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Exploring the Limits of Demand Side Management

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Abstract

The current focus on energy management and conservation has led to an acknowledged need for better control of facilities and plant within both commercial and domestic buildings.

Demand Side Management (DSM) tries to reduce the peak load and change the shape of the load profile through the techniques of energy conservation, peak clipping and load shifting.

Many energy saving control systems have been attempted in commercial buildings in an attempt to manage demand for economic and environmental reasons.

This study presents the development of a load shifting algorithm for the domestic environment which will use DSM measures to save energy by optimising loads in a building to allow a best-fit arrangement for the demand profiles whilst maintaining power quality.

Two control methods are developed; the first is to remove peaks by shifting demand to a flat profile and the second is to allow a household to better take advantage of the output from small-scale renewable generation.

The algorithm will shift loads over the course of a 24-hour period as dictated by the supply conditions and the method of control selected.

The testing of the algorithm shows that an algorithm can shift loads on and off in order to match a single target value or follow the output from renewable energy generation, but the success of the match between supply and demand is dependent upon a number of factors.

It is hoped that the creation of a DSM algorithm will help solve the existing problem of supply demand matching which exists with power generation from renewable sources and help implement further use of renewable generation in the built environment.

Introduction

Energy is not an end in itself but a means to provide a number of services. Businesses and households view energy as an input, an expense of doing business or maintaining a home. In general people are less concerned with how many kilowatthours they purchase than with the services such as heat, light and appliances which electricity can provide. This relationship provides the basis of Demand Side Management (DSM).

DSM is defined as “The planning and implementation of strategies designed to encourage consumers to improve energy efficiency, reduce energy costs, change the time of usage or promote the use of a different energy source”, It is a partnership between the utility and customer with benefits to both. [1]

DSM tries to reduce the peak load and change the shape of the load profile through the techniques of energy conservation, peak clipping and load shifting. Correctly implemented, DSM can reduce energy consumption with the associated financial and environmental benefits.

Some strategies such as energy efficiency measures, education in energy use and technical advances in control can help with DSM. Of these strategies, education in energy use is the cheapest to implement, energy efficiency is often the easiest to carry out and load shifting is the most difficult to accomplish with technical, financial and social factors to overcome.

Energy efficiency is defined largely as cost-effective measures to reduce energy consumption through existing and improved technologies, as well as through sound energy use practices. The idea behind energy efficiency is quite simple - if people consume less energy, there will be less emission of greenhouse gases as the result of the burning of fossil fuels in power stations. Energy efficiency technologies and practices can therefore play a significant role in reducing the threat of global climate change. [2]

Load shifting is the process of manipulating loads to remove the problematic peaks that occur in demand profiles that aggregate across the community to give large temporal peaks. It attempts to move the demand that gives rise to these peaks to times of lower demand, or valleys, between peaks present in the demand profile.

By attempting to maintain the demand at a more or less constant level, the stress placed upon equipment and the wastage imposed upon the generating facilities by the need to maintain spinning reserve will be much reduced, leading to lower operating costs that will eventually be passed onto the consumer.

Managing the demand in the network is a good way of saving expenditure on infrastructure, as the cost of this type of scheme is considerably less than reinforcing or upgrading existing infrastructure.[3]

The technique of load shifting can be utilised once other more cost effective measures have been addressed and implemented, such as the range of energy efficiency measures.

There is only a relatively small amount of historical data concerning load shifting. Most of the information that is available concerns the effects of bringing metering with two rates, a high and low rate, into the domestic electricity market.

The literature review of the area showed that any load shifting that occurred was generally quite crude. The loads were shifted from their normal period of operation during the high rate period to a time to the lower rate period by the use of time switches in order to take advantage of lower overnight tariffs.

Energy expenditure is rising inexorably with an increased amount of disposable income per household allowing more labour saving and leisure appliances to be purchased and operated. Managing this option would seem to be the sensible option, as it will hopefully allow better operation of generation plant and propagate a degree of energy awareness through the population.

With the steady increase in price of all types of fuel over the past few years, there has been an increased focus on the entire area of energy management.

DSM has been embraced as a way forward as it is seen as a way to increase profitability by the saving of needless expense.

Project Aim

The research problem that emerged from the literature review was that currently there are limited options to automate the manipulation and temporal shifting of loads. Therefore the aim of this research is to investigate load shifting as a demand side management technique and to create an algorithm to manage and optimise loads in a building or estate to allow a best-fit arrangement for the demand profiles.

In order to fully understand the multiple inputs to this program there will need to be an investigation into the range of loads and their associated control actions on the demand side and the range of supply options currently available. The supply options will cover both the standard grid connection and output from renewable generation.

The algorithm will take into account the priorities for the loads connected to the network and will have to work within these limitations.
The effect of shifting loads will then be assessed with an impact matrix consisting of economic, technical and social metrics.

The occupants will provisionally set the appliance use, with the actual use being determined by the supply option an method of control. If generation from renewable sources is chosen, the supply will be determined by the environmental conditions present.
The loads, once scheduled by the occupants, will then compare the building or estate's supply and demand and reschedule the loads according to their priority of use priorities and the load characteristics of the appliances.

The automation of the DSM algorithm should allow building services personnel more time to attend to other matters of concern in the day-to-day management of the building or estate.

In this study the DSM algorithm has been designed for use with electrical loads, although it could also be adapted for use with thermal loads.

With the creation of a DSM algorithm, it is hoped that it will help solve the existing problem of supply demand matching which exists with power generation from renewable source and help implement further use of renewable generation in the built environment. Increased use of renewable generation in this context can only help the diversity and hence security of supply.

Chapter 1

Managing Energy Use in Buildings

This focus on energy management and conservation has led to an acknowledged need for better control of facilities and plant within both commercial and domestic buildings. The push for more gains in energy efficiency has been well publicised through various Government agencies such as the Carbon Trust for commercial customers and the Energy Saving Trust for the domestic market. [4] [5]

For both types of buildings, the message that is broadcast is that the buildings occupants should take a step and evaluate all of the processes and operations that take place in the building. Once the processes are streamlined, then technological solutions should be sought to reduce energy consumption.

This approach is relatively simple for a single household, but obviously becomes more complex as the buildings size and number of occupants increases. [6]

Building Energy Management Systems (BEMS)

For large buildings the main problem has been the feedback of information about the building’s state to the building services personnel. However with the introduction of Building Energy Management Systems (BEMS) and peripheral components, the availability of data has been solved. With a BEMS installed the conditions in the building are recorded by sensors distributed throughout building being sent back to a central processing unit, via intelligent outstations. [7]

However, in some cases the BEMS are not used to their fullest capacity and are generally only used to monitor and control the plant within the building in order to deliver the optimum services and conditions for the occupants. With additional instrumentation and control strategies, the performance of the plant can be tailored to provide the desired conditions for the occupants whilst consuming the minimum amount of energy possible. [8] [9]

A function of BEMS that is often underused is the ability to maintain the current electrical demand below that of the site's maximum capacity. When the demand approaches the capacity limit, loads will be switched off or shed so that the demand is reduced and the total demand remains under an agreed limit.

The penalty for the actual demand rising above the site's agreed capacity could be an invoice for the entire month at the peak capacity rate. The supply capacity may also remain at the higher limit for a fixed period, with the customer being required to pay for supply capacity far above their normal average requirements. [10] [11]

If load shifting were to be carried out in these situations, reducing peaks in demand, economies will not be realised through lower overall use, but through the ability to remain within measured tariff bands and by the shifted loads taking advantage of cheaper electricity at off peak periods. [9]

If load shifting were pursued for the maximum energy savings possible, loads would be required to be shifted on or turned on at times of cheap or surplus electricity and shifted off or turned off, when the cost of electricity rises.

The control system will need to be planned and executed well so that there will be no disruption in the services provided to the buildings occupants. If an engineer on emergency callout were required, the callout fees could negate any savings made from using this control scheme.

On a larger scale the arrangement where appliances are used when power is available and allowing them to idle when it is not, would be an ideal solution for islanded grids or grids that depend very heavily upon renewable generation.

Grids that are particularly reliant on renewable generation should already have a degree of reserve back up as electricity generation from renewable sources is neither a constant nor a one hundred percent reliable source of power. The generator must operate when the conditions are favourable because in general it is not cost effective to provide large energy stores for small renewable energy schemes, so their output varies with the available resource.

However with the equipment sited in a suitable location, it should be exposed to optimum conditions and contribute a reasonably constant amount of electricity or heat towards the total demand. [12]

Managing Microgrids

At the moment there are only a few truly islanded grids in the UK, with most of the more remote communities relying on a grid connection to supplement any power requirements. Examples of islanded networks in the UK include Shetland and Lundy.

On Shetland the relatively high and constant wind speeds are used to generate electricity from wind turbines. However the wind turbines only supply approximately seven percent of the island's electricity, with the rest being generated in the Lerwick power station from imported oil and gas.

Lundy is has a much smaller population than Shetland and turned to renewable energy to avoid the rising costs of imported fuel for the diesel generators that used to supply the islands electricity. Data from a study in 1984 stated that wind supplied 88% of the total network demand. [13] [14]

Power Quality

A primary concern in managing power generation in Microgrids is the quality of the electricity supplied to the consumer. The standard supply voltage in domestic single-phase 50 Hz installations in the UK has been 230 V AC (rms) since 1 January 1995 and harmonises the UK with the standardised supply voltage across Europe. [15] [16]

The Electricity Supply Regulations state that electricity should be supplied at 230 V +10%/−6% which equates to between 216.2 V and 253 V. Given that electricity supply has been standardised, it follows that the range of consumer electronics avaliable in the high street have been designed to operate within these limits. If the electricity supply deviatiates from these limits malfunction or damage of the appliances will result. [17]

Power quality itself is defined as voltage and frequency stability, together with absence of various forms of electrical noise, such as flicker or harmonic distortion. [18]

Frequency stability mainly depends on the inertia of the grid, the load fluctuations and the responsiveness of both the control system and the prime mover to these changing power flows. The more rapidly the prime mover can respond to changes in power flow that occur, the better the regulation of the frequency in the power system.

The sudden connection of a large amount of reactive or resistive loads to a network will have the effect of causing the prime mover to work harder to match the demand and the grid frequency will decrease.

If the prime mover cannot respond fast enough or the load is too large to be supplied by the prime mover, the frequency and amplitude of the generated electricity will collapse.

If a large load is suddenly removed, the prime mover will have to react and throttle back its actions. In the period that it takes to do so, both the frequency and voltage of the supply will rise fractionally.

So it can be seen that conventional power plants not only provide power to be distributed and consumed but an inherent part of their function is to manage the power quality of the grid.

In the UK with a few exceptions, coal fired power stations tend to be slightly older than the rest of the power stations on the grid. Their overheads are towards the lower end of the range of generating technology and this is reflected in their low price per kWh. The lower price coupled with the older plant means that these power stations have a particularly flexible power output to the grid.

Since the base load is usually dominated by the output from nuclear power stations and combined cycle gas turbines the thermal plant has to operate in a flexible manner to help balance any large increases in demand. Typically the degree of readiness with which they can connect and supply power to the grid will vary from a relatively instantaneous connection up to 30 minutes. Thermal plant will often operate in a load following or frequency response mode. This

involves running at reduced output in order to provide spare capacity. It will then constantly alter its output, according to the needs of the grid.
Developments in load prediction have reduced, but not entirely eliminated the need for thermal power stations to be kept operating as hot spinning reserve. This involves running the power station at a reduced output, in order to keep its generation capacity in reserve for balancing large surges in demand. This spinning reserve is a significant expense to the power utilities as often fuel must be burned or potential power sales lost to maintain the reserve.
Once the immediate priority of keeping the grid stable is dealt with, the reserve may be replaced for longer-term power production by a more economical type of reserve that has a longer start-up time. [19]

With the focus on renewable energy there have been a number of wind turbines that have been connected to the grid in recent years. There are some installed at key sites in the UK, with more applications awaiting approval. Although modern wind turbines are designed to smooth out some of the peaks in their generation, changing power flows are a characteristic of electricity supplied by wind turbines. With the direct connection to the grid, the wind turbines must be considered along with the rest of the generation plant as a tool to maintain the grid inertia.
With their rapidly fluctuating power flows, there may be occasions when the output from the turbine exceeds consumer load, which has the effect of making the grid voltage rise and move outside the required limits stated in the Electricity Supply Regulations.
The turbines would then be treated the same as any plant in a load following role and would be disconnected from the grid. However this situation is far from ideal because wind energy is being shed unnecessarily and there are problems associated with turbines being connected and disconnected to the grid. [20]

These changes in the frequency become apparent in islanded grids with high levels of wind power penetration, where the prime mover is usually in the form of diesel generators. Initially the generator will run faster to satisfy the demand and consume more fuel in the process. However it may be unable to respond to a large power fluctuation and additional buffers, such as energy storage, may be required to balance the system. [21]

It is possible for appliances that form part of the base load of a building, to be used as an energy storage tool to help control power quality.
If the frequency starts to increase, moving outside set tolerance bands, more loads can be shifted on which will act as an energy buffer absorbing excess power and helping the supply frequency to be restored to the desired level.
The opposite will happen when the renewable generating conditions are not as favourable. In these conditions, loads will be shifted off and the reduction in load will place less stress on the generating equipment and allow the grid frequency to recover.
If a control program were devised to manage the loads supplied by mixture of renewable, conventional diesel generators and grid electricity, loads would essentially be able to track the output of the renewable generation and efficiently provide services to the community.

Load Control Systems

The concepts of Load Shifting and Load Shedding have been used before to protect supply stability. Load shedding on a national scale functions as a shock absorber for the electricity industry. Load shedding gives the ability to call upon thousands of megawatts at relatively short notice and provides a virtual energy storage system. This virtual storage system can be used to balance unexpected peaks in demand, provide a degree of flexibility and help prevent the capital expenditure for the upgrading of power generation and distribution network.

Load Shifting

Load shifting is an arrangement when appliances or processes that consume a large amount of power are moved or shifted from a period when there is a high power demand to one when the aggregate demand is lower, in an attempt to reduce peak demand. This mechanism is generally brought into effect by Time of Use (TOU) tariffs in both the industrial and domestic sectors.

[22] For domestic customers, it is well worth shifting loads to off peak periods where possible, because TOU tariffs can offer a cost reduction of up to 50 percent per kWh over standard day rates. [23] [24]

It is relatively easy to take advantage of cheaper electricity by shifting non-essential loads to an off peak period. A simple time switch that is placed between the appliance and the main electricity supply will allow access to the cheaper off peak electricity.

For industrial use, time switch or programmers are relatively simple cost effective pieces of equipment and many domestic appliances are now designed with integral delay timers located on the main control panel along with all of the other appliance controls.

However the practical outcome from many domestic users using time switches for this purpose can create another set of problems. All of the displaced loads can create another surge in demand later in the evening, shortly after the time when the off peak rate comes into effect. [25]

Load Shedding

Load shedding is a more defensive application than load shifting, as there is often no provision for the timely rescheduling of the load. The main objective of this type of policy is to keep demand below a critical threshold. For interruptible and direct load control to happen in real time, remote switching needs to be put in place.

Voluntary load shedding can also be encouraged and rewarded where the onus is put on the customer to keep below a certain demand threshold. To reinforce this, penalties can be charged if consumption rises above an agreed level.

Currently due to the expense and complications of installing direct load control, only the larger customers are approached to participate in this scheme. These customers tend to be industrial in nature, although large commercial facilities may also be approached. To be eligible significant amounts of load in the region of 1000kW should be available to be controlled remotely. This load shedding will by necessity have an effect within a short period of time, anywhere between ten minutes to a few hours.

However this type of system is far from perfect with feedback from participants highlighting room for improvement. Some of these include; a disparity between contractual and actual operating conditions, employee discomfort during loads cycling and relatively low incentives to participate in the scheme.

The objective of load shedding is to keep demand below a critical threshold, so that it can ensure the stability of the power supply. It is normally carried out by monitoring the frequency of the supply voltage and disconnecting the load when the frequency starts to dip. Conventional load shedding makes use of different relays that react at different frequency thresholds so that predefined load groups are given different priorities of use.

In a system that makes use of a controlled load shedding system, the loads that are present can be given a priority weighting that can be defined according to the requirements of the site at that time. Depending on the range of loads on the site this list of priorities could be relatively fluid and can be updated according to the actual activities on the site.

When the aggregate demand reduces, the selected plant that has been shed can be programmed to come back online, but often is not. When the plant is started and stopped in this manner, problems may ensue with the efficiency of the plant and maintenance requirements could also increase.[26] [27]

Frequency Response

Frequency Response takes the load shedding control strategy further. By monitoring the frequency of the grid in addition to power utility control parameters, individual loads could time their operation in response to system load, resulting in a reduction in peak load. The selected loads would need to operate a duty cycle and possess a degree of inertia in their operation, so that the disruption from the switching would not be apparent.

The ability to measure grid frequency from any power outlet connected to the grid means that it is possible to design controllers for electrical appliances that can detect frequency imbalances as they occur in real time.

Frequency response appliances would react to frequency imbalance and similar to load shedding, when the frequency decreases they will switch off , reducing the load on the grid and helping to restore the balance.

However, unlike load shedding, when the frequency increases, the appliances will switch on, absorbing excess generating capacity. Obviously, the controller must also ensure that at no point does the appliance stray out of its acceptable operating range.

The aggregate effect of millions of such devices across the country acting together would be similar to a large, fast-reacting power plant. This technology could also be an efficient and cost effective route to implement more renewable generation onto the grid by creating a reasonably predictable distributed storage capacity. [28]

Chapter 2

Current Energy Use in Domestic Buildings and Emerging Trends

Traditionally load shedding techniques have been applied to larger buildings which contain a variety of loads. The economics of scale mean that this route could make far greater returns for the time and effort invested. However there is also need to address the steadily increasing energy use in the UK domestic sector. (Figure 2.1)

People have become complacent with respect to energy use because of the low energy prices that have been a feature of the energy market since the mid 1990's. The proportion of household expenditure on energy has decreased by approximately half, from 6.3% in 1970 to 2.9% in 2001.[29]
However, recent increases following years of relatively cheap electricity have forced customers to become more aware of their energy habits. (Figure 2.2)
The rise in domestic sector energy use can be attributed to both the number of households growing steadily and the relative reduction in costs of luxury appliances, leading to an increase in the general standard of living.
(Figure 2.3)
It is recognized that availability to electricity is a key indicator of standard of living and it can be readily measured at the household level in the community. [30] In the UK the number of households is increasing at a faster rate than the population, which would suggest that the number of occupants per household have been decreasing.

Despite the rise in domestic sector energy use, average household energy use in 2001 was marginally below the average household energy use in 1970. This is an indication that there are other factors influencing energy use and efficiency within the housing stock.

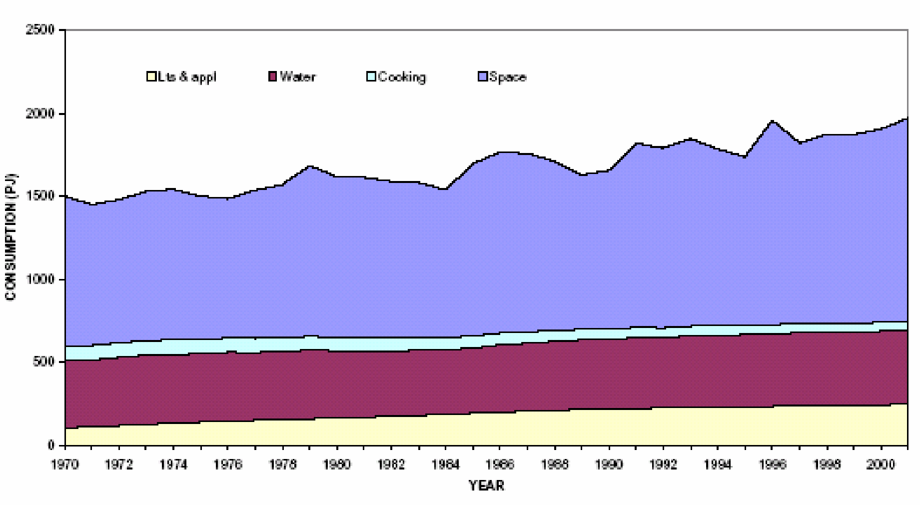


Figure 2.1 - Domestic energy consumption by end use [29]

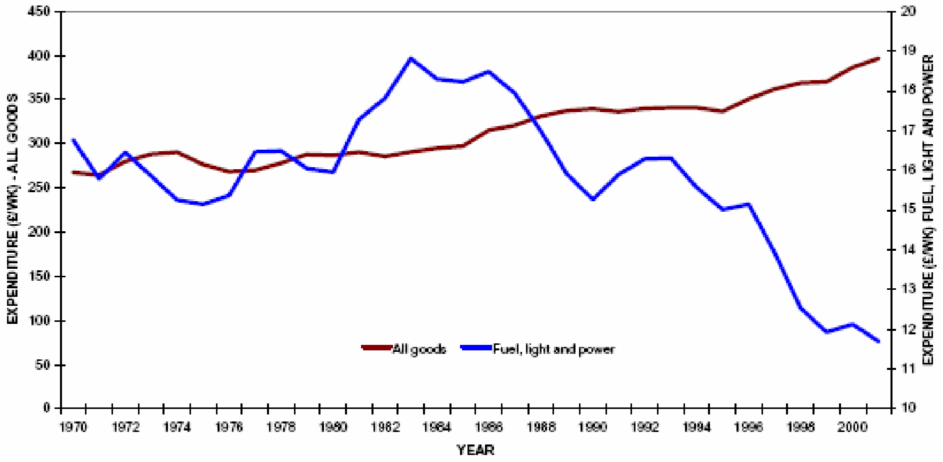


Figure 2.2 - Average Weekly expenditure on all goods and on fuel light and power at 2001 prices [29]

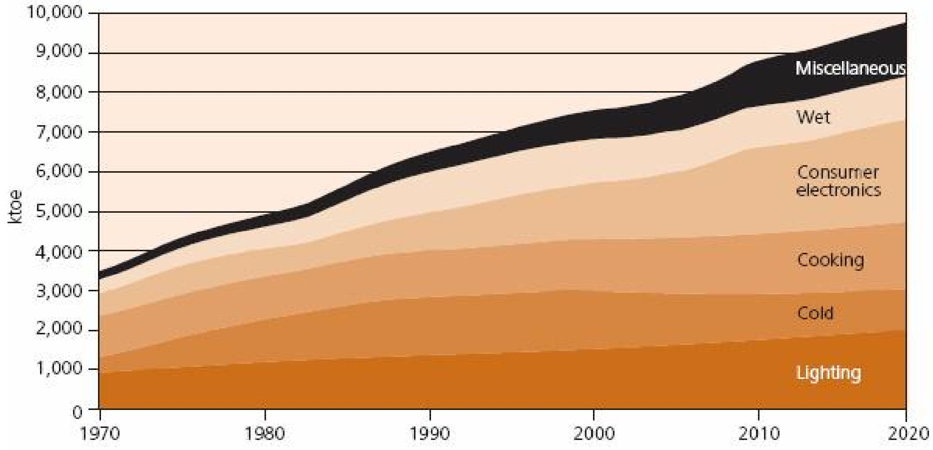


Figure 2.3 - Past and projected use of electricity by appliance [31]

Improvements in Housing

The housing stock across the country has been changing over the past decades, with the incorporation of some features that help to lower energy demand for the residents. Construction methods in the post-war period have changed so that more use is made of energy-saving features such as cavity walls. Building regulations were brought into force in 1965 to ensure that there are minimum standards of construction in the built environment.

