# How does Rooftop Solar Penetration Affect Generator Efficiency and Market Power?

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29 May 2019

*NBER Economics of Electricity Markets and Regulation Workshop*

# Solar panel penetration has been linked to higher electricity prices

- Retail electricity prices
  - Recovery of feed-in-tariffs and subsidies (ACCC 2018; Nelson et al. 2011)
  - Distribution network upgrades (Wolak 2018)
  - Pass-through of REC costs from Renewable Portfolio Standards (Greenstone et al. 2019)
- Wholesale electricity prices?
  - Lower prices in daylight hours, higher prices at sunrise/sunset? (Bushnell and Novan 2018)

# Objective + primary finding

This paper: How changing system demand patterns from mass-solar adoption are impacting **costs** and **competition** in wholesale electricity generation?

- Setting, Western Australia: Rooftop solar now covers $\approx 25\%$ of daylight load
- Using estimates of generator costs and gross margins, we find that over the recent rooftop solar boom in WA:
  - Payments to thermal generators increased 3%
  - Fuel costs incurred by thermal generators decreased 9%
  - Gross margins to thermal generators increased 19%
- These changes driven by changing shape of daytime to sunset load patterns (Bushnell and Novan 2018)
- Results emphasize benefits of a multi-settlement market design

1 Introduction

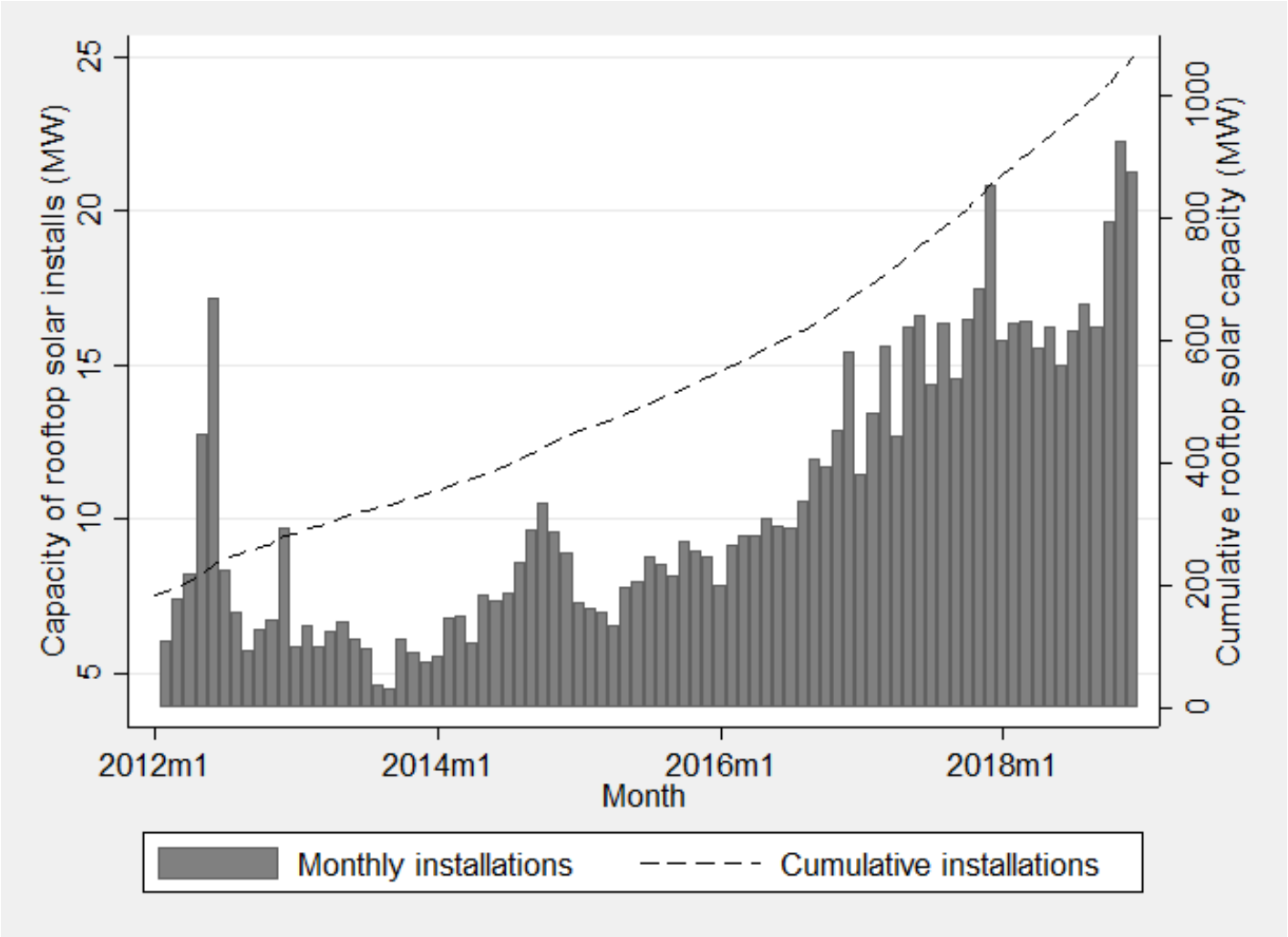
2 Background and setting

3 Conceptual framework

4 Analysis

5 Conclusion

# The growth in rooftop solar: Western Australia




- >5-fold increase in rooftop solar capacity in 7 years
- Regularly covered 20-25% of daylight load in 2018

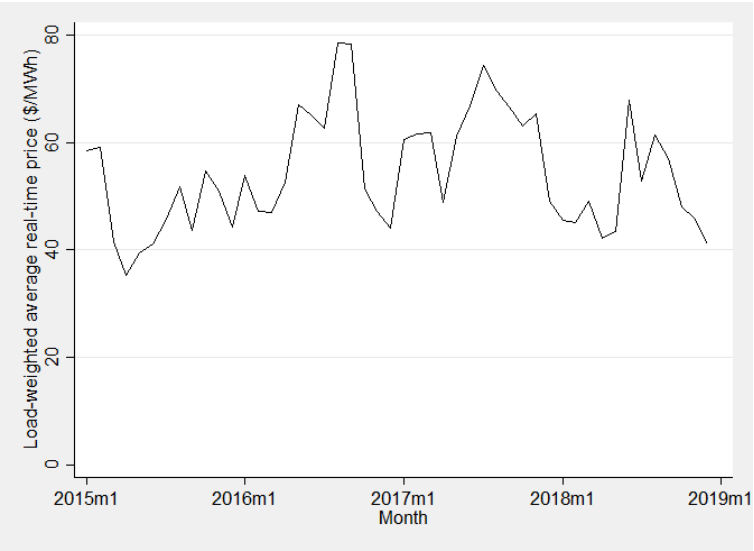
# What we can learn from the WA wholesale market (SWIS)

Since 2015:

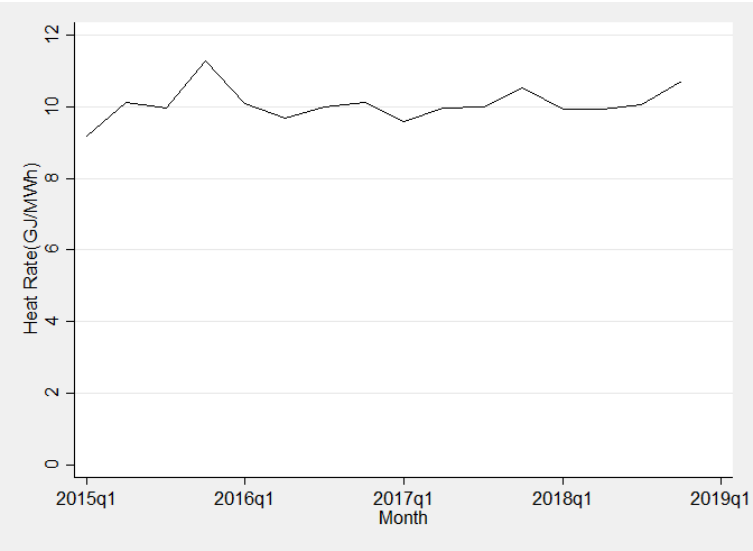
- Large rooftop solar penetration, utility-scale renewable capacity almost negligible
- No major entry / exit of thermal plants
- Aside from rooftop solar impact, system demand similar
- Uniform price market with no interconnections

$\Rightarrow$ Great conditions to study the impacts from mass rooftop solar adoption on wholesale market prices, costs and competition

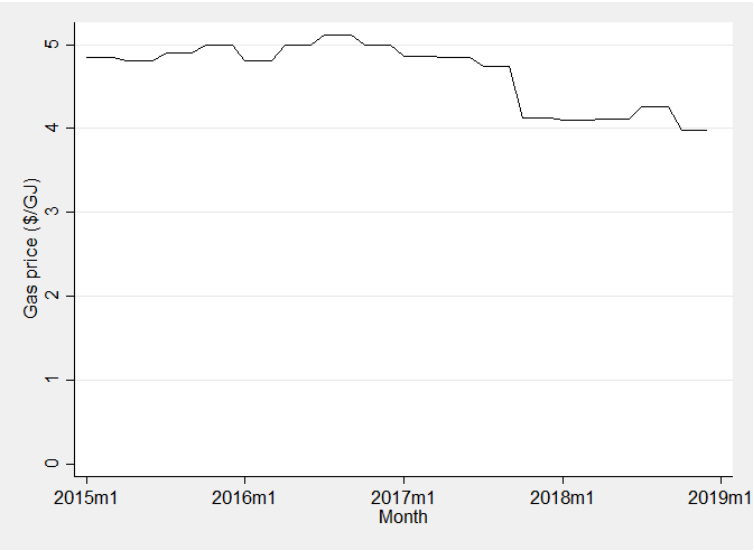
# Trends in electricity price, fuel prices and heat rates



