16.86)	26.95 (22.05)	24.13 (17.75)
Daily expenditure (AUD\$) (s.d.)	6.09 (4.71)	6.67 (4.37)	7.37 (4.83)	7.72 (6.31)	6.91 (5.08)
Count of observations for balanced panel for 2018–2019 financial year	306,600	229,585	296,380	213,160	1,045,725

The regression estimates confirm that electricity use differs notably by temperature, climate zone and month (Fig. 3). Estimates for temperature-related increases in electricity use are shown in Fig. 3, with the number of days that these temperatures occurred and the estimates for the monthly change in electricity use (without the daily temperature effect). These estimates for temperature and monthly effects should be interpreted in relation to the reference temperature range (daily average temperatures between 20°C and 25°C).

Given that the climate across the northern half of the NT is characterized by tropical heat (and mild cool nights only during a short winter season), daily electricity use was on average higher in the hottest periods of the year (November to March). This seasonal increase in electricity consumption was most pronounced in high-use households, which also experienced a reciprocal reduction in monthly electricity consumption in the cooler months. As expected in the NT, which generally has a prevailing hot climate, household energy expenditure is greatest during hotter weather due to the need for cooling.

Beyond seasonal effects, the need for heating and cooling can influence the daily use of electricity. The hot persistently dry grassland climate zone is the region that predominantly determines the all-regions result (Fig. 3b). It is the combination of the Central Australian climate zones shown in Fig. 1a. For this climate zone, which unlike the other regions experiences cold nights, the

households with the highest electricity use (top tenth percentile of average daily load) increased their electricity use by 30 kWh (on average) on the coldest of nights (between 0°C and 10°C). The average increase was 17 kWh across all houses in this climate zone. Extremely hot days with average temperatures between 30°C and 40°C corresponded to a 16–19 kWh increase (on average) for the households with the highest electricity use. When considering all houses, the average increase was 6–8 kWh.

Disconnection during temperature extremes

To assess the question of whether temperature influences the probability of disconnection, we used random-effects probit regressions to estimate the probability of same-day and multi-day disconnections. Figure 4 shows the estimates for temperature-related increases in the probability of a same-day disconnection, which includes daily estimates and the estimates for the monthly change in disconnections (without the daily temperature effect). The estimates are interpreted in relation to a reference temperature range (daily average temperatures between 20°C and 25°C). These estimates are also re-estimated by the level of electricity use and climate zones.

The probability of a same-day disconnection occurring on any given day (except during weekends and public holidays when disconnection is prohibited) is high (0.04–0.06) and increases on the first day that credit can expire, predominantly the next business day (approximately 0.19). This is captured in our results, with a large

