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ANALYSIS AND OPTIMISATION OF RETROFIT AND ENERGY SUPPLY STRATEGY ACROSS A DIVERSE URBAN BUILDING PORTFOLIO

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ABSTRACT

This paper presents a study in support of decision making for building retrofit and energy supply strategy at the Royal Botanic Gardens, Kew in southwest London, England. The study considers the issues that affect simulation at the building scale specific to this site, in particular simulation of heat flow in botanical glasshouses, retrofit of heritage structures and simulation of power load for buildings with high equipment density. In addition, the study considers the potential benefits to be gained from energy microgeneration and supply at the district scale, investigating supply optimisation for a cluster of buildings within the Kew site.

INTRODUCTION

The Royal Botanic Gardens at Kew (Kew Gardens) form an internationally renowned botanical research and education institute, comprising 121 hectares of gardens and botanical glasshouses. It is an energy intensive site; the glasshouses require strict regulation of internal temperature and humidity in order to protect and preserve plants from all over the world, and there are research laboratories and archive facilities which require strict environmental controls. Together with the administrative and leisure spaces, there are more than 50 buildings of which many are of historic importance recognised by the English Heritage Grade I and II listing and World Heritage Site status.

With such a varied and demanding building stock, it is important to prioritise a programme of building improvements based on an understanding of the building performance criteria, development restrictions and the potential efficiencies to be derived from considering buildings in groups. This study aims to improve understanding of the significant parameters by using simulation of building energy consumption to assess the effect of viable retrofit technologies, both at the building level and the district level. The challenges in using such an approach are threefold:

- simulating heat transfer in a glasshouse requires development of a stand-alone model;
- simulation of power loads for a building with high equipment density requires a representation of the stochastic nature of the demand;
- the heritage status of the site imposes restrictions on the suitability of certain retrofit technologies.

However, as an organisation, Kew Gardens are committed to reduction of carbon emissions which justifes investigation of retrofit options. Significant financial and legislative drivers also exist; Kew Gardens are subject to the UK Government's 'Greening Government Commitment' which requires a reduction in greenhouse gas emissions of 25% by 2015, relative to a 2009/2010 baseline. In addition, they are a mandatory participant in the UK Carbon Reduction Commitment scheme, which requires all large organisations supplied more than 6000MWh of electricity in 2008 to monitor emissions and purchase allowances for every tonne of CO_2 emitted.

A description of the site is given first, followed by details of the simulations performed at the building scale and the retrofit opportunities identified. District energy supply network optimisation studies are then described, and the optimal supply strategies for minimising cost and carbon emissions within the current UK legislative framework are identified.

THE ROYAL BOTANIC GARDENS, KEW

The Kew site is illustrated in Figure 1. The map shows the site extending alongside the River Thames, and indicates the location of some of the main buildings. There are 3 large glasshouses, namely the Palm House (building 1 on the map), the Temperate House (2) and the Princess of Wales Conservatory (POWC) (3). These three glasshouses present a significant heat demand, with the POWC alone consuming 32% of the total gas consumption for the site and generating 11% of the building-related carbon emissions. By comparison, the Jodrell Laboratory (4), which is the principal research building, is the most significant power consumer on site, consuming approximately 15% of the total electricity usage and generating 10% of the carbon emissions.

Over the years, continuous expansion has resulted in new buildings and changing functions of some of the older buildings, resulting in ad hoc extension to gas and electricity supply networks. Efficiencies could potentially be achieved from supplying energy to clusters of buildings located in close physical proximity. The cluster of buildings around the Jodrell Laboratory is highlighted on the map. This includes the laboratory itself, the POWC, the School of Horticulture (9), plant nurseries (6) and administrative buildings (5, 7 and 8),

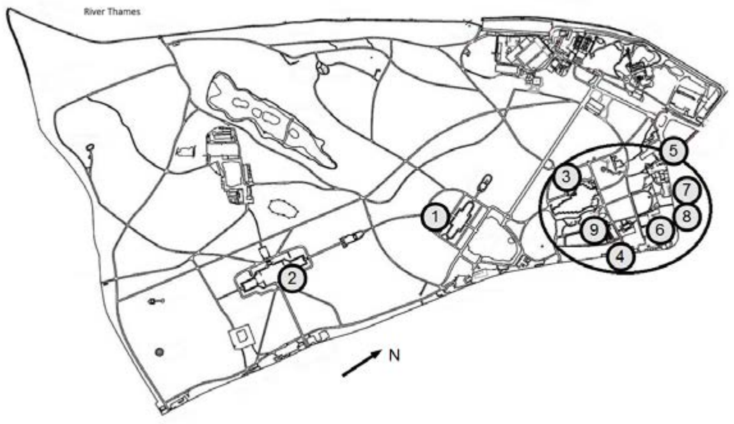

Figure 1: Royal Botanic Gardens, Kew, London

and represents the highest consuming area within the site.

