



Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

Daylight time and energy: Evidence from an Australian experiment

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ARTICLE INFO

Article history:

Received 30 April 2007

Available online 15 August 2008

Keywords:

Energy

Daylight saving time

Difference-in-difference-in-difference

ABSTRACT

Several countries are considering using daylight saving time (DST) as a tool for energy conservation and reduction of greenhouse gas emissions, and the United States extended DST in 2007 with the goal of reducing electricity consumption. This paper assesses DST's impact on electricity demand by examining a quasi-experiment in which parts of Australia extended DST in 2000 to facilitate the Sydney Olympics. Using detailed panel data and a difference-in-difference-in-difference framework, we show that the extension did not reduce overall electricity consumption, but did cause a substantial intraday shift in demand consistent with activity patterns that are tied to the clock rather than sunrise and sunset.

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I say it is impossible that so sensible a people...should have lived so long by the smoky, unwholesome, and enormously expensive light of candles, if they had really known that they might have had as much pure light of the sun for nothing.

Benjamin Franklin, 1784

1. Introduction

One principal socio-economic problem is the optimal allocation of individuals' activities—sleep, work, and leisure—over 24 h of the day. In today's world of artificial lighting and heating, people set their active hours by the clock rather than by the natural cycle of dawn and dusk. In one of the earliest statistical treatments in economics, "An Economical Project," Benjamin Franklin [9] observes that this behavior wastes valuable morning daylight as people sleep until long after sunrise, and requires expensive candles to illuminate the night. Franklin calculates that this misallocation causes Paris to consume an additional 64 million pounds of tallow and wax annually.

Governments have since attempted to address this resource allocation problem through the mechanism of daylight saving time (DST).¹ Each year, we move our clocks forward by 1 h in the spring, and adjust them back to Standard Time in the fall. The intuition behind this DST adjustment relies on the premise that people's activities shift forward with the clock, so that, during the summer, the sun appears to set 1 h later and the "extra" hour of evening daylight cuts electricity demand.

Today, heightened concerns regarding energy prices and greenhouse gas (GHG) emissions are driving interest in extending DST in several countries, including Australia, Canada, Japan, New Zealand, and the United Kingdom [17,22,24–26]. The United States has already passed legislation to extend DST by 1 month, beginning in 2007, with the

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¹ Historically, DST has been most actively implemented in times of energy scarcity. The first application of DST was in Germany during World War I. The US observed year-round DST during World War II and implemented extensions during the energy crisis in the 1970s [7]. Today, DST is observed in over seventy countries worldwide. For more information on the history of DST, see [6,20].

specific goal of reducing electricity consumption by 1% during the extension [8]. Therefore, the United States now switches to DST in March rather than in April. The energy legislation also explicitly calls for research into the energy impacts of extending DST, and suggests reverting to the prior DST system if it is demonstrated that the policy goal will not be achieved. Beyond this federal initiative, California is considering even more drastic changes—year-round DST and double DST—that are predicted to save up to 1.3 billion US dollars annually [5].

Our study challenges the energy conservation predictions that have been used to justify these calls for the expansion of DST. Across the studies and reports we surveyed, estimates of an extension's effect on total electricity demand range from savings of 0.6% to 3.5%. The most widely cited savings estimate of 1% is based on an examination conducted over 30 years ago [27]. Arguably, these findings are not applicable today. For example, the widespread adoption of air conditioning has altered intraday patterns of electricity consumption. Further, the 1% savings estimate may be confounded by other energy conservation measures enacted during the oil crisis.

More recent efforts to predict the effect of extending DST on electricity demand employ simulation models, which use data from the status quo DST system to forecast electricity use under an extension. One prominent recent study is being used to argue in favor of year-round DST in California [4]. It predicts three benefits of an extension: (1) a 0.6% reduction in electricity consumption, (2) lower electricity prices, driven by a reduction in peak demand, and (3) a lower likelihood of rolling blackouts. However, this study is not based on firm empirical evidence; it instead uses electricity consumption data under the current DST scheme to simulate demand under extended DST. It may therefore fail to capture the full behavioral response to a change in DST timing.²

Our study obviates the need to rely on simulations by examining actual data from a quasi-experiment that occurred in Australia in 2000. Typically, three of Australia's six states observe DST beginning in October (which is seasonally equivalent to April in the northern hemisphere). However, to facilitate the 2000 Olympics in Sydney, two of these three states began DST 2 months earlier than usual. Because the Olympics can directly affect electricity demand, we focus on the state of Victoria—which extended DST but did not host Olympic events—as the treated state, and use its neighboring state, South Australia, which did not extend DST, as a control. We also drop the 2-week Olympic period from the 2-month treatment period to further remove confounding effects. Using a detailed panel of half-hourly electricity consumption and prices over 7 years, as well as the most detailed weather information available, we examine how the DST extension affected electricity demand in Victoria.

Our treatment effect estimation strategy is based on the difference-in-difference (DD) framework that exploits, in both the treatment state and the control state, the difference in demand between the treatment year and the control years. We augment the standard DD model to take advantage of the fact that DST does not affect electricity demand in the mid-day. This allows us to use changes in mid-day consumption to control for unobserved state-specific shocks via a difference-in-difference-in-difference (DDD) specification. We show that this technique allows us to employ a mild identifying assumption that is more appropriate for the data than that of a standard DD model.

Our results confirm policy-makers' expectations that the extension of DST causes electricity demand to decrease significantly in the evening. However, we also find an opposing effect in the morning: the Australian extension significantly increased electricity consumption between 07:00 and 08:00. Overall, the evening decrease in demand did not outweigh the morning increase, so that total electricity consumption in Australia was not reduced as a result of the DST extension. These effects are consistent with waking and sleeping behaviors that are tied to the clock, rather than to sunrise and sunset. In particular, the residents of Australia do not appear to have substantially altered the clock time at which they awoke following the extension of DST; they therefore rose before sunrise and needed electric power for lighting.

These results contradict the claims made by prior studies that extending DST will conserve energy, and indicate that proposals in Australia to extend DST permanently are unlikely to reduce energy use and GHG emissions. Furthermore, the morning peak demand caused by Australia's 2000 extension is associated with significantly higher wholesale electricity prices, indicating that the steep morning ramp-up in demand likely caused an increase in generation costs. This outcome undercuts claims that extending DST leads to generation efficiencies by smoothing the hourly demand profile.

While we cannot directly apply our results to other countries without adjustments for behavioral and climatic differences, this study raises concern that the recent DST extension in the United States is unlikely to result in energy conservation. To investigate the degree to which our results extend to the US, we reconstruct the simulation model that was used to forecast energy savings for California [4], and apply it to the Australian data. Noting that Victoria's latitude and climate are similar to those of central California, we find that the simulation systematically overstates energy savings in both the morning and evening, casting further suspicion on claims that extending DST in California and the rest of the United States will reduce electricity consumption.

2. Background on daylight saving time in Australia

The geographical area of interest is the southeastern part of Australia. Three states in the southeast of the mainland observe DST: South Australia (SA), New South Wales (NSW), and Victoria (VIC). DST typically starts on the last Sunday in

² Rock [21] also uses a simulation model, and finds that year-round DST decreases electricity consumption by 0.3% and expenditures by 0.2%. However, his study does not include non-residential electricity use, which accounts for 64% of US total electricity consumption [28].

