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Does Extending Daylight Saving Time Save Energy? Evidence from an Australian Experiment

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ABSTRACT

Does Extending Daylight Saving Time Save Energy? Evidence from an Australian Experiment*

Several countries are considering extending Daylight Saving Time (DST) in order to conserve energy, and the U.S. will extend DST by one month beginning in 2007. However, projections that these extensions will reduce electricity consumption rely on extrapolations and simulations rather than empirical evidence. This paper, in contrast, examines a quasi-experiment in which parts of Australia extended DST in 2000 to facilitate the Sydney Olympics. Using detailed panel data and a triple differences specification, we show that the extension did not conserve electricity, and that a prominent simulation model overstates electricity savings when it is applied to Australia.

JEL Classification: Q48, C21

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Introduction

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, causing a misalignment between waking hours and hours of sunlight. In one of the earliest statistical treatments in 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 fuel combustion are driving interest in extending DST in several countries, including Australia, Canada, Japan, New Zealand, and the U.K.[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 therefore 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 1.3 billion U.S. dollars annually (California Joint Senate Resolution, 2001).

Our study challenges the energy conservation predictions that have been used to justify these calls for the expansion of DST. Across the studies and reports we surveyed, estimates of an extension's effect on total electricity demand range from savings of 0.6%

to 3.5%. The most widely cited savings estimate of 1% is based on an examination of a U.S. extension to DST that occurred in response to the Arab oil embargo (U.S. DOT, 1975). Due to the age of this study, it is likely that its findings are no longer applicable today. For example, the widespread adoption of air conditioning has altered intraday patterns of electricity consumption. Further, the 1% savings estimate may be confounded by other energy conservation measures enacted during the oil crisis.

More recent efforts to predict the effect of extending DST on electricity demand employ simulation models, which use data from the status-quo DST system to forecast electricity use under an extension. The most prominent such study, by the California Energy Commission (CEC, 2001), is being used to argue in favor of year-round DST in California. It predicts three benefits of an extension: (1) a 0.6% reduction in electricity consumption, (2) lower electricity prices, driven by a reduction in peak demand, and (3) a lower likelihood of rolling blackouts. However, this study is not based on firm empirical evidence; it instead uses electricity consumption data under the current DST scheme to simulate demand under extended DST. It may therefore fail to capture the full behavioral response to a change in DST timing.[3]

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

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

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 and high morning wholesale electricity prices. These results contradict the DST benefits claimed in prior literature, and indicate that proposals in Australia to extend DST permanently are unlikely to reduce energy use and GHG emissions.

While we cannot directly apply our results to the U.S. or other countries without adjustments for behavioral and climatic differences, this study raises concern that the planned DST extension in the U.S. is unlikely to result in energy conservation. To investigate the degree to which our results extend to the U.S., we reconstruct the simulation model that was used to forecast energy savings for California (CEC 2001), and apply it to the Australian data. We find that the simulation overstates energy savings in Australia, casting further suspicion on claims that extending DST in California and the rest of the U.S. will reduce electricity consumption.

The paper is organized as follows: the next section provides an 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 in section 3, section 4 discusses our identifying assumption and the treatment effect estimation strategy. Section 5 presents the empirical findings and tests them against electricity saving hypotheses. In section 6, we discuss the application of the CEC simulation model to Australia, and section 7 concludes by summarizing our main results and providing policy implications.

2. Background on Daylight Saving Time in Australia

The geographical area of interest is the southeastern part of Australia, displayed in figure 1. Three states in the southeast of the mainland observe DST: South Australia (SA), New South Wales (NSW), and Victoria (VIC). DST typically starts on the last Sunday in 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.

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 Olympic Games that took place in Sydney, in the state of NSW, from 15 September to 1 October. Specific rationales for the extension included easing visitor movements from afternoon to evening events, and reducing shadows on playing fields during the late afternoon (NSW Legislative Assembly Hansard, 1999). None of the justifications for the extension were related to curbing energy use.

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 other visitors who would likely arrive prior to the opening of the Games. VIC adopted the NSW timing proposal to avoid inconveniences for those living near the NSW-VIC border. However, SA did not extend DST in 2000 due to the opposition of the rural population (NSW Legislative Assembly Hansard, 1999 and 2005).

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

3. The Australian data and graphical results

3.1 Data

Our study uses detailed electricity consumption and wholesale price panel data, obtained from Australia's National Electricity Market Management Company Limited (NEMMCO).[4] These consist of half-hourly electricity demand and wholesale prices by state from 13 December, 1998 to 31 December, 2005. Wholesale prices are market prices paid by utilities to generators, while end-use customers instead pay a regulated price for electricity and are not exposed to fluctuations in wholesale prices. Therefore, these prices do not affect electricity consumption.

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

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

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

The goal of the empirical analysis is to examine the effect of the extension of DST on electricity use and prices. Prior to a discussion of the econometric model, much can be learned from the graphical analysis presented in figure 3. Panel (a) displays the average half-hourly electricity demand in SA during the treatment dates in 1999, 2000, and 2001. The load shape in SA, the control state, 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 in load until about 04:00 on the following morning.[5] Notably, SA's demand in 2000 appears unaffected by the DST extension in its neighbors VIC and NSW.[6]

In the treated state of VIC, however, the 2000 load shape is quite different from the loads in 1999 and 2001, as shown in panel (b). The treatment of extended DST 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. In particular, the large increase in demand from 07:00 to 08:00 closely matches environmental variables at this time of day. During the treatment period, the latest sunrise in Melbourne (on 27 August) occurs at 07:51, and the average sunrise occurs at 06:55. Further, the 07:00 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 time shift imposed by DST therefore causes people to awaken in cold, low light conditions, driving an increase in electricity demand that persists even one hour after sunrise. Extending DST only conserves energy if this morning increase in consumption is outweighed by the evening decrease; however, in figure 3 it is not clear that this is the case.

