Hotter Days Ahead: Why We Must Prepare Victoria’s Electricity System for Climate Change

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Agenda

1. The consequences of power outages caused by heatwaves
2. Current state of climate-resilience planning in Victoria, Australia
3. How elevated temperatures threaten system security
4. Heatwave risks to the electricity system under a 2°C future climate scenario
    a) Methodology
    b) Development of generalised event definitions
    c) Probabilistic assessment of transmission, generation and whole-system risks
5. Conclusion and Questions

Heatwave-induced power outages in Victoria

- Victoria has experienced several major state-wide blackout events in recent decades, this risk is set to increase with climate change

Social Impacts

- Over **500,000** customers lost power (Feb 24, Jan 09)
- Reconnection took **days to weeks** (Feb 09, Feb 24)
- Communications, health, transport disruptions

Economic Impacts

- Power disruptions contributed to **AUD$800 million** in losses (Jan 09)
- Total RERT costs of AUD$34.2 million (Jan 19)

System Impacts

- 12 **load shedding** incidents
- Separation of VIC/NSW systems (Feb 09)
- **Infrastructure damage**
- Breached reliability standards

Current state of climate-resilience planning

Systematic weaknesses in climate change resilience

- Current regulations and industry standards do not consider future climate risks
- Difficult to justify investment in climate resilience to shareholders or regulators
- ESCI on AEMO's long-term plans - "likely to result in an overestimation in the reliability of the electricity system"
- Future climate not considered for infrastructure with operational lifetimes of several decades

Accelerating investment in Net Zero

- **$3B+** investment in renewables, grid expansion and large battery systems, including 6 REZs

Increasing system complexity

- 95% renewables target by 2035
- Rapid shutdown of baseload coal and loss of traditional system inertia mechanisms
- 108% increase in demand by 2050

Extreme temperatures and system security

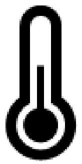
Increased Demand

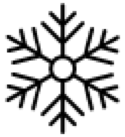
Lower conductor transfer capacity

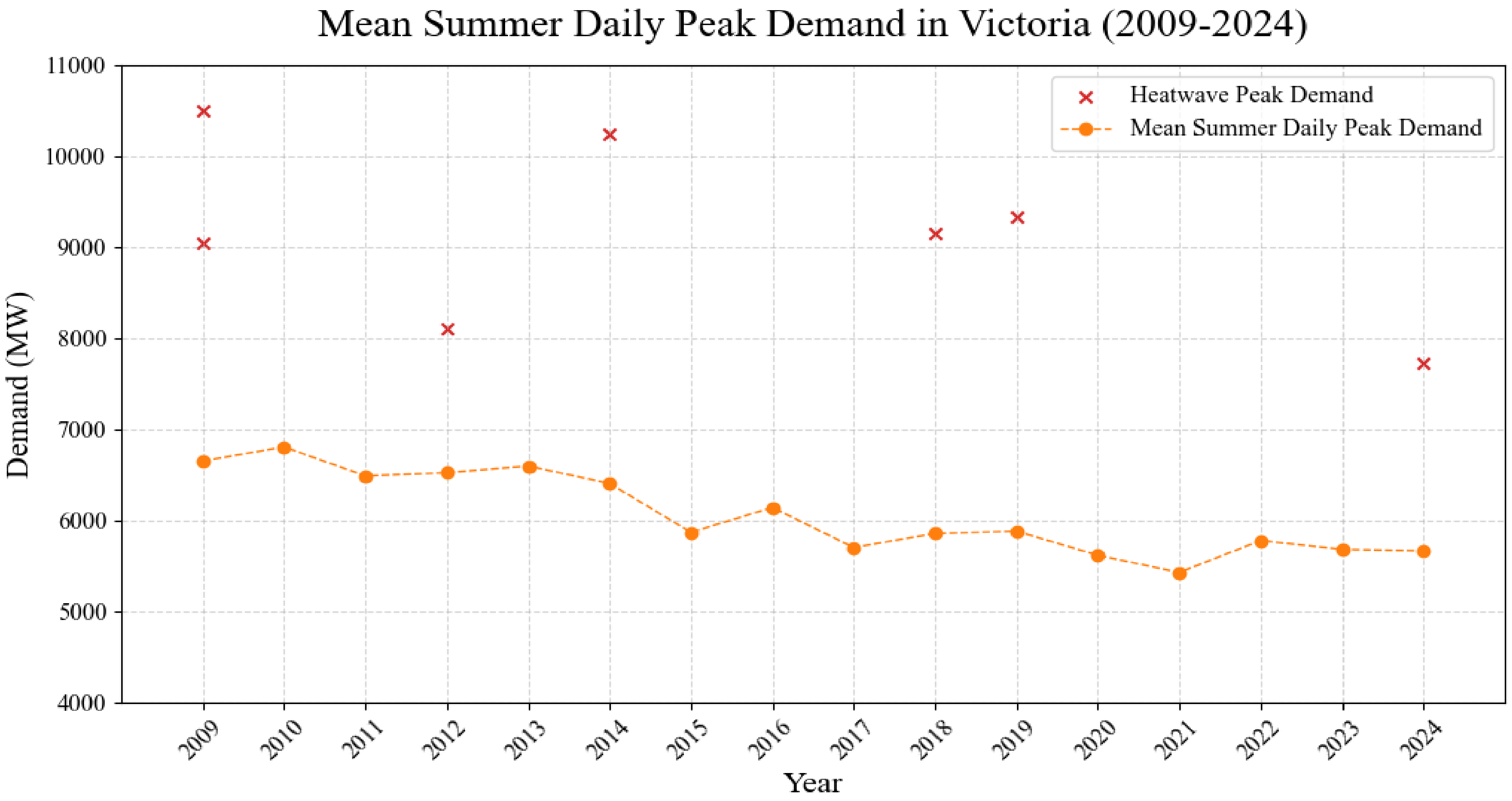
Reduced generation efficiency

Increased system stress

- Increased cooling loads
- Significantly higher peak demand
- Peak shifting later in the afternoon/evening







Data retrieved from: AEMO

Extreme temperatures and system security

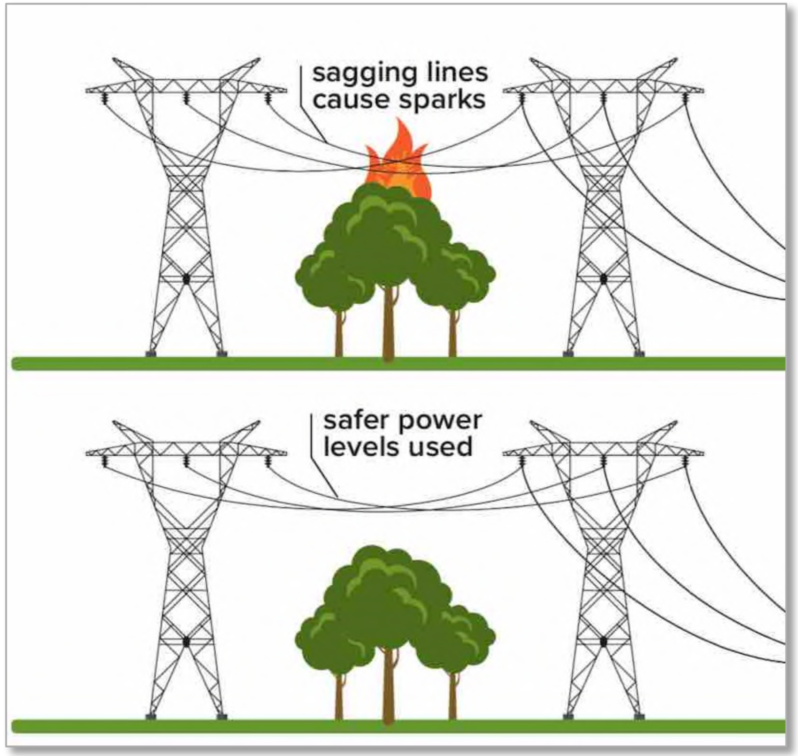
Increased Demand

Lower conductor transfer capacity

Reduced generation efficiency

Increased system stress

- High temperatures causes greater conductor sag, increased risk of flashover, and physical equipment damage
- Passing current through a conductor causes it to heat up, so operators reduce power transfer capacity during high temperature events to minimise risks
- Power lines are assigned static or dynamic temperature ratings indicating the maximum allowable current for safe operation



