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The technical potential for off-peak electricity to serve as backup in wind-electric thermal storage systems

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Abstract

Despite its potential as a secure and environmentally benign source of electricity, wind's intermittency is proving to be a challenge for many electricity suppliers. One approach to overcoming this intermittency is to match it with a load that can be made to follow the wind, such as electric thermal storage systems for space heating. In such configurations, wind-generated electricity can be used for space heating and, if sufficient surplus remains, recharging the thermal storage system. When there is a demand for heat but no wind available, the thermal storage system can discharge, meeting the space heating requirements. In extreme cases, when the thermal storage system is fully discharged and there is no wind, some form of backup energy source is required.

This paper examines the technical potential of off-peak electricity to ensure that wind-charged thermal storage systems are able to bridge periods of insufficient wind. The simulations show that wind-heating with off-peak backup can reduce surplus electricity generated from the wind and greenhouse gas emissions. The benefits as well as the limitations of the approach are discussed.

Keywords: Wind-heating, thermal storage, peak-load electricity

1 Introduction

Since the 1990s, politicians and policymakers in many countries have faced growing pressure to take action on climate change. One of the results of this has been the introduction of energy policies that focus on the reduction of greenhouse gases in electrical generation. A commonly promoted solution is the increased use of wind-generated electricity as it seen as a carbon-free energy source (Tavner 2008) and as a secure and environmentally benign replacement energy source (Hughes 2009a). However, because of its intermittent nature, the large scale integration of wind is limited without storage or some form of backup energy supply (Hall and Bain 2008).

One of the downsides of energy policies that focus on climate change is that they often overlook other issues, such as energy security. In jurisdictions with significant heating seasons, the loss of access to secure sources of energy to meet the heating needs of, for example, the residential and commercial sectors can have considerable impacts on both the populace and the economy (Bang 2009). The January 2009 curtailment of natural gas supplies to parts of the eastern European Union due to a dispute between Russia and Ukraine is one such example (Bilgin 2009).

A companion paper has demonstrated how wind-generated electricity could be used to meet the residential space heating requirements of a jurisdiction in Canada (Hughes 2009b). Rather than trying to accommodate intermittent electricity from the wind into the existing electricity mix, the electricity is stored in thermal storage units for subsequent use in space and hot water heating applications. The benefits of such an approach to meeting the heating needs of a jurisdiction include the improved energy security of local generation; reduced greenhouse gas emissions from, in this jurisdiction, fuel oil; and a reduction in surplus intermittent electricity from the wind.

Despite these benefits, the one shortcoming of the approach was the need for backup energy sources to handle those periods when there was insufficient wind to meet demand. Increasing the number of thermal storage systems only compounds the problem as it becomes more difficult to fully recharge systems during these periods.

This paper presents a solution to the problem of meeting the backup needs of a wind-heating system. Rather than requiring the consumer to rely on a parallel energy system—such as a natural gas or fuel oil furnace which supplies energy for short periods throughout the heating season—the paper proposes the use of off-peak electricity. Electricity suppliers that already support thermal storage systems typically use off-peak electricity to charge consumers' systems, meaning that these suppliers already have experience with this technology.

The paper demonstrates the technical potential of combining wind with off-peak electricity for space heating. The approach offers a means whereby existing energy sources used for residential space heating can be replaced by one that is considerably more secure and environmentally benign than many others. Some of the benefits, including the reduction in greenhouse gas emissions are also discussed.

2 Background

Although Canada is blessed with fossil, hydroelectric, nuclear, and renewable resources, the distribution of these is not uniform. A case in point is Prince Edward Island, Canada's smallest province, situated in the Gulf of Saint Lawrence. It has limited energy resources, importing most of its electricity from the neighbouring province of New Brunswick and all of its refined petroleum products from Canadian refineries. The majority of these consumed in the province (like much of eastern Canada) come from North Sea crude oil, offshore Newfoundland, the Middle East, and Venezuela (Statistics Canada 2009). There is neither natural gas supply nor infrastructure on the island; most of the limited supply of natural gas in the region is exported to the United States. The high cost of electricity has made fuel oil the primary method of meeting heating needs for about 75 percent of residential structures in the province (NRCan 2008a).

The province's reliance on imported energy (both oil and electricity) has been of concern to successive federal and provincial governments since the 1970s. Over the past decade, many politicians and policymakers have seen the modern wind turbines, coupled with the province's excellent wind resource, as a means whereby the province could meet much of its own electrical needs as well as to become an energy exporter to the lucrative New England renewable electricity market (PEI 2008).

