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The effect of Daylight Saving Time on lighting energy use: a literature review

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Abstract

The principal reason for introducing (and extending) Daylight Saving Time (DST) was, and still is, projected energy savings; particularly for electric lighting. This paper presents a literature review concerning the effects of DST on energy use. Simple estimates suggest a reduction in national electricity use of around 0.5%, as a result of residential lighting reduction. Several studies have demonstrated effects of this size based on more complex simulations or on measured data. However, there are just as many studies that suggest no effect, and some studies suggest overall energy penalties, particularly if gasoline consumption is accounted for. There is general consensus that DST does contribute to an evening reduction in peak demand for electricity, though this may be offset by an increase in the morning. Nevertheless, the basic patterns of energy use, and the energy efficiency of buildings and equipment have changed since many of these studies were conducted. Therefore, we recommend that future energy policy decisions regarding changes to DST be preceded by high quality research based on detailed analysis of prevailing energy use, and behaviours and systems that affect energy use. This would be timely, given the extension to DST underway in North America in 2007.

Keywords: Daylight Saving Time (Summer Time), energy use, lighting

1. Introduction

Lighting has a profound effect on the lives of humans. It facilitates vision, which is our most important source of information on the world, it affects our basic biological functioning through its effect on our 'body clocks' (Webb, 2006), access to daylight and sunlight affects the form of our buildings and our cities, and provision of electric lighting is one of the world's biggest end-uses of electricity. For industrialized countries, national electricity use for lighting ranges from 5% to 15% of total electrical energy use (Mills and Orlando, 2002). Because this energy is often supplied by fossil-fuel generation, provision of lighting results in the large-scale release of greenhouse gases (GHGs): 1775Mt of carbon-dioxide emissions, according to a 2002 estimate (Mills and Orlando, 2002). Further, lighting is a major contributor to the peak demand for electrical power, which is often met by expensive, high-GHG generators.

Because of its high-energy burden, lighting has often been the target of energy efficiency initiatives. One such initiative is Daylight Saving Time (DST). The principal reason for the introduction of DST was to shift human activity patterns to make better use of the daylight, and thus reduce the amount of electric lighting necessary to support these activities. There are several other effects of DST, including changes to traffic fatalities, and commercial activities.

Beginning in 2007, DST - or Summer Time in Europe[1] - was extended by one month in the US and Canada (with some exceptions). DST started on the second Sunday in March and will end on the first Sunday in November. The new begin and end dates are set in the 2005 US Energy Policy Act (Energy Policy Act, 2005). To investigate the influence of the extension, the Act included the commitment that "not later than nine months after the effective date of the 2007 DST, the Secretary will report to the US Congress on the impact of the extension on energy use in the US". Depending on the results, the Congress retains the right to revert DST back to the 2005 time schedules. Canada followed the US in extending DST; this decision may have been more about avoiding chaos in financial and commercial areas due to lack of clock synchronization, than about expectations of energy savings (Beauregard-Tellier, 2005). In Europe, agreements are signed until 2007 (Fontaine and Ringholm, 2001). The European Commission will submit a report in 2007 with suitable proposals for continuation or change (Fontaine and Ringholm, 2001; De Bruin and Van Poppel, 2005; EurLex, 2000).

[1] This paper will use the term 'DST' for both of these time changes from this point onwards.

North America and Europe are not the only areas in the world to observe DST. For example, on the African continent, Egypt, Tunisia, and Namibia have DST. Israel, Palestine, and Jordan observe DST and both Australia and New Zealand introduced DST to save energy. Mexico has observed DST since 1996, and Cuba, Honduras, and Guatemala introduced DST in 2006.

The purpose of this paper is to review the literature concerning the effects of DST on energy use, particularly with regard to lighting, and to derive implications for energy policy. First, a short overview of the historical background of DST is given. Second, we give some simplified estimates of effect size, with a focus on residential lighting. Third, research conducted between 1968 and 2006 is discussed (mainly in chronological order). This research was conducted to better estimate likely effects, or to demonstrate effects from measured energy use data. We also briefly describe some of the research into the non-energy effects of DST. Finally, a general discussion with regard to the available knowledge, better effect estimates, and design possibilities is presented.

