Kings College Cambridge Decarbonisation Report

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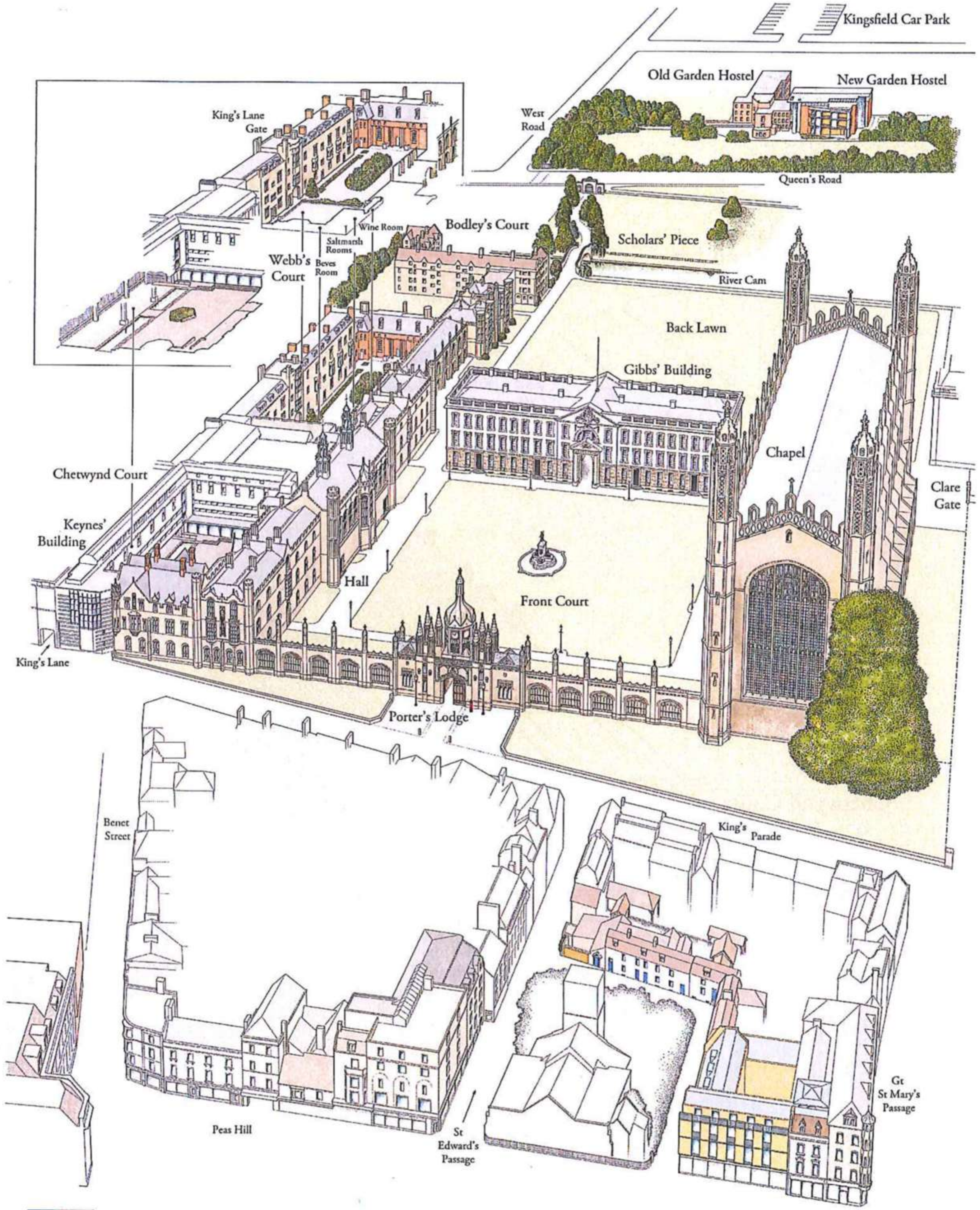
1.0 SUMMARY & SCOPE OF THE REPORT

King's College Cambridge site encompasses many different buildings, all with very high architectural standards. With the range of historic buildings every building has a differing energy demand, most of these historic buildings have high heating loads and high carbon footprints which is common with other contemporary buildings.

Max Fordham have been appointed to undertake an energy assessment and a decarbonisation overview of the whole estate.

This report sets out a high-level review of the whole site, current energy demand, the potential for improving energy losses, energy strategies and the potential contribution of self-generated electricity and overall operational carbon impact.



KING'S COLLEGE MAP

King's College, King's Parade, Cambridge, CB2 1ST

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2.0 CONTEXT

2.1 Climate emergency

Our reliance on carbon intensive energy has driven an increase in global temperatures. The current impact of our collective actions can be visualised with warming stripes, which portrays the long-term increase of average global temperature from 1850 to 2018

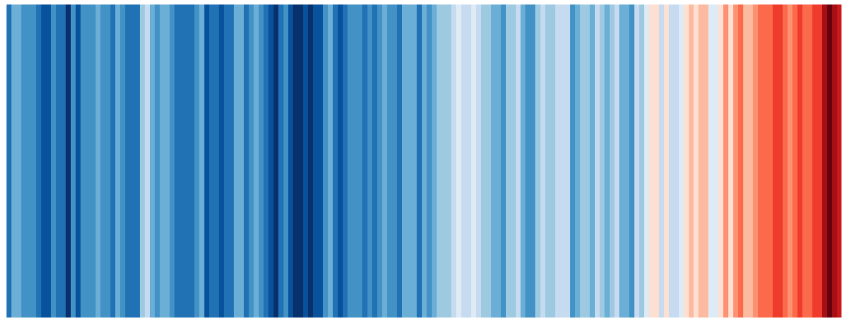

Figure 1
By Ed Hawkins, climate scientist at University of Reading

This is set to be a continuing trend unless more action is taken to reduce our carbon emissions via more efficient energy usage and a better renewable energy network.

2.2 Decarbonisation of heat

Heating has moved from being a luxury to now being considered a basic living standard. This has been aided by rise of gas in our heating network. Burning gas for heat releases CO_2 into the atmosphere. The best way to decarbonise heat is to electrify our heating network

2.3 Decarbonisation of grid supplied electricity

Until recently, any energy consumed either from electricity or heat came from burning fossil fuel that in turn releases Carbon Dioxide [CO_2]. The metric of kgCO_2/kWh (also called carbon intensity) is a measure of how much CO_2 is released to generate energy. One has to bear in mind that heat-energy and electrical-energy do not have the same usefulness or value. Burning one kWh of gas will produce nearly one kWh of heat, yet two to three kWh of gas are needed to make a single kWh of electricity.

The carbon intensity of electricity will depend on the method of generation. Coal fired generation is the highest, followed by gas-fired generation, while nuclear, wind and solar do not burn fossil fuels and are carbon neutral. The grid contains a mix of generators and its overall carbon intensity is an aggregate of its constituent generators carbon intensity. As coal-fired generation has reduced and more renewables have come on line, the average is falling as shown in Figure 2. The government has set out an ambition to continue this reduction until it is carbon free in 2050.

While the average grid intensity is falling, it is possible to buy electricity that has come from specific zero carbon sources. There are various ways of doing this.

2.4 Future of Distributed Energy

"Natural Gas" is almost pure methane [CH_4] and burning it produces heat, water and CO_2 in a constant ratio. Hydrogen [H_2] is a flammable gas that will burn to produce only water [H_2O]. It can be mixed in with natural gas to reduce the carbon intensity of the gas mixture. Up to 20% of the gas can be hydrogen without needing significant changes to the gas network and appliances. While 100% hydrogen is possible, the grid and appliances [boilers, cookers etc.] will need modifications to cater for the change.

Hydrogen is not naturally occurring in any quantity and has to be manufactured. Using renewable electricity to break up the water molecule to make "renewable" hydrogen makes it a zero carbon fuel and energy store. The longer term value of hydrogen is being able to store and distribute the energy in a similar way to natural gas currently. However, it is not an efficient process. Producing hydrogen requires four to six times as much electricity as a heat pump to produce the same amount of heat.

As we move to electrifying our heat the national grid will need to react and expand to compensate for the increased load.

In order to reduce carbon emissions as quickly as possible heat should be produced from electrically driven heat pumps as the lowest source of carbon. Hydrogen may become available in a gas grid but there is currently no defined strategy or timescale for this.

2.5 The costs of carbon emissions - offsetting, taxation, repairing environmental damage

The cost of carbon is a measure of the future economic and social harm from those impacts. As the climate changes, extreme weather events are becoming more likely, so it becomes our responsibility to reduce our impact to a more sustainable level.

Offsetting costs reduce with higher performing buildings as the operational carbon emissions are lower. Offsetting costs are variable, but the UK Green Building Council recommends using a value of £80/tonne/year. It is currently possible to buy offsets at less than £10/tonne/year. A German study has valued the cost of lifetime environmental damage created by 1tonne CO_2 at 180 Euros.

The cost of energy is a function of the engineering and technology, business and politics. The cost of the technology to produce renewable electricity from wind and solar has significantly decreased over the past 10 years with technical innovation.

However, in the UK the cost of electricity is loaded with many of the environmental taxes to de-carbonise energy while gas is left with a light 5% rate of VAT. Questions are being asked about gas prices and how we source our energy, all to the backdrop of the voters in the 20 million households and disadvantaged heavy industry that relies on gas. As the landscape changes something will have to happen to meet the 2050 net zero carbon targets to narrow the gap. The higher electricity prices are also partially to maintain the "spark spread" – the margins available to energy supply companies who generate electricity using gas fired plant, which the UK still relies on.

Investment into low carbon strategies now rather than reacting to the cost of environmental damage, creates a better future for all.

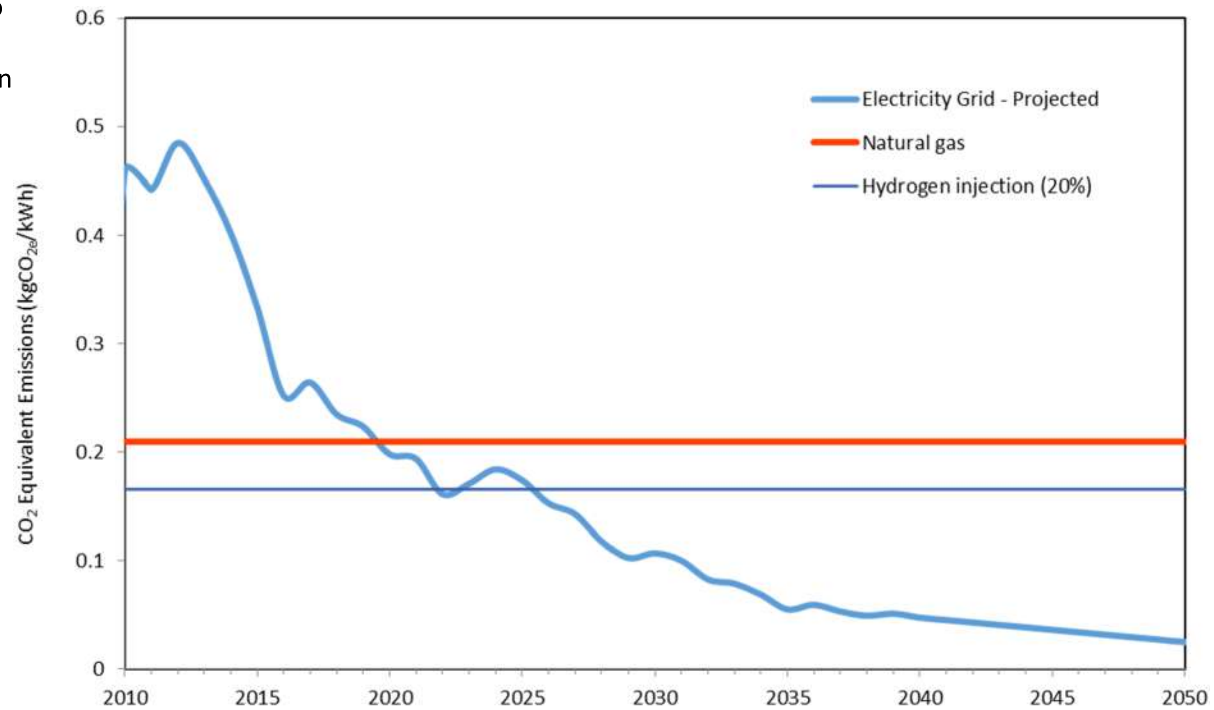

Figure 2

2.6 Timescale to zero carbon

This is a summary of the relevant external and internal policies relating to climate change and carbon reduction. Policies are presented from global level to college level with a brief overview and decarbonisation goals.

Table 1

Level	Document	Description	Decarbonisation Goals
Global	The Paris Agreement 2015	The Paris Agreement is a **legally binding international treaty on climate change**. It was adopted by 196 Parties at COP 21 in Paris, on 12 December 2015 and entered into force on 4 November 2016.	The agreement aims to substantially reduce global greenhouse gas emissions to **limit the global temperature increase in this century to 2 degrees Celsius above preindustrial levels, while pursuing the means to limit the increase to 1.5 degrees**. The agreement includes commitments from all major emitting countries to cut their climate pollution and to strengthen those commitments over time.
	UN Sustainable Development Goal	The Global Goals* – also known as the Sustainable Development Goals or SDGs – are a set of universal goals and targets adopted by 193 UN member states that outline a vision for the future for people and the planet.	Out of 17 UN Sustainable Development Goals, specifically goal 7 is relevant to this project which is "**affordable, reliable, sustainable and modern energy for all**" by 2030 SDG 7.2 - Renewable energy – increase the share of renewable energy in the global energy mix SDG 7.3 - Energy efficiency – double the global rate of improvement in energy efficiency
European Union	Renewable Energy Directive II	The Renewable Energy Directive establishes an overall policy for the production and promotion of energy from renewable sources in the EU.	The Commission proposal raises **the EU's renewable energy target** from 32% to **40% by 2030**. This means the EU will need 451 GW of wind power capacity by 2030, up from 180 GW today. This means the EU will need to install 30 GW of new wind farms every year between now and 2030 – a major acceleration in the expansion of wind energy. As it stands, the EU expect to build only 15 GW a year over 2021-25.
National	Climate Change Act 2019	The Climate Change Act is legally binding basis for the UK's approach to tackling and responding to climate change. It requires that emissions of carbon dioxide and other greenhouse gases are reduced and that climate change risks are adapted to. The Act also establishes the framework to deliver on these requirements. The Act supports the UK's commitment to urgent international action to tackle climate change.	The Act makes it the duty of the Secretary of State to ensure that **the net UK carbon account for all six Kyoto greenhouse gases for the year 2050 is at least 100% lower than the 1990 baseline.** i.e. Net Zero by 2050.
	Building Regulation Part L 2021 Conservation of fuel and power APPROVED DOCUMENT L1A	Part L of the Building Regulations (England and Wales) contains requirements relating to the conservation of fuel and power. Part L is a direct outcome of the government's Energy White Paper commitment to raising the energy performance of buildings by limiting heat losses and excessive solar gains and ensuring that energy-efficient fixed building services are installed, and that the building owner is provided with the information required to maintain the building and its services.	Part L compromises four sections as follow aiming to provide guidance on thermal envelope, HVAC system design benchmarks and efficiency, lightning, and controls. • L1A New dwellings • L1B Existing dwellings • L2A New buildings other than dwellings • L2B Existing buildings other than dwellings
	25 Year Environment Plan	This 25 Year Environment Plan sets out UK government action to help the natural world regain and retain good health. It aims to deliver cleaner air and water in our cities and rural landscapes, protect threatened species and provide richer wildlife habitats. It calls for an approach to agriculture, forestry, land use and fishing that puts the environment first.	The plan is very broad in scope: it will cover cleaner air and water, public forests and woodland, marine protected areas, species protection, administrative and governance issues. By adopting this Plan will achieve: • Clean air. • Clean and plentiful water.

			• Thriving plants and wildlife. • A reduced risk of harm from environmental hazards such as flooding and drought. • Using resources from nature more sustainably and efficiently. • Enhanced beauty, heritage, and engagement with the natural environment. In addition, this Plan will manage pressures on the environment by: • Mitigating and adapting to climate change. • Minimising waste. • Managing exposure to chemicals. • Enhancing biosecurity.
City	Cambridge City Council Climate Change Strategy 	Cambridge Climate Change Strategy (2021-2026) shares a vision for Cambridge to be net zero carbon by 2030, subject to Government, industry and regulators implementing the necessary changes to enable the city and the rest of the UK to achieve this.	It sets out six key objectives on the causes and consequences of climate change: • Reducing carbon emissions from city council buildings, land, vehicles, and services • Reducing energy consumption and carbon emissions from homes and buildings in Cambridge • Reducing carbon emissions from transport in Cambridge • Reducing consumption of resources, reducing waste, and increasing recycling in Cambridge • Promoting sustainable food • Supporting Council services, residents, and businesses to adapt to the impacts of climate change
University	Cambridge Zero	Cambridge Zero is not just about developing greener technologies. It will harness the full range of the University's research and policy expertise, developing solutions that work for our lives, our society, and our economy.	The University set a 1.5-degree Science Based Target in 2019; committing itself to reduce its energy-related carbon emissions to absolute zero by 2038, with a 75 per cent decrease on 2015 emissions by 2030. Other changes: • Withdraw investments with conventional energy-focused public equity managers by December 2020 • Build up significant investments in renewable energy by 2025 • Divest from all meaningful exposure in fossil fuels by 2030 • Aim to achieve net zero greenhouse gas emissions across its entire investment portfolio by 2038, in line with the broader targets of the University.
College			The College has embraced the 10:10 campaign, in which schools, businesses and other organisations try to cut their carbon by 10% in a year.

