DAYLIGHT TIME AND ENERGY

EVIDENCE FROM AN AUSTRALIAN EXPERIMENT

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JOB MARKET PAPER

November, 2006

Abstract

Rising energy prices and environmental concerns are driving countries to consider extending Daylight Saving Time (DST) in order to conserve energy. Beginning in 2007, the U.S. will lengthen DST by one month with the specific goal of reducing electricity consumption by 1%. In this paper we question the findings of prior DST studies, which often rely on simulation models and extrapolation rather than empirical evidence. By contrast, our research exploits a quasi-experiment, in which parts of Australia extended DST by two months to facilitate the Sydney Olympic Games in 2000. We test the electricity-saving hypothesis using detailed panel data on half-hourly electricity consumption, prices, and weather conditions. We show that the extension failed to reduce electricity demand. We further examine prior DST studies and apply the most sophisticated simulation model available in the literature to the Australian data. We find that prior models significantly overstate electricity savings. These results suggest that current plans and proposals to extend DST will fail to conserve energy.

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, and David Zilberman for valuable discussions and suggestions. We are also grateful for helpful comments from participants at a UCEI lunch presentation and the Environment and Resource Economics Seminar at UC Berkeley. 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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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 –

Introduction

One principal socio-economic problem is the optimal allocation of individuals' activities—sleep, work, and leisure—over the twenty-four hours 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 resource economics, *An Economical Project*, Benjamin Franklin (1784) criticizes this behavior because it wastes valuable sources of morning daylight and requires expensive candles to illuminate the nights. Franklin calculates that this misallocation causes Paris to consume an additional 64 million pounds of tallow and wax annually.

Governments have also recognized this resource allocation problem, and have attempted to address it through the mechanism of Daylight Saving Time (DST).[1] Each year we move our clocks forward by one hour in the spring, and adjust them back to Standard Time in the fall. Thus, during the summer, the sun appears to set one hour later and the "extra" hour of evening daylight is presumed to cut electricity demand.

Today, heightened concerns regarding energy prices and the externalities of fossil fuels are driving renewed interest in implementing DST in many countries.[2] The United States recently passed legislation to extend DST by one month with the specific goal of reducing electricity consumption by 1% during the extension (*Energy Policy Act*, 2005). Beginning in 2007, the U.S. will switch to DST in March rather than in April. California is considering even more drastic changes—year-round DST and double DST—that are predicted to save up to one billion U.S. dollars annually (*Joint Senate Resolution*, 2001).

Our study challenges the DST-energy literature findings that have been directly used to justify these calls for the expansion of DST. Across the studies we surveyed, estimates of an extension's effect on electricity demand range from 0.6% to 3.5%. The most widely cited savings estimate of 1% is based on an examination of a U.S. extension to DST that occurred

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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 U.S. observed year-round DST during World War II and implemented several substantial extensions during the energy crisis in the 1970s (*Emergency Daylight Savings Time Energy Conservation Act*, 1973). Today, DST is observed in over seventy countries worldwide. But DST is also heavily criticized for the inconveniences it creates on the days when the switch between DST and Standard Time occurs. For more information on the history of DST, see the recent books by Prerau (2005) and Downing (2005); Beauregard-Tellier (2005) provides an overview on the recent DST-energy literature.

[2] Non-U.S. regions currently considering extending DST are Japan, Canada, New Zealand, and Australia with cited electricity savings of 2.2%-3.5%. The purpose for the extension plans differ by country and range from cutting greenhouse gas emissions by 440,000 tons of CO_2 in Japan to conserving water resources used in New Zealand to generate hydropower. For details see ECCJ (2006), Young (2005), Eckhoff (2001) and Hansard (2005).

in response to the Arab oil embargo (DOT, 1975). Due to the age of this study, it is possible that its findings are no longer applicable today—for example, because the widespread adoption of air conditioning has altered intraday patterns of electricity consumption.

One primary method for predicting the effects of DST on electricity use is to employ simulation models, such as the 2001 study by the California Energy Commission (CEC) that is being used to promote year-round DST in California.[3] It predicts three benefits: (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, instead it uses electricity market 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.[4]

An alternative approach is to examine electricity consumption a week before and a week after currently existing springtime changes. The set of studies taking this approach forecast larger drops in electricity use: from 2.2% in Ontario, Canada (Young, 2005) up to 3.5% in New Zealand (Eckhoff, 2001). However, the week after the springtime change has longer and warmer days which, even in the absence of DST, would change electricity consumption, potentially biasing the studies' results.

In our study, we offer a new test of whether extending DST decreases energy consumption by evaluating 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, (located in New South Wales), two of these three states began DST two months earlier than usual. Because the Olympics can directly affect the electricity demand we focus on Victoria—which did not host Olympic events—as the treated state, and use its neighbor state, South Australia, which did not extend DST, as a control. Furthermore by dropping the two week long Olympic period from the two month treatment period we remove confounding effects. Using a detailed panel of half-hourly electricity consumption and prices, as well as the most detailed weather information available, we examine how the DST extension affected electricity demand in Victoria. This experimental setting and rich dataset obviate the need to rely on simulations in our study.

Our treatment effect estimation strategy is based on a difference in differences (DID) method 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 DID

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[3] Until today, the DST system proposed in California's *Joint Senate Resolution* (2001) has not been implemented. *"Congress and the White House did not act on the request because of the world-changing events of September 11, 2001"* (Aldrich, 2006). Subsequently, the federal *Energy Policy Act* has been considered more urgent, rather than changing DST state by state.

[4] We found one more study by Rock (1997). Using a complex simulation model he finds that year-round DST decreases demand by 0.3% and electricity expenditures decrease by 0.2%. However, the simulation does not include non-residential electricity use, which accounts for 74% of U.S. total electricity consumption (EIA, 2005).

model in several innovative ways. Most notably, we take advantage of the fact that DST does not affect electricity demand in the afternoon; we can therefore use changes in relative afternoon consumption to control for unobserved shocks that are not related to DST. We show that this allows us to employ a much more relaxed identifying assumption compared to the standard DID setting.

Our results show that the extension failed to conserve electricity. The point estimates suggest that energy consumption increased rather than decreased, and that the within-day usage pattern changed substantially, leading to a high morning peak load. The morning wholesale electricity prices therefore increased sharply. These results contradict the DST-benefits claimed in the prior literature.

We further analyze whether the prior approaches to forecasting electricity demand could have predicted the outcomes of the Australian experiment. This is a relevant question for many countries that wish to evaluate the benefits of an extension. We find that both the simulation model used in California and the "week before / week after" technique produce estimates that are biased in the direction of energy savings, which casts suspicion on the models' previous policy recommendations.

Finally, it should be noted that Australia—ranked highest in greenhouse gas (GHG) per capita emissions worldwide—is currently debating whether to permanently extend DST in a manner similar to that done in 2000 (Turton and Hamilton, 2001; Hansard, 2005).[5] Our results indicate that the claims that extending DST in Australia will significantly decrease energy use and GHG emissions are at best overstated, and at worst carry the wrong sign. Also, while we cannot apply our results to other countries without adjustment for behavioral and climatic differences, this study raises concern that the U.S. is unlikely to see the expected energy conservation benefits from extending DST.

The remainder of this paper is organized as follows: the next section provides a brief overview of the DST system in Australia and the changes that occurred in the year 2000. After describing our dataset and presenting preliminary graphical results, section 4 discusses our exogeneity assumption and the treatment effect estimation strategy. Section 5 presents the empirical findings. In section 6, we provide an overview of the two methods previously used to analyze the effects of extending DST on energy use. Section 7 and 8 then discuss the application of these two methods to Australia. We conclude by summarizing our main results and provide policy implications.

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[5] In Australia, 92% of the electricity produced relies on the burning of fossil fuels, which substantially contributes to the GHG emissions.

2. Background on Daylight Saving Time in Australia

The geographical area of interest is the Australian continent's eastern part, displayed in Figure 1. Three states in the south east of the mainland observe DST—South Australia (SA), New South Wales (NSW) and Victoria (VIC). DST typically starts on the last Sunday in 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.

Figure 1: East Australia, states and major cities

NSW, VIC, and SA in mainland Australia regularly begin DST on the last Sunday in October each year. In 2000, however, NSW and VIC began DST on 27 August, whereas SA did not begin DST until 29 October.

In 2000, NSW and VIC started DST two 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 seventeen days of the Olympic Games that took place in Sydney, in the state of NSW, from 15 September to 1 October.

Three rationales for the extension were put forward in 1991 when Sydney applied to the International Olympic Committee (Hansard, 1999a and 1999b).

(a) Many afternoon Olympic events ended near 17:30, and evening events began between 18:00 and 19:00. Extended DST would allow the movements of visitors to and from stadia to take place in sunlight rather than twilight. This was expected to improve the visitors' well-being by providing higher temperatures, more daylight, and better security.

Table 1: Geographic and population characteristics in east Australia

State Capital	State	State Income/Capita in 1000 AUD	City Population in millions	State Population in millions	Latitude South	Longitude East	Sunrise	Sunset
Sydney	NSW	41.4	4.3	6.5	33°5'	151°1'	5:50	17:45
Melbourne	VIC	39.3	3.7	4.8	37°47'	145°58'	6:20	18:10
Adelaide	SA	33.4	1.1	1.5	34° 55'	138° 36'	6:50	18:35

All estimates are of 2000. Sunrise and sunset hours refer to Eastern Australian Standard Time in the month of September. Additional astronomical data are detailed in Appendix A.

(b) Extended DST would reduce on-field shadows on the playing fields that could hinder both athletes and television broadcasting quality.

(c) Due to wind and weather conditions in September, rowing would need to start at 7:30am under Standard Time. DST permits rowing to start at 8:30am, to the benefit of spectators.

Notably, none of the justifications for the DST extension were related to energy usage.

A timeline of events is displayed in Figure 2. The decision to start DST three weeks prior to the beginning of the Olympic Games was intended to avoid confusion for athletes, officials, media and broadcasters and other international visitors who would likely arrive prior to the opening of the games. The opening of the Olympic village was scheduled for 3 September 2000. VIC adopted the NSW timing proposal to avoid inconveniences for those living on the NSW-VIC border (see Figure C1 in Appendix C). However, SA did not extend DST in 2000 due to the opposition of the rural population (Hansard 1999a, 1999b, 2005).

Figure 2: Timeline of 2000 events in New South Wales, Victoria and South Australia

Table 2: Summary statistics of data used from 1999 to 2001, 27 August to 27 October

State	Summary of all years, 8928 observations per state						Summary by year, Olympic dates excluded					
							1999		2000		2001	
	Variable	[unit]	mean	std	min	max	mean	std	mean	std	mean	std
Victoria	Demand	[MW]	5253.68	550.56	3777.31	6861.32	5153.71	526.74	5331.40	562.57	5403.20	570.17
	Price	[AUD/MWh]	27.36	97.20	-305.78	4527.21	19.72	6.37	45.09	187.72	29.55	88.02
	Temperature	[Celsius]	12.88	4.26	2.15	27.30	13.61	4.56	11.75	3.71	12.24	3.84
	Precipitation	[mm/hour]	0.08	0.48	0.00	15.40	0.07	0.52	0.15	0.76	0.04	0.24
	Wind	[meter/sec]	5.11	3.09	0.00	18.75	4.84	2.99	5.47	2.82	4.88	2.70
	Pressure	[hPa]	1015.23	7.61	990.30	1031.95	1017.81	6.40	1011.44	7.21	1011.93	6.33
	Sunshine	[hours/day]	6.29	3.65	0.00	12.20	6.76	3.85	5.81	3.61	5.72	3.57
	Humidity	[RH%]	71.00	17.18	19.00	101.50	70.38	16.73	73.36	15.65	71.70	17.55
	Employment	[in 1000]	2254.21	43.67	2154.81	2303.30	2192.68	14.71	2271.98	12.53	2289.37	11.92
	Non-Working Day	[% of days]	0.44	0.50	0.00	1.00	0.29	0.46	0.29	0.46	0.27	0.44
	School-Vacation	[% of days]	0.16	0.37	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
	Holiday	[% of days]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
South Australia	Demand	[MW]	1368.48	196.92	909.87	1954.26	1339.32	179.99	1397.31	202.81	1424.02	203.35
	Price	[AUD/MWh]	41.06	120.75	3.50	5000	55.66	167.16	52.57	168.27	27.69	18.63
	Temperature	[Celsius]	14.91	4.24	4.05	31.60	15.76	4.87	14.08	3.20	13.66	3.25
	Precipitation	[mm/hour]	0.07	0.38	0.00	7.60	0.00	0.00	0.13	0.56	0.12	0.48
	Wind	[meter/sec]	4.54	2.76	0.00	17.00	4.28	2.58	5.23	2.87	4.69	2.78
	Pressure	[hPa]	1016.21	6.91	989.95	1030.80	1017.81	6.73	1014.18	7.01	1013.41	6.45
	Sunshine	[hours/day]	7.39	3.44	0.00	12.40	8.52	3.10	7.22	3.43	6.48	3.41
	Humidity	[RH%]	66.40	18.41	9.00	98.00	62.73	19.24	69.06	16.45	70.00	17.38
	Employment	[in 1000]	679.28	7.33	662.94	687.75	668.83	2.80	684.35	2.50	682.81	2.42
	Non-Working Day	[% of days]	0.45	0.50	0.00	1.00	0.34	0.47	0.29	0.46	0.39	0.49
	School-Vacation	[% of days]	0.16	0.37	0.00	1.00	0.05	0.22	0.00	0.00	0.12	0.33
	Holiday	[% of days]	0.02	0.12	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00

Abbreviations: MW = Megawatts; AUD/MWh = Australian Dollars per Megawatt-hour; mm = millimeters; hPa = Hectopascal; RH% = relative humidity %. 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 (NEMMCO, 2005).