Extreme temperatures and system security

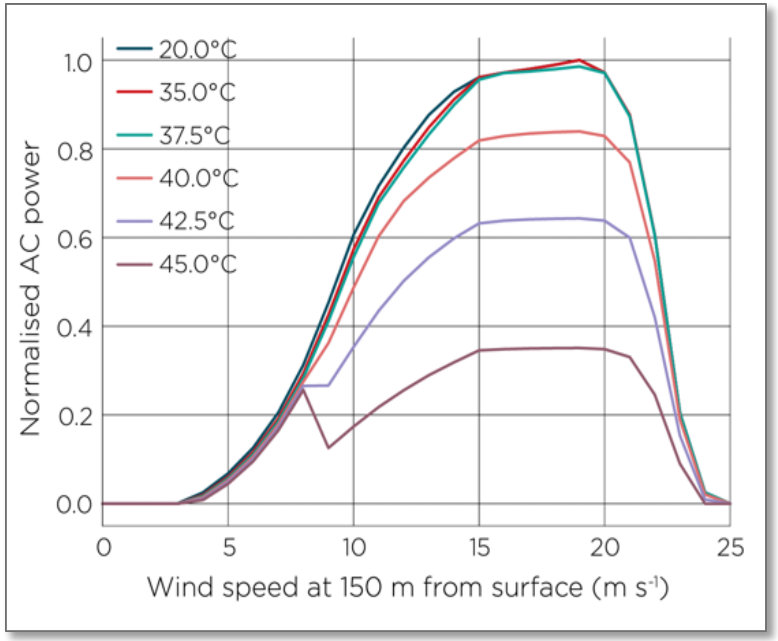
Increased Demand

Lower conductor transfer capacity

Reduced generation efficiency

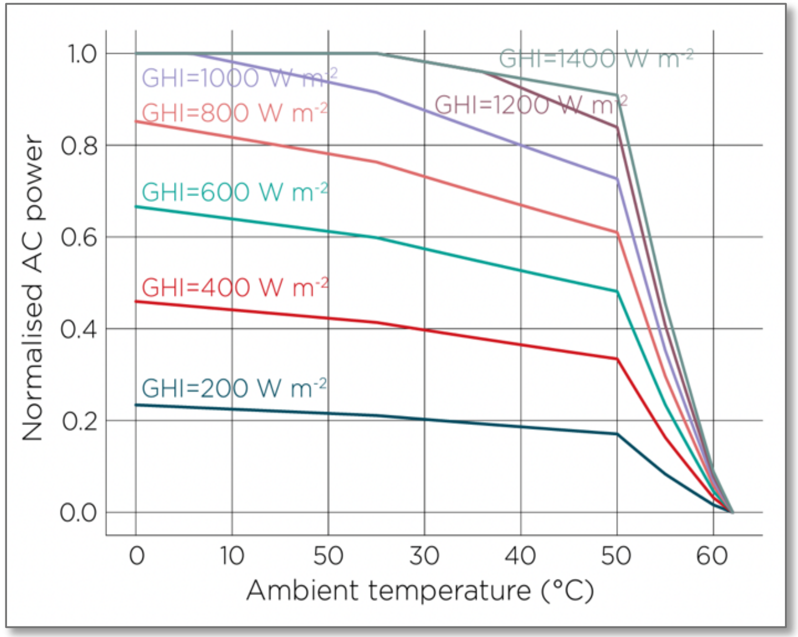
Increased system stress

Power temperature curve for **wind generation** in the NEM



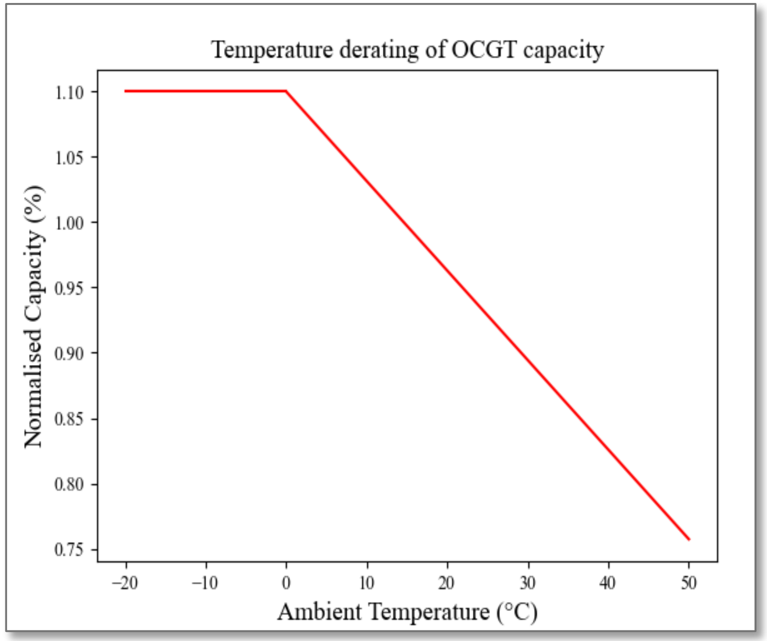
Source: ESCI

Power temperature curve for **solar generation** in the NEM



Source: ESCI

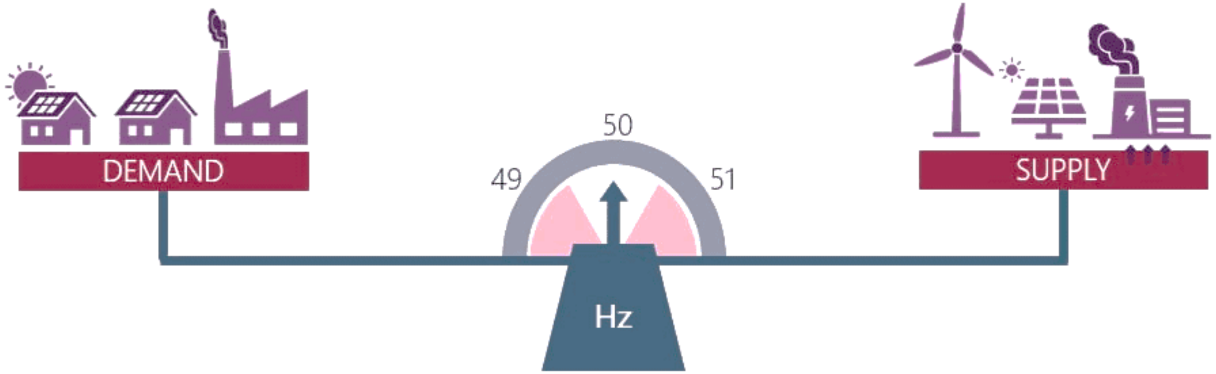
Temperature derating of open-cycle **gas turbines** (OCGT)



Source: X. Ke et al. (2016)

Extreme temperatures and system security

Increased Demand	Lower conductor transfer capacity	Reduced generation efficiency	**Increased system stress**
↑	↓	↓	↑



- Harder to balance supply and demand
- Spatially distributed demand increases risk of cascading line failures
- System operator can activate load shedding
- Overloading and equipment faults can cause localised outages at the distribution level

Overview of methodology

Adapted from climate attribution studies to determine the change in likelihood of an extreme event under current climactic conditions compared to a future 2°C scenario

1. Analysis of seven historic heatwave-outages in Victoria to understand the physical heatwave conditions, system dynamics and event impacts
   - AEMO reports, NEM market reports, newspaper articles
   - ERA5 Climate Reanalysis temperature data
   - Outage data from 4 DNOs

2. Event definition:
   - Physical, spatial and temporal components, identifiable in historic meteorological data and climate model outputs
   - Defined in relation to system impact, generalised to represent class of similar events

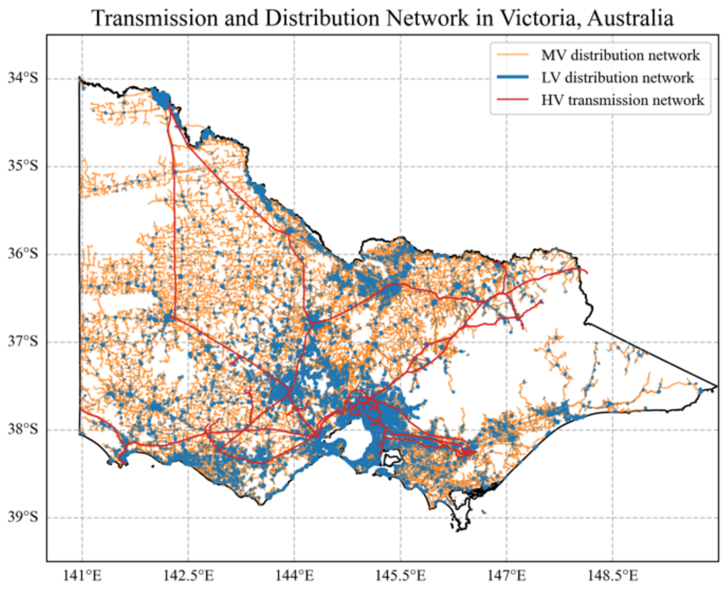
Overview of methodology

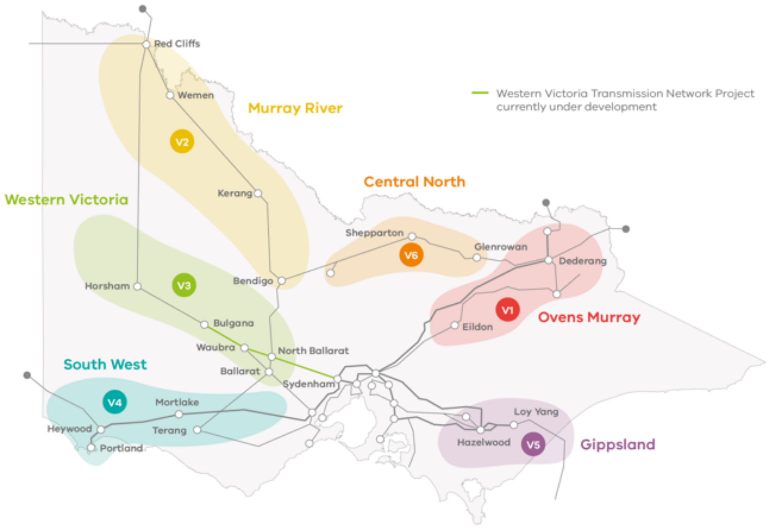
3. Model Evaluation of HADAM4 outputs

- ERA5 Data, Q-Q plot, Overlap Percentage

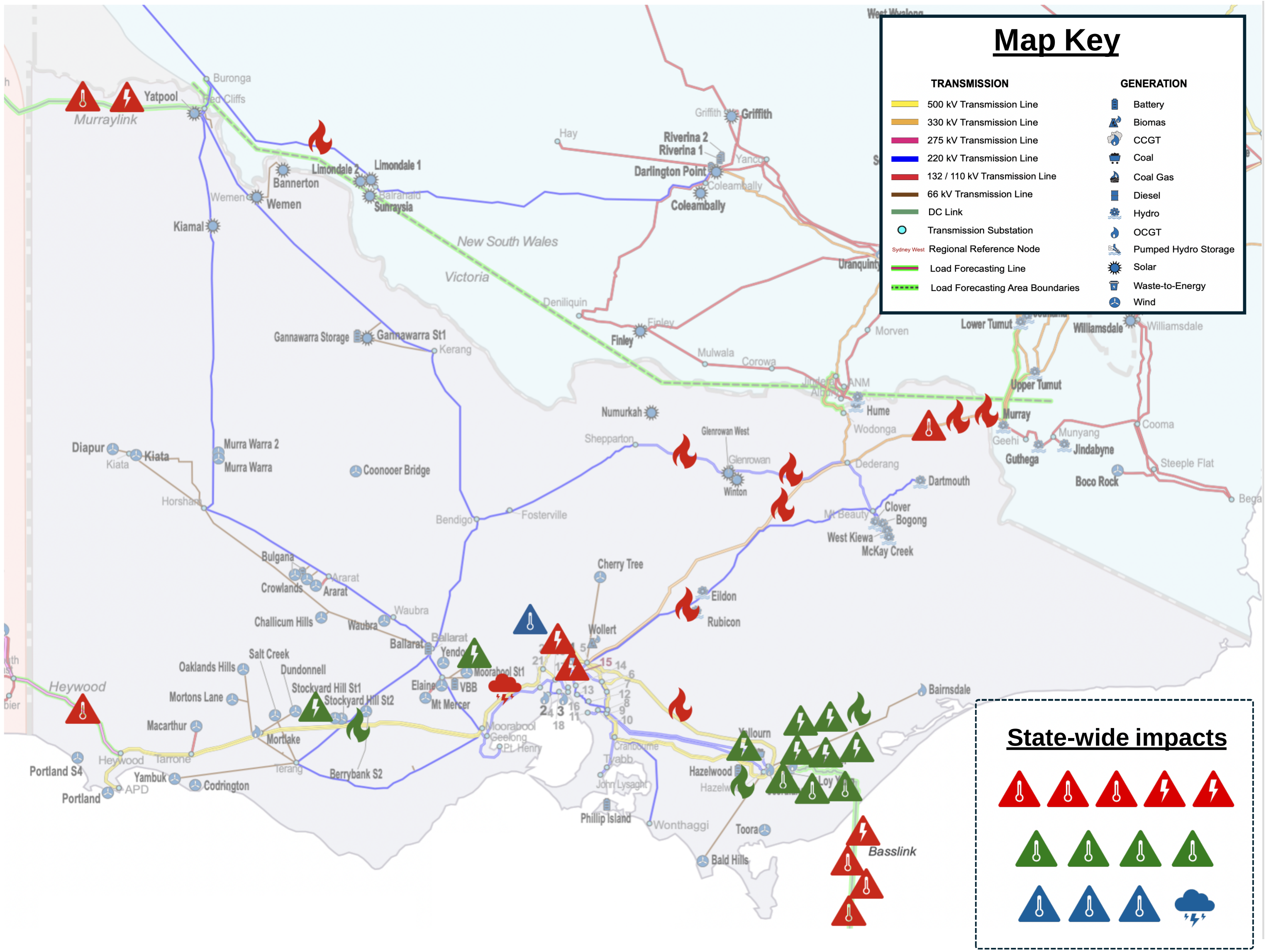
4. Estimation of the changes in event risk

- Mean temperatures calculated across spatial scopes for 1,380 simulated periods
- Empirical cumulative distribution function (ECDF) to calculate event likelihoods and probability ratios
- Non-parametric bootstrap approach to determine 5th and 95th percentile confidence intervals