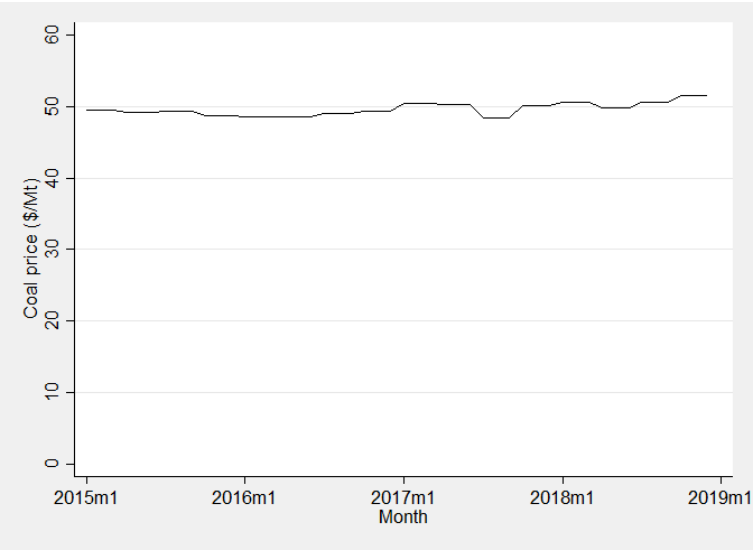

Load-weighted real-time elec. price




Aggregated gas-fleet heat rate




Gas prices



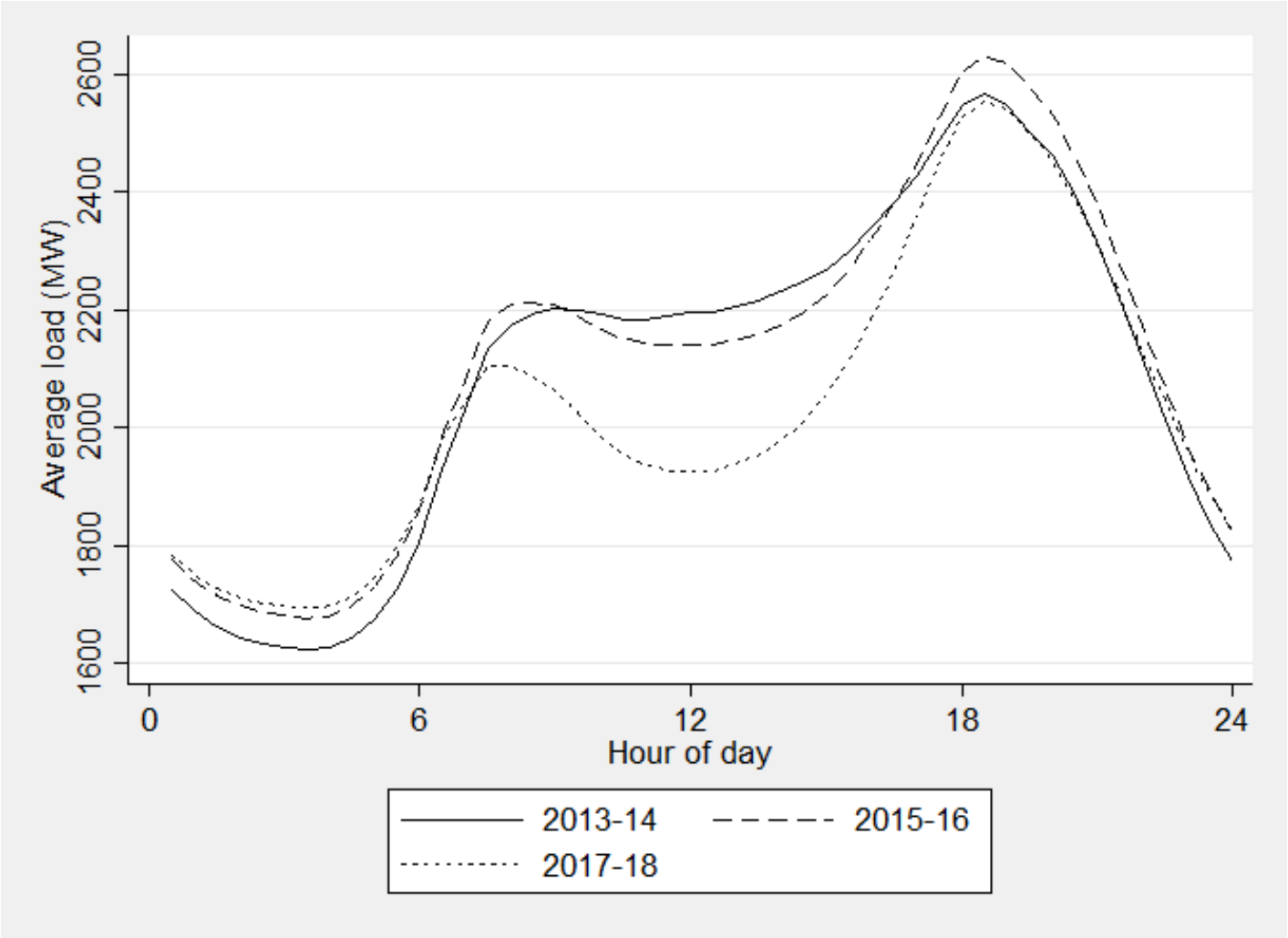

Coal prices

# Trends in electricity price, fuel prices and solar

January 2015 to December 2018:

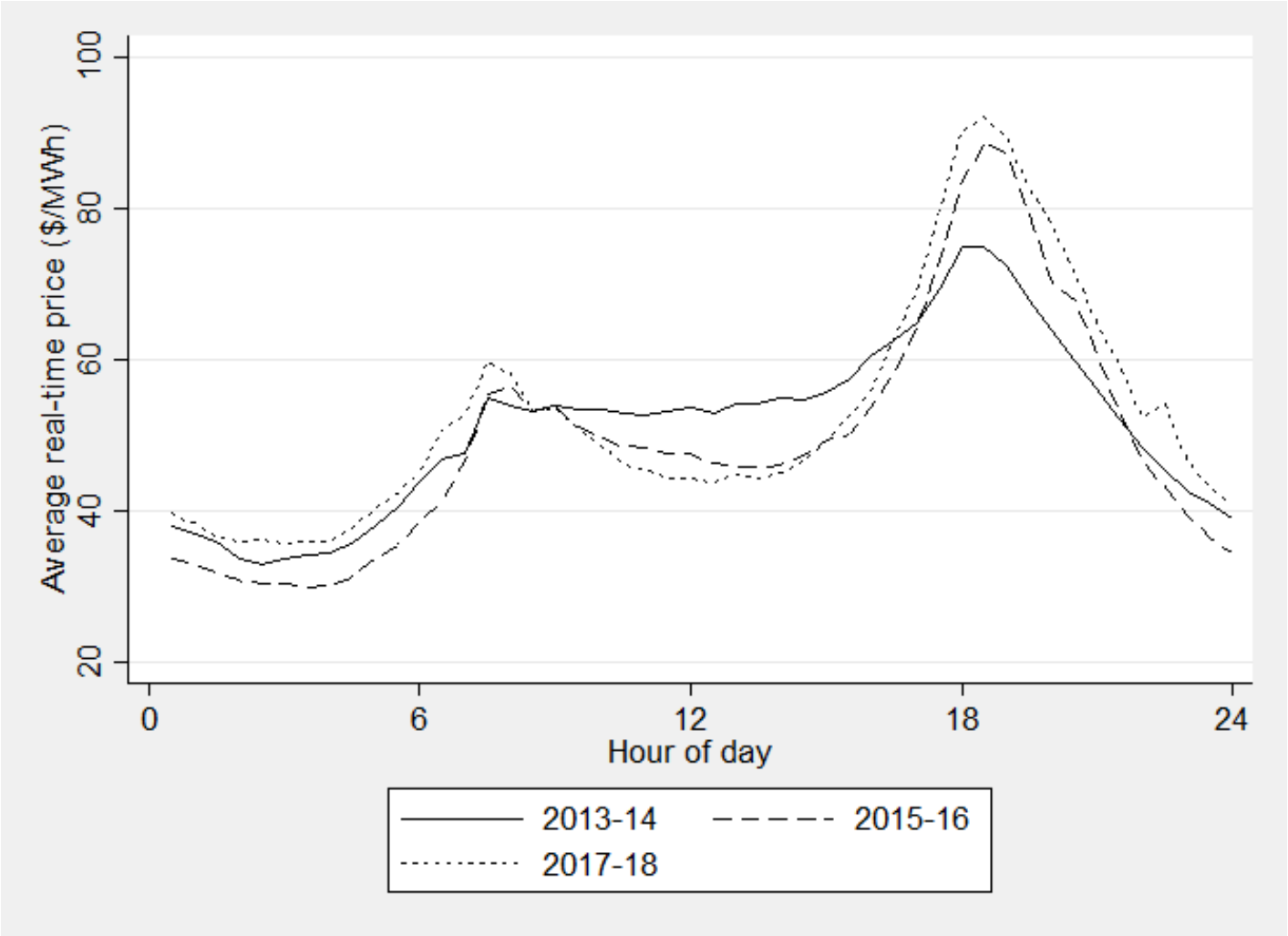
- Wholesale electricity prices $\Uparrow$ 6%
  - \$47.4/MWh to \$50.2/MWh Annual load-weighted average balancing market price
- Aggregate gas-fired generating fleet heat rate $\Uparrow$ 1%
  - Calendar year 2015 versus 2018
- Natural Gas prices $\Downarrow$ 17%
  - Natural gas accounts for $\approx$ 41% of system demand
- Coal prices $\Uparrow$ 5%
  - Coal accounts for $\approx$ 50% of system demand
- Rooftop solar generating capacity $\Uparrow$ 133%
  - 448 MW to 1,045 MW (from $\approx$ 10% of middle-of-day load to 20-25%)
- Why isn't the growth in rooftop solar adoption resulting in lower wholesale electricity prices?