3. The Australian data and graphical results

3.1 Data

Electricity consumption and price data are obtained from Australia's National Electricity Market Management Company Limited (NEMMCO). These consist of half-hourly electricity demand and prices by state from 13 December, 1998 to 31 December, 2005.

Because electricity demand is heavily influenced by local weather conditions, we use two datasets 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 3 cities that primarily drive electricity demand in each state. The data cover 1 January, 1999 to 31 December, 2005 and include temperature, wind speed, air pressure, humidity and precipitation. The second dataset consists of daily weather observations, including the total number of sunshine hours per day.

We also collected information regarding state-specific holidays and public school vacations to control for their effect on electricity usage. We identify "transition vacation days" as working days sandwiched between a holiday and a weekend. For example, the Melbourne Cup in Victoria is on the first Tuesday of November each year. Because many employees take an extended weekend vacation, we model the Monday as a transition vacation day.

Table 2 provides summary statistics for each of these variables by state in the period during the DST extension, end of August to end of October, as well as for the treatment period in 2000 and the adjacent years 1999 and 2001. Displayed are the mean, standard deviations (std), minimum (min) and maximum (max). More details on the entire dataset as well as on our procedures for dealing with missing data are provided in Appendix B.

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. Before presenting the econometric model, the main intuition can be obtained by the graphical analysis presented in Figure 3. Panel (a) displays the average half-hourly electricity demand in Megawatts (MW) in the control state of SA during the treatment period[6], in 1999, 2000, and 2001, and the panel (b) shows the same for VIC. SA's load shape is very stable over these three 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 until about 04:00 on the following morning. In particular, SA's demand in 2000 appears unaffected by the DST extension in its neighbors VIC and NSW.[7]

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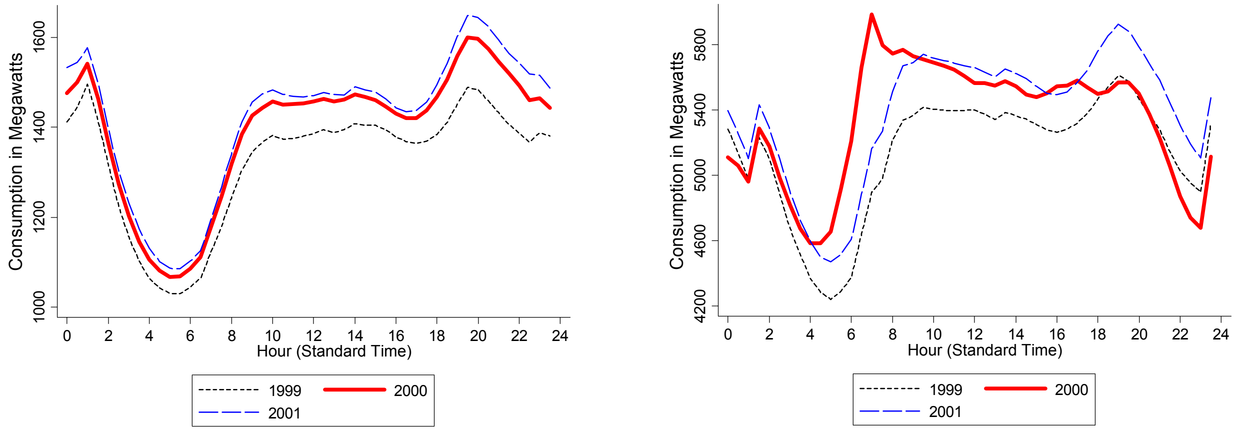
[6] The treatment period covers 27 August, 4am to 27 October, excluding 15 September to 2 October. This corresponds to the extension period in 2000, less the 17 days of the Olympic games.

[7] Hamermesh et al. (2006) 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

In VIC, however, the 2000 load shape is quite different from the loads in 1999 and 2001—the treatment dampens evening consumption, but leads to higher morning peak demand. This behavior is consistent with the expected effects of DST's one-hour time shift: less lighting and heating are required in the evening, and more in the morning—particularly from 07:00 to 08:00—driven by reduced sunlight and lower temperatures. 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 to 08:00 interval is the coldest hour of the day; the average temperature for this hour is only 9^{o}C. The one-hour clock time shift imposed by DST causes people to awaken in cold, low light conditions. This causes an increase in electricity demand that persists even one hour after sunrise.

Figure 3: "September and October" average half hourly electricity demand in South Australia (control) and Victoria (treated in 2000)[8]



(a) South Australia (control)

(b) Victoria (treated in 2000)

Panel (b) also casts doubt on the claims that extended DST brings additional benefits in the form of higher system reliability due to a more balanced load shape (for a discussion on these benefits see CEC, 2001). While the extension does reduce the evening peak load in VIC in 2000, it creates a new, sharp peak in the morning. This 2000 morning peak is even higher than the evening peak in 2001, and its sharp increase and decrease around 07:00-8:00 are steeper than those for any peak period found elsewhere in our data set.

Our preliminary analysis also casts doubt on the claims that extending DST brings additional benefits in the form of reduced electricity prices.[9] As shown in Figure 4, below,

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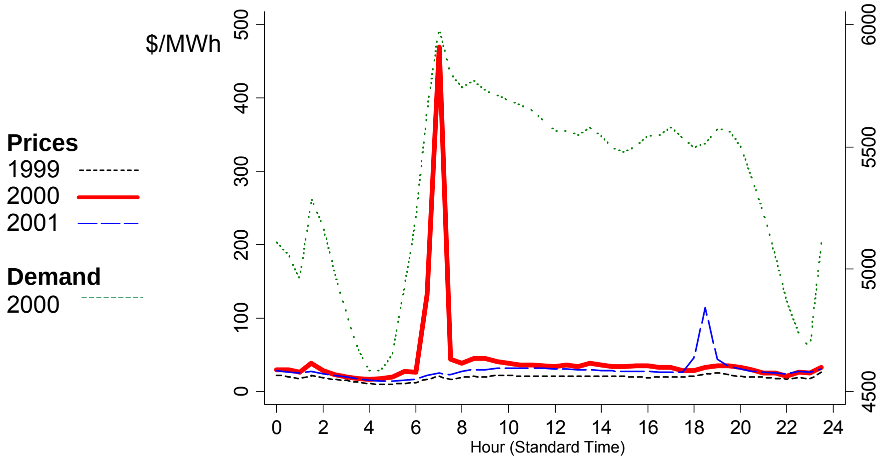
with their neighbors in VIC. However, the effects that Hamermesh et al. calculate are small, and Panel (a) of Figure 3 does not show evidence of such a time shift.

[8] The "zig-zag" pattern that occurs between 11pm and 2am in both states is due to centralized off-peak water heating that is activated by automatic timers (Outhred, 2006). The yearly increases in electricity demand can be attributed to population growth (2% in VIC and 1% in SA) and state specific economic conditions—the real gross state income per capita grew by 3% and 5% in VIC and SA respectively. Despite these level shifts, the load patterns are remarkably similar for the control years.

the new morning peak in demand is coincident with a large spike in wholesale prices. Morning price spikes occurred on every working day during the first two weeks of the extension, suggesting that the generation system was initially stressed to cope with the steep ramp in demand.

Figure 4: "September and October" average half hourly electricity prices and demand in Victoria (treated state in 2000)



The answer to the central question of whether the evening decrease outweighs the morning increase, or vice-versa, is, however, not clear from this cursory analysis since it does not account for important determinants, such as economic conditions, school vacations, weather and other factors that change over time. To obtain the unconfounded effect of the treatment, we employ regression analysis, as described in the following sections. The variables used to undertake this are displayed in Table 2.

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[9] The fixed costs of electricity generation are largely determined by the peak load. Econometric studies suggest that higher peak loads, relative to the average load, increase average costs significantly (e.g. Filippini and Wild, 2000). The intuition for this is that when the load shape is flat, supply can be generated by coal-fired base-load generators with low variable costs. Volatile load shapes, however, require natural gas and oil-fired generators which can quickly ramp up or down, but have higher variable costs. Characteristics of the different generators used in Australia, their warm up times, supply costs, environmental impacts and the market mechanism to determine the wholesale prices of Figure 4 are further detailed in Appendix C.

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

The following two subsections describe our empirical strategy to identify (4.1) and quantitatively measure (4.2) the effect of extending DST on electricity use.

4.1 Identification

For the purpose of estimating the effect of the DST policy on energy use, a fundamental difficulty is that one cannot simultaneously observe both, how a state consumes energy under DST (the treatment) and how this state would behave in the absence of the treatment (the counterfactual). The optimal experiment would be to randomly allocate different timing schemes across states. While such an experiment cannot be observed, we believe that the DST modification that occurred in Australia in 2000 comes close. In this case we directly benefit from observations during the treatment period and the control period in both the treated and the non-treated state.

While we noted that the DST extension was implemented solely for operational purposes, and that we are not aware of any energy-based justifications, there may still be reasons to suspect that electricity consumption may have changed 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 TVs by millions of Australians in Sydney and elsewhere.

Our identification strategy incorporates several features designed to account for these potential confounders. First, we exclude the seventeen days of the Olympic period 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—for example by pre-Olympic construction activities and by 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. This technique eliminates the impact of any confounders that operate on a national level.[10]

To control for unobservables that may have affected VIC and SA differentially, we use relative demand in the afternoon as an additional control. That is, because DST does not affect demand in the middle of the day, variations in demand levels that are not explained by observables such as weather can be attributed to non-DST-related confounders. With that, our model is robust against any "level shocks" affecting the level of the consumption in any state at any day *d*, but do not affect the shape of the half-hourly load pattern at date *d*. We

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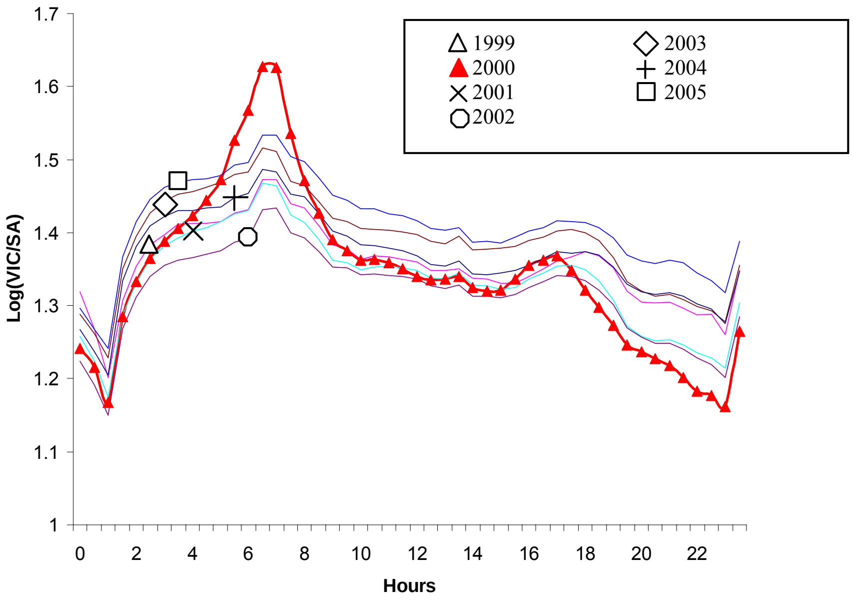
[10] To further analyze whether visitors before and after the Olympic Games spent extended vacations in VIC or SA, we collected tourism information. These data clearly show that while NSW was affected by tourism in September, VIC and SA were unaffected. Details on the tourism data are provided in Appendix D.

verify the assumption that DST does not affect afternoon demand by examining time changes in non-treatment years, as described in appendix E.

These three features of our model imply that a mild identifying assumption guarantees that our regressions 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. Strong support for this is found by plotting the ratio of consumption in VIC to that in SA for 1999-2005, as shown in Figure 5. The demand ratio exhibits a regular pattern in all non-treated years, even without controlling for observables. The figure also illustrates the large intra-day shift in consumption that occurred in VIC in 2000, in response to the DST extension.

Moreover, the level of the log ratio is unsystematically changing from smallest to largest over the years 2002, 2000, 2001, 1999, 2004, 2003, to 2005. This is consistent with the premise that level shocks, which we control for, affect one or the other state temporarily only. Finally, the decrease in evening demand in VIC in 2000 and the increase in the morning are clearly visible, being consistent with the analysis of section 3.

Figure 5: Demand ratio between VIC (treated) and SA (control) averaged between 27 August and 27 October



4.2. Treatment effect model

Our specification of the treatment effect model is primarily drawn from the difference-in-differences (DID) literature (Meyer 1995 and Bertrand et al., 2004). We augment the standard DID model by estimating a "triple-DID" specification because, as outlined in section 4.1, our control structure is three-fold:

(a) cross-sectional over states (using VIC as the treated state and SA as the control)
(b) temporal over years (using the untreated years in SA and VIC as controls)
(c) temporal within days (using afternoon hours as "within-day" controls)

Our linear specification is

$$\ln(q_{idh}) - \ln(\overline{q}_{id}) = T_{idh}\beta_h + X_{idh}\alpha_h + W_{idh}\phi_h + \varepsilon_{idh} \qquad (1)$$

The dependent variable for each observation is the difference in logs between demand, q, in state i in day d in half-hour h, and $\overline{q}$, the average electricity demand between 12:00-14:30 in the same state and day, whereby $i \in$ {VIC, SA}, $d = \{1,2,\ldots,186\}$, and $h = \{1,2,\ldots,48\}$. The reference case model uses data from VIC and SA during 27 August to 27 October in 1999, 2000, and 2001; that corresponds to the time period of the DST extension in 2000, while in the years 1999 and 2001 during this period Standard Time is observed.