Energy conservation was not mentioned in the 1965 Building Regulations but part of these new regulations was the requirement for roofs and walls to have a degree of insulation. In 1961 Parker Morris suggested minimum standards for modern homes and the Building Regulations then ensured that they were applied to new residential housing from 1965 and applied to social housing from 1969. [32]

The construction industry has been further directed by changes in the Building Standards. Each subsequent issue of these regulations has moved towards ever more efficient housing with the U value requirement of roofs being reduced over this period. An additional U value requirement for ground floor construction was introduced in 1990.

The 2006 editions of Approved Document L1A /L1B have significantly revised the provisions for the conservation of fuel and power in dwellings. Apart from increasing the standards of thermal insulation, there is now greater emphasis on the use of energy efficient heating systems, control systems, lighting systems.

All new dwellings without full building plans approved by 6 April must comply with the new Part L building regulations from 6 April 2006, which increase the energy efficiency of new housing by 20 per cent from April and by 40 per cent since 2002. [33] [34]

Strict adherence to the regulations coupled with the reduction of the construction time for residential housing has led to the changing of some construction methods from the traditional entirely brick built houses to lighter timber framed constructions.

Over this period there has also been a change in the demographic of home ownership, with the expansion of towns and more single people moving away from the family home, to their own place of residence. This change in the residential sector has brought with it a changing trend in energy use within the home.

The major behavioural influences on residential energy consumption include changes in family size, income, average length of daily occupancy, age of household members, thermostat settings and the number of employed members of household.

Physical changes that have affected residential energy consumption include the size of the household and floor space available, the age of the building and types of fuel supplied to the property. These behavioural and physical effects have an effect on energy consumption and must be taken into account when comparing energy-intensity indicators over this period.

An example of this would be the increase in floor space per household member, which in turn has increased the demand for space heating, air conditioning and lighting. The increasing availability of floor space has also raised the popularity of convenience appliances such as dishwashers in the home.

A demographic change that is affecting energy consumption is the growing number of single member households. Although differences are present across the range of household sizes, they are more marked when the household size is smaller. These households with fewer members will often acquire the same number and size of major appliances and as a result will consume more energy per household member than a larger household. There is also a minimum level of energy consumption that is required to run a property that is independent of household size.

Single persons, with a more flexible lifestyle, may spend less time at home than traditional families, which can result in a more intense energy demand over a smaller number of hours.

Over the whole population, disposable income per capita has also increased. While single-member and two-person households may spend less time at home, thereby using less energy, the larger households may increase residential energy consumption with purchases of equipment such as computers, expansive home entertainment systems and swimming pools. [35] [36]

The now widely accepted theory of Global Warming and the increasingly erratic and powerful weather patterns that it brings is exacerbating energy and electricity use at the domestic level. People counter the effects of extremes in weather by increasing the use of air-conditioning and heating to maintain comfort levels within their home.

Previously in Britain, air-conditioning was seldom used because it was generally felt that there was no need and it did not warrant the expense of an installation. However, it has recently become cheaper and more commonplace, with the placing of advertisements in the media during the summer months offering domestic air conditioning units for self-installation by DIY enthusiasts.

Load Shifting in a Domestic Setting

Set against the background of rising domestic energy use, it seems a natural progression to attempt to bring proven methods of industrial load control into the domestic environment. There are already BEMS based on the EIM Instabus Standard that are modular and are designed for use in many different applications including domestic setting.

Although the Instabus system can be expensive to install for smaller houses, they would be viable in a luxury home or estate. In this setting they could achieve savings through better control of the services in the buildings or buildings by the integration of traditionally independent systems such as lighting, fire and security systems.

The Instabus allows different components to communicate with each other on one system, so components often have more than one function. For example, detection sensors used for the security system could also be used to switch off lights automatically when rooms are vacated. [37] [38] [39]

Many of the electrical appliances found in the average household could be used under a frequency response system, so that they are switched on when the frequency rises and are switched off when frequency dips.

The technology needed to bring frequency response into a domestic setting is small and relatively inexpensive. If legislation were used to ensure that the grid frequency tracking technology was built into every appliance that can operate under frequency response, the technology would become even less expensive.

A review of appliances that could make use of this technology is covered later in Electrical Loads, Cold Appliances. [40]

Advocates of a frequency response system have pursued the idea of making it mandatory and on July 21st 2006, the Dynamic Demand Appliances Act 2006 became law. This legislation requires the Government to publish a report outlining the technology's potential for saving CO_2 emissions and if appropriate, what steps Government should take to promote the technology within the next 12 months. The Act states that this should include the creation of both a standard for dynamic demand appliances and an incentive mechanism to reward manufacturers who meet this standard. [41]

The Dynamic Demand Appliances Act 2006 is further supported by the Climate Change and Sustainable Development Bill 2005, which seeks to set targets for the use of microgeneration and remove the existing barriers that prevent greater uptake of these technologies. [42]

System Requirements and Load Prioritisation

If frequency response control systems are used, they need to be practical so that people realise the benefits of the technology and encourage others to use it too. Frequency Response Control (FRC) should enhance the occupants' lives through lower tariffs, or have no impact at all, rather than a system that they have to do battle with every day.

Not all domestic loads will be well suited to running under frequency response. Loads that have a high priority of use or require constant electricity to function clearly cannot operate in this manner. The loads that would be the most suitable will ideally have a duty cycle and a degree of capacitance or storage in the service that they provide. Good examples of these types of appliances would be freezers, storage heaters and water heating. For example, some types of freezers are so well insulated that even if the power is disconnected, their contents can remain in a frozen state for up to 24hours. In a similar way to industrial systems, the loads that are used within the dwelling would be assigned different priorities for their use by the occupant. FRC will take advantage of these different priorities in the shedding process by setting the conditions for disconnection at different grid frequencies. The higher the priority the occupant places on the appliance, the greater the difference between the ideal 50Hz and the disconnection frequency setting.

Applications for Load Shifting Algorithm

National or regional legislation is now encouraging the incorporation of renewables into buildings. Other systems commissioned by Local Authorities (LA), require a high score within the relevant BREEAM System of sustainability ratings. As a result of standards being raised in this manner, people are becoming more aware of environmental and energy issues.
In domestic developments, current building regulations can be passed with careful planning and use of insulation within the construction. However, good SAP, NHER and BRE EcoHomes ratings will be assured if there are contributions from renewable energy to the daily operation of the dwelling. This situation is likely to continue in the future by the proposals for the Code For Sustainable Homes. [43] [44] [45] [46] [47]

Set against the background of the above legislation and assessment systems, it is obvious that renewables will be increasingly incorporated into buildings in the future. FRC can facilitate this process and allow the power contribution from microgeneration to be used in the most effective manner.
Some of the sustainable elements that are designed into new build projects are also being incorporated into existing housing stock. Unfortunately the more visible solutions are often the elements that are incorporated first as people seek to demonstrate to others their commitment to the environment, whilst other solutions that save more energy but are hidden from view, such as cavity wall insulation, can be overlooked.

Small-scale renewables, especially energy generated from wind, have captured the imagination of the public and installations of small wind turbines supplying individual buildings or small estates are becoming more common. This can be seen as a positive outcome but in order to demonstrate benefits from installations of small-scale renewables, the power produced from them has to be managed so that it is effective in order to convince others to follow suit.

It does not matter how generation from renewable sources becomes more mainstream, only that it does so and produce real benefits once installed. When it becomes a recognized solution to a problem, its place in the domestic market will be established.

FRC could find use in community scale projects to the domestic setting, by making the output from renewable generation more practical. When this occurs, a primary goal of reducing the amount of power drawn from the grid and increased efficiency by reducing grid distribution losses will be achieved.[20]

Chapter 3

How to Encourage Demand Side Management?

There are several components that can help with DSM, such as energy efficiency measures, education in energy use and technical advances in control. Of these strategies, energy efficiency is often the easiest to carry out successfully. It is this area that has attracted the most attention as countries across Europe start to implement DSM.

The other ways of raising people's awareness of their energy use and involving them in the larger scheme of DSM is publicity campaigns, funding from the government in the form of grants and finance schemes. Energy efficient appliances initially cost more, although this will be more than recovered over the lifetime of the appliance. Despite the increased purchase costs, it can be seen that there has been a growth in the market share of A rated appliances. [48] (Figure 3.1)

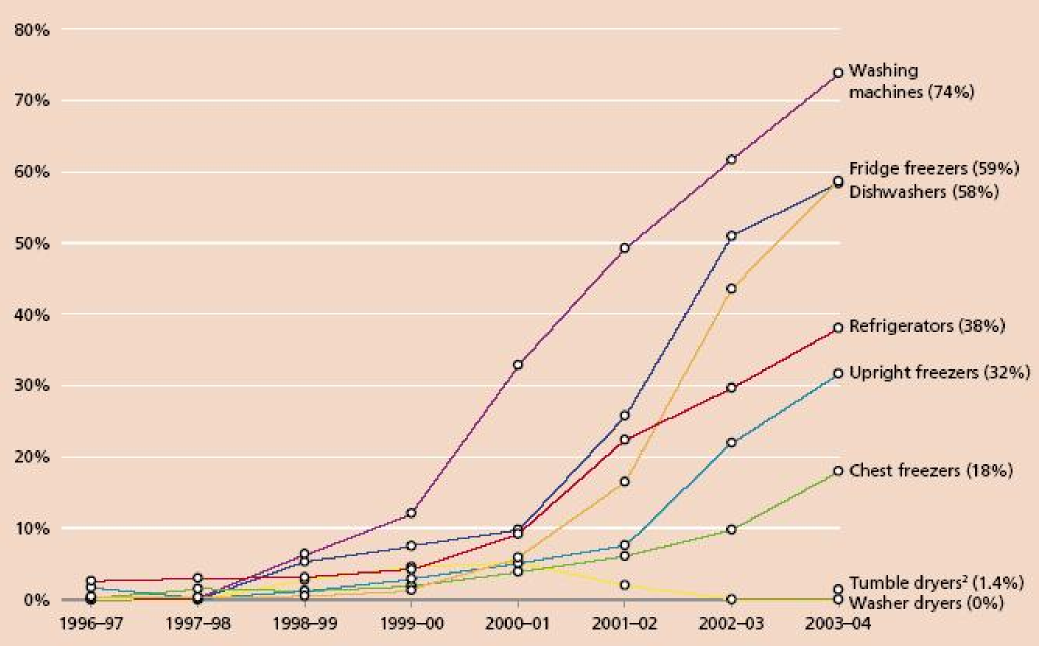


Figure 3.1 - Growth and market share of A rated appliance sales [28]

Grants from the Government can be used to offset this higher cost and allow a higher degree of uptake of these appliances. Examples of these types of schemes would be the rebate on condensing boilers and the option to purchase compact fluorescent light bulbs at reduced prices from the Energy Saving Trust (EST).[49] [50]

A key provision in the energy-efficiency process is that more information must be passed on to the consumer. It is then hoped that the consumer will then digest this information and make the necessary changes to their appliances and the way that they use energy in their own home. Better labelling of appliances that are energy efficient is an important part of this communication, which has been mandatory for larger kitchen appliances in the EU since 1996. The message that is broadcast for reducing energy use, is that energy efficiency will save the consumer money as well as helping to save the environment. It is hoped that the combination of these two messages will have the greatest effect by appealing to the majority of the population.[51]

A different approach to DSM would be for utilities to provide demand information for each household more regularly throughout the year. Once they receive accurate energy usage, the emphasis will then be upon the householder to reduce their energy use and payments.

With some encouragement there can be a reduction in energy use, but more demanding national or European standards are necessary to force manufacturers to create more efficient appliances and thus drive appliance energy requirements down.

Once these changes have transferred to production lines and energy efficient appliances have a larger share of the market, the price of these appliances should remain consistently low, by the principle of economy of scale.

A combination of the above, voluntary standards and the raising of consumers awareness should drive this process along so that energy demand from individual appliances will be on the decline and help contribute towards a national policy of DSM. [29]

Barriers to Implementation and Current Action

Domestic

It is generally perceived that energy bills are a fixed or unchangeable outlay and it is difficult to focus people's attention towards measures that may only lower bills by a small amount per year. As a result the general public are quite reluctant to become involved in load shifting schemes at the domestic level. The low levels of participation are also likely to be caused by the additional complexity of entering into such programs.[52] [53]

For tenants, there are other factors influencing what could be achieved with regard to energy efficiency. Most tenants are unlikely to have apartments furnished with the latest energy efficiency appliances, especially those towards the lower end of the rental market. In most situations the landlord has only to supply working facilities, not pay the bills. In this situation capital expenditure is likely to be the primary factor in his choice of appliances. Other tenants may have a fixed energy payment, regardless of the amount of electricity used, which is unlikely to encourage the efficient use of electrical appliances.

Business

The concern over energy expenditure is not reaching high enough up the corporate ladder to positions that allocate resources to tackle the problem. If resources are allocated for this area, the measures should be publicised as the company can often benefit from a green image.

However energy costs are often a small overhead and can more than be offset by economies in other areas. If a business is in financial difficulties, it is unlikely that there will be the capital necessary to invest in measures that have a medium to long payback period. Instead, in order to reduce outgoings, it is more likely that they would favour making some employees redundant.

In order to create more awareness and to motivate people into becoming more willing to act to reduce their energy costs, the relative costs have to rise and become more of a concern. [57]

Tariffs

Electricity is a commodity that is difficult and expensive to store on a large scale. As a result, the generation and demand has to be in balance across the network at all times. Regulating authorities have been put in place to protect the consumer from the price fluctuations that accompany this sometimes volatile market.

There are various tariffs that are employed with the intention of making people aware of their energy use through their energy bills.

Flat tariffs

The traditional flat tariff, with its single rate per kWh, does not provide any incentive for the consumer to shift load away from times of high supply prices.

Time of Use Pricing (TOU)

TOU tariffs operate with a high or standard rate per kWh during peak hours and a low rate per kWh during off peak hours. They can offer a financial incentive to move demand from times of high prices to low prices, which can be readily accessed by a change in consumer behaviour or timers programmed to switch on appliances once the tariff has moved from the higher rate to the reduced night rate.

TOU tariffs also offer non energy rewards to households, such as the intrinsic satisfaction of "doing the correct thing", similar to recycling. However TOU prices are not ideal because they are designed for use during regular generation and supply conditions and do not take into account the inherent uncertainty associated with supply and distribution of electricity. [23] [24] [54]

Dynamic Pricing

Dynamic pricing refers to any tariff that takes into account the risks associated with the supply and distribution of electricity. In general these schemes build upon TOU tariffs by using the standard daily times for TOU, but also incorporating an additional daily rating scheme. The daily rating will be composed of at least two rates, but often use three. There will be more of the lower day tariffs and the number reduces up to the highest day tariff. The day when the highest tariff is in effect will not be known in advance but will be announced the day before it takes effect.

Dynamic tariffs are not often used because it is generally believed that customers will not switch from accepted TOU rates to a system with dynamic pricing incorporating tariffs that vary over time. It is also felt that the benefits from the introduction of such a scheme would not outweigh the costs of implementing such a scheme.

An example of this type of scheme in operation is EDF's Tempo scheme that has been in operation since 1996. In this scheme the year consists of 300 blue days when the tariff is cheapest, 43 white and 22 red when the tariff is most expensive. The colour of the days is selected by EDF according to temperature, with the rate per kWh rising during colder weather. [55] [56]

Real Time Pricing

This tariff argues that electricity sales should be removed from the current system where regulating authorities cushion the consumer from the often vastly different tariffs that are paid by the utilities and those that are charged to the customer. [53]

Freed from this mechanism, consumers will see the full range of electricity prices, from the very cheap to extremely expensive rates per kWh. However the very much cheaper off peak electricity will more than compensate for times when there is the occasional spike in price. If customers were given feedback information concerning the current price of electricity, then there would be more emphasis on individuals managing demand of their own accord. It is hoped that by peak-time electricity becoming prohibitively expensive, some of the characteristic peaks will be removed from the daily demand profile, by the displacement of all non-essential loads from periods of high demand.[57]

Once customers are more accustomed to a flexible approach towards energy use, more sophisticated contracts could be negotiated with the utility, with selected loads being shed during periods of high demand and prices.

If there were a reasonable proportion of companies or individuals subscribing to this scheme, the overall effect on electricity prices and network stability could be considerable.

There are examples of load shedding in the USA where direct load control has shed residential air conditioning loads to reduce peak demand. The plan was promoted with an incentive of reduced bill payments. There have been reports of up to 200MW reductions within a few minutes of a request from the utility.[58] [59]

Chapter 4

Equipment Loads Within Buildings

Within a building there will be a variety of loads on the system that can be split into two categories, electrical loads and thermal loads. The electrical load will be met from a grid connection or from renewable sources. The thermal load can once again be met by heat generated from renewable sources but will more likely be derived from the burning of fossil fuels.

Electrical loads are generally shifted to take advantage of cheaper off peak tariffs that occur outside the periods of peak demand during the day. They can also be shifted to keep the total demand from a site below a tariff threshold. Thermal loads can be a product of electrical loads and would then follow the same patterns. If the thermal load is generated from fossil fuels and only requires a minimal electrical load then it will be best if the thermal load is scheduled to meet its demand requirements.

Electrical Loads

When electrical networks are designed they have a safety factor incorporated into their design and the network can be over specified as a result. For these calculations the rated or nameplate load of all the appliances or equipment will be used. However the nameplate load will be the absolute maximum load that the appliance will use. This will be drawn infrequently, for example only when starting up and shutting down.

There is also the assumption that for a worst-case scenario, all of the plant will be used together. This is not often the case as there will be a diversity factor for each piece of equipment.

The demands on appliances and plant are governed by the needs of the users. Daily routines tend towards two peak times of use in a general demand profile, especially in a domestic setting. Naturally the utilities attempt to flatten the demand profile by matching the peak electricity tariffs with these two peaks in electricity use. [29]

The whole economics of a situation have to be considered to see if it is an effective solution to the problem. Although there can be some financial benefits from using electricity at a cheaper rate, constant cycling of certain loads can cause excessive wear on certain types of equipment. This wear can lower the overall performance of the system and it may require more regular maintenance as a result. The cost of spare parts and equipment downtime need to be evaluated along with the fiscal savings from load manipulation. Shifting demand will only be possible if there is an element of capacitance or storage within the process, such as the duty cycle of a piece of equipment, a pause in the process or the creation of an intermediate product such as heat or electrical energy. [57]

Often applications that consume energy as part of a base load of a building are not considered as part of a load shifting strategy but there should be further analysis of these areas to determine the extent to which they can participate.

A selection of the main types of appliances that are typically encountered in a domestic setting will be considered in this study. These include:

- **Cold appliances**, refrigerator, freezer cabinets and air conditioning
- **Wet appliances**, washing and drying appliances
- **Brown appliances**, audio visual leisure appliances
- **Cooking appliances**, lighting,
- **Heating**, electric storage heaters
- **Domestic hot water**, immersion hot water systems.