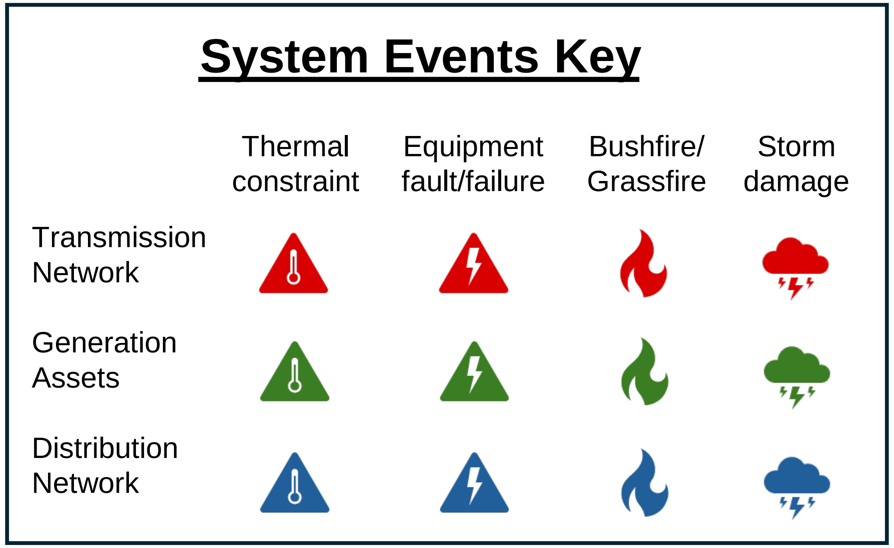




Event Definition: Whole System



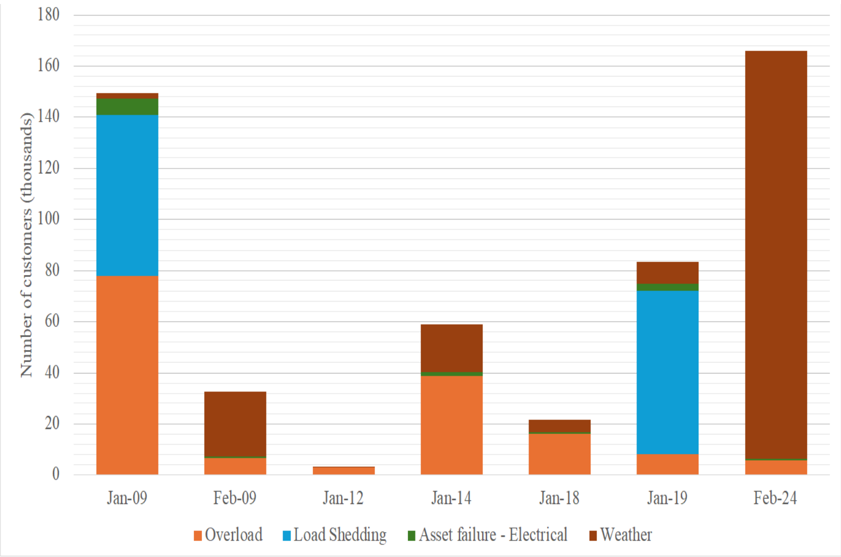
Causes of the seven large-scale heatwave-outage events



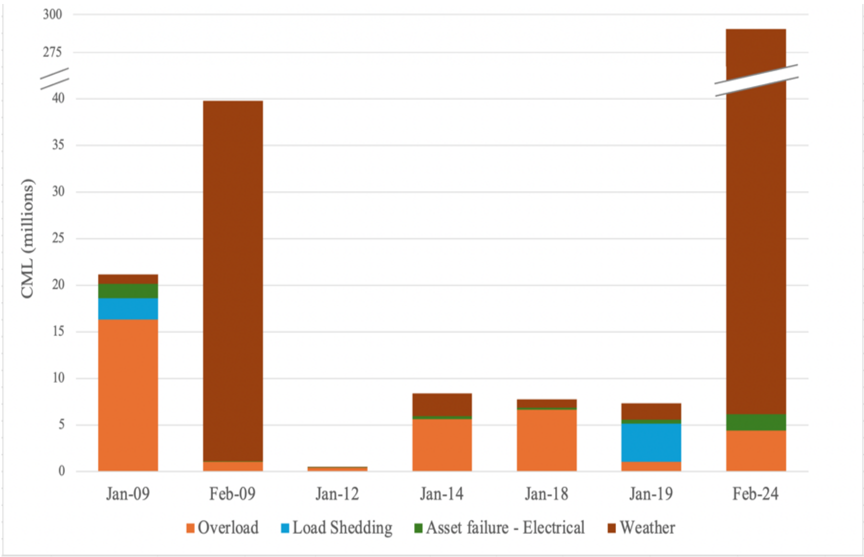
- Twelve separate incidences of load shedding
- Two incidents over 1GW, ~18% of average peak daily summer load

Event Definition: Whole System

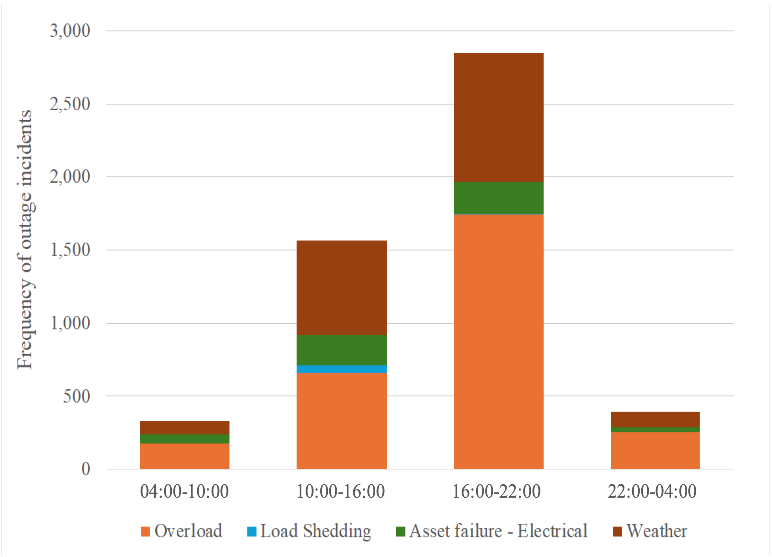
Number of customers affected by outage cause



Total customer minutes lost by outage cause



Frequency of outages by 6-hour period and cause



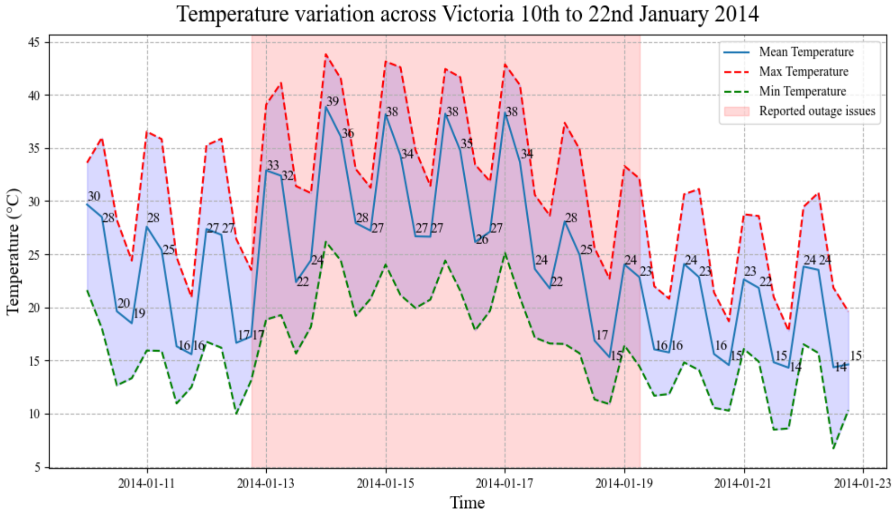
Overload Load Shedding Asset failure - Electrical Weather

Data retrieved from: PowerCor, CitiPower, UnitedEnergy, Ausnet

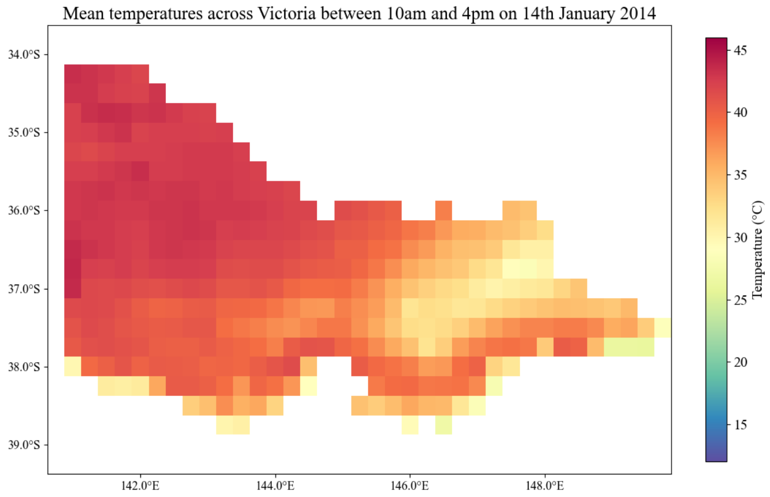
- Overloading and extreme weather were primary drivers of outages and outage severity
- The presence of concurrent extreme weather during heatwaves greatly exacerbates the severity of outages

Event Definition: Whole System

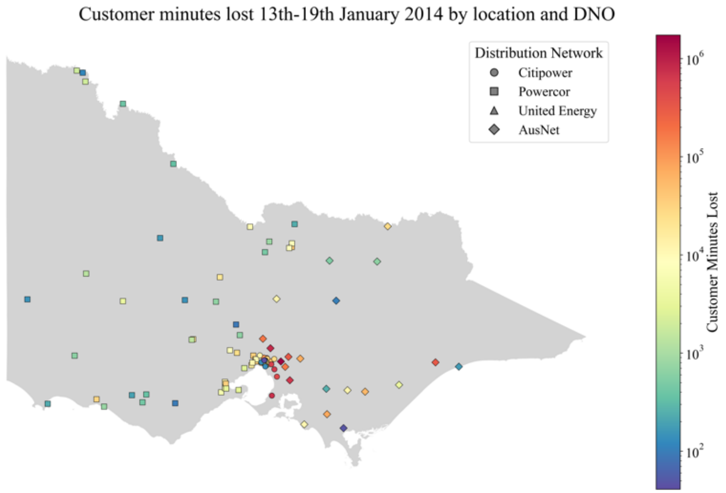
Temporal Temperature Variation



Spatial Temperature Variation



Spatial Distribution of Outage Severity



ERA5 climate reanalysis temperature data shows:

- High state maximum and minimum temperatures (0.25° x 0.25° resolution)
- Mean state temperature close to maximum temperature
- Outages correlated with high temperatures
- Lower standard deviation of gridded 6-hour mean temperatures compared to non-heatwave days
- High temperatures across state

DNO outage data shows:

- Correlation between outage location and ambient temperature
- No strong correlation between consecutive heatwave days and CML