2.1 Wind resource

Prince Edward Island's wind resource encouraged the provincial and federal governments to establish the Atlantic Wind Test Site at North Cape (AWTS 1999). By 2002, a wind farm with a capacity of about 5.15 MW had been established by the Prince Edward Island Energy Corporation (Energy, Environment and Forestry 2007). Maritime Electric, the province's electricity distributor, purchases the electricity and sells it to its customers. Between July 2002 and June 2003, the wind farm produced 17,453 MWh of electricity, giving it an annual capacity factor of 38.6 percent.

Production from the North Cape wind farm exceeded 1,500 MWh each month between October and March, with October and December reaching 2,002 MWh and 2,235 MWh, respectively. All other months, with the exception of July and May, had production values in excess of 1,000 MWh per month. Figure 1 shows the monthly totals (from hourly data) for one year (1 July 2002 to 30 June 2003). This year was chosen because it was the only complete dataset available from five years of site data.

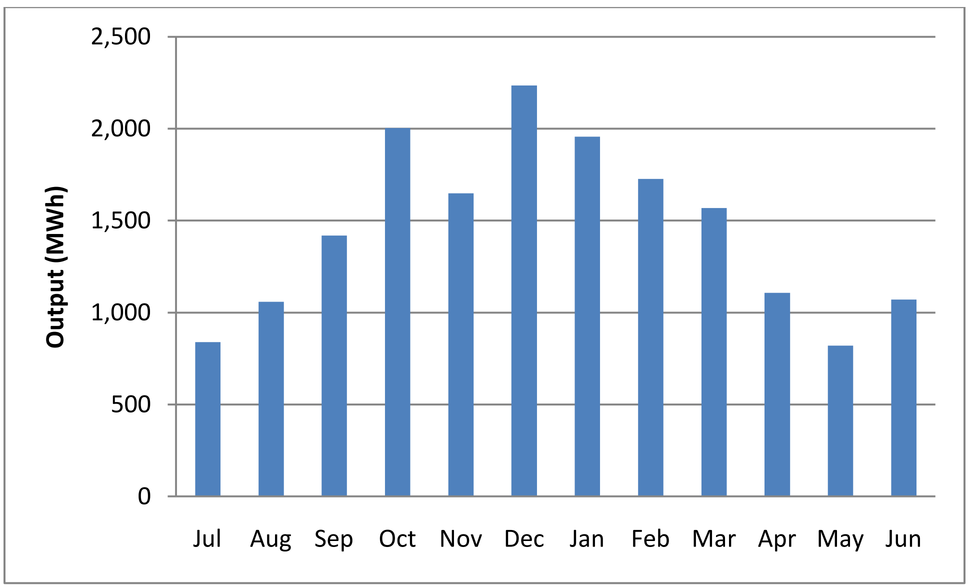

Figure 1: Monthly output from North Cape wind farm for 2002-03 heating season

2.2 Residential heating demand

In Prince Edward Island, as in many other northern jurisdictions, space heating is the dominant energy service in the residential sector, with domestic hot water (DHW) a distant second. The demand by service for an average single-detached house in 2003 is shown in Table 1.

Table 1: Demand distribution by residential energy service (NRCan 2008b)

Service	Percent	kWh
Space Heating	68.4%	18,539
Water Heating	21.7%	5,879
Appliances	7.3%	1,969
Lighting	2.5%	673
Space Cooling	0.1%	16

For the purposes of this paper, hourly space heating demand is determined from the annual space heating demand (Table 1) and the hourly ambient temperature for Prince Edward Island's regional airport (Environment Canada 2008).

Figure 2 shows the monthly profile of space heating (from hourly data) for an average single-detached home where demand is dominated by hot water supply during the summer months and space heating during the 2002-03 heating season (September through May). The data is centered on January, as this is the midpoint of the heating season.