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3.0 KING'S COLLEGE SITE

Figure 3 and 4 represents most of the buildings that form the king's college estate, highlighted are the gas boiler and metered zones that feed each building. A black border represents the edge of the distribution, where appropriate.

In addition, there are The Boathouse and 13 – 14 Fitzwilliam Street which are part of the estate but are not shown on the map.

The main site has two main gas meters - the Bike Store meter and the Wine Cellar meter. The Bike Store meter feeds Bodley's boiler room and Gibb's boiler room which then feeds the Chapel. The Wine Cellar meter feeds the rest of the buildings on the main site including the Porters lodge.

The surrounding buildings at the back of the college have plant rooms serving single buildings, moving towards more domestic style boilers. Except garden hostel, which serves a few student rooms.

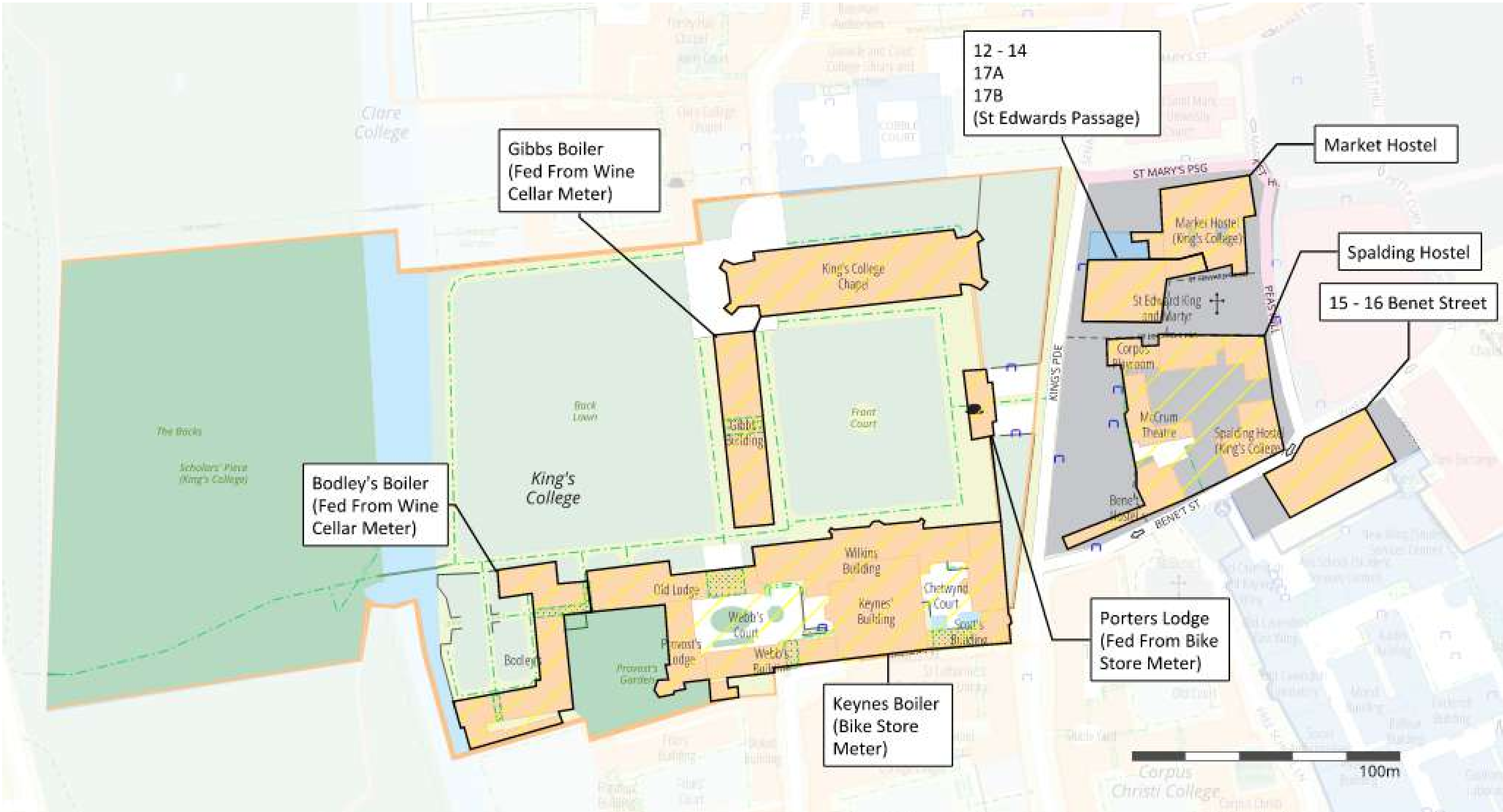


Figure 3

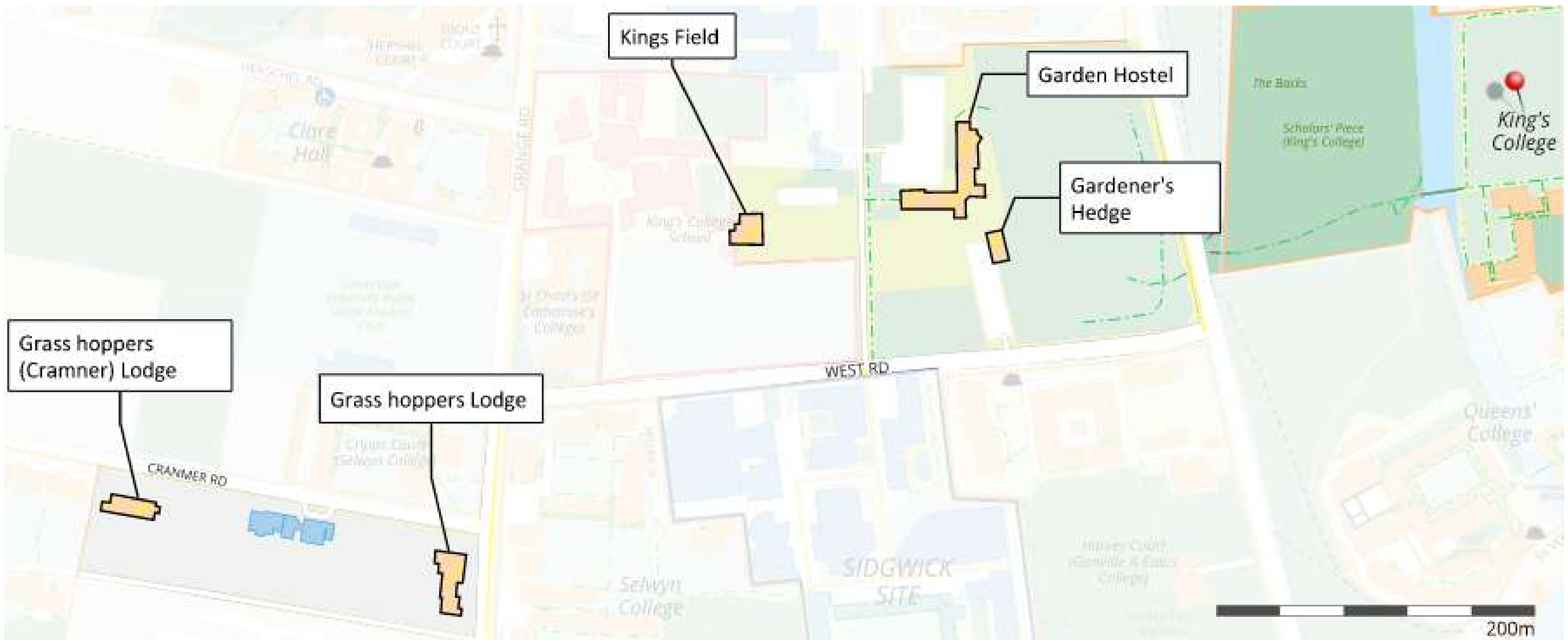


Figure 4

4.0 EXISTING ENERGY DEMANDS

The main energy sources to the estate are natural gas and grid supplied electricity. Raw data from 2018 invoices have been sorted, arranged, and visualised to explain the current energy consumption breakdown. Pre-COVID consumption data has been used to provide data representative of normal use.

4.1 Whole Site Electrical consumption

The electricity meter readings are split between two different providers: Smartest Energy and Opus Energy.

The Electricity data taken form the Smartest Energy is on a zero-carbon tariff which has been specifically arranged with the University. Opus energy is considered a regular tariff and is subject to the carbon impact of the UK grid.

The quality of Opus energy's meter readings is sporadic in places, due to these findings have been extrapolated where possible. To give the best overview of the data the average has been used when needed.

Smartest Energy Meter Readings:

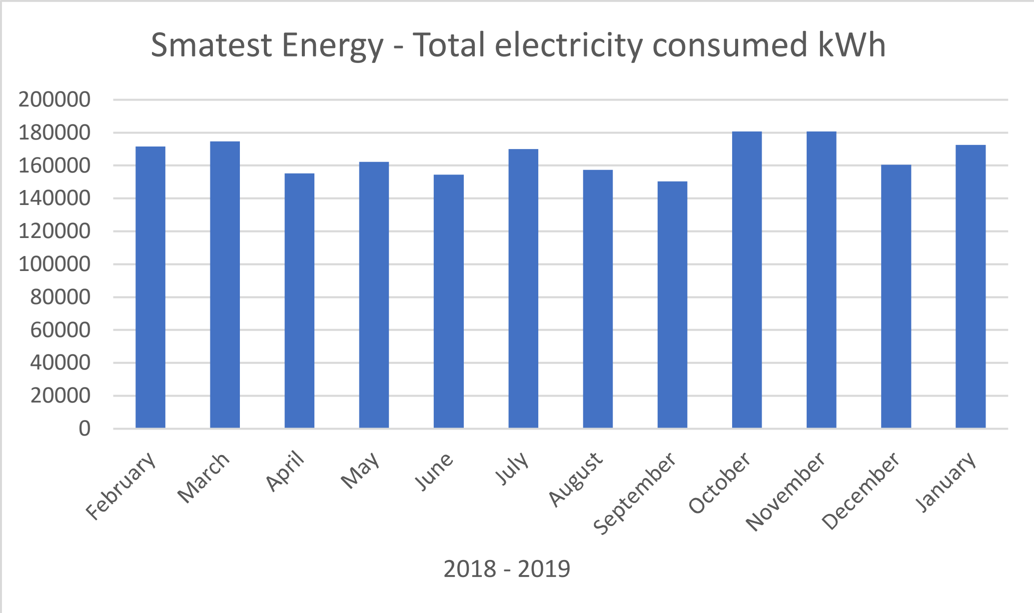


Figure 5

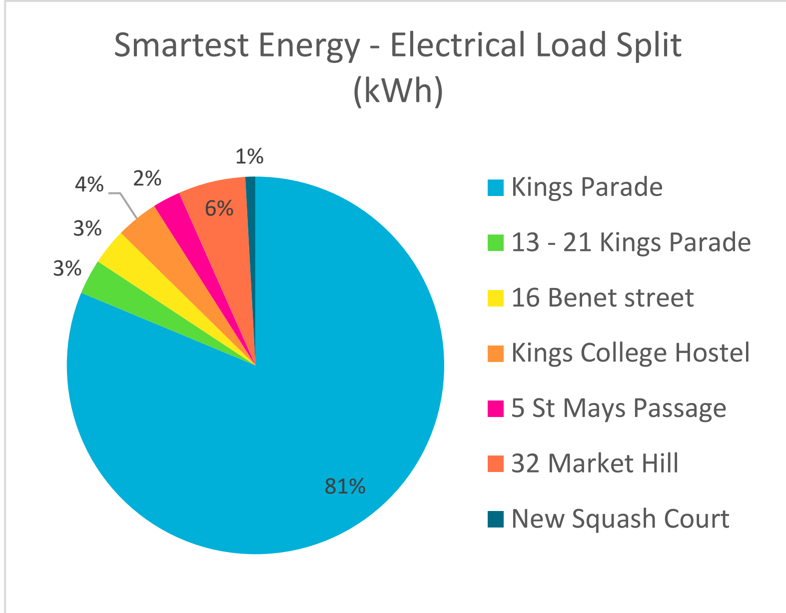


Figure 6

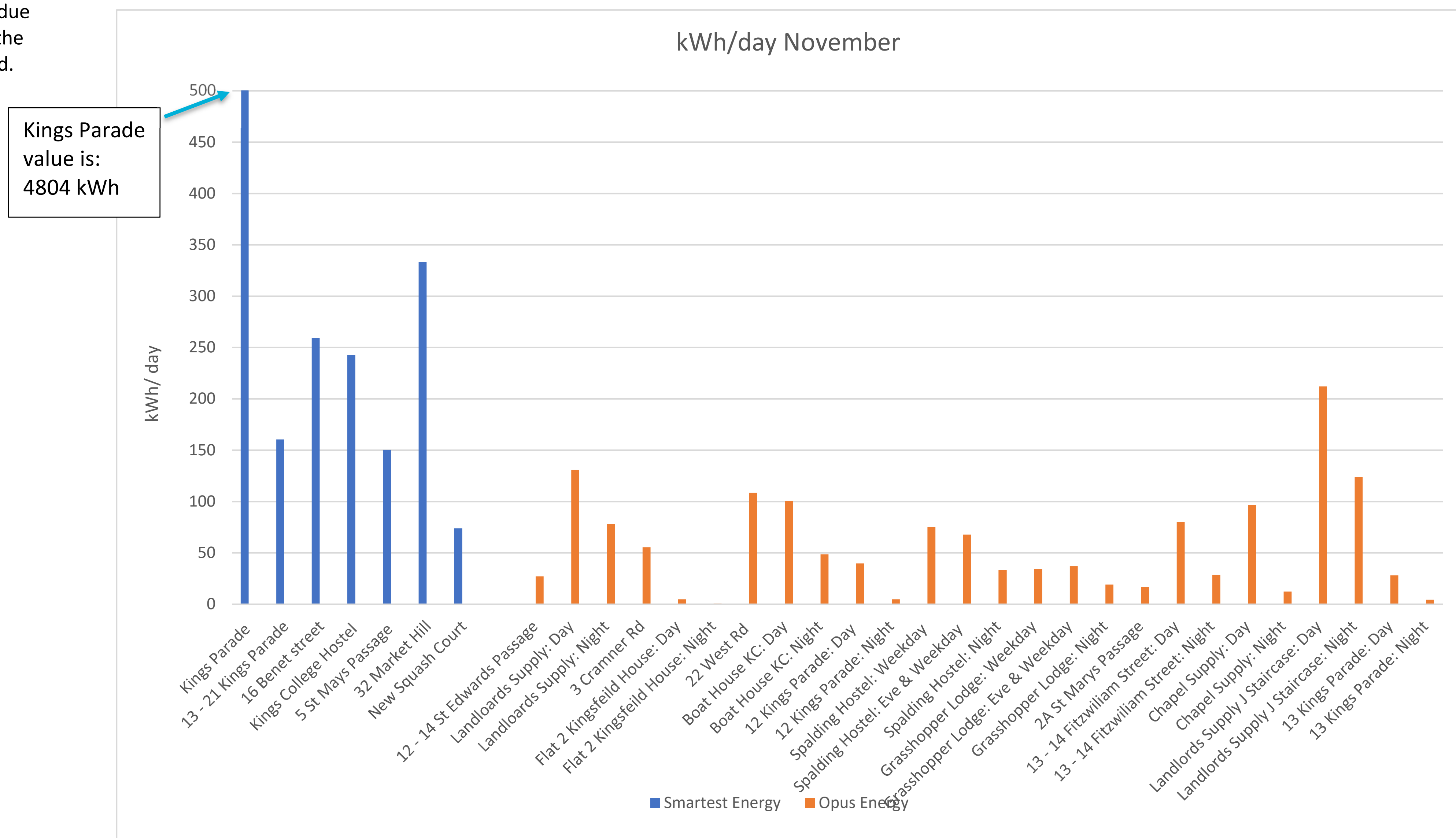


Figure 7

4.2 Gas consumption

The Gas meter readings have been calculated and summarised in the following tables. As gas to a building provides heating and domestic hot water, to break down heating loads an estimated DHW load is required. An indication of the domestic hot water demands can be taken from summer months when no heating is required. We have used this as a basis for estimating the relative contributions of space heating and domestic hot water to the building's overall gas use. While this is imprecise, this still gives a reasonable approximation when analysing energy demands.

For the winter 2018 / 19 the peak monthly heating was 1'020'000 kWh for the buildings.

4.3 Consumption breakdown

Comparing against the Gas map we can see that King's parade -Keynes Boiler (Bike Store meter) and the Bodley's / Gibb's Boilers (Wine Cellar meter) use 68% of the total Gas. This is to be expected due to the size and construction of historic buildings being served.