Panel (b) of figure 3 also casts doubt on claims that extended DST brings additional benefits, in the form of higher system reliability and lower prices, due to a more balanced load shape. While the extension does reduce the evening peak load in VIC in 2000, it creates a new, sharp peak in the morning that is even higher than the evening peak in 2001. This morning peak is also coincident with a large spike in wholesale electricity prices, as shown in figure 4. 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.[7]

The answer to the central question of whether extending DST reduces overall electricity consumption is not clear from this cursory analysis, since it does not account for important determinants of demand, such as weather and holidays. To obtain an unconfounded estimate of the effect of the treatment, we employ a formal econometric analysis, which we now describe in detail.

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

4.1 Identification

While we have noted that the DST extension was implemented solely to facilitate the Olympic Games, and that we are not aware of any energy-based justifications for it, identification of the extension's effect on energy use is made difficult by the presence of potentially confounding factors. In particular, there are reasons to suspect that the Olympics may have changed electricity consumption in Australia significantly, even absent a DST extension. The 2000 Games were the most heavily visited Olympics event in history, school vacations were rescheduled to facilitate participation in carnival events, and the Games were watched on public mega-screens and private televisions by millions of Australians in Sydney and elsewhere.

Our identification strategy incorporates several features designed to account for these potential confounders, and benefits from observations during the treatment year and the control years in both the treated and the non-treated state, as well as from the detailed half-hourly frequency of our data. First, we exclude the seventeen days of the Olympic Games from the definition of the treatment period; this allows us to avoid many of the biases noted above. Second, even with the Olympics excluded from the treatment, electricity demand may have been affected before and after the games by, for example, pre-Olympic construction activities and extended tourism. To control for these, we ignore NSW (where the Olympics took place), and focus on the change in electricity demand in VIC relative to that in SA. This technique eliminates the impact of any confounders that operate on a national level.[8]

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

These features of our model imply that a mild identifying assumption is sufficient for our regressions to produce an unbiased estimate of the extension's effect. We assume that, conditional on the observables and in the absence of the treatment, the ratio of VIC demand to SA demand in 2000 would have exhibited the same half-hourly pattern (but not necessarily the same level) as observed in other years. Support for this is found by plotting the ratio of consumption in VIC to that in SA for 1999-2005, as shown in figure 5. The demand ratio exhibits a regular intraday pattern in all non-treated years, even without controlling for observables. Moreover, the level of the ratio changes non-systematically, from smallest to largest, over 2002, 2000, 2001, 1999, 2004, 2003, and 2005. This is consistent with the existence of the transient state-specific level shocks discussed above that must be controlled for using mid-day demand. Also, the decrease in evening demand in VIC in 2000 and the increase in morning demand are clearly visible, consistent with the analysis of section 3.

As an alternative strategy to control for unobservables that affect each state differently in different years, we also considered taking advantage of demand data for the months adjacent to the treatment dates: August and November. That is, in a standard DID framework (not a triple differences framework) we considered using August and November each year to control for non-DST-related state-specific shocks to demand during the treatment dates. However, this strategy is valid only if the state-specific demand shocks are persistent over several months—if a shock causes VIC's demand to be relatively large in 2001 during the treatment dates, then the shock must also cause VIC's demand to be relatively large in August and November.

Figure 6 instead demonstrates that state-specific demand shocks vary unpredictably across months and years. For example, in 2001, the ratio of VIC demand to SA demand does not vary over August through November. However, in 1999 the ratio is larger during the treatment dates than it is in August or November, and in 2002 the ratio decreases monotonically from August to November. This lack of stability implies that the data cannot support an identification strategy that relies on observations from months adjacent to the treatment period. Indeed, when we estimate a model based on this strategy[9] we find statistically significant treatment effects that are implausibly large—one to two percent increases in demand during the mid-day (and overall). Given that both intuition and evidence instead indicate that DST does not affect mid-day demand, we eschew the "adjacent months" strategy in favor of the "within-day" strategy that uses mid-day demand to control for state-specific shocks.

4.2. Treatment effect model

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

(a) cross-sectional over states (with VIC as the treated state and SA as the control)

(b) temporal over years (with the untreated years in SA and VIC as controls)

(c) temporal within days (with the mid-day hours as "within-day" controls)

Our specification is given in equation (1):

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

The dependent variable for each observation is the difference in logs between electricity demand, q, in state i in day d in half-hour h (in clock time), and $\overline{q}$, the average mid-day demand in the same state and day. The reference case model uses data from VIC and SA during 27 August to 27 October in 1999, 2000, and 2001; these dates correspond to the period when DST was observed in VIC in 2000, and when standard time was observed in 1999 and 2001.

The covariates of primary interest are the indicator variables T_{idh} for the treatment period. These are equal to one in VIC during the treatment period in half-hour h, and zero otherwise. Dummy variables X_{idh} include 48 half-hour dummies, and interactions of these dummies with indicator variables for the following: state, year, day of week, holidays, school vacations, the interaction of state with week of year, and the interaction of state with a flag for the Olympic period. The weather variables W_{idh} are also interacted with half-hour dummies[10] and include a quadratic in hourly heating degrees,[11] daily hours of sunlight, the interaction of sunlight with temperature, hourly precipitation, the interaction of precipitation with temperature, and the average of the mid-day heating degrees. 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 in half-hour h caused by the DST extension is given by $\exp(\beta_h) - 1$.[12] The main parameter of interest, however, is θ, the percentage change in demand aggregated over all 48 half-hours. This is given by the following function of the vector of treatment coefficients, $\boldsymbol{\beta}$:

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

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

Our objective is to obtain the mean and variance of the probability density function of the estimate $\hat{\theta} = f(\hat{\boldsymbol{\beta}})$. Because $\hat{\theta}$ is the weighted sum of non-iid lognormally distributed random variables $\exp(\hat{\beta}_h)$, this distribution, denoted $g(\hat{\theta})$, does not have a closed form solution and must be estimated numerically (see Vanduffel, 2005).