BUILDING SCALE SIMULATION

Energy Demand of Glasshouses

The primary energy demand for a glasshouse is for heat. In order to simulate the flow of heat through a glasshouse it is necessary to include the interaction of the vegetation with its surroundings, specifically the heat and mass flow due to transpiration. This is not included in typical building simulation models, and hence a stand-alone model has been developed (Brown et al., 2012), to be applicable to ornamental glasshouses such as buildings 1-3 in Figure 1. The model has been adapted from the Gembloux Dynamic Greenhouse Climate Model (GDGCM)(Pieters et al., 1996; Pieters and Deltour, 1997) which was originally created for application to commercial greenhouses. It is a one-dimensional model, composed of a system of differential equations calculating the temperature variation in defined layers of the greenhouse with time, subject to boundary conditions of the external weather conditions and the deep soil temperature. For each layer, namely soil, vegetation, internal air and cover, a heat balance equation is defined, together with a mass balance equation for the moisture content of the internal air. The GDGCM has been adapted to simulate a greenhouse with multiple internal zones, using a U-value calculation to simulate heat flow between the zones, and to account for solar gains on a number of different surfaces of different tilt and orientation.

As ventilation control and reduction of infiltration of external air through the building envelope are important potential retrofit technologies, it is necessary to include a representative assessment of ventilation and infiltration in the simulation. The model has been adapted to simulate the opening and closing of air vents by varying the ventilation rate with the temperature of the internal air. Below a defined set-point temperature, a minimum value corresponding to the flow rate associated with the mechanical ventilation is assumed. Above this value, a ventilation rate proportional to the difference between the actual inside air temperature and the ventilation set-point temperature is calculated, representing the opening of vents. At a defined temperature, it is assumed that all windows are open, and that a maximum possible ventilation rate, $R_{a,max}$, is achieved.

Infiltration has been simulated by calculating the contributions from wind pressure and stack effect according to external and internal wind speed and temperature. The flow rate has been simulated using the crack flow equation (Hagentoft, 2001).

As an example, consider the POWC. This is a complex glasshouse, composed of 10 zones, each maintained at a different temperature and humidity in order to replicate various climatic conditions from around the world. For this study the six largest zones were simulated, representing 97% of the total floor area. Set-point temperatures are detailed in Table 1. The ventilation set-point temperatures for each zone were set to be 4°C above the daytime set-point value. The minimum ventilation rate has been assumed to be currently zero, while the maximum ventilation rates, shown in the table, are calculated based on the vent opening area of each zone, and are assumed to be reached once the internal air temperature reaches a value of 10 °C above the ventilation set point temperature.

Table 1: Zone set point temperatures

Zone	Climate	Day (°C)	Night (°C)	$R_{a,max}$ (ACH)
1	Wet tropics	20	18	53
2	Winter garden	20	18	65
3	Dry topics	14	12	104
4	Tropical ferns	22	18	77
5	Temperate ferns	15	13	36
6	Tropical orchids	21	18	43

Infiltration has been calculated and added to these ventilation rates to estimate the overall fresh air rate for each zone. The POWC is constructed from overlapping panes of glass with seals to fill in the gaps between the panes. Over the years the seals have degraded to an extent where the gaps between the panes are up to 8mm in places. Infiltration has been calculated at each timestep according to the temperature and wind conditions, assuming that the mean gap depth is 4mm. This approach gives rise to typical mean infiltration values of between 1.6 and 2.2 ACH for the different zones, with minimum values of around 0.1 ACH and maximum values of 8.2 ACH.