The covariates of primary interest are the indicator variables T_{idh} for the treatment period, unpooled by half-hour and active from 27 August to 14 September, 2000 and from 2 October to 28 October, 2000, thereby excluding the Olympic Games from the treatment.

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, transition days, 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[11] and include a quadratic in hourly heating degrees,[12] daily sunlight hours, the interaction of sunlight with temperature, hourly precipitation, the interaction of precipitation with temperature, and the average of the afternoon heating degrees. All weather variables enter the model lagged by one hour.

In equation (1) the treatment effect parameters to be estimated are given by β_h. The percentage change in electricity demand caused by the DST extension is given by

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[11] Our final specification pools some hours to improve efficiency of the weather models. Doing so has no impact on the reported results on the treatment effects. In total, this specification has 48 treatment effects, 1019 fixed effects, 288 variables characterizing different days of the week, 144 variables to account for school-vacations, holidays, and transition days, 222 weather related variables and 96 indicators to dummy out the Olympic period.

[12] Heating degrees are calculated as the difference between the observed temperature and 18.33^{o} Celsius (65^{o} Fahrenheit). The motivation of squaring the heating degree is that as the temperature deviates from 18.33, cooling or heating efforts increase nonlinearly. This functional form is consistent with other electricity demand models in the literature (see Bushnell and Mansur 2005).

$\exp(\beta_h)$-1.[13] The main parameter of interest, however, is the percentage change in demand aggregated over all 48 half-hours, given by

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

That is, θ is calculated as 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 27 August to 27 October, exclusive of the Olympic dates.

Our objective is to obtain the mean and other statistics of interest of the probability density function of the estimate $\hat{\theta}$, denoted $g(\hat{\theta})$. Because $\hat{\theta}$ is the weighted sum of non-iid lognormal variables, this distribution does not have a closed form solution and must be estimated numerically.[14]

To do so, we first develop a covariance estimator for $\hat{\boldsymbol{\gamma}} = [\hat{\boldsymbol{\beta}}^{\mathsf{T}}\ \hat{\boldsymbol{\alpha}}^{\mathsf{T}}\ \hat{\boldsymbol{\varphi}}^{\mathsf{T}}]^{\mathsf{T}}$, which in turn relies on the covariance structure of the disturbance $\boldsymbol{\varepsilon} = \mathbf{Y}\text{-}\mathbf{Z}\gamma$. We allow ε to be both heteroskedastic and clustered on a daily level,

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

The motivation for selecting this block-diagonal structure is that it accounts for autocorrelation as well as for common shocks that affect both states contemporaneously. The clustered sample covariance matrix estimator is therefore used for γ (Wooldridge, 2003; Bertrand et al., 2004).

As an alternative to the clustered disturbance structure, we also estimate the model using the Newey and West (1987) estimator with 50 lags.[15] To adapt this estimator to our panel data, we block-diagonally partition the covariance matrix of ε into six groups (the three years by two states) and do not permit the lag structure to overlap across groups. For each block $\boldsymbol{\Omega}_j$, j=1,..,6, we assume the same covariance so that $\boldsymbol{\Omega}_j = \boldsymbol{\Omega}$.

With an estimate of the covariance of $\hat{\boldsymbol{\beta}}$ in hand, we numerically estimate the probability distribution $g(\hat{\theta})$ by taking 100,000 draws from the distribution $N(\hat{\boldsymbol{\beta}}, \mathbf{Cov}(\hat{\boldsymbol{\beta}}))$, and calculating $\hat{\theta}$ by (1) for each draw. It turns out that this numerical estimation produces a

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[13] To derive $\exp(\beta_h)$, we make use of the afternoon assumption that $E[\overline{q_{id}}\ |T_{id}=1] / E[\overline{q_{id}}\ |T_{id}=0] = 1$.

[14] Dependence between the estimates of the neighboring half-hours, $\hat{\beta}_h$ and $\hat{\beta}_{h-1}$ theoretically can lead to an a-typical shaped distribution g (see e.g. Vanduffel, 2005 for a recent treatment). Dependence structures vary by different covariance estimators. This is further illustrated in Appendix E.

[15] 50 lags allow the errors to be correlated over slightly more than one full day. Tests of AR(p) models on ε suggest that the disturbances are correlated over the first six hours of lags, but not beyond that. However, the coefficient on the 48th lag is significant. Also, note that the triple DID specification considerably decreases the autocorrelation properties of the dependent variable, relative to a standard DID. See Bertrand et al., 2003 for a discussion of the problems of autocorrelation and DID models.

distribution $\hat{g}(\hat{\theta} \mid \mathbf{Z})$[16] that is indistinguishable from a normal distribution with a mean given by the empirical analogue of (2),

$$\hat{\theta} = \frac{\sum_{h=1}^{48} \exp(\hat{\beta}_h)\omega_h}{\sum_{h=1}^{48} \omega_h} - 1, \tag{3}$$

and a variance $\hat{\theta}$ calculated by the delta method,

$$V(\hat{\theta}) = \nabla_\beta \theta(\hat{\boldsymbol{\beta}})^T \mathbf{Cov}(\hat{\boldsymbol{\beta}}) \nabla_\beta \theta(\hat{\boldsymbol{\beta}}), \tag{4}$$

with $\nabla_\beta \theta$ as the (48 x 1) gradient vector of $\theta(\cdot)$ evaluated at $\hat{\boldsymbol{\beta}}$. We therefore report $\hat{\theta}$ and $V(\hat{\theta})$ as estimated by (3) and (4), rather than as the mean and variance of $g(\hat{\theta})$ and we can directly approximate any further statistic used in the below hypothesis tests as a Student's *t* distribution, which leads to the same results as if one were bootstrapping throughout.

5. Results

5.1 Reference case results

The primary goal of the empirical analysis is to examine the effect of the two-month extension of DST on electricity consumption. Figure 6 displays the estimated percentage impact of the DST extension on electricity demand in each half hour; these are the point estimates given by $\exp(\hat{\beta}_h) - 1$. Extending DST affects electricity consumption in a manner consistent with the preliminary graphical analysis: there is a transfer in consumption from the evening to the morning. This behavior agrees with the expected effects of DST's one-hour time shift. Less lighting and heating are required in the evening; however, demand increases in the morning—particularly from 07:00 to 08:00—driven by reduced sunlight and lower temperatures.

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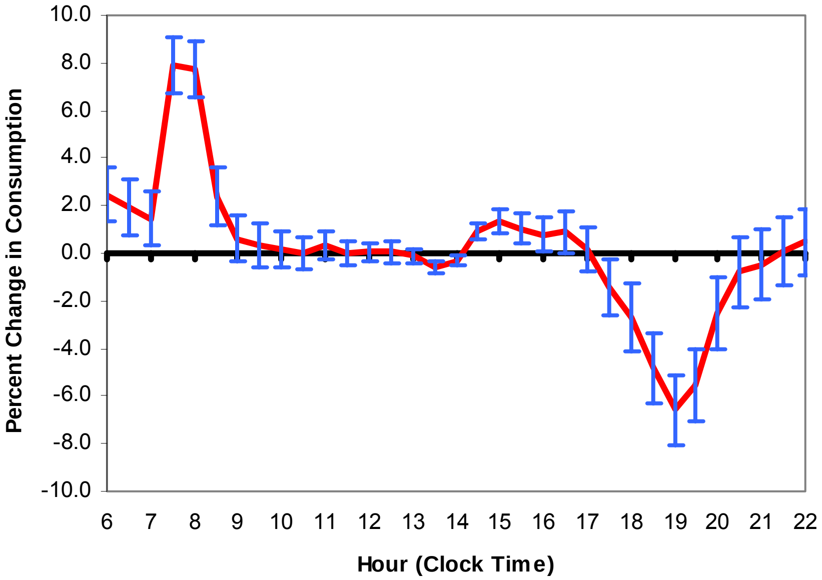
[16] Appendix E compares the numerical with the analytical approximation methods. The 'hat' on *g* indicates that this distribution is itself estimated using the numerical approximation. Strictly speaking, we estimate the posterior of $\hat{\theta}$ that is conditional on **Z**.

Figure 6: Half hourly treatment effects of extending DST on electricity use



The estimated effect of extending DST in VIC, disaggregated by half-hour, with 95% confidence intervals. Standard errors are clustered by day.

To assess whether the evening decrease in demand outweighs the morning increase, we aggregate the half-hourly estimates using (3) to yield an estimate of θ. We find that the extension of DST failed to conserve electricity. The point estimate of the percentage change in demand over the entire treatment period is +0.11% with a clustered standard error of 0.39.[17]

Table 3: Summary of percentage change treatment effects

	All days	"September"	"October"	Weekdays	Weekends
% change	0.11	0.34	-0.06	0.44	-1.94
standard error	(0.39) [0.32]	(0.43) [0.34]	(0.43) [0.36]	(0.40) [0.33]	(0.41) [0.40]

Clustered standard errors are in parentheses and Newey-West standard errors are in brackets.

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[17] In DID panel settings, Bertrand et al. caution that results are sensitive with respect the chosen standard errors. Our results very clearly confirm such bias. In our case, assuming homoskedasticity would result in a standard error of $\hat{\theta}$ of 0.08. Instead applying the Newey-West covariance estimator results in a standard error of 0.32. Although the Newey-West correction in large sample sizes promises a good approximation, here we chose to report our main results using the more conservative clustered standard errors (0.39). For a discussion on the comparison between the latter two approaches, see Petersen, 2006.

We also examine the impact of the DST extension separately for the "September" period and the "October" period.[18] Because September in the southern hemisphere is seasonally equivalent to March in the northern hemisphere, this examination has policy implications—recent efforts to extend DST in the U.S., California, and Canada concern an extension into March, as DST is already observed in April in these locations. Prior studies suggest that such an extension creates electricity savings of 1% (U.S.), 0.6% (California), and 2.2% (Ontario, Canada). By contrast, our estimate shows that the extension of DST into September in Australia *increased* electricity demand by 0.34%.[19] This result raises a concern that extending DST in North America will fail to yield the anticipated electricity savings.

To formally compare our estimates to the previous literature, we define four null hypotheses, H_0:, (1) $\theta = 2.2\%$, (2) $\theta = 1.0\%$, (3) $\theta = 0.6\%$, and (4) $\theta = 0.0\%$. In each case, the alternative, H_A, is that the change in electricity demand is greater than the cited value. Table 4 displays *p*-values for rejection of each null hypothesis, given both our overall estimate and our unpooled estimate. Even with conservative clustered standard errors, we reject at the 5% level the most modest estimate of the prior literature—a 0.6% reduction in electricity use in September. Over the entire treatment period, we reject a 1% reduction in demand at the 1% level, and reject a 0.6% reduction at a 10% level. These rejections are strengthened with the use of Newey-West standard errors.

All told, our results indicate that claims that extending DST will significantly decrease energy use and GHG emissions are at best overstated, and at worst carry the wrong sign. In particular, a long, two-month, extension is more likely than not to increase electricity consumption.

Table 4: *p*-values of testing the energy saving hypotheses

		"September" ($\hat{\theta}$ =+0.34%)	**"September" and "October"** ($\hat{\theta}$ =+0.11%)		
	Null hypothesis	Cluster	Cluster	Newey-West	"OLS"
Electricity Savings	**-2.2%**	0.000***	0.000***	0.000***	0.000***
	-1%	0.003***	0.007***	0.001***	0.000***
	-0.6%	0.037**	0.075*	0.033**	0.000***
Electricity Neutrality	**0.0%**	0.292	0.384	0.375	0.135

*** rejected at *p* = 0.01, ** rejected at *p* = 0.05, * rejected at p = 0.1

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[18] "September" covers the time period from 27 August, 4am to 14 September, and "October" covers 2 October to 27 October—these dates correspond to the treatment period in 2000: the extension period excluding the 17 days of the Olympic games.

[19] The point estimate in "October" is that the extension conserves electricity by 0.06%. While the difference between the "September" and "October" estimates is 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.

5.2 Robustness

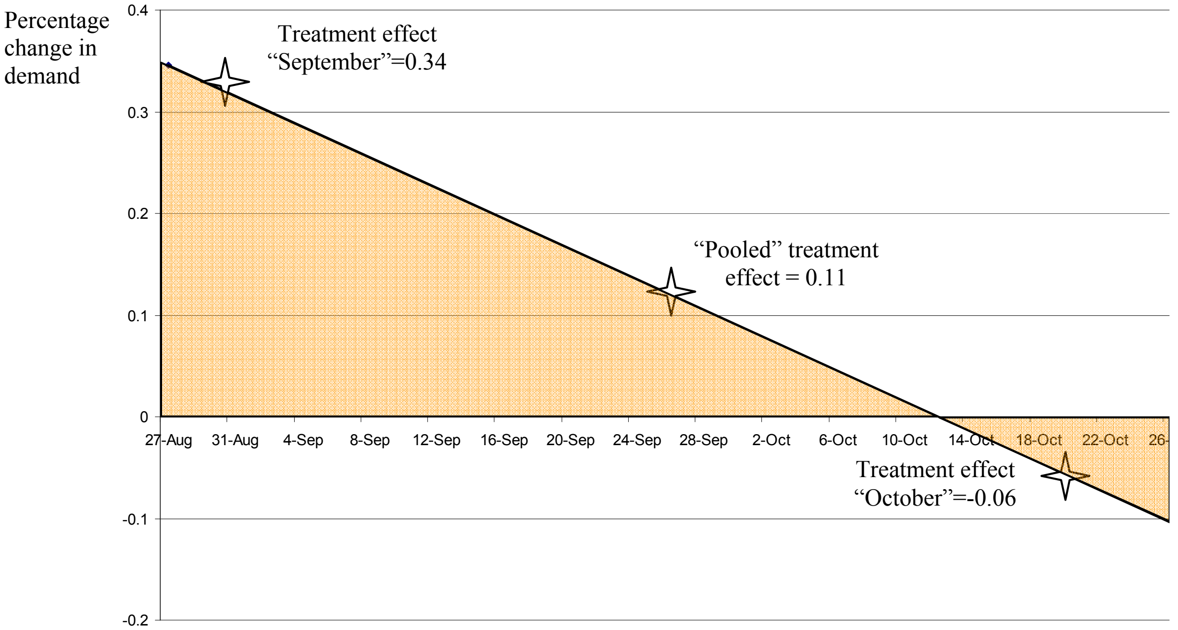
Our results are robust to many alternative specifications. The use of time trends rather than weekly dummies does not affect the results, nor do alternative weather specifications. In particular, our results are invariant to the choice between a weather model taken from Bushnell and Mansur (2005) and one from CEC (2001) (described in detail in section 7). Further, our results do not change if we include years and months of data beyond what we use in our reference case. This robustness is underlined by the precise fit of our model—the adjusted R^2 is greater than 0.94.