2. Historical background

In 1784, Benjamin Franklin, the American Minister to France, wrote a letter to the editors of the *Journal of Paris* about "the waste of both candlelight and daylight". Franklin was not proposing DST, but rather suggested that people get up and go to bed earlier thus saving money on the purchase of candles (Franklin, 1784).

In 1907, the Briton William Willett published a pamphlet entitled "The Waste of Daylight". In this document he proposed advancing clocks by 80 minutes in the summer. On successive Sundays in April, the clocks should be advanced by 20 minutes at 2 a.m., and be retarded by the same amount on Sundays in September. He suggested that this would increase daylight recreation time, and save £2.5million on energy for lighting. A parliament committee examined the idea in 1909, but the idea was not adopted (Willett, 1907; Churchill, 1934).

During World War I, Germany began observing DST (1916), and as the war continued the rest of Europe adopted DST. The US followed two years later, in 1918. After the war, all countries went back to standard time until the outbreak of World War II. In that war, year-round DST (abbreviated as YRDST) was instituted, and after the war many countries adopted summer DST. This lasted until 1973 when the American Congress enacted a trial period (1974-1975) of

YRDST to save fuel during the oil embargo. After the trial, the US returned to DST. Since then, DST in the US has started on the first Sunday in April (or the last Sunday in March), and ended on the last Sunday in October (Gurevitz, 2005). As stated in the introduction, DST in most of the US and Canada will be extended in 2007.

3. Simple Estimate of Potential Lighting Energy Savings

The potential of DST to save energy rests primarily on projected effects on residential lighting use. The assumption is that with more daylight in the evening, residents will delay switching on electric lighting in their home. Advancing the clocks one hour implies that lights will be switched on an hour later in the evening. Assuming the bedtime of residents does not change, this suggests that the "on time" of lighting with DST will be one hour less than without DST. Combining this basic assumption with knowledge of overall lighting energy use allows a simple estimate of the savings that may accrue with the adoption of DST.

Electricity use in residences comprised around 36% of total electricity use in the US in 2005 (EIA, 2005). Lighting makes up around 9% of all electricity use in US residences (EIA, 2001). Therefore, residential lighting is responsible for 3.5% of all electricity use in the US; the data for Canada are very similar (NRCan, 2006). Metering and survey studies show that lights are switched on for an average of 2-3 hours per day in houses [Vine and Fielding, 2006], and that most of this use occurs in the evening (Enertech, 2002). Therefore, if DST reduces this use by one hour for approximately half the year, total annual electricity use would be reduced by approximately 0.7%. Of course, not all lighting is used at night, and DST may increase the use of lighting during darker mornings, so a final rough estimate of the total annual electricity reduction may be closer to 0.5%.

This might seem like a very small number, especially to those used to studying energy savings associated with specific technologies at the single building level. Nevertheless, at the national scale, it is a saving worthy of pursuit. By way of comparison, again in the residential lighting arena, we can perform a similar rough potential saving estimate for compact fluorescent lamps (CFLs). There has been much effort to promote CFLs, and many utilities have offered various incentive schemes to encourage homeowners to replace incandescent lamps with CFLs, which use about 80% less energy to deliver the same amount of light. A survey of households in

California showed around 21 light fixtures per household (HMG, 1997). Of these 21 light fixtures, only one uses a CFL, on average. Replacing an additional four incandescent fixtures with CFLs would reduce installed lighting power by about 15%, and therefore total annual electricity use would be reduced by approximately 0.5%. This simple analysis shows that the estimated savings associated with DST are of the same magnitude as a huge improvement in the market penetration of CFLs.

Lighting is used in many places other than residences, of course. But first-order estimates suggest no substantial effect of DST for other lighting end uses. Commercial and industrial buildings generally do not have lighting controls that respond to external conditions, the lights are on at the same level for all working hours. For street and other outdoor lighting, there are still the same number of hours of darkness with or without DST, and therefore no change in energy use.