The simulation outputs temperatures in each layer through time together with the heat required to maintain set point temperatures in each zone. Factoring the data up to incorporate the additional 4 zones, estimating boiler efficiency at 85%, and including an estimated value for water heating based on the summer metered gas consumption, the predicted gas consumption can be calculated for comparison against metered data, as shown in Figure 2 for a period from February 2009 to January 2010.

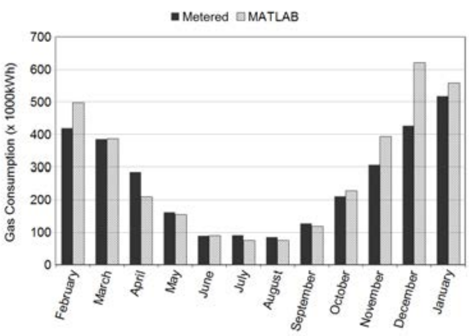

Figure 2: Simulated and metered gas consumption

The simulation is overpredicting gas consumption in the latter half of the year, but overall the agreement is good. Over the 12 month period considered, the total consumption predicted by the model is 3161MWh compared against a metered value of 3109MWh, a difference of 2%. The overprediction in the winter months could be due to heat retained by the soil being released during the winter months, and could also be due to a confirmed inability of the current heating regime to maintain set-point temperatures at all times, implying that the heat demand is not being matched by the heat supplied.

Energy Demand of Non-Horticultural Buildings

The primary energy demand of the remaining buildings at Kew depends on their function. The Jodrell laboratory is the principal research facility on site and is a mixed-use space consisting of laboratories, meeting rooms, offices and a lecture theatre. The laboratory was constructed in three phases; the original building was built in 1965, it was extended in 1994 and in 2004 the Wolfson wing was added to enable expansion of the research facilities and to house the library of fungi specimens which is maintained under strict environmental conditions. The power demand is substantially higher than the heat demand and it is therefore necessary to develop a validated simulation model which allows assessment of retrofits designed to reduce power consumption. While gas consumption is determined by the external weather conditions and the building fabric heat transfer, and can be simulated reasonably accurately by a deterministic model, the power demand is dependent on the power rating of equipment and how it is used by the building occupants so there is an inherent variability in the consumption pattern which cannot be represented deterministically.

A stochastic model, DELORES, has been used in order to investigate the impact of changes to lighting and laboratory equipment (Rysanek and Choudhary, 2012). For appliance loads, the approach uses a probabilistic modelling strategy in which the equipment is parametrised by power rating and operational probability. Two layers of decisions govern the demand for a particular appliance at a given time; one at the daily and weekly level and the other at a monthly level. Each day is divided into three periods, daytime, evening and overnight, and the week is divided into weekday, Saturday or Sunday, thus giving 9 possible time periods in each week. In each time period, any item of equipment can be in one of three states, namely off, standby or on, and monthly variations are specified to account for holidays and other known periods of reduced consumption. The power demands of each item of equipment under off, standby and operational conditions are defined, and it is also necessary to specify, for a given time period, the probability of the item of equipment changing state e.g. from on to off or standby. For example, desktop computers are assumed to have a 90% probability of being on during the day, a 50% chance of being switched off in the evening and no change in status overnight i.e. if they are on they stay on and vice versa. Lighting is also simulated stochastically, parametrised by power rating and operational probability in each zone, which may be temporal or dependent on zone occupancy.

For each building zone equipment density has been specified according to supplied data. Typical power ratings have been collated from manufacturers' data and literature searches. Cooling and ventilation system power consumption has been estimated from observed consumption and defined ventilation rates.The simulation outputs hourly electricity consumption as shown in Figure 3 compared against metered data for a typical week in March, 2010. The simulation predicts a wider diurnal variation than displayed in the metered data for this particular week, but the comparison of the monthly predicted electricity consumption against metered data given in Figure 4 indicates good agreement at this scale.