Regression equation (1) contains over 1800 parameters. While the point estimates and the standard errors for the parameters of primary interest—the treatment effect—are discussed above, most of the other coefficients are significant and carry signs that agree with intuition. For example, weekends, holidays, and vacations lower electricity consumption at all hours of the day and particularly in the morning. Deviations from the base temperature of 18 degrees Celsius increase electricity consumption, consistent with the effects of air-conditioning (when above 18 degrees) and heating (when below 18 degrees).

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 $\exp\{X_{VICdh}\alpha_{VICdh} + W_{VICdh}\phi_{ih}\} \cdot \overline{q}_{VICd}$. Doing so does not affect our estimate of $\hat{\theta}$.

To verify the robustness of our unpooled result, we modify the pooled specification to include the interaction of the treatment dummies with a daily time trend. That is, we add the term $t \cdot T_{idh} \cdot \beta_h^t$ to regression specification (1) for each half-hour $h = 1,\ldots,48$, where t denotes the day of the year. Figure 7 displays the estimated treatment effect over the period 27 August to 27 October (calculated as $\theta(t) = [\Sigma_h \exp\{\beta_h + t \cdot \beta_h^t\} \cdot \omega_h/\Sigma_h\omega_h)]-1)$. Victoria marginally benefits from DST after 14 October; however, DST increases energy use prior to this date. This result agrees with our unpooled "September" and "October" treatment effects.

Figure 7: Optimal timing of DST



As a final check of our estimates, we evaluate whether extending DST causes relatively greater reductions 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 will mitigate the morning increase in demand. We estimate that electricity consumption on working days increased by 0.4% during the extension, while consumption on weekends and holidays decreased by 0.9%. This difference is significant at the 2% level.

6 Two alternative methods to measure the effect of DST on electricity use

In the remainder of the paper we examine two alternatives to measure the effect of DST on energy. This is useful for at least two reasons: first, the Australian data provide us with the unique opportunity to evaluate the proposals to extend DST in the U.S., Canada, New Zealand and Australia (*Energy Policy Act*, 2005; *Joint Senate Resolution*, 2001; Young, 2005; Eckhoff, 2001; Hansard, 2005) as we can analyze the predictive power of the prior modeling approaches. Second, the data provide a validation tool to examine the structure of the prior modeling methods of the DST literature, which can be categorized into two types: the "week before / week after" technique (Eckhoff, 2001; Young, 2005) and the simulation approach (Rock, 1997; CEC, 2001).

The simulation approach uses data on hourly electricity consumption under the status quo DST timing policy to simulate consumption under a DST extension. This procedure first employs a regression analysis to assess how electricity demand in each hour is affected by light and weather, and then uses the regression coefficients to predict demand in the event of a one-hour time shift lagging the weather and light variables appropriately. The simulation results rely on the assumption that extending DST will not cause new patterns of activity than those observed in the status quo. This may not hold in practice. For example, to simulate demand under extended DST at 07:00, the model must rely on observed status quo behavior at 07:00 under cold and low-light conditions. Without a DST extension, these conditions are observed only in mid-winter. The simulation will be inaccurate if people awaken later in winter than they do in spring under extended DST, perhaps because they rise earlier as they become accustomed to increasing morning light in the spring and continue this behavior even after the extension causes mornings to be dark again.

With the Australian quasi-experiment, by contrast, we can estimate the treatment effect directly, based on the comparison of both regimes, the *status quo* and the *treatment period* (the period of the DST extension in 2000). By re-estimating the simulation models based on the status quo observations and then forecasting the electricity demand under the treatment, we have a tool to evaluate the performance of this approach in detail.

The "week before / week after" technique examines electricity use before and after the existing spring and fall time changes. These studies confirm the conventional wisdom that DST saves energy. However, an extension introduces DST to a time of year when the days are shorter and cooler than they are when the time shift usually occurs. Secondly, the first week of DST has longer and warmer days than the week prior to the springtime change. Therefore, these studies likely overestimate the energy savings of an extension.

We first show that both methods significantly overstate electricity savings. We then try to understand why these biases arise. We find that by carefully modifying the sample selection, the simulation models' aggregate predictive power improves; however, they still fail to accurately predict the intraday changes in demand. For the "week before / week after technique", we show that by controlling for differences in weather reduces the bias, but the variance of the estimates remains high. Overall, these results cast suspicion on the models' previous policy applications.

7 Evaluation of the Simulation Approach

A natural question to ask is whether or not the simulation approach would have predicted the DST effects sufficiently well. To test the simulation approach, we employ the most recent model developed by CEC, 2001, which has been used in the U.S. to argue in favor of a year-round DST extension in California. The first stage of the model is a regression of hourly electricity demand, q_{dh}, on employment, weather, and sunlight variables:

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

The disturbance $\boldsymbol{u}_d$ is correlated across the $h = 1,\ldots,24$ hourly equations, per the Seemingly Unrelated Regression method (Zellner, 1962). The regression allows the weather and light coefficients to vary across the twenty-four hours of the day, and the weather specifications are very detailed. For example, the temperature variables are separated into hot, cold, and warm days, because a hot hour which follows other hot hours will have higher electricity demand than a hot hour which follows cool hours (because buildings retain heat).[20] Once the vector of regression coefficients is estimated, they are used in the second stage to forecast electricity consumption under a DST extension. This is accomplished by lagging the weather and lighting variables by one hour and adding the first stage realized error term to project

$$\hat{q}_{dh}^{sim} = \hat{a}_h + \hat{b}_h \text{Employment}_{dh} + \hat{c}_h \text{Weather}_{dh-1} + \hat{d}_h \text{Light}_{dh-1} + \hat{u}_{dh} \quad \forall d \in \{\underline{D}, \underline{D}+1, \ldots, \overline{D}\}$$

for the days $d = \underline{D}, \ldots, \overline{D}$ for which a DST extension is being considered.

Figure 8 displays observed electricity demand in California during March 1998-2000 when Standard Time was in effect, as well as the simulated demand for extended DST. Recall that March in California is equivalent to September in Australia. The simulation predicts that under DST electricity consumption will be significantly lower in the evening, between 17:00 and 19:00, leading to an overall 0.6% decrease in electricity use for the month of March.

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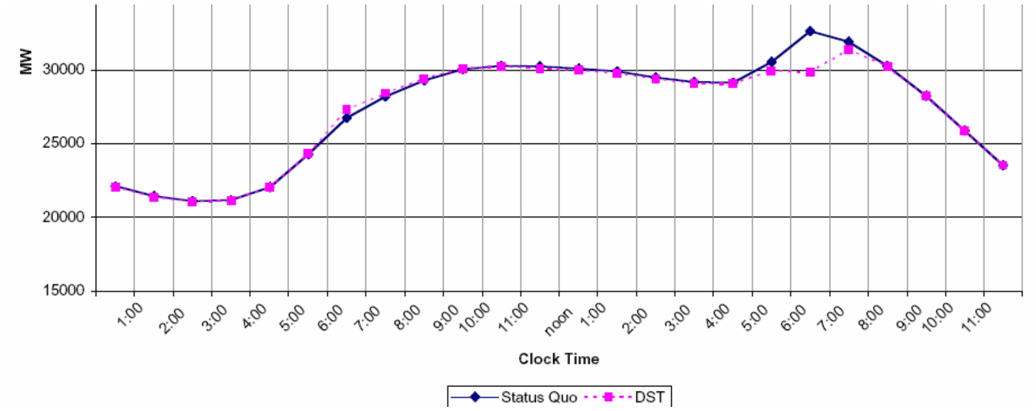
[20] For each half hour the weather and light regressors consist of temperature variables by (1) a one-hour weighted average of its quadratic and cubic, where the weights are .45 times the temperature in the hour that includes the last half-hour of an electricity use hour, .45 times the temperature in the hour that includes the first half-hour of an electricity use hour, and .10 times the previous hour; and (2) a three day weighted average of the temperature separately for hot spells, warm spells and cold spells, with 60% weight on average temperature one day lagged, 30% on 2 days lagged, and 10% on 3 days lagged. Hot, warm and cold are defined by the temperature cut-off values 21.11°C and 10.00°C. Humidity, precipitation, barometric pressure, wind speed, visibility, and cloud cover also enter the weather specification. The lighting variables are the percentage of the hour in daylight throughout California and the percentage in twilight. The light variables are included only for those hours in which light conditions vary over the year, under either standard time or DST. Details on the definition on these variables, the estimation of the model and simulation are explained in CEC, 2001.

Figure 8: If DST had been imposed in March 1998-2000 in California



Source: CEC, 2001.Actual status quo demand is observed under Standard Time. The forecasted demand is simulated under the assumption that DST had been imposed. For California, the observed and simulated load shapes for a DST extension into January and February look similar. More details are provided in CEC, 2001.

We apply the CEC model to the Australian data for the state of VIC, with a few changes to the specification.[21] Figure 9 illustrates the simulated electricity demand under a DST extension in "September" and "October". The simulated load shapes in VIC very closely resemble those for the California simulation, and predict energy savings of 0.41% to 0.44%.

Figure 10 compares the characteristics of actual demand under the VIC treatment with simulated consumption. The figure shows that the simulation fails to predict a morning increase in electricity consumption similar to that observed in 2000, and also overestimates the evening savings. The simulated decrease in consumption is inconsistent with what actually happened in VIC. Based upon our triple DID estimate and clustered standard error presented earlier, we reject the -0.41% prediction of the simulation at a 5% significance level.

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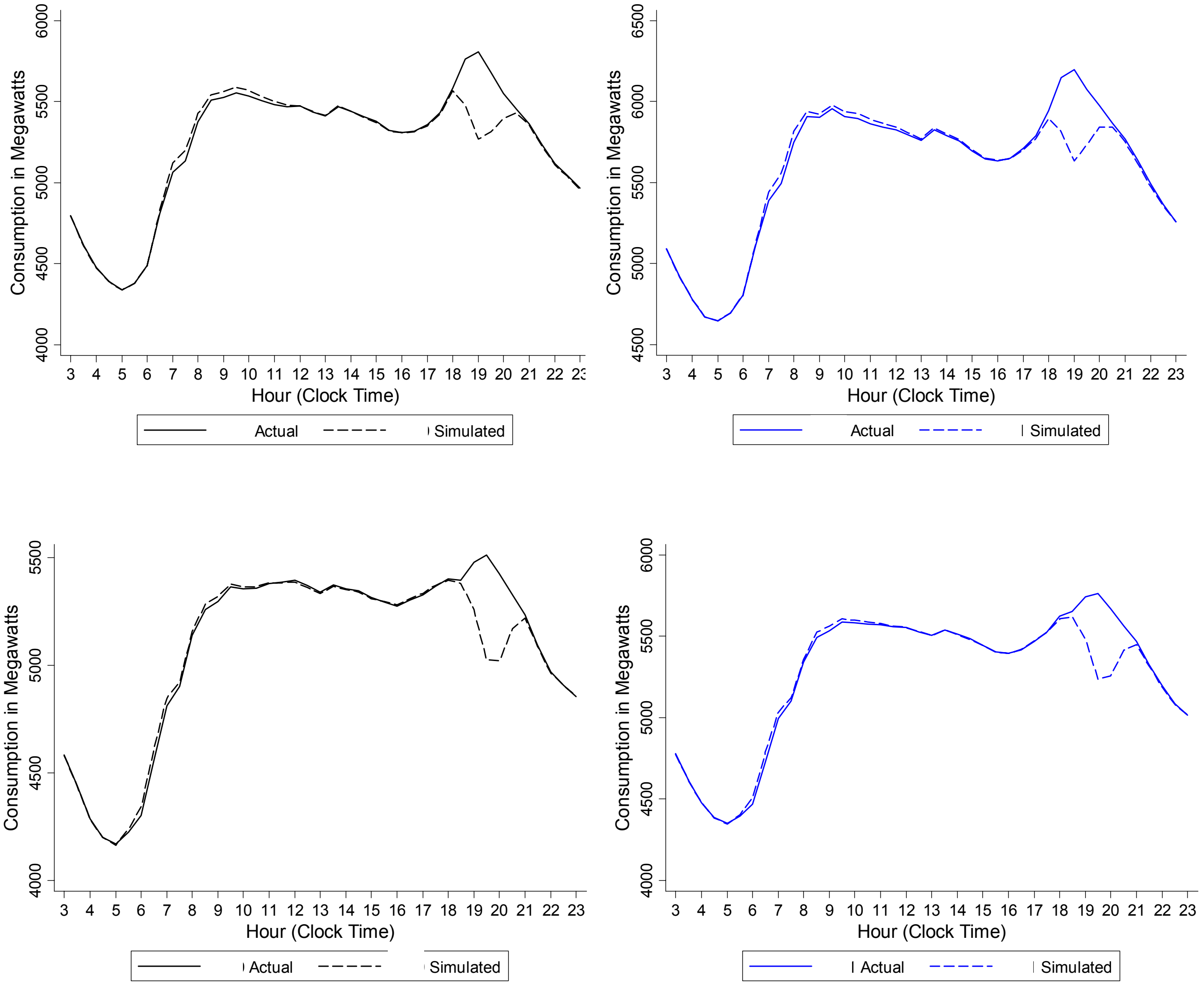
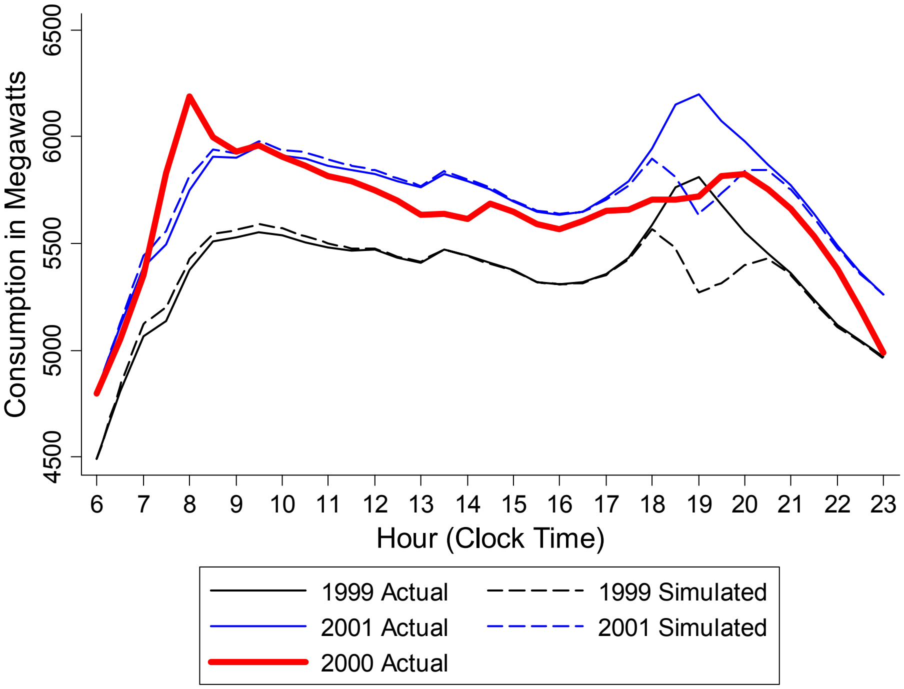
[21] Instead of using 24 hourly equations, we take advantage of the more detailed Australian dataset and estimate the model with 48 half-hourly equations. We also improve the explanatory power of the model by including six day-of-week dummies and an indicator variable for vacations, holidays, and transition days. Finally, the Australian weather data do not contain variables for visibility and cloud cover that were used in CEC, 2001. Instead we use the number of hours of sunshine per day and the interaction of this variable with temperature. Also, the humidity and precipitation variables are correlated with visibility. In total the model applied to Australia has 1052 parameters to be estimated (48 equations with 24 parameters each) based on the data from 1 January, 1999 to 31 December, 2002, but excluding the treatment period in 2000.