Table 1
Characteristics of capital cities in southeast Australia

Capital	State	Population in millions	Population in millions	Per capita in 1000 AUD	Latitude south	Longitude east	Average sunrise	Average sunset
Sydney	NSW	4.3	6.5	41.4	33°5'	151°1'	5:50	17:45
Melbourne	VIC	3.7	4.8	39.3	37°47'	145°58'	6:20	18:10
Adelaide	SA	1.1	1.5	33.4	34°55'	138°36'	6:50	18:35

All data are for 2000. Sunrise and sunset times are in East Australian Standard Time, and averaged during September.

October and ends on the last Sunday in March. Queensland, the Northern Territory, and Western Australia do not observe DST. Table 1 provides summary statistics and geographical information for the capitals of these states, where the populations and electricity demand are concentrated.³

In 2000, NSW and VIC started DST 2 months earlier than usual—on 27 August instead of 29 October—while SA maintained the usual DST schedule. The extension was designed to facilitate the Olympic Games that took place in Sydney, in the state of NSW, from 15 September to 1 October.⁴ Specific rationales for the extension included easing visitor movements from afternoon to evening events, and reducing shadows on playing fields during the late afternoon [16]. None of the justifications for the extension were related to curbing energy use.

In the analysis that follows, we define the *treatment period* to be 27 August to 27 October 2000, exclusive of the Olympic period from 15 September to 1 October. While we discuss our rationale for excluding the Olympics in Section 4.1, we note here that we exclude 28 October because, in the control year of 2001, this date marks the beginning of the regularly scheduled DST period in both VIC and SA. For ease of exposition, we will also use the term *treatment dates* to refer to 27 August to 27 October, exclusive of 15 September to 1 October, in any year, including the control years.

3. The Australian data and graphical results

3.1. Data

Our study uses detailed electricity consumption and wholesale price panel data, obtained from Australia's National Electricity Market Management Company Limited (NEMMCO).⁵ These consist of half-hourly electricity demand and wholesale prices by state from 13 December 1998 to 31 December 2005. Wholesale prices are market prices paid by utilities to generators, while end-use customers instead pay a regulated price for electricity and are not exposed to fluctuations in wholesale prices. Therefore, these prices do not affect electricity consumption.

Because electricity demand is heavily influenced by local weather conditions, we use two data sets from the Bureau of Meteorology at the Australian National Climate Centre. The first consists of hourly weather station observations in Sydney, Melbourne, and Adelaide—the three cities that primarily drive electricity demand in each state of interest. The data cover 1 January, 1999 to 31 December, 2005 and include temperature, wind speed, air pressure, humidity, and precipitation. The second data set consists of daily weather observations, including the total number of hours during which the sun shines, unobstructed by clouds, each day.

Table 2 provides summary statistics for each of these variables during the treatment dates for 1999–2001, and also reports the frequency of school vacations and holidays. Additional details regarding the data set as well as our procedure for dealing with missing observations are provided in Appendix A at the online archive.

3.2. The impact of the DST extension on electricity consumption and prices

The goal of the empirical analysis is to examine the effect of the extension of DST on electricity use and prices. Prior to a discussion of the econometric model, much can be learned from the graphical analysis presented in Fig. 1. Panel (a) displays the average half-hourly electricity demand in SA during the treatment dates in 1999, 2000, and 2001. The load shape in SA,

³ A figure displaying the relevant geographic area is contained in an appendix that is available through JEEM's online archive of supplementary material, which can be accessed at <http://www.aere.org/journal/index.html>.

⁴ The decision to start DST 3 weeks prior to the beginning of the Olympic Games was intended to avoid confusion for athletes, officials, media, and other visitors who would likely arrive prior to the opening of the Games. VIC adopted the NSW timing proposal to avoid inconveniences for those living near the NSW–VIC border. However, SA did not extend DST in 2000 due to the opposition of the rural population [16,17].

⁵ NEMMCO data can be obtained at http://www.nemmco.com.au/data/market_data.htm.

Table 2
Summary statistics: 1999–2001, treatment dates only

State	Variable	Unit	2160 observations per state, per year					
			1999		2000		2001	
			Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Victoria	Demand	MW	5131.86	528.87	5347.71	554.17	5405.90	553.66
	Price	AUD/MWh	19.22	6.34	43.30	179.29	29.11	84.04
	Temperature	°C	13.51	4.46	12.12	3.90	12.11	3.73
	Precipitation	mm/h	0.07	0.50	0.14	0.73	0.05	0.24
	Wind	m/s	4.72	2.94	5.57	2.92	4.69	2.61
	Pressure	hPa	1018.18	6.30	1011.97	7.17	1012.09	6.17
	Sunshine	h/day	6.78	3.89	5.90	3.71	5.78	3.43
	Humidity	%	71.02	17.18	72.51	15.83	72.58	17.11
	Employment	in 1000	2192.72	14.14	2272.06	12.05	2289.02	11.46
	Non-working day	% of days	0.31	0.46	0.24	0.43	0.33	0.47
	School-vacation	% of days	0.00	0.00	0.00	0.00	0.09	0.28
	South Australia	Holiday	% of days	0.00	0.00	0.00	0.00	0.00
Demand		MW	1324.23	185.70	1398.49	201.43	1428.66	197.66
Price		AUD/MWh	54.12	166.53	56.27	178.97	27.50	17.85
Temperature		Celsius	15.95	4.81	14.41	3.69	13.48	3.20
Precipitation		mm/h	0.00	0.00	0.12	0.54	0.12	0.48
Wind		m/s	4.22	2.53	5.05	2.87	4.73	2.88
Pressure		hPa	1017.93	6.53	1014.51	6.89	1013.79	6.32
Sunshine		h/day	8.53	3.12	7.20	3.54	6.38	3.31
Humidity		%	62.99	19.20	68.52	17.76	70.46	16.93
Employment		in 1000	668.76	2.69	684.22	2.43	682.85	2.33
Non-working day		% of days	0.42	0.49	0.27	0.44	0.44	0.50
School-vacation		% of days	0.11	0.31	0.00	0.00	0.20	0.40
Holiday		% of days	0.02	0.15	0.02	0.15	0.00	0.00

Abbreviations: MW = megawatts; AUD/MWh = Australian dollars per megawatt-hour; mm = millimeters; hPa = hectopascal. Note that the maximum wholesale electricity price is capped at 5000 AUD/MWh from 1999–2000, and at 10,000 AUD/MWh in 2001. The cap is designed to mitigate generator market power [15].