# Is it the "duck curve?" (or WA's "black swan?")




- System demand: Middle of day dip, but end of day ramp has increased

# Is it the "duck curve?" (or WA's "black swan?")




- Prices: Middle of day now cheaper, but sunrise / sunset more expensive

# Is it the "duck curve?" (or WA's "black swan?")

- Can envisage two reasons why mass rooftop solar adoption could result in higher wholesale prices:
  1. Costs: Base load generation (high start-up costs, low marginal costs) becomes less viable and is replaced by peaking generation (lower start-up costs, higher marginal costs)
  2. Competition: Less generating units are capable to ramp up for peaks. Those left operating face less competition and therefore might be able to exercise market power to capture more rents
- The analysis considers these two factors
  - Construct variable fuel cost and gross margin measures (BBW 2002); supply function semi-elasticity (McRae & Wolak 2014)
  - Study changes in these measures with the adoption of rooftop solar across hours of the day (Bushnell and Novan 2018)

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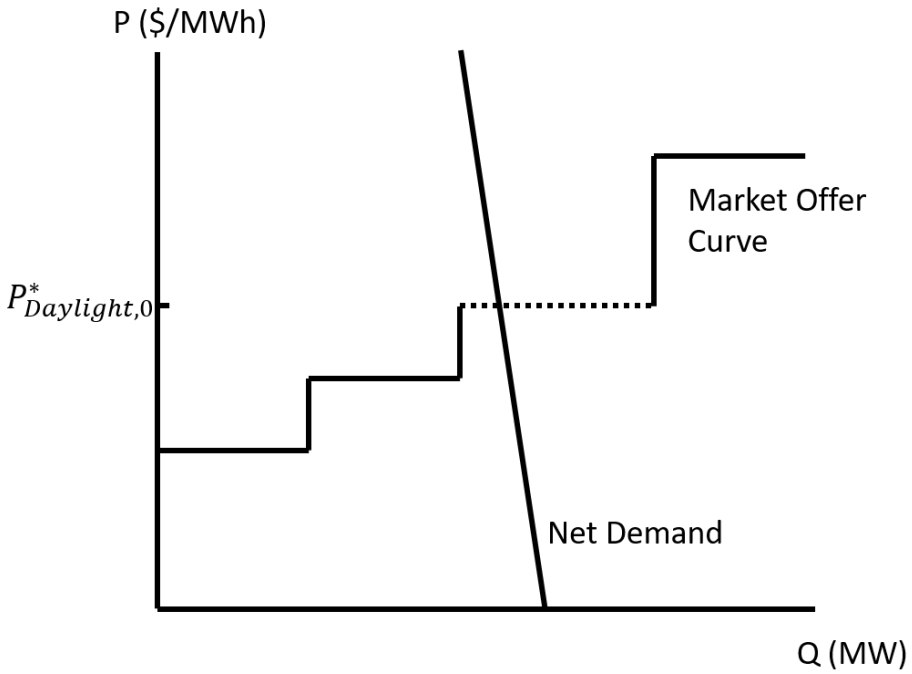
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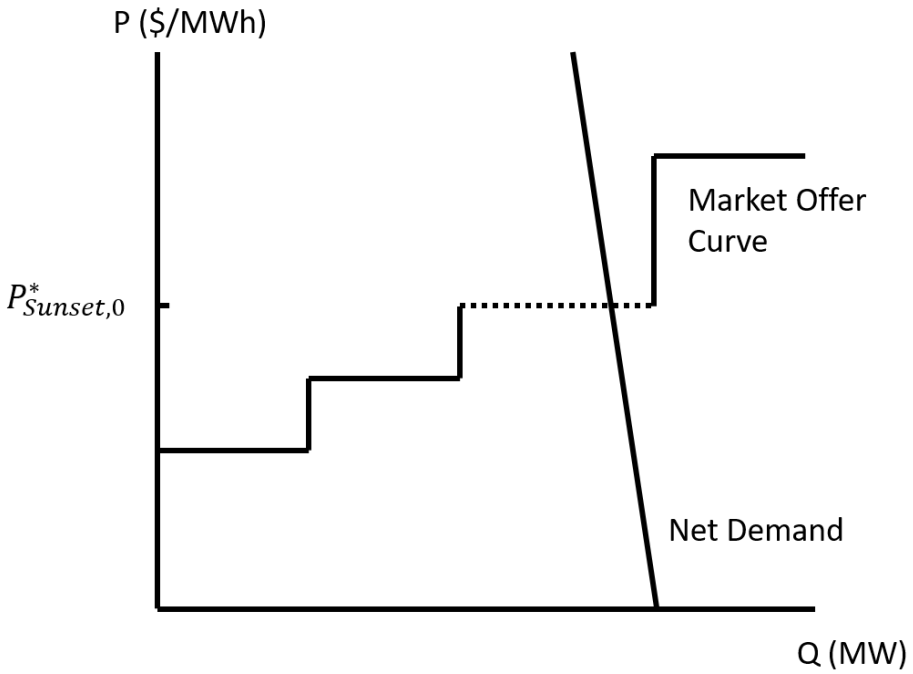
4 Analysis

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# Pre-solar penetration market outcomes



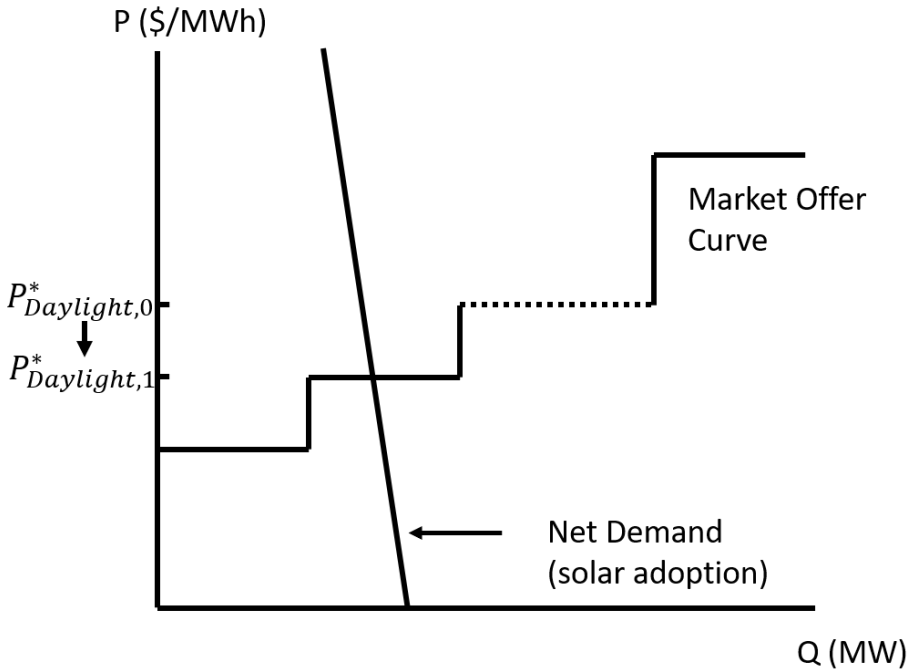

Daylight hours



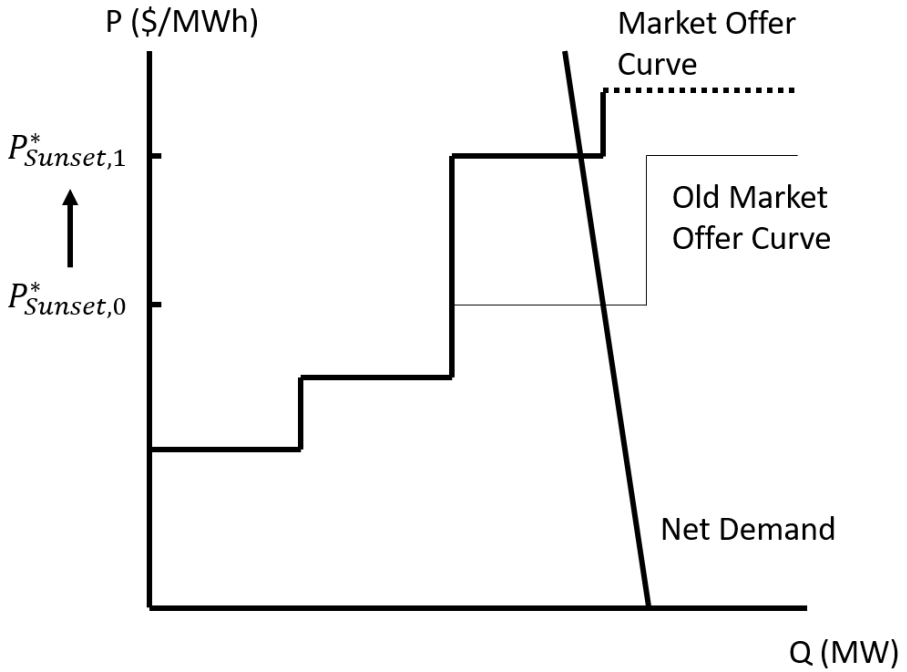

Sunset hours (daily demand peak)