DST may also have an effect on the thermal energy use in buildings. For example, with DST it will tend to be sunnier and warmer when people get home from work in the Summer, compared to the case with no DST. This may encourage increased use of air conditioning, thus increasing electricity use. Similarly, it will be cooler and less sunny in the early morning when people wake, which may increase the need for heating energy, especially in Spring and Autumn months. Similar effects will apply in commercial buildings, where there is a concern that the increased air conditioning in the late afternoons may be coincident with system-wide electricity demand peaks. However, building thermal effects are much more difficult to estimate than direct lighting energy effects, and are highly dependent on the local climate, and the characteristics of each building and its heating and cooling system.

There have been several studies over the past four decades to make more detailed estimates of saving potential, or to demonstrate that savings actually occurred as a result of DST transitions. These studies are summarized in the following section.

4. Research on Daylight Saving Time (1968 – 2007)

In 1968, the UK began a three-year trial of so-called British Standard Time (BST), which was implemented year round (YRDST). The clocks were advanced one hour in March 1968 and not put back until October 1971. A review of this trial by Her Majesty's Stationery Office (HMSO, 1970) concluded that it was impossible to quantify important advantages and disadvantages and drew no conclusions either in favour or against YRDST. Demand for electricity increased by 2.5% in the morning peak period, but reduced by 3% in the higher evening peak, as expected from the shift in lighting needs (Hillman and Parker, 1998). This shift in demand was expected to reduce the overall need for generating capacity. Nevertheless, the net effect of YRDST was not considered adequate for the system to be continued (HMSO, 1970; RoSPA, 2005).

The US Uniform Time Act of 1966 specified DST to begin on the last Sunday of April and to end on the last Sunday of October. Following the 1973 oil embargo, most of the US went on extended DST for two years in the hope of saving extra energy. In 1974, the US Department Of Transportation (DOT) was assigned to perform a study of the effects of YRDST (Ebersole et al., 1974), which was introduced in the US on January 6th, 1974. The extended period ended on April 27th, 1975. The comprehensive study addressed different impact areas, such as energy, travel, safety, crime, commerce, and recreation. First, DOT analyzed public opinion, and roughly 680 persons were surveyed each month (September to April). This analysis demonstrated that YRDST was generally popular, but not in the winter months. Secondly, the DOT study categorized the effects of YRDST in three broad areas: community effects, industry/commerce effects, and energy effects. With regard to energy use, the researchers hypothesized that lighting electricity use would decrease, gasoline use (for travel) would increase, and heating needs would decrease. DOT compared the electricity use (hourly electric load data for 22 electrical utility systems) before and after the YRDST introduction. They made a 4-day comparison directly before and after January 6th, and compared two 28-day periods (in January/February 1974 with YRDST, and January/February 1973, the corresponding period without YRDST). They also compared the electricity use before and after DST transitions in Fall and Spring from 1967 to 1973. Data were normalized for temperature variations.

The four-day approach showed an estimated overall reduction in electricity use of 0.87% or 0.74% (depending on the analysis method) following the introduction of DST. The 28-day comparison showed that the electricity use was approximately 4.6% or 0.73% lower (again, depending on the analysis method); the authors cautioned that the higher number was probably largely due to causes other than YRDST.

During the Spring transition (March to April), there was a decrease in electricity use after DST was introduced for 6 of the 10 years analysed (1963-1972). An overall reduction of 0.6% was found. However, the Fall transitions showed an increase in all 10 years (October to November). Shifting back to Standard Time (ST) caused an overall increase in electricity use of 1.5%. Because the actual effect of DST could be isolated from the change in energy use due to temperature changes, DOT compared the changes against weekly trends. This comparison showed electricity savings in the order of 1% (in March and April only). Peak loads were decreased by approximately 0.75% (in January and February) with the daily winter peak shifted from early evening to later in the evening, or to the morning.