Figure 9: Actual vs. forecasted VIC demand based on the CEC simulator



Actual demand is observed under Standard Time. The forecasted demand is simulated under the assumption that DST had been imposed.

Figure 10: Actual and simulated electricity consumption in VIC over “September” in various years. DST is in effect only during 2000.



Average electricity consumption in VIC by half-hour in “September” in various years. Solid lines represent observed consumption, and dashed lines represent simulations of what consumption would have been if DST were observed.

The first row of Table 5 summarizes our simulation results. It is striking that for all the periods from 1999 to 2001, the estimates of energy savings fall in a narrow range from 0.41% to 0.45% and strongly reject our treatment effect estimate of section 6.[22] Table 5 further displays the test statistics for the comparison of the simulation results to a 0.6% reduction in energy use—the simulated prediction for California (CEC, 2001). Our simulations cannot reject savings of 0.6%, confirming the preliminary result that the VIC simulation is very similar to that for California.. As a robustness check we repeat this exercise for the month of October (which is equivalent to the month of April in the northern hemisphere), leading to very similar results.

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[22] To perform the hypothesis tests we need to calculate the variance of the sum of simulated energy demand $\Sigma_{d=\underline{D}}^{\overline{D}}\Sigma_{h=1}^{48} q_{dh}^{sim}$. This is given by $\Sigma_i\Sigma_j[\mathbf{X}_{\text{sim}}{}^{\text{T}}\mathbf{Cov}(\boldsymbol{\beta})\mathbf{X}_{\text{sim}}]_{ij}$, that is as the sum of the elements of the matrix $\mathbf{X}_{\text{sim}}{}^{\text{T}}\mathbf{Cov}(\boldsymbol{\beta})\mathbf{X}_{\text{sim}}$, whereby $\mathbf{X}_{\text{sim}}$ is the block-diagonal “simulation” regressor matrix of dimension $48\cdot(\overline{D} - \underline{D})$ x 1052 with each block $h = 1,2,\ldots,48$ defined as columns of [1, Employment_{dh}, $\text{Weather}_{dh\text{-}2}$, $\text{Light}_{dh\text{-}2}$, $\text{Weekday1}_{dh},\ldots,\text{Weekday6}_{dh}$, Workday_{dh},] and $\mathbf{Cov}(\boldsymbol{\beta})$ is the 1052 x 1052 estimated covariance matrix of $\boldsymbol{\beta}$.

Table 5: Simulating a DST extension using the CEC methodology

Year		1999		2001		“September” 1999	“September” 2001
Period		September	October	September	October		
%-change between DST and Standard Time		-0.44	-0.44	-0.43	-0.41	-0.43	-0.41
t-value with respect to	energy neutrality	-2.02	-1.82	-1.42	-1.64	-1.81	-1.40
	energy savings of 0.6%	0.72	0.64	0.54	0.53	0.73	0.65

We attempted to understand the causes of the simulation’s misprediction. We found that, by shrinking the sample in the first stage regression, the predictive power can be increased considerably.[23] We use a sample period in which sunset, sunrise, light and weather conditions are most similar to the simulated extension period in September.[24] Table 6 displays the regression results from the revised simulation model—the results now show that the DST impacts are statistically indistinguishable from zero, which more closely corresponds to what actually happened in VIC. Also, with this improved specification the prior electricity savings estimates of 0.6% and 1% in the U.S. are now rejected at the 10% significance level and lower. However, when we analyze the refurbished model on a half-hourly basis we still find that it substantially under-predicts morning electricity demand between 07:00 and 09:00, and over-estimates the evening demand. These two mispredictions cancel one another, leading to the more accurately predicted overall effect. We conclude that despite extensive adjustments this simulation model cannot predict the substantial intra-day shifts that occur due to the early adoption of DST.

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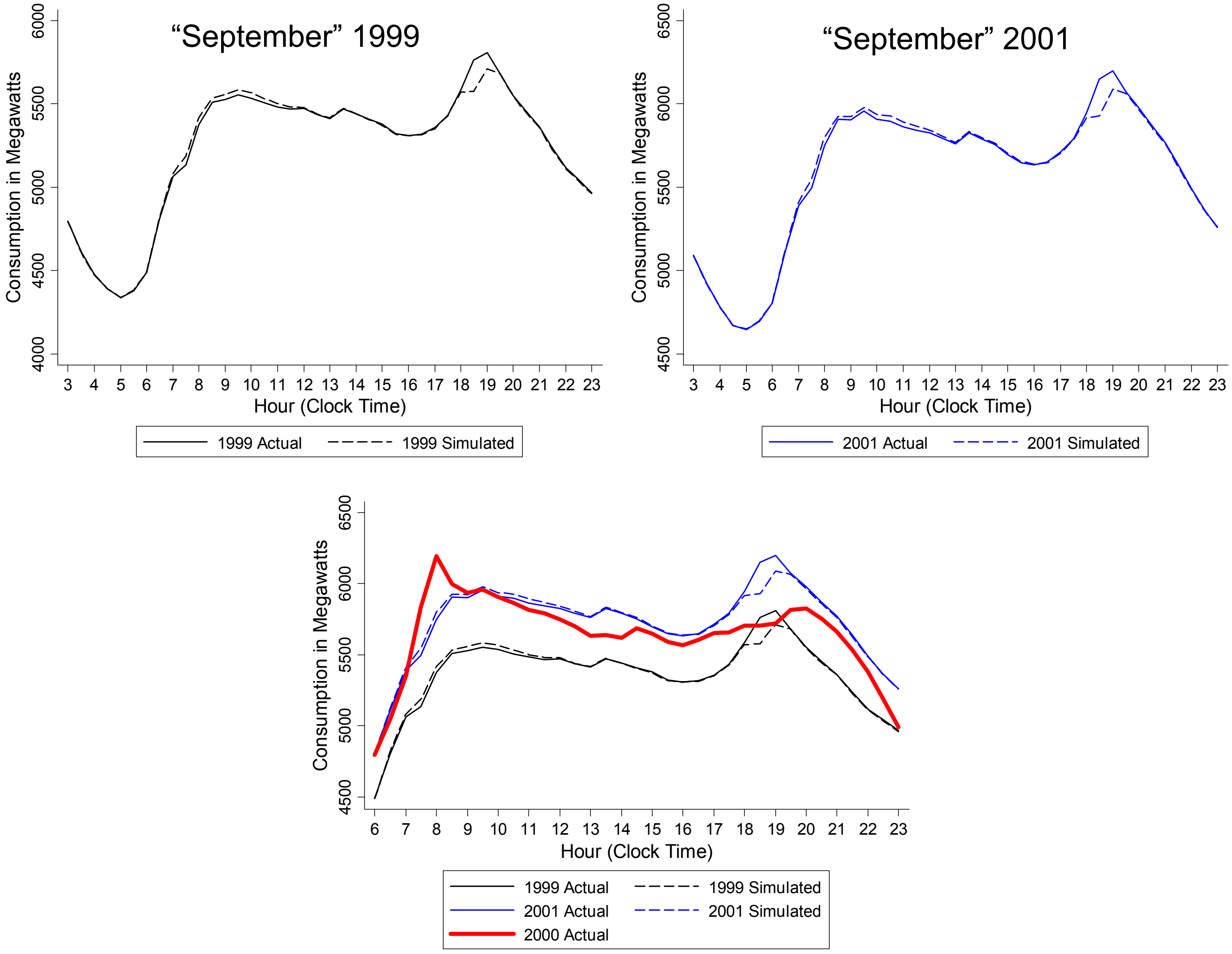
[23] The original simulation models’ parameters are estimated based on the status quo data from all twelve months of the year. On the one hand, one might expect that this variation in weather improves the forty-eight weather models especially because they explicitly account for the nonlinearities and discontinuities by use of hot, warm and cold weather spells. On the other hand, we show that significant improvements are made by being more selective.

[24] For example, to predict an extension into September, we suggest to limiting the sample size to the months from March to September and excluding the full month of July and the first half of August. See the sunrise, sunset, weather table A1 in Appendix A for the more detailed motivation for choosing these periods.

Table 6: Simulating a DST extension using the refurbished simulation model

Year		1999	1999	2001	2001
Period		September	“September”	September	“September”
%-change between DST and Standard Time		-0.005	-0.027	-0.026	-0.025
t-value with respect to	energy neutrality 0.0%	-0.02	-0.01	-0.06	-0.07
	energy savings 0.5%	1.75	1.6	1.210	1.24
	energy savings 0.6%	2.10	1.92	1.34	1.50
	energy savings 1%	3.51	3.19	2.27	2.54

Figure 11: Actual versus simulated VIC demand based on the refurbished simulator



8 Evaluation of the "week before / week after technique"

Applying the "week before / week after technique" (WBAT), to VIC, as used in New Zealand and Canada, would lead to a prediction of electricity savings of 1.77%.[25] The point estimate is slightly lower than the savings predicted in Ontario (2.2%) and New Zealand (2.0%-3.5%), however, with a clustered standard error of 1.60, the estimate is statistically insignificant. Still, this correlation estimate is consistent with the intuition that in summertime the requirement for indoor electricity use decreases due to improved weather conditions. Once we control for weather and day weekday/workday dummies, however, the point estimate on the DST coefficient increase to +1.11%. Table 7 shows that varying the number of days before and after the springtime change causes the WBAT estimates to vary from -1.21% to -1.77% when weather variables are not included, and from 0.52% to 1.11%, when weather variables are included. This variance is not surprising given the large standard errors. We believe that this lack of robustness makes this approach unsuitable for policy analysis in Australia.

Table 7: Percentage change due to DST using the "week before / week after technique"

	Days used before and after the springtime change					
	7 days		10 days		4 days	
	%-change	s.e.	%-change	s.e.	%-change	s.e.
WBAT	-1.77	1.60	-1.34	1.29	-1.21	1.92
WBAT conditional on weather	1.11	0.69	0.52	0.55	0.72	1.31

Standard errors (std) based on clustered covariance matrix by date. The original WBAT approach employs data of one week before and one week after the springtime changes over the years from 1999 to 2005, excluding the year 2000 (7 days column).

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[25] The WBAT approach used data one week prior to and one week after the springtime changes over the years from 1999 to 2005, excluding the year 2000.

9. Summary and Conclusions

Given the economic and environmental imperatives driving efforts to reduce energy consumption, policy-makers are considering extending Daylight Saving Time (DST). Doing so is widely believed to reduce electricity use.[26] 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 of DST that occurred in the state of Victoria, Australia in 2000. Using half-hourly panel data on electricity consumption and a triple-difference treatment effect model, we show that, while extending DST does reduce electricity consumption in the evening, the increased demand in the morning cancels these benefits out. We statistically reject electricity savings of 1% or greater at a 1% significance level.