Event Definition: Whole System

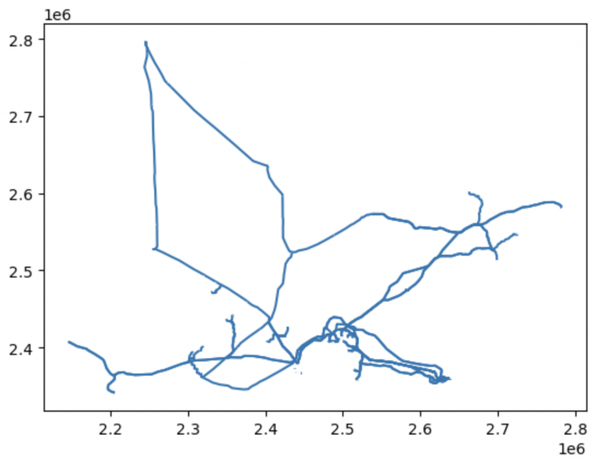
Event Definition	Physical, Spatial and Temporal Components	Event severity thresholds
Whole system	Mean 6-hourly ambient temperature averaged over Victorian state boundaries	100% failure rate: 39°C 70% failure rate: 38°C 41.18% failure rate: 37°C 31.25% failure rate: 35°C

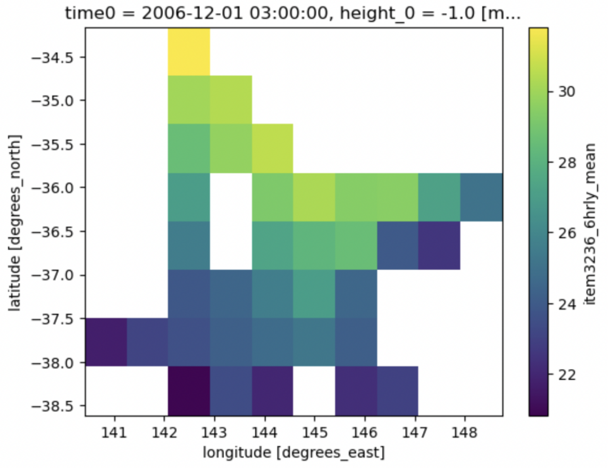
The *percentage failure rate* indicates the proportion of 6-hour periods between December 2008 and March 2024 when exceeding a temperature threshold resulted in significant state-wide load shedding or power outages

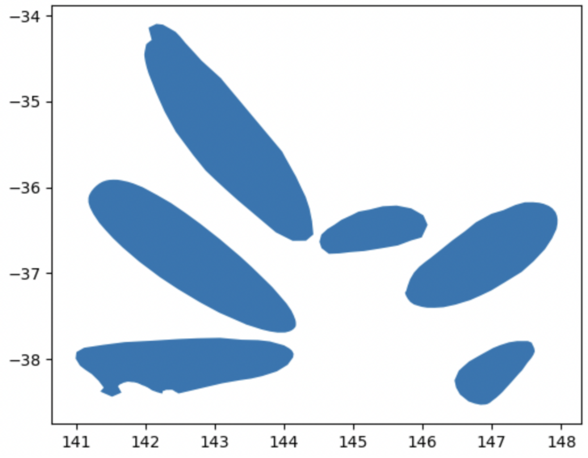
Mean 6-hourly state temperatures above 39°C only occurred three times, all of which resulted in severe state-wide power outages

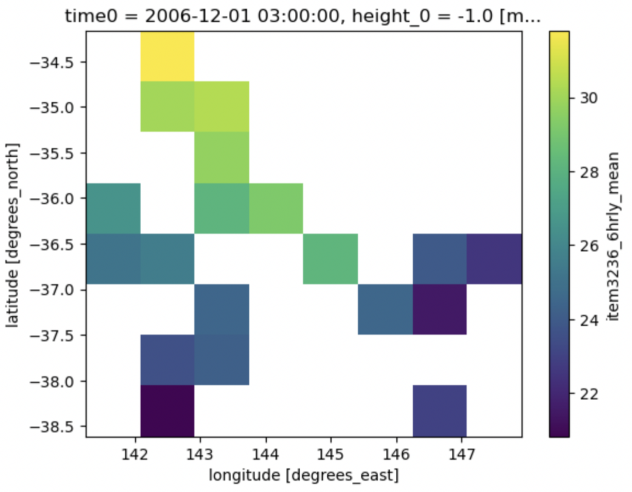
Event Definitions: Transmission and Generation

Event Definition	Event scale	Event severity thresholds
Transmission	Mean 6-hourly ambient temperature averaged over area covered by transmission network	Static ratings: 35°C and 40°C Dynamic ratings: 28°C and 24°C
Generation	Mean 6-hourly ambient temperature averaged over area covered by REZs	Wind: 40°C and 45°C Solar: 40°C and 50°C BSS and gas power plants: 35°C