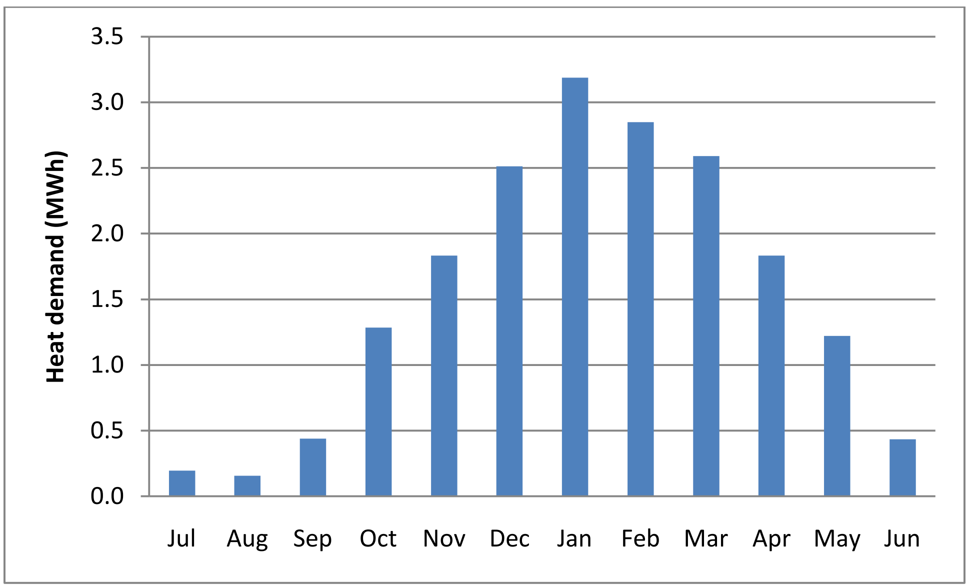

Figure 2: Monthly space heating demand for an average single-detached home

3 Thermal storage for space heating

Electric space heating typically falls into one of two categories: baseboard (or resistance heaters) and thermal storage systems. Since baseboard heaters require a continuous (or immediately available) supply of electricity, it has been demonstrated that thermal storage systems lend themselves well to taking advantage of an intermittent supply of wind-generated electricity (Hughes 2009b).

There are two types of thermal storage system: room and central. A room-sized system is intended to heat a limited number of rooms in a house, whereas a central system stores sufficient energy to heat an entire house. House-sized systems are further subdivided into forced hot air and hydronic. Manufacturers specify an upper-limit on the amount of energy that can be stored in a thermal storage system; this dictates the system's maximum charging and, to a lesser extent, the discharging rates. Most thermal storage systems are designed to run in a stand-alone fashion at a defined maximum output, typically 16 hours between charges.

3.1 Space heating without the wind

In jurisdictions with electricity suppliers that support electric thermal storage, the systems are typically charged during times of low-demand, for example, during the overnight hours of traditionally low demand between the hours 23:00 and 06:00. Depending upon the installation, the systems are either sent a signal or use an accurate clock that indicates when charging is to begin. Systems stop charging when signaled or after a specific interval of time has elapsed. In addition to recharging the system, electricity from the grid is required to offset any heating demand that occurs during each hour.

The thermal storage systems under consideration have a maximum recharge rate and a maximum storage capacity (for example, see (Steffes n.d.)). The responsibility of the electricity supplier is to ensure that when the recharging period is over, the thermal storage system has sufficient heat to meet the demand during the non-charging hours. The amount of energy required during charging is expressed in the following equation:

$$(SystemSize - SystemState) + \sum_{Hour=23}^{6} demand_{Hour} \qquad \mathbf{1}$$

where $SystemSize$ is the maximum thermal storage capacity of the system, $SystemState$ is the level of charge at the start of the charging period, and $demand$ is the demand at each hour of the charging period.

Two approaches to recharging a thermal storage system are now considered. The first is referred to as *fast-recharge*, which attempts to recharge the system as quickly as possible by applying the maximum allowable recharge during each hour (as well as meeting the hour's demand); when the maximum capacity has been reached, the electricity supplier simply maintains the capacity by meeting the hourly demand. The fast-recharge method will result in a peak in electricity demand during the hours the capacity of the thermal storage system is less than its allowable maximum.

The second method, referred to as *slow-recharge*, is intended to reduce the size of the peak by recharging the thermal storage system over the time available for recharging. The level of recharge required each hour is constant and increases the system state, as shown in the following equation:

$$SystemState_{Hour} = SystemState_{Hour-1} + \frac{SystemSize - SystemState_{Hour-1}}{Hours\ remaining\ in\ recharge} \qquad \mathbf{2}$$

The reciprocals of the hourly divisor are expressed as multipliers in Table 2.

Table 2: Hourly recharge constants for slow-recharge

Hour	**23:00**	**00:00**	**01:00**	**02:00**	**03:00**	**04:00**	**05:00**	**06:00**
Multiplier	0.125	0.143	0.167	0.200	0.250	0.333	0.500	1.000

An example of the differences between fast- and slow-recharge is shown in Figure 3, where at the start of hour 23:00, the system state of a 180 kWh storage system is 117.9 kWh. The fast-recharge returns the system state to 180 kWh in the first three hours (22.5 kWh, 22.5 kWh, and 17.1 kWh), while simultaneously meeting the demand. With the system fully charged, the remaining five hours are spent meeting the demand.