We also cannot confirm two additional DST extension benefits that have been discussed in California: a reduction in electricity prices and a reduction in the likelihood of blackouts driven by a more balanced hourly load shape. We instead show that the Australian DST extension significantly increased expenditures on electricity 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 an extension to DST. Moreover, the lessons from Australia may carry over to the U.S. and to California—Victoria's latitude and climate are similar to those of central California.[27] In particular, the planned extension that will occur in the U.S. will cause DST to be observed in March—a month that is analogous to September in Australia, when our point estimates suggest that DST will increase rather than decrease electricity consumption. With this, our results run contrary to recent simulation-based studies and suggest that current proposals to extend DST may be misguided.

To further investigate the relationship of our study to previous simulations, we re-estimate the simulation model that supported a DST extension in California, using Australian data. We find that simulation models over-estimate energy savings casting suspicion on its previous policy applications in the U.S. Similarly, we scrutinize the "week before / week after technique" which has been employed in Canada and New Zealand and find that this method also predicts savings that are too large.

It should be noted that our estimates of energy use likely represent a lower bound, as we account for electricity consumption only. Considering gasoline demand as well may

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[26] On signing the Energy Policy Act on 8 August, 2005, President Bush stated that it is primarily a "*security bill*" to become "*less dependent on foreign sources of energy*" (Bush, 2005). The U.S. government emphasized this by expressing the estimated 1% electricity savings of extended DST as "*to reduce energy consumption by the equivalent of 100,000 barrels of oil for each day of the extension"* (CENR, 2005).

[27] While we are not in a position to extend our results to *any* country, it is worth noting that there are several other major coastal cities around the world at approximately the same latitude as Melbourne (latitude 37.5 South)—for example, Buenos Aires (34.4) in the southern hemisphere and San Francisco (37.77), Washington D.C. (38.5) and Tokyo (35.4) in the northern hemisphere—locations within countries that are considering changes to their DST systems. These countries may find our results helpful in order to assess potential costs and benefits of such measures.

increase the estimate of DST's effect on energy consumption, as longer and warmer evening hours drive an increase in evening leisure travel (Lawson, 2001).

Finally, our study leaves scope for future work. First, an *ex-post* evaluation of the pending U.S. DST extension will be a worthwhile enterprise. Second, the non-energy impacts of extending DST also require investigation—potential studies include impact analyses on crime, traffic accidents, and economic coordination, which could build upon prior work in these areas (Coren, 1996; Coate and Markowitz, 2004; Kamstra et al., 2000; Lambe and Cummings, 2000; Varughese and Allen, 2001; Hamermesh et al., 2006). Such work will allow the research community to provide policy-makers with evidence to support informed decisions regarding the future status of DST.

References

Aldrich, B. (2006): Daylight Saving Time, Its History and Why We Use It. California Energy Commission. Also downloadable at: http://www.energy.ca.gov/daylightsaving.html.

Australian Bureau of Statistics (2001): Tourism Indicators, Report 8634.0, December Quarter 2000, Canberra.

Australian Bureau of Statistics (2001): Tourist accommodation: an analysis over the Olympic period. Tourism Indicators, December Quarter 2000.

Beauregard-Tellier, F. (2005): Daylight Saving Time and Energy Conservation. Economics Division**,** 29 July, 2005. Library of Parliament, Canada.

Bertrand, M, E. Duflo, and S. Mullainathan (2004): How much should we trust differences-indifferences estimates? *Quarterly Journal of Economics,* 119, 249-275.

Bush, G.W. (2005): Office of the Press Secretary, 8 August, 2005. President Signs Energy Policy Act, Sandia National Laboratory, Albuquerque, New Mexico.

Bushnell, J.B. and E.T. Mansur (2005): Consumption under Noisy Price Signals: A Study of Electricity Retail Rate Deregulation in San Diego. *Journal of Industrial Economics*, 53. pp. 493-513.

CEC, 2001: Effects of Daylight Saving Time on California Electricity Use. California Energy Commission. Report authored by Adrienne Kandel and Daryl Metz .

CENR (2005): Press release of the Committee on Energy and Natural Resources. Energy Policy Act of 2005 Bill Summary. Also available on the internet at: energy.senate.gov/public/_files/PostConferenceBill

Coate, D. and S. Markowitz (2004): The effects of daylight and daylight saving time on US pedestrian fatalities and motor vehicle occupant fatalities. *Accident Analysis and Prevention*, 36, 351.

Coren, S. (1996): Daylight saving time and traffic accidents. *New England Journal of Medicine*, 334, 924.

DOT (1975): The Daylight Saving Time Study: A Report to Congress by the US Department of Transportation. *Washington*, GPO, 1975. 2 v. HN49.D3U65 1975, Vol. 1, final report of the operation and effects of daylight saving time and Vol. 2, supporting studies: final report of the operation and effects of daylight saving time.

Downing, M. (2005): Spring Forward: The Annual Madness of Daylight Saving Time. Shoemaker Hoard, Washington D.C.

ECCJ (2006): Report on the National Conference on the Global Environment and Summer Time. The Energy Conservation Center, Japan (ECCJ). Available on the Internet at http://www.eccj.or.jp/SummerTime/conf/index_e.html

Eckhoff, G. (2001): Minister Urged to Consider Early Daylight Saving. Press Release by ACT New Zealand, published i.e. in *Scoop Independent News* on August 14, 2001.

EIA (2005): Direct Use and Retail Sales of Electricity to Ultimate Customers by Sector, by Provider. Report Released November 2005.

Emergency Daylight Savings Time Energy Conservation Act (1973): U.S. Public Law 93-182, H.R. 11324 (87 Stat. 707), signed by President Richard Nixon 15 December, 1973.

Energy Policy Act (2005): U.S. Public Law 109-58, signed into law by President George W. Bush, 8 August, 2005.

Filippini, M. and J. Wild (2001): Regional differences in electricity distribution costs and their consequences for yardstick regulation of access prices. Energy Economics, vol. 23(4), pp. 477-488.

Franklin, B. (1784): An Economical Project, Essay on Daylight Saving. Letter to the Editor. *The Journal of Paris*, April 26th, 1784.

Hamermesh, D.S., Myers, C.K. and Pocock, M.L. (2006): Time Zones as Cues for Coordination: Latitude, Longitude and Letterman. National Bureau of Economic Research (NBER) Working Paper 12350.

Hansard (1999a): Legislative Assembly Hansard: Standard Time Amendment Bill, Second Reading, 26 May 1999, article 40, New South Wales.

Hansard (1999b): Legislative Council Hansard: Standard Time Amendment Bill, Second Reading, 2 June 1999, article 9, New South Wales.

Hansard (2005): Legislative Assembly Hansard: Standard Time Amendment (Daylight Saving) Bill, Article 44, September 13, 2005, New South Wales.

Japan Economic Newswire (1999): US Raps Japan on Car Fuel Efficiency Rules. Publication of March 8, 1999.

Joint Senate Resolution (2001): Joint Senate Resolution 2nd extension session. Bill number SJRX2-1, California. Introduced by Senator Karnette, filed with Secretary of State June 27, 2001 and adopted in Senate June 25, 2001.

Kamstra, M., Kramer, L and M. Levi (2000): Losing sleep at the market: The daylight saving anomaly. *American Economic Review*, 90(4).

Kemp, D. (2003): Australia Moves Closer to Kyoto Target. The Australian Government Department of the Environment and Heritage Media Release, 18 September, 2003.

Kyodo News (2005): 140 Lawmakers to Submit Daylight Saving Time Bill. *Kyodo News* from March 17th, 2005.

Lambe, M. and P. Cummings (2000): The shift to and from daylight savings time and motor vehicle crashes. *Accident Analysis and Prevention* 32, 609.

Lawson, L (2001): Testimony of Linda Lawson, Acting Deputy Assistant Secretary for Transportation Policy, U.S. Department of Transportation, before the House Science Committee, Energy Subcommittee, concerning daylight saving time and energy conservation, 24 May, 2001.

Meyer, B. (1995): Natural and Quasi-Experiments in Economics, *Journal of Business & Economic Statistics* 13, 151-161.

NEMMCO (2005): An Introduction to Australia's National Electricity Market. National Electricity Market Management Ltd.

Newey, W. and K. West (1987): A simple, positive definite, heteroskedasticity and autocorrelation consistent covariance matrix. *Econometrica* 55(3), 703-708.

Outhred, H. (2006): Email communication with Hugh Outhred, Director, Center for Energy and Environmental Markets and Head, Energy Systems Research Group, School of Electrical Engineering & Telecommunications, Sydney, July 20, 2006.

Pepin, N. (1997): Time for a Change? *Area*, 29(1), 57-71.

Petersen, M.A. (2006): Estimating Standard Errors in Finance Panel Data Sets: Comparing Approaches. National Bureau of Economics Research (NBER) Working Paper 11280.

Prerau, D. (2005): Seize the Daylight: The Curious and Contentious Story of Daylight Saving Time. Thunder's Mouth Press, New York.

Rock, B. (1997): Impact of daylight saving time on residential energy consumption and cost. Energy and Building, 25, 63-68.

Sayers, C. and Shields, D. 2001, Electricity Prices and Cost Factors, Productivity Commission Research Paper, AusInfo, Canberra.

The Japan Times (2004): Daylight-saving time wins support. *The Japan Times*, 26 November, 2004.

Turton, H. and Hamilton, C. (2001): Comprehensive emissions per capita for industrialised countries, The Australia Institute, September 2001.

US Hearing (2001a): Congressional Perspectives on Electricity Markets in California and the West and National Energy Policy. Hearing 107-8 before the subcommittee on energy and air quality of the Committee on Energy and Commerce House of Representatives 107th Congress, First Session, March 6, 2001.

US Hearing (2001b): Congressional Perspectives on Electricity Markets in California and the West and National Energy Policy. Hearing 107-30 before the subcommittee on energy and air quality of the Committee.

Vanduffel, S. (2005): Comonotonicity: From Risk Measurement to Risk Management. *Academisch Proefschrift*. Faculteit der Economische Wetenschappen en Econometrics, Amsterdam.

Varughese, J. and R.P. Allen (2001): Fatal accidents following changes in daylight savings time: the American experience. *Sleep Medicine* **2**, 31.

Wooldridge, J.M. (2003): Cluster-Sample Methods in Applied Econometrics. *American Economic Review*, Vol. 93, 133-138.

Young, T. (2005): Independent Electricity System Operator, Ontario, Spokesperson, in Peter Gorrie: Get set for darker November mornings, *The Toronto Star*, 21 July, 2005, p. A1.

Zellner, A. (1962): An efficient method of estimating seemingly unrelated regression equations and tests for aggregation bias. *Journal of the American Statistical Association* 57, 348–368.

Appendix A: Historical Weather, Sunrise and Sunset data

Melbourne (VIC)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature in Celsius	20	20	19	16	13	11	10	11	13	15	17	19
Rainfall in mm	50	45	50	55	55	50	50	50	60	65	60	60
Average Sunrise	06:15	06:50	07:15	06:45	07:15	07:30	07:30	07:00	06:20	05:30	06:00	05:55
Average Sunset	20:45	20:20	19:40	17:50	17:20	17:05	17:20	17:45	18:10	18:40	20:10	20:40
Time: GMT+	11	11	11	10	10	10	10	10	10	10	11	11

Sydney (NSW)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature in Celsius	23	23	21	19	15	13	12	14	16	18	20	21
Rainfall in mm	100	110	130	120	120	125	100	75	65	75	80	75
Average Sunrise	06:00	06:30	06:55	06:20	06:40	07:00	07:00	06:30	05:50	07:15	05:40	05:40
Average Sunset	20:10	19:50	19:15	17:30	17:00	16:50	17:00	17:30	17:45	18:10	19:40	20:00
Time: GMT+	11	11	11	10	10	10	10	10	10	10	11	11

Adelaide (SA)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature in Celsius	20	20	19	17	15	12	12	12	14	16	17	21
Rainfall in mm	20	20	25	40	65	70	70	60	50	45	30	25
Average Sunrise	06:20	06:50	07:15	06:40	07:00	07:20	07:20	06:50	06:20	05:30	06:00	05:55
Average Sunset	20:30	20:10	19:35	17:50	17:20	17:10	17:20	17:45	18:05	18:30	20:00	20:25
Time: GMT+	10.5	10.5	10.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	10.5	10.5

Table A1: Historical Weather, Sunrise and Sunset data

All sunrise/sunset hours are displayed in clock time (typical DST schedule), GMT: Greenwich Mean Time

Source: auinfo PTY LTD, Hornsby, NSW

Appendix B: Data Processing

Electricity data[28] are missing for occasional half-hours. We estimated the missing observations via interpolation using adjacent half hours. Hourly weather data are also missing for some occasional hours as well for four entire days (none of which fall in within 27 August – 29 October in any year, except for the air pressure variable). Hourly unobserved data were interpolated using adjacent hours. To estimate hourly weather in unobserved days, we applied a regression analysis which used information from the daily-level data set. Details and code for this procedure can be obtained from the authors upon request.

Schedules for most school vacations, state holidays, and federal holidays were obtained from the Australian Federal Department of Employment and Workplace Relations, The Department of Education and Children's Services (SA), and The Department of Education and Training (VIC). For years in which information was not available from the above institutions, the dates were obtained by internet search. Federal holidays in Australia include Australia Day, Good Friday, New Years Day, Easter Monday, Boxing Day, Anzac Day, and the Queen's Birthday. In years when Boxing Day and Anzac Day were moved to a different weekday than usual, both the original and the rescheduled holidays were modeled as holidays. State-specific holidays include Labor Day, the Melbourne Cup Day, and the Adelaide Cup Day. Public school vacations include Christmas break, Easter break, Winter break and Spring break.