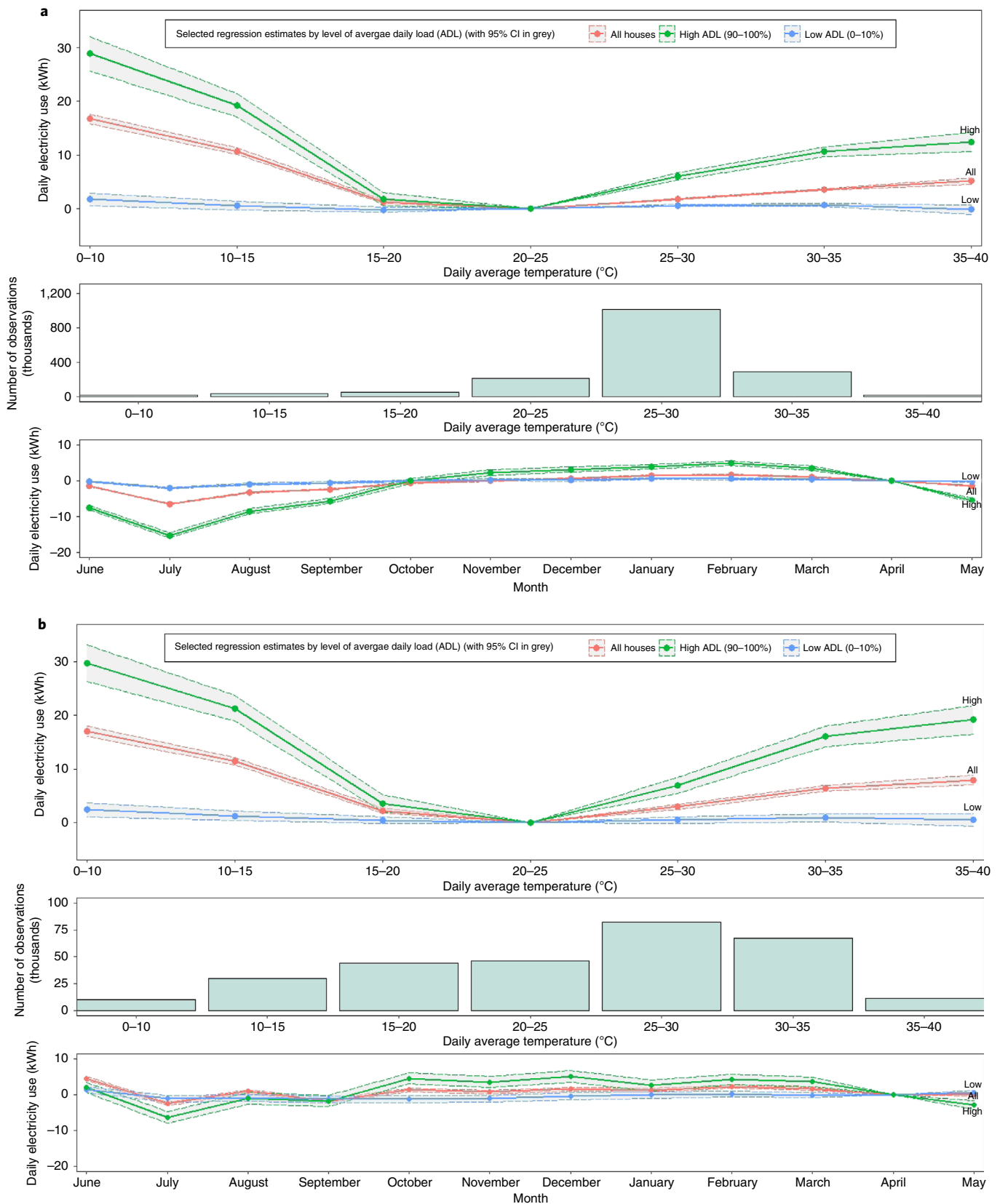


Fig. 3 | Daily electricity use by temperature and month. a, All regions. **b**, Hot persistently dry grassland climate zone. These are the coefficient estimates and 95% confidence intervals from multiple regressions for a sample with 1,674,786 daily observations across 3,300 houses. Regressions were grouped by percentile of electricity use (that is, average daily load) and climate zones. Estimates for all houses, low-electricity-use households and high-electricity-use households are shown here (Supplementary Tables 2–6 have all of the electricity use estimates). Temperature bins are specified using daily average temperatures (in °C). Temperature-based estimates are for a three-day period (that is, temperature on the day of electricity use and the two days before). Temperature estimates are interpreted using 20–25 °C as the reference temperature range. Monthly estimates are interpreted using April as the reference month.

increase in disconnections occurring on Monday and the day after a public holiday (Fig. 4). There is a significant relationship with temperature that is most notable for the households with the highest electricity use in the two southern climate zones.

For the full sample, there was a one in seventeen chance (probability of 0.06) of a same-day disconnection occurring on moderate days with average temperatures between 20°C and 25°C. This increased to a one in eleven chance (probability of 0.9) on hot days with average temperatures between 35°C and 40°C. A series of cold nights had a significant effect with an almost one in six chance (probability of 0.18) of a same-day disconnection occurring on cold days with average temperatures between 0°C and 10°C.

The households with the highest electricity use had a much greater probability of same-day disconnection. For this group, there was almost a one in seven chance (a probability of 0.15) of experiencing a same-day disconnection on moderate days with average temperatures between 20°C and 25°C. This increased to one in three (probability of 0.35–0.39) for the coldest temperatures (0°C to 15°C) and one in four (probability of 0.24 to 0.27) for the hottest temperatures (30°C to 40°C).