Cold Appliances

In the UK ownership of refrigerators and refrigerators with a small freezer compartment is declining. They have been replaced with combined fridge-freezers with a separate freezer compartment, often both combined in a upright unit. Almost 90% of households owned some form of frozen space in 1994. The average ownership of any cold appliance is assumed to saturate at 1.5 per household in 2020.

The refrigerator is the single biggest power consumer in many households with a typical refrigerator using between 600 and 900 kWh per year, although an efficient one will use somewhat less. Refrigerators and freezers typically make up over 20% of total domestic electricity consumption

The cold appliances use energy to drive the refrigerant circuit and remove heat from the cabinet. The appliances' energy use will be determined by the rate of heat transfer through the walls into the unit and the efficiency of the refrigerant circuit. For most categories of refrigerator and freezer, improving insulation is more cost effective than improving the efficiency of the refrigerator circuit.

More or higher quality insulation and seals are the key to improving the efficiency of operation. The efficiency of the refrigerant circuit can be improved by increasing the use of better temperature control systems, variable speed drives and condenser fans to improve the rate of heat transfer. Large compressors and evaporators with a smaller temperature change for the refrigerant could also increase the efficiency of the appliance. [35 60]

Refrigerators

Although the cold appliances are good candidates for load shifting, within this group the refrigerators should be treated with the most care because a small change in temperature could ruin the contents of the refrigerator. However, even these appliances can be shifted on and off for short periods. The duration of these periods will vary between appliances and will be dependant on the insulation present around the cabinet on individual models and the delicate nature of the fridge contents. In each case, the control that can be delivered will be dependent on sensitivity of the sensors within the cold compartment.

Fridges operate by cooling down the contents over the course of the day. However when the door is opened regularly during the day, the contents will rarely reach the lower set point when the power would be turned off. The main part of the cooling will be achieved over the night period when the cold compartment space is kept sealed. This lowering of the contents temperature should then sustain it over the following day.

If refrigerators are used for load shifting, their use must not conflict with domestic guidance, or statutory limits set out under Health and Safety law. Health and Safety law states that it is good practise to maintain the food in refrigerators at 2-5°C, although the upper permissible legal limit is 8°C.
In the worst case, it is a possibility that the daytime cooling will only maintain the food under the upper legal temperature limit. It seems that there is only a small margin before the temperature rises to a level where there could be spoiling of the food within the appliance.

There have been experimental cooling schemes carried out in warehouses where the contents have been ‘overcooled’ with cheap overnight energy so that the cool or cold temperatures will sustain the contents through the following day.
There were some problems that were encountered as the temperature was pushed towards the lower end of the cooling plants range. As the goods became cooler, so more energy was required to chill them further. By using this technique it seems that more energy is required to achieve the same task but the load is displaced to a time of low demand. The economics of this approach were approximately the same, but the benefits of cheaper off peak electricity were offset by the larger amounts required for the task.[61]
If refrigerators are to be included in a load-shifting scheme, it could only be for short periods at any one time. It would also be advisable to connect an alarm to a sensor in the fridge that would operate when the temperature approached critical levels. [62] [63]

Freezers
Freezers may also operate in the same way as fridges if the door is opened regularly. However, they generally are used less frequently and as a result will be an ideal appliance to be included in a load-shifting scheme.
It is good practice to maintain freezers at -18 to -15°C for meat and dairy produce, although the upper permissible legal limit is -12°C. Ice cream normally has a separate freezer that should be maintained at -12°C. In the event of a power outage, the food in the freezer will survive unspoiled for a period of approximately 24 hours provided the door is kept closed. There are

some freezers currently available for food storage that will operate at temperatures down to -40°C.

With these properties it can be seen that freezers have more capacity to be shifted than fridges. If the appliances that can freeze food to a much lower temperature are included, there will be a large opportunity to shift loads, although once again the installation of an over temperature alarm would be advisable.

Fridge-Freezers

Fridge-freezers will operate as a combination of the two individual appliances. The appliance can be switched off or shifted for short to medium periods. This will be dependant on the insulation present around the cabinet. It is likely that the shifting capacity of a fridge freezer will follow that of a refrigerator rather than a freezer, with caution being exercised to protect the contents of the refrigerated compartment.

Air Conditioners

Air Conditioning (AC) is difficult to shift because its impact on the user. However I believe that AC could be shifted by a very small amount of time, with a limited social impact. There may be a reduction in the efficiency of the system with this rapid cycling and the lifetime of the unit may be shortened as a result. Other plant such as ice generation and storage could be used to help shift demand from peak hours and to store energy in the form of ice.

A possible solution to reduce energy expenditure on AC would be to use a Ground Source Heat Pump (GSHP). If the GSHP were operated in reverse, it would extract the heat from the building and transfer it to the ground. The energy used in this type of system will be far lower than an AC unit. A GSHP used in this way will only be able to supply low level cooling, although this may be enough in some cases. [64]

In larger buildings, the BEMS can change the temperature set point of the building outside the occupied hours resulting in a two-fold reduction in AC. If the internal set point is raised on a warm day, then the increase in internal temperature will not only reduce the energy required for cooling, the building will not absorb as much heat from the environment due to the reduction in temperature differential between the ambient temperature and set point temperature.

To prepare for the following day's occupation the BEMS could employ a night time cooling program, prior to returning to the original set point. The night time cooling, coupled with a slightly higher set point from the previous day will mean that the amount of heat absorbed into the fabric of the building will be reduced, so it will require less energy to cool the following day. [8]

Wet Appliances

The EU Group for Efficient Appliances (GEA) groups washing machines, condensing dryers, tumble dryers, combination machines and dishwashers together to form the Wet Appliances. [29]

Washing Machines

Over the past 25 years average wash temperatures have declined by almost 10 ºC, with energy savings being made by not heating the water to near boiling point. Maintaining the same washing performance at lower temperatures has been allowed by the introduction of better designed machines that give a higher washing performance, coupled with better detergents and advances in textile technology.

The cycle as a whole can be shifted over the course of the day, although it would be recommended that once the cycle had started, it should be allowed to finish. If the power is started and stopped repeatedly during the cycle, the quality of the wash will be very much reduced. The amount of shifting possible obviously depends on when the washing is required.

The demand profile of washing machines has many peaks at the beginning and end of the cycle when it will be heating water or spinning the load. This could ultimately cause problems by generating large fluctuations in demand if many of these loads were scheduled to operate in the same period.

There are possible technical implications for the newer machines that have electronic controls. For these machines, the removal of power could be disastrous because it would be likely to reset the electronic programmer.

This type of load shifting would be more applicable to those machines with mechanical controllers, although back up power sources may be developed for those machines with electronic controllers, if the market dictated that this was necessary.

There may also be a deterioration of the laundry in the machine if it were left unattended in the appliance for long periods of time, either pre or post wash.

Washer-Dryers

They will have similar characteristics to washing machines, as it is likely that they will only be used for that purpose. If they are used in a combined mode there may be a deterioration of the laundry with the formation of mildew.

Tumble Dryers

The use of tumble dryers varies widely, with some households using them as little as once per month while others use them to dry every load that they wash. However, for households owning both appliances, it has been estimated that the tumble dryer is used for 60% of the washing machine loads. The rest of the loads are allowed to dry naturally, whether inside or outside the house. The length of drying time for each tumble dryer load is dependent on the moisture content of the clothing, which has been declining as a result of increasing spin speeds in washing machines. [29]

The two main types of tumble dryers are controlled by a timer or by humidity sensors. The timer-controlled dryer will operate for a preset duration, with the risk of over drying the load and wasting energy in the process. The dryer with the humidity sensor is obviously more efficient because it will finish the cycle when the load is dry, avoiding using excess electricity and causing unnecessary expense.

Other types of tumble dryers are available for those who are medium to heavy users of this appliance. Gas fired dryers, although more expensive to buy and install, are cheaper to operate and dry clothes faster. They also have lower greenhouse gas emissions due to the majority of the energy being supplied from gas.

Heat pump dryers work in a slightly different way to conventional tumble dryers. Conventional tumble dryers operate by heating air, then passing it over the laundry and exhausting the hot air and moisture to the atmosphere. Heat pump dryers dehumidify the hot air after it is passed over the laundry and then recirculate the hot air back into the drum, saving the expense and energy needed to heating a new volume of air.

The drying cycle as a whole can be shifted over the course of the day, although it once started it should be allowed to run until completion. If the cycle is interrupted, it is likely that there will be similar quality and technical problems to those encountered when load shifting washing machines.

Dishwashers

A relatively common assumption is that washing dishes by hand saves hot water. However, washing dishes by hand several times a day could be more expensive than operating some dishwashers with a full load and if used properly, an efficient dishwasher can consume less energy than washing dishes by hand.

As with washing machines, the majority of energy required to run a dishwasher is used to heat the water. However most modern dishwashers come equipped with a range of programs, which should help save energy and water by tailoring the dishwasher's performance to the household’s needs.

The dishwasher cycle can be shifted although once started it should be allowed to run until completion. It is likely that there will be similar quality and technical problems to those encountered when load shifting washing machines and tumble dryers if the cycle is interrupted.[65]

Brown Appliances

The term ‘Brown Appliances or Goods’ covers the range of equipment that is the audio/video market. It is constantly expanding as products with new functions are developed and quickly make those currently available obsolete. When a new appliance is brought into a household the older version will move down the ownership chain and be distributed elsewhere in the house so that the ownership of these appliances will often greater than one per household. In general there seems to be little energy awareness amongst consumers, with the purchasing decisions being driven by the functions and price of the appliances.

Technical advances in electronics and display media have reduced the national power load from television use. The average demand of televisions whilst in use is now approximately 70W, compared to 250W in the 1970's.

Standby Consumption

Although present in some other appliance groups, the standby function is most prevalent in the brown appliances. Standby can be defined as a mode of operation where energy is consumed even when the appliance is not being used for its primary designed purpose.

Being able to switch on the appliance using the remote control may be a necessity for some groups of the population, but for most it is a matter of convenience rather than function. There are a growing number of appliances that cluster around the television and require power to be supplied permanently as they receive software updates overnight.[66]

With more appliances using this function, the small amount of energy required for standby mode is aggregating across the country to become a large percentage of base-load electricity consumption. In1994 it was estimated that standby accounted for approximately 5TWh pa in the UK, which is the equivalent output of one large power station. It appears that the brown appliances are going to be a significant and rising component of domestic electricity consumption with the projected emissions from set-top boxes is predicted to peak at over 0.5 Mt of carbon dioxide emissions in 2012 if there is no intervention in the form of legislation.[67]

The power consumed during standby is independent of the TV screen size and features. Since the introduction of remote controls in the late 1970s, there has been a small drop in standby power demand from around 10W to 8W in 1994. From this it seems unlikely that manufacturers will design appliances with lower power consumption in standby mode unless they are forced to do so

One of the trends that has developed over the past few years is the move towards larger screens and better audio signals to accompany the video image. Often the audio signal will be processed through a separate amplifier connected to a range of speakers to give a professional surround sound effect. This move towards home cinema packages will only increase the power demand from the brown appliances.

Within this market plasma televisions are rated as the ultimate in video entertainment. It is unfortunate then that they have an energy demand of approximately 3 to 4 times that of a standard CRT television.

The introduction of LCD televisions has been a move in the right direction, however until they become cheaper and more available to the average consumer, it is unlikely that they will change this upward trend of power consumption.[29]

Televisions

In line with other European countries, despite the reduction in average household, the average number of television viewing hours per household in the UK has been rising steadily. It has risen from 4.5 hours per day in 1970 to just over 6 hours per day in 1994 and with the spread of satellite and cable services, is projected to rise to 7.5 hours by 2020.

Increasing viewing hours obviously increases demand from the units themselves but also with people in the dwelling for a longer period, there is an associated rise in energy use from other appliances, such as kettles and lighting. [68]

Computers

Computer use has become much more widespread with an increasing number of households possessing a computer. Faster and cheaper connections to the Internet are becoming available resulting in an increase in computer use across the nation. As of May 2005, 55 per cent of households in Great Britain could access the Internet from home. [68]

Computers have a power rating which is the maximum power demand for that appliance. However this rating will only reached when all of the components are in use and contributing towards the power demand of the appliance. The ratio of demand during normal use to that of the nameplate rating, can often be lower by as much as a factor of ten. [69]

The brown appliances and home electronics sector cannot be shifted once they are in use. There may be some power saving to be made from shifting a number of appliances from standby to off, but they cannot be used in a load shifting scheme. If the network were completely islanded it would be likely that and computers it would be one of the last appliances to be shed and would be connected via an uninterruptible power supply to allow it to be shut down safely should there be an outage.

Lighting

Lighting is a high priority load and cannot be load shifted. However it is another area where there is a great energy saving potential to be made. These savings are likely to be accessed by promoting energy efficiency policies rather than the large-scale uptake of load shifting. By reducing the load to as low as possible with a review of the lighting demand, replacing older incandescent lamps and the magnetic ballasts in fluorescent fixtures, lightings contribution towards the daily demand would be a fraction of other appliances or activities.

Especially lighting and to a lesser degree entertainment, are unusual because they are areas where enforced reduction in demand does not encourage people to make up for time spent without. For example, the public would not feel that it was necessary to turn on extra lights to make up for lighting services being cut earlier in the day. Entertainment follows this example too, although there is a wealth of pre-recorded media available in different formats that can be viewed at any time of day. [57] [70]

Thermal Loads

Circulation Pumps

Pumps are used in a large number of both domestic and industrial settings to circulate a heat-transfer medium through a heating system that comprises the following elements: a heater, a circulation pump, piping and heat-emitters.

In a domestic setting, pumps are typically used in central heating systems but they also find use in number of renewable technologies such as solar water heating and ground source heat pumps. In some exemplar energy efficient housing or estates there will be a number of the above technologies and it may not be unusual to find three or four pumps per dwelling.

The pumps are controlled by the central heating boiler and are switched on or off over a 24-hour period depending on the heat demand of the user. Other factors that can affect the operation and efficiency of the pump are, the status of safety checks built into the boiler, the control requirements on the plumbed heat transfer circuit and the heat transfer medium itself.

The pumps energy consumption will depend on its hours of operation and the matching of the pump’s rating to the job in hand. External factors such as climate, ventilation and the building type will affect when the central heating system and hence pump is switched on.

If a pump is sized to cope with the maximum flow through a system, but rarely experiences flow of this magnitude, the pump could be replaced one that could operate as a variable speed drive.

Variable Speed Drives (VSD) operate by varying the frequency of the power supplied to the drive. Their benefit comes from the cubic relationship between power and speed where Power consumed is directly proportional to Speed.

The only disadvantage of installing a VSD is that on the few occasions that they do operate at their rated output, they will have a slightly increased running cost.

There will be limited opportunity to shift these loads, as the pumps action will be integral to a central heating system that generally has a high priority of use. However in some cases the systems, of which they are a component, can be scheduled to times of when off peak tariffs are in operation. [71]

A system where water is heated, then stored is a good candidate for load shifting due to the heat capacity characteristics of water. If a hot water tank is of a sufficient size and correctly insulated, then it will be able to maintain the water temperature for a number of hours.

Immersion Heaters

Immersion heaters are an ideal load to be included in a load shifting scheme. The system consists of an electrical resistive load that generates heat, which is then transferred to a container of water. The resistive element has simple on/off control by a thermostat and timer to enable loads to be switched on during off peak tariffs.

Immersion heaters are substantial loads, often in the region of 3kW. When the immersion water heater operates it will do so at the nameplate rating. For the appliance to be used efficiently, the reservoir should be well insulated and heated up to the required temperature during the off peak period. The reservoir will be sized to be able to supply hot water to the average household for the rest of the day, although it may have to be switched on later in the evening if there is a large demand for hot water. Immersion heaters are an expensive way to supply constant hot water throughout the day and will not be suitable for all applications.[72]

Storage heaters

This is a similar type of load to the immersion heater, with an electrical resistive load surrounded by a dense medium. The controls and characteristics of the loads are also similar which means that it is another excellent candidate to be included in a load shifting scheme. The flexibility of the system will be dependant on the insulation surrounding the storage compartment of the heater. With more insulation, the system will be able maintain its heat for a longer period of time and hence make the system more flexible.

Once again, the degree to which the load can be shifted will also depend upon the central heating requirements. If a constant high temp is required, then it may not be possible to shift the load.

Despite good insulation around the storage compartment, storage heaters tend to heat the room when charging due to heat being lost to the room through the outer case.

Some utilities design special tariffs that are specific to this type of load. By encouraging customers to subscribe to a cheaper tariff the customers give control of their heating over to the utility who then operate their storage heaters remotely as part of a load management scheme. [73]

Electric Showers

There is little scope for the shifting of electric showers. Electric showers consist of an electrical resistive load and a pump that operates for the duration of the shower. They are sizeable loads in the region of 10kW, but are seldom operated for long periods of time.

Their use is harder to predict and as one of their main features is that hot water is available on demand, the social impact would be unacceptable should they be included in a load shifting scheme.

Cooking appliances

The major electric cooking appliances such as hobs, ovens, grills, kettles and microwaves together account for over 90% of all electricity consumption by cooking appliances.

A number of trends need to be taken into account when analysing electricity consumption by cooking appliances. In addition to changes in ownership and efficiency over the past decade there have been changes in the way food is prepared and the type of fuel used for its preparation.

Social Trends

There are many separate social trends affecting cooking, but most of these cannot be quantified in energy terms. The structure of the household is changing with a rise in one-person households who are more likely to eat food

outside the home or foods that have been precooked and only a small amount of reheating.
With this tendency towards individual dwellings, there is also is a tendency towards smaller appliances with more than one function in order to economise on space and financial outlay. These smaller appliances may not function as effectively as dedicated large appliances in all modes and could compromise energy efficiency within the kitchen.[74]

There is obviously scope for an information campaign to raise awareness of the issues of energy efficiency in the kitchen. However, the advice that would be handed out may be misconstrued as patronising or another intrusive campaign by the ‘nanny state’.

The standard oven that was considered for this study was a pressed steel compartment with insulation surrounding the cooking compartment. The compartment is accessed via a door on the front of the appliance. Some appliances may have an exhaust at the rear, depending upon fuel type. The temperature is regulated by the supply of the either gas or electricity.

Almost all of the electricity used in cooking is used to provide heat, so any potential to improve energy consumption is associated with reducing heat loss or reducing the thermal mass of the appliance.
The addition of food into the oven and the frequent opening of the door of the oven will exacerbate heat loss. The efficiency of the oven is also likely to deteriorate over time as seals deteriorate and allow draughts to replace heated air with ambient air. Dirt also increases radiative heat loss by changing the surface finish from being smooth and shiny, to one that is matt and rough in texture. [75]
The current drawn by an electric oven starting up from cold is one of the larger loads experienced in a domestic setting. The profile of the demand for the cooking process is not constant either with a large demand at the start when warming up, then as the thermostat controls the temperature the cycling of power being applied to the elements can clearly be seen as spikes in the profile.

Due to its thermal inertia the oven can be used as part of the load shifting scheme. However it can only be shifted for a small period at a time before the social impact of will become untenable through mealtimes being delayed and food being ruined. There are also health and safety issues surrounding the heating and cooling of ovens that are cooking food for human consumption.

Hobs

Hobs come in various forms, for different fuels and provide a hot surface on which to heat the contents of pots and pans. The efficiency of cooking in the home can vary widely and can often depend upon the equipment used. For example if an older pot with a distorted bottom surface is used on an electric hob, the heat flow into the pot will be reduced and up to 50% more energy may be needed.

It can be seen that both the pan and the hob have a role to play in increasing efficiency because the hob to pan contact and the amount of energy radiated needs to be increased whilst there needs to be a reduction in the amount of heat reflected or reradiated from the pan. [76]

Due to their component parts electric hobs tend to be energy intensive. It is unfortunate that hobs cannot be load shifted due to the social impact this would have. [71]

Kettles

Kettles have a similar construction to immersion heaters and operate in a similar manner. Both appliances make use of electrical resistive loads to generate heat and then transfer this heat to a body of water. The kettle is of a much smaller scale and allows the water to boil, switching off automatically once it has done so. The main issue with kettle use is that they have a high nameplate load and they operate at this rated load at all times during use. They are used frequently during the day and for a typical period of 3-5 minutes.

Users expect a fast response from a kettle and usually time its use to coincide with breaks from activities or scheduled breaks in television programming. For this appliance, users expectation is high and it will not be possible to shift these loads even for a short period.

Chapter 5

Algorithm Development

The aim of the algorithm was create an algorithm that would enable a building to take advantage of renewable generation. The fundamental part of this program was to examine how the loads were scheduled in a 24-hour period. The algorithm was designed to have the ability to shift loads as a function of current demand, in a step-by-step manner and avoid attempting to move loads after they had occurred, as is often the case when observing scheduled loads in a 24-hour period.

This could allow the program to be used as a module within a BEMS that could ultimately control loads from a central point, if the BEMS was fed real time data from the outstations distributed throughout the building.

A simplified diagram of the structure of the Algorithm is shown in Figure 5.1. The algorithm has been designed to be as generic as possible, with respect to the loads, so the loads could be related to either a thermal or electrical demand. However for this study, only electrical loads have been entered into the algorithm.