- Third generator has start-up costs, recovers them over both intervals
- Same clearing price daylight and sunset

# Post-solar penetration market outcomes



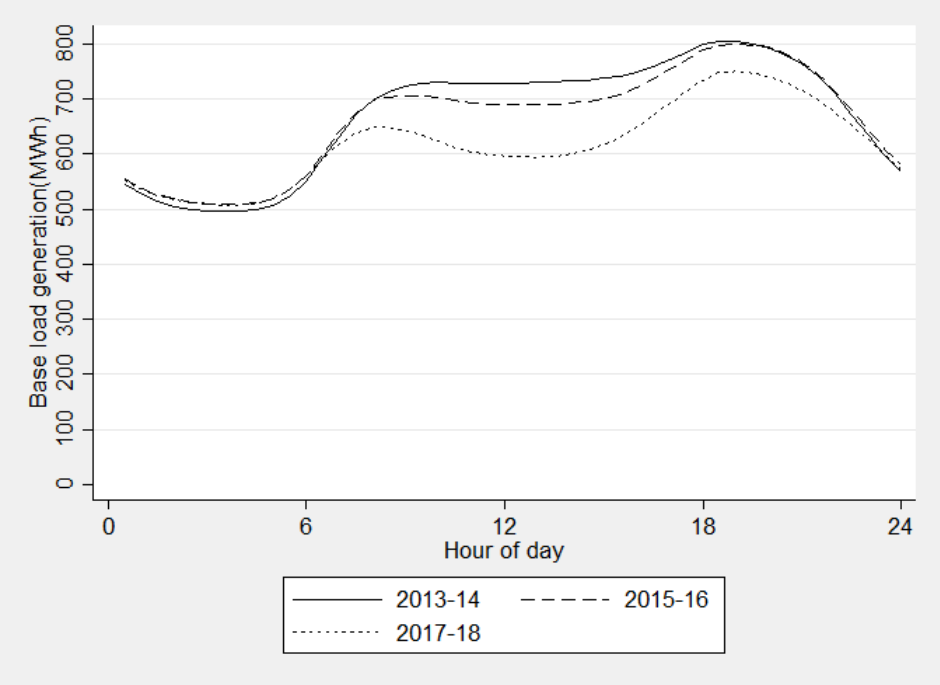

Daylight hours (r'top solar demand shift)



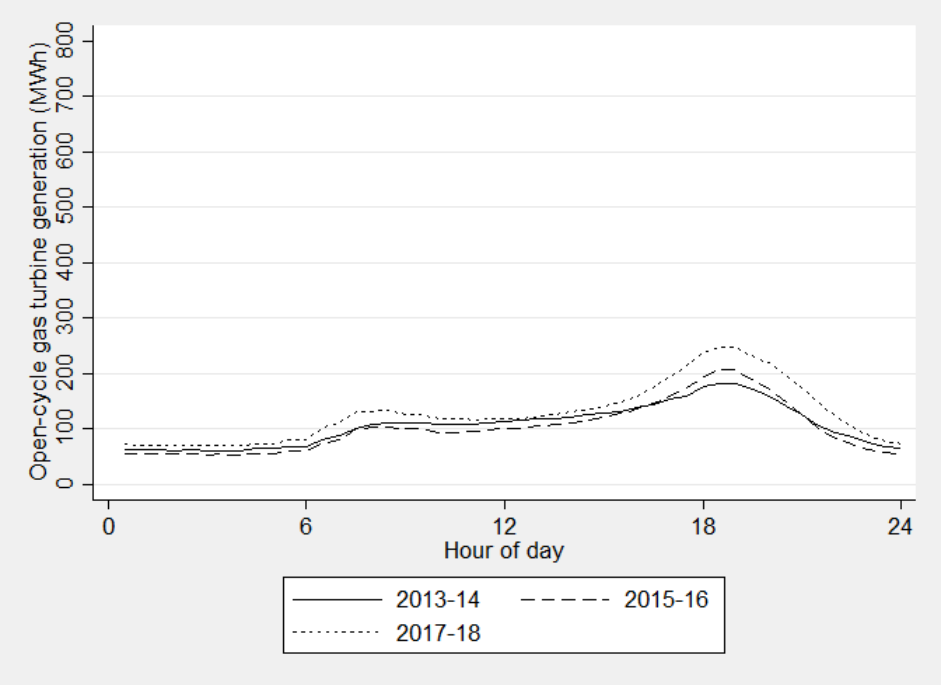

Sunset hours (daily demand peak)

- Third generator not running in daylight, increases bid price at sunset
  Observed behaviour
- Prices fall in daylight, rise in the evening

# Base load and peaker substitution




Coal + CCGT generation (base load)




OCGT generation (peakers)

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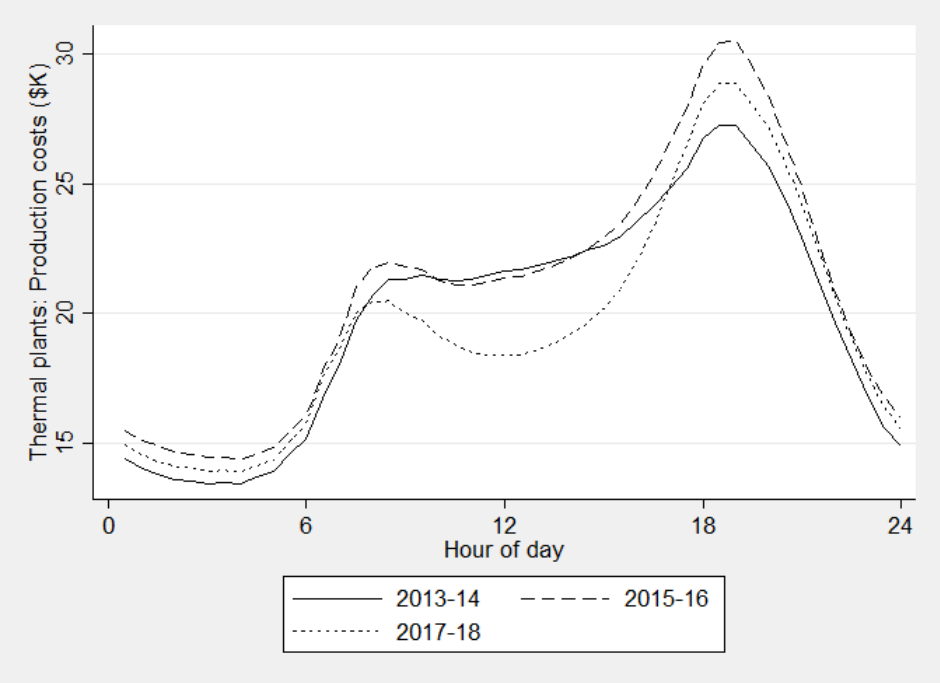
# Changes in costs and competition over time

Similar to BBW (2002), examine changes in variable fuel costs and gross margins for thermal generators over time

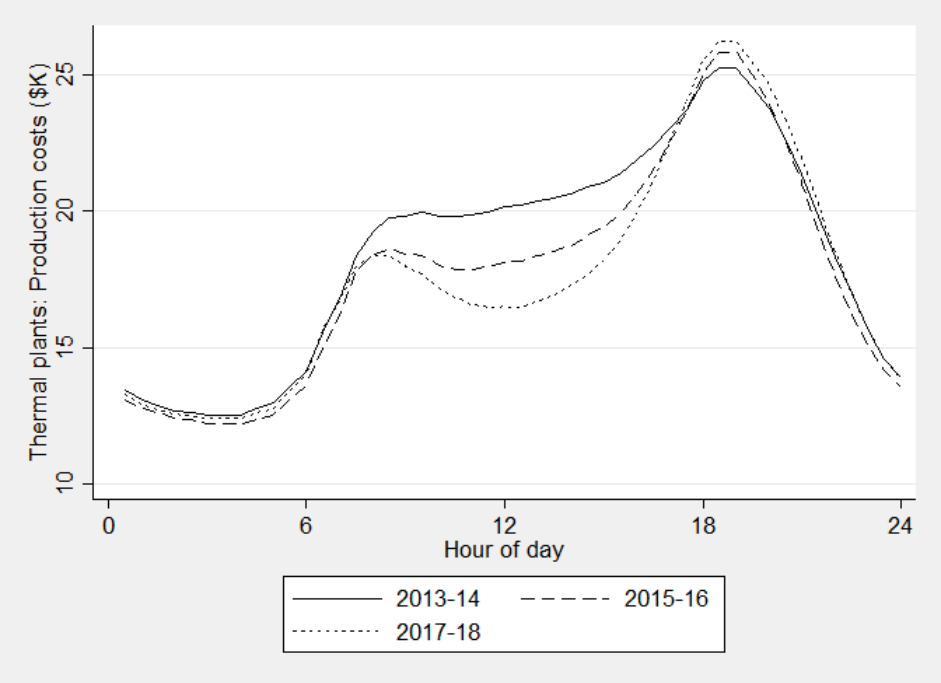
- Variable fuel costs estimated using heat rate estimates, fuel costs and output
- Gross margins is the difference in total revenues (assuming real-time price applies to all output) and variable fuel costs