Climate zones also influenced the probability of a same-day disconnection occurring (Fig. 4b and Supplementary Information). For households with the highest electricity use in the southern-most climate zone (that is, hot persistently dry grasslands shown in Fig. 4b), a one in seven chance (probability of 0.14) of same-day disconnection for temperatures between 20°C and 25°C, increased to one in three (probability of 0.31) for the coldest temperatures (0°C to 10°C) and one in four (probability of 0.23) for the hottest temperatures (30°C to 40°C). For the households with the highest electricity use in the savannah tropical climate zone, there was a one in four chance (probability of 0.23) of disconnection for temperatures between 20°C and 25°C, which increased to one in three (probability of 0.37 to 0.39) for the hottest temperatures (3°C to 40°C).

Only a weak relationship between temperature and multi-day disconnections was found. The estimation results are provided in Supplementary Table 12. While rarer (approximately one-tenth as common), multi-day disconnection events lasted for an average of 4 days (Table 2).

Number of disconnections during temperature extremes

Temperature-related disconnections are driven by an increased need for electricity to maintain thermal comfort and safety during extreme temperatures. We now focus on the proportion of disconnections that occurred during hot and cold temperatures for two reasons. First, these are critical events where expenditure on energy has increased due to cooling/heating, leading to a disconnection that compromises the other functioning of the home, including refrigeration, lighting and life support medical equipment (for example, oxygen concentrators, sleep apnoea machines, home renal dialysis equipment). Second, there is a concern about the impact on health. Protections internationally include several examples of restricting disconnection for vulnerable customers, including on the basis of health risks and outdoor temperatures^{7,26,48}. These protections can include disconnection prohibitions based on the time of year (for example, no disconnections during winter months in cold climates), on reaching specific temperature thresholds, and on declarations of

extreme weather events (for example, no disconnections during a declared heat wave event)²⁶. Using example temperature thresholds to determine the number of temperature-related disconnections, we find that over 49,000 incidences of disconnection (29% of disconnections) occurred during hot and cold temperature extremes (Table 2). We examine both 35°C and 40°C as the threshold for extreme heat.

Discussion

We begin to address the need to better understand how temperature affects energy insecurity in Australia's remote communities by examining (1) whether temperature affects electricity use, (2) whether temperature influences the probability of disconnection and (3) the proportion of temperature-related disconnections (that is, disconnections that occur during extreme temperatures). Temperature is confirmed to effect electricity use. Correspondingly, disconnections are more likely during extreme temperatures. We find that in the 28 remote Indigenous communities that are the focus of this study, disconnections increase from an already high baseline of one in seventeen during mild temperatures (20–25°C), to a one in eleven chance of disconnection during hot days (34–40°C) and a one in six chance during cold days (0–10°C). Disconnection occurs more frequently for households with the highest electricity use in the central climate zones, which had a one in three chance of a same-day disconnection on very hot or very cold days. This indicates that households are having trouble cooling/heating their homes, which in turn compromises access to other essential services including refrigeration, lighting and essential medical devices. While the level of energy service that is viewed as 'essential' can vary over time and with changing social norms⁵⁸, a complete loss of access to energy services constitutes a level of energy insecurity that can harm wellbeing². In the financial year July 2018 to June 2019, disconnection was experienced by 91% of households in the remote NT communities that we have data for.

There are multiple levels of energy injustice in remote Indigenous Australia, and the effects of climate change will exacerbate pre-existing energy insecurity and subsequent effects on health and wellbeing. In considering how to address these issues, it needs to be recognized that there is a disproportionate prevalence of prepayment metering in remote Indigenous communities compared to the rest of Australia⁴⁶. There are questions about whether prepayment is a good option for remote communities that already face compounding distributional injustices. While some studies find that prepayment may be preferred to the accrual of unsustainable debts^{50,51}, this is only a weak endorsement of prepayment when compared to worse options. The framing of household electricity payment for communities needs to be extended beyond individual fiscal responsibility to incorporate a broader economic lens that accounts for the effects of frequent disconnection from the services that energy provides on Indigenous wellbeing.