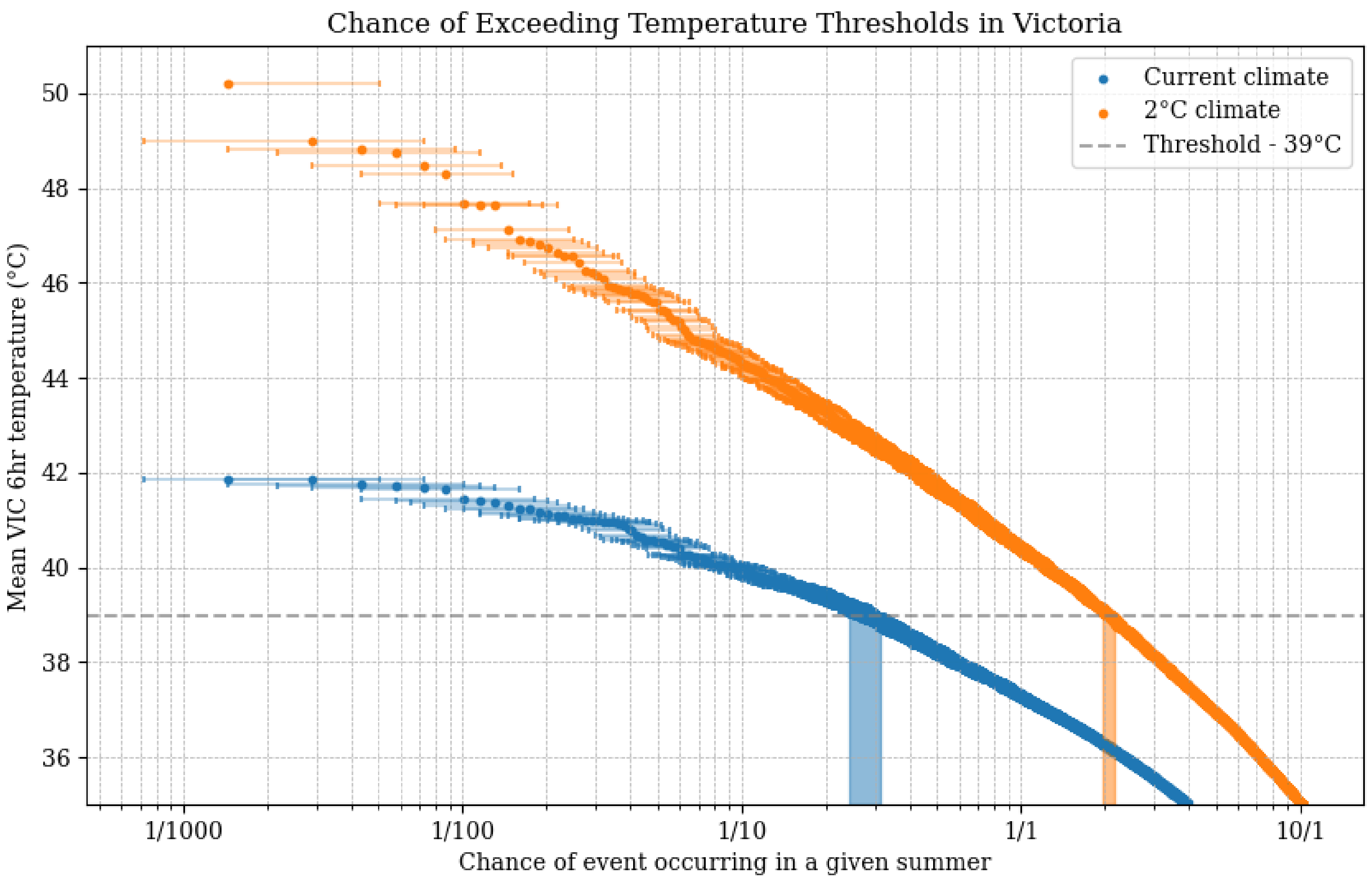








Results: Whole system risks

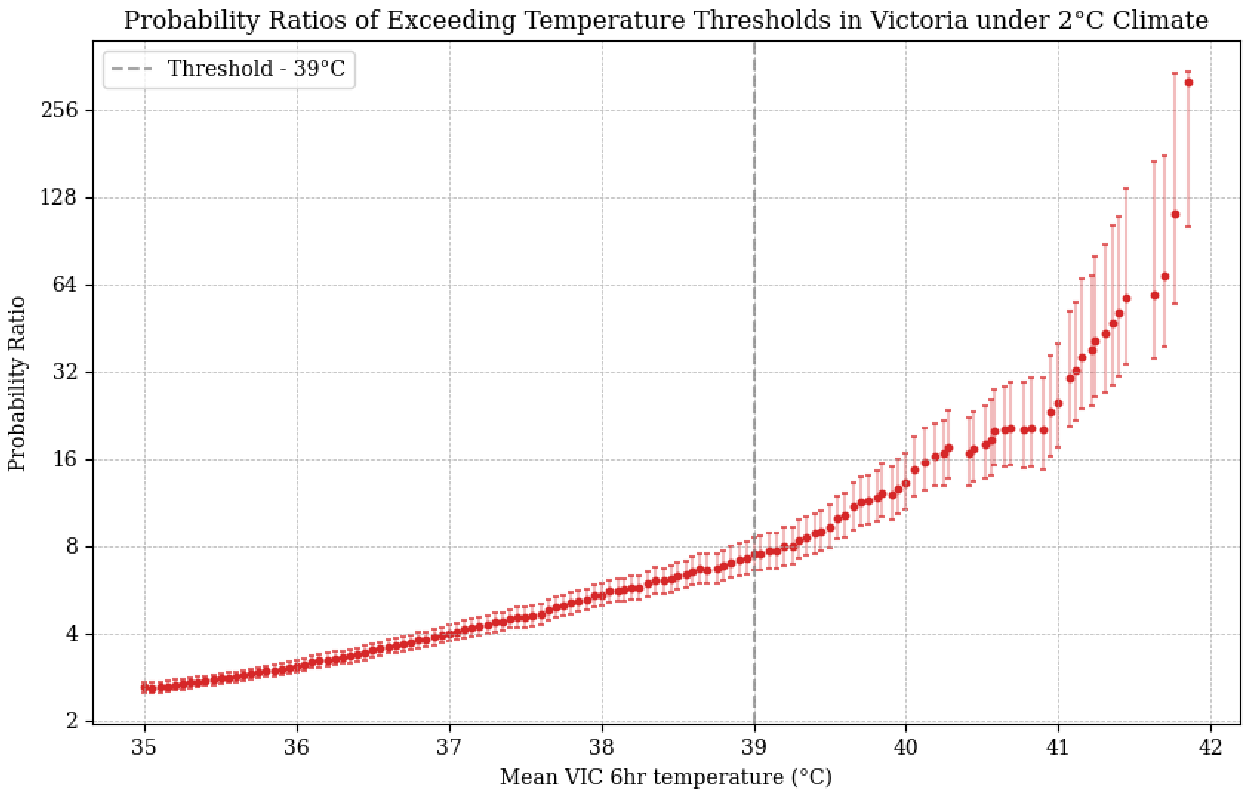


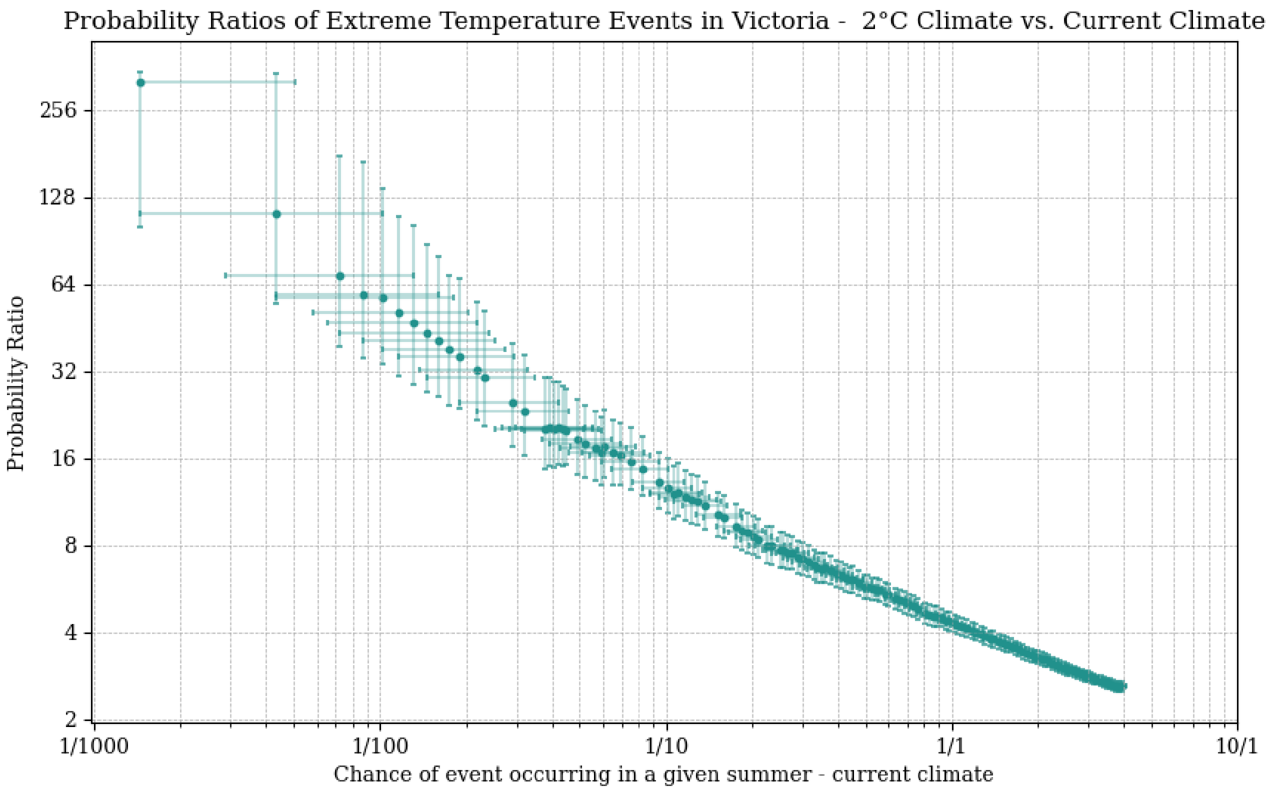
Exceedance Likelihood of 39°C

28% (+4%/-3%) ➡ 206% (+9%/-9%)

Corresponding to 100% failure rate assuming the current level of system resilience

Results: Whole system risks



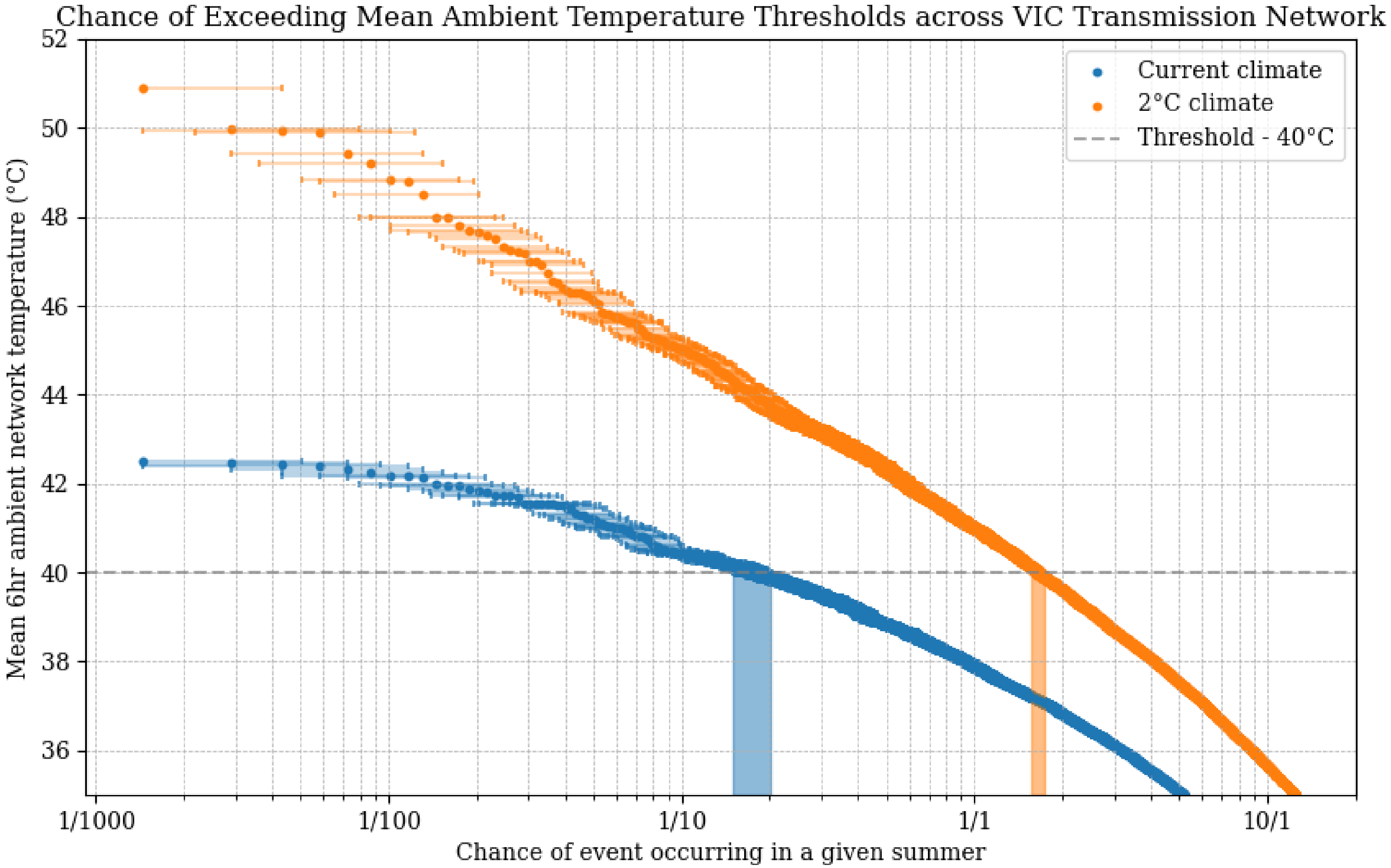


Probability Ratio of 39°C

7.48 (+1.07/-0.92)

Increased probability of extreme events – Increasing challenge to meet infrastructure resilience standards

Results: Transmission risks



Exceedance Likelihood - 40°C

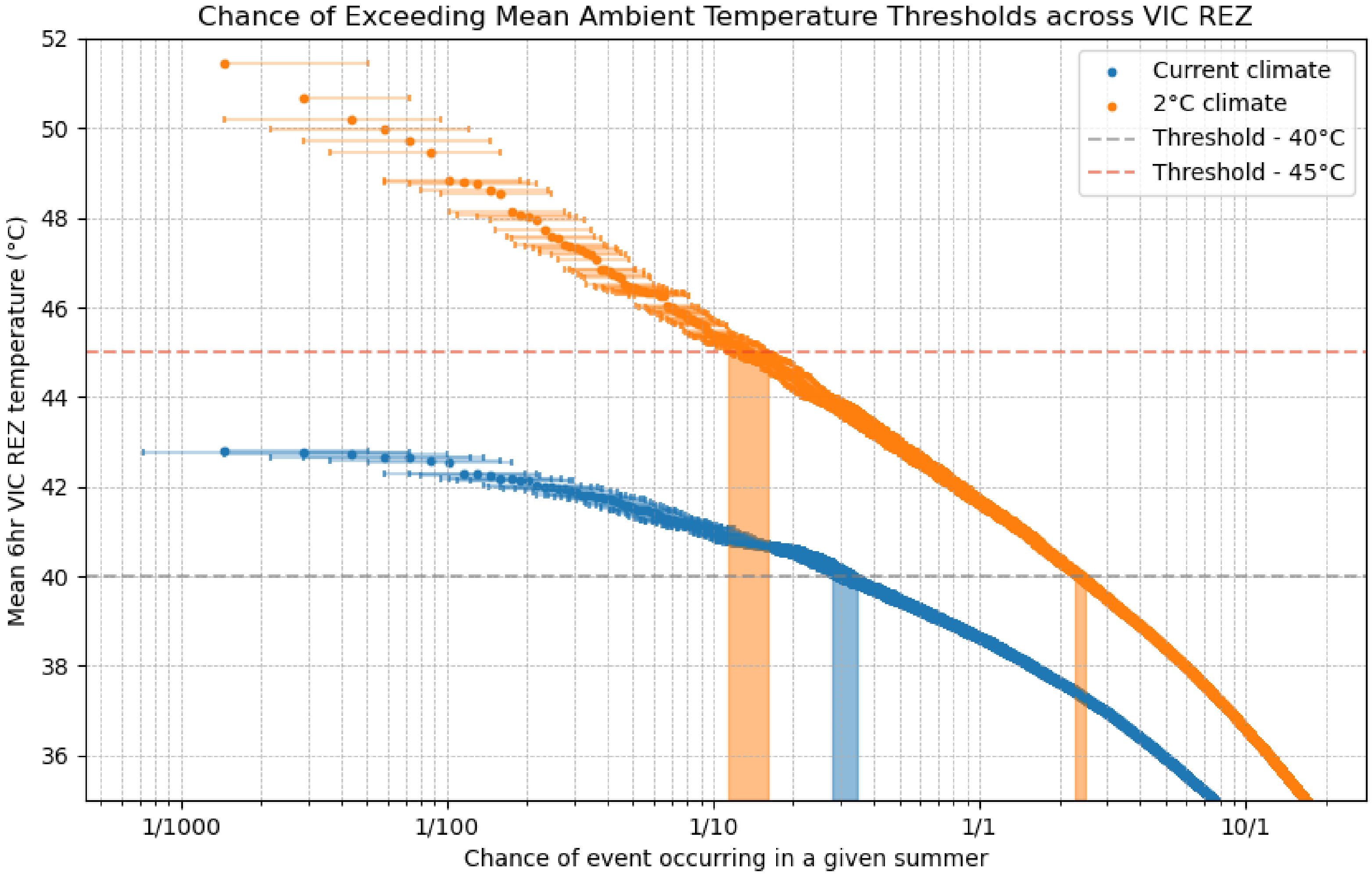
18% (+2%/-3%) ➡ 165% (+8%/-8%)

Probability Ratio

9.45 (+1.95/-1.38)

Corresponding to maximum static and dynamic temperature ratings in Victoria

Results: Generation risks REZs



~20% reduction in wind and solar - 40°C

Exceedance Likelihood

31% (+4%/-3%) ➡ 239% (+10%/-10%)