Travel analysis indicated that increased gasoline use (0.5-1%) might have occurred in some states: with an extra hour of daylight in the evening people tend to go out more, using cars and therefore increasing fuel use. With regard to (home) heating, the report concluded YRDST had no direct effect on fuel use overall, but that there would be savings in locations that used heating only at night. Comments at the end of the study acknowledge that the results were of low technical reliability because of “the nature of the data”, and state that results are “probable” rather than conclusive. Further, sociological/economical (e.g. age, income) and climatological (e.g. latitude) factors may also have had effects on fuel use but they were not specifically taken into account. The DOT researchers also recognised the difficulty of isolating the small effects of time change from the much larger effects of the prevailing energy shortage.

Two years after the DOT report was published, the US National Bureau of Standards (NBS) was asked to conduct a technical evaluation of the DOT study. The review (Filliben, 1976) did not support the 1% electricity saving finding, due to lack of reliability in the original data and in the analysis techniques.

A German study by Bouillon (1983) noted that total energy use in Europe doubled from 1960 to 1983, while the proportion due to lighting decreased substantially, from 25% to 10%. This would tend to reduce the energy benefit of DST, if indeed the main effect is on lighting use. Based on a simulation model, the energy use for lighting in residential buildings was compared for the years 1979 (with ST) and 1980 (with DST), resulting in savings of 3.9% due to DST. On average, 1.2% more energy was used for heating related to DST introduction. Bouillon also investigated the energy use in commercial buildings, and found that on April and September mornings more energy was used with DST in place. Nevertheless, the Bouillon study concluded that overall electricity use had been reduced by 1.8% as a result of DST.

After the HMSO, DOT, NBS, and Bouillon reports, we found very little published research on DST effects on energy use until the work of Littlefair in 1990. For both commercial and residential buildings in the UK, Littlefair (1990) discussed three options for setting clocks in relation to daylight hours: DST from March to October, DST from March to September, and DST year-round with extra DST from March to September (Single/Double DST, abbreviated as SDST). The author suggested that a change to SDST (from the prevailing DST) would lead to a better match between daylight availability and working hours. Littlefair's work differs from the work of others by implementing a model of manual light switching behaviour based on the light level when a space is entered. For commercial buildings, and with assumptions for daylight access and switching regimes, he found that the overall energy effect of a change in practice from DST-March-to-October to SDST was a 5% increase in lighting energy use. The increase was due to the fact that it would be darker in the early morning, when commercial building occupants decide whether to switch on the electric lighting on or not. Littlefair argued that a similar switching behaviour model would be observed in residential buildings. He then predicted that a change from DST-March-to-October to SDST would reduce the overall domestic lighting use by just over 5%.

Hillman (1993) discussed the impacts of SDST on leisure, accidents, energy use (Hillman and Parker, 1998), and well-being in the UK. By calculating the number of hours when interior illumination requirements could be expected to be lit by daylight alone, the authors estimate a 9% reduction in domestic lighting energy use, and a corresponding 4% reduction in the commercial and public administration sectors. Hillman also predicted a small increase in lighting energy use in some industrial sectors, and no effect on outdoor lighting. No overall effect on heating energy was anticipated.

The study conducted by Rock (1997) used a simulation model (DOE-2.1) to predict residential annual energy use at 224 locations in the US. The house used for this case study was based on a floor area and construction quality typical of moderately priced US single-family houses. The study concluded that average total electrical energy use increases slightly (0.24%) when DST is used instead of ST; natural gas use also increases slightly (0.05%). Changing from

ST to YRDST had virtually no overall effect on electrical energy (-0.02%) and natural gas use (0.02%). When the time-shifting practice was changed from DST to YRDST, the energy uses were slightly reduced: electricity -0.27% and natural gas -0.03%. The author concluded that energy use in residences could be reduced more effectively through traditional energy conservation programs such as using more efficient lighting, HVAC equipment, and insulation.