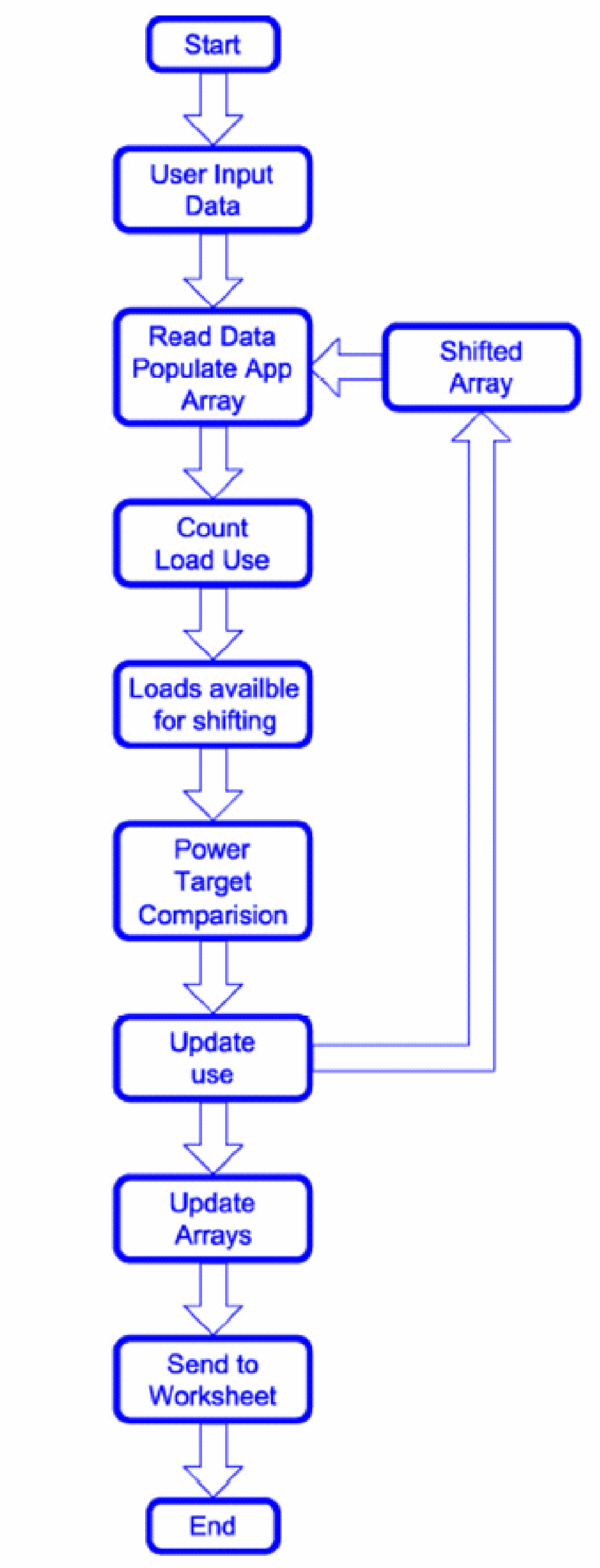


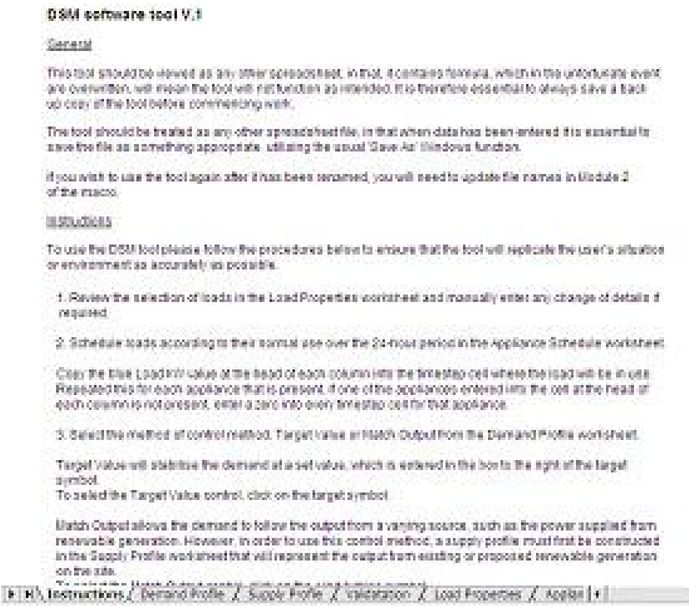
Figure 5.1 – A simplified diagram of the algorithm structure

Design of the Interface

The design of the interface was a relatively simple task with information being placed on the main page, with the load and scheduling data on the sheets that followed. The individual sheets and a description of their contents are as follows:

Instructions

Step by step instructions on how to operate the load shifting evaluation tool. (Figure 5.2)



DSM software tool V.1

General

This tool should be viewed as any other spreadsheet, in that, it contains formula, which in the unfortunate event are overwritten, will mean the tool will not function as intended. It is therefore essential to always save a back up copy of the tool before commencing work.

The tool should be treated as any other spreadsheet file, in that when data has been entered it is essential to save the file as something appropriate, utilising the usual 'Save As' Windows function.

If you wish to use the tool again after it has been renamed, you will need to update file names in Module 2 of the macro.

Instructions

To use the DSM tool please follow the procedures below to ensure that the tool will replicate the user's situation or environment as accurately as possible.

1. Review the selection of loads in the Load Properties worksheet and manually enter any change of details if required.

2. Schedule loads according to their normal use over the 24-hour period in the Appliance Schedule worksheet.

Copy the blue Load kW value at the head of each column into the timestep cell where the load will be in use. Repeated this for each appliance that is present. If one of the appliances entered into the cell at the head of each column is not present, enter a zero into every timestep cell for that appliance.

3. Select the method of control method, Target Value or Match Output from the Demand Profile worksheet.

Target Value will stabilise the demand at a set value, which is entered in the box to the right of the target symbol.
To select the Target Value control, click on the target symbol.

Match Output allows the demand to follow the output from a varying source, such as the power supplied from renewable generation. However, in order to use this control method, a supply profile must first be constructed in the Supply Profile worksheet that will represent the output from existing or proposed renewable generation on the site.

Figure 5.2 – Instructions for DSM tool

Demand Profile

This is used as the main sheet of the tool. It has an overview of the demand profile, with a visual representation of the demand before and after load shifting has occurred.

The tool has two control options that are accessed from this sheet, Target Value and Match Output.

Target Value seeks to stabilise the demand at a set value, which is entered in the box to the right of the target symbol. To select the Target Value control, click on the target symbol.

Match Output allows the demand to follow the output from a varying source, such as the power supplied from renewable generation. In order to use this control method a supply profile must first be entered via the Supply Profile worksheet. To select the Match Output control, click on the wind turbine symbol.

The main button used to start the load shifting algorithm is located midway down the left hand side of the sheet.

There is a reset button at the bottom of this sheet on the left hand side that resets the Shifted Array to equal the Scheduled Array. The arrays should be reset prior to starting the main algorithm. (Figure 5.3)

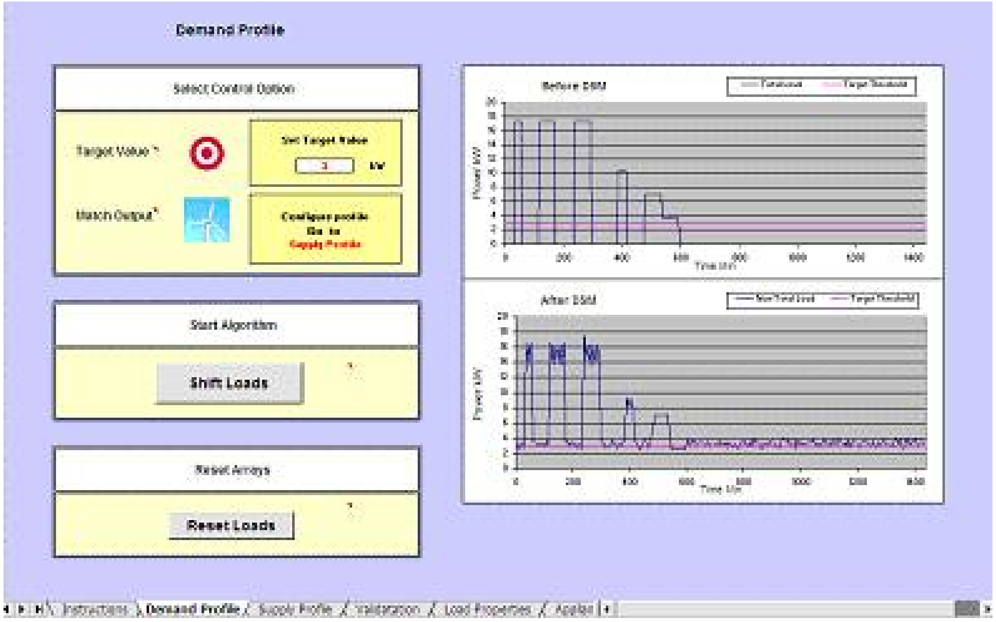


Figure 5.3 – Demand Profile worksheet

Supply Profile

This worksheet contains the data necessary to simulate a renewable supply comprising of electricity generated from wind turbine and solar photovoltaic (PV) panels.

The wind data has been taken from a larger installation and has been reduced to an output per kW of the turbine. Although this approach allows an approximate output from any size turbine to be input into the software, it will not be accurate for sizing purposes due to the relationship between the size and output of a wind turbine. This study solely focuses on matching a demand profile to a supply profile, which required a method of creating a modular supply profile.

The solar photovoltaic panel data was generated from ESP-r and has been calculated for a 1m^2 photovoltaic panel. Data has been provided for both a sunny day and a cloudy day in July. Two profiles are provided because the shape of the supply profile was considered particularly important.

The size and make up of the renewable input is decided upon and by scaling up the values of the modular outputs of the reference data a supply profile is generated. [5 77]

(Figure 5.4)

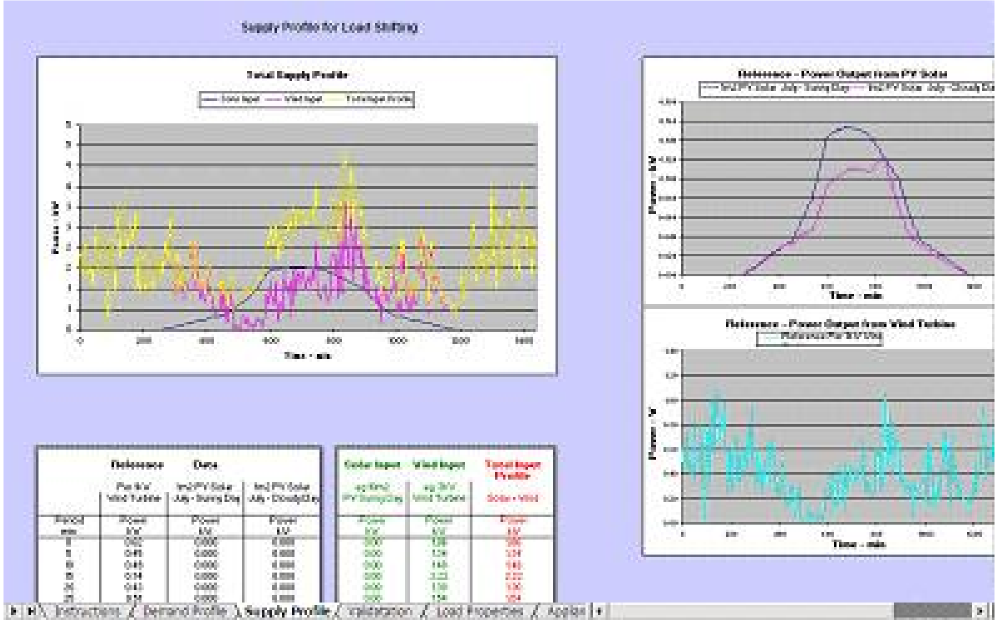


Figure 5.4 – Supply Profile worksheet

Validation

This sheet displays the metrics covering the match between supply and demand profiles. At the top left hand side of the sheet small before and after graphs are displayed as a reminder of the output from the algorithm.

The supply and demand data both before and after load shifting are displayed in a column at the bottom of the sheet. Headline match results are displayed at the top of the sheet.

The match metrics consist of two parameters and two measurements that calculate the common area between the supply and the demand profiles and the power used in the algorithm. These are Shared Area, Excess Supply, Total Power Before Load shifting and Total Power After Load shifting. (Figure 5.5)

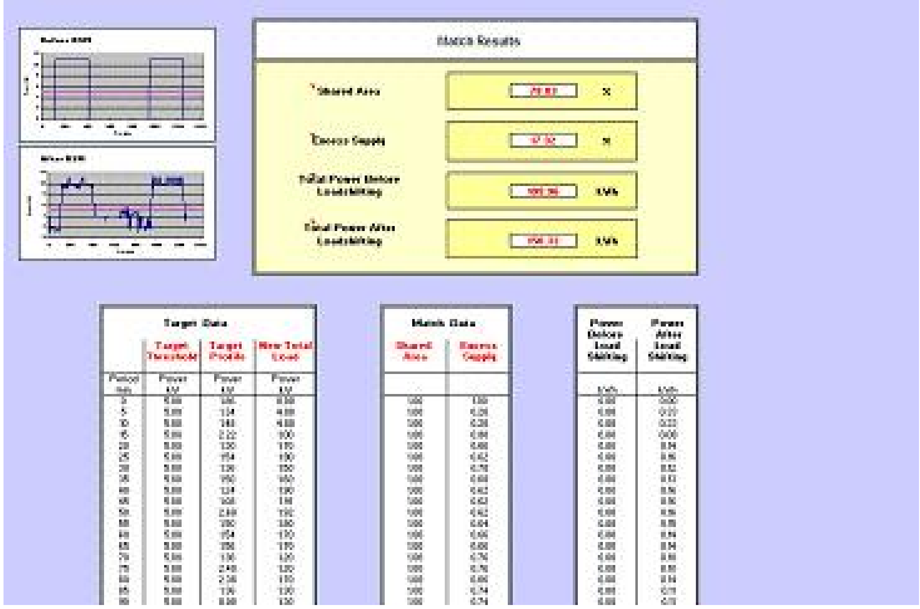


Figure 5.5 – Match Results worksheet

Load Properties

Specific details concerning the loads and their characteristics, such as type and duration, are entered on this sheet. On this sheet the loads' energy requirements are calculated per time step.

The priorities of the different loads are also entered here so that the priorities of loads within the environment are accurately represented within the algorithm. (Figure 5.6)

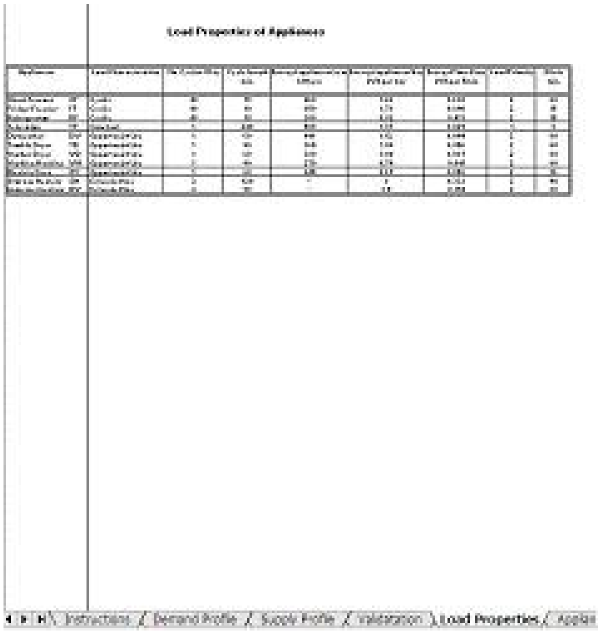


Figure 5.6 – Load Properties worksheet

Appliance Schedule

The times of the normal operation of the appliances are manually entered into the Schedule Appliances Sheet. For the times when each appliance present will be in use, the blue load value for that appliance should be entered into the corresponding timestep cell.

The sum of all of the loads that are in use for each timestep is displayed in red beside the timestep column.

At the top of the worksheet the Target value is repeated from Demand Profile worksheet. (Figure 5.7)

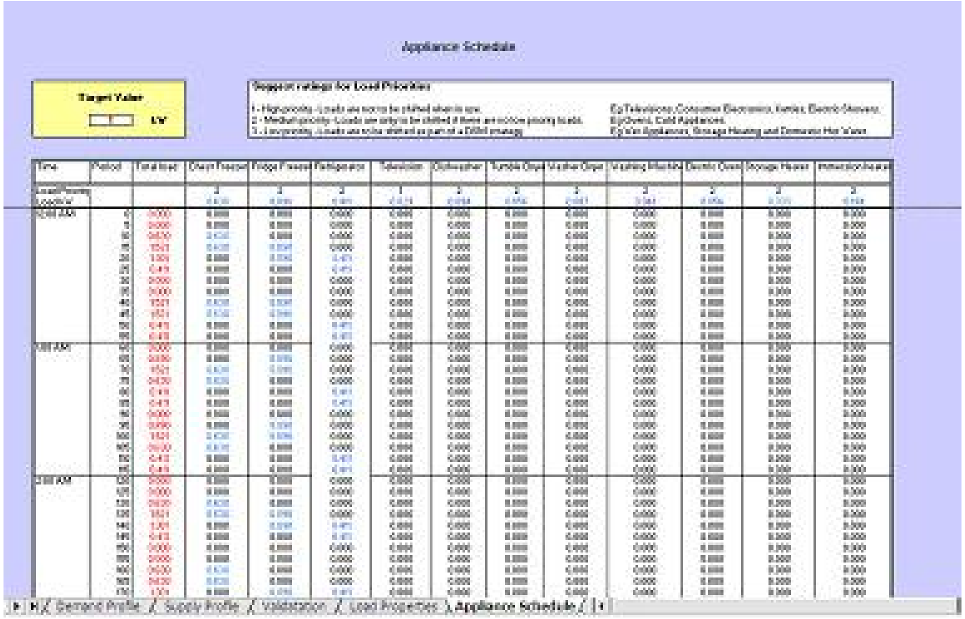


Figure 5.7 – Appliance Schedule worksheet

Target and Shifted Profile

The total demand is compared against a target value determined by the control option chosen on the sheet Profile. The actual demand will be compared with the Target Value or Supply profile and the initial action will be identified. The load shifting will then be carried out and each stage of the new total load will be shown. (Figure 5.8)

The key to the sheet follows:

P=T Power equals Target, Load shifting stops.