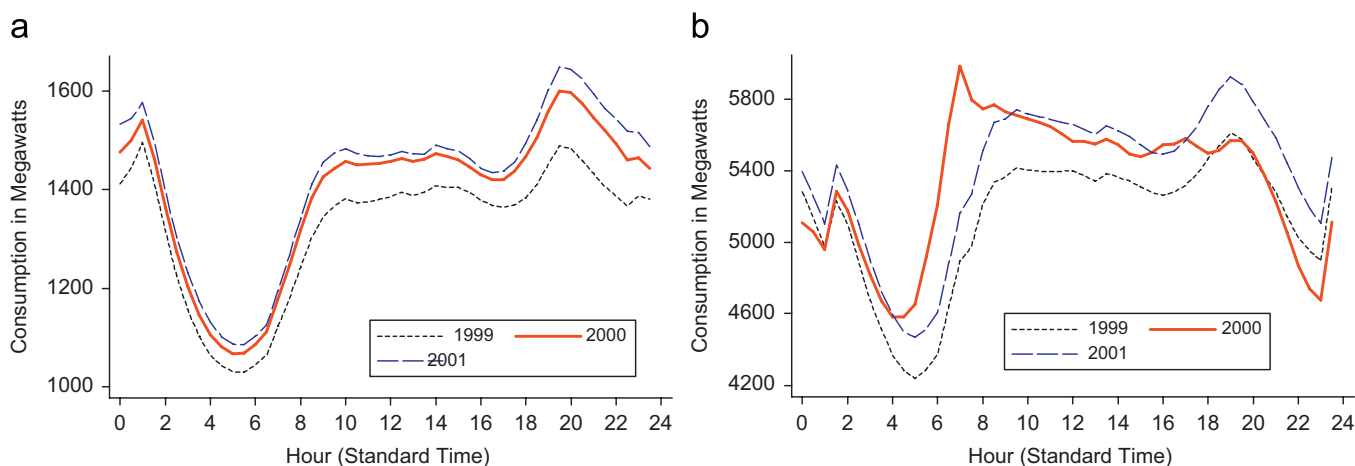


Fig. 1. Average half-hourly electricity demand in South Australia and Victoria during the treatment dates (a) South Australia (control) and (b) Victoria (treated in 2000).

the control state, is very stable over these 3 years, featuring an increase in consumption between 05:00 and 10:00, a peak load between 18:00 and 21:00, and then a decrease in load until about 04:00 on the following morning.⁶ Notably, SA's demand in 2000 appears unaffected by the DST extension in its neighbors VIC and NSW.⁷

⁶ The “zigzag” pattern that occurs between 23:00 and 02:00 in both states is due to centralized off-peak water heating that is activated by automatic timers, set to standard time [19].

⁷ Hamermesh et al. [11] examine spatial coordination externalities triggered by time cues. Their results imply that SA in 2000 may have adjusted its behavior in response to the treatment in VIC. In particular, their model predicts that people in SA would awaken earlier in the morning to benefit from aligning their activities with their neighbors in VIC. However, the effects are small, and panel (a) of Fig. 1 does not show evidence of such a time shift.

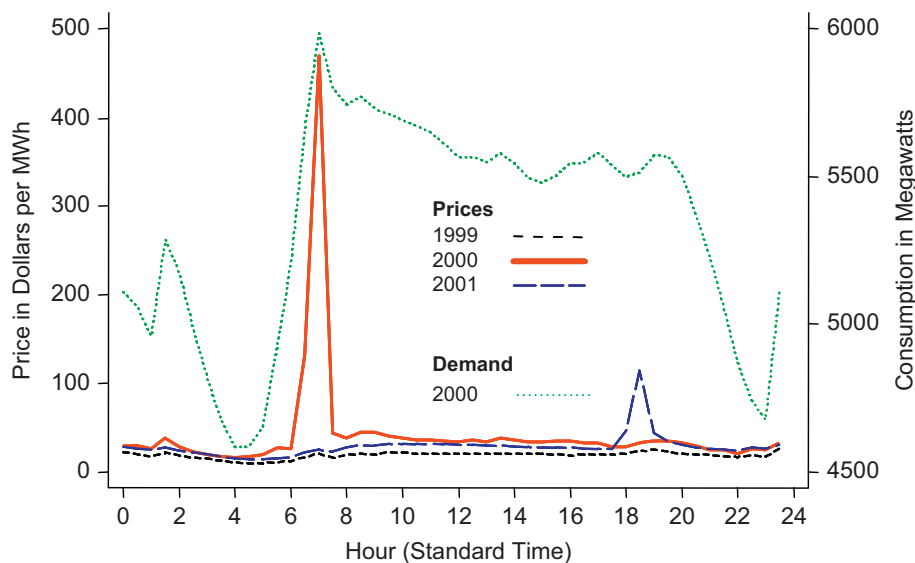


Fig. 2. Average half-hourly electricity prices and demand in Victoria during the treatment dates.

The 2000 load shape in VIC is quite different from the loads in 1999 and 2001, as shown in panel (b). Consistent with the prior literature, the treatment of extended DST dampens evening consumption. However, the 2000 treatment also raises morning demand to a peak that is even higher than the 2001 evening peak load. The intraday shift is consistent with the expected effects of DST's 1-h time shift: less lighting and heating are required in the evening, and more in the morning. In particular, the large increase in demand from 07:00 to 08:00 closely matches environmental variables at this time of the day. During the treatment period, the latest sunrise in Melbourne (on 27 August) occurs at 07:51, and the average sunrise occurs at 06:55. Further, the 07:00–08:00 interval is the coldest hour of the day; the average temperature for this hour is only 9 °C. Therefore, when people shift their activities forward with the clock in response to the imposition of DST, they awaken in cold, low-light conditions, driving an increase in electricity demand that persists even 1 h after sunrise. Extending DST only conserves energy if this morning increase in consumption is outweighed by the evening decrease; however, in Fig. 1 it is not clear that this is the case.

Panel (b) of Fig. 1 also casts doubt on claims that extended DST brings additional benefits, in the form of higher system reliability and lower prices, due to a more balanced load shape. While the extension does reduce the evening peak load in VIC in 2000, it creates a new, sharp peak in the morning that is even higher than the evening peak in 2001. This morning peak is also coincident with a large spike in wholesale electricity prices, as shown in Fig. 2. Morning price spikes occurred on every working day during the first 2 weeks of the extension, suggesting that the generation system was initially stressed to cope with the steep ramp in demand.⁸

Furthermore, this analysis suggests that, contrary to common claims, the extension of DST is not likely to reduce GHG emissions from electricity generation. The quantity of these emissions is dictated primarily by the quantity of energy generated: without a reduction in electricity consumption, significant reductions in GHG emissions are unlikely. Holland and Mansur [12] note, however, that changes in the variance of the load shape can affect production of GHGs, even holding total electricity production constant. If the generation units that serve peak load are dirtier (cleaner) than the baseload units, then an increase in variance can slightly increase (decrease) emissions. However, because the extension of DST appears to merely shift the peak load from the evening to the morning, rather than smooth the daily load, such effects seem unlikely to be significant here.

Our graphical analysis does not, of course, account for important determinants of electricity demand, such as weather and holidays. To obtain an unconfounded estimate of the effect of extended DST on electricity use, we employ a formal econometric analysis, which we now describe in detail.

4. Empirical strategy for measuring the effect of DST on electricity use

4.1. Identification

While we have noted that the DST extension was implemented solely to facilitate the Olympic Games, and that we are not aware of any energy-based justifications for it, identification of the extension's effect on energy use is made difficult by

⁸ Because the Australian electricity market is integrated across state boundaries, demand shocks in VIC caused by extended DST affect not only wholesale prices in VIC, but also prices in SA. We therefore do not undertake a formal analysis of extended DST's effect on prices, because a control state does not exist.