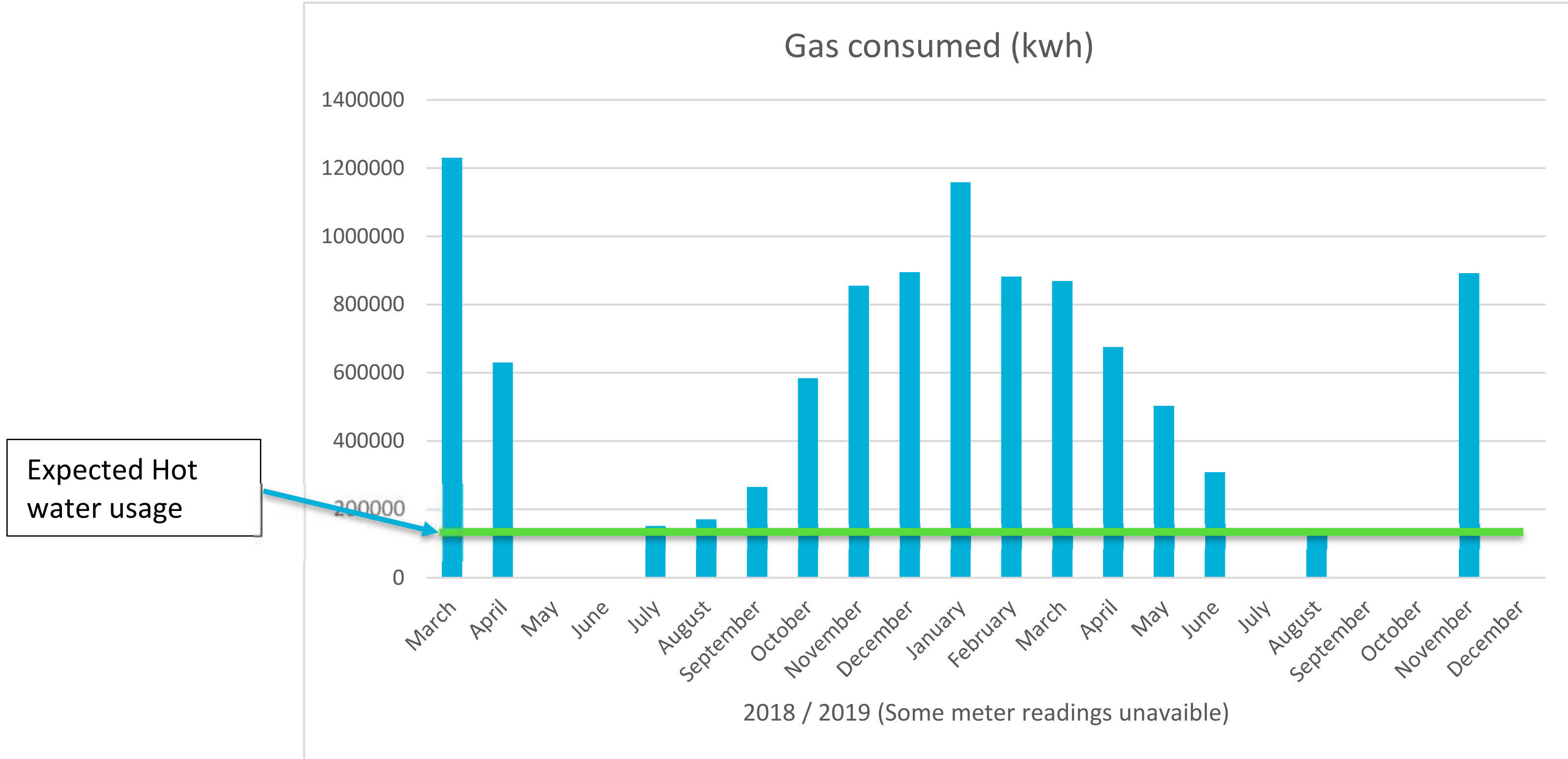


Figure 8

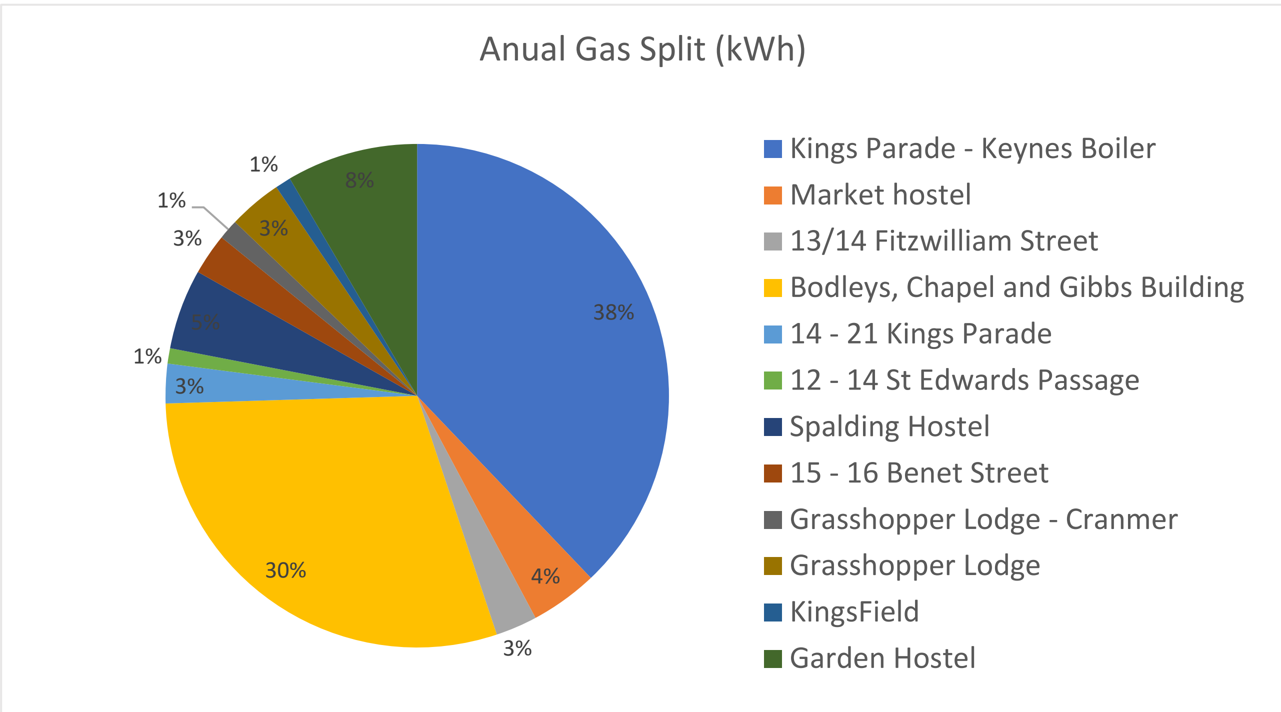


Figure 9

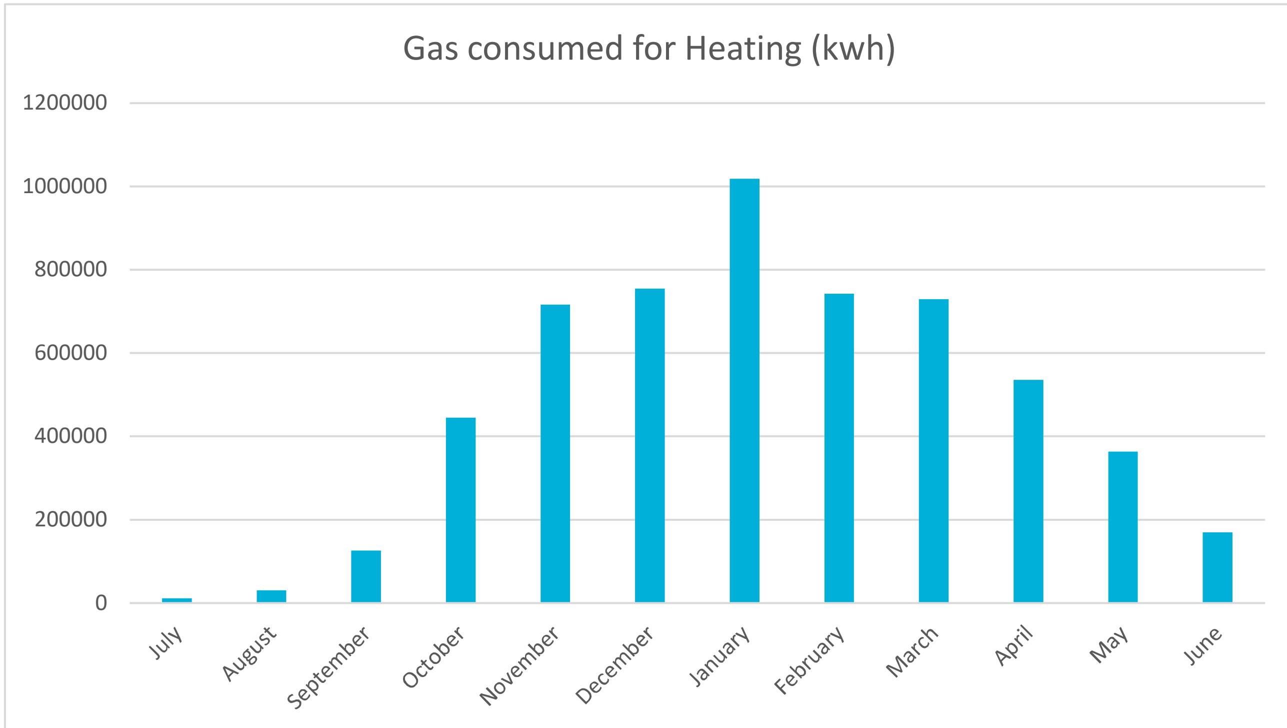


Figure 10

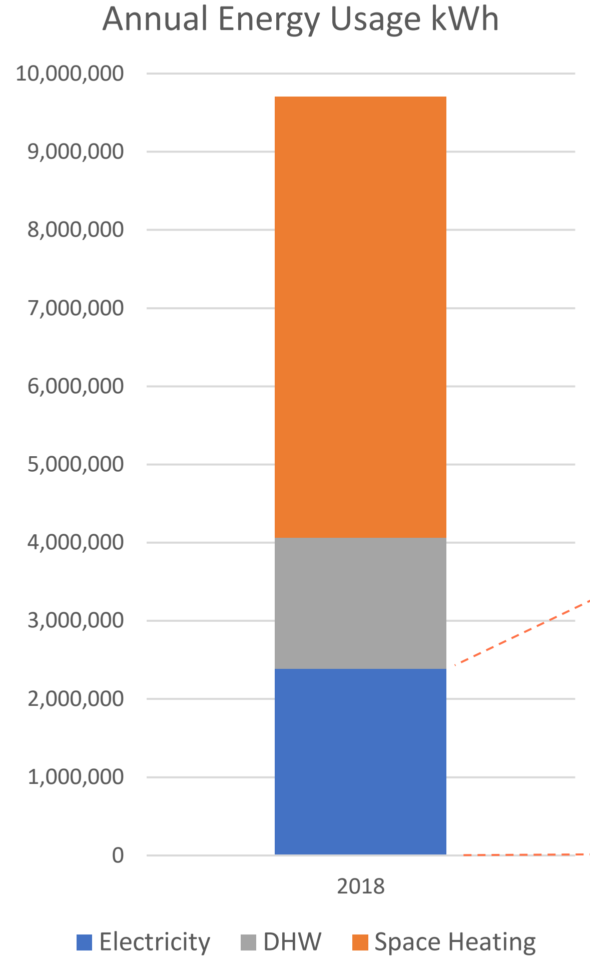
5.0 CURRENT BASELINE

5.1 Annual Energy

Unsurprisingly for buildings of this age, space heating dominates. The spaces within the buildings include student residential, catering and offices all leading to a large domestic hot water and heating demand.

Heat for both space heating and domestic hot water is produced by burning gas, a fossil fuel. At a large enough scale, the breakdown of electrical energy into its various uses does not tend to vary greatly for buildings of a particular type – people's small power use is statistical and largely independent of the building itself. While the total electrical energy consumption shown here is based on meter readings for Kings College, the finer grained breakdown shown here is based on Post Occupancy Evaluation data for similar buildings.

This energy breakdown is also made on the basis that energy used for cooking is provided by electricity, both in individual flats and in the main kitchen.



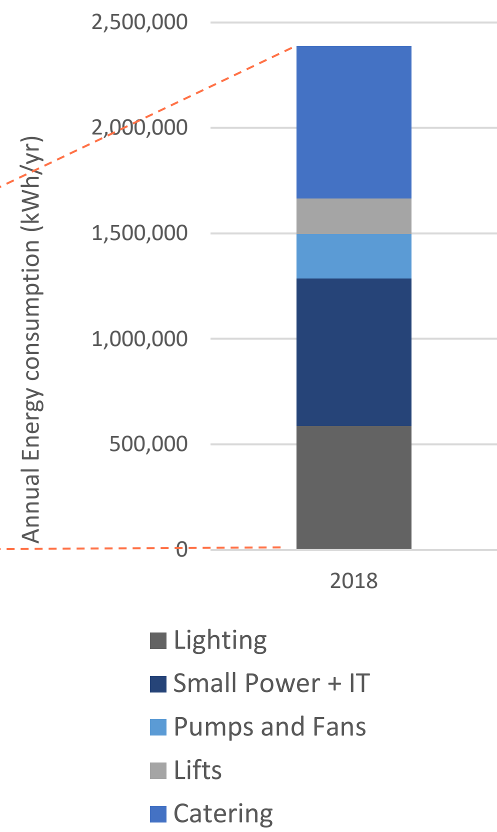


Figure 12

5.2 CO_2 Emissions

Carbon emission conversion factors have been obtained from the UK Governments (BEIS) Fuel Conversion Factor Chart. For 2018 the conversion factor is 0.20437 kg CO_2e /kWh for natural gas consumption and 0.28307kg CO_2e /kWh for electricity. The college has agreed a zero carbon tariff with Smartest Energy using a local solar panel array. This means that 80% of the colleges electrical energy can be considered to have a carbon intensity of 0 CO_2 /kWh. These carbon intensity factors have been used to calculate the overall carbon emissions associated with the electrical consumption in Figure 13.

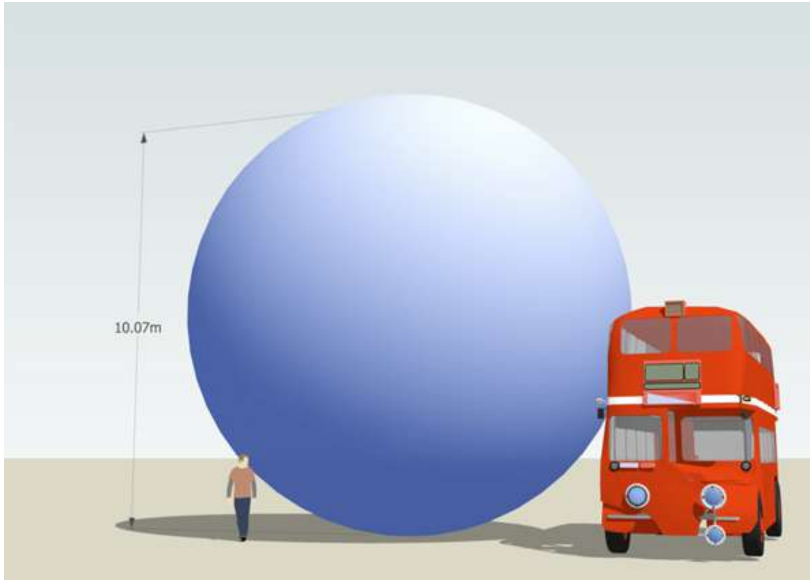


Figure 11
One tonne of CO2, that's a sphere about 10m across

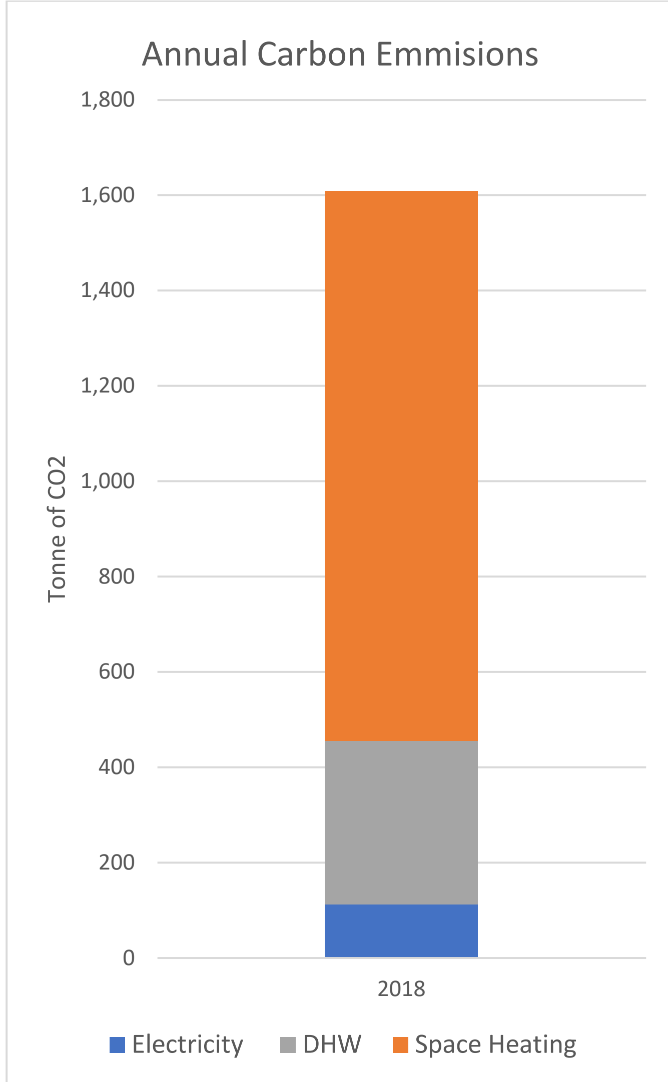


Figure 13

6.0 REDUCTION OF HEAT LOADS

The first part of the carbon reduction strategy is to reduce the demand of energy required; this can be achieved through a variety of fabric improvements with lower U values and reduced infiltration.

6.1 Fabric Improvements

A review of the building fabric at the King's college Cambridge has been conducted. This review allowed all site buildings to be clustered into groups with specific thermal properties so that a simplified computational heating model for the overall site could be generated using the PHPP calculation and proportional improvements.

The three defined categories were as follows:

- Type 1 – Historic mostly uninsulated buildings
- Type 2 – More modern buildings partially insulated which do not meet 2013 Part L Standards
- Type 3 – Buildings which do meet 2013 Part L Standards

After calculating the buildings in the above notional state, it was possible to systematically apply upgrades to their fabric such that they first met the current NCM notional building standard and then finally the Enerphit Standard. Upgrades are detailed in the following pages but roughly follow the order: windows, roof, walls, & ground

The NCM and Enerphit Standards used are shown in the tables in Figure 14.