Employment data are obtained from the Australian Bureau of Statistics, the Labor Force Spreadsheets, Table 12, using the series on the total number of employed persons by state for each quarter of the year.[29]

Sunrise, sunset, and twilight data were sourced from the U.S. Naval Observatory.[30] These data were then used to calculate the percentage of daylight and twilight in each half hour from January 1, 1999 to December 31, 2005 for Sydney, Melbourne, and Adelaide. Finally, we obtained the days and times of switches to and from DST from the Time and Date AS Company, located in Norway.[31]

While our data are provided in standard time, we conduct our analysis in nominal clock time. We therefore need to convert our data to clock time, which, for most affected observations, requires a simple one-hour shift. However, at the start of a DST period, the 02:00-03:00 interval (in clock time) is missing. To avoid a gap in our data, we duplicate the 01:30-02:00 information into the missing 02:00-02:30 half hour, and likewise equate the missing 02:30-03:00 period to our 03:00-03:30 observation. Further, when the DST period terminates, the 02:00-03:00 period (in clock time) is observed twice. Because our model is designed for only one observation in each hour, we average these dual observations.

Throughout the paper, several times we compare dates in Australia to equivalent dates in the northern hemisphere: In terms of sunrise sunset hours, the usual Australian DST starting date—the last Sunday in October—would *approximately* correspond to the last Sunday in April on an equivalent latitude in the northern hemisphere. Equivalently, the date of the 2000 DST start in NSW and VIC (the last Sunday in August) corresponds *approximately* to the last Sunday in February in the northern hemisphere. Note, however, that the south latitude versus north latitude comparison can only be of an 'approximate' nature. Seasons are observed differently due to the fact that the earth is tilted toward the elliptic orbit

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[28] The NEMMCO data can be downloaded at http://www.nemmco.com.au/data/aggPD_2000to2005.htm.

[29] For the employment data we used the series IDs A163206C, A163563A, A163257C, A163308T and A163359T.

[30] The astronomical data may be downloaded from http://aa.usno.navy.mil/.

[31] "Time and Date AS Company" provides data online at http://www.timeanddate.com/worldclock/timezone.html?n=240&syear=1990.

in 23.5 degrees and the distance of the earth to the sun is not constant. This results into the following: on the dates of winter and summer solstices as well as the spring and fall equinoxes, the times of sunrise and sunset at a given latitude-longitude coordinate at the southern hemisphere are the same with the sunrise and sunset pattern at the same northern hemisphere latitude-longitude coordinate. However at all other dates, the sunrise-sunset times are slightly off, with differences increasing up to 15 minutes about 30 to 40 days after the equinox. Note that this approximation problem reduces with the dates of introducing DST earlier into the spring as the current DST switching dates discussed are closer to the equinox.[32]

Appendix C: Information on Australia and the electricity market

Figure C1: Population density of Australia in the year 2004

Figure C2: Electricity Grid

Source: NEMMCO, 2005

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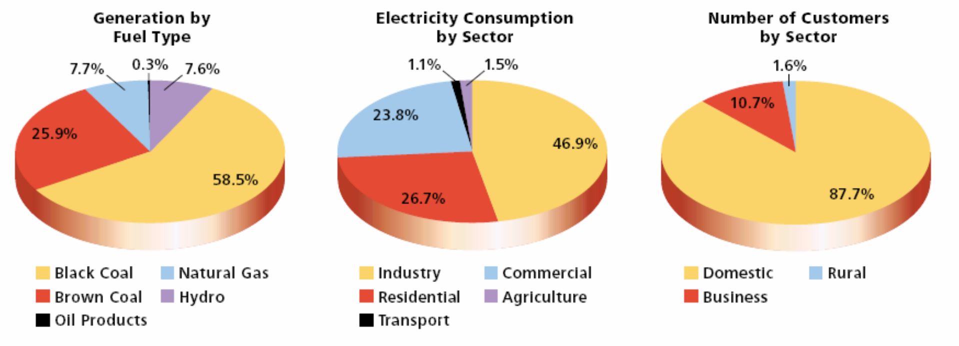
[32] For example, 36 days after the spring equinox (i.e. corresponding to the usual start of DST in VIC around 28 October) Melbourne, at latitude 37.8 south and longitude 144.6 east observes sunrise and sunset at 19:17 and 08:52 UTC respectively. At the northern hemisphere, by contrast, 36 days after equinox (corresponding to about 27 April) sunrise-sunset at the corresponding latitude 37.8 north and longitude 144.6 east was at 19:31 and 09:06 UTC respectively. So while the total number of the daylight hours is the same, the time of daylight is shifted by around 14 minutes.

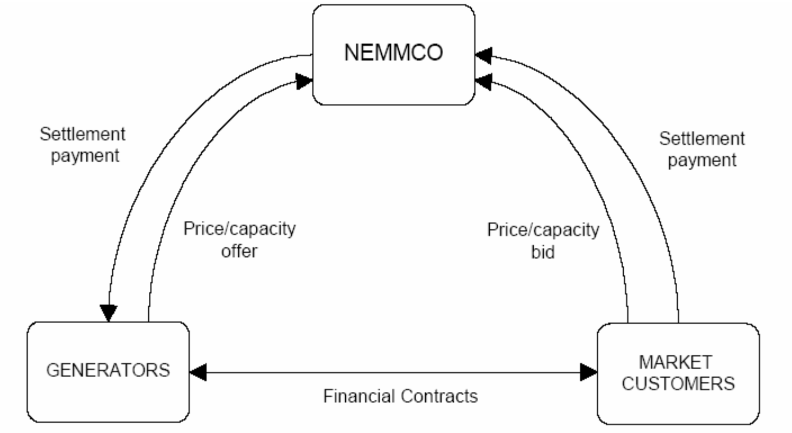
Figure C2 maps the world's longest interconnected power system, trading about 7 billion Australian dollars of electricity annually in the semi-privatized NEMMCO, serving about eight million end-use consumers. In this grid, 92% of the electricity produced relies on the burning of fossil fuels, and in total about 48% of the total per capita GHG emissions in Australia stem from the electricity sector (Kemp, 2003). Figure C3 displays the fuel mix in electricity production, and the split of consumption across economic sectors.

Figure C3: Electricity Production and Consumption in Australia



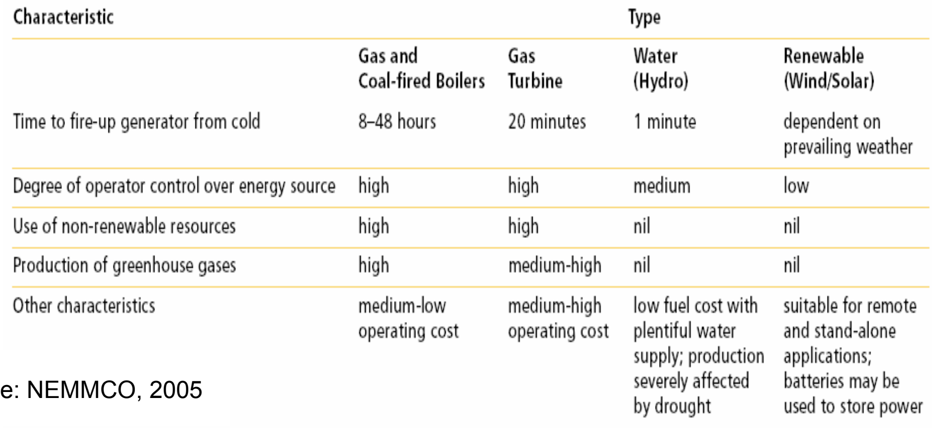
Source: NEMMCO, 2005

Figure C4: Settlement of Electricity Prices in the Electricity Market of VIC, NSW, QLD and SA



Source: Sayers, C. and Shields, 2001

Table C1: Characteristics of generators



Characteristic	Type			
	Gas and Coal-fired Boilers	Gas Turbine	Water (Hydro)	Renewable (Wind/Solar)
Time to fire-up generator from cold	8–48 hours	20 minutes	1 minute	dependent on prevailing weather
Degree of operator control over energy source	high	high	medium	low
Use of non-renewable resources	high	high	nil	nil
Production of greenhouse gases	high	medium-high	nil	nil
Other characteristics	medium-low operating cost	medium-high operating cost	low fuel cost with plentiful water supply; production severely affected by drought	suitable for remote and stand-alone applications; batteries may be used to store power

Source: NEMMCO, 2005

Appendix D: On Tourism to Australia

Figure D1 displays tourism data for VIC and SA, demonstrating that the 2000 Olympics did not significantly impact tourism in the third and fourth quarters of 2000. Tourism data for Sydney in NSW (Figure D2), however, shows that tourism increased in September 2000, and that there was no such increase in 1998 or 1999 (Australian Bureau of Statistics, 2001). Moreover, anecdotal evidence from Melbourne newspapers shows that Melbourne (the most frequently touristed location in VIC) did not experience any change in tourism before, during, or after the Olympic Games in 2000. Further details on tourism may be found in the Australian Bureau of Statistics' special report on Tourism related to the Olympics (2001).

Figure D1: Quarterly Room Nights Occupied in VIC (left panel) and SA (right panel)

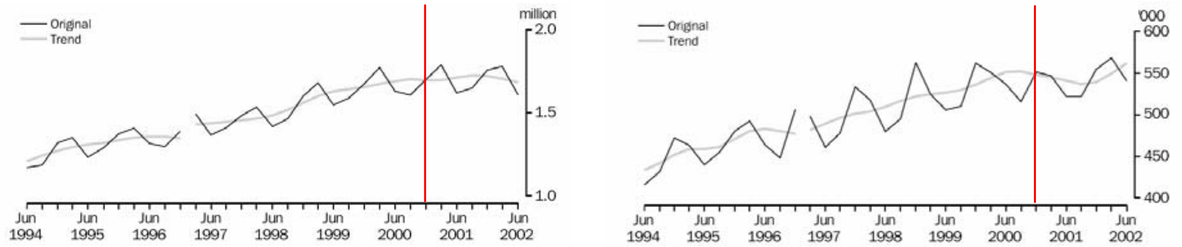
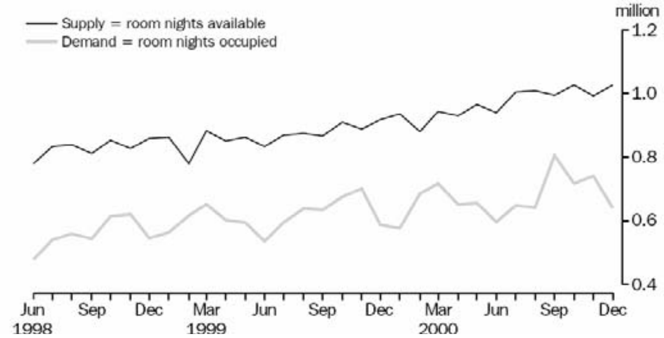


Figure: D2: Supply and Demand for Tourist Accommodations in Sydney



Source: Australian Bureau of Statistics, 2001. The vertical line indicates the 4th quarter in 2000 (December quarter). The treatment period "September" falls within the 3rd quarter 2000 and the treatment period "October" in the 4th quarter.

Appendix E: Estimation of Treatment Effect Model and Robustness

Table E1: Estimated treatment effects of the DST extension by half hour

Half hour beginning at	β_h	Std error	t-statistic	$\exp(\beta_h)-1$	Half hour beginning at	β_h	Std error	t-statistic	$\exp(\beta_h)-1$
00:00	-0.129	0.007	-18.24	-0.121	12:00	0.001	0.002	0.33	0.001
00:30	-0.012	0.007	-1.77	-0.012	12:30	0.000	0.002	0.19	0.000
01:00	0.019	0.007	2.75	0.019	13:00	-0.001	0.001	-0.71	-0.001
01:30	-0.050	0.006	-7.66	-0.048	13:30	-0.006	0.001	-4.72	-0.006
02:00	-0.045	0.007	-6.81	-0.044	14:00	-0.003	0.001	-2.48	-0.003
02:30	0.055	0.006	8.53	0.057	14:30	0.009	0.002	5.25	0.009
03:00	0.076	0.006	12.10	0.079	15:00	0.013	0.003	5.31	0.013
03:30	0.073	0.006	11.31	0.075	15:30	0.010	0.003	3.08	0.011
04:00	0.068	0.007	10.27	0.071	16:00	0.008	0.004	2.09	0.008
04:30	0.057	0.006	8.77	0.059	16:30	0.009	0.005	1.97	0.009
05:00	0.045	0.006	7.19	0.046	17:00	0.002	0.005	0.41	0.002
05:30	0.032	0.006	5.16	0.033	17:30	-0.014	0.006	-2.32	-0.014
06:00	0.025	0.006	4.18	0.025	18:00	-0.027	0.007	-3.63	-0.026
06:30	0.019	0.006	3.23	0.019	18:30	-0.048	0.007	-6.48	-0.047
07:00	0.015	0.006	2.58	0.015	19:00	-0.066	0.007	-8.84	-0.064
07:30	0.079	0.006	12.87	0.082	19:30	-0.055	0.008	-7.08	-0.054
08:00	0.077	0.006	12.70	0.080	20:00	-0.026	0.008	-3.33	-0.025
08:30	0.024	0.006	3.82	0.024	20:30	-0.008	0.008	-1.04	-0.008
09:00	0.006	0.005	1.23	0.006	21:00	-0.005	0.008	-0.62	-0.005
09:30	0.004	0.005	0.79	0.004	21:30	0.001	0.007	0.13	0.001
10:00	0.002	0.004	0.48	0.002	22:00	0.005	0.007	0.68	0.005
10:30	0.000	0.004	0.01	0.000	22:30	-0.006	0.007	-0.85	-0.006
11:00	0.003	0.003	1.06	0.003	23:00	-0.027	0.006	-4.33	-0.026
11:30	0.000	0.003	0.13	0.000	23:30	-0.124	0.007	-18.69	-0.117

Table E1 displays the estimated percentage impact of the DST extension on electricity demand in each half hour: these are the point estimates given by $\exp(\beta_h) - 1$, and correspond to Figure 6. Note that the large effects in the late-night hours are caused by centralized off-peak water heaters in Melbourne (Outhred, 2006). These are triggered by timers set on Standard Time—groups of heaters are activated at 23:30 and 01:30. Each turns off on its own once its heating is complete. During the DST extension, each heater turns on one hour "late" (according to clock time). This drives the negative, then positive, overnight treatment effects.