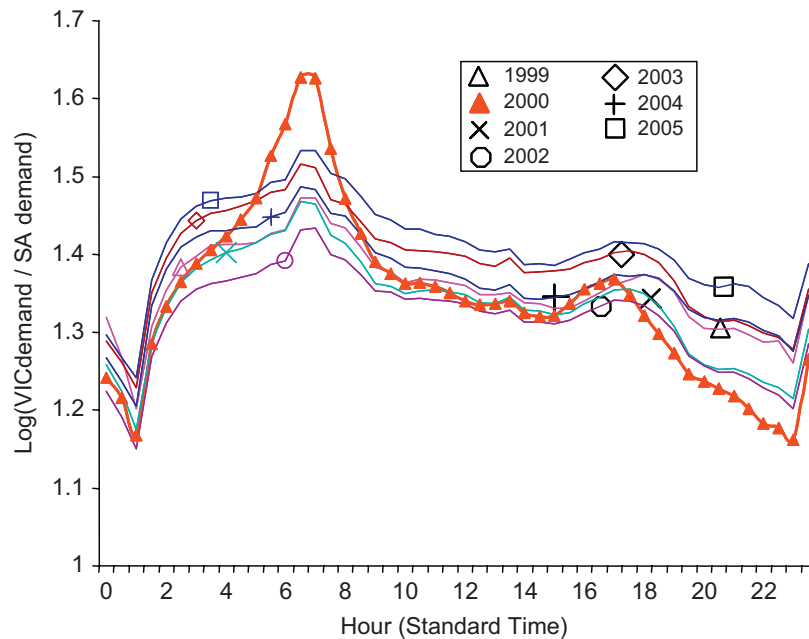


Fig. 3. Ratio between average VIC demand and average SA demand during the treatment dates, 1999–2005.

the presence of potentially confounding factors. In particular, there are reasons to suspect that the Olympics may have changed electricity consumption in Australia significantly, even absent a DST extension. The 2000 Games were the most heavily visited Olympics event in history, school vacations were rescheduled to facilitate participation in carnival events, and the Games were watched on public mega-screens and private televisions by millions of Australians in Sydney and elsewhere.

Our identification strategy incorporates several features designed to account for these potential confounds, and benefits from observations during the treatment year and the control years in both the treated and the non-treated state, as well as from the detailed half-hourly frequency of our data. First, we exclude the 17 days of the Olympic Games from the definition of the treatment period; this allows us to avoid many of the biases noted above. Second, even with the Olympics excluded from the treatment, electricity demand may have been affected before and after the games by, for example, pre-Olympic construction activities and extended tourism. To control for these, we ignore NSW (where the Olympics took place), and focus on the change in electricity demand in VIC relative to that in SA.⁹ This strategy eliminates the impact of any confounders that operate on a national level, and accounts for all differences between the two states that are constant over time.

Further, to control for unobservables that may have affected VIC and SA differentially over time, we use relative demand in the mid-day as an additional control. That is, because DST does not affect demand in the middle of the day, variations in state-specific mid-day demand levels that are not explained by observables such as weather can be attributed to non-DST-related confounders. Thus, our model is robust against transient state-specific shifts in demand that affect the overall level of consumption in any state on any day, but do not affect the shape of the half-hourly load pattern. We verify the assumption that DST does not affect mid-day demand by examining changes from standard time to DST in non-treatment years. We discuss this verification, as well our choice of 12:00–14:30 as mid-day, in Appendix B at the online archive.

These features of our model imply that a mild identifying assumption is sufficient for our regressions to produce an unbiased estimate of the extension's effect. We assume that, conditional on the observables and in the absence of the treatment, the ratio of VIC demand to SA demand in 2000 would have exhibited the same half-hourly pattern (but not necessarily the same level) as observed in other years. Support for this is found by plotting the ratio of consumption in VIC to that in SA for 1999–2005, as shown in Fig. 3. The demand ratio exhibits a regular intraday pattern in all non-treated years, even without controlling for observables. Moreover, the levels of these curves change non-systematically, from smallest to largest, over 2002, 2000, 2001, 1999, 2004, 2003, and 2005. These level shifts are consistent with the existence of transient state-specific shifts in consumption that must be controlled for using demand in the mid-day.

As an alternative strategy to control for unobservables that affect each state differently in different years, we also considered taking advantage of demand data for the months adjacent to the treatment dates: August and November. That is, we considered using August and November each year to control for non-DST-related state-specific shocks to demand

⁹ To further analyze whether visitors before and after the Olympic Games spent extended vacations in VIC or SA, we collected tourism information. These data show that, while NSW was affected by tourism during the Olympics, VIC and SA were unaffected. Additional details are provided in Appendix D at the online archive.

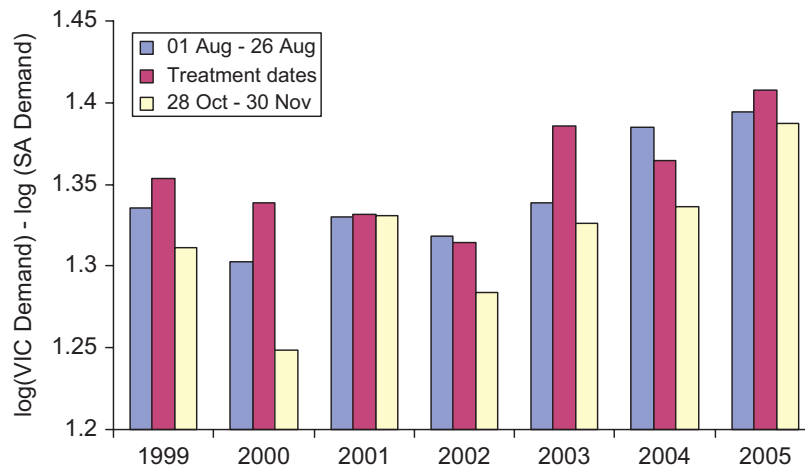


Fig. 4. Ratio between average VIC demand and average SA demand, August–November, 1999–2005.

during the treatment dates. However, this strategy is valid only if the state-specific demand shocks are persistent over several months—if a shock causes VIC's demand to be relatively large in 2001 during the treatment dates, then the shock must also cause VIC's demand to be relatively large in August and November.

Fig. 4 instead demonstrates that state-specific demand shocks vary unpredictably across months and years. For example, in 2001, the ratio of VIC demand to SA demand does not vary over August–November. However, in 1999 the ratio is larger during the treatment dates than it is in August or November, and in 2002 the ratio decreases monotonically from August to November. This lack of stability implies that the data cannot support an identification strategy that relies on observations from months adjacent to the treatment period. Indeed, when we estimate a model based on this strategy we find statistically significant treatment effects that are implausibly large—1–2% increases in demand during the mid-day (and overall).¹⁰ Given that both intuition and evidence instead indicate that DST does not affect mid-day demand, we eschew the “adjacent months” strategy in favor of the “within-day” strategy that uses mid-day demand to control for state-specific shocks.

4.2. Difference-in-difference-in-difference (DDD) estimation

We implement our identification strategy using a DDD framework [10]. This technique is illustrated in Table 3, which displays the raw DDD estimate of the DST extension's impact on electricity consumption. Each cell contains the mean logarithm of electricity consumption per half-hour for the indicated state, year, and hours, as well as the standard error and number of observations. The top panel A concerns consumption during the treated hours; that is, all 24 h of the day excluding the mid-day hours of 12:00–14:30. This panel shows that there was approximately a 2.0% increase in electricity consumption in VIC, the treated state, during the extension, compared to a 2.4% increase in the control state SA. These values imply that, in a DD estimate, the extension of DST decreased electricity consumption by a statistically insignificant 0.4%.