According to The Passivhaus Institute (PHI) Weather Criteria, UK falls into the cool-temperate climate zone. The critical U-values to note are: "Exterior insulation" which would apply to the building roof, walls and ground = 0.15 W/(m^{2}K), the window glazing = 0.85 W/(m^{2}K), and airtightness of 1 m^3/(h m^2).

Table 1 Construction element U-values and thermal capacity for the Notional building		
Exposed element	U-value (W/m²K)	Thermal capacity[1] (kJ/m²K)
Roofs[2] (irrespective of pitch)	0.18	88.3 (1.40 if metal-clad)
Walls	0.26	21.8 (1.40 if metal-clad)
Exposed floors and ground floors (subject to paragraph 33)	0.22	77.7
Windows*	1.60	-
Roof windows and roof-lights*	1.80	-

Table 2 EnerPHit criteria for the building component method

Climate zone according to PHPP	Opaque envelope[1] against... ...ground	...ambient air			Windows (including exterior doors) Overall[4]			Glazing[5]	Solar load[6]	Ventilation	
	Insulation	Exterior insulation	Interior insulation[2]	Exterior paint[3]	Max. heat transfer coefficient ($U_{D/W,installed}$)			Solar heat gain coefficient (g-value)	Max. specific solar load during cooling period	Min. heat recovery rate[7]	Min. humidity recovery rate[8]
	Max. heat transfer coefficient (U-value)			Cool colours							
	[W/(m²K)]			-	[W/(m²K)]			-	[kWh/m²a]	%	
Arctic	Determined in PHPP from project specific heating and cooling degree days against ground.	0.09	0.25	-	0.45	0.50	0.60	$U_g - g*0.7 \le 0$	100	80%	-
Cold		0.12	0.30	-	0.65	0.70	0.80	$U_g - g*1.0 \le 0$		80%	-
Cool-temperate		0.15	0.35	-	0.85	1.00	1.10	$U_g - g*1.6 \le 0$		75%	-
Warm-temperate		0.30	0.50	-	1.05	1.10	1.20	$U_g - g*2.8 \le -1$		75%	-
Warm		0.50	0.75	-	1.25	1.30	1.40	-		-	-
Hot		0.50	0.75	Yes	1.25	1.30	1.40	-		-	60 % (humid climate)
Very hot		0.25	0.45	Yes	1.05	1.10	1.20	-		-	60 % (humid climate)

Table 4 General EnerPHit criteria (always applicable, irrespective of the chosen method)

			Criteria[1]	Alternative Criteria[2]
Airtightness				
Pressurization test result n_{50}	[1/h]	≤	1.0	

Figure 14

6.2 Type 1 – Historic buildings

Current Case Type 1 - All windows are single glazed and there is no insulation in any fabric.

Fabric Improvement Options

Scenario 1 – Windows and roof only upgraded to NCM notional building standard

Scenario 2 – All parts upgraded to current NCM notional building standard

Scenario 3 – All parts upgraded to Enerphit standard

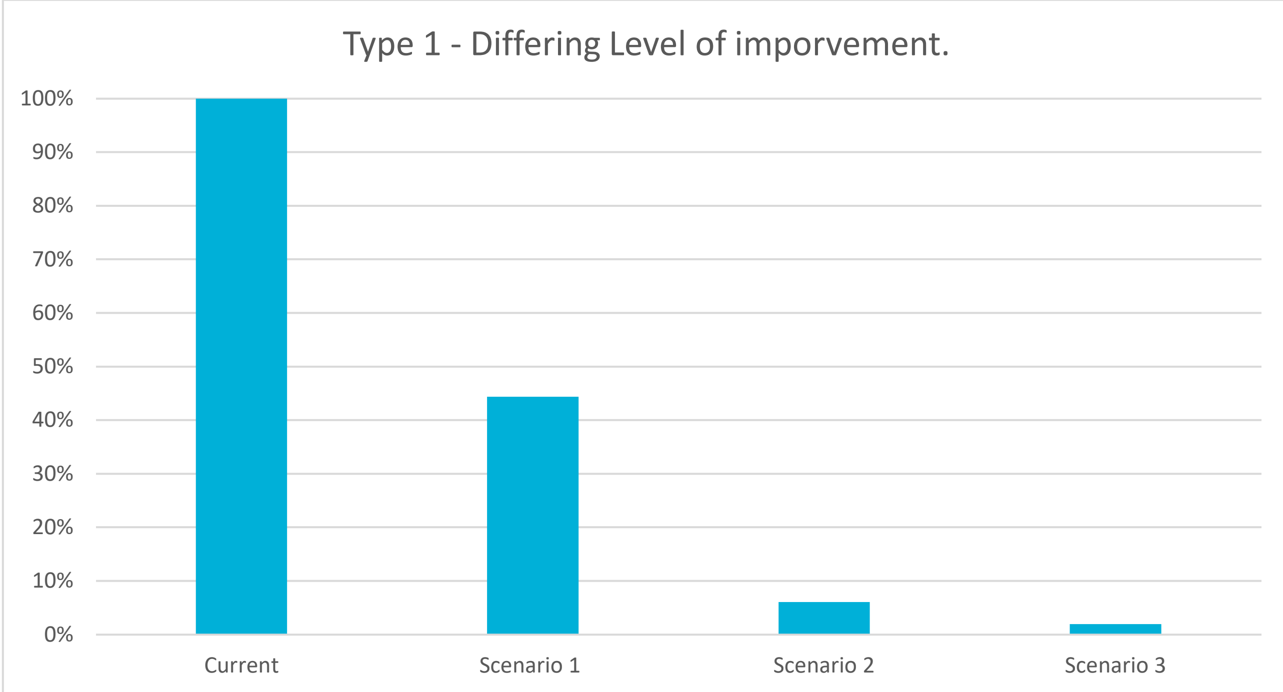


Figure 15

Table 2

Scenario	Component	U-Values W/(m² K)	Upgrade: window Glazing	Upgrade: Type	Upgrade: Insulation Thickness mm	Upgrade: Conductivity W/(m K)	Infiltration m³/(m² h)	Percentage of Peak load %
	Window	5.60	Single	-	-	-		
	Roof	2.41	-	-	-	-		
	Wall	1.68	-	-	-	-		
Current	Ground	1.62	-	-	-	-	13	100%
	Window	1.60	Double	-	-	-		
	Roof	0.18	-	Insulation	130	0.025		
	Wall	1.68	-	-	-	-		
1	Ground	1.62	-	-	-	-	3	44%
	Window	1.60	Double	-	-	-		
	Roof	0.18	-	Insulation	130	0.025		
	Wall	0.26	-	Insulation	80	0.025		
2	Ground	0.22	-	Insulation	100	0.025	3	6%
	Window	0.90	Triple	-	-	-		
	Roof	0.15	-	Insulation	160	0.025		
	Wall	0.15	-	Insulation	150	0.025		
3	Ground	0.15	-	Insulation	150	0.025	1	2%

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6.3 Type 2 - Partially insulated buildings not meeting 2013 part L standard

Current Case type 2 – All windows are double glazed and the existing insulation in fabric not meeting Part L 2013. U- values have been derived from existing standards at the time and typical U-values taken from similar aged buildings.

Fabric Improvement Options

Scenario 1 – Windows and roof only upgraded to NCM notional building standard (Only allows for a marginal gain due to existing quality)

Scenario 2 – All parts upgraded to current NCM notional building standard

Scenario 3 – All parts upgraded to Enerphit standard

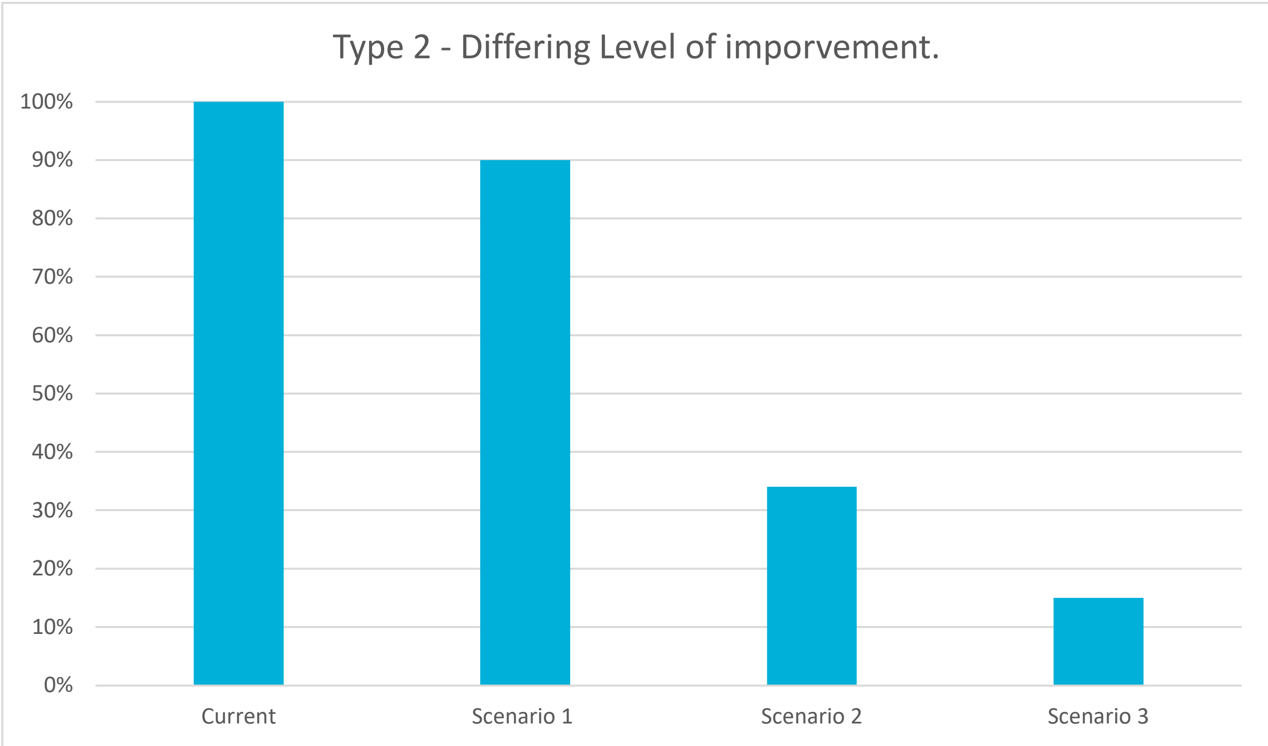

Figure 16

Table 3

Scenario	Component	U-Values W/(m² K)	Upgrade: window Glazing	Upgrade: Type	Upgrade: Insulation Thickness mm	Upgrade: Conductivity W/(m K)	Infiltration $m^3/(m^2 h)$	Peak Load Per Floor Area %
	Window	1.93	Double	-	-	-		
	Roof	0.41	-	Insulation	50	0.025		
	Wall	0.36	-	Insulation	50	0.025		
Current	Ground	1.62	-	-	-	-	10	100%
	Window	1.60	Double	-	-	-		
	Roof	0.18	-	Insulation	130	0.025		
	Wall	0.26	-	Insulation	80	0.025		
2	Ground	0.22	-	Insulation	100	0.025	3	34%
	Window	0.90	Triple	-	-	-		
	Roof	0.15	-	Insulation	160	0.025		
	Wall	0.15	-	Insulation	150	0.025		
3	Ground	0.15	-	Insulation	150	0.025	1	15%

6.4 Type 3 - Buildings meeting 2013 part L standards

Current Case type 3 – All windows are double glazed and the existing insulation in the fabric meeting Part L 2013.

Fabric Improvements Options

Scenario 1 – Windows and roof only upgraded to NCM notional building standard (Only allows for a marginal gain due to existing quality)

Scenario 2 – All parts upgraded to current NCM notional building standard.

Scenario 3 – All parts upgraded to Enerphit standard

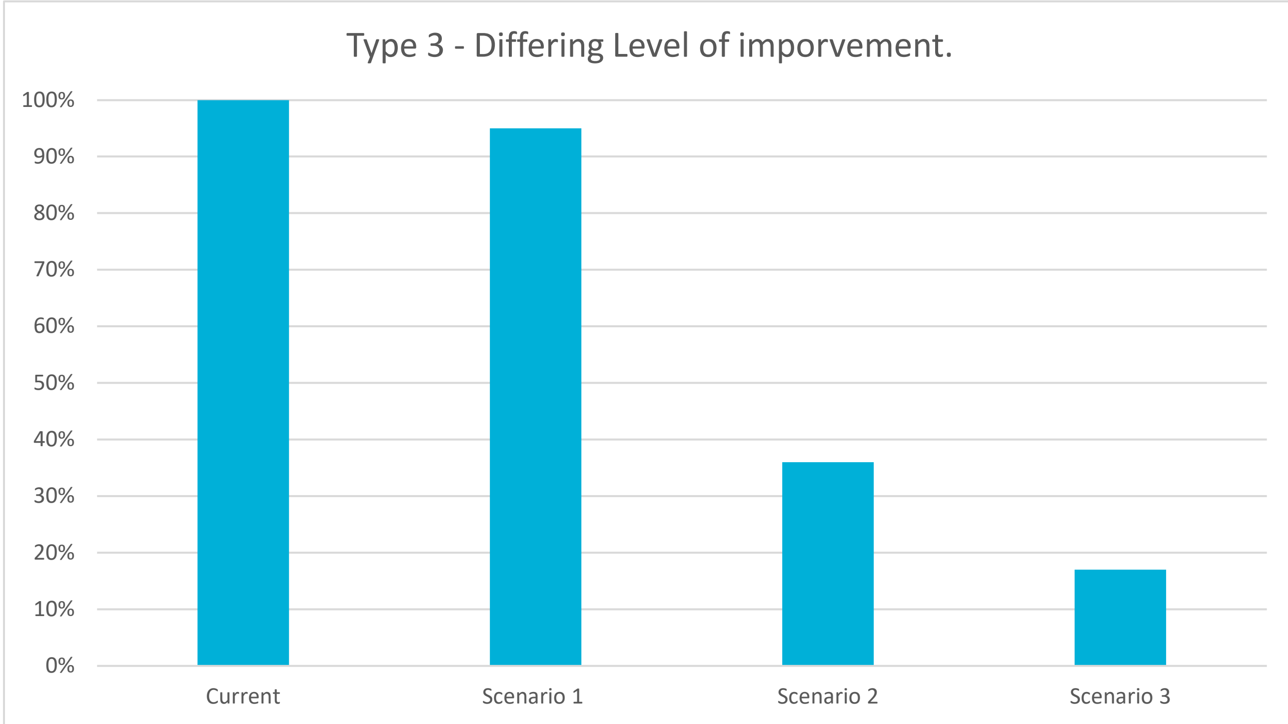

Figure 17

Table 4

scenario	Component	U-Values W/(m^2 K)	Upgrade window Glazing	Type	Insulation Thickness mm	Conductivity W/(m K)	Infiltration m^3/(m^2 h)	Peak Load Per Floor Area %
	Window	1.93	Double Glaze	-	-	-		
	Roof	0.25	-	Insulation	90	0.025		
	Wall	0.35	-	Insulation	50	0.025		
Current	Ground	0.35	-	Insulation	60	0.025	10	100%
	Window	1.60	Double Glaze	-	-	-		
	Roof	0.18	-	Insulation	130	0.025		
	Wall	0.26	-	Insulation	80	0.025		
2	Ground	0.22	-	Insulation	100	0.025	3	35%
	Window	0.90	Triple Glaze	-	-	-		
	Roof	0.15	-	Insulation	160	0.025		
	Wall	0.15	-	Insulation	150	0.025		
3	Ground	0.15	-	Insulation	150	0.025	1	17%

6.5 Site Map Current Fabric

The site map in Figure 18 and 19 represents a guide to the fabric age and thermal performance of each building in the College sites. Some notes have been added to describe the renovations that have included fabric improvements.