NA No more same priority loads to shift

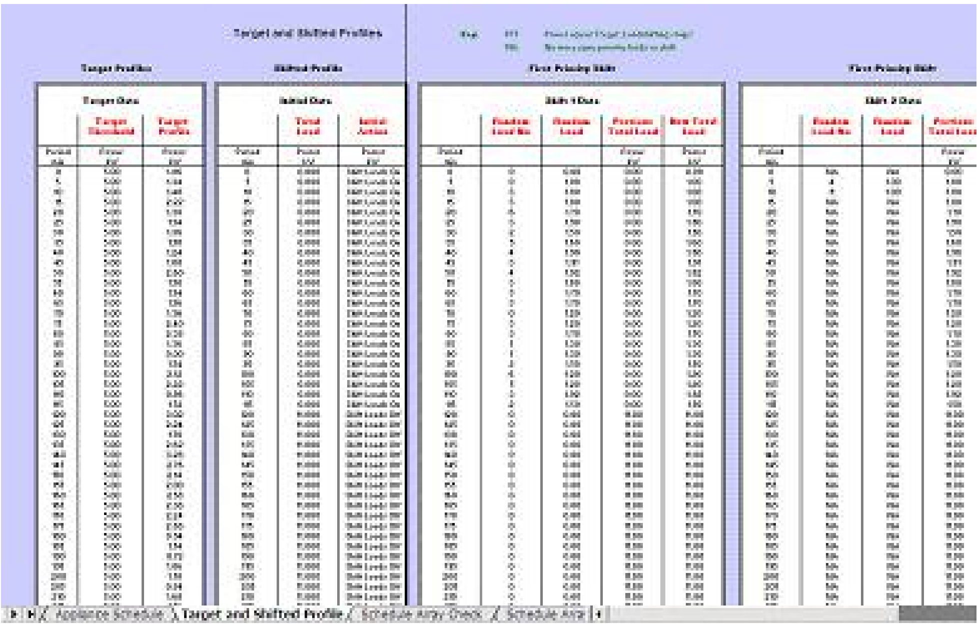


Figure 5.8 – Target and Shifted Profile worksheet

Schedule Array Check

The contents of the Appliance Array and Priority 2 and 3 Loads that are available for shifting are displayed on this sheet to allow further analysis and checking of array values. (Figure 5.9)

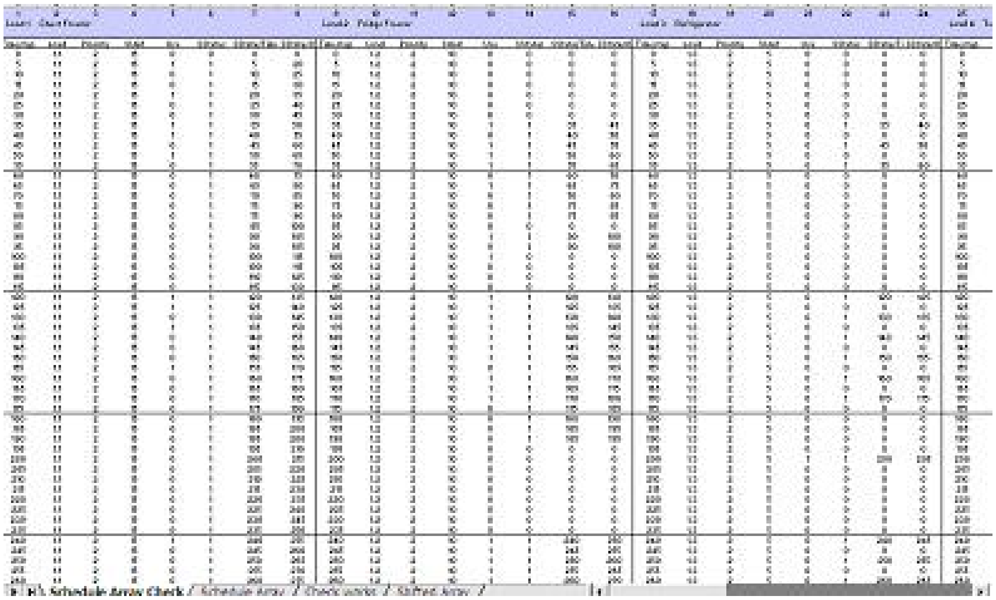


Figure 5.9 – Schedule Array Check worksheet

Schedule Array

The information concerning the initial appliance use on the Appliance Schedule sheet is converted into the format required for entry and storage in the Appliance Array. (Figure 5.10)

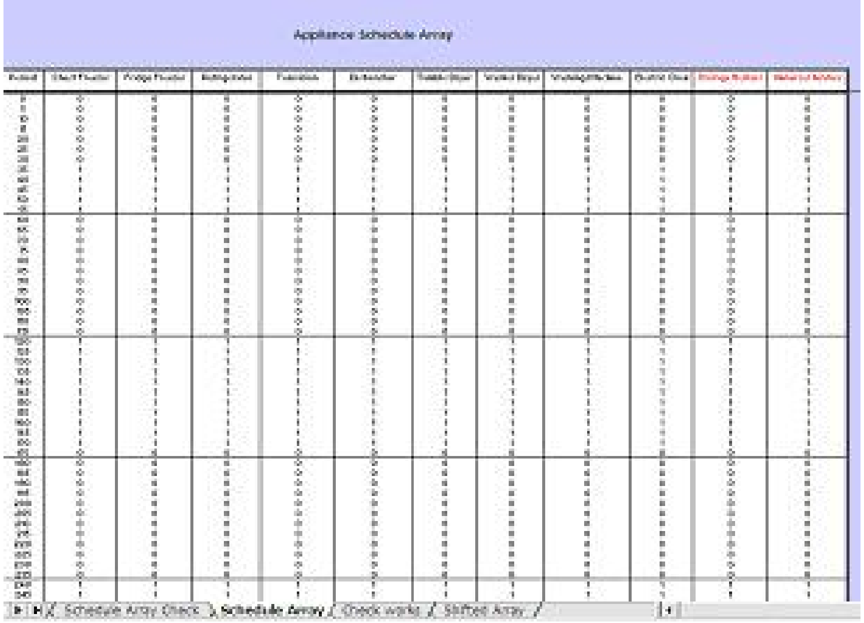


Figure 5.10 – Schedule Array worksheet

Shifted Array

The information concerning the shifted appliance use from the operation of the algorithm is converted into the format required for entry and storage in the Appliance Array.

There is a reset button at the top of this sheet on the right hand side that resets the Shifted Array to equal the Scheduled Array. The arrays should be reset prior to starting the main algorithm. (Figure 5.11)

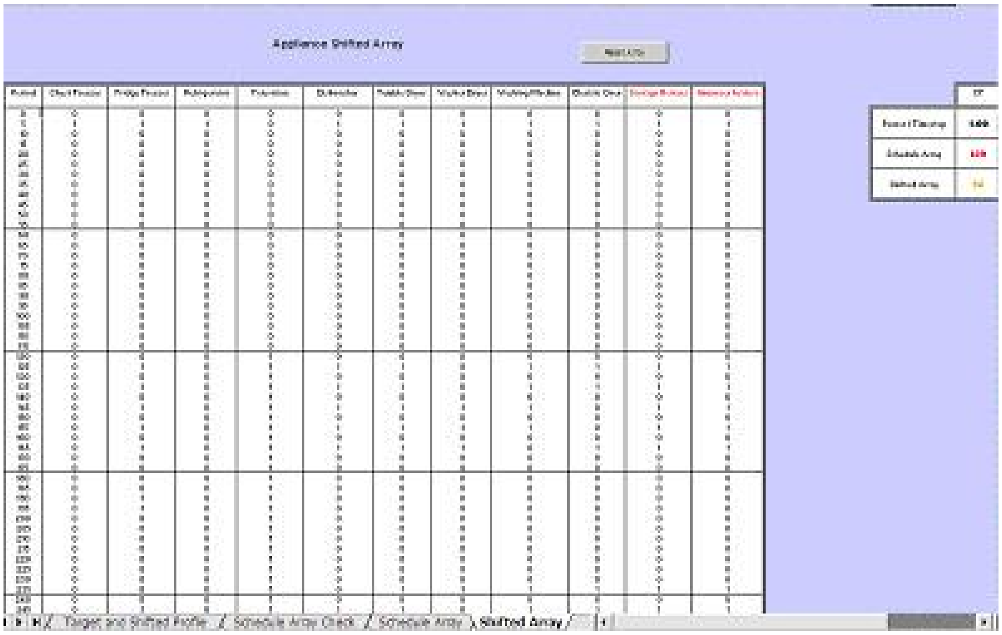


Figure 5.11 – Shifted Array worksheet

Detail of Construction

As part of the structure required to control the algorithm there are a number of variables that have been created to describe different aspects of the load assessment and load shifting process.

During the operation of the algorithm two main arrays are created along with several smaller arrays. The first array holds scheduling information and information about the loads themselves per timestep. This is a resource that the entire program can access.

The second array holds the actual Power value, which is used as part of the comparison process for load shifting throughout the algorithm.

There are four smaller arrays, which are availability arrays and list the state of the various loads so that they can be shifted to match current demand to the target Power value.

Other smaller arrays hold values which act as markers throughout the load shifting process.

The scheduling array was set up for 5 minute timesteps and was arranged with the time on the y-axis and loads on the x-axis, so that the results could be presented within Microsoft Excel.

The algorithm is modular and the commands are repeated for each load that is controlled. The program could be therefore increased in size with the addition of further modules and some changes to the coding that calls the different procedures.

Variable Definitions and Values

A range of appliances and equipment with a high energy use was selected from the review of loads conducted earlier. Further information concerning the annual energy consumption of these appliances was deconstructed to give a daily energy use and energy use per five minute timestep.

Within the algorithm there are different characteristics of the individual loads that have been defined. These are as follows:

Timestep

This is the smallest period of time into which appliance use is divided and monitored. A timestep of 5 minutes is used within this algorithm.
For different variables during the algorithm the timestep is often referred to as a row number for the appliance in question, such as ScheduleCFApplianceRowNo, SheduleApplianceRowNo, P2ShiftOnArrayNo etc.

Appliance

This is an electrical unit that is connected to the network and requires power to operate. The electrical appliances that are used for this study perform a variety of functions in the domestic setting.
The appliances are abbreviated to a 2-letter code, for example CF - Chest Freezer. A full list of the 2-letter codes is included at the start of the algorithm code.

Use

This is a simple variable that describes whether the appliance is in use for each timestep. This is represented by either 0 or 1, with 1 representing the appliance in use. The initial use variable is generated from the figures manually entered on the Appliance Schedule worksheet.

Priority

The loads that are connected to the network are given a priority of use, which is determined by the social impact of shifting the load. The priority rating of loads ranges from 1 to 3. Priority level 1 is the highest priority and loads with this rating should not be shifted unless it is absolutely essential in order to preserve the stability of the supply. In this study, there is no scope for shifting Priority 1 loads.
The hierarchy of loads will mean that priority is given to maintaining power to Priority 2 loads above Priority 3 loads. For example when there is a need to

shift loads on, the Priority 2 loads (P2) will be shifted on first, followed by the Priority 3 loads (P3). When loads are shifted off, P3 loads will be shifted off first then P2 loads.

The priority values are manually entered on the Load Properties worksheet. Default figures have already been entered from the review of loads conducted earlier.

Load

This is the power required for the operation of each load per timestep. The load shifting process will add and subtract loads to the total demand in order to try to match the target value.

The load value is in kW and is calculated to 2 decimal places from annual energy use figures.

Power

This variable is the total power demand for the dwelling and is calculated from the sum of the individual loads operating during that timestep.

The Power value is in kW and is calculated to 2 decimal places.

Target

This is the target demand value and will vary for each dwelling studied or method of supply. One of the next stages in the algorithm will be to compare the value of Power, to the value of Target. Depending on this result, load will be shifted on or off to try to match the current demand to the target demand. Entering a value in the appropriate cell on the Demand Profile worksheet will change the target value throughout the software.

The target value is in kW and is calculated to 2 decimal places.

SUnit (min/ time)

Shift Unit is the amount of time by which individual appliances may be shifted, with minimal or no adverse effects to the user. SUnit is measured in minutes and will vary between appliances.

A default value of SUnit is set for each appliance from the review of loads conducted earlier, although this value can be modified through the Load Properties worksheet.

SStatus

Shift Status is a variable that describes whether the appliance is available to be load shifted or has recently been load shifted and is recovering from this action. The SStatus is applied from start of the appliance's use and ensures that the whole SUnit is observed at the end of the unit's cycle.

It is believed that any appliance will have recovered stability during this period so that the load will be able to be shifted again without any undue social or technical implications once the time has expired.

SStatus is represented by either 0 or 1, with 1 representing the appliance not being able to take part in a load shifting scheme. A default value of SStatus is set for each appliance from the review of loads conducted earlier, although this value can be modified through the Load Properties worksheet.

SStatusTime

Shift Status Time is the time when appliance use changes from 0 to 1. The algorithm generates this variable as it advances through the appliance schedule and the value is displayed in minutes.

SStatus0

Shift Status 0 is the time when SStatus returns to 0, indicating that the appliance will be available to be load shifted again if required to do so. SStatus0 values are calculated from the SStatus variable and are displayed in minutes.

Assumptions Concerning Appliance Function and Use

All of the loads that are modelled in this tool will have either duty cycles or operate with a diversity factor.

Appliances that have a duty cycle were considered to operate with a diversity factor of 25%. The load per timestep was then calculated from total annual energy use figures. The energy in kWh that an appliance used per day was then divided amongst the number of duty cycles the appliance used per day. It was assumed that the duty cycles normally occur with the appliances experiencing steady state conditions.

This proportion of energy use per cycle was then entered into each timestep in the Appliance schedule worksheet when the appliance is considered to be in use.

The occupancy of the house is modelled on the routine of a standard workday, which is experienced by a large proportion of the population. It is assumed that the occupants will have left by 9am and the house will be vacant all day until 5pm. It is envisaged that much of the load shifting will occur overnight or within this 8 hour period.

Cold Appliances

All of the cold appliances were assumed to be in constant operation. The chest freezer SUnit was decided upon as this appliance has the maximum capacitance of all of the domestic equipment due to the hard frozen state of its contents. The SUnit of the chest freezer is 60 minutes.

The SUnits for refrigerators and fridge-freezers were relatively small as the scale of their SUnits relies on the capacity of the fridge to maintain its temperature. The SUnit of the refrigerators and fridge-freezers are both 15 minutes.

Wet Appliances

The dishwasher’s use is based on a schedule of the appliance being switched on overnight, with the requirement of the dishes to be clean for a 7am start.

The period of operation for the dishwasher has been set at one hour. This will be quite flexible with a SUnit of 60 minutes.

The tumble dryer is modelled on having two standard routines for tumbledrying clothes during the day. The first is that an item of clothing is required quickly and the second is a full load, because of inclement weather. Both cycles will occur during the day. On aggregate the tumbledryer has been given a SUnit of 60 minutes.

The washing machine is modelled on having two possible periods of use. The first is based on a schedule of an overnight wash, with the clothes being available for drying by 7am in the morning. The second period considers a routine with the machine being loaded for use in the morning and the cycle needing to be completed for the occupants returning in the evening. The long period in which the cycles can be completed means that the SUnit of a washing machine is 60 minutes.

A dual-purpose machine such as a washer-dryer will more commonly be used as a washing machine, as they tend to operate relatively inefficiently in the drying mode. This means that the washer-dryer has been given an SUnit of 60minutes.

Kitchen Appliances

The thermal inertia of the oven and contents mean that ovens can be shifted for a small period, as all except the most delicate cooking processes would not suffer adversely. The oven has been given a SUnit of 10 minutes.

Hobs and kettles cannot be shifted during use because the effect of load shifting would have a very large impact on the user.

Other Loads

Storage heaters can be shifted a great deal and are ideal loads to be used as part of a demand side management scheme. However for residents who are at home and require heating during the day there should be enough stored residual heat that can be used in the short term should it be required. The SUnit of storage heaters is 90 minutes.

The immersion heaters can also be shifted for relatively long periods due to the thermal insulation around the tank and the thermal mass of the water. The immersion heater has been modelled to have the water ready for 7am. After occupants using the water heater in the early morning, further hot water will be required for the early evening. These periods allow for a large degree of flexibility in the load and so the hot water immersion heater has a SUnit of 60 minutes.

Electric showers are appliances of convenience and it would be unacceptable to shift their demand, despite the shower's high power rating. This type of appliance would be a priority 1 appliance and as such would have a SUnit of 0 minutes.

Lighting and electrical appliances, such as those for entertainment, cannot be load shifted and these two categories would also be priority 1 appliances with a SUnit of 0 minutes.

Methodology and Components of the Algorithm

The main algorithm is a process for comparing the current demand with a target value for each timestep. If the current demand differs from that of the target value, then loads will be turned on or off in order to match the target value, until the number of timesteps that the appliance is in use equals the number of timesteps that the appliance is scheduled to be in use.

In order for the algorithm to act as a demand side management tool, it is imperative that the total energy used before load shifting equals the total energy used after load shifting.

The above process happens for each timestep, with the algorithm attempting to match the power to target values as it progresses through a 24-hour period. The aim of this process is to manage and optimise loads to allow a best-fit arrangement between the supply and demand profiles.

The information that is present or calculated from values in the Profile, Load Properties and Schedule Appliance sheets is stored in different arrays within the Algorithm. All of the arrays have been declared as public arrays so that if required, any of the sub-procedures can access data from them. These arrays are as follows:

Appliance Array

The Appliance Array, (AppArray), is a three dimensional array and is the main array that holds the appliance information for each timestep. The first dimension refers to the timestep, the second refers to the appliance and the third dimension refers a load property.

The load properties are as follows:

1	Timestep
2	Load (kW)
3	Priority
4	SUnit
5	Use
6	SStatus
7	SStatusTime
8	SStatus0

The Appliance Array is filled and the contents sent to Schedule Array Check worksheet, by running the Read and Write functions.
The Read function calculates the eight load properties from the information entered in the tool, which is then stored in the Appliance Array. This is carried out for all of the appliances described in the Load Properties worksheet.
At the end of the algorithm the information is sent to the Schedule Array Check worksheet by running the Write function for each appliance.

Load Select Arrays

The Load Select Arrays, (eg. P2OnLoadSelectArray), are two dimensional arrays which hold the loads that are available for load shifting from the priority and state named.

The arrays are named after the **priority** and **current state** of the loads that they contain, not the purpose that the loads are being selected for.

For example, if the Power value is below the Target value, the algorithm will select a load to switch on. This load will initially be selected from the P2OffLoadSelectArray.

In order for the Load Select Arrays to be populated, there are a number of processes that feed into this load selection process. A flow diagram of these processes can be seen in Figure 5.12.

These processes cover the steps Count Load Use and Loads Available for shifting in the main flow diagram of the algorithm, which can be seen in Figure 6.1.

The Count function contains a number of smaller functions. Each appliance that is monitored has its own individual function that looks for certain load properties. If a load is suitable, the load's kW per timestep is placed in the Loads Available Arrays.

The Loads Available Arrays, (eg. LoadsAvailableP2OnArray), contain the loads that are available for load shifting from the priority and state named. The Loads Available Arrays from 0 to 11, for each priority and state are assigned to individual loads and are not interchangeable.

When the results are viewed as a table, there will be empty cells in between the individual loads power values that are distributed across the worksheet.

As will be seen in section Algorithm Processes, it is necessary for the load selection and shifting procedure that the loads that are available per timestep for load shifting are aligned in consecutive cells, from left to right across the table.

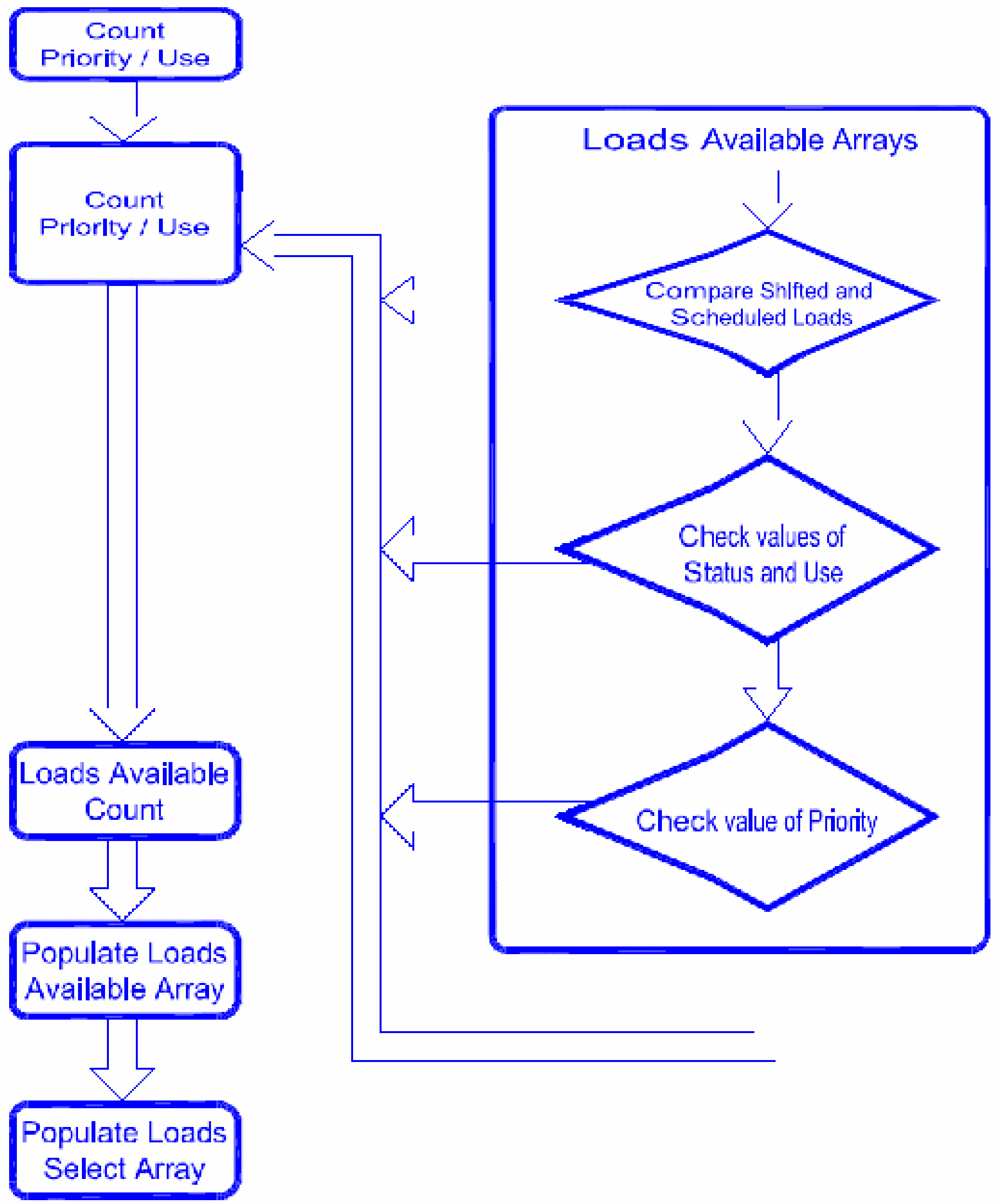


Figure 5.12 – Flow diagram of the population of Load Select Arrays

To rearrange the loads in this order, the loads are copied from the Loads Available Arrays, reordered and transferred into the Load Select Arrays. The loads then populate Load Select Arrays from zero, up to the maximum number of loads available as can be seen on the Schedule Array Check worksheet.

In order to maintain power to the higher priority loads, when the value of Power is below that of Target, the algorithm will shift Priority2 loads on first, followed by Priority3 loads. Similarly, when the value of Power is above that of Target, the algorithm will shift Priority3 loads off first, followed by Priority2 loads.

As the algorithm progresses through the 24-hour period, the number of loads available for load shifting will change as loads are switched on and off. Other functions contained within and ran from the Update All function carry out this task. The functions included with Update All are:

UpdateUseP2PTLowShiftOn, UpdateUseP3PTLowShiftOn,
UpdateUseP3PTHighShiftOff, UpdateUseP2PTHighShiftOff,
UpdateAppArray,
CountUse, CountP2Off, CountP2On, CountP3Off, CountP3On,
LoadsAvaliableP2Off, LoadsAvaliableP3Off,
LoadsAvaliableP3On, LoadsAvaliableP2On.