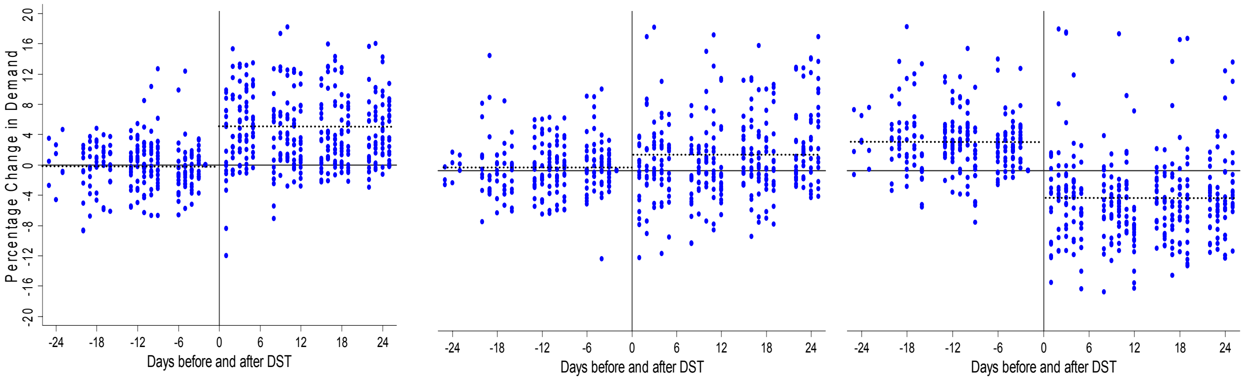
Justification of using 12:00 to 14:30 as the control period

Our estimation strategy uses the assumption that electricity demand in the afternoon is not affected by DST. The purpose of this subsection is to offer graphical and regression results to justify this assumption and to explain our specific choice of 12:00 to 14:30 as the base demand period for setting $\overline{q}$.

Figure 8 displays electricity demand for VIC and SA in 1999 and 2001-2005, one month before and one month after the late-October switch to DST in each year. Panel (a) indicates that morning demand increases immediately after the time change, while panel (c) shows that evening demand decreases. However, panel (b) demonstrates that afternoon demand is unaffected by the time change.

To verify the preliminary evidence offered by Figure E1, we perform a regression discontinuity analysis using the pre- and post-DST data in 1999 and 2001 to 2005, in both SA and VIC. The dependent variable is demand and the regressors consist of state and year fixed effects, their interaction, weather variables, a linear time trend, and a binary variable “DST” that is equal to one if DST is observed and zero otherwise.

Figure E1: Effect of DST on morning, afternoon and evening consumption



(a) morning 7:30-8:00 (b) afternoon 13:00-13:30 (c) evening 19:30-20:00

Vertical axis: Electricity demand relative to demand on the Friday preceding the start of DST. Each day contains a maximum of 12 data points (2 states over 6 years). Data excluded are: the year 2000, weekends, holidays, school holidays and “transition vacation days”.

When we run this regression using only data from the morning hours of 7:30-8:00, we estimate that the coefficient on the DST variable is positive and significant: the point estimate is +121 with a standard error of 46. This agrees with the increase in morning demand shown in panel (a) of Figure E1. Similarly, we find that DST decreases evening demand: the point estimate during 19:30-20:00 is -103 with a standard error of 30.

During the afternoon, however, the estimated effect of DST is insignificant. Table E2 displays estimates of the DST coefficient, along with standard errors and *t*-values, for several afternoon half-hour intervals.[33] Our base period choice of 12:00–14:30 is driven by both the *t*-values shown and a desire to be conservative in our reference case estimate. While the lowest available *t*-value is for 13:00-13:30, suggesting that this would be an appropriate base period, its use yields a large estimate of the overall treatment effect θ: an increase in electricity consumption of 1.0%. To be more conservative in our final estimate, we instead report reference case results using 12:00-14:30 as the base period, even though the estimates reported in Table E2 suggest that DST may slightly increase electricity demand at this time. Despite this choice of base period, we still find a point estimate of θ that is positive, and reject prior studies' claims that extending DST conserves electricity.

Table E2: Half-hourly DST effects on demand for VIC and SA

Halfhour	DST	std.error	t-value
11:00-11:30	40.19	45.89	0.88
11:30-12:00	34.22	46.43	0.74
12:00-12:30	42.05	46.11	0.91
12:30-13:00	36.33	47.14	0.77
13:00-13:30	13.28	48.74	0.27
13:30-14:00	19.41	51.08	0.38
14:00-14:30	46.83	51.70	0.91
14:30-15:00	59.03	52.00	1.14
15:00-15:30	53.46	52.77	1.01
15:30-16:00	43.28	52.08	0.83

The half hour from 13:00-13:30 exhibits the lowest t-value. The neighboring hours show monotonically increasing *t*-values respectively up to the period from 12:00-14:30 that is the base period used for $\bar{q}$.

Figure E2 displays the covariance matrix of the treatment coefficients $\hat{\boldsymbol{\beta}}$ estimated from the reference case model. Each data series shown corresponds to the square root of the *h*th row of our estimated 48 x 48 clustered covariance matrix, $\mathbf{cov}(\hat{\boldsymbol{\beta}})$. The peak value of each series coincides with the diagonal-element var($\hat{\beta}_{hh}$). The off-diagonal elements become smaller with increasing distance from the diagonal element, because the dependency between neighboring half-hours decreases over time. The U-shaped pattern stems from the fact that the treatment effects between 12:00-14:30 have very small standard errors, by the design of the triple-DID method.

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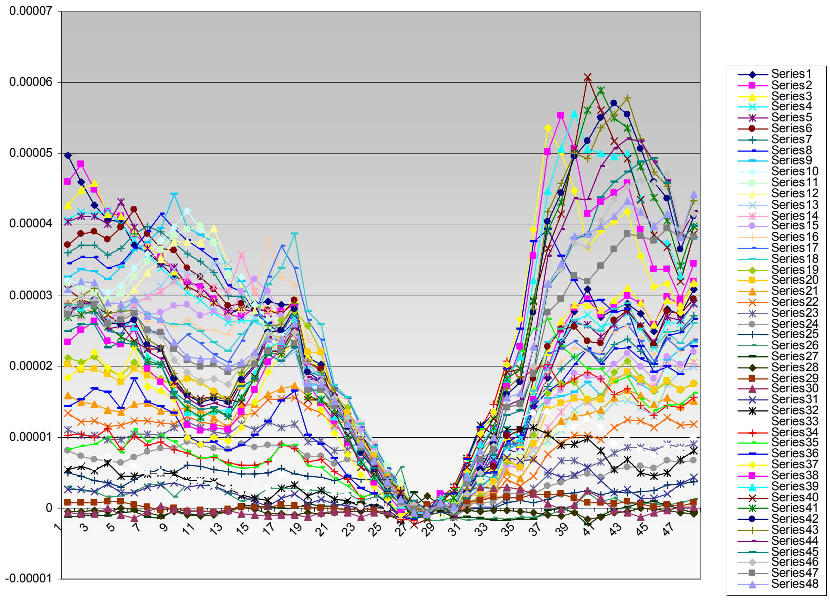
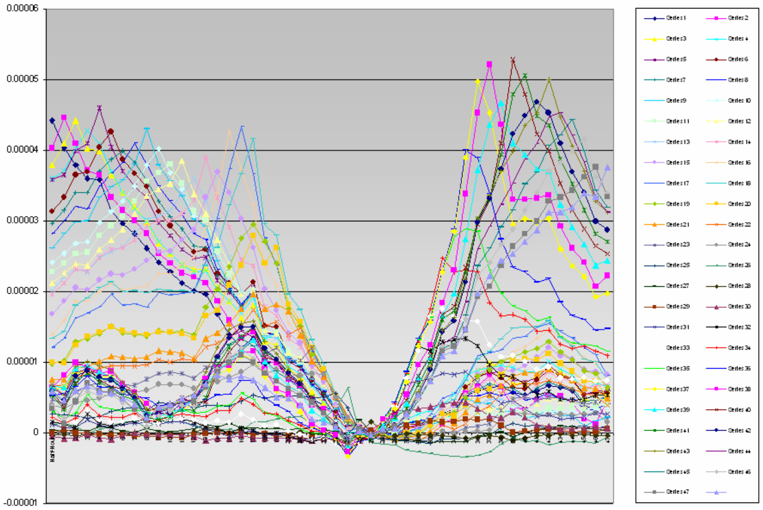
[33] Robustness checks for varying the sample size (changing the number of dates included before and after DST takes effect), using single hour equations or aggregating the hours did not yield results substantially different from those displayed in table E2.

Figure E2: Illustration of the clustered covariance matrix of $\hat{\boldsymbol{\beta}}$



The estimated Newey-West covariance matrix is displayed in Figure E3. Here, the dependency between $\hat{\beta}_h$ and $\hat{\beta}_{h+i}$ declines more quickly than was the case with the clustered covariance because the Newey-West explicitly accounts for the serial correlation of ε so that the remaining covariance structure of $\hat{\boldsymbol{\beta}}$ exhibits less dependency among the neighboring half hours.

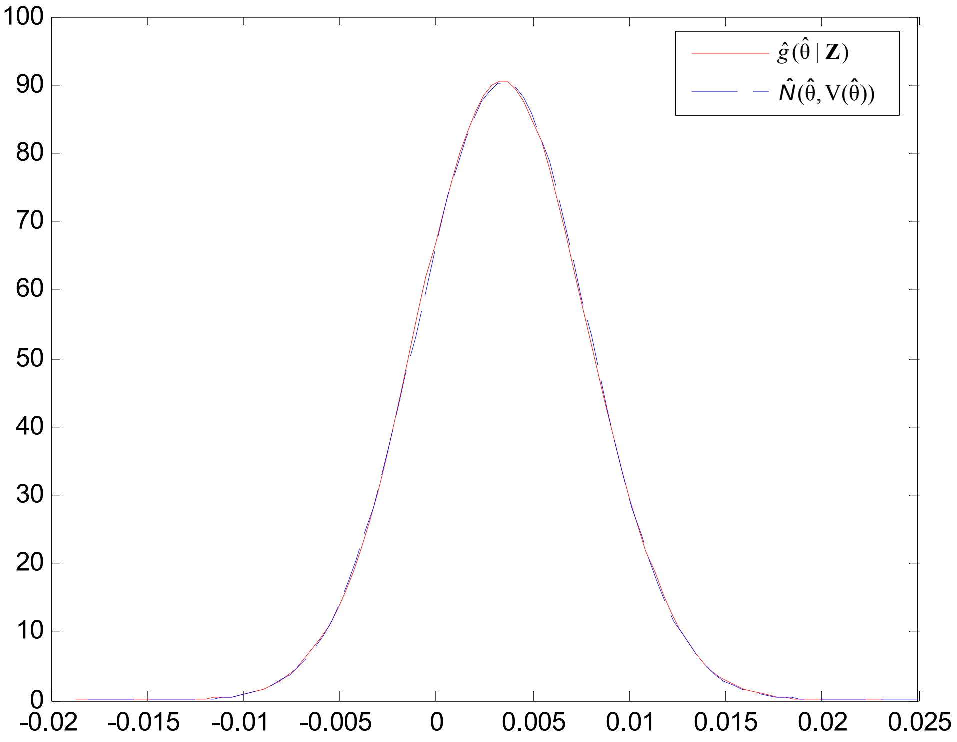
Figure E3: Covariance matrix estimated by Newey-West



On the numerical equivalence between $\hat{g}(\hat{\theta} \mid \mathbf{Z})$ and $N(\hat{\theta}, \mathrm{V}(\hat{\theta}))$

In section 5 we approximate $g(\hat{\theta})$ by $N(\hat{\theta}, \mathrm{V}(\hat{\theta}))$. Figure E4 displays $\hat{g}(\hat{\theta} \mid \mathbf{Z})$ and $N(\hat{\theta}, \mathrm{V}(\hat{\theta}))$ in the case of the pooled treatment effect. Given the large sample, the close match between these two approaches justifies the approximation of the posterior $\hat{g}(\hat{\theta} \mid \mathbf{Z})$ with the simulated likelihood $\hat{g}(\hat{\theta})$ and the normal approximation $N(\hat{\theta}, \mathrm{V}(\hat{\theta}))$.[34]

Figure E4: Estimated density function $\hat{g}(\hat{\theta} \mid \mathbf{Z})$ and simulated normal density



	$\hat{g}(\hat{\theta} \mid \mathbf{Z})$ approximated by 100,000 draws	$N(\hat{\theta}, \mathrm{V}(\hat{\theta}))$ approximated by 100,000 draws	Analytical Estimates based on (3) and (4)
Mean	0.00343	0.00345	0.00341
Std	0.00433	0.00434	0.00432
Skewness	0.02274	0.00110	
Kurtosis	3.00578	3.00422	

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[34] The equivalence of these results is driven by central limit theorem: the sum of the 48 non-iid lognormals is large enough relative to the dependency, so that the asymptotics take over.