To do so, we first develop a covariance estimator for the vector of estimated treatment coefficients $\hat{\boldsymbol{\beta}}$, which in turn relies on the covariance structure of the disturbance ε. We allow ε to be both heteroskedastic and clustered on a daily level,

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

where **Z = [T,X,W]**. 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 estimator is therefore used to obtain the covariance matrix of $\hat{\boldsymbol{\beta}}$ (Arellano, 1987, Wooldridge, 2003, and Bertrand et al., 2004). As an alternative, we also estimate the model using the Newey and West (1987) estimator with 50 lags.[13]

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($\hat{\boldsymbol{\beta}}$,**Cov(**$\hat{\boldsymbol{\beta}}$**)**), and then calculating $\hat{\theta}_i$ via (2) for each draw *i*. Conveniently, this numerical estimation produces a distribution $g(\hat{\theta}_i \mid \mathbf{Z})$ that is indistinguishable from a normal distribution with a mean given by $\hat{\theta} = f(\hat{\boldsymbol{\beta}})$ and a variance given by the delta method, per equation (3):

$$V(\hat{\theta}) = \nabla_{\beta}\theta(\hat{\boldsymbol{\beta}})^{T}\mathbf{Cov}(\hat{\boldsymbol{\beta}})\nabla_{\beta}\theta(\hat{\boldsymbol{\beta}}), \qquad (3)$$

In the results below, we therefore report point estimates of θ as $f(\hat{\boldsymbol{\beta}})$, with standard errors given by the delta method. We also report test statistics using the Student's *t* distribution, which leads to the same results as those that would be obtained from bootstrapping.

5. Results

5.1 Reference case results

Estimates from equation (1) of the percentage change in electricity demand caused by the DST extension in each half-hour are displayed in figure 7, and presented in tabular format in appendix C. Extending DST affects electricity consumption in a manner consistent with the preliminary graphical analysis: there is a transfer of 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.

To assess whether the evening decrease in demand outweighs the morning increase, we aggregate the half-hourly estimates using (2) to yield an estimate of θ. We find that the extension of DST did not conserve electricity, as shown in the first column of table 3. 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.

We also examine the impact of the DST extension separately for the pre-Olympic and post-Olympic treatment periods, which we will now refer to loosely as September and October. That is, we unpool each treatment dummy T_{idh} and estimate separate coefficients β_h^{Sep} and β_h^{Oct} for each half-hour. Because September in the southern hemisphere is seasonally equivalent to March in the northern hemisphere, this examination has policy implications beyond Australia—recent efforts to extend DST in the U.S. and California concern an extension into March, as DST is already observed in April in these locations. Prior studies have found that such an extension reduces electricity consumption by 1% in the U.S. and by 0.6% in California. In contrast, we estimate that the extension of DST into September in Australia *increased* electricity demand by 0.34%, as shown in table 3.[14]

To formally compare our estimates to the previous literature, we define three null hypotheses: (1) θ = -1.0%, (2) θ = -0.6%, and (3) θ = 0.0%, and test whether they are rejected by our estimates. Table 4 displays *p*-values for rejection of each null hypothesis in a two-sided test, given both our pooled and unpooled results. Even with clustered standard errors, our estimate of the effect of the DST extension in September rejects the most modest energy savings estimate in the literature of 0.6% (CEC, 2001) at a 5% level. Over the entire treatment period, we reject a 1% reduction in demand at a 1% level, and reject a 0.6% reduction at a 10% level. These rejections are strengthened with the use of Newey-West standard errors.

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

5.2 Robustness

Our results are robust to many alternative specifications, as shown in table 5. Our results are invariant to the choice between a weather model based on Bushnell and Mansur (2005) and one from CEC (2001). Further, our results do not change appreciably if we include years and months of data beyond what we use in our reference case, if we use Queensland as a control state rather than SA, or if we estimate (1) in standard time rather than clock time. This robustness is underlined by the precise fit of our model: the adjusted R^2 across all models is greater than 0.94.

Regression equation (1) contains over 1800 parameters. While the point estimates and the standard errors for the parameters of primary interest—the treatment effects—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, and deviations from the base temperature of 18°C increase electricity consumption, consistent with the effects of air-conditioning (when above 18°C) and heating (when below 18°C).

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

As a final check of our estimates, we evaluate whether extending DST causes a relatively greater reduction in electricity consumption on weekends and holidays than on working days. This would be consistent with the intuition that, on non-working days, less early activity mitigates the morning increase in demand. We estimate that electricity consumption on working days increased by 0.4% during the extension, while consumption on weekends and holidays decreased by 0.9%. This difference is significant at the 5% level.

6. Evaluation of the simulation technique

It is natural to ask is whether the simulation technique used by CEC (2001) to predict energy savings in California would have accurately predicted the outcome of the Australian DST extension. A successful validation would lend credence to the model's results in California, and suggest that California and the rest of the U.S. may experience reduced energy use due to an extension, even if Australia did not.