(Preliminary, but indicative)

# Variable fuel costs for fleet of thermal units



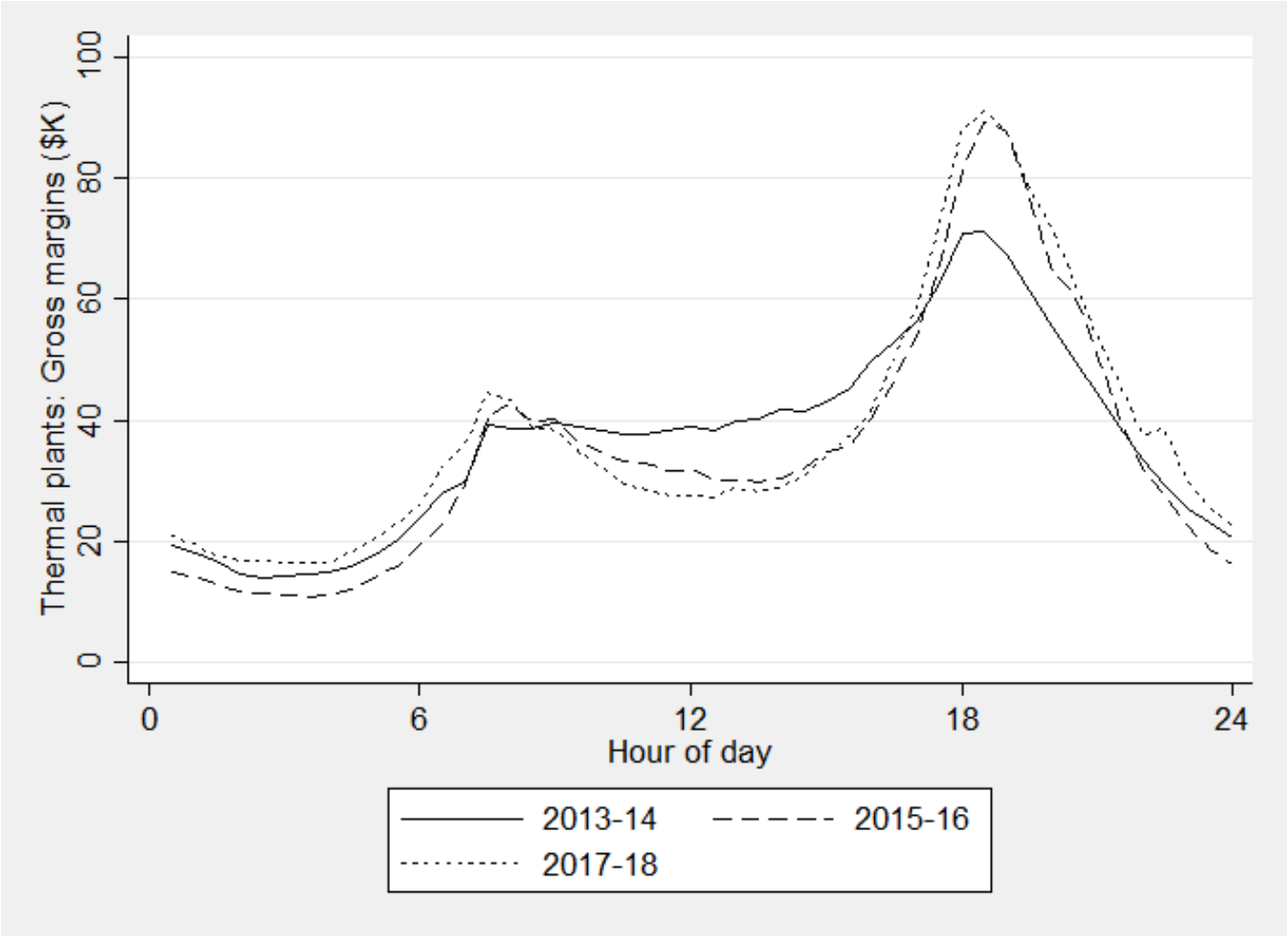

Average fuel costs for thermal fleet




Average fuel costs for thermal fleet, fixing fuel prices to 2013 levels

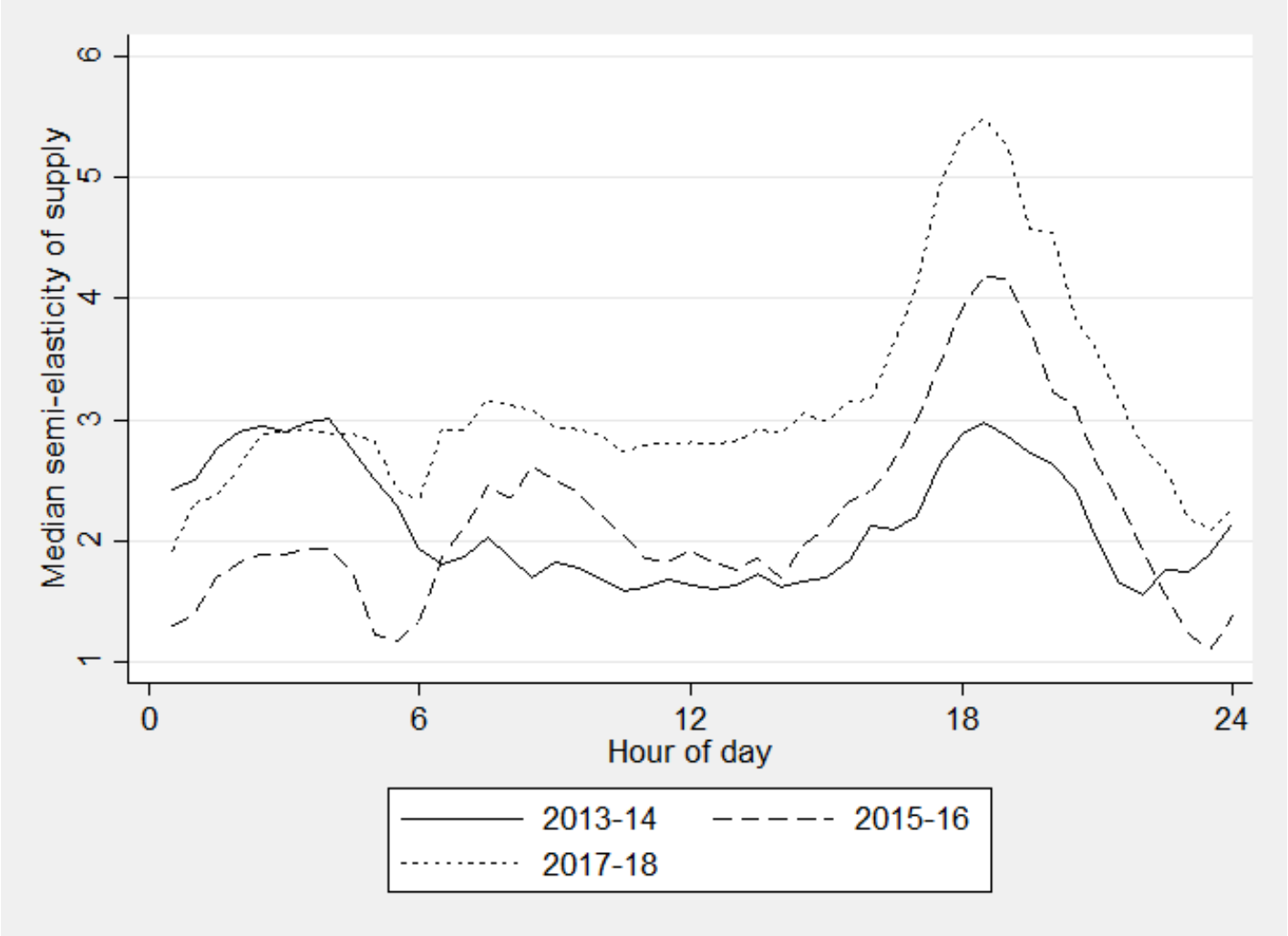
- Costs at sunset peak have risen over time (when holding fuel prices fixed)

# Gross margins for fleet of thermal units




- Profitability at sunset (and sunrise) is improving, daytime diminishing

# Supply function semi-elasticity




- Reports the median \$/MWh change from a 1% increase in net load
- Increased ability for firms to raise prices over time (esp. at sunset)

# Summary: Competition + costs over time

- Comparing 2015 to 2018, under the constant HR assumption for estimating costs and assuming that load pays the real-time price for all energy:
  - Total payments to thermal generators increased $32m (3%)
  - Total fuel costs incurred by thermal generators decreased $21m (-9%)
  - Total gross margins to thermal generators increased $53m (19%)
    - Gross margins to coal increased $9m (3%)
    - Gross margins to CCGT gas increased $18m (290%)
    - Gross margins to OCGT gas increased $26m (260%)
  - Peakers (but also inframarginal generators that operated) have profited from the diminished competition at sunset
  - Despite the cost-of-generation decrease, load / consumers have not received lower prices (and are unable to respond to new dynamics)