Probability Ratio

7.62 (+0.90/-0.83)

~65% reduction in wind - 45°C

Exceedance Likelihood

Not simulated ➡ 14% (+2%/-3%)

Results: Generation risks REZs

Description	Temperature Threshold (°C)	Likelihood of Exceeding Threshold Under the Current Climate (%)	Likelihood of Exceeding Threshold Under the 2 Degree Warming Scenario (%)	Probability Ratio
Drop in gas power plant and BSS efficiency	35	762 (+16/-16)	1686 (+24/-28)	2.21 (+0.06/-0.05)
Significant drop in solar PV production	50	Was not simulated	0.6 (+0.6/-0.4)	N/A

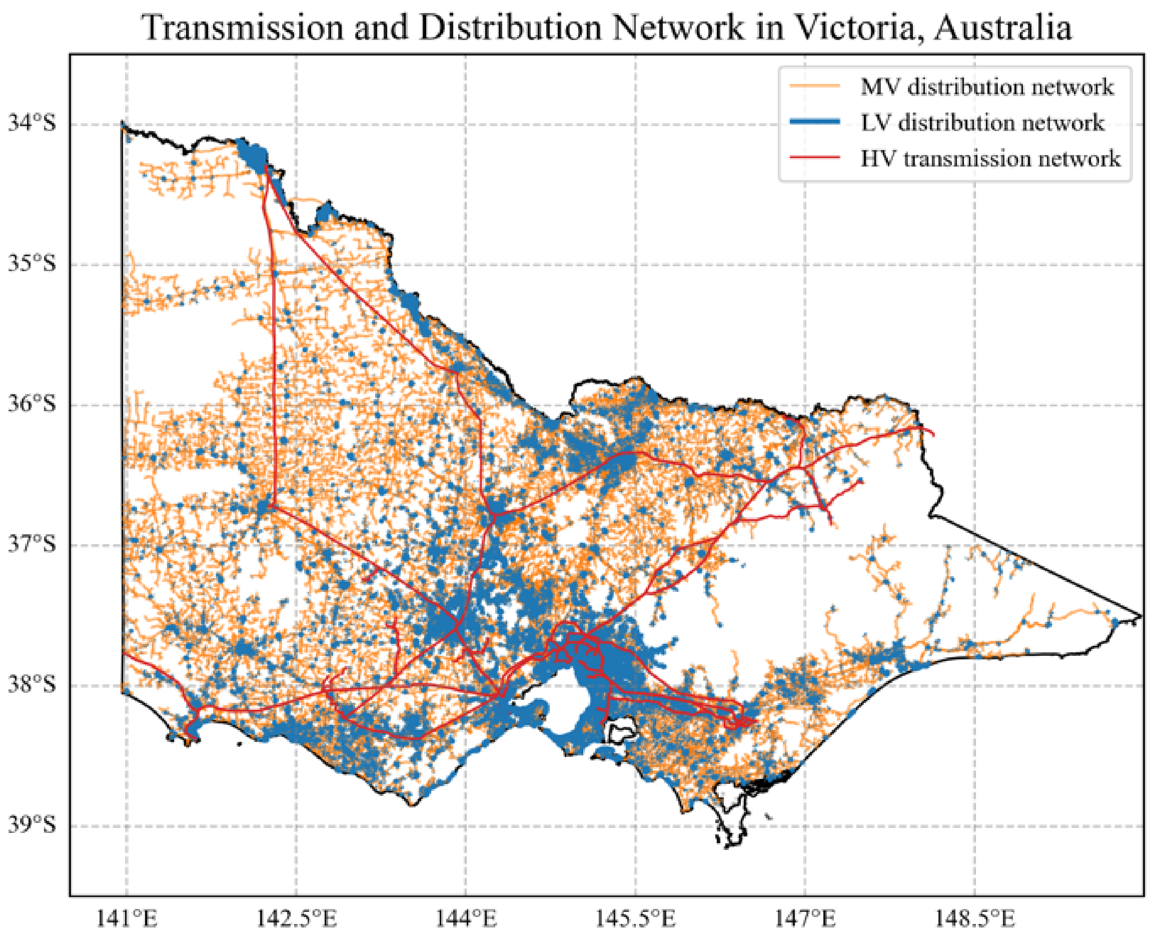
Conclusion

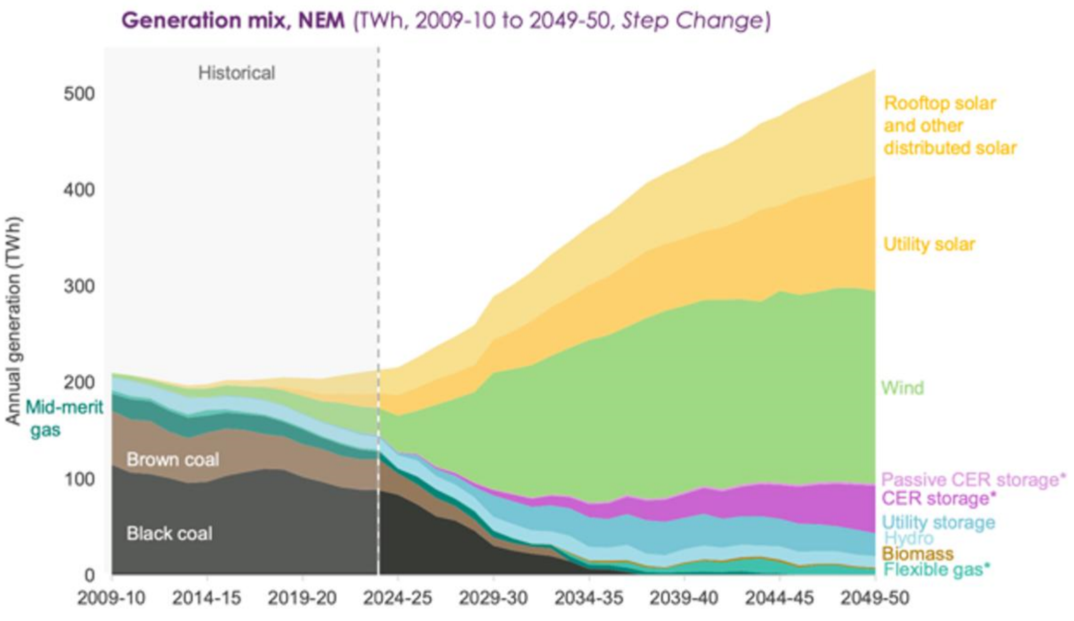
- Heatwaves are expected to intensify with future climate change, posing a risk to the security of Victoria’s electricity system
- Lack of regulations and industry standards to adequately assess and mitigate future climate risks
- Probabilistic approach shows significantly increased likelihood of exceeding critical whole system, transmission and generation temperature thresholds under a 2°C warming scenario
- Results demonstrate the need to incorporate climate-resilience into energy security planning to ensure system security at least cost

Questions?

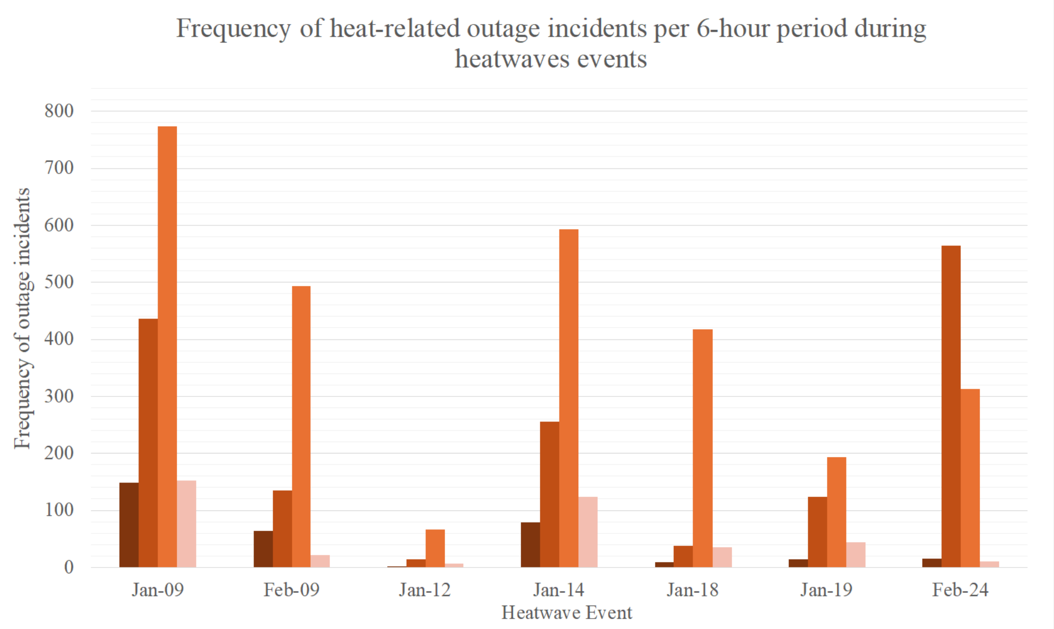
Limitations

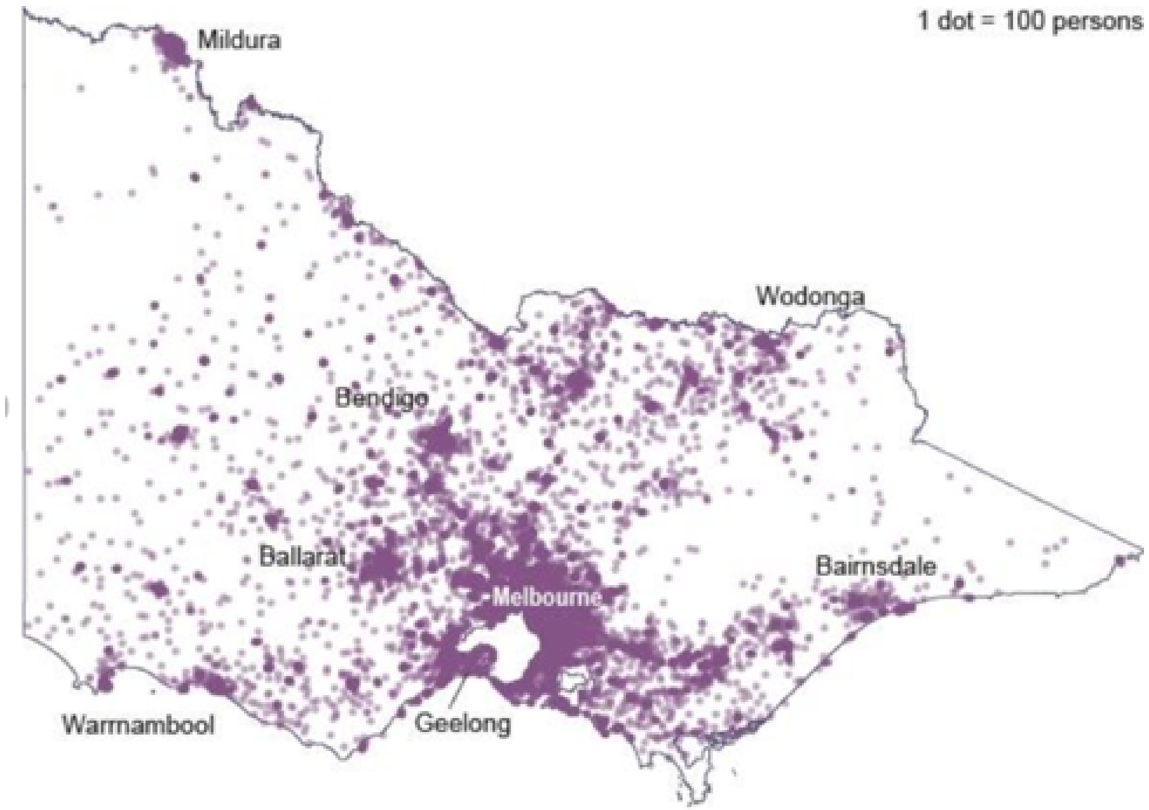
- **Dependence on Event Definition Robustness**
- **Uncertainty whether failure rates will remain constant**
- **Potential Changes in System Resilience – increase or decrease**
- **Impact of concurrent extreme weather events**
- **Exclusion of Wider NEM Influences**
- **Single model and scenario assessed**
- **Exclusion of Demand Dynamics**
- **Neglect of Urban Heat Island Effect and Humidity**