The simulation approach uses data on hourly electricity consumption under the status quo DST policy to simulate consumption under a DST extension. This procedure first employs a regression analysis using status quo data to assess how electricity demand in each hour is affected by weather and light, and then uses the regression coefficients to predict demand in the event of a one-hour time shift, lagging the weather and light variables appropriately. The consistency of the simulation results relies on the assumption that extending DST will not cause patterns of activity that are not observed in the status quo. This may not hold in practice. For example, to simulate demand under extended DST at 07:00 in March in the U.S., the model must rely on observed status quo behavior at 07:00 under similarly cold and low-light conditions. Without a DST extension, these conditions are observed only in mid-winter. The simulation will be inaccurate if people behave differently in the morning in mid-winter than they do in spring under extended DST.

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

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

$$q_{dh} = a_h + b_h Employment_d + c_h Weather_{dh} + d_h Light_{dh} + u_{dh}$$

The disturbance $\boldsymbol{u}_d$ is correlated across the h = 1,…,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, involving several lags and moving averages of half-hourly temperatures, with different coefficients for hot, warm, and cold conditions.[15] Once the vectors of regression coefficients are estimated, they are used in the second stage of the model to forecast electricity consumption under a DST extension. This is accomplished by lagging the weather and light variables by one hour and by adding the first stage realized error term to construct the following projection:

$$q_{dh}^{sim} = \hat{a}_h + \hat{b}_h Employment_d + \hat{c}_h Weather_{dh-1} + \hat{d}_h Light_{dh-1} + \hat{u}_{dh}$$

We apply the first stage of the CEC model to the Australian data for all of 1999 and 2001, and then simulate electricity consumption under extended DST in VIC in September 1999 and 2001 (we are unable to simulate demand under an extension in 2000 using the CEC's method because we do not observe demand under Standard Time in that year). Figure 8 illustrates the simulated demand, as well as actual demand (under standard time), in both years. The simulations predict a substantial decrease in demand in the evening and only a minor increase in demand in the morning, with overall energy savings of 0.43% in 1999 and 0.41% in 2001. Both the hour-by-hour and overall results closely align with the 0.6% savings predicted for California in the original study (see Figure 9). The results disagree, however, with the actual outcome of the Australian DST extension in 2000. Figure 8 also includes, in bold, the realized demand in VIC under the 2000 treatment. In both 1999 and 2001, the simulation fails to predict a morning increase in electricity consumption similar to that observed in 2000, and also overestimates evening savings. The simulated decrease in overall consumption is inconsistent with what actually happened in VIC. Based upon our triple DID estimate of a 0.34% *increase* in consumption in September presented earlier, we reject the simulated 0.41% savings at a 10% significance level. The simulation is unable to predict the substantial intra-day shifts that occur due to the early adoption of DST, a result that holds even after we attempt to improve the model's fit by selecting a smaller first-stage sample in which light and weather conditions most closely resemble the extension period in September.

7. Conclusions

Given the economic and environmental imperatives driving efforts to reduce energy consumption, policy-makers in several countries are considering extending Daylight Saving Time (DST), as doing so is widely believed to reduce electricity use. Our research challenges this belief, as well as the studies underlying it. We offer a new test of whether extending DST decreases energy consumption by evaluating an extension that occurred in the state of Victoria, Australia, in 2000. Using half-hourly panel data on electricity consumption and a triple-differenced treatment effect model, we show that, while extending DST did reduce electricity consumption in the evening, these savings were negated by increased demand in the morning. We further find that the extension caused sharp peak loads and prices in the morning hours.

From an applied policy perspective, this study is of immediate interest for Australia, which is actively considering using DST as a tool for energy conservation. Moreover, the lessons from Australia may carry over to the U.S. and to California in particular, as Victoria's latitude and climate are similar to those of central California. The planned extension that will occur in the U.S. in 2007 will cause DST to be observed in March—a month that is analogous to September in Australia, when our results suggest that DST increases rather than decreases electricity consumption. Further, we find that the simulation model that supported a DST extension in California over-estimates energy savings when we apply it to Australia. This casts suspicion on its previous policy applications in the U.S., and provides further evidence that the planned U.S. extension is unlikely to achieve its energy conservation goals.

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Appendix A: Data processing

Electricity data are missing for occasional half-hours, so we estimate the missing observations via interpolation using adjacent half hours. Weather data are also missing for some occasional hours as well for four entire days (none of which fall in within the treatment dates in any year, except for the air pressure variable). While we estimate weather for isolated missing hours via interpolation, we estimate weather for unobserved days via a regression analysis using information from the daily-level weather dataset. Details and code for this procedure are available 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. Employment data were obtained from the Australian Bureau of Statistics' Labor Force Spreadsheets, Table 12. Sunrise, sunset, and twilight data were sourced from the U.S. Naval Observatory, and the days and times of switches to and from DST were obtained from the Time and Date AS Company.

While our data are provided in Standard Time, we conduct our analysis in clock time. We therefore 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 a 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 half-hour, we average these observations.

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

Our identification strategy uses the assumption that electricity demand in the mid-day is not affected by DST. The purpose of this appendix is to offer regression results to justify this assumption and to explain our choice of 12:00 to 14:30 as the base demand period for setting $\overline{q}$ in equation (1).

In VIC and SA, we observe "typical" switches from standard time to DST in late October of 1999 and 2001-2005. These observations allow us to examine DST's effect on mid-day electricity consumption by performing a regression discontinuity analysis of demand near the date of each switch. Specifically, we form a regression sample consisting of half-hourly demand observations during the week before and week after the switch to DST in each year. We then regress, separately for each half-hour, the logarithm of demand on an indicator variable for when DST is in effect, state-specific within-year time trends, fixed effects for the interaction of state and year, fixed effects for day of week, fixed effects for holidays and vacations, and weather variables.