# Impact of rooftop solar growth on the wholesale market

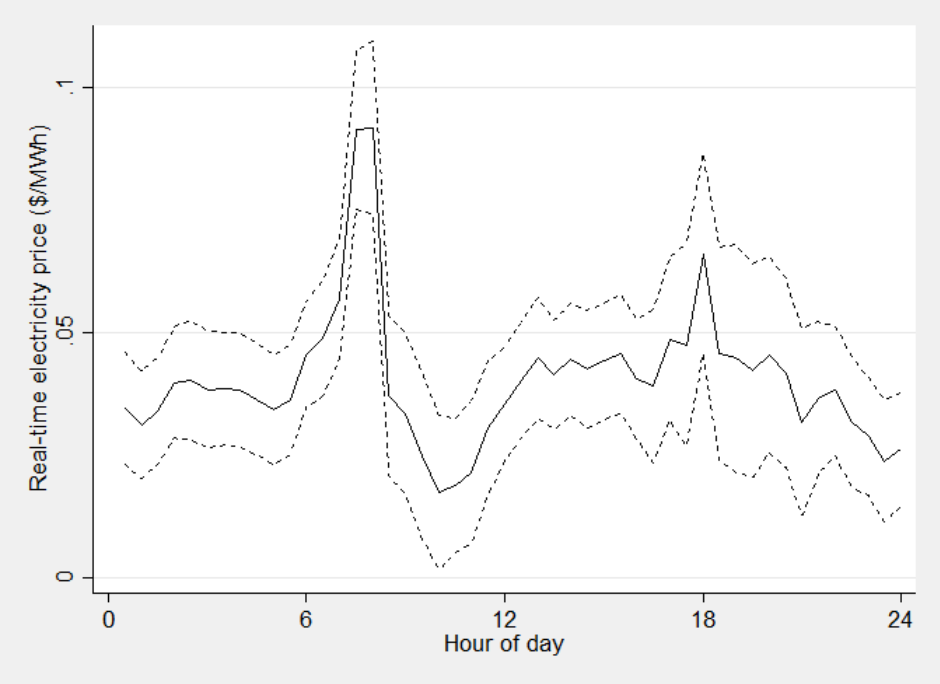
For each half-hour of day sample, estimate $\beta$:

$$y_t = \alpha_{m(t)} + \beta.RSC_t + \theta.\mathbf{X_t} + \epsilon_t \quad (1)$$

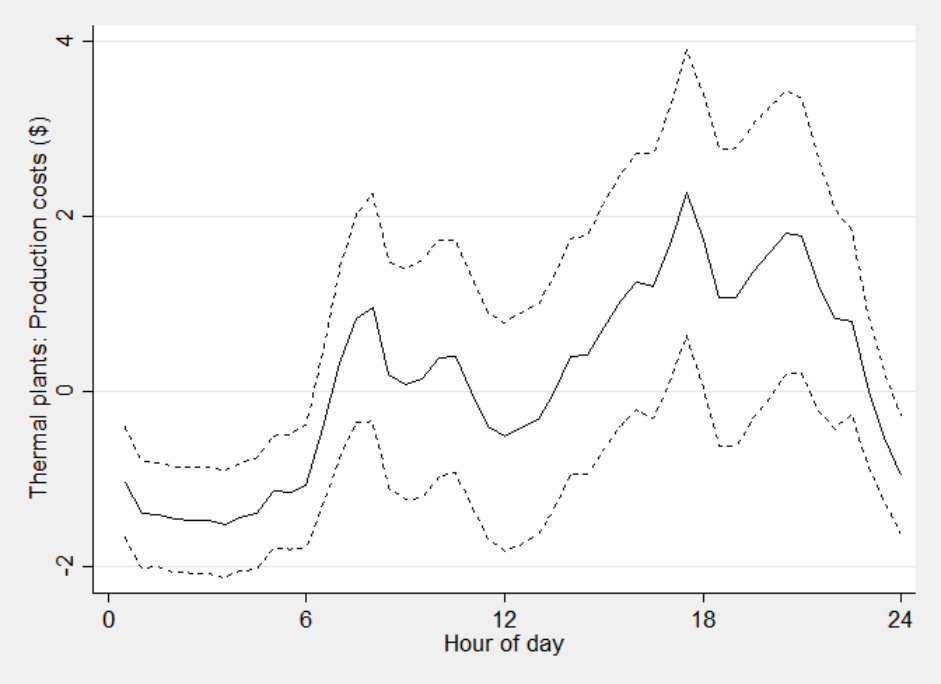
- $t$ indexes the day (with $\alpha_{m(t)}$ a month-of-year fixed effect).
- $RSC_t$: Rooftop solar capacity in MW
  - Not an output measure as in Bushnell and Novan
- Controls $X_t$: load, output from dispatchable thermal generating plants, coal prices and natural gas prices. Summary Statistics

- Static world with no start-up/ramping cost dynamics: $\beta = 0$.
- Reality: $RSC$ can affect non-daylight outcomes via impact on shape of system demand throughout day.

# Predicted change in wholesale market outcomes per additional MW of rooftop solar capacity



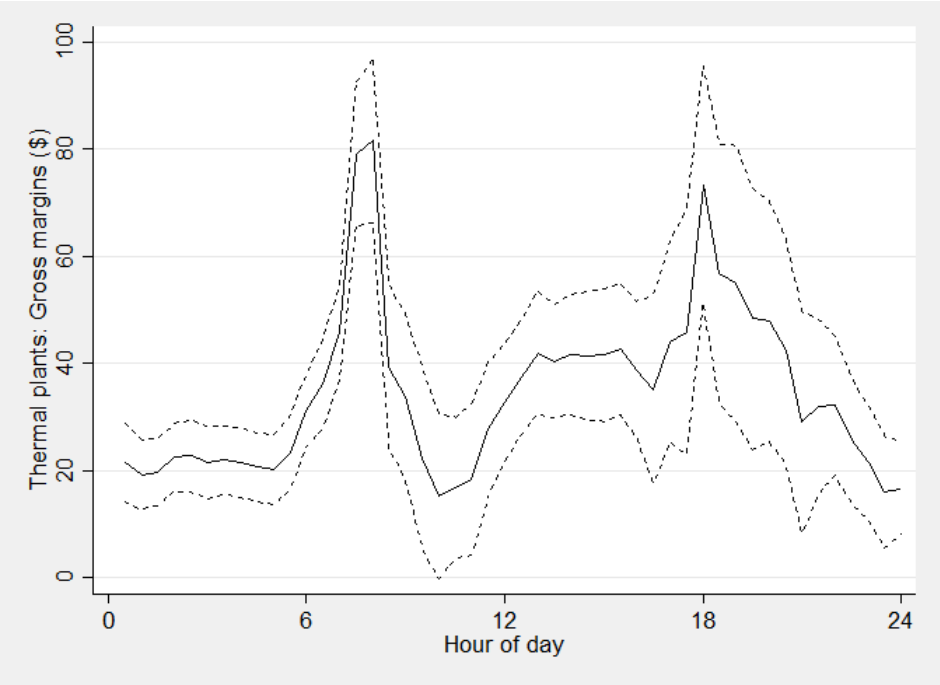

Real-time electricity price



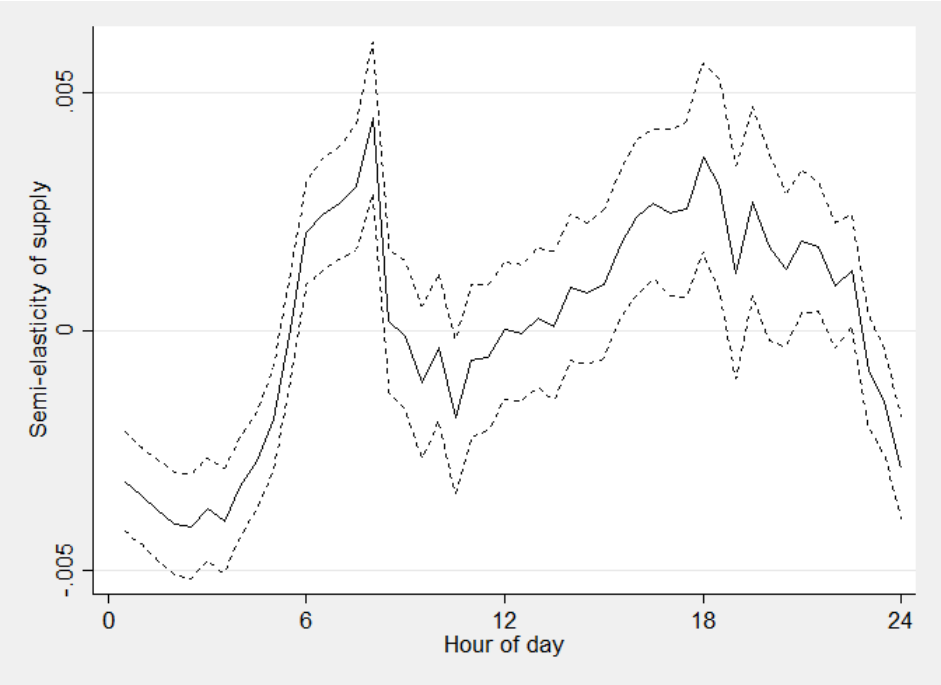

Average fuel costs for thermal fleet

- Prices: 100MW increase in RSC predicted to raise prices by \$6/MWh at sunset (average sunset load $\approx$ 2400MW)
- Fuel costs: Noisy, but sunset point estimate for 1MW $\uparrow$ in RSC $\approx$ substitution of 0.2MW CCGT to OCGT