Ramos et al. (1998) referred to two theoretical studies to evaluate the saving potential due to DST in Mexico. The studies estimated annual savings from 0.65% to 1.10% of the total national use from reduced use of artificial lighting. The Mexican government introduced DST in 1996 and, to assess the implementation, the energy use of 1996 was compared with 1995's use. In 12 cities, 560 residential, 28 commercial, and 14 industrial customers were monitored. For the energy use of the residential customers, the data were corrected for temperature, type of housing, and hour of the day during the data analysis (Ramos and Diaz, 1999). Results showed that implementation of DST in 1996 brought overall electrical use savings of 0.83%. These savings came exclusively from residential buildings; no changes in use were detected for industrial and commercial customers. The annual maximum demand was reduced by 2.6% (Ramos and Diaz, 1999) (see also Friedmann and Sheinbaum (1998)).

Reincke and van den Broek (1999) conducted a DST study in 15 countries of the European Union. With regard to energy, the authors quoted ADAS[2] (1995), ACHE[3], and ADEME[4] (1995) reports. Using simulation, ADAS (1995) indicated that DST would reduce the demand for lighting in the evening for households by 1% or less, and increase demand for heating by 9%. In their conclusion, the authors indicate an overall positive but small effect of DST, with overall electricity savings ranging from 0 to 0.5%, depending on the country. However, ACHE noted that the extra use of air-conditioning during warmer evenings is often not accounted for, and could increase overall energy use. The energy savings for lighting alone as a result of DST can be up to

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[2] Agriculture Development Advisory Service (ADAS) is the UK's provider of environmental and rural solutions and policy advice.

[3] l'Association Contre l'Heure d'Été double (ACHE) is a French organization against DST in Europe

[4] Agence De l'Environnement et de la Maîtrise de l'Énergie (ADEME) is a French organisation

4%, according to a reviewed report by ADEME (1995). Reincke and van den Broek also found that increased traffic in evening hours can increase the fuel use by 0.3%.

Fisher (2000) took a different approach. For two weather stations at different locations in Germany (Berlin and Trier), he calculated what percentage of the yearly working time a workstation could function with daylight only ("daylight autonomy"). He assumed minimum illuminances of 200 lux and 500 lux on the horizontal plane. Calculations were made for situations without DST, with DST from March 28th to October 31st 1999 and with DST from March 21st to September 23rd 1999. The research contained three target groups (manufactures, shops and schools) with different working hours (respectively 7 am to 4 pm, 9 am to 7 pm, and 7:30 am to 2:30 pm). The results showed that there were reductions in lighting energy use in some sectors and increases in others, but the overall effect was close to neutral. With DST, factories and schools had 1.8% and 2.2% fewer hours of daylight autonomy (criterion 500 lux), respectively. For shops, the number of hours of daylight autonomy increased by 2.3% with the introduction of DST.

In New Zealand, an estimate by electricity market company M-Co in 2001 (Small, 2001) showed that power usage decreased 3.5% in the first week after introducing daylight saving time in 2000, with an average decrease of 2% over the previous 3 years. In the same week, peak evening demand, between 5 pm and 8 pm, dropped 7.5% in 2000, and on average 5.5 % over the previous three years. Contrary to other studies, peak morning demand, between 7 am and 9 am, also fell, but by smaller amounts.

The California Energy Commission studied the effects of DST on overall California electricity use (CEC, 2001). Along with their status quo situation (DST), the scenarios considered were: ST[5], YRDST[6], and Double DST (abbreviated as DDST, where "Double" indicates a clock change of two hours in Summer). The research hypothesized two specific beneficial energy-

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[5] This study used the term 'No DST' to indicate that there was standard time and no clock change. For this review, the abbreviation ST is used to make the mutual investigations comparable

[6] This study used the term 'Winter DST' to indicate that there was DST all year round. For this review, the abbreviation YRDST is used.

related effects: first, more daylight in the evening keeps people outside and away from indoor activities that use electricity, and secondly, the peak demand (when electricity is most expensive) is pushed back an hour. A regression model was constructed based on system-wide electricity use measured over several DST transitions. The model included variables for employment, workday, weather variables, and lighting variables, and involved a system of 24 linear equations (CEC, 2001; IFPI, 2001).