In considering such distributional injustices, procedural injustices first need to be addressed by supporting participatory community engagement in energy policy development (for example, increase local access to data/information and community consultations). Indigenous Australians have distinct societal values and perspectives of wellbeing, and for progress across all spheres of inequity

Fig. 4 | Probability of a same-day disconnection by temperature, day and month. a, All regions. b, Hot persistently dry grassland climate zone.

Coefficient estimates and 95% confidence intervals from multiple regressions for a sample with 1,674,786 daily observations across 3,300 houses are presented above. Regressions were grouped by percentile of electricity use (that is, average daily load) and by climate zone. Estimates for all houses, low-electricity-use households and high-electricity-use households are shown here (Supplementary Tables 7–11 have all same-day disconnection estimates). Temperature bins are specified using daily average temperatures (in °C). Temperature-based estimates are for a three-day period (that is, temperature on the day of disconnection and the two days before). Temperature estimates are interpreted using 20–25°C as the reference temperature range. Day of the week estimates are interpreted using Wednesday as the reference day. Monthly estimates are interpreted using April as the reference month.

and injustice faced by Indigenous communities there needs to be a recognition of these world views in the context of the realities that these communities face⁵⁹.

The Partnership Agreement on Closing the Gap calls for the greater sharing of, and access to, data and information to support shared decision-making (Fig. 2)⁶⁰. With respect to disconnections,