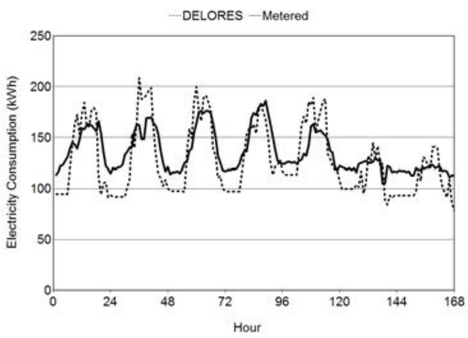

Figure 3: Typical week, March 2010

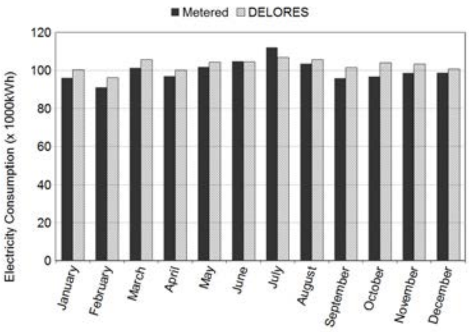

Figure 4: Simulated and metered power consumption

Significant quantities of electricity are consumed by fume hoods; two types of fume hoods are installed in the laboratory, fixed speed and variable speed, and the latter tend to be more energy efficient in operation even if peak rated power consumption is the same. The simulation reflects the increased probability of the variable speed fume hood being switched off or to low power between periods of high power usage. Validation of this approach has been supplied in the form of a trial in which the fume hoods throughout the building were switched off almost completely for 5 days.

Comparing the metered consumption against the predicted consumption for each part of the building with and without operational fume hoods gives the mean hourly power consumption values for day and night periods illustrated in Figure 5. Agreement between the simulation and the metered data is better before the switch-off, primarily because it wasn't possible to switch all fume hoods off completely in the trial, particularly in the Wolfson wing.

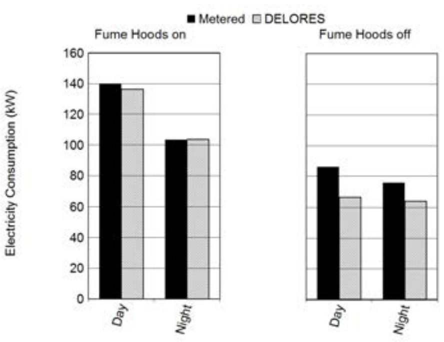

Figure 5: Mean hourly power consumption

Although the heat demand of the Jodrell laboratory is lower than the power demand, it is necessary to simulate the thermal performance of the building in order to assess the impact of building retrofits. The transient dynamic simulation environment TRNSYS (SEL, 1994) has been used to simulate the Jodrell Laboratory. Building fabric properties were estimated based on available drawings and site inspection; the three parts of the building were constructed in line with the building regulations imposed at the time, and as a consequence have different construction details and different thermal properties, as detailed in Table 2. No improvements to building fabric have been made since construction.

Table 2: Jodrell laboratory properties

Year	Wall U-value (W/m^2K)	Roof U-value (W/m^2K)
1965	1.67	0.90
1994	0.56	0.40
2004	0.32	0.17

The TRNSYS simulation was constructed using drawings and available data together with site observations and supplemented where necessary by the NCM database for non-residential buildings (Building Research Establishment, 2010). Appliance loads have been taken from the DELORES model. The simulation outputs heating and cooling demand for the period under consideration, as illustrated in Figure 6. The heating demand is considerably higher than the cooling demand, but is only 24% of that of the POWC and 8% of the site gas consumption. The predicted cooling demand is low as only a small proportion of the space is cooled.

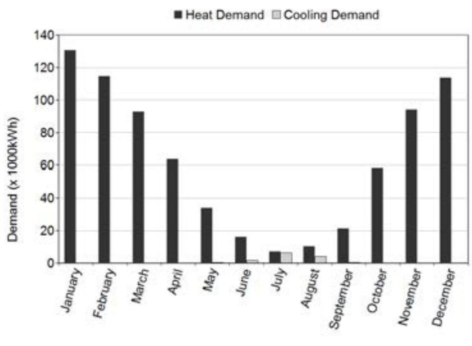

Figure 6: Simulated heating/cooling demand

Validation of this simulation is not straightforward as gas consumption data are not generally available, but confidence in the results can be derived from comparison against benchmark values (CIBSE, 2012). Combining the benchmarks for a higher education science laboratory, air-conditioned library and naturally ventilated office according to the area defined for each function within the building predicts a consumption of 154 kWh/m^2, compared against a value of 141kWh/m^2 predicted by TRNSYS. The only metered gas consumption data that are available are for the 2004 building from June 2012 onwards. A comparison of the simulation against the data is shown below. The model output overpredicts the gas consumption for the winter, possibly due in part to the difference between the weather data used and the unusually warm winter months experienced in the UK up to December 2012.