Power Result Array

During the load shifting process, when Power and Target are being compared and loads being shifted, the results are placed in an array for security. This is carried out as an interim measure, before the results are sent to the Target and Shifted Profile worksheet and to ultimately be displayed graphically.

The Power Result Arrays are populated by the function Power Target Comparison (PTC), whose actions will be explained in much greater detail in Algorithm Process.

There are 11 Power Result Arrays, one for each individual load. The Power Result Arrays, (PowerResultArray), hold values which are referred to throughout the load shifting process.

PTC sends values to one of locations in the PowerResultArray, depending upon which load shifting has taken place. If Power is less than Target, loads will be shifted on and the aggregate value of the load in use during that timestep, will be placed in PowerResultArray(1).

If Power is greater than Target, loads will be shifted off and the aggregate value of the load in use during that timestep, will be placed in PowerResultArray(2). If Power is equal to Target, no action will occur and loads will be placed in PowerResultArray(3).

If, or when, another load is shifted on, the previous total load value will be overwritten by a new total load value, consisting of a random load value selected from the appropriate Load Select Array and added to the old total load value.

This is repeated in PowerResultArray(1) for loads that are shifted off and again in PowerResultArray(2) when no load shifting is to occur. The final value for Power held in a Power Result Array will be sent to the Target And Shifted Profile worksheet.

Chapter 6

Algorithm Operation

To use the DSM tool there are some procedures that the user must follow to ensure that the tool will replicate their situation or environment as accurately as possible.

Review and Schedule Loads

Initially the user must review the selection of loads in the Load Properties worksheet and manually enter any change of details if required.

The loads must then be scheduled in the Appliance Schedule worksheet. The user should schedule the loads according to their normal use over the 24-hour period. To do this the blue Load kW value at the head of each column must be copied into the timestep cell where the load will be in use. This should be repeated for each appliance that is present. If one of the appliances stated across the top of the scheduling table is not present, enter a zero into every timestep cell for that appliance.

Select Control

The method of control is selected from the Demand Profile worksheet. The tool has two control options for controlling the load shifting process, Target Value and Match Output.

Target Value will attempt to stabilise the demand at a set value, which is entered in the box to the right of the target symbol. To select the Target Value control, click on the target symbol.

Match Output allows the demand to follow the output from a varying source, such as the power supplied from renewable generation. To select the Match Output control, click on the wind turbine symbol. However, in order to use this control method, a supply profile must first be constructed in the Supply Profile worksheet that will represent the output from existing or proposed renewable generation on the site.

The next procedure is to ensure the Shifted Array worksheet equals the Schedule Array worksheet, so that the first load shifting operation occurs with the appliance use entered by the user. Press the reset button on the Demand Profile worksheet to make the two worksheets equal.

When the tool is configured for use then the process can be started by pressing the Shift Loads button on the Demand Profile worksheet.

The Supply Profile worksheet contains the data necessary to simulate a renewable supply comprising of electricity generated from wind turbine and solar photovoltaic (PV) panels.

The wind supply data has been taken from a larger installation and has been reduced to an output per kW of the turbine to allow an approximate output from any size turbine to be input into the software.

However it must be restated that this tool will not be accurate for turbine sizing purposes due to the relationship between size and output of a wind turbine.

The solar photovoltaic panel data was generated from ESP-r and has been calculated for a 1m^2 PV. Data has been provided for both a sunny day and a cloudy day in July.

The size and make up of the renewable input is decided upon and by scaling up the values of the modular outputs of the reference data, a supply profile is generated.

Algorithm Processes

Once the algorithm is started information from the Demand Profile, Load Properties and Schedule Appliance worksheets along with new variables calculated from this information are entered into the Appliance Array. The Arrays used to store information, follow the convention described earlier with their name describing the purpose and current state of the contents.

The Count functions start to run the load selection procedure, which identifies whether a load is suitable for load shifting. Each Count function contains 11 smaller functions, one to monitor each appliance.

The selection process subjects loads to three criterions in series, with the load passing to the next level if it is found to be suitable. If the load is not suitable, then the individual appliance function will exit and return to the Count function where it will then run the next individual appliance function.

The first criterion selects loads by comparing the appliance use totals on the Shifted Array worksheet. To select loads for the P2 and P3 Off Arrays the total use calculated on the Shifted Array worksheet must be less than the total use that the load is scheduled for on the Shifted Array worksheet. To select loads for the P2 and P3 On Arrays the total use calculated on the Shifted Array worksheet must be greater than the total use that the load is scheduled for on the Shifted Array worksheet.

If it is thought there will be problems with the selection of loads, a small factor can be introduced at this stage in order to apply a degree of flexibility to the comparison process. However the default setting of the tool is for the factor not to be applied.

The second criterion selects loads by SStatus. To select loads for the P2 and P3 Off Arrays, the load needs to have an SStatus of 0 and to select loads for the P2 and P3 On Arrays, the load needs to have an SStatus of 1.

The third criterion checks the priority of the load. If it is of the priority that is required, then the load’s information will be placed in the appropriate Loads Available Array.

The Load Select Arrays then rearranges the loads contained in the Loads Available Arrays, so that the available loads are aligned in consecutive cells, from Load Select Arrays from zero, up to the maximum number of loads available, as can be seen on the Schedule Array Check worksheet.

Load Shifting

A flow diagram of the load shifting process can be seen in Figure 6.1. Once the Use, Priority and SStatus conditions of all of the Priority 2 and Priority 3 loads have been stored in the respective arrays, the algorithm is compares two variables, Power and Target.

Power is the aggregate demand from the appliances and depending upon the control option selected, Target is target value set in the Demand Profile worksheet or the output from the renewable generation for that timestep.

Depending upon whether the values of Power and Target are less than, more than or within a small tolerance of the Target value, loads are shifted on, off or no action is taken.

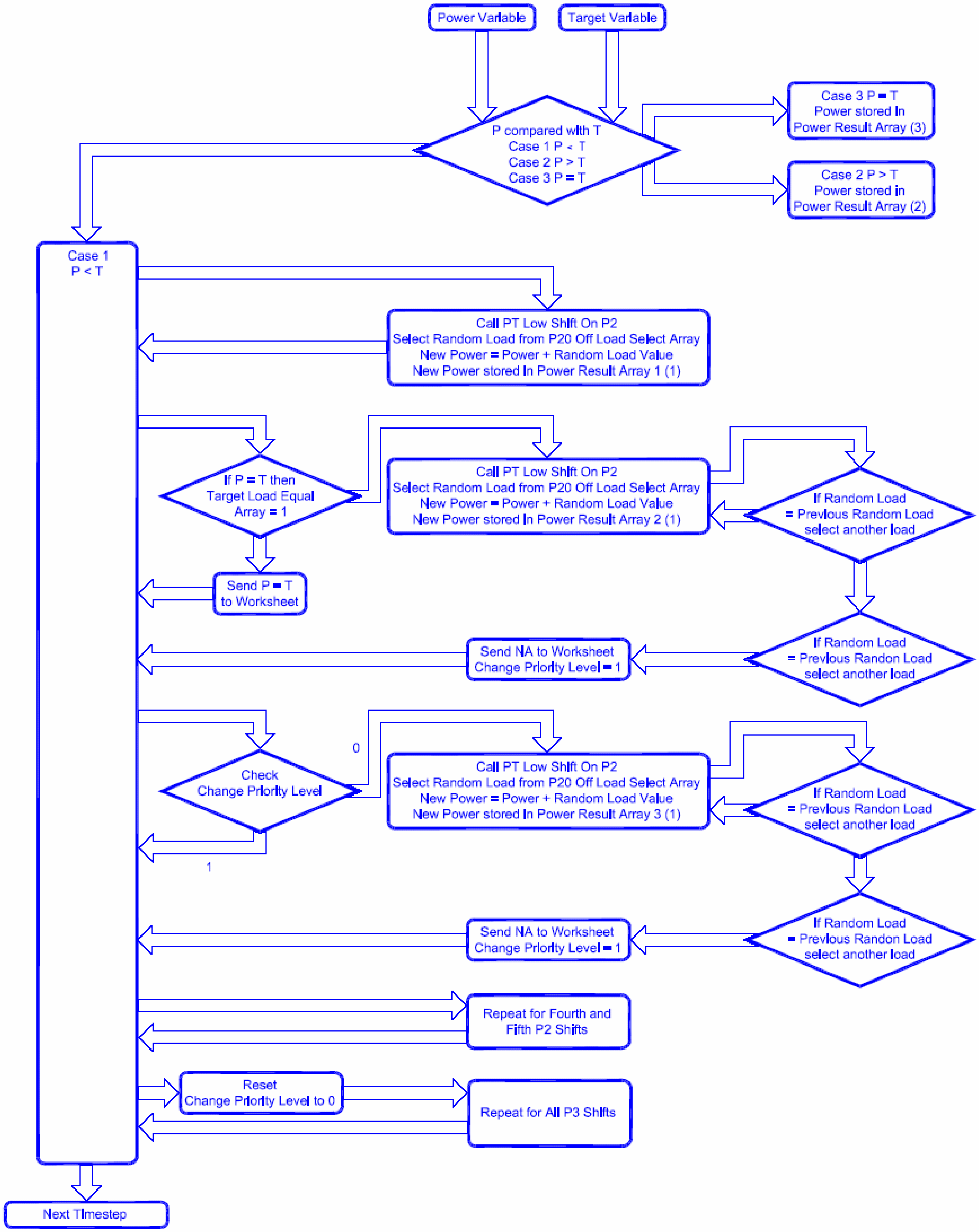
However a mechanism is built into the function, Power Target Comparison (PTC), which contains the entire set of load shifting functions. Not all of the loads are put forward for inclusion in the Load Select Arrays. This approach is taken because one timestep may have a perfect match using the entire contents of the Load Select Arrays, but there will be a glaring mismatch with the following timestep because there will be no load available.

Without this mechanism, a system or network supplemented with a grid connection could experience large excesses and deficits in power, which would be supplied from the grid. This would cause small power fluctuations, which if amplified on the community level would be extremely difficult to balance and could cause network instability.

In PTC, only 5 shifts are allowed for each priority regardless of the number of loads available. This is the first restriction and should build in a degree of conservation in the selecting and shifting.

A load is selected for shifting by generating a random number, LSArrayNumber, between 0 and the maximum number of loads available with that priority. Priority 2 loads will be counted for shifting on and Priority 3 loads

Figure 6.1 – Flow diagram of Load Shifting process



will be required for shifting off. The maximum number of loads can be found for each priority in the variable LoadsAvaliable(Priority, State)Count.

The load with the LSArrayNumber is selected, the value of the load added to the Power variable and the result stored in PowerResultArrays. The contents of this array are then sent to the Target and Shifted Profile worksheet.

For the second shift the same process will occur, a load is selected at random from the available loads in LoadSelectArrays.
If the random LSArrayNumber is not the same as that generated previously, then the function proceeds as before. The load with this LSArrayNumber is selected, the value of the load added to the Power variable and the result stored in PowerResultArrays. The contents of this array are then sent to the Target and Shifted Profile worksheet.

However if a random LSArrayNumber is generated, which is the same as any previous LSArrayNumber, then it will be discounted and a second random LSArrayNumber is generated. This too, will be compared with previous LSArrayNumbers.
If the second random number is the same as Shift 1's LSArrayNumber, then it will also be discounted and a third and final random LSArrayNumber will be generated. This too will be compared to previous LSArrayNumbers.
If this final random LSArrayNumber is the same as any previous LSArrayNumbers, then the function deems there no loads of that priority available for load shifting and will send a NA – Not Applicable, to the relevant calls in Target and Shifted Profile worksheet. In addition a variable named ChangePriorityLevel will then be changed from 0 to 1, so the algorithm is aware that there are no further loads available of that priority for the current timestep.
In addition, after each load is selected, the number of timesteps when the load has been used is compared with the number of timesteps it was scheduled to be used. If the timestep requires loads to be shifted off and the loads use is less than the number it is scheduled for, then it will not be put forward for load shifting. If the timestep requires loads to be shifted on and the loads use is

greater than the number it is scheduled for, then it will not be put forward for load shifting. If after the three attempts a suitable load cannot be found then the load is not suitable then ChangePriorityLevel will then be changed from 0 to 1.

If there are no more Priority 2 loads, then the algorithm will start to shift Priority 3 loads, if there are any available. When the algorithm starts to consider Priority 3 loads, the variable ChangePriorityLevel will be reset to 0. The process will be repeated for the Priority 3 loads and once there are no more Priority three loads, the function will exit and return to PTC.

This process is the second restriction because, especially for timesteps when there are relatively few loads available, because once the loads have been shifted, it will be increasingly hard to obtain the remainder with only a total of three opportunities to generate random numbers.

The outcome that is most desired, is when existing loads and shifted loads equalling demand and shifted loads resulting in Power becoming equal to Target will bring about the end of load shifting.

If after load shifting Power is the same as or more than Target then the algorithm has completed its purpose and load shifting will stop. There is a tolerance associated with the Target variable that allows a degree of flexibility of whether load shifting occurs.

When loads are being shifted on, the Power Result Array from the previous load shift must be less than 75% of Target in order to proceed.

When loads are being shifted off, the Power Result Array from the previous load shift must be greater than 110% of Target for load shifting to proceed.

These default values may benefit from a degree of tailoring depending upon the size of the loads that are involved in the DSM scheme.

PTC will continue, with loads being shifted on until P is within tolerance of T, there are no more loads of the same priority to shift or the shifting functions have been exited because the variable, ChangePriorityLevel is equal to 1.

The algorithm will then move to the next timestep and repeat the process.

For the timesteps when Power is greater than Target, the procedures described above will operate with the intention of shedding loads. The same procedure will occur, but load values will be subtracted from Power until P is within tolerance of T, there are no more loads of the same priority to shift or the shifting functions have been exited because the variable, ChangePriorityLevel is equal to 1. The algorithm will then move to the next timestep and repeat the process.

Key to Processes

A number of indicators are sent to the Target and Shifted Profile worksheet to inform the user of the various outcomes from the load shifting process. These are:

- NA - Not Applicable

If the value of the variable ChangePriorityLevel = 1, then the function will send an "NA", to the relevant calls in the Target and Shifted Profile worksheet, indicating that there are no more loads of that priority to shift.

- P=T - Power = Target

If the value of the Power variable is within tolerance of the Target variable, then the function will send a "P=T", to the relevant calls in the Target and Shifted Profile worksheet, indicating that load shifting is complete.

An example of the load shifting process, which is shown in detail, can be found in Appendix 2: An Example of Load Shifting.

Updating Load Properties with a Change of Use

If the value of Use for any appliance within the array changes from 0 to 1, then the values of SStatus, SStatusTime and SStatus0 are updated accordingly, in order to display the availability of the load, when the change occurred and when the load will become available again in the future.

For the first timestep, the load information input from the user and accessed through the Schedule Array worksheet will be translated into the information contained within the AppArray.

Once Power Target Comparison has been run, load use will change. These changes in Use have to be fed back into the algorithm so that it can update the AppArray as to the actual load use. This feedback has to happen so that loads that are scheduled as being available, truly are available and have not been shifted in a previous timestep.

This is carried out by number of functions starting with UpdateUse followed by the priority number, the state of the loads and the action that the loads were used for, eg UpdateUseP2PTLowShiftOn

The functions Update AppArray, Count functions and Loads Available functions also contribute to the update process.

These are ran after the function PTC has ended in order capture all of the new load Use information. Once the load use information is updated, the information is stored in the Shifted Array where loads that have been shifted off have a 0 inserted in the timestep cell and conversely loads that have recently been shifted on will have the contents of their timestep cell changed to a 1.

The AppArray is then updated from the information stored in the Shifted Array. The contents of the AppArray are then sent to Schedule Array Check as before.

From the second timestep, until the last timestep, the Read Functions look to the Shifted Array to check the status of the Load. It is now the contents of this array that determines whether the load could eventually end up in the AppArray.

At the end of every procedure, before the next timestep is considered the contents of the relevant PowerResultArray will be sent to the Shifted Profile column in the sheet Target and Shifted Profile.

The algorithm will continue to compare the values of Power and Target and choose one of the three sets of instructions until timestep 288, which is the final timestep of the 24hour period.

Chapter 7

Testing the Algorithm

After the algorithm was created, it checked for errors before it's functionality was tested in order that the control could be refined. From the outset, the main function of the algorithm was the ability to shift loads in order to match different supply profiles with different control strategies.

Initially I had to build confidence in the algorithm and ensure that the total power used before load shifting was equal to the total power use after load shifting.
The first test of the algorithm was to schedule a known amount of loads with a known amount of energy in the algorithm. For this, I changed every load value to 1kW and entered a period of appliance use as a solid block, with two defined step changes in demand. This test needed the loads to be arranged in this pattern because all of the loads needed to be interchangeable and load shifting would be made easier with round figures for demand. The round figures should also allow a particularly good match between supply and demand should the algorithm operate as intended.
The second was that it would be much easier to calculate the total electricity demand from the schedule appliances manually for comparison with the total demand calculated by the algorithm.
This was then set in operation and the results can be seen in the Results section.

Once the energy used in the algorithm could be accounted for, it was tested to see how it would perform in two possible scenarios.
The first of these scenarios was to check the algorithm's ability to shift loads to match a flat target profile, which would represent the loads being successfully manipulated to make the demand profile completely flat. This type of demand profile would benefit the utilities because the load

manipulation would remove troublesome peaks in demand that require maintaining hot spinning reserve that contribute to CO_2 emissions.

The domestic loads were arranged for use in a domestic setting, using the assumptions made earlier in Assumptions Concerning Appliance Function and Use. The loads that have been scheduled are representative of those used during a typical day during summer. The demand profile is shown in Figure 7.1.

A measured domestic demand profile for a dwelling is shown in Figure 7.2. The scheduled loads in the algorithm create an overall profile, which is comparable to the measured profile, once details like the resolution of the two profiles are taken into account. [78] The domestic profile data was sampled at approximately 6Hz whereas the output from the DSM tool is plotted using a period of 5 minute.

The loads were also given representative power values in the Load Properties worksheet and a value of 1kW was entered in Set Target Value Cell on the Demand Profile worksheet. Target Value was selected on Demand Profile worksheet. Once the Shifted and Schedule Arrays were made to equal each other by pressing the reset button, the program was started by pressing the Shift Loads button.

The results from this test can be seen in the Results section.

The second of these scenarios was to check the algorithm's ability to shift loads to match the output from with microgeneration with a backup supply consisting of a standard grid connection.

This type of demand profile would primarily be of benefit to the occupant because the reduction of power drawn from the grid would mean lower bills and even the possibility of payments from the utility from generated being returned to the grid.

However, for the utility the news is balanced, with the advantage of less power being drawn from the grid resulting in less distribution losses being balanced by the obligation to purchase intermittent renewable power generated from renewables and install the necessary infrastructure to deal with bi-directional power flows.