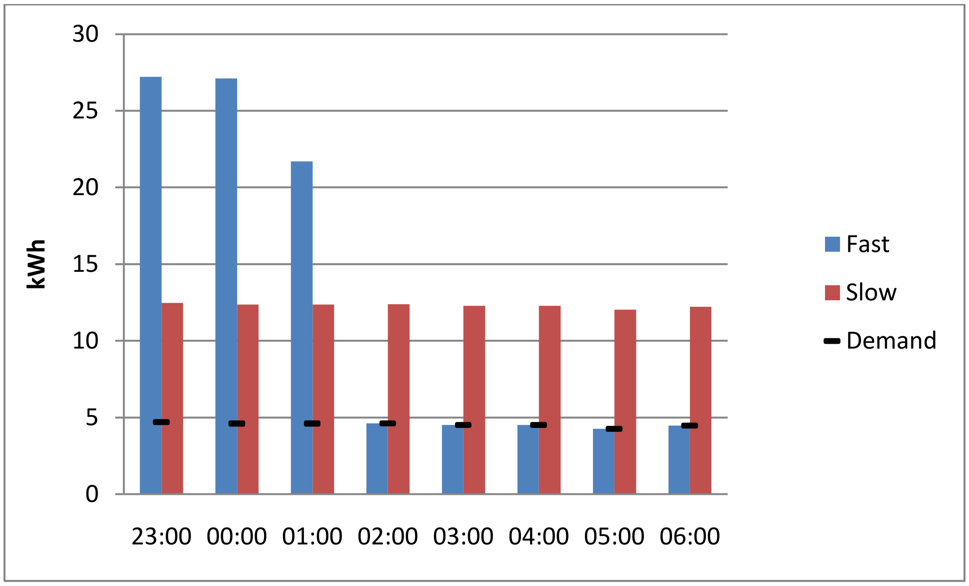

Figure 3: Example of fast- and slow-recharge rates

On the other hand, the slow-recharge ensures that the system is fully recharged by the end of hour 06:00. The hourly recharge is a constant 7.8 kWh. As with the fast-recharge, the demand is also met during this time.

The total energy required to recharge the system (62.1 kWh) and meet the demand (45.5 kWh) is the same for both the fast-recharge and the slow-recharge. However, the peak energy consumption for fast-recharge and slow-recharge are 27.2 kWh and 12.5 kWh, respectively.

3.2 Space heating with wind

Although most thermal storage systems are intended to be charged with electricity during off-peak hours, they can be charged at any time (Hughes 2009b). One of the benefits of using thermal storage systems this way is that it can reduce the amount of surplus intermittent electricity that must be accommodated in the grid. However, there is a tradeoff: as the number of systems increases, so does the need for backup energy supplies to meet the heating demand.

This problem is highlighted in Figure 4, where the thermal storage systems are allowed to fully discharge before a backup source of energy is employed. As the demand from the wind approaches the maximum available energy (about 17.4 GWh), the demand for backup increases linearly, in keeping with the increasing number of thermal storage units.

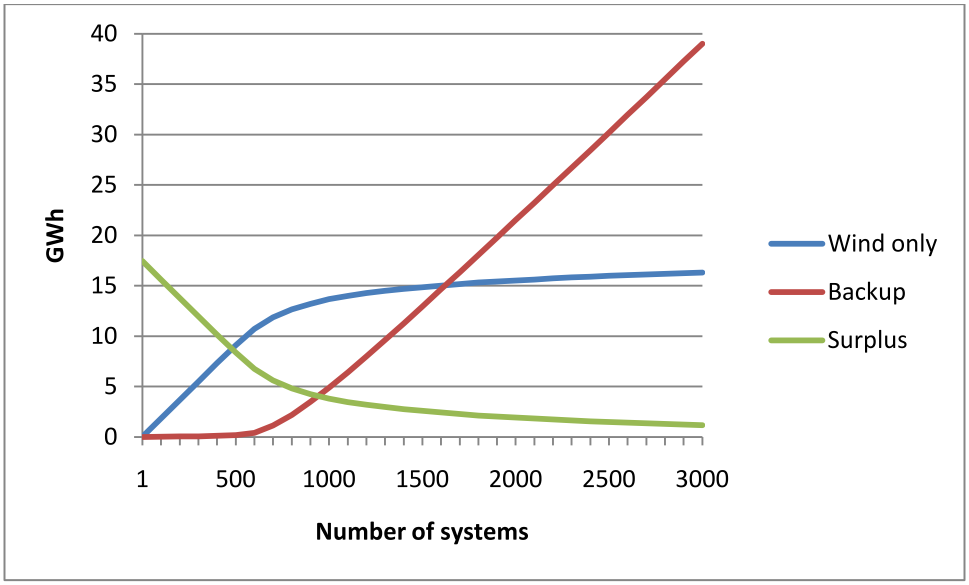

Figure 4: Increasing need for backup energy supply as the number of systems increases

4 Thermal storage with wind and off-peak backup

There are many different sources of energy that can be used to backup a thermal storage system, ranging from wood stoves to oil furnaces. However, consumers may be reluctant to accept wind-heating if the backup energy supply requires effort on the part of the consumer or is a completely different energy source. Since the thermal storage systems are already connected to the electrical system, the possibility of using electricity from non-intermittent sources to act as the backup is now considered.