The results forecasted that for DST, compared to ST, the total electricity use would be unchanged. There were no peak demand reductions during the Summer, but the average peak demand was reduced by up to 5% in cooler months. However, an extension of DST during the Winter (YRDST) caused an extra drop in average Winter peak demand of over 3%, and the total Winter electricity use dropped 0.5%. DDST for the Spring/Summer/Fall months was less effective, with Summer savings of approximately 0.2%. The authors noted that with DST and DDST people will get home from work to hotter homes, which may encourage additional purchase and use of air-conditioning. Because Summer air-conditioning loads dominate lighting loads, this might increase energy use in the long-term.

The California Energy Commission method was modified to analyze the effect of DST for Indiana (IFPI, 2001). The Indiana model extended the California model to account for several other climate-related factors. The results had some similarities to those from California. In both cases, there was a change in energy use over the day and most noticeably during the additional hour of daylight in the evening. However, the Indiana results showed lower energy use in the morning and increases during the additional daylight hour in the evening, the Californian study showed the opposite. The authors concluded that the model was not reliable enough to make recommendations regarding DST for Indiana.

Researchers from the Center for the Study of Energy Markets (CSEM) (Kellogg and Wolff, 2007) questioned the findings of prior DST studies and used data from a quasi-experiment to test for effects. They examined data from two states in Australia: Victoria and South-Australia. Victoria started to observe DST two months earlier than usual due to the 2000 Olympic games, while South-Australia maintained ST. The researchers analyzed data, and developed a simulation model. The study found that introducing DST in Victoria caused a reduction in the evening demand, but led to a higher morning peak, and there was no overall reduction in electricity use. This suggested neither a reduction in electricity prices nor a reduction in likelihood of blackouts.

In addition, Kellogg and Wolff tested whether the CEC (2001) model could predict the Australian results They found that the CEC model failed to predict the measured increase in morning peak, and overpredicted savings in the evening. Kellogg and Wolff concluded that this casts doubt on the accuracy of the model, and of the predicted savings for California generated with the model.

New studies have been initiated. Both Japan and Korea, which currently do not implement DST, are exploring the consequences, with both countries anticipating energy savings and economic stimulation. In 2004, the Sapporo Chamber of Commerce and Industry launched a three-year pilot study on the Japanese island of Hokkaido, with the goal of saving energy by reducing the use of electric lighting. However, rather than resetting clocks, the employees of a sample of local governments and commerce departments made an equivalent change in their work schedules by starting work an hour earlier than usual during the Summer (Information Center Japan, 2006; Sapa, 2005). First results showed that two-thirds of the participants were positive about the national introduction of DST. Opponents reported a lack of sleep and more overtime. The South Korean Ministry of Commerce, Industry and Energy has initiated new research, encouraged by a 1997 study by the Korea Energy Economics Institute that found that "daylight saving time during the summer would reduce the home lighting electricity use by 8.1% and electricity for air conditioning by 4.95%" (e.sinchew-i, 2006).

5. Non-energy effects of DST

The primary reason for the introduction of DST was, and still is, to save energy. Nevertheless, the one-hour clock change influences more than energy use alone. Therefore, some authors have discussed other DST effects in their reports. DST may affect traffic safety, business, and leisure time, and may have physiological and psychological effects.

Shapiro et al. (1990) indicated that neither the change in photoperiod nor the effect of a small change in circadian rhythm, both associated with DST, had an effect on the psychiatric symptoms investigated (e.g. suicide). Olders (2003) suggested going to YRDST may help to diminish depressive disorders, due to effects on REM sleep.

Monk and Folkard (1976) used the DST time shift in the Fall of 1974 to study adaptation to small time shifts and disruptions in behaviour. The authors concluded that waking time and associated alertness and body temperature were all affected, and that adjustment to the time changes took several days. They speculated that the Spring transition would be more disruptive, and indicated that preliminary data showed an increase in road accidents.