This DD estimate, however, does not identify the impact of the extension if there were state-specific demand shifts in VIC and SA during these time periods. To examine this possibility, we repeat the above exercise in panel B of Table 3, using the within-day control period of 12:00–14:30. Our DD estimate during this control period also indicates a slight decrease in consumption, with a magnitude of 0.2%. Though statistically insignificant, this estimate is of the same order of magnitude as that obtained during the treated hours, suggesting that it is important to control for state-specific demand shifts in our analysis.

We obtain the DDD estimate of the effect of the extension by taking the difference between the DD estimates in the two panels of Table 3. We find that electricity consumption in the treated state during the treated year and treated hours decreased by 0.2%. While this result suggests that the impact of extending DST is of small magnitude, the estimate is imprecise, with a standard error of 1.5%. To improve our precision, we employ a regression framework, below, in which we may control for other factors that affect electricity consumption, such as day-of-week and weather.

¹⁰ The specification is the same as Eq. (1), as described in Section 4.3, except that treatment dummies are included for all 24 h of the day, and the id are replaced with fixed effects for the interaction of state with year.

Table 3
DDD estimate of extended DST's impact on the log of electricity consumption

Location/year	Control period in 1999 and 2001	Treatment period in 2000	Time difference for location
<i>(A) Treated hours 00:00–11:59 and 14:30–24:00</i>			
Victoria (Treated state)	8.554 (0.001) [5332]	8.574 (0.002) [1935]	0.020 (0.003)
South Australia (Control state)	7.202 (0.002) [5332]	7.226 (0.003) [1935]	0.024 (0.004)
Location difference at point in time:	1.352 (0.003)	1.348 (0.004)	
Difference-in-difference		–0.004 (0.005)	
<i>(B) Control hours: 12:00–14:30</i>			
Victoria (Treated state)	8.603 (0.004) [620]	8.624 (0.006) [225]	0.021 (0.007)
South Australia (Control state)	7.263 (0.005) [620]	7.286 (0.008) [225]	0.023 (0.009)
Location difference at a point in time:	1.340 (0.006)	1.338 (0.010)	
Difference-in-difference		–0.002 (0.012)	
DDD		–0.002 (0.015)	

Note: Cells display the mean logarithm of electricity consumption per half-hour for the indicated state, year, and hours. Standard errors are provided in parentheses and the sample sizes in squared brackets. Data apply only to the dates of 27 August to 27 October in each year. The difference-in-difference-in-difference (DDD) estimate is the subtraction of the DD estimate of panel B from that of panel A.

4.3. Treatment effect model

Our specification of the treatment effect model is drawn primarily from the DD literature [2,14]. We augment the standard DD model by estimating a DDD specification [10] because our control structure is three-fold:

- (a) cross-sectional overstates (with VIC as the treated state and SA as the control),
- (b) temporal over years (with the untreated years in SA and VIC as controls), and
- (c) temporal within days (with the mid-day hours as “within-day” controls)

The reference case model uses data from VIC and SA during 27 August to 27 October in 1999, 2000, and 2001; these dates correspond to the period when DST was observed in VIC in 2000 and Standard Time was observed in 1999 and 2001. Our specification is given by Eq. (1), in which states are subscripted with i , and time is jointly subscripted with d (for date) and h (for hour):

$$\ln(q_{idh}) = T_{idh}\beta_h + \delta_{id} + X_{idh}\alpha_h + W_{idh}\varphi_h + \varepsilon_{idh}. \tag{1}$$

The dependent variable q_{idh} for each observation is the logarithm of electricity demand in state i , day d , and half-hour h (in clock time). We use the log of demand rather than its level to account for the large difference in size between SA and VIC. As indicated in Table 2, the average electricity demand in VIC is approximately four times that in SA. Given this difference, a linear model will not be robust to proportional shifts in demand that are common to both states.

The covariates of primary interest are the indicator variables T_{idh} for the treatment period. These are equal to one in VIC during the treatment period in 2000 for all half-hours except those in the mid-day, and are zero otherwise. The variables δ_{id} are fixed effects for the interactions between each date in the sample period and indicator variables for each state. These variables effectively force the “omitted” treatment effect in the mid-day to be zero for every day of the treatment period. The dummy variables X_{idh} include 48 half-hour dummies, and interactions of these dummies with indicator variables for the following: state, year, day of week, holidays, school vacations, the interaction of state with week of year, and the interaction of state with a flag for the Olympic period. The weather variables W_{idh} are also interacted with half-hour

dummies and include a quadratic in hourly heating degrees, daily hours of sunlight, the interaction of sunlight with temperature, hourly precipitation, the interaction of precipitation with temperature, and the average of the mid-day heating degrees.^{11,12} All weather variables enter the model lagged by 1 h.

In Eq. (1) the treatment effect parameters to be estimated are given by β_h and the percentage change in electricity demand in each half-hour h is given by $\exp(\beta_h)-1$ (parameters for the mid-day half-hours are omitted). To obtain the overall effect of the DST extension, we use two separate methods. First, we estimate a version of Eq. (1) in which we pool the treatment effect overall half-hours of the day. That is, instead of including separate treatment effect dummies for each half-hour, we only specify a single treatment dummy that is equal to one for all non-mid-day hours in VIC in 2000.

In the second method, we first estimate the half-hourly coefficients β_h (again excluding the mid-day hours) and then aggregate them to obtain the overall percentage change in demand caused by the DST extension. Denoting the vector of half-hourly treatment coefficients as β , the overall effect θ is given by (2)

$$\theta = f(\beta) = \frac{\sum_{h=1}^{48} \exp(\beta_h)\omega_h}{\sum_{h=1}^{48} \omega_h} - 1. \tag{2}$$

That is, θ is the weighted sum of the half-hourly percentage effects, where the weights ω_h are the average of the baseline 1999 and 2001 half-hourly demands during the treatment dates.

Given a set of half-hourly treatment effect estimates $\hat{\beta}$, the point estimate of θ is given by $f(\hat{\beta})$ and its estimated variance is given by the delta method, per equation:

$$V(\hat{\theta}) = \nabla_{\beta} f(\hat{\beta})^T \mathbf{Cov}(\hat{\beta}) \nabla_{\beta} f(\hat{\beta}). \tag{3}$$

In (3), $\nabla_{\beta} f(\hat{\beta})$ denotes the gradient of $f(\hat{\beta})$ with respect to each element $\hat{\beta}_h$, and $\mathbf{Cov}(\hat{\beta})$ denotes the estimated covariance matrix of $\hat{\beta}$. Our estimation of $\mathbf{Cov}(\hat{\beta})$ allows the disturbance ε_{idh} to be both heteroskedastic and correlated within each day,

$$E(\varepsilon_{idh}\varepsilon_{idh}|\mathbf{Z}) = \sigma_{idh}^2, \quad E(\varepsilon_{dj}\varepsilon_{dk}|\mathbf{Z}) = \rho_{dj}\forall j \neq k, \\ E(\varepsilon_d\varepsilon_{d'}^T|\mathbf{Z}) = 0 \quad \forall d \neq d',$$

where $\mathbf{Z} = [\mathbf{T}, \delta, \mathbf{X}, \mathbf{W}]$. This block-diagonal covariance structure accounts for both autocorrelation and common shocks that affect both states contemporaneously. We therefore use the clustered sample estimator to obtain the covariance matrix of $\hat{\beta}$ [1,2,29]. As an alternative, we also estimate the model using the Newey and West [18] estimator with 50 lags.¹³

5. Results

5.1. Reference case results

We use two separate methods to obtain the overall effect of the DST extension. First, we estimate a version of (1) in which the treatment variables are pooled overall half-hours of the day. These results indicate that the extension of DST did not significantly affect overall electricity consumption in VIC in 2000. Our point estimate indicates a 0.02% increase in consumption due to the extension, with a clustered standard error of 0.43.