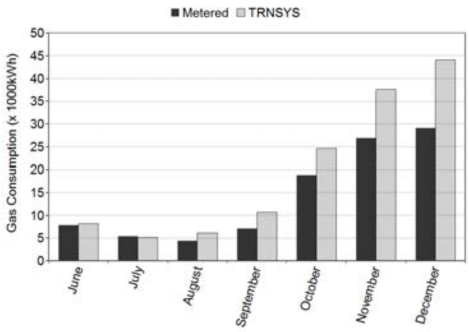

Figure 7: 2004 building - simulated and metered gas consumption

BUILDING RETROFIT

The retrofit technologies considered for each building are tailored to the building type, situation and occupant demand profile. For the POWC, retrofits need to address the thermal performance of the building without impacting on plant health, and are constrained by the heritage nature of the site. It was designed as an energy efficient building (Bunn, 1986), and operational controls are generally efficient, but temporal degradation has opened up some retrofit opportunities. The following retrofits have been considered:

- a 7% increase in boiler efficiency.
- reduction of infiltration, estimating 50% potential improvement from seal replacement.
- application of low-emissivity glazing film, resulting in a reduction of emissivity from 0.84 to 0.22.
- night-time shading, assuming that during the hours of darkness the emissivity is zero.

The impact of the retrofits are given in Table 3. The base gas consumption value for the POWC for the weather data file used is 3095MWh.

Table 3: POWC retrofit analysis results

Retrofit	Annual Gas Consumption (MWh)	Saving (%)
Improved boiler efficiency	2799	9.6
Infiltration reduction	2866	7.4
Low-E glazing film	2882	6.9
Night-time shading	2814	9.1
Combined	2219	28.3

It should be noted that not all retrofits have an additive effect; installation of low-E glazing film and night-time shading together, for example, will not result in a combined night-time reduction in heat demand as the night-time shading alone stops all heat loss. Based on the assumptions made, the single most effective retrofit would be to improve the boiler efficiency, but improvement of the glazing seal performance is the most cost-effective retrofit.

Whereas retrofit for the POWC aims to improve the thermal performance of the building, for the Jodrell laboratory reducing consumption requires reduction in lighting and appliance power ratings, together with improvements to control strategies, with no detrimental effect on the research processes being performed.

A recent programme of retrofitting lighting in the 1965 and 1994 parts of the building has been performed in which the fluorescent tubes have been replaced with energy efficient LED lighting. While laboratory equipment could be replaced with more energy efficient units as and when replacement is required, individual items of equipment typically consume a small percentage of the total consumption, and the impact of ad hoc replacement would only be significant after a large proportion of equipment was replaced. One project which could lead to significant improvements quickly would be a programme of improvement in fume hood efficiency. As seen in many other laboratories (Mills and Sartor, 2005), and observed in the switch-off, this could have a significant impact on the total power load. This has therefore been the focus of our retrofit strategy for the Jodrell laboratory. It has been assumed that all fixed-speed fume hoods are replaced by variable speed units, with a corresponding reduction in energy use.

Figure 8 illustrates the effect of the lighting improvement programme that has been performed, and the benefits that could be expected from a programme of fume hood efficiency improvement. The annual predicted saving in electricity demand is 5% for the LED lighting installation and a further 11% for the fume hood retrofits.

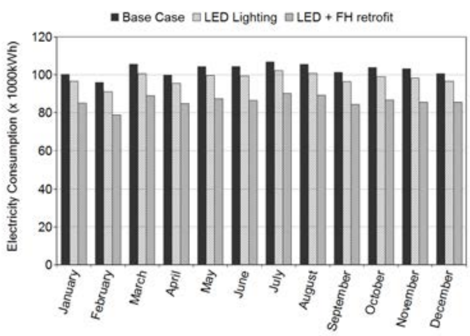

Figure 8: Retrofit comparison

While power loads are more significant, reduction of power consumption will also reduce the heat generated by the appliances and can lead to increased demand for space heating, just as improvements to the building fabric to reduce heat loss can lead to an increased need for cooling in summer. Consequently, it is also of benefit to explore the impact of these changes, together with retrofits intended to reduce the heat demand. The simplest and most cost-effective retrofit is to reduce set-point temperatures; daytime set-point temperatures currently range from 19 to 21^{o}C, so for the retrofit study, all have been reduced to 19^{o}C, set back to 10^{o}C overnight. Secondly, insulation in the oldest parts of the building can be improved; typically, addition of cavity wall insulation would reduce the U-value of the walls from 1.67 to 0.60 W/m^{2}K, and installation of mineral wool roof insulation would reduce the U-value of the roof from 0.88 to 0.32 W/m^{2}K. Finally, as for the POWC, the efficiency of the boilers could be improved. The impact of the retrofits on the gas consumption of the building are shown in Table 4.