4.1 Anytime backup

Once a thermal storage unit has exhausted its supply of energy, it requires a backup energy source to meet the demand and recharge the system. One approach is to meet the demand and backup whenever a thermal storage unit is exhausted. Such an approach can be troublesome since the thermal storage systems can be exhausted at any time of day, potentially adding to the system peak.

4.2 Off-peak backup

An alternative to anytime backup is to recharge the thermal storage units during specific hours of the day to avoid the hours of peak demand. By recharging during the off-peak hours, the problem of increasing the system peak by recharging during peak hours is avoided. Off-peak backup is a combination of off-peak recharging (section 3.1) and wind-electric recharging (section 3.2) consisting of four steps:

1. Attempt to meet the hourly demand from the supply of wind-electricity.
2. Apply any surplus wind-electricity to the thermal storage unit, up to the maximum allowable recharge.

3. If the hour falls into the off-peak period:
   a) Meet any remaining demand from grid-electricity
   b) Meet any remaining recharge from grid-electricity
4. Any remaining demand is met from the thermal storage unit.

In steps 1 and 2, electricity from the wind is used to meet as much of the demand and recharge as possible each hour. The demand is met first to ensure that the thermal storage unit has energy to meet future demand that occurs during periods of limited or no wind. Should the wind fail to satisfy the demand or if additional recharge is required, these can be met during the off-peak hours (step 3). Finally, in step 4, the thermal storage system meets any remaining demand; this can only occur outside the off-peak hours when the wind has failed to meet the demand.

There are two limits placed on recharging the thermal storage system: first, the maximum thermal capacity of the system as specified by the manufacturer and second, the maximum hourly recharge (obtained by dividing the maximum thermal capacity by the length of the recharge period). The thermal storage systems used in the simulations for this research had a maximum capacity of 180 kWh and a maximum allowable recharge of 22.5 kW (adapted from (Steffes n.d.)).

5 Simulations and results

Simulations were conducted using the wind and space heating data from Prince Edward Island to determine the potential benefits of using off-peak electricity (from 23:00 to 06:00, inclusive) from the grid to backup the thermal storage systems. The system configurations considered were:

- Fast thermal storage recharge.
- Slow thermal storage recharge.
- Wind-heating using off-peak electricity with slow recharge.

The total energy required by both the fast and slow recharges were, as expected, identical. The addition of wind combined with off-peak recharging results in a reduction in the total energy supplied by the grid to meet the heating requirements of the houses, as a percentage of the heating needs met from the wind. This is illustrated in Figure 5, where, for example, in the case of a single thermal storage system, the wind meets about 93 percent of the demand, whereas at 3,000 units, the wind takes care of about 26 percent of the demand. Any shortfall is met by the grid during the off-peak hours.

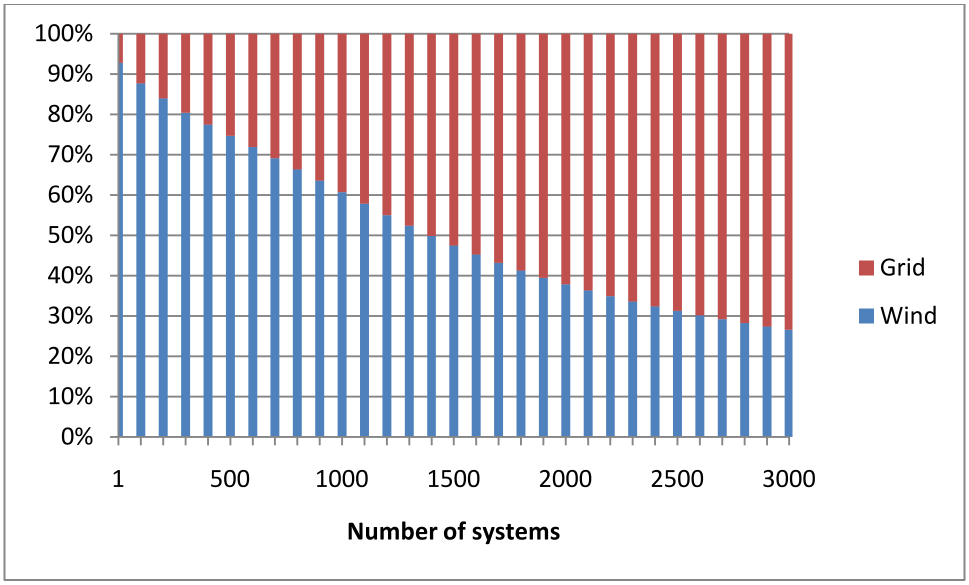

Figure 5: Percentage of wind meeting the heating demand of thermal storage units

When the thermal storage systems are charged by both the wind and the grid during the off-peak hours, the amount of wind-generated electricity being consumed by the systems is less than it is if off-peak electricity is not used for backup. Without off-peak backup, the thermal storage systems can fully discharge before requiring backup, whereas when supplied by off-peak backup, less wind is required because the system is recharged from the grid before it completely discharges. Since less wind-generated electricity is used by the thermal storage systems with off-peak backup, the amount of surplus electricity from the wind increases. The differences between wind with and without backup are shown in Figure 6.