Second, we estimate a separate treatment effect for each half-hour. These results are displayed graphically in Fig. 5; a tabular version is presented in Appendix C at the online archive. Extending DST affects electricity consumption in a manner consistent with the preliminary graphical analysis: there is a substantial, statistically significant transfer of consumption from the evening to the morning. This behavior agrees with the expected effects of DST's 1-h time shift. Less lighting and heating are required in the evening, from 17:00 to 19:30; however, demand increases in the morning—particularly from 07:00 to 08:00—driven by reduced sunlight and lower temperatures.

We aggregate the half-hourly estimates using (2) to yield an estimate of θ , the overall effect of the extension. Consistent with the result of the pooled model, we find that the extension of DST did not conserve electricity, as shown in the first column of Table 4. The point estimate of the percentage change in demand overall hours of the treatment period is +0.09% with a clustered standard error of 0.40. This result is very similar to that of the pooled model, above. Because the unpooled specification (1) yields a better fit to the data than the pooled specification (pooling of the half-hourly treatment coefficients is strongly rejected), the remainder of the paper will focus on estimates using the unpooled model, with aggregation per Eq. (2).

¹¹ Our final specification pools some hours to improve efficiency of the weather models. This does not impact the reported estimates of the treatment effects.

¹² Heating degrees are calculated as the difference between the observed temperature and 18.33 °C (65°F). The motivation behind squaring the heating degree is that, as the temperature deviates from 18.33 °C, cooling or heating efforts increase nonlinearly. This functional form is consistent with other electricity demand models [3].

¹³ Fifty lags allow the errors to be correlated over slightly more than 1 full day. Tests of AR(p) models on ε suggest that the disturbances are correlated over the first 6 h of lags, but not beyond that. However, the coefficient on the 48th lag is significant. Also, note that the DDD specification considerably decreases the autocorrelation of the dependent variable, relative to a standard DD.

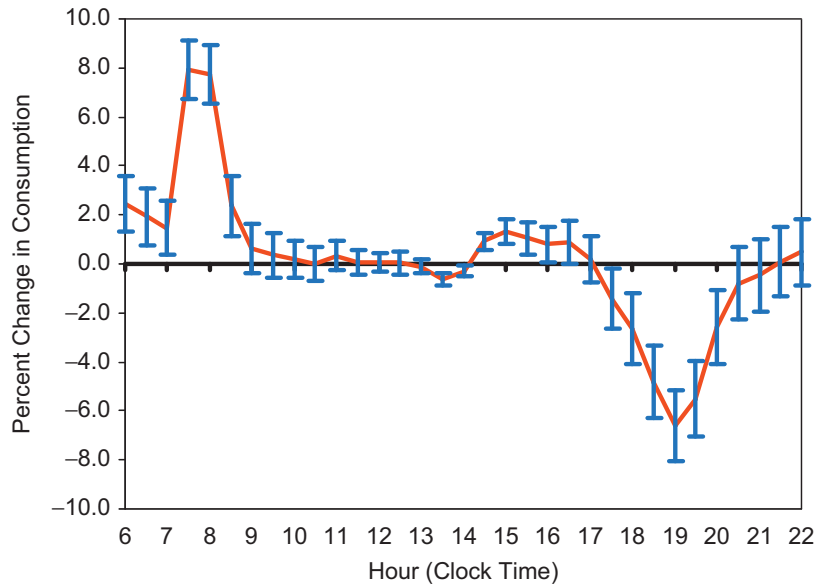


Fig. 5. Half-hourly effects of extending DST on electricity use. 95% confidence intervals are indicated, with standard errors clustered by day. Effects in mid-day half-hours are zero by assumption.

Table 4
Summary of estimated treatment effects, aggregated over all half-hours

	All days	September	October	Working days	Non-working days
Percent change in demand	0.09	0.39	-0.06	0.43	-0.82
Standard error	(0.40)	(0.43)	(0.47)	(0.44)	(0.43)
	[0.38]	[0.43]	[0.43]	[0.41]	[0.50]

Standard errors clustered on date are in parentheses and Newey-West standard errors are in brackets.

Table 5
p-Values for rejection of electricity saving hypotheses

Null hypothesis	September estimate (+0.39%)		October estimate (-0.06%)		Pooled estimate (+0.09%)	
	Clustered std. error	Newey-West	Clustered std. error	Newey-West	Clustered std. error	Newey-West
<i>Electricity savings</i>						
$\theta = -1.0\%$	0.001	0.001	0.048	0.047	0.007	0.004
$\theta = -0.6\%$	0.023	0.019	0.257	0.290	0.085	0.069
<i>Electricity neutrality</i>						
$\theta = 0.0\%$	0.371	0.344	0.895	0.738	0.814	0.804

5.2. September vs. October

We also examine the impact of the DST extension separately for September and October. Because September in the southern hemisphere is seasonally equivalent to March in the northern hemisphere, this examination has policy implications beyond Australia—the recent change to DST in the United States concerns an extension into March, as DST is already observed in April in the US. Prior studies have found that such an extension reduces electricity consumption by 1% in the US and by 0.6% in California. In contrast, we estimate that the extension of DST into September in Australia *increased* electricity demand by 0.39%, as shown in Table 4.¹⁴

¹⁴ More precisely, we estimate the effects of DST separately for the pre-Olympic and post-Olympic treatment periods, which we refer to loosely as the months of September and October. That is, for each half-hour *h*, we interact the treatment dummy T_{idh} with indicators for each month and estimate separate coefficients β_h^{Sep} and β_h^{Oct} . We then aggregate these half-hourly estimates to yield estimates of the overall treatment effects θ^{Sep} and θ^{Oct} . The point estimate of θ^{Oct} indicates that the extension reduces electricity demand by 0.06%. While the difference between the September and October estimates is

Table 6

Robustness tests: estimated overall effect of the DST extension in VIC

	Reference case	CEC weather	Include data to 2005	Exclude week before/after Olympics	Queensland as control state	Run in Standard Time
Percent change in demand	0.09	0.08	0.12	0.42	−0.08	0.51
Standard error	(0.40)	(0.39)	(0.35)	(0.50)	(0.28)	(0.41)

Standard errors are clustered on date.

To formally compare our estimates to the previous literature, we define three null hypotheses: (1) $\theta = -1.0\%$, (2) $\theta = -0.6\%$, and (3) $\theta = 0.0\%$, and test whether they are rejected by our estimates. Table 5 displays p -values for rejection of each null hypothesis in a two-sided test, given both our pooled and unpooled results. Even with clustered standard errors, our estimate of the effect of the DST extension in September rejects the most modest energy savings estimate in the literature of 0.6% [4] at a 5% level. Over the entire treatment period (September and October), we reject a 1% reduction in demand at a 1% level, and reject a 0.6% reduction at a 10% level. These rejections are strengthened with the use of Newey–West standard errors.