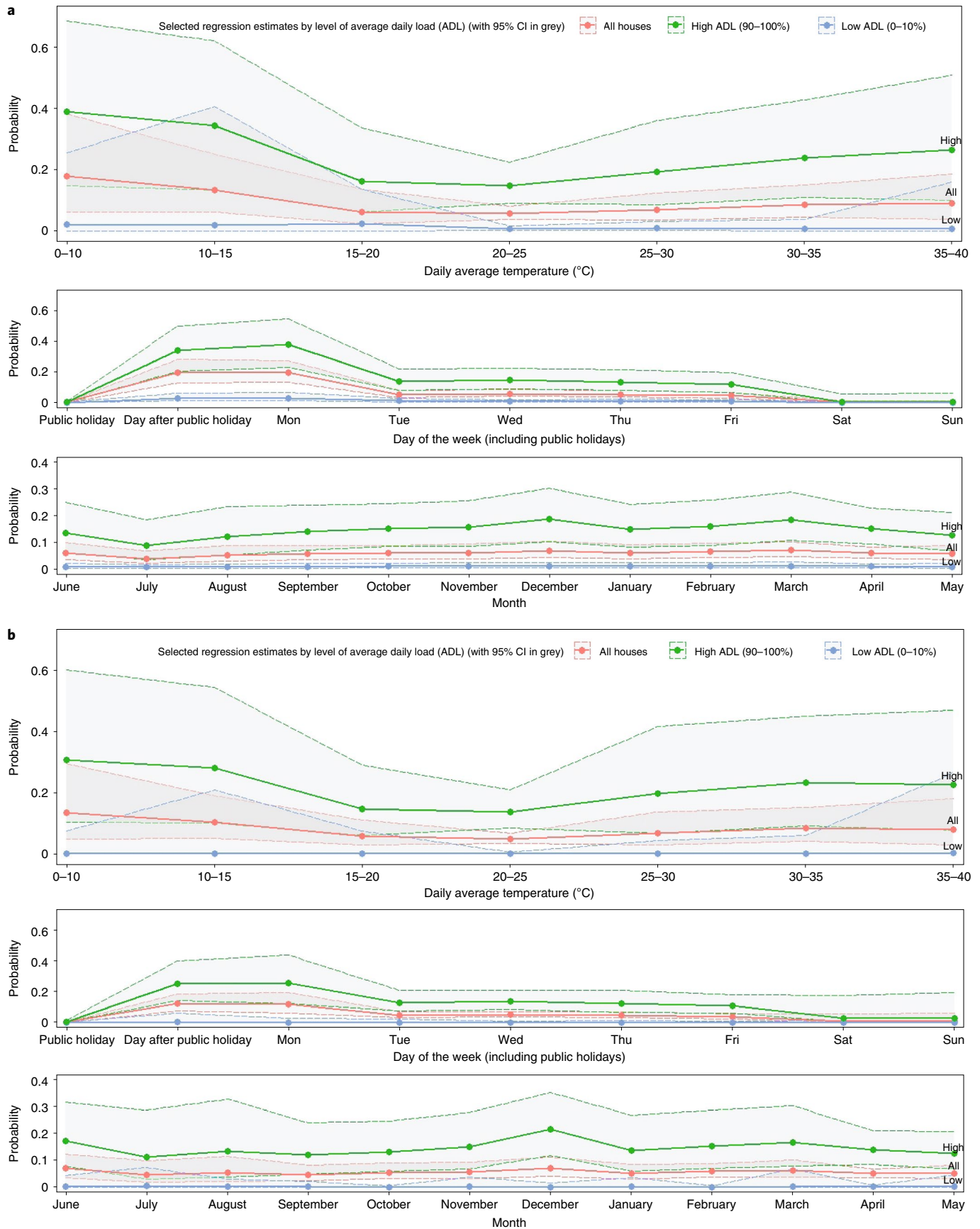


Table 2 | Electricity use and disconnections by climate zones

	Equatorial climate zone (most northern)	Coastal tropical climate zone	Savannah tropical climate zone	Hot persistently dry grassland climate zone (most southern)	All regions
Percentage of disconnections above maximum temperature of 35 °C					
Percentage of same-day disconnections	7	12	34	42	24
Percentage of multi-day disconnections	6	11	36	40	28
Percentage of all disconnections	7	12	34	42	25
Percentage of disconnections above maximum temperature of 40 °C					
Percentage of same-day disconnections	0	0	4	18	5
Percentage of multi-day disconnections	0	0	3	18	7
Percentage of all disconnections	0	0	4	18	5
Percentage of disconnections below minimum temperature of 0 °C					
Percentage of same-day disconnections	0	0	5	12	4
Percentage of multi-day disconnections	0	0	6	11	6
Percentage of all disconnections	0	0	5	12	4
Number of disconnections					
Number of same-day disconnections	32,133	39,212	54,309	30,281	155,935
Number of multi-day disconnections	1,971	2,787	4,841	4,692	14,291
Number of all disconnections	34,104	41,999	59,150	34,973	170,226

a key aim will be reducing the frequency, duration and effects of disconnection. This might include: improving the accessibility and affordability of energy through changes to tariffs or direct access to the benefits of renewable energy such as residential rooftop solar on community housing; improving energy efficiency of infrastructure, buildings and appliances; and improving energy provision for particular critical needs, for example, disconnection prohibitions or tariff reductions during temperature extremes, protections for critical care customers and the use of protected circuits for refrigeration, lighting and essential medical equipment.

In addition to better policy, the language around disconnection events needs to recognize and reflect community experience. The term ‘self-disconnection’, while in common use, is a misrepresentation as it incorrectly implies that households were making a voluntary choice to disconnect themselves^{21,50,61}. The term ‘involuntary self-disconnection’ emphasizes ‘that the household has not chosen to cease their electricity supply’⁶².

Limitations

On considering these results there are limitations that need to be considered. First, we were unable to identify the reasons for multi-day disconnections. Once a disconnection occurs, whether it becomes a multi-day disconnection will depend on a number of factors including whether residents can ‘top up’ credit, pay off ‘friendly credit’ debt, or make other arrangements. Inter- and intraregional mobility in remote and rural Australia is common (refs. ^{63–65} and E. Ings, personal communication), which could influence the onset and length of multi-day disconnections. Residents may choose to temporarily relocate to the residence of kin for socio-cultural reasons or because of a disconnection, and disconnection-associated relocations may themselves exacerbate overcrowding and increase electricity demand on households that are not yet disconnected. Future studies should focus on the experiences of energy poverty in these communities and further investigate these issues.