Before discussing the estimated effect of DST in the mid-day, we first note that this specification produces estimates which show that DST increases demand in the morning and decreases demand in the evening. For example, during 07:00-07:30, we estimate that demand increases by 5.9% following the switch to DST, with a standard error of 1.0% (we report standard errors clustered on year, though these are not appreciably different from OLS standard errors). During 18:30-19:00 we estimate a decrease in demand of 4.9%, with a standard error of 1.7%. The signs and statistical significance of these results are consistent with intuition, and indicate that this specification has sufficient statistical power to resolve non-zero effects where they exist.

In the mid-day, however, the effect of switching to DST is statistically insignificant. Table B displays estimates of the percentage effect of switching to DST, along with standard errors, for several half-hour intervals. These results are robust to the addition of another week of data before and after each switch to DST, and to the addition of quadratic state-specific within-year time trends. The point estimates are smallest in magnitude from 12:30-14:00, and increase both before and particularly after this time period.

Selection of this 12:30-14:00 interval as the base period for estimation of the main specification, equation (1), ultimately yields an estimate of θ of +0.3% (which is statistically indistinguishable from zero). Expanding the base period symmetrically around 12:30-14:00 includes within it hours of the day in which our regression discontinuity estimates in table B indicate that DST is likely to increase demand. Therefore, as we expand the base period, the estimates of θ decrease. This is demonstrated by the fact that the reference case estimate of θ, which uses the longer 12:00-14:30 interval as the base period, is +0.1%. We choose this interval to be our base period, rather than 12:30-14:00, to be conservative in our final estimate.

Appendix C: Half-hourly estimation results

Table C displays the estimated percentage impact of the DST extension on electricity demand in each half hour: these are the point estimates given by $\exp(\hat{\beta}_h)-1$ 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. Regressing equation (1) in standard time, rather than clock time, eliminates these overnight effects, and produces a point estimate that the extension increased overall electricity consumption by 0.4%.

Notes

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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 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. For more information on the history of DST, see the recent books by Prerau (2005) and Downing (2005).

[2] See NSW Legislative Assembly Hansard (2005), *The Toronto Star* (2005), The Energy Conservation Center, Japan (2006), *Scoop Independent News* (2001), and U.K. House of Commons (2007)..

[3] Rock (1997) also uses a simulation model, and finds that year-round DST decreases electricity consumption by 0.3% and expenditures by 0.2%. However, his study does not include non-residential electricity use, which accounts for 64% of U.S. total electricity consumption (U.S. EIA, 2005).

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

[5] The “zigzag” pattern that occurs between 23:00 and 02:00 in both states is due to centralized off-peak water heating that is activated by automatic timers, set to standard time (Outhred, 2006).

[6] 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 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.

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

[8] To further analyze whether visitors before and after the Olympic Games spent extended vacations in VIC or SA, we collected tourism information. These data show that, while NSW was affected by tourism during the Olympics, VIC and SA were unaffected. Data are available from the authors upon request.

[9] The specification is the same as equation (1), as described in section 4.2, except that mid-day demand is not subtracted from the left-hand-side.

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

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

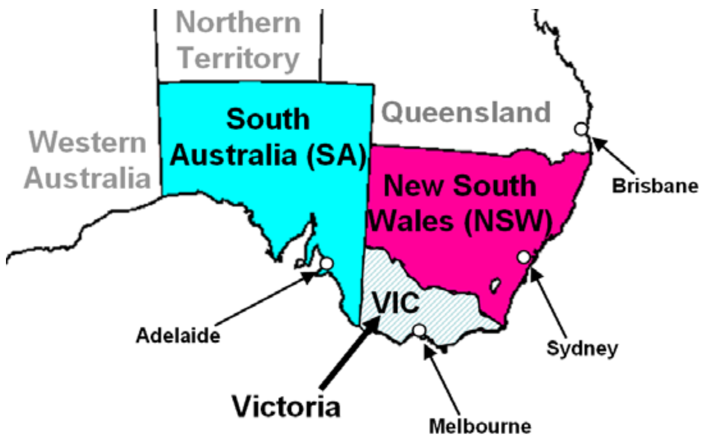
[12] To derive this, we make use of the assumption that mid-day demand is invariant to the treatment.

[13] 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 of the dependent variable, relative to a standard DID.

[14] The point estimate in October is that the extension reduces electricity demand 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.

[15] Details of the definition on these variables, the estimation of the model, and the simulation are explained in CEC (2001). We make minor changes to the CEC specification to account for our half-hourly, rather than hourly data, and for the fact that we observe humidity, precipitation, and daily unobstructed sunshine, but not hourly cloud cover. Computer code is available from the authors upon request.

Figure 1: Southeastern 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.