In summary, the results indicate that extending DST did not significantly reduce electricity demand in VIC. In September in particular, the extension was more likely to have increased than decreased electricity consumption.

5.3. Robustness

Our results are robust to many alternative specifications, as shown in Table 6. Our results are invariant to the choice between the two alternative weather models in [3,4]. Further, our results do not change appreciably if we include more recent data, use Queensland as a control state rather than SA, exclude the weeks immediately preceding and following the Olympics from the treatment period definition, or estimate (1) in Standard Time rather than clock time. This robustness is underlined by the precise fit of our model: the adjusted R^2 across all models is greater than 0.99.

Regression equation (1) contains over 1800 parameters. While the point estimates and the standard errors for the treatment effects are our primary interest, most of the other coefficients are significant and carry signs that agree with intuition. For example, weekends, holidays, and vacations lower electricity consumption, and deviations from the base temperature of 18 °C increase electricity consumption, consistent with the effects of air conditioning (when above 18 °C) and heating (when below 18 °C).

The weights ω_h used to calculate $\hat{\theta}$ are based on the average of the 1999 and 2001 half-hourly demands. As an alternative set of weights, we also use the estimated half-hourly counterfactual demand in 2000, given by $\exp\{\delta_{VICd} + X_{VICdh}\alpha_{idh} + W_{VICdh}\phi_{ih}\}$. Doing so does not affect our estimate of θ .

As a final check of our estimates, we evaluate whether extending DST causes a relatively greater reduction in electricity consumption on weekends and holidays than on working days. This would be consistent with the intuition that, on non-working days, less early activity mitigates the morning increase in demand. We estimate that electricity consumption on working days increased by 0.43% during the extension, while consumption on weekends and holidays decreased by 0.82%. This difference is significant at the 1% level.

6. Evaluation of the simulation technique

It is natural to ask whether the simulation technique used in [4] to predict energy savings in California would have accurately predicted the outcome of the Australian DST extension. A successful validation would lend credence to the model's results in California, and suggest that California may experience reduced energy use due to an extension, even if Australia did not.

The simulation approach uses data on hourly electricity consumption under the status quo DST policy to investigate the impact of a DST extension. This procedure first employs a regression analysis using status quo data to assess how electricity demand in each hour is affected by weather and light, and then uses the regression coefficients to predict demand in the event of a 1-h time shift, lagging the weather and light variables appropriately. The consistency of the simulation results relies on the assumption that extending DST will not cause patterns of activity that are not observed in the status quo, which may not hold in practice. For example, to simulate demand under extended DST at 07:00 in March in the US, the model must rely on observed status quo behavior at 07:00 under similarly cold and low-light conditions. Without a DST

(footnote continued)

significant at only the 30% level, the sign of the difference is intuitive: in October there is more morning sunlight and temperatures are warmer, so the morning increase in demand is mitigated.

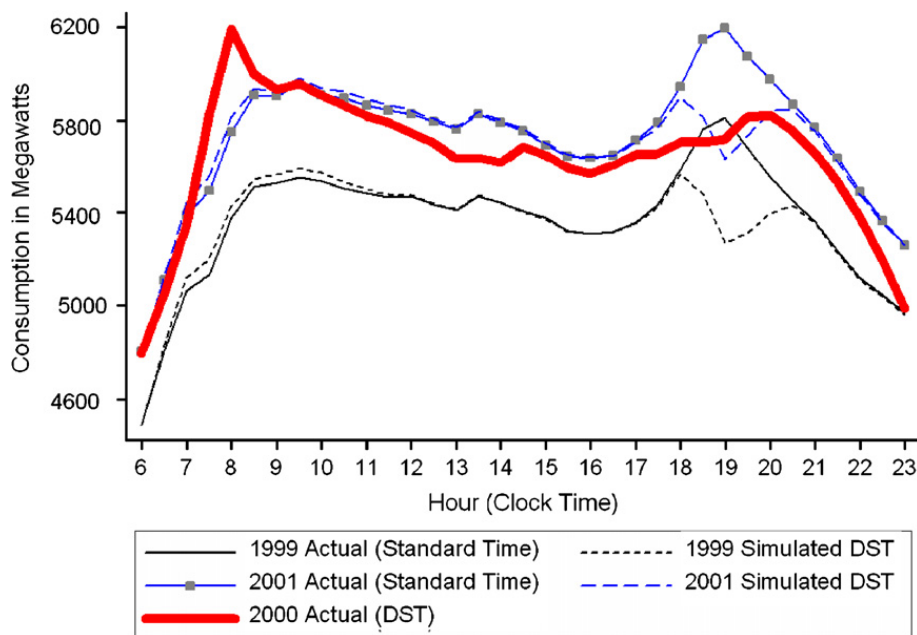


Fig. 6. Actual and simulated electricity consumption in VIC, September 1999–2001.

extension, these conditions are observed only in mid-winter. The simulation will be inaccurate if people behave differently in the morning in mid-winter than they do in spring under extended DST.¹⁵

In contrast, in the Australian quasi-experiment, we have already estimated the effect of the DST extension directly, by comparing observations under both the status quo and the extension. We can therefore evaluate the simulation's performance by re-estimating its first stage using status quo observations, forecasting electricity demand under an extension, and then comparing these results to those estimated from actual data.

The first stage of the simulation model is a regression of hourly electricity demand, q_{dh} , on employment, weather, and astronomical sunlight and twilight variables, for a full year of observations:

$$q_{dh} = a_h + b_h \text{Employment}_d + c_h \text{Weather}_{dh} + d_h \text{Light}_{dh} + u_{dh}.$$

The disturbance u_d is correlated across the $h = 1, \dots, 24$ hourly equations per the Seemingly Unrelated Regression method [30]. The regression allows the weather and light coefficients to vary across the 24 h of the day, and the weather specifications are very detailed, involving several lags and moving averages of half-hourly temperatures, with different coefficients for hot, warm, and cold conditions.¹⁶ Once the vectors of regression coefficients are estimated, they are used in the second stage of the model to forecast electricity consumption under a DST extension. This is accomplished by lagging the weather and light variables by 1 h and by adding the first stage realized error term to construct the following projection:

$$q_{dh}^{\text{sim}} = \hat{a}_h + \hat{b}_h \text{Employment}_d + \hat{c}_h \text{Weather}_{dh-1} + \hat{d}_h \text{Light}_{dh-1} + \hat{u}_{dh}.$$

We apply the first stage of the CEC model to the Australian data for all of 1999 and 2001, and then simulate electricity consumption under extended DST in VIC in September 1999 and 2001 (we are unable to simulate demand under an extension in 2000 using the CEC's method because we do not observe demand under Standard Time in that year). Fig. 6 illustrates the simulated demand, as well as actual demand (under standard time), in both years. The simulations predict a substantial decrease in demand in the evening and only a minor increase in demand in the morning, with overall energy savings of 0.43% in 1999 and 0.41% in 2001. Both the hour-by-hour and overall results closely align with the 0.6% savings predicted for California in the original study (see Fig. 7). The results disagree, however, with the actual outcome of the Australian DST extension in 2000. Fig. 6 also includes, in bold, the realized demand in VIC under the 2000 treatment. In both 1999 and 2001, the simulation fails to predict a morning increase in electricity consumption similar to that observed in 2000, and also overestimates evening savings. The simulated decrease in overall consumption is inconsistent with what actually happened in VIC. Based upon our DDD estimate of a 0.39% increase in consumption in September presented earlier,

¹⁵ It may be the case that, as winter turns into spring, people move their waking time earlier with the sun, and do not adjust their behavior after the sudden time shift imposed by extended DST. Thus, there could be more early morning activity under extended DST in the spring than under Standard Time in the winter, resulting in higher electricity use.