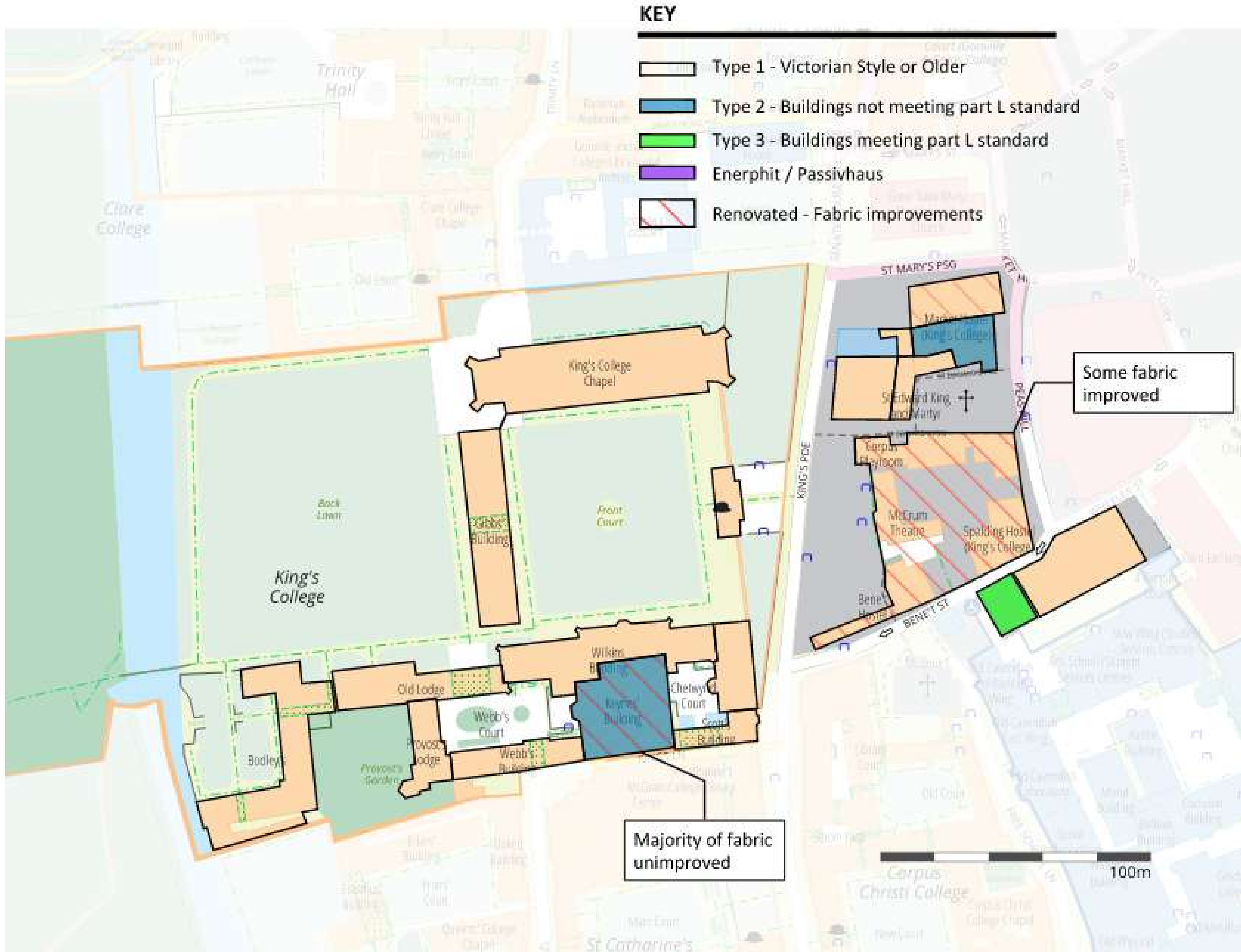

Figure 18

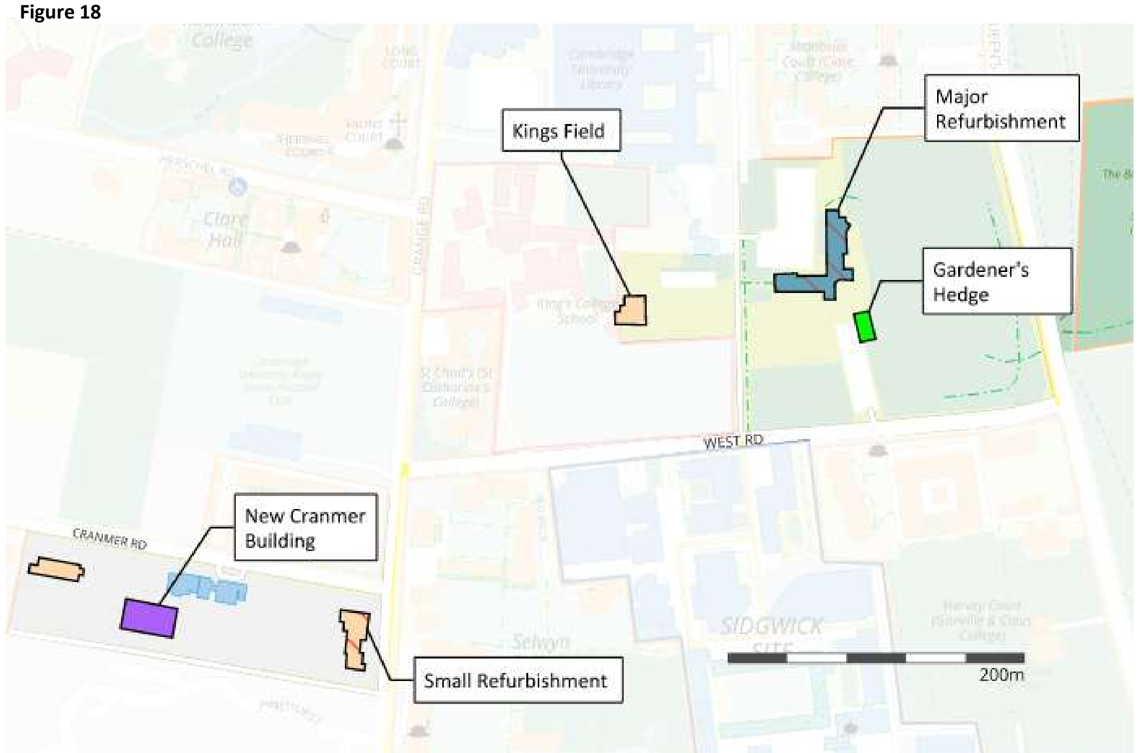

Figure 19

6.6 Opportunities for buildings - Historic to modern

Due to the historic and archtectural significance of buildings at Kings College there are likely to be limitations to the fabric improvements that may be achieved.

Roof insulation and the addition of secondary glazing are generally possible for most historic buildings. Work on other projects has demonstrated that addition of internal wall insulation is technically possible without causing long term damage to historic masonry.

Figure 20

Figure 21

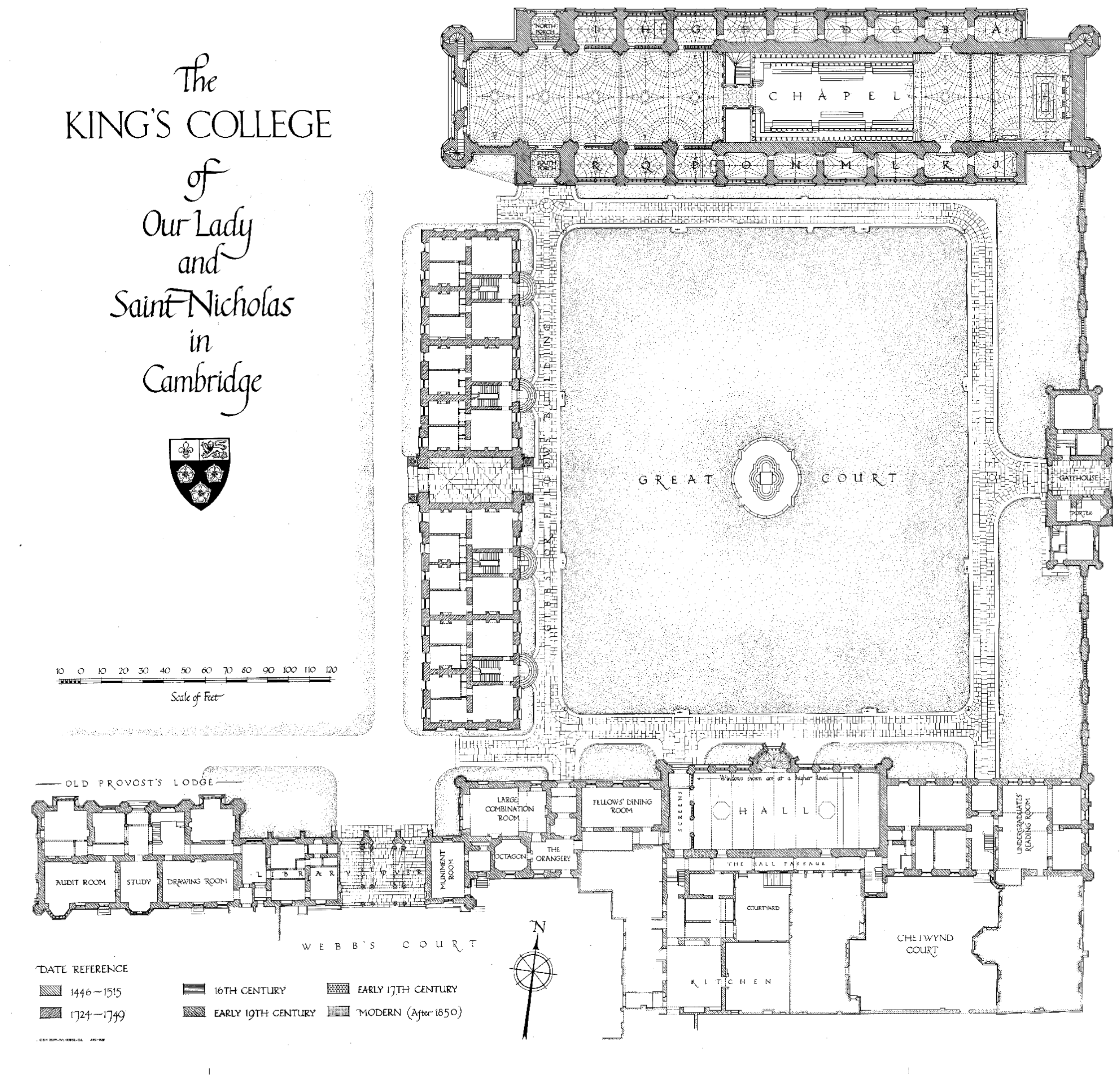

Figure 22

MAX FORDHAM

7.0 MODELLED ENERGY LOSSES

To demonstrate the level of improvement insulation makes, the Gibbs building has been modelled with differing level of fabric improvements detailed in section 6.

PHPP Model at current case, no fabric improvements

Table 5

Inputs into PHPP for Area of Building	
Roof U-value (W/m²K)	2.4
Floor U-value (W/m²K)	1.6
Walls U-value (W/m²K)	1.68
Window U-value (W/m²K)	~5
Glazing g-value	~0.87
Infiltration rate (m³/h.m²)	13
Provision for fresh air	Negligible building is sufficiently leaky
Occupancy density (m²/person)	15
Floor area m²	3767

Annual heating demand	229.4	kWh/(m²a)
Heating load	87.4	W/m²

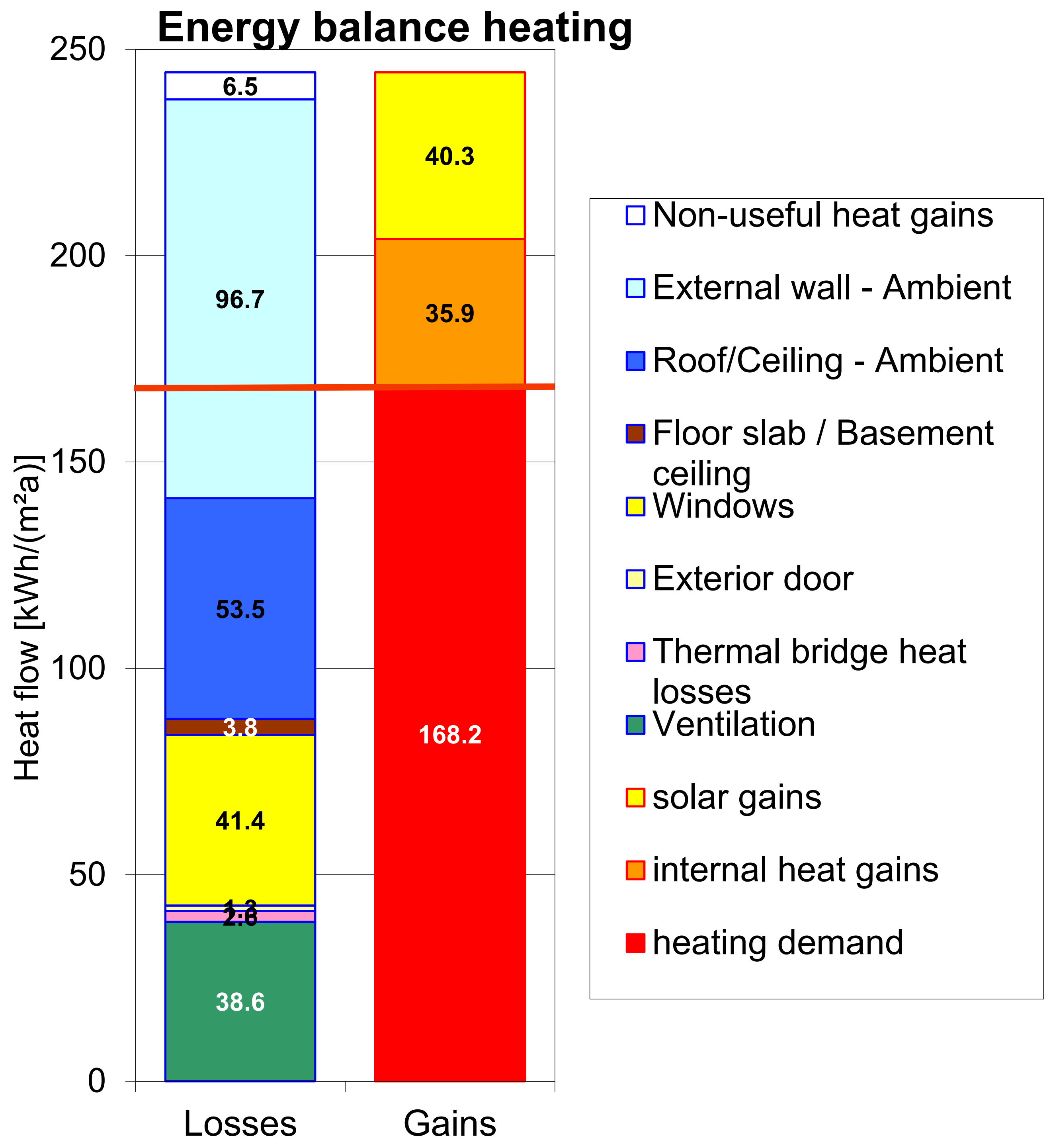

Figure 23

Fabric improvements: Improved Windows, leakage, and Roof insulation

Table 6

Inputs into PHPP for Area of Building	
Roof U-value (W/m²K)	0.18
Floor U-value (W/m²K)	1.6
Walls U-value (W/m²K)	1.68
Window U-value (W/m²K)	~1.6
Glazing g-value	~0.77
Infiltration rate (m³/h.m²)	3
Provision for fresh air	Negligible building is sufficiently leaky
Occupancy density (m²/person)	15
Floor area m²	3767

Annual heating demand	74.6	kWh/(m²a)
Heating load	32.4	W/m²

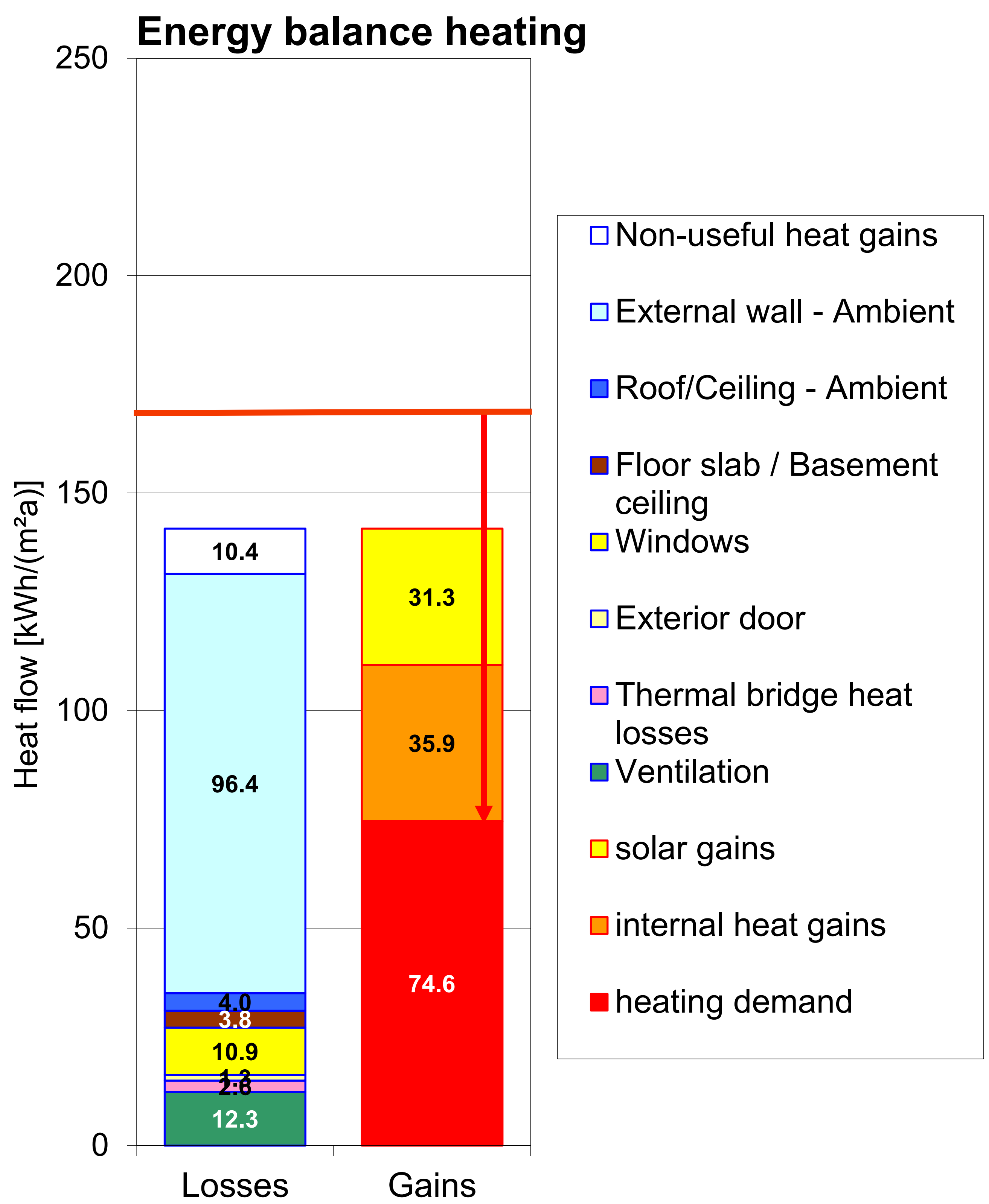

Figure 24

Notional Building U values

Table 7

Inputs into PHPP for Area of Building	
Roof U-value (W/m^2K)	0.18
Floor U-value (W/m^2K)	0.22
Walls U-value (W/m^2K)	0.26
Window U-value (W/m^2K)	~1.6
Glazing g-value	~0.77
Infiltration rate ($m^3/h.m^2$)	3
Provision for fresh air	Negligible building is sufficiently leaky
Occupancy density (m^2/person)	15
Floor area m^2	3767