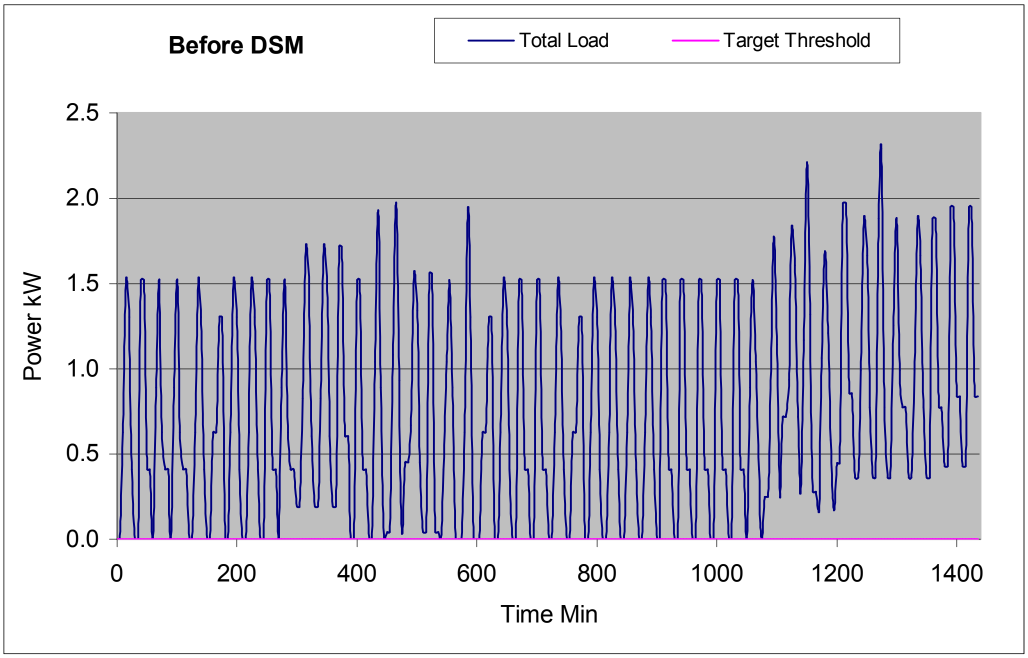


Figure 7.1 – Scheduled Loads before DSM

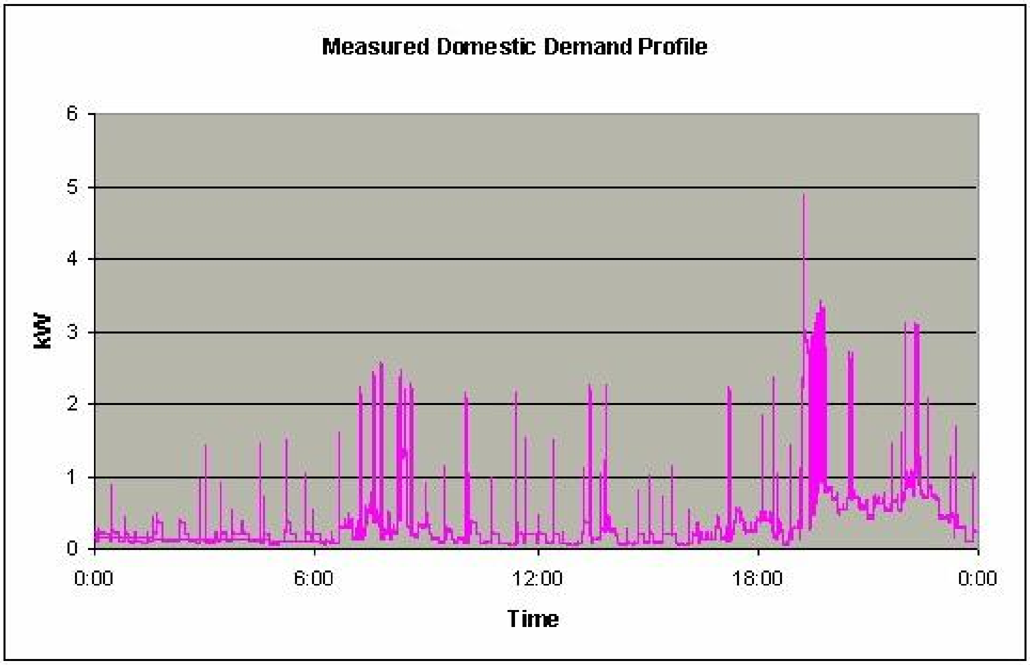


Figure 7.2 – A measured domestic demand profile

The domestic load settings were kept from the previous test and the algorithm was tested with a supply profile from a combination of 4m^2 PV panels and a 3kW wind turbine. The output from the PV was the sunny day data set.
Once the supply profile was constructed, Match Output was selected as a control method on the Demand Profile worksheet. As before, the Shifted Array was set to equal the Schedule Array and the program was started.
The results from this test can be seen in the Results section.

Accounting for Energy

Once the loads have been manipulated, the effects have to be evaluated to see what the benefit was from this action. To allow the benefits to be quantified, they need to be assessed by a series of metrics. The match metrics consist of four parameters. These are Shared Area, Excess Supply, Total Power Before Load Shifting and Total Power After Load Shifting. The metrics are displayed on the Validation worksheet as can be seen in Figure 5.5.

Shared Area

This is a metric that is based on the area common to both the supply and demand profiles. This common area is calculated by measuring the area between the x–axis and the lowest value between the supply profile and demand profile for every timestep and is expressed as a percentage of the demand area, as shown by equation 1.

$$SA\% = \frac{\left(\int_0^n D(t)dt\right) U \left(\int_0^n S(t)dt\right)}{\int_0^n D(t)dt} \qquad \text{Equation 1}$$

Excess Supply

Equation 1 covers the any match from the x-axis to the lowest value between the supply profile and demand profile. In order to measure any supply in excess of the demand, another metric will be needed. Subtracting the shared area from the supply area and presenting the result as a percentage of the supply will give us an excess supply metric. This is shown in equation 2. [79]

$$ES\% = \frac{\int_0^n S(t)dt - \left[\left(\int_0^n D(t)dt\right)U\left(\int_0^n S(t)dt\right)\right]}{\int_0^n S(t)dt} \qquad \text{Equation 2}$$

Total Power Before Load Shifting

This is a subtotal of all of the loads that contributed towards the daily demand prior to running the load shifting algorithm.

Total Power After Load Shifting.

This is a subtotal of all of the loads that contributed towards the daily demand after running the load shifting algorithm.

Validation

Loads were scheduled as described above, with the two square blocks of load totalling 110 kWh, peaking at 11kW. There was a period of two hours scheduled with no load at the beginning of the 24 hour period, a period of nine hours in between the blocks of load and a period of three hours at the end of the 24 hour period. The target for the validation was set at 2kW.
The scheduling of the loads before load shifting can be seen in Figure 7.3 and after load shifting in Figure 7.4.

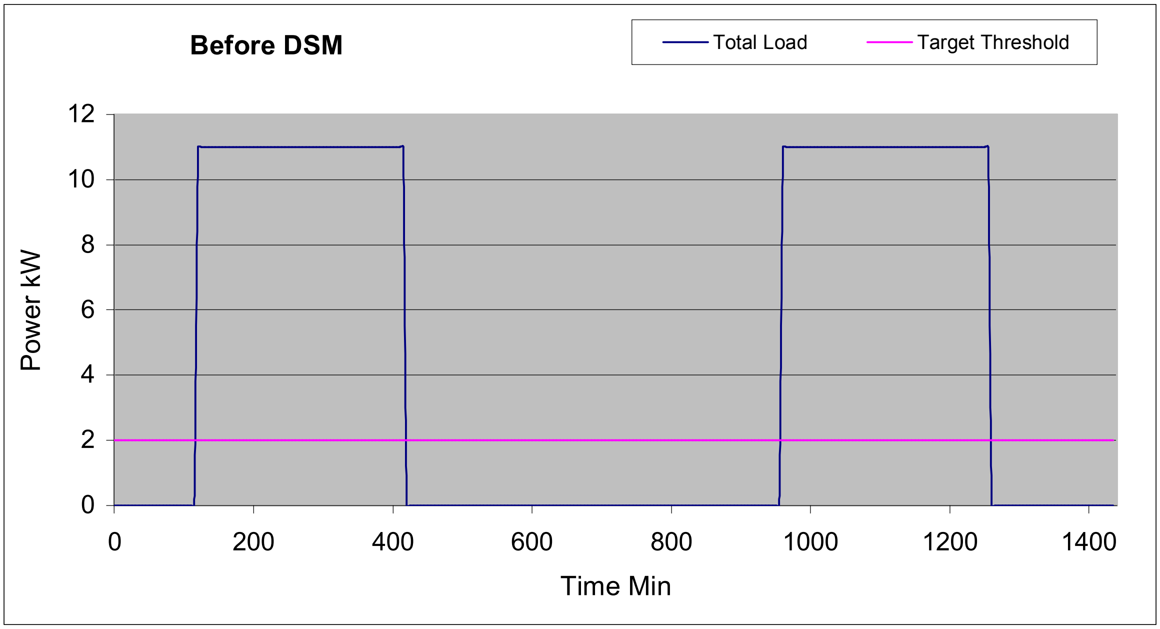


Figure 7.3 – Load scheduling before validation test

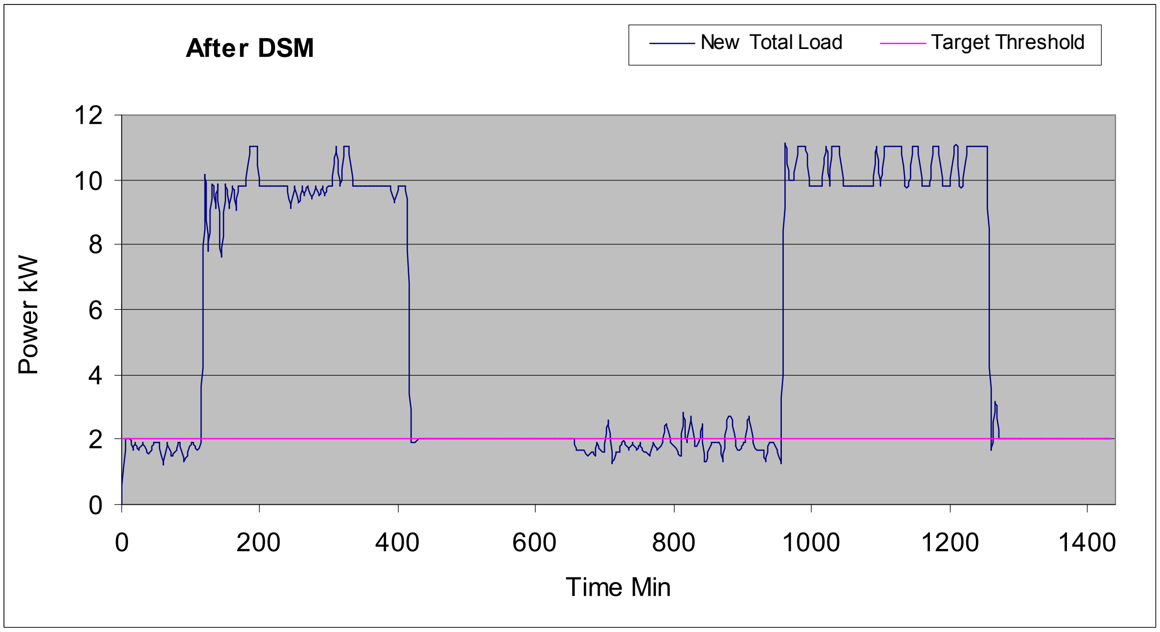


Figure 7.4 – Load scheduling after validation test

Initially the output from the algorithm is good and the loads rise to meet the target level quickly. At the start of the blocks of load as there is a plentiful supply of loads to switch off, the shape of the load block begins to change with a rounding of the front edge. When all of the loads have been shifted and are unavailable because they are waiting to become eligible again, a peak can be seen.

Once the loads become available again, the peak is removed. This pattern is repeated earlier on this load block, before the demand returns to zero.

When loads are shifted on again to meet the target value, initially there is a good match that deteriorates when loads become unavailable towards the end of the nine hour period.

The second block of scheduled loads follows a similar pattern to the first, but as the loads approach the limit when their Shifted Use is greater than their Scheduled Use, fewer loads are shifted and as a result the second block of load is higher and more saw toothed than the first.

Loads are shifted to meet the target for the remaining three hours resulting in a smooth match between supply and demand.

This validation test produced a Shared Area of 65.83, with an Excess Supply of 4. The Total Power before Load Shifting was 109.96kWh and after Load Shifting was 127.51kWh. The file DSM Validation is available to download from the ESRU website.

In order for there to be a perfect match there must be a Shared Area of 100, with an Excess Supply of 0 and the total power before and after load shifting must be within a certain tolerance. The power from shifted loads is 116% of the scheduled loads.

This result lies outside the limits of ± 10% that I was expecting and the control mechanism would benefit from some refinement before being used as a control mechanism for a selection of live loads.

Chapter 8

Results

The algorithm is designed so that any shifting that occurs is done in a slightly conservative manner. This is deliberate so that if there is a mismatch between supply and demand, the networks voltage will decrease rather than increase. Any difference between the power available and the power required will then be supplied by a grid connection. This arrangement will not lead to the collapse of the network whilst avoiding any damage to sensitive equipment.

Fixed Target Value

The full range of loads was scheduled to represent a domestic demand profile. The profile consists of a number of recurring peaks which vary in magnitude over the 24 hour period, peaking in the morning, reducing slightly then building towards an evening peak before reducing again towards the end of the day.

The target value has been set at 1kW, which is far above 0.367kW that is the average demand of the measured domestic profile. The 1kW target is approximately three quarters of the peak demand for the earlier part of the day, and approximately half the peak demand towards the end of the day. This will allow both loads to be shifted on and off. The scheduling of the loads can be seen in figure 8.1.

The first section of the results show loads being shifted on and these are often in excess of the target value. About midday, the demand begins to return to the target value before increasing again towards the evening.

If the shifting of the loads is monitored on the worksheet Target and Shifted Profile it can be see for the most part that only one load is shifted per timestep. However size of the loads the in relation to the target value will mean that if any loads are shifted on at all, then the total demand will be far in excess of the target value. (Figure 8.2)

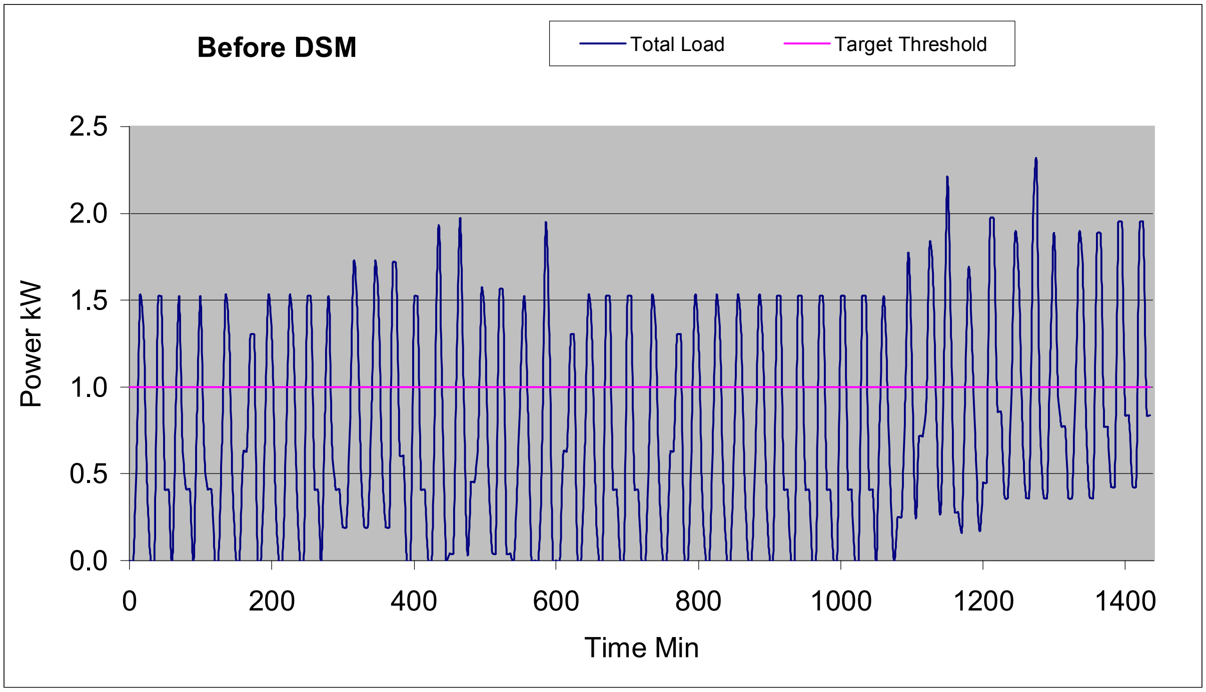


Figure 8.1 – Load scheduling before target test

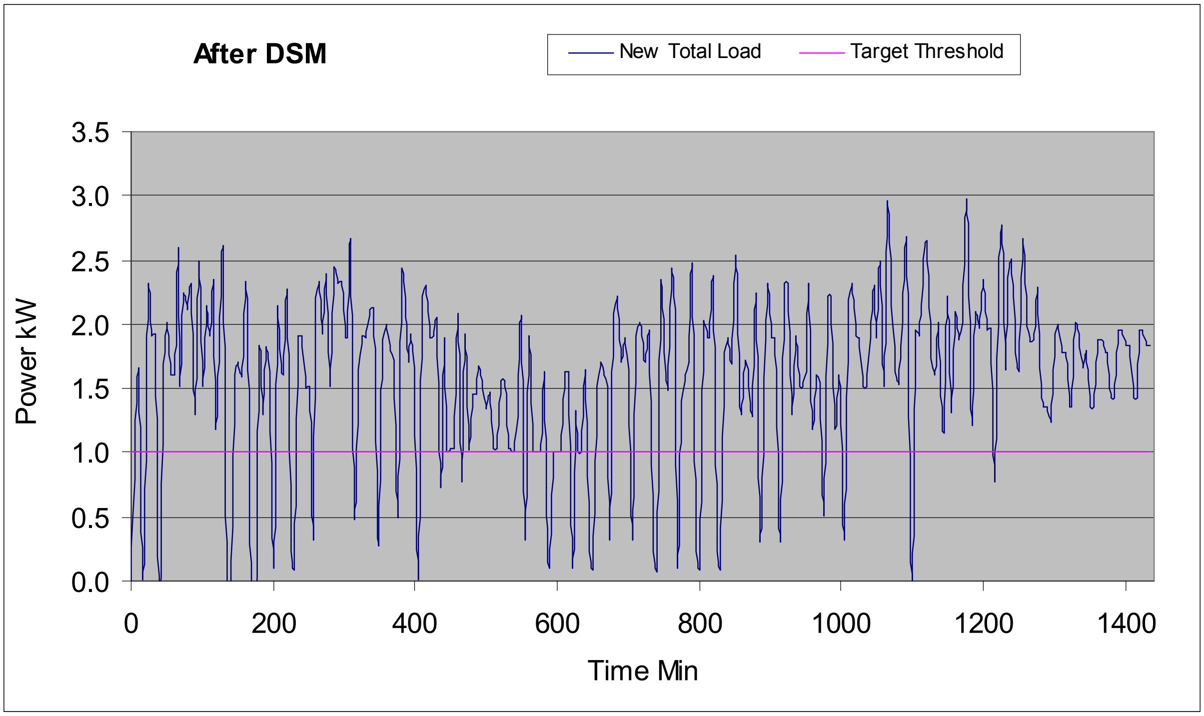


Figure 8.2 – Load scheduling after target test

A further example of this can be seen towards the end of the 24 hour period when the slightly higher evening demand facilitates a load to be shifted off, resulting in a better match for the last two or three hours.

Overall the net outcome of the test has reduced the peaks of the demand profile, but has resulting in the raising of the average demand to a level of 1.5 to 2 kW.

This test of the Target Value control method has produced a Shared Area of 64.44, with an Excess Supply of 10.58. The Total Power before Load Shifting was 17.86 kWh and after Load Shifting was 38.07kWh. The file DSM Test – Target is available to download from the ESRU website.

The match characteristics imply that there is a good match between the supply and demand, but the 213% increase in demand cannot be ignored. This is far outside the limit of ± 10% although a degree of mismatch was to be expected due to an extremely changeable demand profile and a flat target value.

Using an approximate price of £0.05 per kWh unit, the 213% increase in demand would represent the running costs increasing from £0.89 to £1.90 per day.

Variable Supply Profile

The simulated domestic demand profile was kept from the fixed target value test. The supply from renewable sources was configured to represent a combination of $4m^2$ PV panels and a 3kW wind turbine.

A supply of this size and composition is particularly representative of equipment currently available for the domestic market. Once again the supply output from the PV was the sunny day data set.

The varying nature of the renewable supply offers opportunities for the shifting of loads on and off over the 24 hour period. The supply and demand can be seen in Figure 8.3.