¹⁶ Details of the definition on these variables, the estimation of the model, and the simulation are explained in CEC [4]. We make minor changes to the CEC specification to account for our half-hourly, rather than hourly data, and for the fact that we observe humidity, precipitation, and daily unobstructed sunshine, but not hourly cloud cover. Computer code is available in Appendix E at the online archive.

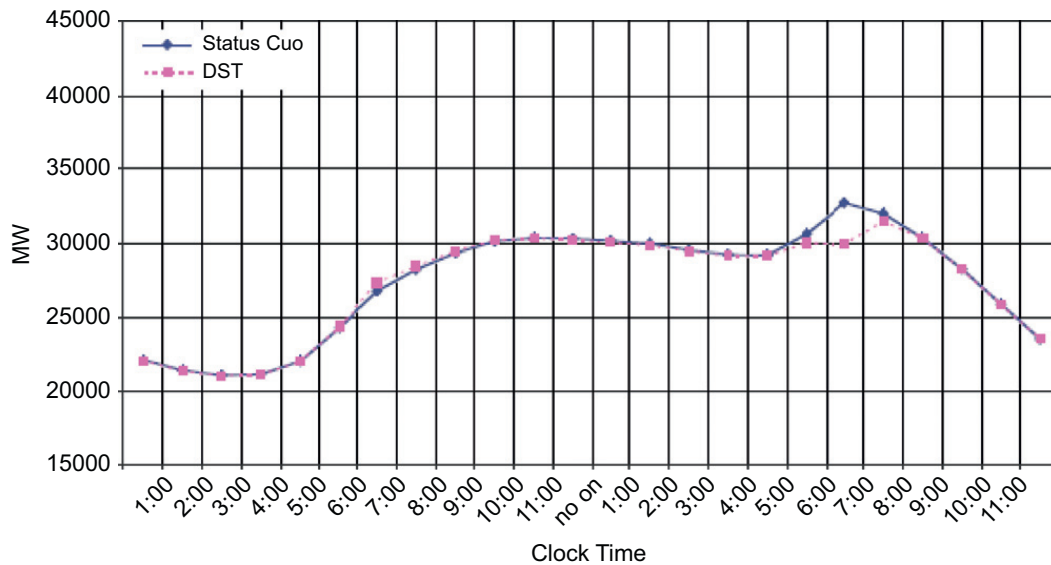


Fig. 7. Simulation of DST in California, March 1998–2000 (CEC [4]). Status quo demand is observed under Standard Time.

we reject the simulated 0.41% savings at a 10% significance level. The simulation is unable to predict the substantial intraday shifts that occur due to the early adoption of DST, a result that holds even after we attempt to improve the model's fit by introducing higher order terms for the continuous variables or by selecting a smaller first-stage sample in which light and weather conditions most closely resemble the extension period in September.

7. Conclusions

Given the economic and environmental imperatives driving efforts to reduce energy consumption, policy-makers in several countries are considering extending daylight saving time (DST), as doing so is widely believed to reduce electricity use. Our research challenges this belief, as well as the studies underlying it. We offer a new test of whether extending DST decreases energy consumption by evaluating an extension that occurred in the state of Victoria, Australia, in 2000. Using half-hourly panel data on electricity consumption and a difference-in-difference-in-difference treatment effect model, we show that while extending DST did reduce electricity consumption in the evening, these savings were negated by increased demand in the morning. These effects are consistent with the alignment of daily activities to the clock rather than the sun, so that the 1-h shift associated with DST caused people to awaken in darkness.

Further, the evidence does not support the existence of two additional DST extension benefits that have been discussed in the prior literature: a reduction in electricity prices and a reduction in the likelihood of blackouts, driven by a more balanced hourly load shape. The data instead show that the Australian DST extension substantially increased wholesale prices and caused a sharp peak load in the morning.

From an applied policy perspective, this study is of immediate interest for Australia, which is actively considering using DST as a tool for energy conservation and greenhouse gas (GHG) emission abatement. Moreover, the lessons from Australia may carry over to the United States and to California in particular, as Victoria's latitude and climate are similar to those of central California. The 2007 DST extension in the United States causes DST to be observed in March—a month that is analogous to September in Australia, when our results suggest that DST increases rather than decreases overall electricity consumption. Moreover, there is little reason to believe that the lack of electricity demand reduction associated with Australia's 2000 extension was driven by the extension's temporary nature. Because the demand response appears to be caused by behavioral changes rather than long-term investments, significant differences between short- and long-term effects are unlikely. Finally, we find that the simulation model that supported a DST extension in California overestimates energy savings when we apply it to Australia. This casts suspicion on its previous policy applications, and provides further evidence that the US extension is unlikely to achieve its energy conservation goals.

Given the evidence presented in this paper, why do policy-makers believe that extending DST will conserve energy? While reliance on prior literature, particularly the 1975 US DOT study [27], may play a role in this belief, a deeper reason may come from attempts to extrapolate from DST's effects in the summer to its effects in the spring and autumn. There exists a reasonable intuition for why DST may reduce electricity use in the summer: the days are sufficiently long that DST should not cause people to awaken in the dark, and the "extra" sunlight in the evening will reduce energy use. In the spring and fall, however, the days are shorter and this intuition is no longer valid: DST causes the sun to rise after 07:00 and people awaken in the dark. A failure to recognize this distinction between the seasons may therefore result in a belief that extending DST will conserve energy.

As for the future status of DST, the 2005 US energy bill prescribes that the recent extension be repealed should studies demonstrate that it does not reduce energy consumption. However, extending DST may have non-energy impacts that are economically important and, given the lack of a significant effect on electricity use, be worthy of greater consideration in the setting of DST policy. For example, recent papers have found that DST significantly affects stockmarket trading and traffic accidents [13,23]. In addition, extending DST may directly affect welfare by altering the opportunities for outdoor recreation. A deeper understanding of these impacts would be both economically interesting and of value to policy-makers in assessing the overall merit of extending DST.

Acknowledgments

We are indebted to Michael Anderson, Maximilian Auffhammer, Severin Borenstein, Jennifer Brown, Kenneth Chay, Michael Hanemann, Ann Harrison, Guido Imbens, Enrico Moretti, Jeffrey Perloff, Susan Stratton, Muzhe Yang, David Zilberman, and two anonymous referees for valuable discussions and suggestions. We further thank Alison McDonald from NEMMCO and Lesley Rowland from the Australian Bureau of Meteorology for helping us understand the electricity and weather data, and Adrienne Kandel from the California Energy Commission (CEC) for conversations regarding the details of the CEC simulation model.

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