Several investigations have studied the effects of DST on traffic fatalities (e.g. RoSPA, 2005; Ebersole et al., 1974; Hillman, 1993; Whittaker, 1996; Coren, 1998). With regard to traffic fatalities in general, there are two possible relations between the number of accidents and the clock shift. First, concentration is reduced due to a disturbed circadian rhythm. Second, in general, pedestrians are more than twice as likely to be killed in darkness than in daylight. The results of prior investigations differ and are sometimes contradictory, which may be explained by differences in chosen target group, time shift type (e.g. DST, BST, or SDST), or geographical location. For example, specific to schoolchildren in the Spring transition, the DOT-report (Ebersole et al., 1974) found an increase in fatalities during the darker morning hours, but an offsetting decrease in accidents during early evening hours. Whittaker (1996) found a reduction in road accidents during the Spring shift (both morning and evening); for the Fall shift there was a decrease in the morning and an increase in the evening. The RoSPA (2005) reviewed several studies and concluded that, on balance, road casualties are reduced by the introduction of DST. Coren (1998) studied DST effects on traffic from the viewpoint of sleep duration. He found a significant increase in the number of traffic accidents (early evening) following the Spring shift and no reduction of accidents following the Fall shift.

Several studies above have suggested that DST leads to an increase in recreational traffic and fuel consumption. Hecq et al. (1993) translated this increased fuel use into increases in ozone and other air pollutants. On the other hand, Reincke and van den Broek (1999) give a rough estimate of the turnover increase for the leisure sector of around 3% for the EU as a whole. However, industries that traditionally start work early in the day (e.g. farming, construction) have generally opposed DST regimes (e.g. RoSPA, 2005; Worthington, 2005).

DST has been a popular topic in the popular media recently, spawning books (e.g. Downing, 2005a; Prerau, 2005) and interviews (e.g. Engber, 2005; Downing, 2005b) which cover the myriad of effect described above.

6. General discussion

Studies have demonstrated effects of DST on traffic, health, leisure, and safety. However, the principal reason for introducing and extending DST was projected energy savings, particularly for electric lighting. Support for this in the research is mixed. Several studies claim to have demonstrated the expected reductions in overall electricity use (~ 0.5 to 2%), largely as a result of residential lighting reduction. However, there are just as many studies that suggest no effect, or that the data are too unreliable to draw a conclusion. There are also some studies that suggest overall energy penalties associated with DST, particularly if gasoline consumption is accounted for. Comparison of different studies is hampered by many factors, including: a lack of consistency of methods, assumptions, building types, climates, and locations. Further, the reliability of the data from which conclusions have been drawn has been called into question. Studies that have looked at real system-wide energy use before and after clock changes have experienced great difficulty in isolating the effect of DST from other day-today variations.

Conversely, all studies that have looked at peak demand for electricity have concluded that DST causes a change in the hourly demand profile. However, studies do not always agree on the nature of the change, or the value to utilities and their customers

Even if one were to accept the validity of early findings suggesting small energy savings (e.g. Ebersole et al., 1974) the basic patterns of energy use have changed since these studies were conducted. Indeed, in her 2001 DST-related testimony to the House Science Committee Lawson (2001) stated “that these studies [US Department of Transportation] are over 25 years old and were limited in scope”. In addition, she stated that “there have been dramatic changes in lifestyle and commerce since we completed our studies that raise serious questions about extrapolating conclusions from our studies into today’s world.” Overall, energy use has increased substantially since the earliest studies were conducted, but lighting system efficacy has also improved dramatically. Further, thermal energy use patterns have altered substantially: for example, buildings are much better insulated, and residential air-conditioning use has increased rapidly (US House of Representatives, 2001).