Annual heating demand	10.2	kWh/(m²a)
Heating load	10.9	W/m²

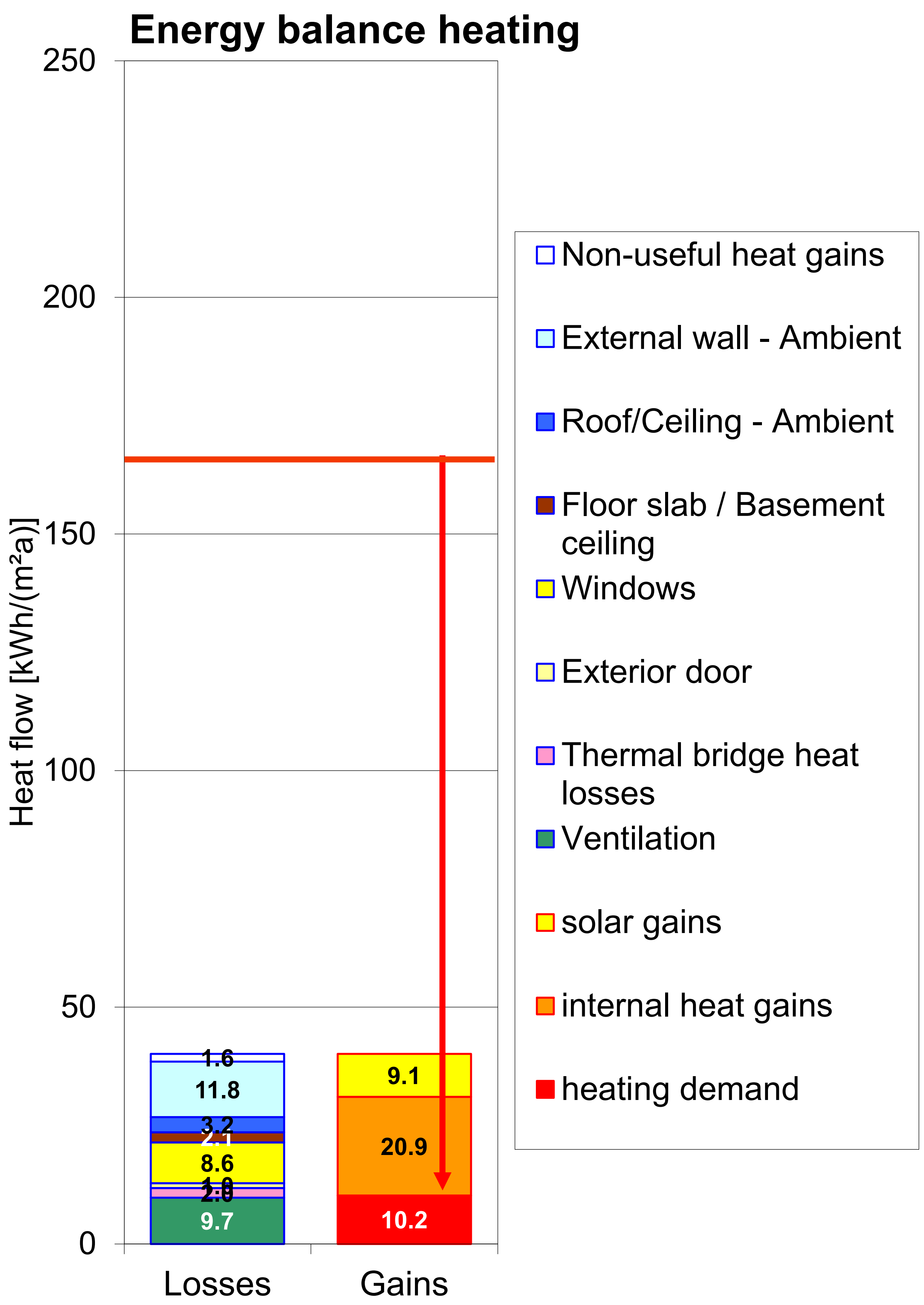

Figure 25

Additional Fabric improvements: Enerphit standard

Table 8

Inputs into PHPP for Area of Building	
Roof U-value (W/m²K)	0.15
Floor U-value (W/m²K)	0.15
Walls U-value (W/m²K)	0.15
Window U-value (W/m²K)	~0.9
Glazing g-value	~0.5
Infiltration rate (m³/h.m²)	1
Provision for fresh air	MVHR
Occupancy density (m²/person)	15
Floor area m²	3767

Annual heating demand	3.2	kWh/(m²a)
Heating load	5.5	W/m²

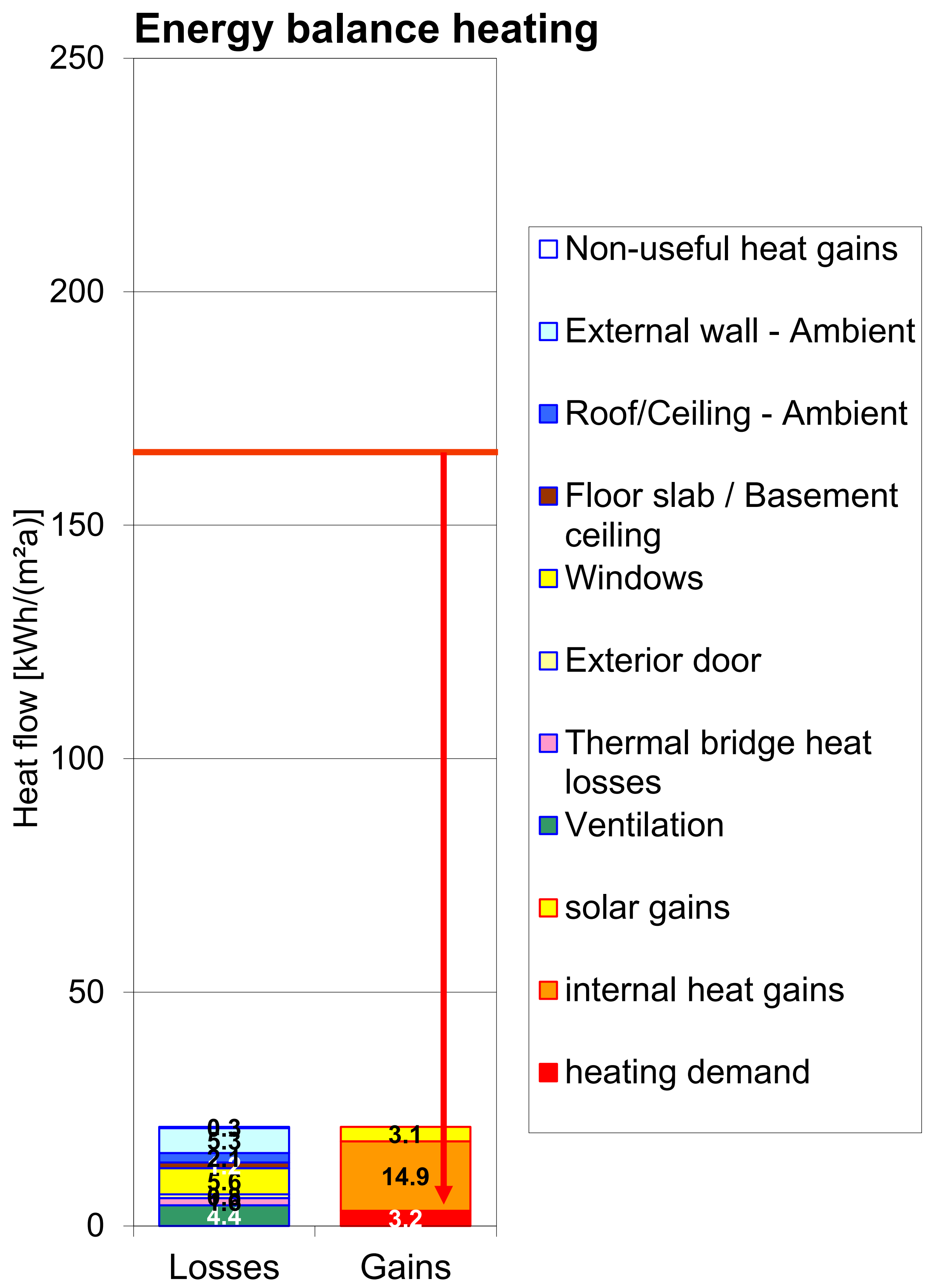

Figure 26

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7.1 Site Wide

We can apply PHPP model principals to the whole estate, using the relative improvements from the Gibbs building for the remaining buildings. Where we can calculate the annual heating loads against varying level of improvements:

Scenario 1 – Windows and roof only upgraded to NCM notional building standard

Scenario 2 – All parts upgraded to current NCM notional building standard

Scenario 3 – All parts upgraded to Enerphit standard

The calculations consider the differing types of buildings already in place, upgrading performance in relation to scenario when appropriate.

Allowance has been made for buildings that are historically and architecturally sensitive and are unlikely to be refurbished. This includes the Chapel building and any stained-glass windows that would be left untouched.

We can represent anticipated levels of realistic improvements throughout the site as seen below.

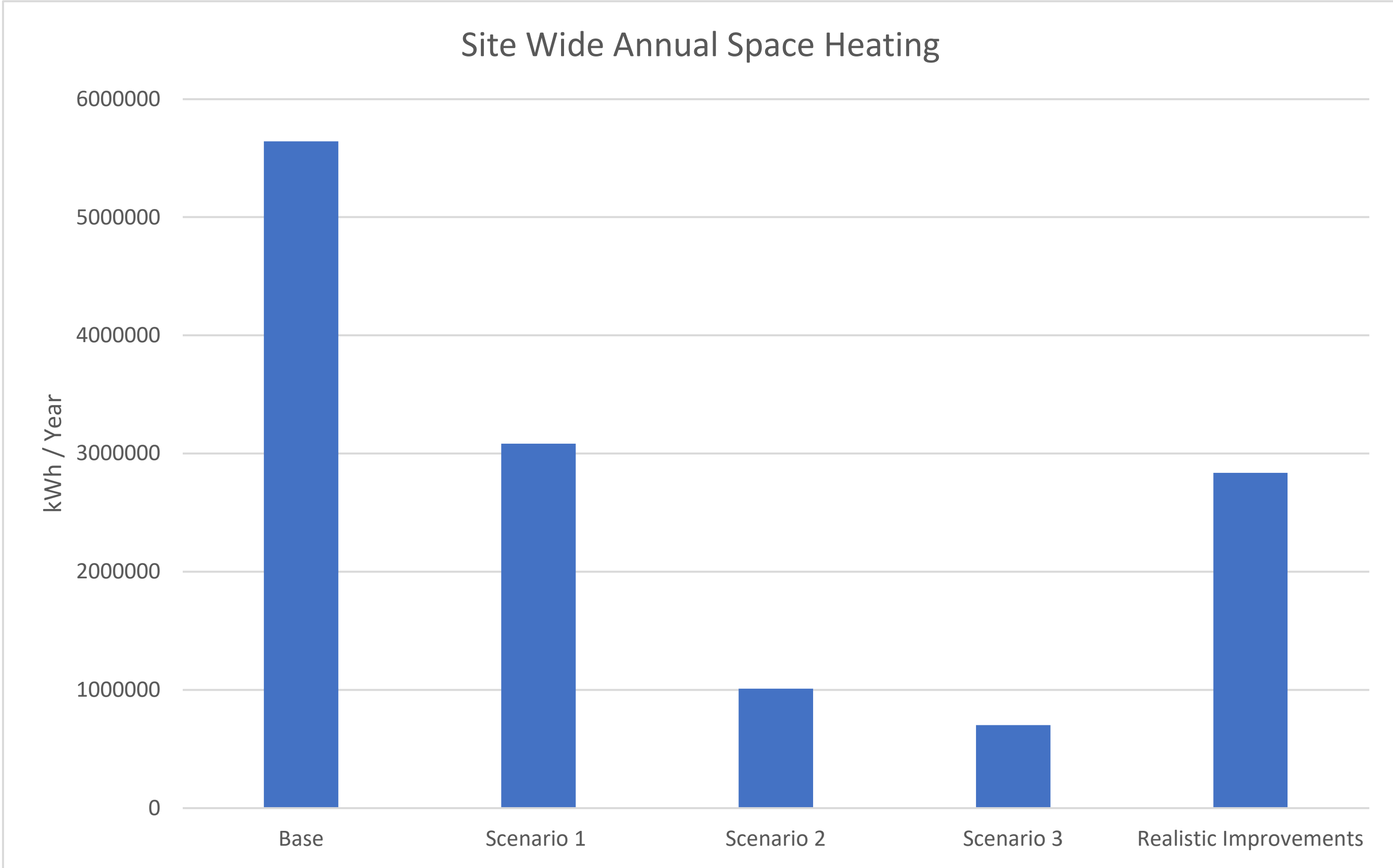
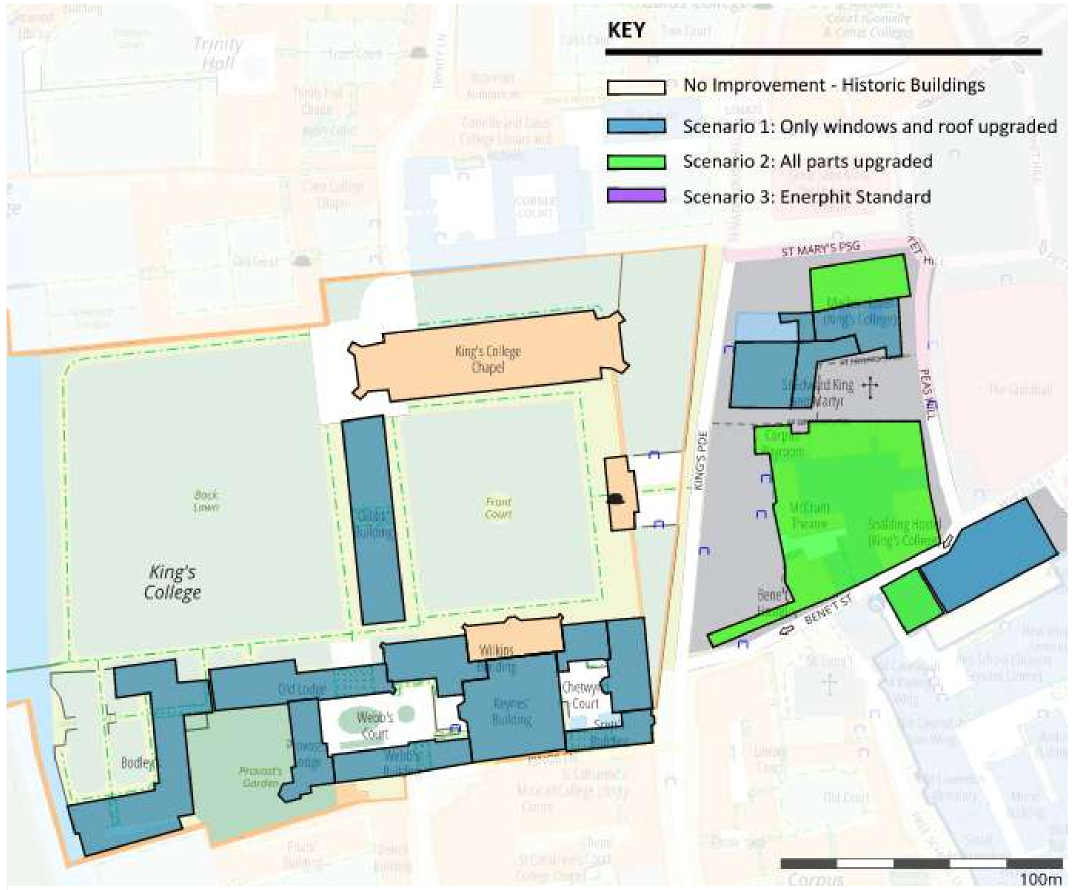


Figure 27



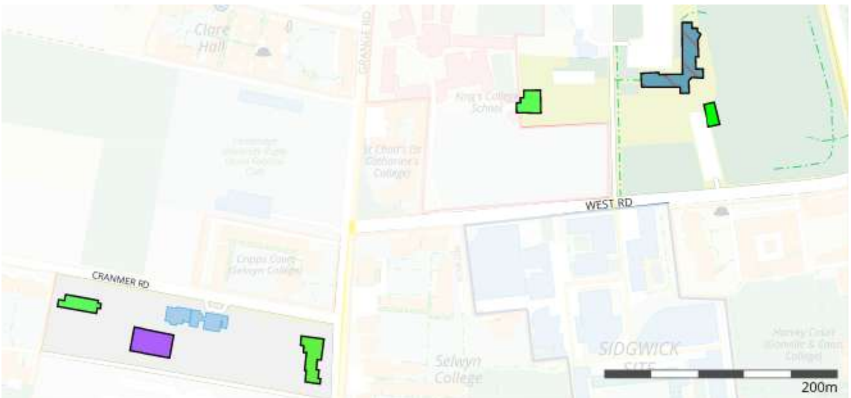


Figure 28

Figure 29

8.0 ENERGY STRATEGIES

The main approach to decarbonise heating currently is the use of electricity to drive electric heat pumps or boilers.