Table 1: Characteristics of capital cities in southeast Australia

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

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

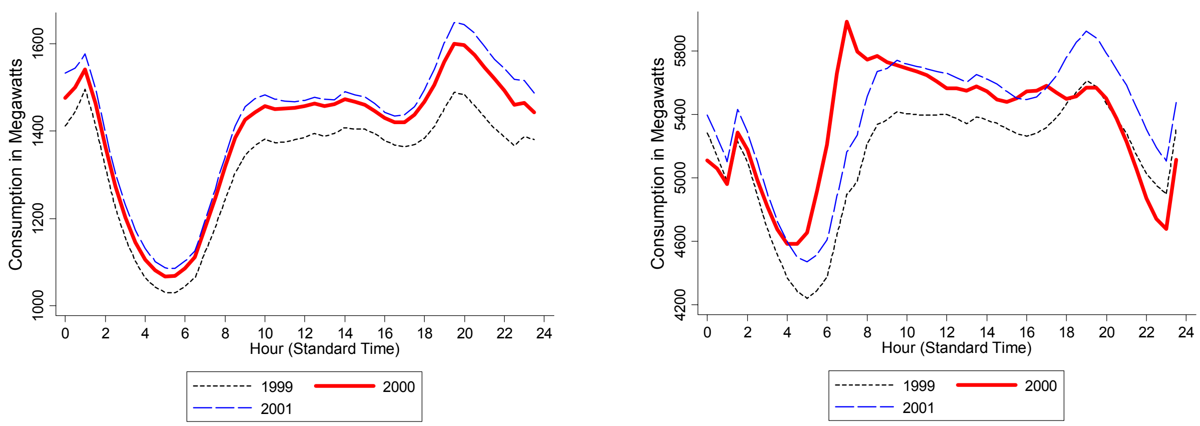
Figure 2: Timeline of 2000 events in New South Wales, Victoria, and South Australia

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

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

Abbreviations: MW = Megawatts; AUD/MWh = Australian Dollars per Megawatt-hour; mm = millimeters; hPa = Hectopascal. Note that the maximum wholesale electricity price is capped at 5000 AUD/MWh from 1999-2000, and at 10,000 AUD/MWh in 2001. The cap is designed to mitigate generator market power (NEMMCO, 2005).

Figure 3: Average half hourly electricity demand in South Australia and Victoria during the treatment dates



(a) South Australia (control)

(b) Victoria (treated in 2000)

Figure 4: Average half hourly electricity prices and demand in Victoria during the treatment dates

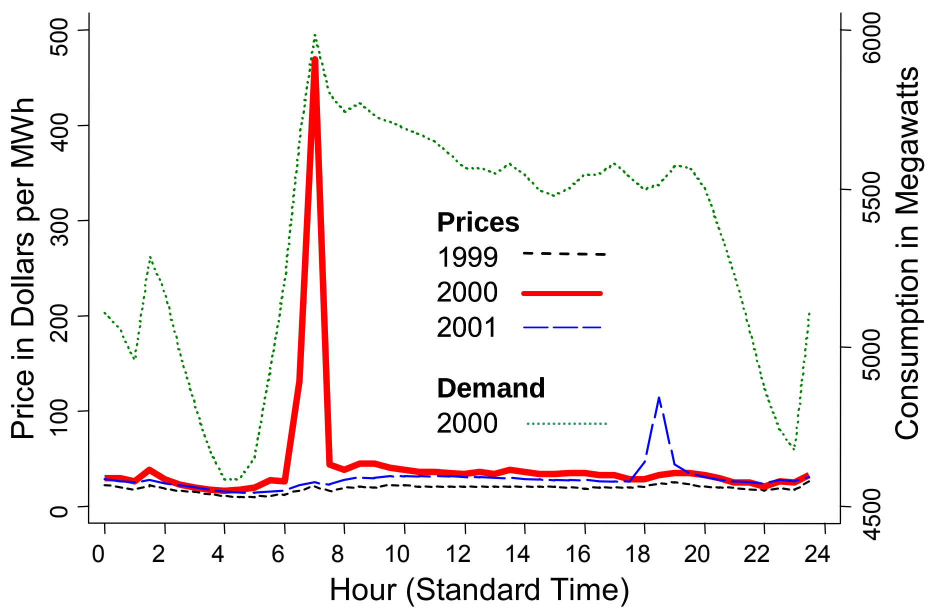


Figure 5: Ratio between average VIC demand and average SA demand during the treatment dates, 1999-2005

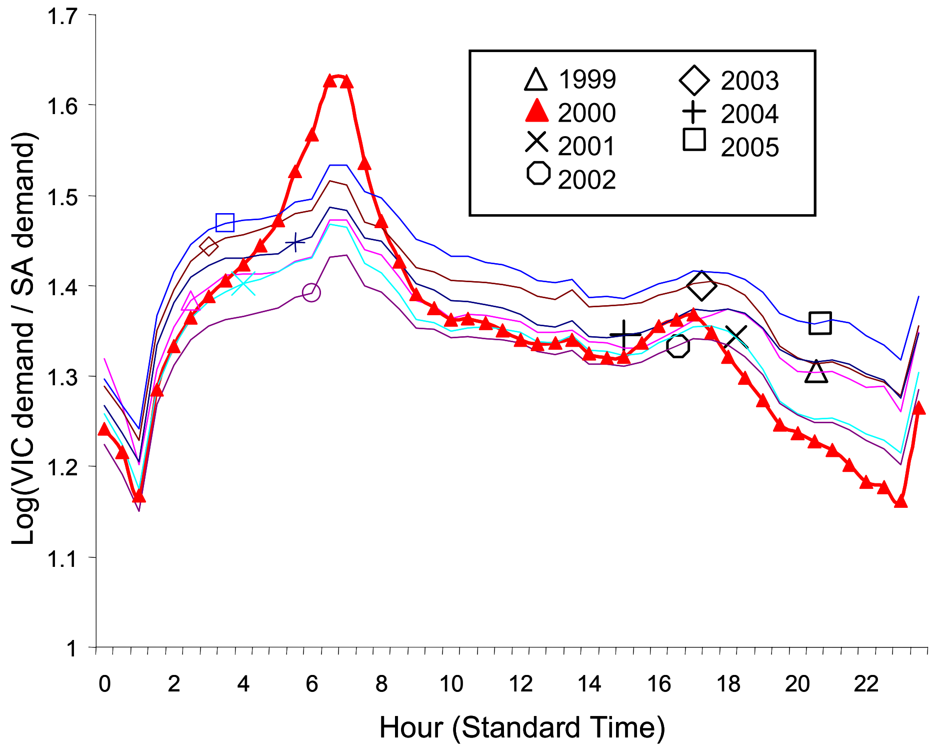


Figure 6: Ratio between average VIC demand and average SA demand, August through November, 1999-2005