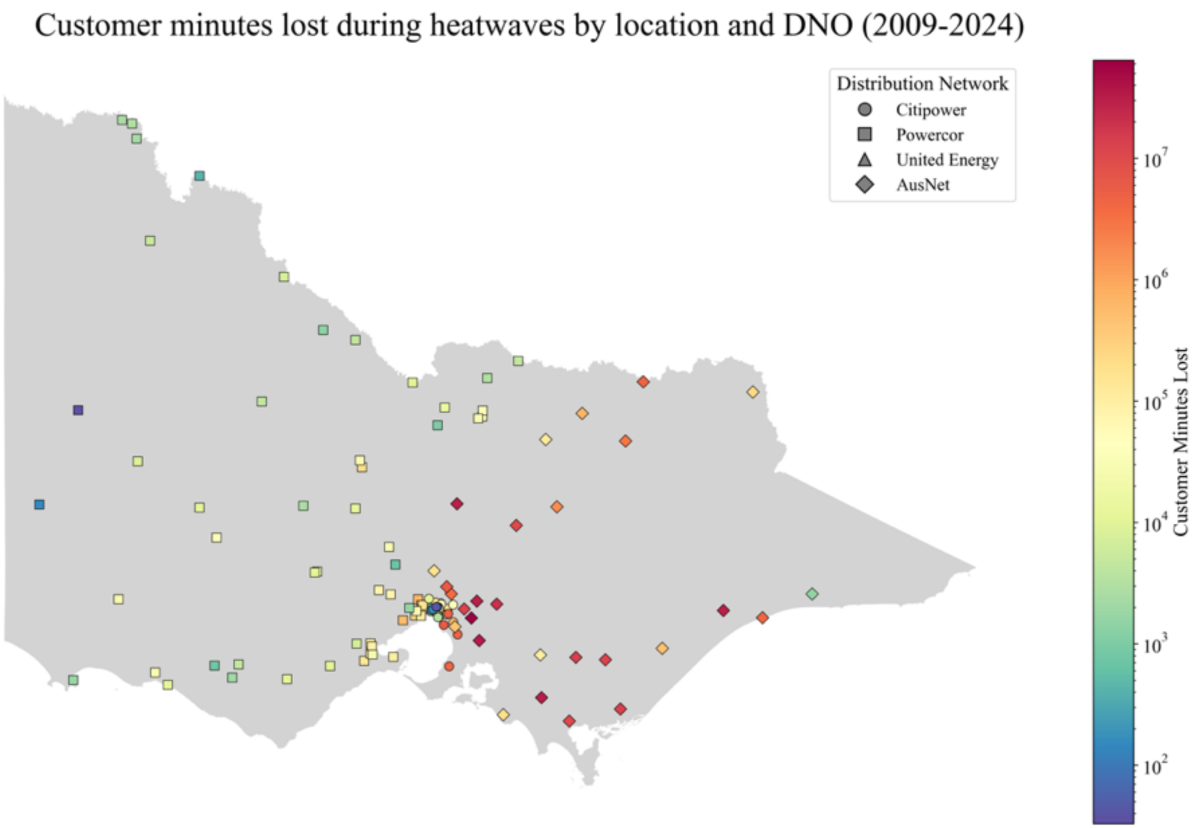


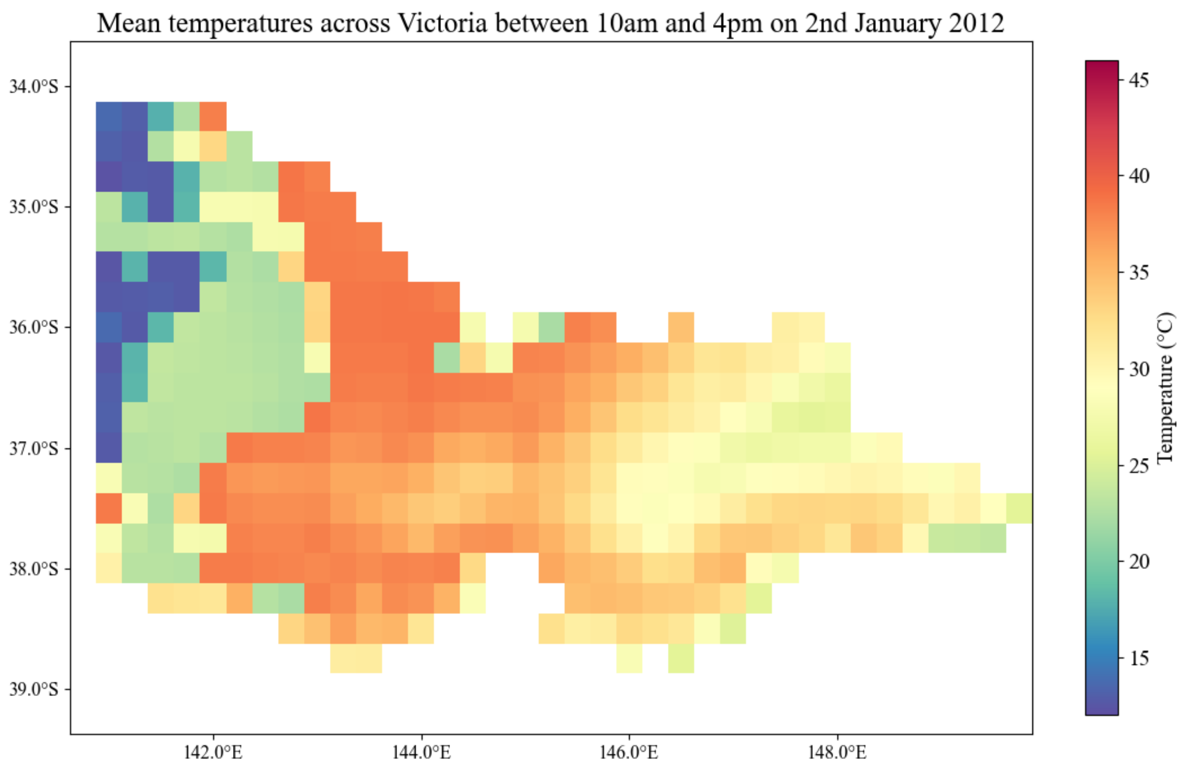
Notes: Annual generation for 2023-24 has been estimated for the full financial year.
"Flexible gas" includes gas-powered generation and potential hydrogen capacity.
"CER storage" means consumer energy resources such as batteries and EVs.