At present in the college, heat is produced in plant rooms by gas fired boilers serving one or many buildings providing both space heating and domestic hot water.

8.1 Electric Boiler

An electric boiler uses electricity to heat water via a resistance heater. 1kW of electricity produces almost 1kW heat. While technically simple and compatible with existing heating systems electric boilers are substantially less efficient than heat pumps at generating heat from electricity and should be thought of as a last resort for buildings that are otherwise hard to deal with. The current peak monthly heating load is approximately 10 times larger than the peak monthly electricity consumption and it is likely that a significant increase in the site electrical supply infrastructure would be needed to support this approach generally.

8.2 Heat Pump

A heat pump uses an electrical supply to drive a refrigerant cycle to move heat from one place to another. Well designed systems typically allow 1kW of electricity to generate 3-4kW of heat. These typically supply low temperature hot water at about 50^{0}C, and some design consideration is required to allow heat to be effectively delivered to existing buildings at this temperature. There are three main types of heat pumps detailed below.

8.3 Air source

For this type of system, the heat pump is typically located externally rather than inside a plant room and heat is exchanged with ambient air by passing over a coil. External air is a convenient and abundant source of heat exchange which is accessible without the need for significant civil engineering.

Air temperature varies seasonally which significantly influences the efficiency of operation of air source heat pumps. Air temperature is reduced in cold weather thus increasing the temperature difference between the source and the sink and reducing operating efficiency at a time of year when the heat demand for space heating is at its highest. Conversely, during the warmer months of the year, the CoP of an air

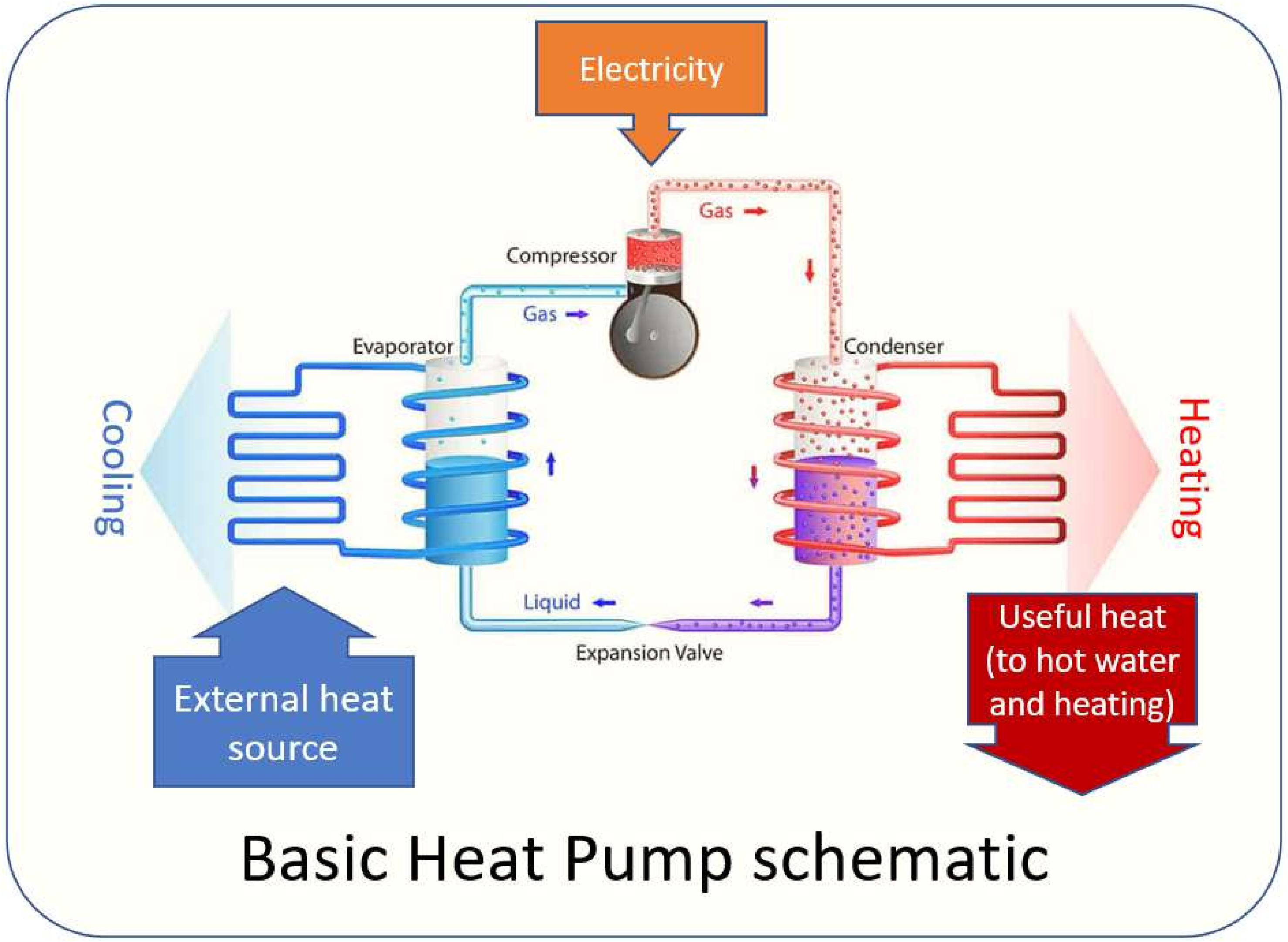


Figure 30

Proposed Heating & Domestic Hot Water Schematic A

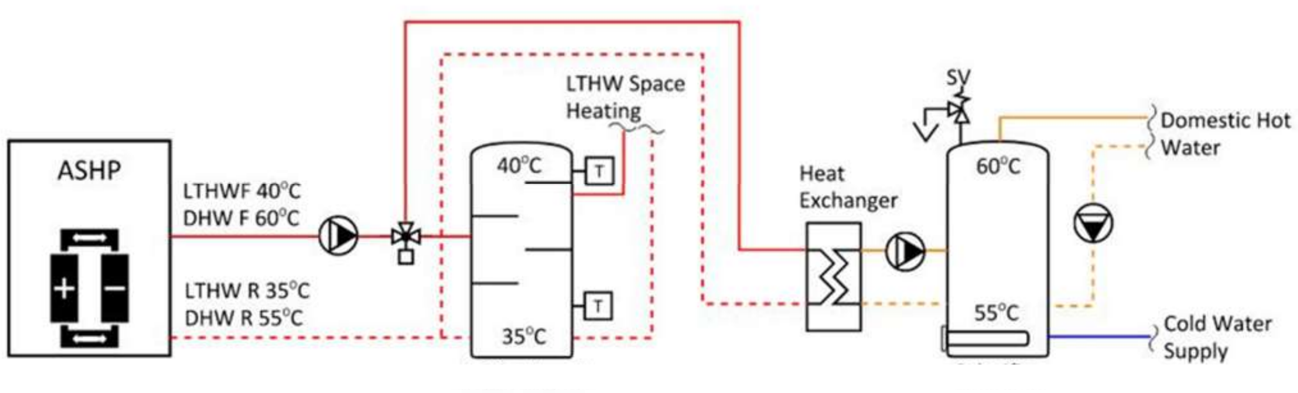


Figure 31

source heat pump is at its maximum when meeting the daily demand for domestic hot water.

At times of low external air temperature, the coil of an air source heat pump can get very cold to the point where ice may form from atmospheric moisture. This reduces air flow through the coil and decreases heat transfer. This requires the heat pump to be switched off and the coil automatically defrosted from time to time. ASHPs generate some noise which needs to be accommodated in the design approach to prevent nuisance.

8.4 Ground Source

8.4.1 Ground source, horizontal heat exchanger, closed loop

For this type of system, heat is exchanged with the ground through horizontal coiled pipe work installed at a shallow depth of 2m below the surface. Using a rule of thumb, 10m of length with 5m centres ($50m^2$) gives 1kW of energy.

8.4.2 Ground source, vertical heat exchanger, closed loop

For this type of system, heat is exchanged with the ground through pipe work contained within boreholes drilled vertically into the ground. The boreholes are typically, 60 – 150m deep but deeper systems are possible where the geology is suitable. Usually, one or two loops of high-density polyethylene HDPE heat exchange pipes are contained within each borehole, with the boreholes set out with a minimum spacing of 5 to 6 m. Boreholes of this type are known as conventional U tube boreholes. The thermo-geological properties of the ground determine the heat extraction rates that can be supported in a specific location. In Cambridge, the geology generally allows simple unlined boreholes to be drilled to a depth of approximately 50m. Beyond this depth boreholes typically need to be lined in order to maintain their integrity when the drill is extracted.

Borehole heat exchangers are usually grouted using a mixture of bentonite and silica sand, the thermal quality of the grout influences the heat transfer properties of the borehole.

The individual pipe work loops from the top of each of the boreholes are run below ground in a shallow trench to an external manifold chamber where they are connected together and run as a single flow and return pipe work pair, to the heat pump located within an internal plant room. The pipe work arrangement forms a closed fluid system between internal heat pump and external borehole heat exchange array. Water or more commonly a water and glycol mixture is typically used as the heat transfer fluid.

In Cambridge, approximately 30m borehole length is typically needed for 1kW heat exchange and a balance of heating and cooling loads across the year is beneficial to reduce long term changes in ground temperature.

8.4.3 Ground source, vertical heat exchanger, open loop

For this type of system, heat is exchanged with the ground by the abstraction and reinjection of water from and to, a below ground aquifer or other source of ground water. Ground water is usually abstracted from a borehole, passed through the heat pump then reinjected at a location in the downstream direction of the ground water movement or back into the aquifer.

All abstractions of ground water are subject to the licensing requirements of the Environment Agency, including impact assessment on drinking water supply and may also be subject to a standing and metered charge on the volume of water abstracted.

Owing to the long term reduction in the water table level in the Cambridge area and the need to prove abstraction capacity with physical pumping prior to the granting of abstraction licences there is significant risk associated with this approach.

8.5 Water Source

8.5.1 River source, open loop

For this type of system, heat is exchanged with a body of surface water such as a river, lake or sea, the heat pump is located internally within a plant room. The open loop heat exchange is achieved by pumping water directly out of the river, passing it through the internal heat pump, then pumping it back into the river. Heat is exchanged by a combination of mass flow, evaporation and conduction.

An open loop system must be protected from ingress of river sediment, debris and organic matter. This is usually achieved at the point of abstraction by design of a suitable intake chamber, including filters and settlement sumps. The design of the intake is very important to reduce the risk and frequency of physical and biological clogging of pipe work and heat exchangers. The design of intake and return chambers is bespoke and specific to its location and the nature of the waterway.

Consents are required from the Environment Agency and for the River Cam, the Cam Conservators are also a consultee. Thorough analysis and computational modelling are usually required in order to satisfy the Environment Agency that the river source heat pump system will not damage the environment or cause disturbance to plant and aquatic life within the river. The time taken to obtain approval can be considerable, 6 months or more is not unusual.

An open loop system does not require any equipment or pipe work within the body of water itself. This is a clear advantage for a navigable river such as the River Cam that is used heavily for activities such as punting.

The availability and easy access to the River Cam makes a river source heat pump system worthy of consideration. The temperature of river water varies seasonally from 0 degrees Centigrade in Winter to 18-20 degrees Centigrade in Summer. The source temperature is therefore less stable and consistent than a ground source system but more stable than an air source system.

Using previous studies, we can estimate the amount of heat that can be extracted from the river, during the heating season (September to May)

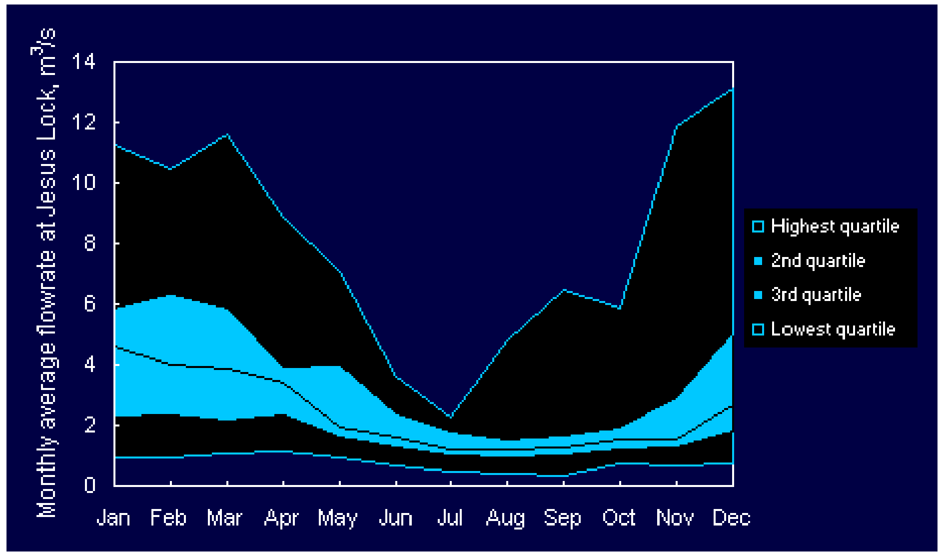


Figure 32

The heat capacity of water is $4{,}182kW/degC/m^3s^{-1}$. With a minimum flow rate of about $1m^3/s$ during a dry spell the energy removed becomes dependent on the temperature difference between the water in the river and the water discharged back to the river after heat is exchanged with it:

- 4.2MW @ 1 degC
- 8.4MW @ 2degC
- 12.6MW @ 3 degC

From the extrapolated PHPP modelling (fabric improvement scenario 1) a typical figure for the peak heat required during winter is 1.2MW. This is very comparable with the figures listed above. As per the open loop design, the installation would typically pump water from the side of the river at mid-level on the east bank into a heat pump, requiring about $0.3m^3/s$ at a delta T of 1.

As more sites realise the potential of the Cam, careful management of the water temperature would need to be considered, especially when the flow rate is low.

Water can also freeze during winter, during the time when the need for heating is the greatest. A backup source of heat is likely to be needed to meet this eventuality.

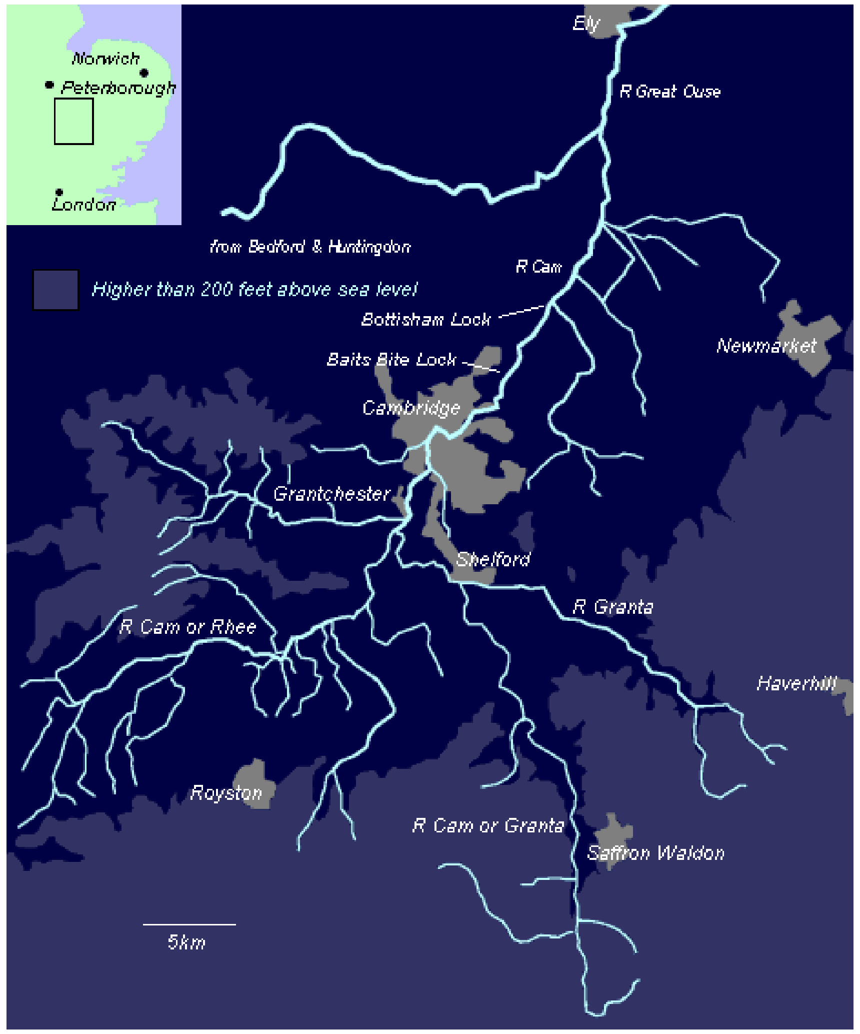


Figure 33

Additionally, sections of the river along the backs are occasionally completely drained to allow maintenance to the bed and banks, during which times a backup source of heating and cooling would also be needed to maintain service.

8.5.2 River source, closed loop

As with river source open loop, heat is exchanged with a body of surface water such as a river, lake or sea, the heat pump is located internally within a plant room. For a closed loop system, the heat exchange is achieved by pipe loops or a heat exchanger grid submerged within the river.

A closed loop system is not susceptible to direct clogging or blocking as the river water is not used directly by the heat pump, but the heat exchanger gradually fouls externally over time and needs to be cleaned periodically to maintain effectiveness.

The area of the pipe work array required within the water is considerable which is a significant challenge for a relatively narrow river. The water filled pipe work loops are buoyant and will float unless they are fixed or anchored to the bed of the river. The heat exchange pipe work remains exposed on the riverbed where there is a high risk of accidental damage from boating and punting activities. For these reasons, this type of river source heat pump system is not considered appropriate.