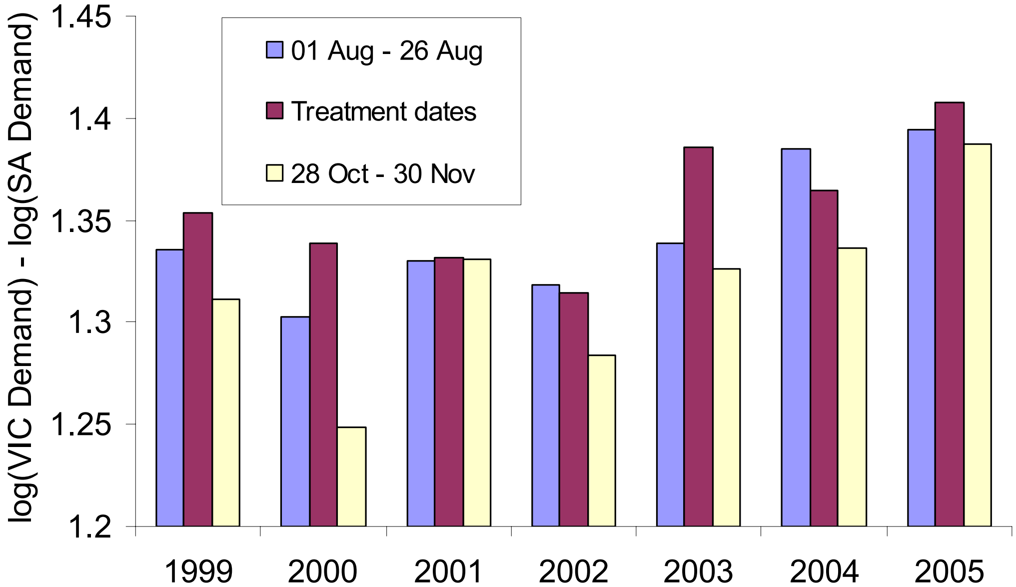
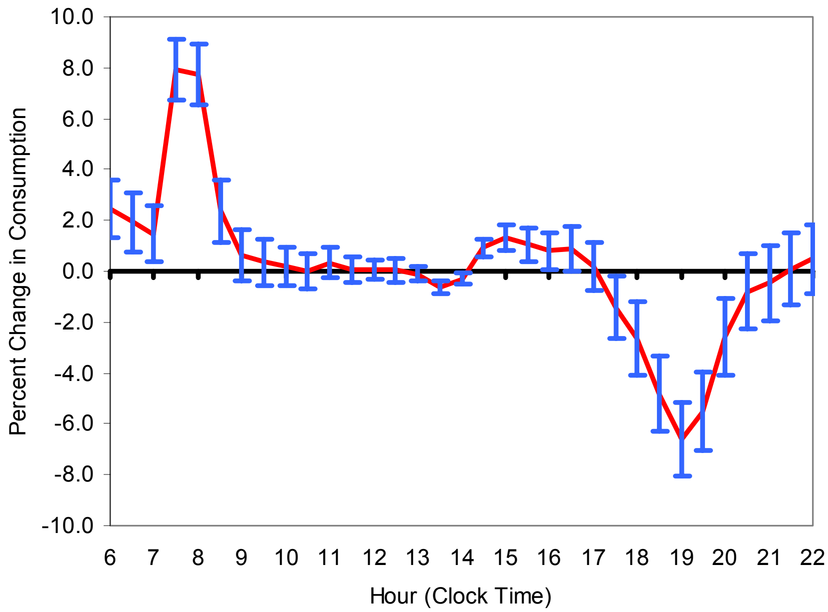


Figure 7: Half hourly effects of extending DST on electricity use



95% confidence intervals are indicated, with standard errors clustered by day.

Table 3: Summary of estimated treament effects, aggreagated over all half-hours

	All days	September	October	Working days	Non-working days
Percent change in demand	0.11	0.34	-0.06	0.44	-0.94
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

Table 4: p-values for rejection of electricity saving hypotheses

		September estimate (+0.34%)		October estimate (-0.06%)		Pooled estimate (+0.11%)	
	Null hypothesis	Clustered std error	Newey-West	Clustered std error	Newey-West	Clustered std error	Newey-West
Electricity savings	θ = -1.0%	0.002	0.000	0.029	0.009	0.004	0.001
	θ = -0.6%	0.030	0.006	0.208	0.131	0.067	0.026
Electricity neutrality	θ = 0.0%	0.430	0.319	0.891	0.870	0.776	0.729

Table 5: Summary of robustness tests of the pooled specification

	Reference case	CEC weather	Include data to 2005	Include Aug and Nov	Queensland as control state	Run in Standard Time
Percent change in demand	0.11	0.00	0.20	0.39	0.18	0.39
Clustered standard error	(0.39)	(0.38)	(0.35)	(0.35)	(0.28)	(0.40)

Figure 8: Actual and simulated electricity consumption in VIC, September 1999-2001