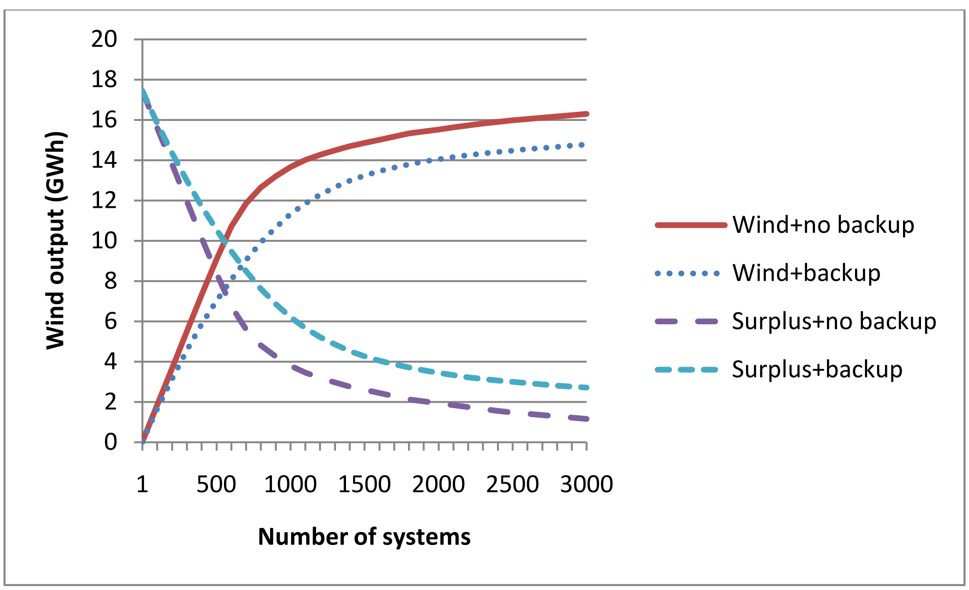

Figure 6: Wind supply and surplus with and without off-peak grid backup.

5.1 Off-peak wind forecasting

In an attempt to reduce the amount of electricity supplied to the thermal storage system by the grid during the off-peak period, the wind-heating software was modified to allow the system to "forecast" the wind during the off-peak recharging period (by inspecting the off-peak wind data). The benefits of forecasting were negligible for a number of reasons, including:

- The maximum recharge limit of a thermal storage system restricted the amount of wind-generated electricity the system could absorb during any hour. Large volumes of surplus electricity could not be used to charge a system that had reached its recharge limit.
- As the number of thermal storage systems increases, the amount of wind-generated electricity available for each system decreases, requiring the system to rely on the grid to ensure that it could recharge during the off-peak.

5.2 Effect on the overnight peak

Despite its name, a peak in demand still occurs each hour during the overnight off-peak period. The addition of thermal storage units requiring recharge would clearly add to this peak. Figure 3 showed a comparison of the effects of changing the off-peak recharge algorithm from a fast-recharge (bringing the system charge to its maximum and maintaining it until the end of the recharge period) to a slow-recharge (having a constant recharge level throughout the entire recharge period); although the total energy required was the same, the peak associated with the slow-recharge was lower. When combining wind with the slow-recharge, the peak is reduced further, as shown in Figure 7.