Second, we did not have information on the socio-economic and demographic composition of households. To address this, we used statistical approaches to control for differences across households and estimated the effect of temperature on the basis of the usual

level of electricity use and disconnections (during moderate temperatures between 20°C and 25°C). As a result, when discussing the estimates, we provide the likelihood of disconnections during moderate temperatures. Electricity consumption data were used to estimate relationships for different groups of households. There will be additional determinants for the differences in electricity use and disconnection, which should be investigated further.

Third, this study uses data from 3,300 smart prepayment meters and finds that over 170,000 disconnections occurred across 28 communities over a period spanning 18 months. Note that our dataset is unbalanced due to the timing of the roll out of smart meters in the NT. Thus, we underestimate the total number of disconnections in the NT as there are many more households currently using prepayment metering than just those represented in this study⁵³. The vulnerability of prepayment customers is often overlooked by government reporting. Further research on prepayment and disconnection in other jurisdictions is needed, as is greater understanding of the direct health effects of these disconnections.

Conclusions

Australia could do much better at providing protections from disconnection. Policymakers are beginning to consider the importance of electricity to wellbeing in approaches that seek to limit the frequency and duration of disconnection events, particularly in relation to temperature extremes and wellbeing. In the USA, for example, despite not having a formalized definition of energy poverty or federal level protections, many states have utility regulation policies that protect customers from disconnection of service in certain cases, including extreme temperatures^{4,26}. Some state consumer protections target vulnerable groups, such as in the state of Texas where prepayment-meter enrolment is prohibited for those diagnosed with severe medical conditions that require electricity services to maintain temperatures or run devices^{26,66}. Many European Union states have also introduced protection from disconnection⁷, many with particular focus on extreme temperatures and vulnerable groups.

In Australia, the Essential Service Commission (for Victoria) observes that “customers who are disconnected from electricity or gas can face significant risks to their welfare... disconnection for

non-payment reasons should only ever be a last resort⁷⁶. Australia's National Energy Retail Rules require that the retailer not arrange for the de-energization of premises having life support equipment or during an extreme weather event⁶⁸, but this is not comprehensively applied in remote NT communities^{47,48}.

Energy insecurity in remote Indigenous Australia remains a pressing issue. Access to energy has been identified as a key part of the 'critical healthy living priorities' for remote living Indigenous Australians³. Ensuring access to essential services is an important prerequisite to improving health and wellbeing outcomes⁶⁹. The focus should not be solely on electricity provision itself, but on maximizing the benefit that households receive from their electricity use and this includes a range of essential services, including heating and cooling.

Methods

Ethics statement. This research was conducted with ethics approval from the Central Australian Health Research Ethics Committee Centre for Remote Health (CA-20-3809).

Autoethnographic quotes. While this is predominantly a quantitative study, our research methodology is based on principles of social justice where Aboriginal people participate in setting the research agenda⁷⁰ and we supplement our analysis with insights through autoethnography⁷¹. These quotes are included by authors, N.E.J. who is a community elder and V.N.D. who is a senior Aboriginal researcher. This paper has more than a single authorial voice, coming as it does from multiple perspectives. These perspectives are from researchers who work at an academic institution (T.L., B.R. and L.V.W.), a regional hospital (S.Q.) and community-based organizations (S.Q., M.K. and V.N.D.).

Dataset. The data used in this paper were sourced from the NT Government owned utility Power and Water Corporation, the Australian Bureau of Meteorology (BOM) and the Australian Bureau of Statistics. Daily electricity use data for 3,300 households with a smart prepayment meter were matched to temperature data from the closest weather station. For cases where there were no temperature data for that day, the next closest weather station was used (6.1% of all observations). If that still resulted in a missing value, then the average for that climate zone was used (0.3% of observations). Data on disconnections were provided along with the time and date that the electricity service was discontinued and subsequently restored. These cases of disconnection were aggregated into daily data and separated into two variables on the basis of whether an electricity service was restored to the household on the same day or not. Selected summary statistics for these data by climate zones are shown in the paper in Tables 1 and 2.

The climate zones we used were sourced from the Australian BOM³¹. We made some modifications to the zones mapped by BOM, which was to reclassify all of the mainland communities that were within 20 km of the coast as a 'coastal tropical climate zone' and combine the Central Australian climate zones into one region that we called the 'hot persistently dry grassland climate zone'. The second modification was due to sample size and a similarity in temperatures. The other climate zones are those prescribed by BOM, shown in Fig. 1c.