The demand follows the rapidly changing supply profile closely over the course of the 24 hours. However the demand retains the characteristic

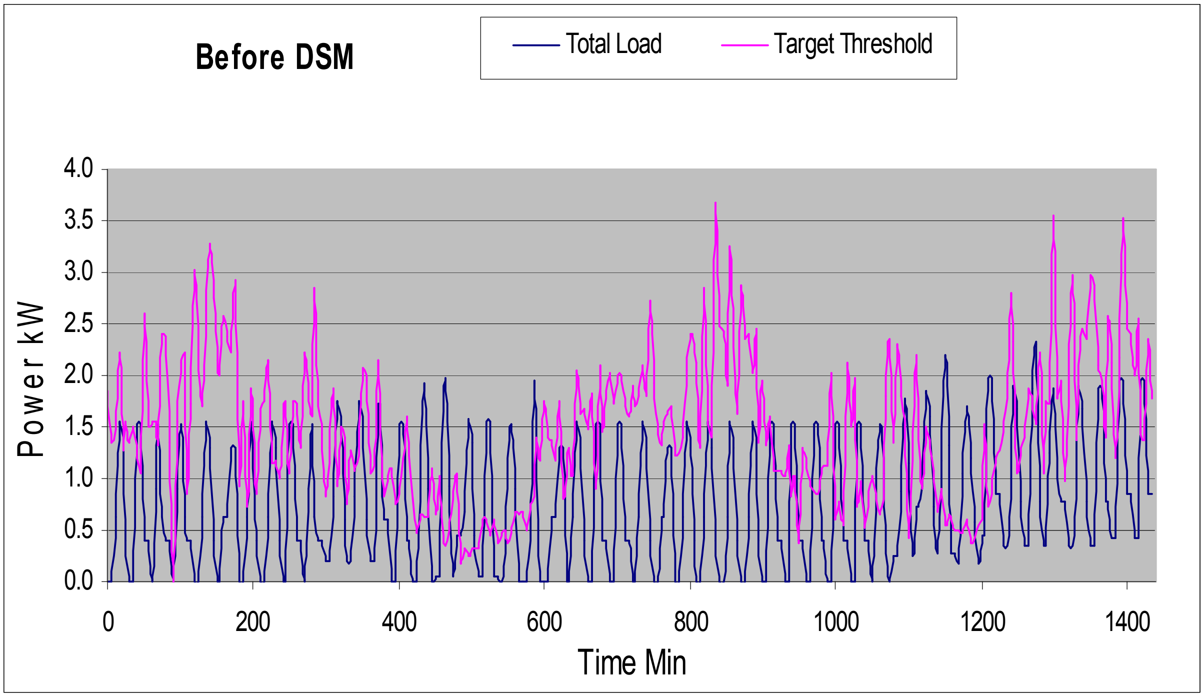


Figure 8.3 – Load scheduling before match output test

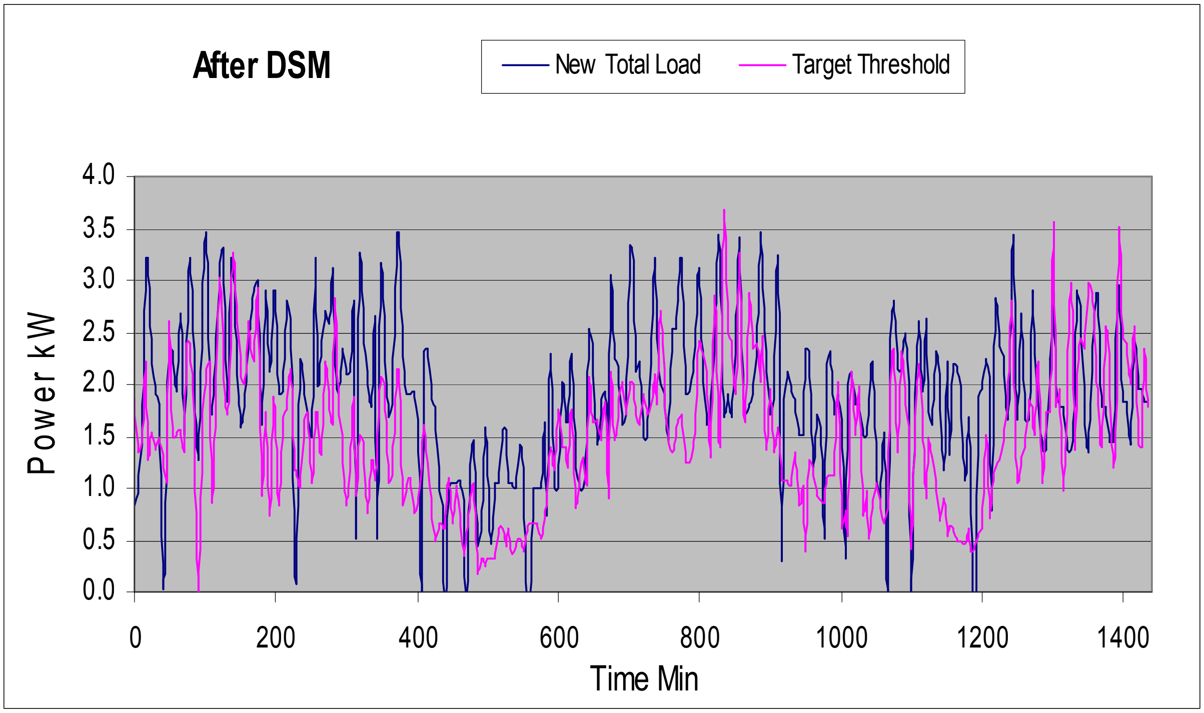


Figure 8.4 – Load scheduling after match output test

exhibited earlier, where loads are shifted above the level of available supply. In this instance it is justified because the conservative load shifting has been carried out with the intentions of protecting network stability.

This test of the Match Output control method has produced a Shared Area of 58.06, with an Excess Supply of 100. The Total Power before Load Shifting was 17.86 kWh and after Load Shifting was 45.83kWh. The file DSM Test – Wind and Solar is available to download from the ESRU website.

The visual match suggests that the overall match between supply and demand is better than that shown by the results. Once again there are reasonable matches between Shared Area and Excess supply, but there is a large increase in demand. This test resulted in an increase in shifted demand over scheduled demand of 257%.
Using an approximate price of £0.05 per kWh unit, the 257% increase in demand would represent the running costs increasing from £0.89 to £2.29 per day.

Chapter 9

Conclusions and Recommendations

The testing of the algorithm has shown that an algorithm can shift loads on and off in order to match a single target value or follow the output from renewable energy generation.

However it has also shown that the control system needs to be tuned and adapted for the number of loads within the bank of loads which will be load shifted. Close attention must also be paid to the type of supply and demand profiles which are attempted to be matched.

The customer must also decide the level of caution to use when operating this system to prevent an increase in overall demand.

This study showed that there was little of no energy saved and the overall running costs of the modelled households increased dramatically.

The algorithm also reminds us that a degree of storage is essential to facilitate supply demand matching. Using a DSM algorithm to control a system with a large amount of generation from renewable sources, but not employing any form of storage, is possible but needs further investigation.

To use an algorithm as a DSM measure is possible but the degree of control and control requirements need refining. The control mechanisms that I used in the algorithm were not robust enough to prevent further loads being shifted on when there was a need.

The algorithm appeared to be better at load shifting than shedding, which may have originated in my control settings. In future it is recommended that less conservative control settings are used.

Once again this is an interesting area that is likely to develop in the future as further efficiencies are being sought and a specialised control algorithm for rapidly changing load profiles could be the subject for further investigation.

The load shifting methodology, with its built in restraint worked particularly well in allowing demand to be manipulated to follow a target value or profile.
It has identified that there will always be the potential for an increase in overall demand with the use of a control algorithm because it looks to protect the system.
For load shifting to obtain a good match between supply and demand profiles there needs to a large range of loads available, especially where the average amount of energy consumption is low, for example in households.

It would be interesting to develop the shifting methodology further for a larger total demand. If it were used to represent a community, the larger distribution of loads contained within the community may lead to larger efficiencies. The increasing number of community wind turbines could provide the input for this model.

An alternative area for development would be to develop an algorithm which could be used for the shedding of appliance loads, but shedding load for a shorter period of time. Once again this would need to be investigated on a larger scale because a scheme of this type which results in smaller amounts of loads shed will need a larger number of willing participants.

Appendix A: Users Guide to the Algorithm

DSM Software tool V.1

General

This tool should be viewed as any other spreadsheet, in that, it contains formula, which in the unfortunate event are overwritten, will mean the tool will not function as intended. It is therefore essential to always save a back up copy of the tool before commencing work.

The tool should be treated as any other spreadsheet file, in that when data has been entered it is essential to save the file as something appropriate, utilising the usual 'Save As' Windows function.

If you wish to use the tool again after it has been renamed, you will need to update file names in Module 2 of the macro.

Instructions

To use the DSM tool please follow the procedures below to ensure that the tool will replicate the user’s situation or environment as accurately as possible.

1. Review the selection of loads in the Load Properties worksheet and manually enter any change of details if required.

2. Schedule loads according to their normal use over the 24-hour period in the Appliance Schedule worksheet.

Copy the blue Load kW value at the head of each column into the timestep cell where the load will be in use. Repeated this for each appliance that is present. If one of the appliances entered into the cell at the head of each column is not present, enter a zero into every timestep cell for that appliance.

3. Select the method of control method, Target Value or Match Output from the Demand Profile worksheet.

Target Value will stabilise the demand at a set value, which is entered in the box to the right of the target symbol.

To select the Target Value control, click on the target symbol.

Match Output allows the demand to follow the output from a varying source, such as the power supplied from renewable generation. However, in order to use this control method, a supply profile must first be constructed in the Supply Profile worksheet that will represent the output from existing or proposed renewable generation on the site.

To select the Match Output control, click on the wind turbine symbol.

4. Ensure the Shifted Array worksheet equals the Schedule Array worksheet for the initial timestep. Press the reset button on the Demand Profile worksheet to make the two worksheets equal.

5. Once the tool is configured for use the process can be started by pressing the Shift Loads button on the Demand Profile worksheet.

Appendix B: List of Variables

```
'Loads that can be shifted

'CF - Chest Freezer
'FF - Fridge Freezer
'RF - Refrigerator
'TV - Television
'DW - Dishwasher
'TD - Tumble Dryer
'WD - Washer Dryer
'WM - Washing Machine
'OV - Electric Oven
'SH - Electric Storage Heating
'HW - Electric Water Heating


'Target - Target Power Demand
'Power - Current Demand
'Timestep - 5 minute period of time

'App Array

'Appliance - Appliance
'Load - Load per appliance per 5 min timestep
'Priority - Load Priority 1-3. 1 is high
'SUnit - Shift Unit, Amount of time that individual appliances can be shifted by
'Use - Load in Use
'SStatus - Shift Status, Whether the appliance is able to be shifted, 1 = not able.
'SStatusTime - Time Use changes to 1
'SStatus0 - Time Use changes back to 0

'### NB Array names refer to the Priority, Use or place where they originated, not the future purpose of the contents.
'### eg If a Priority 2load needs to be shifted off, it will be selected from the contents of LoadsAvaliableP2OnArray(12).

'### AppArray
Dim Timestep, Use, Priority, SUnit, SStatus, SStatusTime, SStatus0 As Double

'### axes x,y,z =  appliance, timestep, property
'### Appliance Array - initial appliance settings
Public AppArray(289, 11, 8) As Double


''### PowerArray
'Public PowerArray(288) As Double
```

```
'### PShift Arrays
Dim SheduleApplianceRowNo As Integer

Public LoadsAvaliableP2OnArray(12) As Double
Dim LoadsAvaliableP2OnNo As Integer
Public LoadsAvaliableP2OnCountArray(288) As Integer
Dim LoadsAvaliableP2OnCount As Variant

Public LoadsAvaliableP3OnArray(12) As Double
Dim LoadsAvaliableP3OnNo As Integer
Public LoadsAvaliableP3OnCountArray(288) As Integer
Dim LoadsAvaliableP3OnCount As Variant

Public LoadsAvaliableP2OffArray(12) As Double
Dim LoadsAvaliableP2OffNo As Integer
Public LoadsAvaliableP2OffCountArray(288) As Integer
Dim LoadsAvaliableP2OffCount As Variant

Public LoadsAvaliableP3OffArray(12) As Double
Dim LoadsAvaliableP3OffNo As Integer
Public LoadsAvaliableP3OffCountArray(288) As Integer
Dim LoadsAvaliableP3OffCount As Variant

Public P2OnLoadSelectArray(12) As Double
Dim P2OnLSArrayNo As Single
Public P3OnLoadSelectArray(12) As Double
Dim P3OnLSArrayNo As Single
Public P3OffLoadSelectArray(12) As Double
Dim P3OffLSArrayNo As Single
Public P2OffLoadSelectArray(12) As Double
Dim P2OffLSArrayNo As Single


'### PowerResultArrays: 1 - Dim PowerResultOn, 2 - Dim PowerResultOff, 3 - Dim PowerResultNoAction

Public PowerResultArray1(3) As Variant
Dim PowerResultOn1 As Double
Dim PowerResultOff1 As Double
Dim PowerResultNoAction1 As Double

Public PowerResultArray2(3) As Variant
Dim PowerResultOn2 As Double
Dim PowerResultOff2 As Double
Dim PowerResultNoAction2 As Double

Public PowerResultArray3(3) As Variant
Dim PowerResultOn3 As Double
Dim PowerResultOff3 As Double
```

```
Dim PowerResultNoAction3 As Double

Public PowerResultArray4(3) As Variant
Dim PowerResultOn4 As Double
Dim PowerResultOff4 As Double
Dim PowerResultNoAction4 As Double

Public PowerResultArray5(3) As Variant
Dim PowerResultOn5 As Double
Dim PowerResultOff5 As Double
Dim PowerResultNoAction5 As Double

Public PowerResultArray6(3) As Variant
Dim PowerResultOn6 As Double
Dim PowerResultOff6 As Double
Dim PowerResultNoAction6 As Double

Public PowerResultArray7(3) As Variant
Dim PowerResultOn7 As Double
Dim PowerResultOff7 As Double
Dim PowerResultNoAction7 As Double

Public PowerResultArray8(3) As Variant
Dim PowerResultOn8 As Double
Dim PowerResultOff8 As Double
Dim PowerResultNoAction8 As Double

Public PowerResultArray9(3) As Variant
Dim PowerResultOn9 As Double
Dim PowerResultOff9 As Double
Dim PowerResultNoAction9 As Double

Public PowerResultArray10(3) As Variant
Dim PowerResultOn10 As Double
Dim PowerResultOff10 As Double
Dim PowerResultNoAction10 As Double

'### From Load Shifting
Dim Power, Load, Target As Variant
Dim PowerResult As Variant
Dim PowerTargetRowNo As Integer

Dim RandomP2OnLoad As Variant
Dim RandomP2OnLSArrayNo1 As Variant
Dim RandomP2OnLSArrayNo2 As Variant
Dim RandomP2OnLSArrayNo3 As Variant
Dim RandomP2OnLSArrayNo4 As Variant
Dim RandomP2OnLSArrayNo5 As Variant
```

```
Dim RandomP3OnLoad As Variant
Dim RandomP3OnLSArrayNo1 As Variant
Dim RandomP3OnLSArrayNo2 As Variant
Dim RandomP3OnLSArrayNo3 As Variant
Dim RandomP3OnLSArrayNo4 As Variant
Dim RandomP3OnLSArrayNo5 As Variant

Dim RandomP2OffLoad As Variant
Dim RandomP2OffLSArrayNo1 As Variant
Dim RandomP2OffLSArrayNo2 As Variant
Dim RandomP2OffLSArrayNo3 As Variant
Dim RandomP2OffLSArrayNo4 As Variant
Dim RandomP2OffLSArrayNo5 As Variant

Dim RandomP3OffLoad As Variant
Dim RandomP3OffLSArrayNo1 As Variant
Dim RandomP3OffLSArrayNo2 As Variant
Dim RandomP3OffLSArrayNo3 As Variant
Dim RandomP3OffLSArrayNo4 As Variant
Dim RandomP3OffLSArrayNo5 As Variant

'### Change load attributes
Dim ChangeUseStatusLoadNo As Integer

'### Move to next priority level
Public ChangePriorityLevelArray(2) As Integer

'### Load equal, move to next timestep
Public TargetLoadEqualArray(2) As Integer

'### Provision for 5 Load Shifts
Dim NewPower1 As Double
Dim NewPower2 As Double
Dim NewPower3 As Double
Dim NewPower4 As Double
Dim NewPower5 As Double
```

Appendix C: Subprogram Functions

Subprogram Main

```
Sub Main()

Timestep = 1

        '### Set the ApplianceArray
        ReadCFPropertiesTS1
        ReadFFPropertiesTS1
        ReadRFPropertiesTS1
        ReadTVPropertiesTS1
        ReadDWPropertiesTS1
        ReadTDPropertiesTS1
        ReadWDPropertiesTS1
        ReadWMPropertiesTS1
        ReadOVPropertiesTS1
        ReadSHPropertiesTS1
        ReadHWPropertiesTS1

         '### Count Loads available for shifting and sends to a worksheet
        CountP2OffTS1
        CountP2OnTS1
        CountP3OffTS1
        CountP3OnTS1

        LoadsAvaliableP2Off
        LoadsAvaliableP3Off
        LoadsAvaliableP3On
        LoadsAvaliableP2On

        '### Comparing and shifting loads
        PowerTargetComparison

         '### Updating Arrays
         UpdateUseP2PTLowShiftOn
         UpdateUseP3PTLowShiftOn
         UpdateUseP3PTHighShiftOff
         UpdateUseP2PTHighShiftOff

         UpdateAppArray

         CountP2Off
         CountP2On
         CountP3Off
         CountP3On

         LoadsAvaliableP2Off
```

```
         LoadsAvaliableP3Off
         LoadsAvaliableP3On
         LoadsAvaliableP2On

For Timestep = 2 To 288

        '### Set the ApplianceArray
        ReadCFProperties
        ReadFFProperties
        ReadRFProperties
        ReadTVProperties
        ReadDWProperties
        ReadTDProperties
        ReadWDProperties
        ReadWMProperties
        ReadOVProperties
        ReadSHProperties
        ReadHWProperties

        '### Count Loads avaliable for shifting and sends to a worksheet
        CountP2Off
        CountP2On
        CountP3Off
        CountP3On

        LoadsAvaliableP2Off
        LoadsAvaliableP3Off
        LoadsAvaliableP3On
        LoadsAvaliableP2On

        '### Comparing and shifting loads
        PowerTargetComparison

         '###Updating Arrays
         UpdateUseP2PTLowShiftOn
         UpdateUseP3PTLowShiftOn
         UpdateUseP3PTHighShiftOff
         UpdateUseP2PTHighShiftOff

         UpdateAppArray

         CountP2Off
         CountP2On
         CountP3Off
         CountP3On

         LoadsAvaliableP2Off
         LoadsAvaliableP3Off
         LoadsAvaliableP3On
         LoadsAvaliableP2On
```

```
Next Timestep

    '### Send the ApplianceArray to a worksheet
       WriteCFProperties
       WriteFFProperties
       WriteRFProperties
       WriteTVProperties
       WriteDWProperties
       WriteTDProperties
       WriteWDProperties
       WriteWMProperties
       WriteOVProperties
       WriteSHProperties
       WriteHWProperties


End Sub
```

Appendix D: An Example of Load Shifting

In order to follow the load shifting process in more detail, the Power Target Comparison (PTC) process will be applied to an example where the value of Power (P) is less than Target (T). In this example P2 loads will be shifted on first and supplemented by P3 loads if required.

Priority 2 Loads

Shift 1

PTC compares P and T and finds P lower than T. PTLowShiftOnP2 is called from within PTC.
A load is selected at random from the available P2 loads in P2OffLoadSelectArray. The load is selected by generating a random number, LSArrayNumber, from 0 to the maximum number of available P2 loads. The maximum number of P2 Loads can be found in the variable LoadsAvaliableP2OffCount.

Shifted Use compared with Scheduled Use

Once a load is selected, the number of timesteps when the load has been used is compared with the number of timesteps it was scheduled to be used. If the load's use is less than the number it is scheduled for, then it will not be put forward for load shifting. Another load will be selected and its use compared to its scheduled use as before. If after the three attempts a suitable load cannot be found then the function will send a NA – Not Applicable, to the relevant cells in the Target and Shifted Profile worksheet.
A variable named ChangePriorityLevel will then be changed from 0 to 1 and the function will exit and return to PTC.

However in this case a suitable load is selected and the load with the LSArrayNumber is selected, the value of the load added to the Power variable and the result stored in PowerResultArray1 (1). The contents of this array are then sent to the Target and Shifted Profile worksheet.
Shift 1 exits and returns to PTC.

Shift2

At the start of the function, the values of the variables are checked. If the variable Target Load equal Array = 1 then the function exits and returns to PTC.
If the variable Change Priority Level = 1 then the function will exit and return to PTC.

PTC compares P and T again and finds P lower than T. PTLowSecondShiftP2 is called from within PTC.
A load is selected at random from the available P2 loads in P2OffLoadSelectArray.

If the LSArrayNumber is not the same as that generated previously then Shifted Use is less than Scheduled Use, the function proceeds as before. The load with this LSArrayNumber is selected, the value of the load added to the Power variable and the result stored in PowerResultArray2 (1). The contents of this array are then sent to the Target and Shifted Profile worksheet.
Shift 2 exits and returns to PTC.

Repeating Random Selection

However if an LSArrayNumber is generated which is the same as Shift 1's LSArrayNumber, then a second random LSArrayNumber is generated. Once again this is compared with Shift 1's LSArrayNumber. If the second random number is the same as Shift 1's LSArrayNumber, then a third and final random LSArrayNumber is generated. This is then compared with Shift 1's LSArrayNumber.
If this final random LSArrayNumber is the same as Shift1's LSArrayNumber, then the function will send a NA – Not Applicable, to the relevant cells in the Target and Shifted Profile worksheet.
The ChangePriorityLevel variable will then be changed from 0 to 1 and the function will exit and return to PTC.

Shift 3

PTC compares P and T again and finds P lower than T. PTLowThirdShiftP2 is called from within PTC.
The value of the variable ChangePriorityLevel is checked. If it is 0, then the function proceeds as before, generating a random LSArrayNumber and comparing it to previous LSArrayNumbers, creating another random LSArrayNumber should it be necessary. A load will then be selected and added to PowerResultArray3 or the value of the variable ChangePriorityLevel will be changed and the function exited.
If the value of ChangePriorityLevel = 1, then the function will send a NA – Not Applicable, to the relevant cells in the Target and Shifted Profile worksheet.
The function will then exit and return to PTC.

Shift 4 and Shift 5

The process will continue, with loads being shifted on until P is within tolerance of T, until there are no more P2 loads to be shifted or the P2 shifting functions have been exited because the variable ChangePriorityLevel = 1.

Priority 3 Loads

The ChangePriorityLevel variable is reset to 0.
The process then follows the same procedures as PTLowShiftOn, with the exception that the Arrays and Count variables reflect the change in priority from P2 to P3.
For example, for the PTLowShiftOnP3 function will use P3OffLoadSelectArray and LoadsAvaliableP3OffCount.

The Values for the P3PowerResultArray will increase from the last P2 PowerResultArray, (PowerResultArray5), to PowerResultArray6. All of the values from the arrays will still be sent to Target and Shifted Profile worksheet.

If the value of the ChangePriorityLevel variable changes from 0 to 1 and if P is within tolerance of T, then P=T, Power = Target will be sent to the relevant cells in the Target and Shifted Profile worksheet.
The function will then exit and the algorithm will then move to the next timestep.

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