Table 4: Jodrell laboratory retrofit analysis results

Retrofit	Annual Gas Consumption (MWh)	Saving (%)
Base case	888	0
Fume Hood retrofit	966	-8.8
Reduced set-point temperatures	748	15.8
Improved insulation	858	3.4
Increase boiler efficiency	821	7.6
Combined	732	17.6

The increased demand for space heating resulting from improved fume hood efficiency is clearly illustrated. However, in terms of carbon emissions the savings from the reduction in electricity consumption achieved by improving fume hood efficiency outweigh the effects of the increased gas consumption, giving a net annual saving of 55 tonnes CO_2. In addition, reducing the set-point temperatures alone could counteract this effect if 19^{o}C is comfortable for the building occupants, and it is a simple and cost-effective intervention.

DISTRICT SCALE SIMULATION

Further reduction in carbon emissions can be achieved from generating heat and power on-site using renewable technology, and maximum efficiencies can be derived from supply to buildings located in close proximity. The Jodrell cluster, comprising the laboratory, POWC and proximal buildings, generates 30% of the total building related carbon emissions for the site, and lends itself to examination of such a strategy.

Jodrell Cluster

Optimisation of a distributed energy network for the Jodrell cluster has been investigated using DENO, a Distributed Energy Network Optimisation model (Omu and Choudhary, 2013). This model uses the mixed integer linear programming approach to determine the optimal configuration of district energy systems to meet a local energy demand, depending on the spatial scale and local energy demands. It also includes the capability to investigate the impact of external factors such as government legislation on the technology selected. For example it allows examination of the benefits of the UK Government's Renewable Heat Incentive (RHI) scheme; this incentive is a long-term financial support programme for renewable heat, in which installation of qualifying technologies, including biomass boilers (including combined heat and power (CHP)), heat pumps and solar thermal collectors, is rewarded financially over a 20 year period. Tariff levels vary according to size and nature of the technology installed and can significantly impact on the cost-effectiveness of individual technologies.

This approach also enables investigation of whether retrofitting the buildings to reduce energy consumption has an impact on the microgeneration technologies selected for an optimum district energy network.

The Jodrell cluster consists of the Jodrell Laboratory and the POWC, together with a number of smaller administrative, horticultural and educational buildings as detailed in Table 5. The cluster has been selected according to building proximity; the maximum distance between any two buildings is 203m, keeping transmission costs to a minimum. The heritage nature of the site has a significant impact upon microgeneration possibilities; installation of wind turbines or photovoltaic panels is unlikely to be feasible for aesthetic reasons, and siting of energy plant has to be accommodated primarily in existing facilities. However there are non-public spaces which could be utilised in support of microgeneration e.g. for biomass fuel storage.

Table 5: Cluster buildings

Building	Distance (m)	Function
Jodrell Laboratory	0	Mixed-use
POW Conservatory	195	Glasshouse
Admin	203	Office
Melon Yard	50	Glasshouse
Cambridge Cottage	145	Event space
Technical House	60	Office
School of Horticulture	85	Education

The simulation requires as input hourly heating, cooling and power demands for a typical day in each of four three-monthly periods representing the seasons, together with the peak demand for the entire year. The validated simulations described previously have been used to define the power and thermal demands for the primary consumers. For the remaining buildings, power loads have been defined using metered data. The heating demand has also been defined using metered data where available, or factored from similar buildings according to area. Cooling demands have been assumed to be zero for all buildings apart from the Jodrell laboratory.