Extreme temperatures in remote communities. Those communities that we focus on are typically exposed to extremely hot days and cold nights. Supplementary Table 13 shows the breakdown of key temperature statistics by climate zone for these communities. Figure 1 presents maps produced by the Australian BOM showing how temperature differs across both Australia and the NT⁷². Differences in temperature indicators vary across climate zones (shown in Fig. 1a–c). Central Australia experiences prolonged hot daytime temperatures in summer and cold (below zero) nights in winter. For example, the hottest day (46 °C) and coldest night (−4 °C) in our dataset both occurred in the southern-most 'hot persistently dry grassland climate zone'. Northern regions of the NT experience the southern extent of the tropical monsoon, which brings seasonal cyclonic activity and afternoon storms. Average temperatures decrease north to south. The highest maximum temperature (lowest minimum temperature) increases (decreases) as you move from the north to south (Fig. 1b,c and Supplementary Table 13). The regressions were run using daily average temperatures.

Grouping by average daily electricity use. Energy insecurity and disconnection rates are likely to be determined by a range of factors, including the usual level of electricity use and the inability to pay. While we do not have household data on occupancy or income, we are able to categorize the meters into groups using average daily electricity use. The average daily load will be a function of the types of appliance, intensity of use and the number of residents. The percentile groupings used are shown in Supplementary Table 14 along with the aggregate expenditure on electricity. Note that the data are not a balanced panel due to the incremental roll out of smart meters across communities and we excluded those meters with less than 100 observations.

Regression analysis. To estimate the relationship between electricity use and temperature we used linear regression with panel-corrected standard errors that accounted for heteroscedasticity and autocorrelation. The 28 communities were the level for the panel correction. The software that was used to estimate these relationships was Stata MP 16.1. The 'xtpcse' command was used to estimate the results shown in Fig. 3 and Supplementary Tables 2–6. We also tested for normality in linear panel-data models using the 'xtsktest' command, which did not reject the null hypothesis of normality (Chi-square statistic of 3.28–3.42 (*P* value of 0.18–0.19)). The 'xtserial' command was used to perform the Wooldridge test for autocorrelation in panel data, which rejected the null hypothesis of no first-order autocorrelation (*F*-statistic of 6,694.17 (*P* of 0.00)). We used random-effects probit regressions to estimate the relationship between the probability of same-day/multi-day disconnection and temperature. These estimates were estimated using the 'xtprobit' command in Stata and we clustered the standard errors by community to control for regional differences. The results of the same-day disconnection estimations are shown in Fig. 4 and Supplementary Tables 7–11. When discussing these estimates in the paper we compare them to the likelihood of disconnection during moderate temperatures. The probabilities of disconnection events were converted into an odds ratio (for example, 1:2) and then reported as the chance of a disconnection (for example, one in three). Multi-day disconnection estimates are included in Supplementary Table 12, but are not discussed in the paper as there was no clear relationship between multi-day disconnections and daily average temperature. Note that the regression estimates were graphed using the 'ggplot' command in R.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data used in this paper are not freely available and were sourced from the data custodians. The electricity data were sourced from Power and Water Corporation (<https://www.powerwater.com.au/>) and the Australian BOM (<http://www.bom.gov.au/>). We note that access to data will be a key part of local communities helping to develop appropriate policy responses to the challenges outlined in this paper. The Partnership Agreement on Closing the Gap calls for the greater sharing of, and access to, data and information at a regional level noting that "disaggregated data and information is most useful to Aboriginal and Torres Strait Islander organizations and communities to obtain a comprehensive picture of what is happening in their communities and to support decision-making"⁶⁰.

Code availability

The code used to estimate the regressions (in Stata MP 16.1) and create the graphics (in R v.4.1.1) is available on request. The 'xtpcse' and 'xtprobit' commands in Stata MP 16.1 were used for the regressions. The regression estimates were graphed using the 'ggplot' command in R. Statistical tests for normality and autocorrelation were performed in Stata MP 16.1 using the 'xtsktest' and 'xtserial'.