# Predicted change in wholesale market outcomes per additional MW of rooftop solar capacity




Gross margins for thermal fleet




Semi-elasticity of the market supply curve

- Gross margins and slope of the supply curve most responsive to solar additions for sunrise and sunset hours

# Market design implications

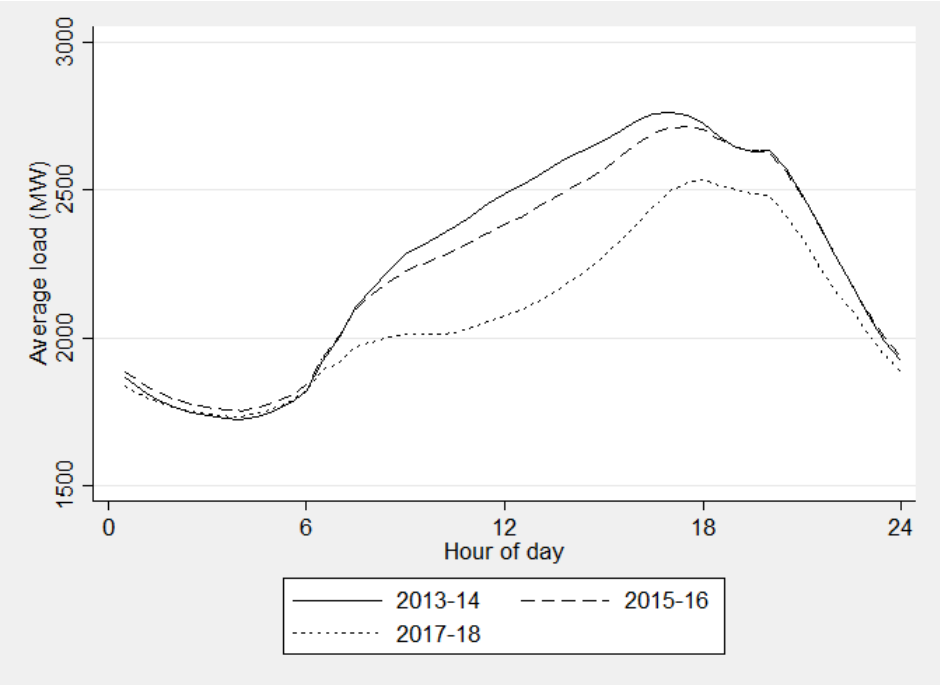
- The impact of changing system demand (or generating behind the meter) is not isolated to the contemporaneous period
- Efficient market design will pay / charge participants based on the impact of their actions on as-bid total system cost across the day
  - Need day-ahead / multi-settlement market to do this (Australia's NEM, are you listening?)

# Market transition

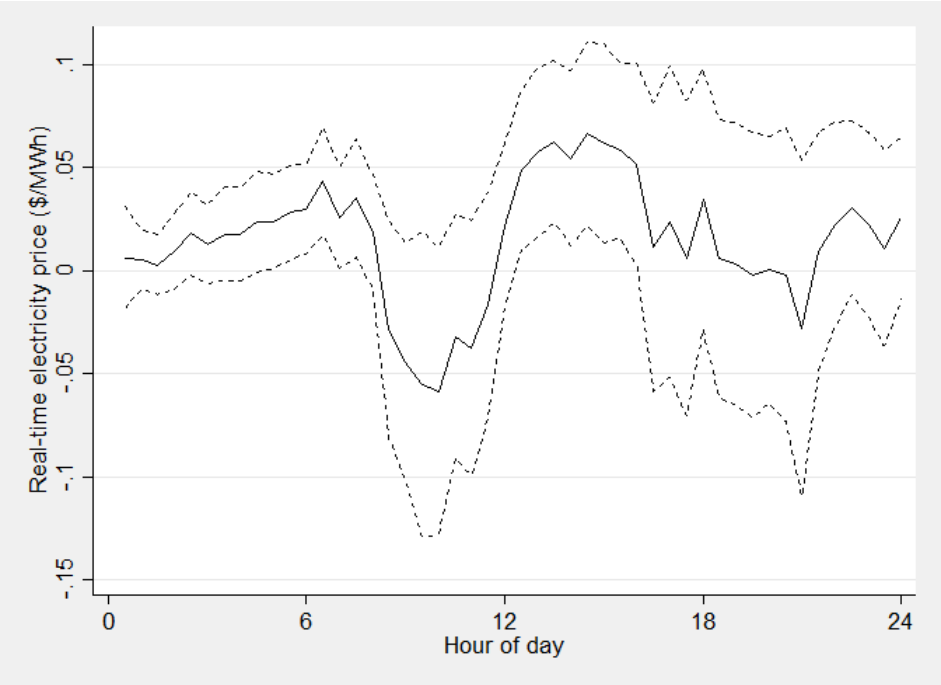
- The mass adoption of rooftop solar has exacerbated the price differences between peaks and troughs in Western Australia
  - Expect benefits to flexible supply and demand technologies
  - Currently, inframarginal units that remain operating are also benefiting
  - Obviously, the wholesale market value of additional solar capacity is diminishing

What climates do we expect the introduction of solar capacity (and the associated change to system demand dynamics) to have a bigger impact on within-day price dynamics?

# Summer



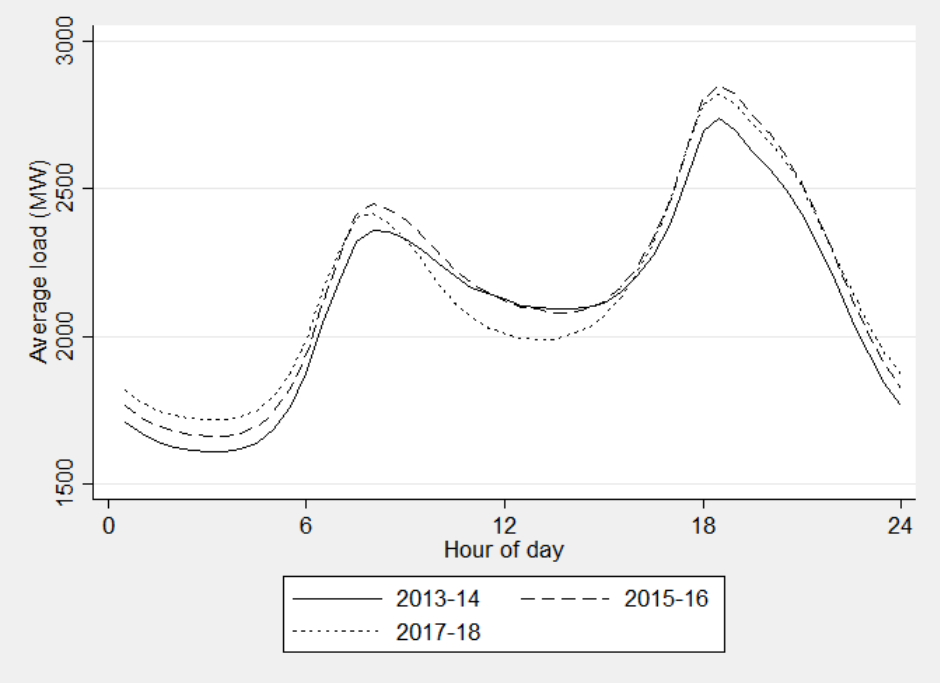

Average system demand by hour-of-day



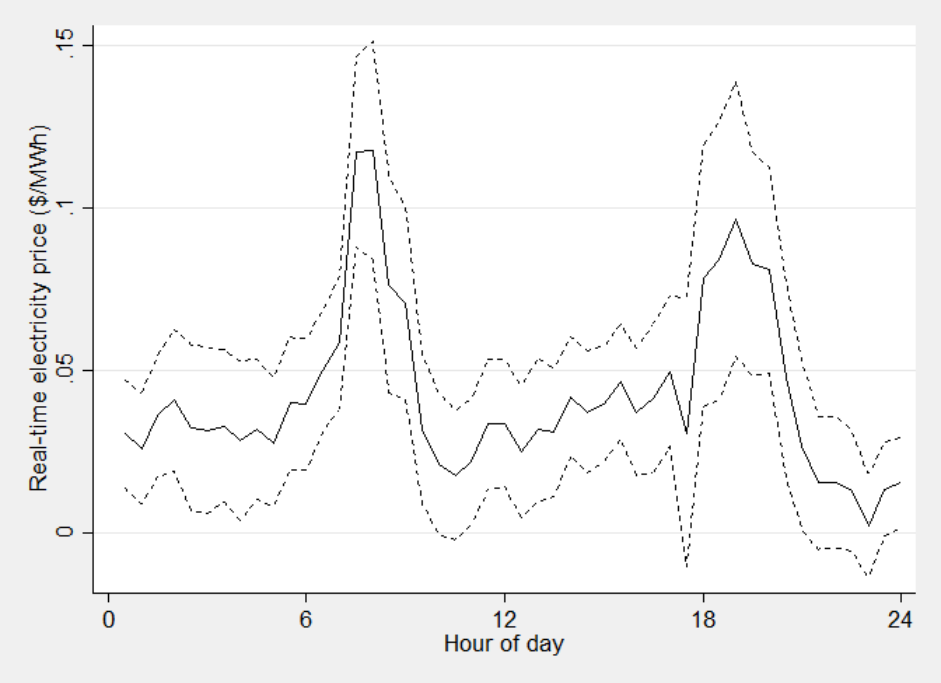

Predicted change in wholesale prices per additional MW of rooftop solar capacity

- Solar output is somewhat load-following: Demand and price peaks and troughs not exacerbated