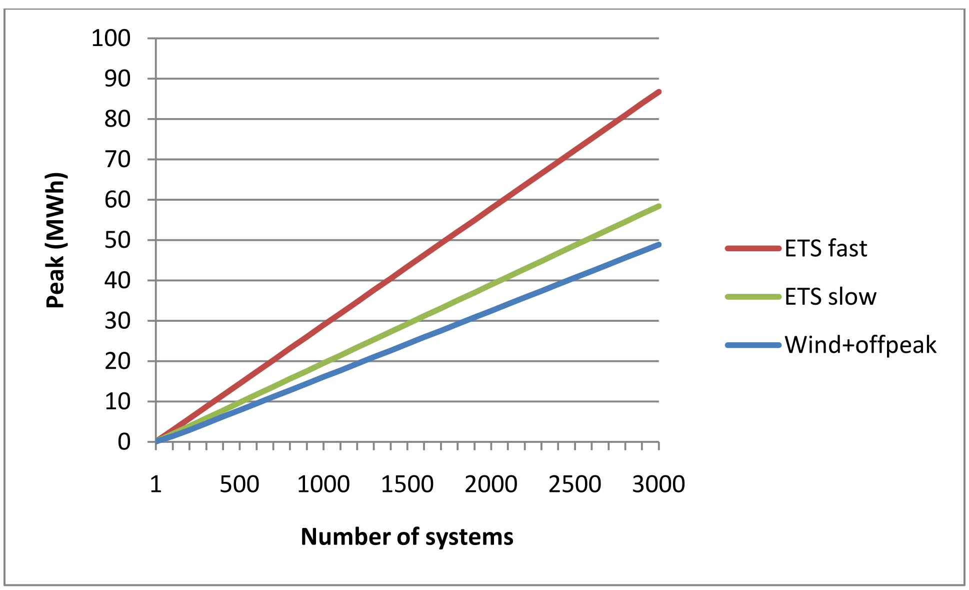

Figure 7: The effect of different recharge algorithms on the peak in off-peak supply

An example of the differences in the effects of recharging a single thermal storage system with fast-recharge, slow-recharge, and wind plus slow-recharge over a three day period is shown in Figure 8. By 07:00 on the first day, the three simulated thermal storage units were charged and the output from the wind had dropped to zero. By 23:00 on the first day, recharging of three units began, with the fast-recharge completing first and the slow-recharge finishing by 07:00 on the second day; since there was no wind, the thermal storage unit normally recharged by the wind received electricity from the grid using a slow-recharge. Wind-generated electricity resumed around 17:00 of the second day, meaning that the thermal storage system could resume charging before the off-peak recharge cycle began. By 23:00 of the second day, the thermal storage system charged by the wind was fully charged, while the other two systems resumed their recharge cycle. The availability of wind throughout the off-peak recharge period of the second and third days meant that the wind-recharged system did not require electricity from the grid. The cycle continued into the third day.

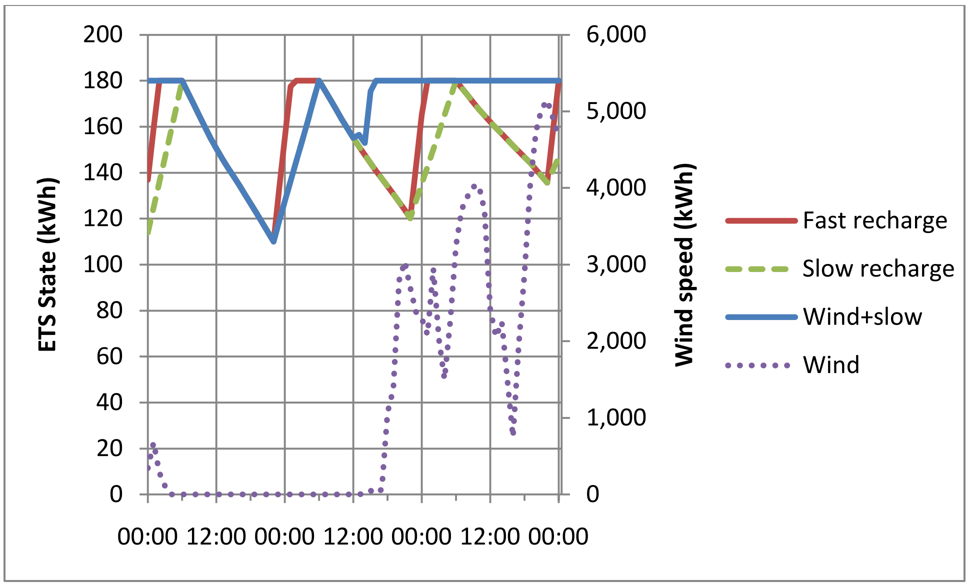

Figure 8: The state of three different thermal storage systems over a three day period

5.3 Greenhouse gas reductions

If backup energy sources are ignored, wind-generation can rightfully be considered a carbon-free source of electricity for space heating. However, even with the thermal storage systems described in this paper, there are times when some form of backup energy is required. If the electricity comes from generation facilities using coal or natural gas, there will be carbon dioxide (CO_2) emissions.

If the emissions associated with spinning reserves are ignored, the quantity of emissions depends upon the backup energy source, its associated emissions per unit energy, and the efficiency of the conversion process. For example, generating electricity from coal or natural gas at 30 percent efficiency will produce 0.984 kg CO_2/kWh and 0.596 kg CO_2/kWh, respectively (NEB 1999). As a point of comparison, burning fuel oil in a 60 percent efficient furnace produces 0.439 kg CO_2/kWh (NEB 1999).

Figure 9 shows the CO_2 emissions from using coal and natural gas to meet the electrical needs of thermal storage systems, both with and without the wind, as well as the expected emissions from a furnace burning fuel oil at 60 percent efficiency. In percentage terms, both coal and natural gas, when combined with the wind, produce 50 percent and 26 percent fewer emissions at 1,400 and 3,000 systems, respectively. However, the benefits of using wind and natural gas become apparent when compared with an inefficient fuel oil furnace: for wind and coal, the threshold is 1,100 systems (beyond which, the furnaces produce fewer emissions), while wind and natural gas always produce fewer emissions.