The optimisation is performed according to specified constraints. Initially, the Jodrell Laboratory and

POWC were considered together without the additional cluster buildings and the following scenarios were specified:

- Minimise cost with no emissions constraint - this is a base case
- Minimise cost subject to a 25% reduction in CO_2 emissions, using CHP and biomass technology, including the Renewable Heat Incentive
- Minimise cost subject to a 25% reduction in CO_2 emissions, using CHP and biomass technology, not including the Renewable Heat Incentive

These analyses were then repeated including the remaining cluster buildings. The use of heat pumps was also assessed but was not found to be an optimal choice for any of the scenarios analysed.

The results of the optimisation analysis before and after retrofitting any energy conservation measures are illustrated in Table 6. The results suggest that to minimise cost and carbon emissions, it would be optimal to install a biomass boiler and natural gas CHP plant, with sizing significantly affected by the availability of the RHI. Increased carbon emission reductions are predicted if the RHI is available and a larger biomass boiler can be specified. The analysis also predicts the best location for the plant, and in this case, all energy generation equipment would be situated at the Jodrell Laboratory, in line with the site constraints.

However, if the Jodrell laboratory and POWC are retrofitted according to our previous analyses, the power and heat demands drop significantly. The effect of this on the optimisation study is illustrated in the Table. Significantly, the power loads are such that if the RHI is available, it is not cost-effective to install a CHP plant. If the RHI is not available, a CHP plant is highlighted as being cost-effective, but the payback time is increased as the demands are lower. Note that the payback time does not include the cost of the building retrofits.

Extending the network to all proximal buildings produces similar results. Adding the current carbon emissions for the remaining cluster buildings to those of the Jodrell laboratory and POWC alone indicates that additional savings in CO_2 emissions between 5 and 16% can be made when considering the cluster as a whole.

CONCLUSIONS

This study has demonstrated a methodology for using simulation to assess the retrofit opportunities at the building scale and to investigate the district energy supply strategy for a building cluster. The potential for 5% reduction in the total Kew Gardens building related carbon emissions has been identified from a consideration of retrofitting just two buildings, the POWC and the Jodrell laboratory. Considering district energy supply to this area, a further 10% reduction may be achieved through specification of optimised renewable energy technologies namely a biomass boiler and CHP system. Together, carbon emission savings of 15%, over half the UK Government's target of 25% can be obtained from a retrofit strategy for this area of Kew gardens alone.

The analysis would be improved with the availability of more detailed energy consumption data to improve specification and validation of the models. Further analysis will focus on development of the glasshouse model to examine the effects of soil heat retention, and will encompass additional retrofit and microgeneration technologies not yet considered.

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Table 6: Energy supply optimisation results

Scenario	Jodrell Laboratory and POWC only					Cluster				
	Installed Capacity			CO_2 emission	Payback	Installed Capacity			CO_2 emission	Payback
	Heating (kW)	Cooling (kW)	Power (kW)	savings (%)	Time (Years)	Heating (kW)	Cooling (kW)	Power (kW)	savings (%)	Time (Years)
Pre-retrofit										
Minimise cost, no emissions constraint	2100 NGB	100 EC	-	-	-	2860 NGB	100 EC	-	-	-
Minimise cost 25% reduction CO_2 emissions, with RHI	1100 NGB 800 BB 130 CHP	10 AC 90 EC	100CHP	38	4.48	1660 NGB 1000 BB 130 CHP	10 AC 90 EC	100CHP	35	4.70
Minimise cost 25% reduction CO_2 emissions, no RHI	1600 NGB 210 BB 238 CHP	10 AC 90 EC	160 CHP	25	4.59	2090 NGB 400 BB 260 CHP	10 AC 90 EC	200 CHP	25	8.28
Post-retrofit										
Minimise cost, no emissions constraint	1560 NGB	100 EC	-	-	-	2320 NGB	100 EC	-	-	-
Minimise cost 25% reduction CO_2 emissions, with RHI	1000 NGB 600 BB	10 AC 90 EC	-	38	4.47	1490 NGB 800 BB	10 AC 90 EC	-	35	4.51
Minimise cost 25% reduction CO_2 emissions, no RHI	1120 NGB 200 BB 238 CHP	10 AC 90 EC	160 CHP	25	7.79	1760 NGB 310 BB 260 CHP	10 AC 90 EC	200 CHP	25	8.90

NGB Natural Gas Boiler BB Biomass Boiler CHP Conventional Combined Heat and Power AC Air Chiller EC Electric Chiller