# Winter




Average system demand by hour-of-day




Predicted change in wholesale prices per additional MW of rooftop solar capacity

- Solar output amplifies trough/peak in system demand and price

# Conclusion (1)

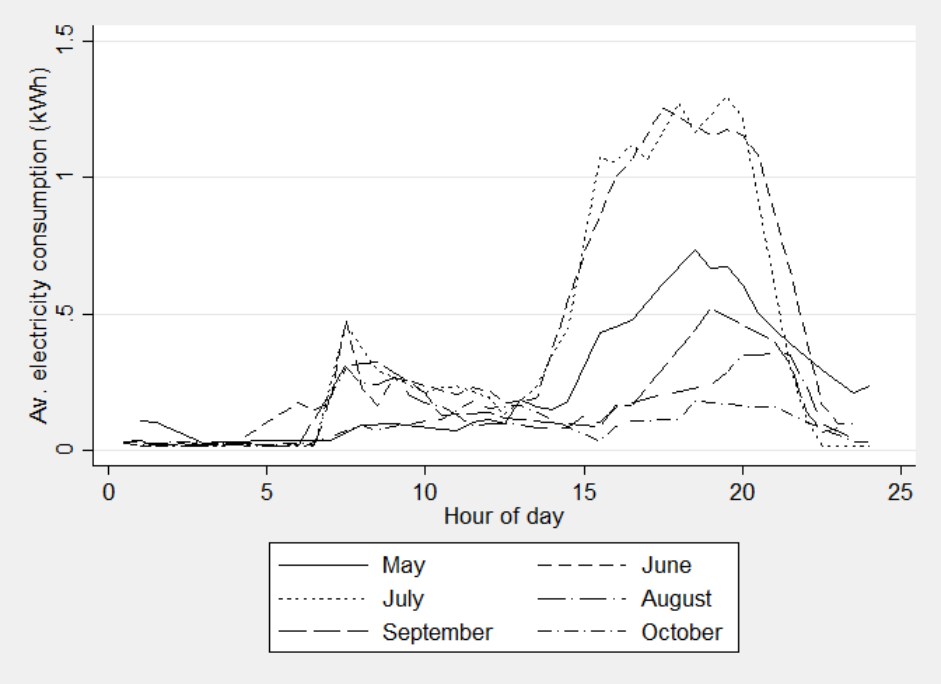
Alongside the WA rooftop solar boom:

- There has been an composition shift in generating technologies that output
- A decrease in middle-of-day fuel costs and an increase in sunset fuel costs has netted out to a 9% decrease in thermal fuel costs
- But thermal generators received a 3% increase in payments and 19% increase in gross margins
  - No price relief for non-solar owners
  - WA customers face a fixed retail price: No ability to self-manage within-day timing of consumption to respond to new wholesale conditions

# Conclusion (2)

Implications:

- Wholesale market price dynamics will incentivise a transition toward more flexible technologies as solar penetration increases
  - The marginal value of solar installations is diminishing, and the marginal value of storage / peakers is increasing
  - Impact from solar tied to whether it attenuates or exacerbates the size of the trough to peak ramp
- Single settlement markets could unlock efficiency gains from moving to multi-settlement
- We might expect the profitability of base load generators to decrease with further renewable penetration, but to date, the plants that have continued to operate have enjoyed profit gains due to the rise in peak prices offsetting the drop in daytime prices

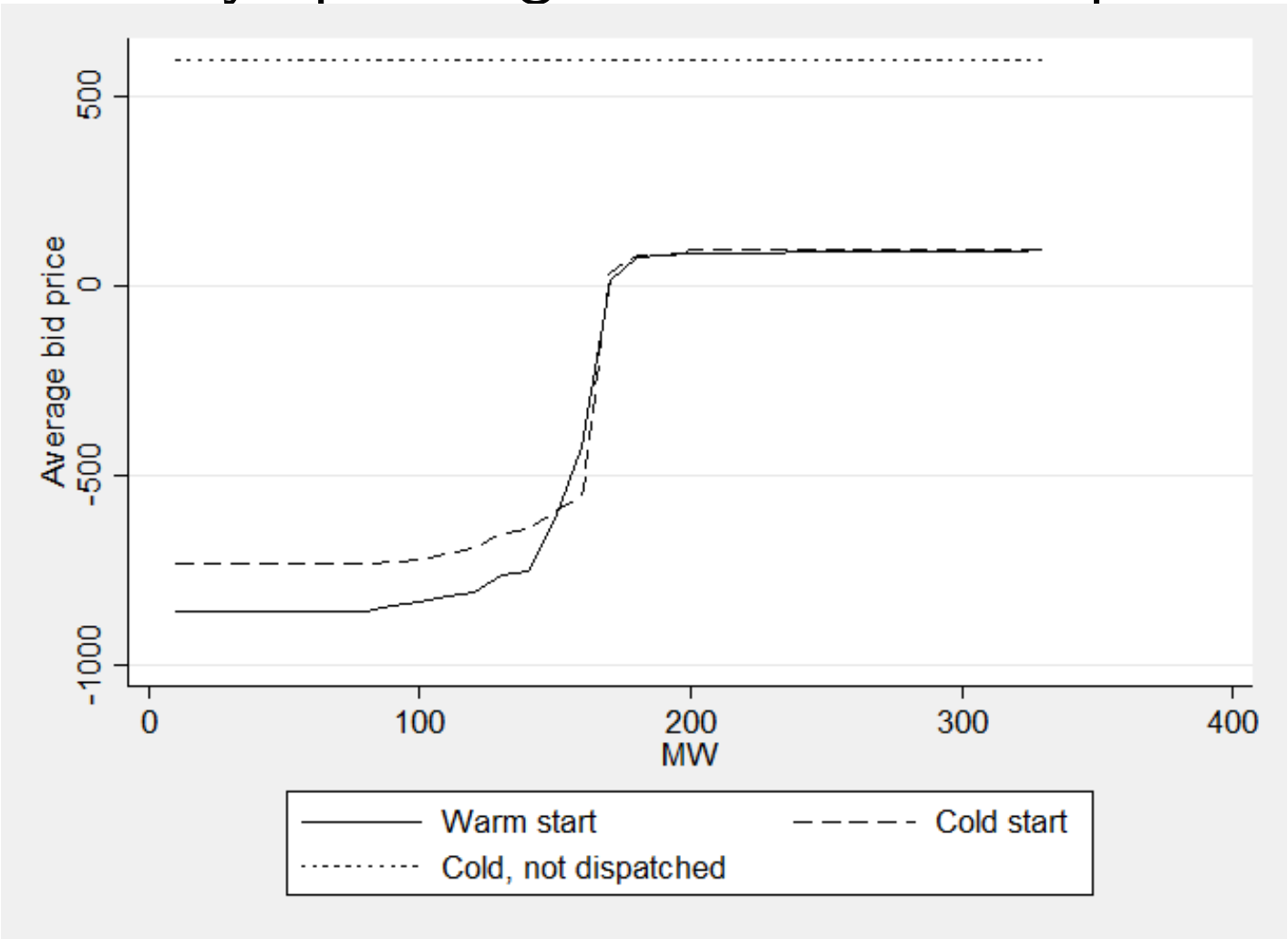



Does the Leslie household have a duck curve? Looks like they feel the cold in Winter...
(Wouldn't it be great if Victoria's smart meter data was available to researchers? Retailers sure don't utilise it)

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https://sites.google.com/site/gwleslie/

# Bid functions by operating state for Neerabup OCGT

Back




- Mostly price ceiling bids if cold
- If warm (or wants to start) then large negative bid up to minimum operating capacity

# Summary Statistics

Back

| Variable | Hours-of-day | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|
| System demand (MWh) | All hours | 1051 | 1063 | 1029 | 1004 |
| | Day (9am-5pm) | 1112 | 1099 | 1044 | 989 |
| | S'set (5pm-9pm) | 1254 | 1286 | 1241 | 1224 |
| Thermal generation (MWh) | All hours | 745 | 784 | 760 | 720 |
| | Day (9am-5pm) | 804 | 827 | 784 | 713 |
| | S'set (5pm-9pm) | 934 | 992 | 966 | 927 |
| Wholesale price ($/MWh) (unweighted) | All hours | 44.13 | 54.10 | 58.41 | 46.84 |
| | Day (9am-5pm) | 47.38 | 52.54 | 57.81 | 41.39 |
| | S'set (5pm-9pm) | 65.30 | 87.24 | 90.16 | 71.80 |
| Rooftop solar capacity (MW) | | 494 | 603 | 763 | 961 |
| Coal price ($/Mt) | | 1.68 | 1.67 | 1.70 | 1.73 |
| Natural gas price ($/GJ) | | 4.89 | 4.98 | 4.64 | 4.11 |
| Number of observations | All hours | 17520 | 17568 | 17520 | 17520 |