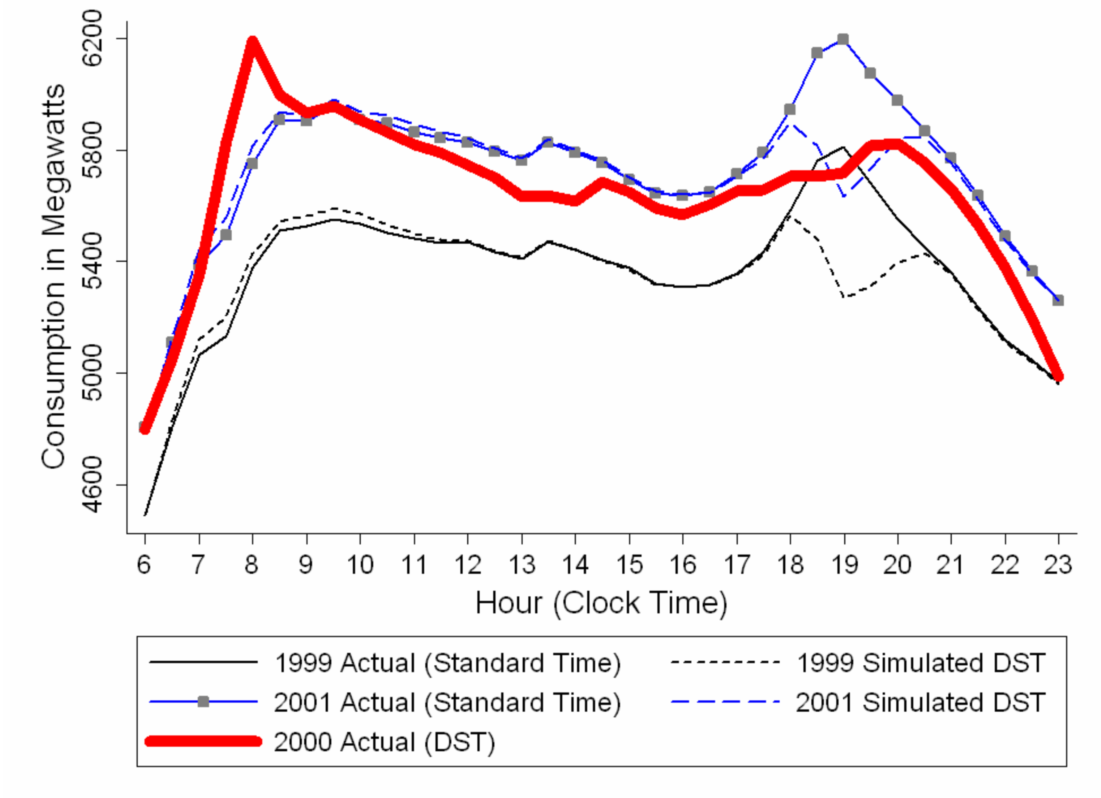
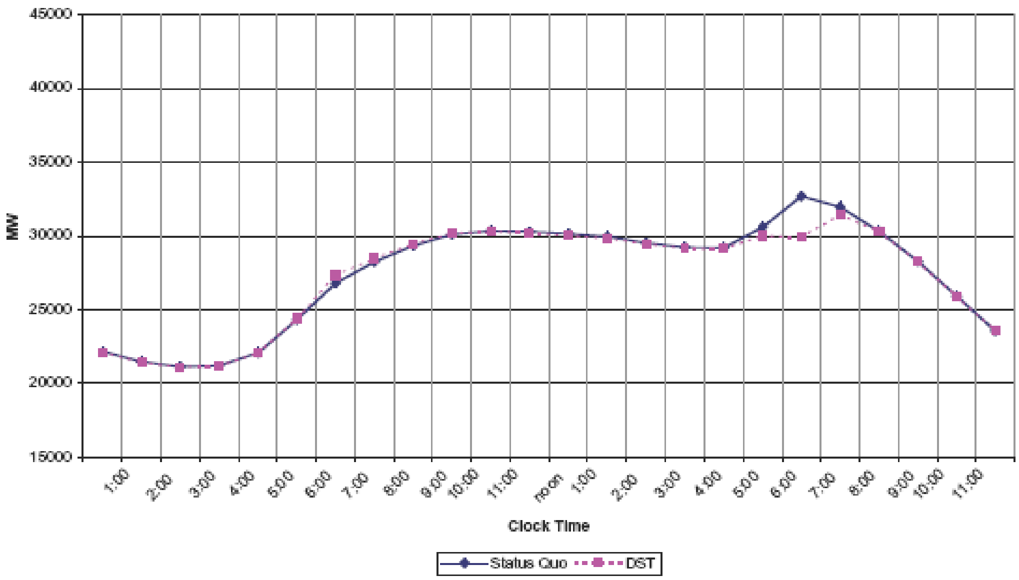


Figure 9: Simulation of DST in California, March 1998-2000 (CEC, 2001)



Status quo demand is observed under Standard Time.

Table B: Regression discontinuity estimates of the effect of switching to DST, by half-hour: late-October switches in VIC and SA in 1999 and 2001-2005

Half-hour	11:00-11:30	11:30-12:00	12:00-12:30	12:30-13:00	13:00-13:30	13:30-14:00	14:00-14:30	14:30-15:00	15:00-15:30
Percent change in demand	1.41	0.44	0.66	0.19	-0.24	0.40	1.35	1.33	1.31
Standard error	(1.74)	(1.43)	(1.56)	(1.54)	(1.41)	(1.64)	(1.90)	(1.37)	(1.56)

Standard errors are clustered on year

Table C: Estimated treatment effects by half-hour

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

Standard errors are clustered on date