In earlier studies the primary route for electricity savings was residential lighting, because the lighting controls in houses (manual switching) can be used by occupants to respond to external daylight conditions. This is not generally true in other building types, but that situation is changing in office buildings. Daylight harvesting systems are now available that sense prevailing daylight levels and automatically dim electric lighting accordingly (Lee and Selkowitz, 2006). Personal control systems are also being marketed that allow for dimming control of lighting even in open-plan spaces (Boyce et al., 2006). The market penetration of these systems in low, particularly in North America, but is expected to grow as the hardware becomes cheaper and energy becomes more expensive. With such systems in place, office building lighting could then respond to DST transitions.

The general population enjoy the recreational benefits of DST, and are likely largely unaware of the other effects. As a result DST is generally popular, and yet the evidence for the basic premise on which it was introduced, energy savings, appears poorly developed. In reference to projected energy savings, Hopkin (2007) writes that "the science behind the numbers remains sketchy at best", and quotes Garnsey (who has studied DST issues at the University of Cambridge) " 'I don't think that any really exhaustive work has been done anywhere' ". Lawson (2001), also recognizing the shortcomings, called for more high-quality research.

7. Conclusions and suggestions for future research

Based on the literature review, conclusions about the effect of Daylight Saving Time on (lighting) energy use are:

- The existing knowledge about how Daylight Saving Time affects energy use is limited, incomplete, or contradictory. Many conclusions are the result of expectations alone, are based on constrained assumptions, or are older than 25 years.
- Economical, geographical, and climatological factors have major effects on electricity end use. Studies should always correct for such factors.

- Energy use and human behavioural patterns have changed substantially since the first introduction of DST. These are likely to have a major influence on the effect of DST on energy use.
- Even if overall energy use is unchanged by DST, hourly energy use is changed, affecting electricity demand profiles.
- Effects of DST on lighting energy use are mainly noticeable in residential buildings.

Given the difficulties of separating DST effects from other effects in system-wide energy data, we suggest that the best prospect for progress in definitively evaluating the effect of DST on energy use is simulation. Such simulation should include a variety of building types in representative climates and latitudes, and should address both lighting and thermal energy effects. Behavioural models for light switching and thermostat setting should be included where appropriate. Interactions between building types should be addressed; for example, lower occupancy of homes on lighter evenings might mean higher occupancy in shopping malls. All assumptions should be supported by empirical data, and the simulations should also be calibrated and validated by empirical data. Further, simulations should include not only existing descriptions of building occupancy patterns, insulation values, equipment efficiencies and controls, but also a variety of future scenarios. Finally, building energy impacts should be weighed against the effect on transportation energy.

We recommend that policy-makers undertake a comprehensive, parametric study of this kind to inform decisions concerning which DST options should be adopted in the future, and for what reasons. This should include a comparison between the costs and benefits of DST vs. other energy efficiency or demand response programs.

It would also be interesting to explore aspects of residential design that may contribute to a delay in switching on lighting in the evening, analogous to DST effects. For example, one might expect skylights, or other design features that enhance daylight penetration, to result in electric light use being delayed.

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Abbreviations

BST	British Standard Time (equivalent to YRDST)
DST	Daylight Saving Time
DDST	Double Daylight Saving Time (PST + 2 hours in Summer)
SDST	Single/Double Summer Time (BST + 1 hour in Summer)
ST	Standard Time
PST	Pacific Standard Time
YRDST	Year-Round Daylight Saving Time
ACHE	Association contre l'Heure d'Eté double
ADAS	Agriculture Development Advisory Service
ADEME	Agence De l'Environnement et de la Maîtrise de l'Énergie
CEC	California Energy Commission
CFLs	Compact Fluorescent Lamps
CSEM	Center for the Study of Energy Markets
DOT	Department of Transportation
EIA	Energy Information Administration
GHG	Greenhouse Gases
HMG	Heschong Mahone Group
HMSO	Her Majesty's Stationery Office
IFPI	Indiana Fiscal Policy Institute
NBS	National Bureau of Standards

NRCan	Natural Resources Canada
OECD	Organization for Economic Co-operation and Development
RvB	Research voor Beleid International
RoSPA	Royal Society for the Prevention of Accidents
Sapa	South African Press Association