Population density, Victoria 2016 Source: ABS Census 2016




Mean temperatures across Victoria between 10am and 4pm on 2nd January 2012
34.0°S
35.0°S
36.0°S
37.0°S
38.0°S
39.0°S
142.0°E
144.0°E
146.0°E
148.0°E
Temperature (°C)
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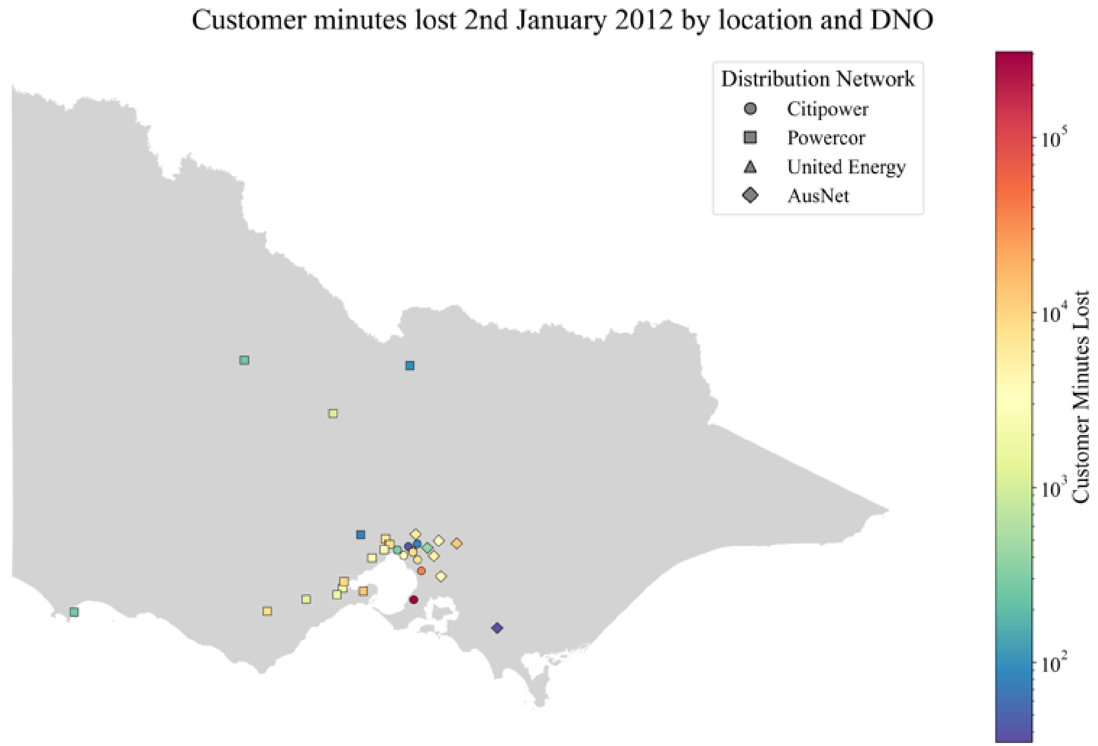
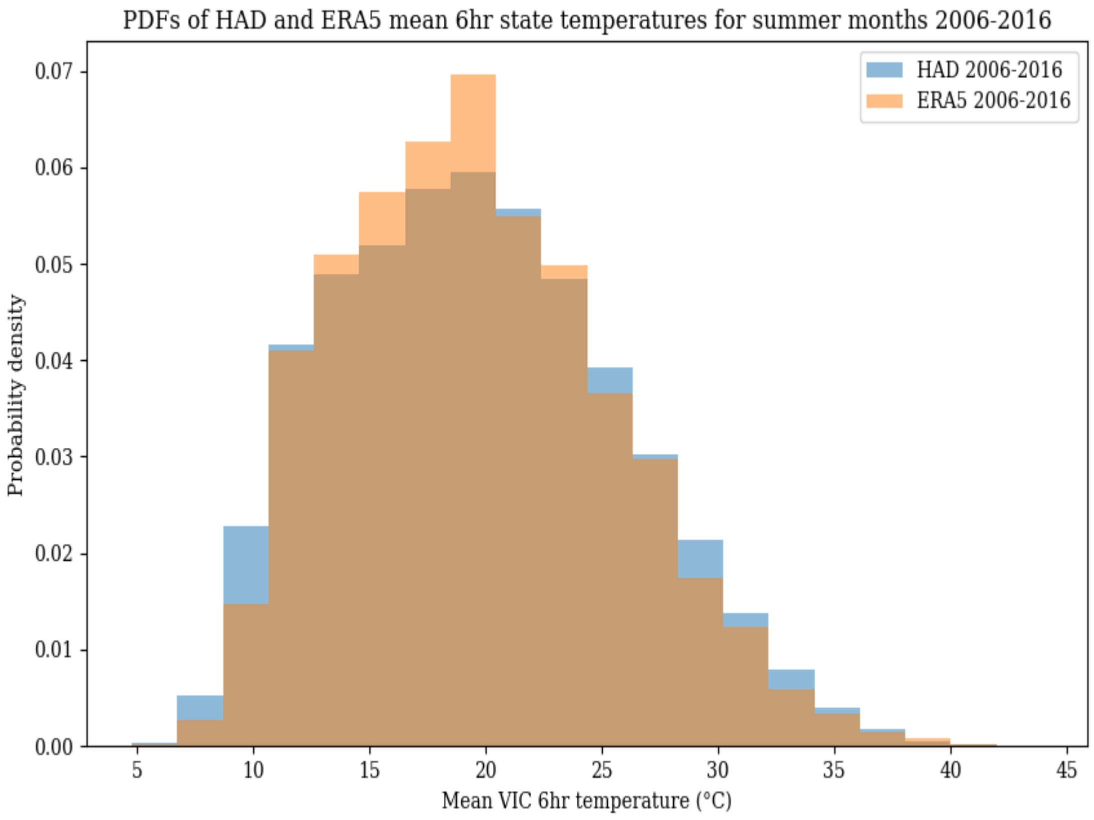
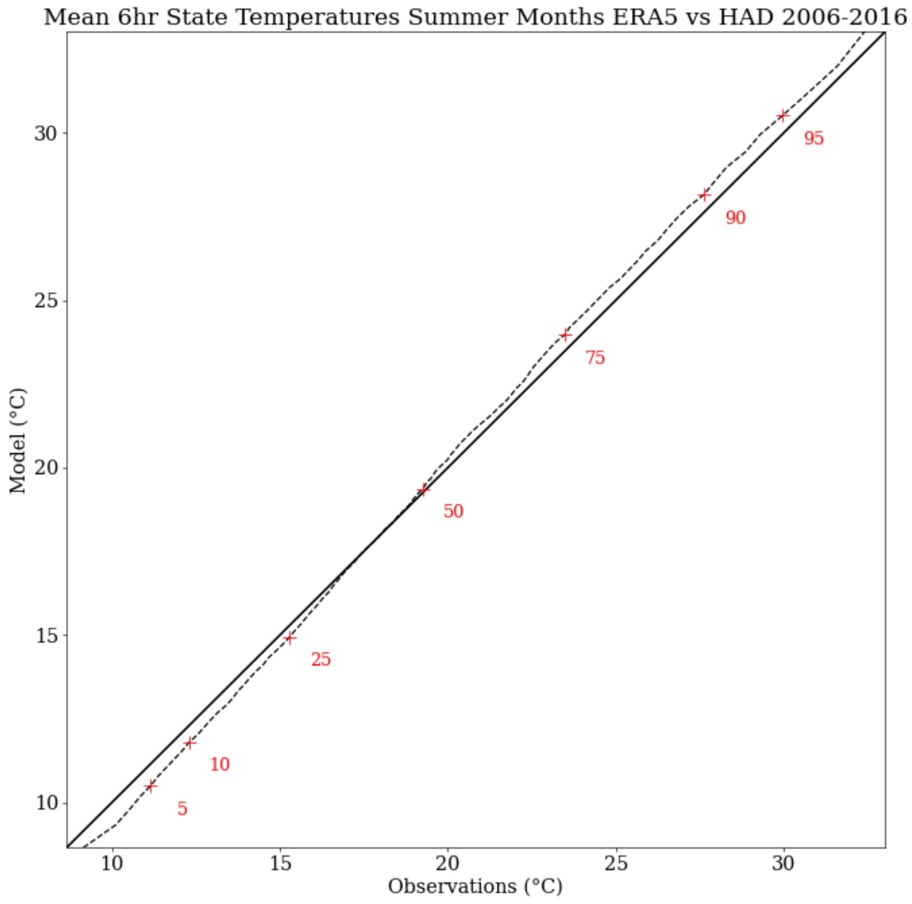
20
25
30
35
40
45


Customer minutes lost 2nd January 2012 by location and DNO
Distribution Network
Citipower
Powercor
United Energy
AusNet
Customer Minutes Lost
10^2
10^3
10^4
10^5

Model Evaluation





The PDFs have a high percentage overlap of 95.28%, indicating the HadAM4 model explains the majority of observed temperature variation.

Q-Q plot shows that the model reproduces the distribution of observed mean temperatures relatively well

Whole System Risks

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Number of instances in ERA5 data above 35 Degrees Celsius for 2009–2024: 48

Number of instances in ERA5 data above 37 Degrees Celsius for 2009–2024: 17

Number of instances in ERA5 data above 38 Degrees Celsius for 2009–2024: 10

Number of instances in ERA5 data above 39 Degrees Celsius for 2009–2024: 3
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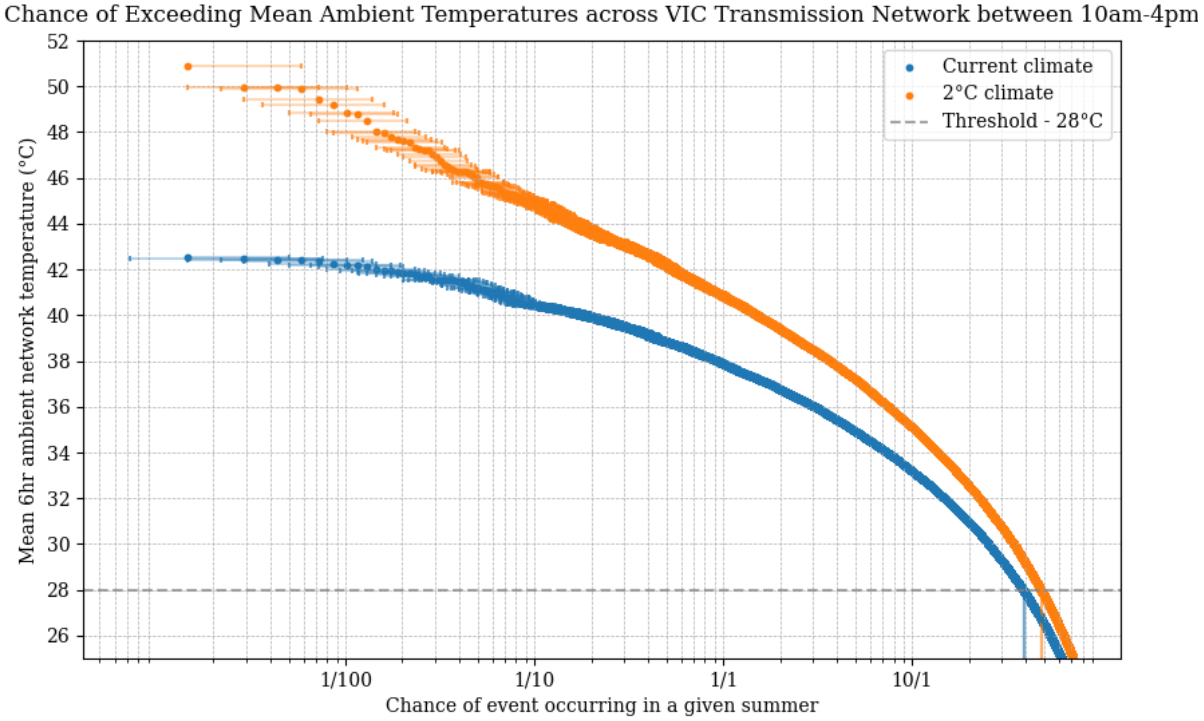
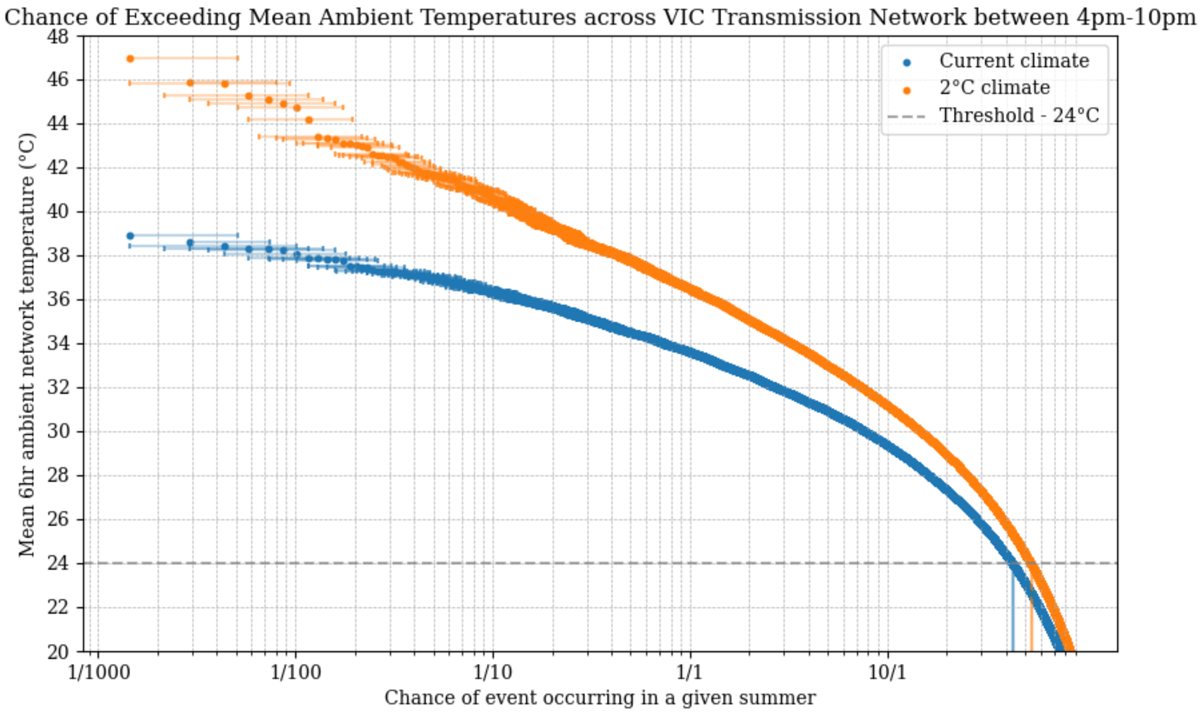
Temperature Threshold (°C)	Failure Rate (%)	Likelihood of Exceeding Threshold Under the Current Climate (%)	Likelihood of Exceeding Threshold Under the 2 Degree Warming Scenario (%)	Probability Ratio
39	100	28 (+4/-3)	206 (+9/-9)	7.48 (+1.07/-0.92)
38	70	59 (+4/-5)	318 (+11/-10)	5.43 (+0.56/-0.45)
37	41.18	122 (+7/-7)	486 (+14/-13)	4.00 (+0.27/-0.25)
35	31.25	394 (+13/-12)	1022 (+4/-5)	2.60 (+0.09/-1.00)

Results: Transmission risks





Conclusions

- limited analysis at both a whole systems and component-level restricts a comprehensive understanding of climate change impacts on Victoria’s electricity system. Compounding these challenges is a regulatory environment that fails to incentivize network operators and generation project developers to adequately integrate climate resilience planning