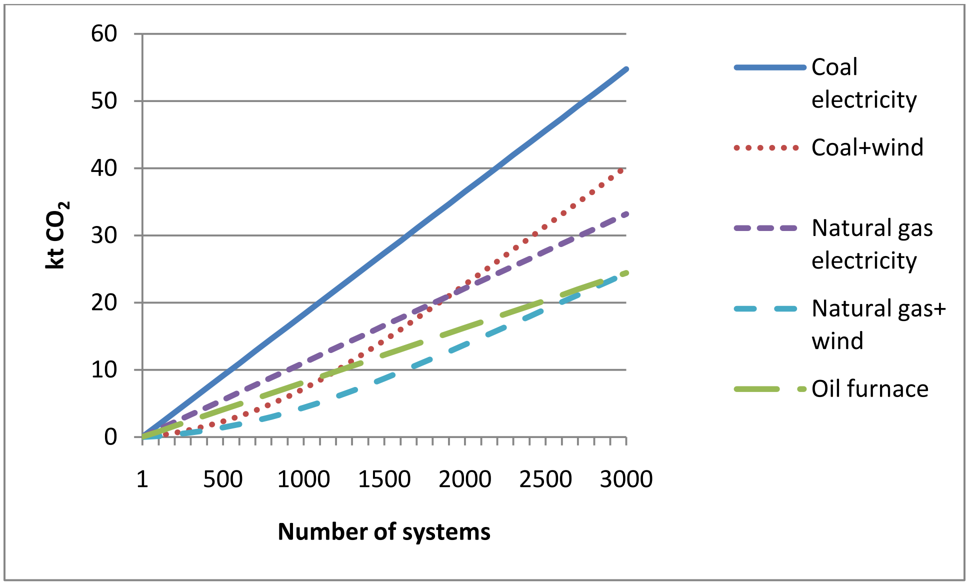

Figure 9: Greenhouse gas reductions

6 Discussion

The simulations discussed in this paper demonstrate that thermal storage systems heated with wind-generated electricity in combination with off-peak electricity, offers an alternative to other forms of space heating. The use of off-peak electricity ensures that the thermal storage systems have sufficient charge to meet periods without wind.

The simulations have highlighted a number of issues that need to be considered when implementing wind-heating with off-peak backup. For example, decreasing the number of systems to increase the percentage of heat each system can receive from the wind will result in a greater surplus of electricity from the wind. On the other hand, decreasing the percentage of heat from the wind that each system receives results in higher peaks during the off-peak and, consequently, more energy must be supplied by the grid.

Although not discussed in this paper, wind-heating with off-peak backup will require metering systems that can register supplies of wind-electricity, off-peak electricity, and electricity for non-heating applications.

Off-peak electricity has been presented as a means of backup for thermal storage systems using wind-generated electricity. An alternative view is to consider wind-generated electricity as a means of reducing the supply of off-peak electricity for thermal storage systems in jurisdictions where off-peak electricity is used for heating. In this view, wind can be used to reduce or offset the amount of electricity needed for the off-peak recharge.

7 Concluding remarks

Volatile energy markets and the need for less carbon intensive fuels is encouraging the use of large-scale wind farms for the generation of electricity; however, despite being a potentially secure and environmentally benign source of electricity, wind's intermittency is proving to be a challenge for many electricity suppliers. One approach to overcoming wind's intermittency is to match it with a load that can be made to follow the wind, such as electric thermal storage systems for space heating. In such configurations, wind-generated electricity can be used for space heating and, if sufficient surplus remains, recharging the thermal storage system. When there is a demand for heat without wind, the thermal storage system can discharge, meeting the space heating requirements. In extreme cases, when the thermal storage system is fully discharged and there is no wind, some form of backup energy source is required.

The paper has discussed the technical potential of off-peak electricity to ensure that thermal storage systems charged from the wind are able to bridge periods of insufficient wind. The simulations demonstrated that wind-heating with off-peak backup can reduce surplus electricity from the wind and greenhouse gas emissions.

Two approaches to recharging thermal storage systems have been discussed. The first, fast-recharge, brought the system to its maximum possible state in as short a period as possible (limited by the maximum hourly recharge), while the second, slow-recharge, brought the system to its maximum possible state over the entire recharge period. Although the same amount of electricity was required in both cases, the peak was lower in the slow-recharge. A further reduction in the peak was found to occur when recharging thermal storage units from the wind and using off-peak electricity for backup.

The Energy Research Group is continuing its research in wind-heating. We are in the process of developing control algorithms for electricity distribution and metering. We are also examining ways of using wind-electricity to meet all of a household's heating needs in order to reduce the supply of surplus wind-electricity to zero.

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