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Author contributions

All authors contributed to the conceptualization of the research. We especially note the contributions of N.F.J. and V.N.D. in shaping our understanding of the key issues faced by Indigenous communities in the NT. S.Q. acquired the key data, and T.L. performed the analysis. T.L., S.Q., B.R., L.V.W. and M.K. wrote the initial draft of the manuscript, and all authors contributed to the review and revision. N.F.J. and V.N.D. were engaged in discussions on key issues with the other members of the authorship team and their selected quotes are provided to highlight those themes and the issues that they raised as being the most important (refer to autoethnographic data section for more information).

Competing interests

The authors declare no competing interests.

Additional information

Extended data are available for this paper at <https://doi.org/10.1038/s41560-021-00942-2>.

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41560-021-00942-2>.

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Data collection No software was used for data collection.

Data analysis The software that was used was Stata MP 16.1 and the 'xtpcse' and 'xtprobit' commands were used for the regressions. The regression estimates were graphed using the 'ggplot' command in R 4.1.1. Statistical tests for normality and autocorrelation were performed in Stata MP 16.1 using the 'xtsktest' and 'xtserial'.

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Study description	This is a quantitative study that assesses the relationship between temperature and electricity use (including disconnection) using daily smart meter data for 28 remote Indigenous communities.
Research sample	The data set includes the electricity use of 3,300 households across 28 remote Indigenous communities. The data set is unbalanced due to the timing of the roll out of smart meters in the Northern Territory. But the data is representative of the communities where the roll out occurred as we had access to all smart meter data. The electricity data was sourced from Power and Water Corporation (https://www.powerwater.com.au/) and the Australian Bureau of Meteorology (http://www.bom.gov.au/).
Sampling strategy	Most of the tables were created and all of the regressions were performed using all available data. Table 1 is limited to the observations for a balanced panel for 2018/19 financial year (i.e. only the observations with data for every day of the year). This was done to compare to other studies with annual disconnection rates.
Data collection	Data was received from two data custodians and matched at the community level. Daily smart meter data was sourced from Power and Water Corporation. Daily temperature data was sourced from the Australian Bureau of Meteorology. Data was matched based on the location of communities and weather stations. Dr Longden was the only researcher with full access to all of the matched data.
Timing	Unbalanced panel data between January 2018 to July 2019.
Data exclusions	We excluded those meters with less than 100 observations as we required temperature and seasonal variation to estimate the regressions.
Non-participation	No individual participants were involved in the study.
Randomization	No randomization occurred. We had access to all smart meters in those communities that had them installed at that point in time. We grouped households based on daily electricity use and climate zones. The key explanatory variables were exogenous (such as temperature and month) so randomization was not necessary.

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Materials & experimental systems

n/a	Involved in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> Antibodies
<input checked="" type="checkbox"/>	<input type="checkbox"/> Eukaryotic cell lines
<input checked="" type="checkbox"/>	<input type="checkbox"/> Palaeontology and archaeology
<input checked="" type="checkbox"/>	<input type="checkbox"/> Animals and other organisms
<input type="checkbox"/>	<input checked="" type="checkbox"/> Human research participants
<input checked="" type="checkbox"/>	<input type="checkbox"/> Clinical data
<input checked="" type="checkbox"/>	<input type="checkbox"/> Dual use research of concern

Methods

n/a	Involved in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> ChIP-seq
<input checked="" type="checkbox"/>	<input type="checkbox"/> Flow cytometry
<input checked="" type="checkbox"/>	<input type="checkbox"/> MRI-based neuroimaging

Human research participants

Policy information about [studies involving human research participants](#)

Population characteristics	The data set includes the electricity use of 3,300 households across 28 remote Indigenous communities. No individual characteristics were collected.
Recruitment	The data set is unbalanced due to the timing of the roll out of smart meters in the Northern Territory. But the data is representative of the communities where the roll out occurred as we had access to all smart meter data.

Ethics oversight

This research was conducted with ethics approval from the Central Australian Health Research Ethics Committee Centre for Remote Health (CA-20-3809).

Note that full information on the approval of the study protocol must also be provided in the manuscript.