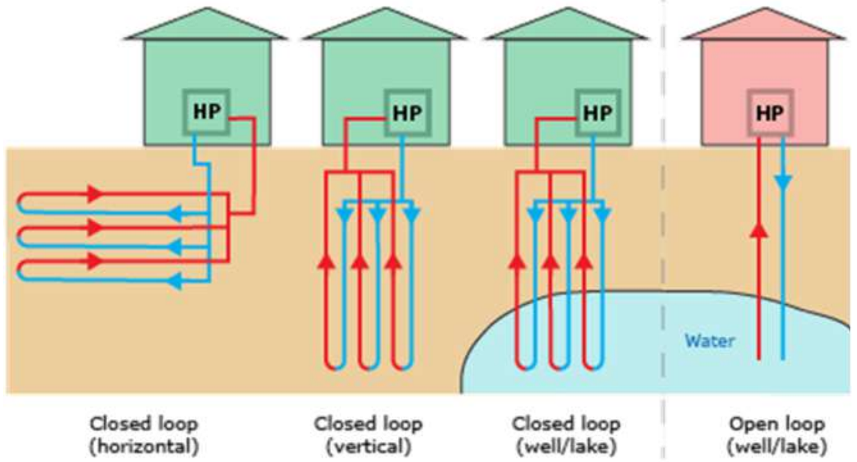


Figure 34

8.6 Ambient loop

For this type of system there is typically one centralised heat exchange system that circulates a body of water to and from a site where heat can be taken or removed at localised plant rooms to meet the needs of individual buildings. This is one of the most efficient measures that can be considered as differing needs are balanced and requires the establishment of a site-wide infrastructure of circulating pipework.

8.7 Conclusion

In the context of the Kings College sites the combination of site-wide heat distribution between some centralised heat exchange(s) and local water to water heat pumps serving each building is likely to be a solution which optimises the balance between carbon reduction efficiency, aesthetic impact, noise control and cost. The following conceptual approach is presented as a model for comparative evaluation of the heat exchange and renewable energy options in the following sections.

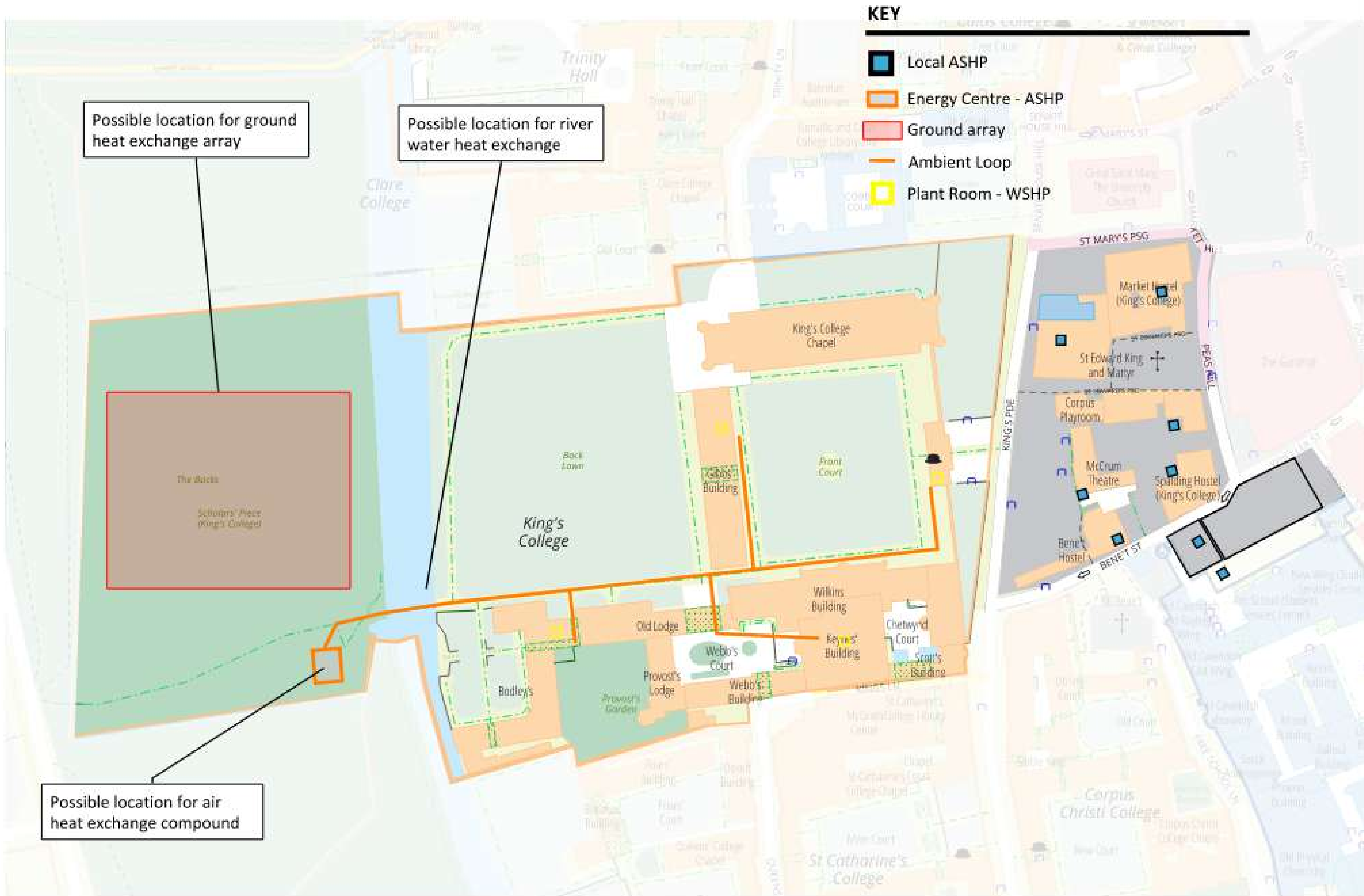


Figure 35

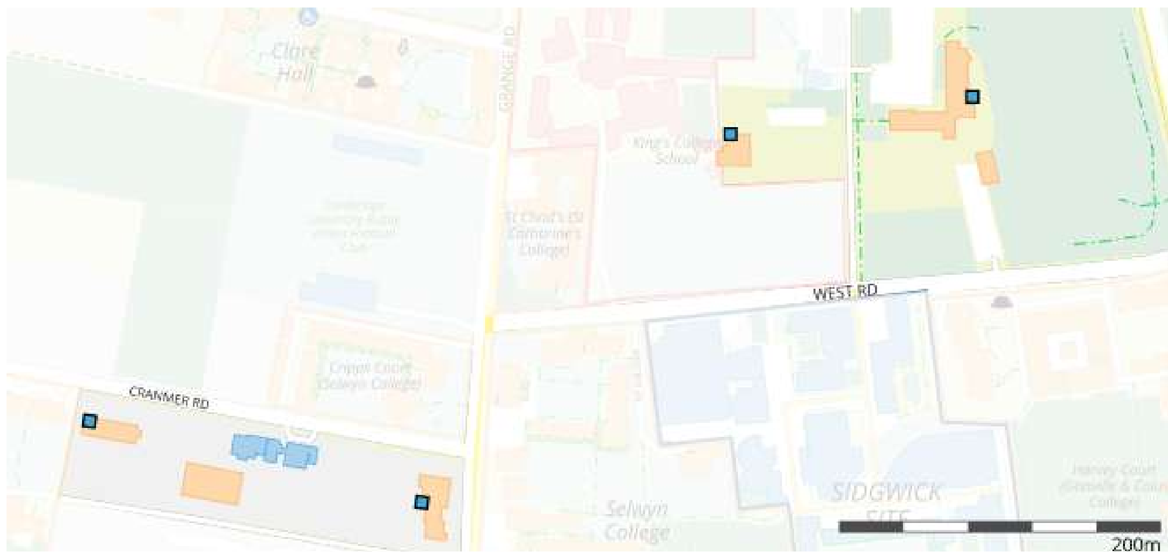


Figure 36

9.0 ENERGY GENERATION

Potential renewable sources of energy generation local to the site are solar power and wind power. Solar energy can be collected as heat or converted directly to electricity by photovoltaic (PV) panels.

The arguments in favour of renewable energy generation have (and still do) revolve around reducing carbon emissions, which is an essential outcome.

A significant part of the decarbonisation strategy for the UK is the reduction in carbon intensity of grid supplied electricity and the shifting of heat loads from fossil fuels to electricity. The carbon intensity of grid supplied electricity has already dropped from approximately 0.5kgCO_2/kWh in 2014 to approximately 0.25kgCO2/kWh now and is committed to become 0kgCO_2/kWh by 2050. The upshot of this is that the carbon emissions savings from renewables will tend to zero by 2050. Over this time we see the benefits of renewable electricity generation shifting from carbon emissions reductions to security of supply (augmenting grid generation capacity) and cost savings through reducing imported energy and carbon taxation costs.

In the meantime, every tonne of carbon emissions saved has value.

9.1 Solar PV

A study was carried out in 2019 to assess the potential of all the roofs on the College main site for solar thermal and PV energy generation. The study concluded that solar thermal heat generation was not cost effective for any roofs but that PV electricity generation was technically and economically viable for a number of roofs. Figure 39 shows a summary of the PV generation potential of al the roof areas. Please see that report for more detailed information of the analysis. Of all the roofs in the college, the chapel roof has the single largest suitable roof areas and the highest generation potential.

Figure 37 shows the area of PV array required to generate sufficient electricity to meet the whole site annual electrical demand for the different fabric improvements, assuming all electric heat pumps with a COP of 2.5

The college has already implemented 2 PV installations:

- Wilkins Hall – 21kWp roof mounted array
- Old Garden Hostel – 12kWp roof mounted array

The chapel roof provides the single largest opportunity for PV generation on the site, with a potential generation capacity of 125kWp.

A sizable PV array may be difficult to accommodate in central Cambridge, but it is possible that a suitable off site location might be found locally or added onto the existing Smartest Energy electrical tariff.

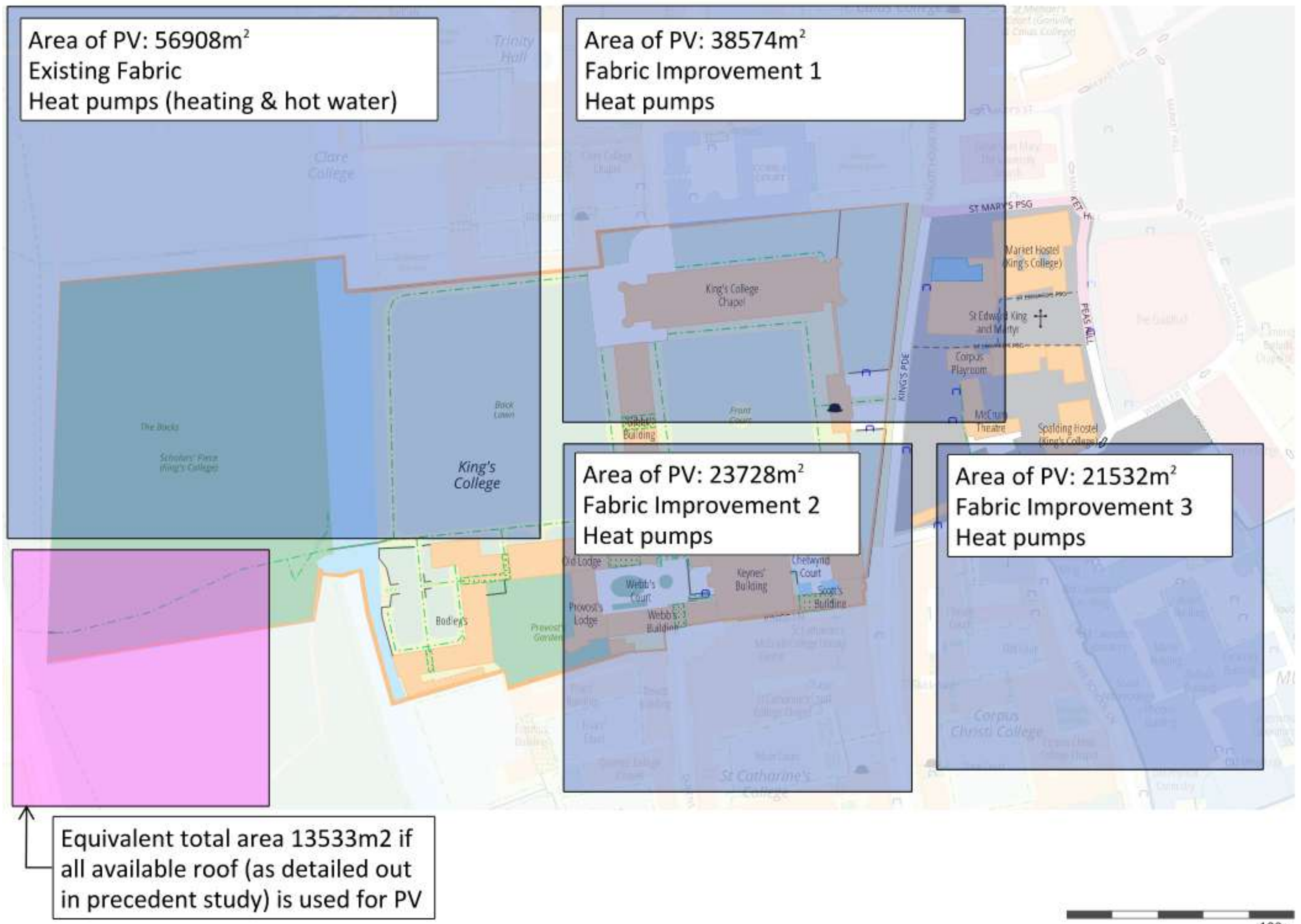


Figure 37

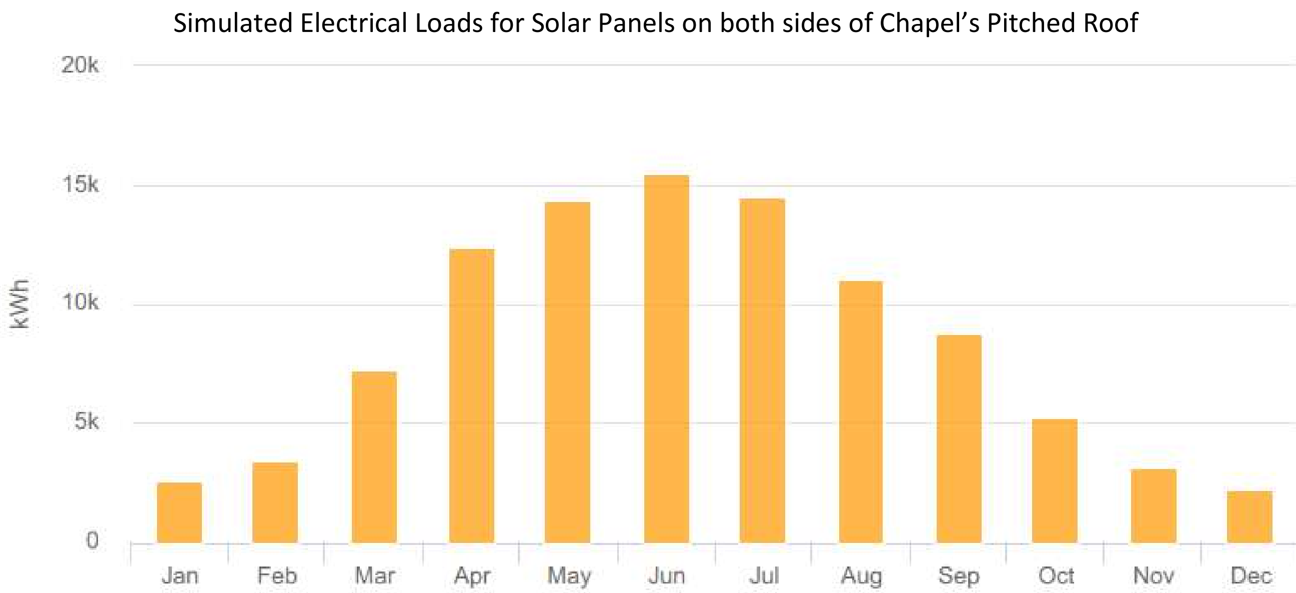


Figure 38

Table 10 represent the cost return for the proposed chapel roof PV installation. Detailed in Table 9 below are the assumptions and sourced values used to calculate the overall benefits. Carbon emissions have used the colleges standard electrical tariff and not the renewable electrical tariff to demonstrate the positive carbon impact.

Table 9

Input	Value	Source
PV Panel Size	1812 mm x 1016 mm	REC Alpha Pure Black REC400AA
PV Panel Output	400 W	https://www.energysage.com/solar-panels/rec/2544/REC400AA_Pure_Black/
PV Panel Life Span	25 – 30 years	REC provide 25 year warranty
Solar annual irradiance	Irradiance Dataset based on orientation and inclination	MCS – based on Norwich https://mcscertified.com/wp-content/uploads/2019/08/Irradiance-Datasets.xlsx
Cost of electricity	14 p/kWh	Estimated cost for the college from utility bills
Fraction of electricity exported	5%	Assumed
Typical PV Installation Costs	For 0-4kW - 1628 £/kW For 4-10kW – 1685 £/kW For 10-50kW – 1088 £/kW	UK Government Solar PV cost data 2020-2021 https://www.gov.uk/government/statistics/solar-pv-cost-data
Grid electricity carbon emissions factor 2021	0.2123 kgCO₂e/kWh	https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting
CO_2 Yearly Saving Equivariant	Driving 130km in an average petrol car	BBC – Smart guide to climate change
Trees Required to Offset PV CO_2, Each Year	11715 trees (23 Tonnes)	Forestry Commission – Mitigation: Planting more trees

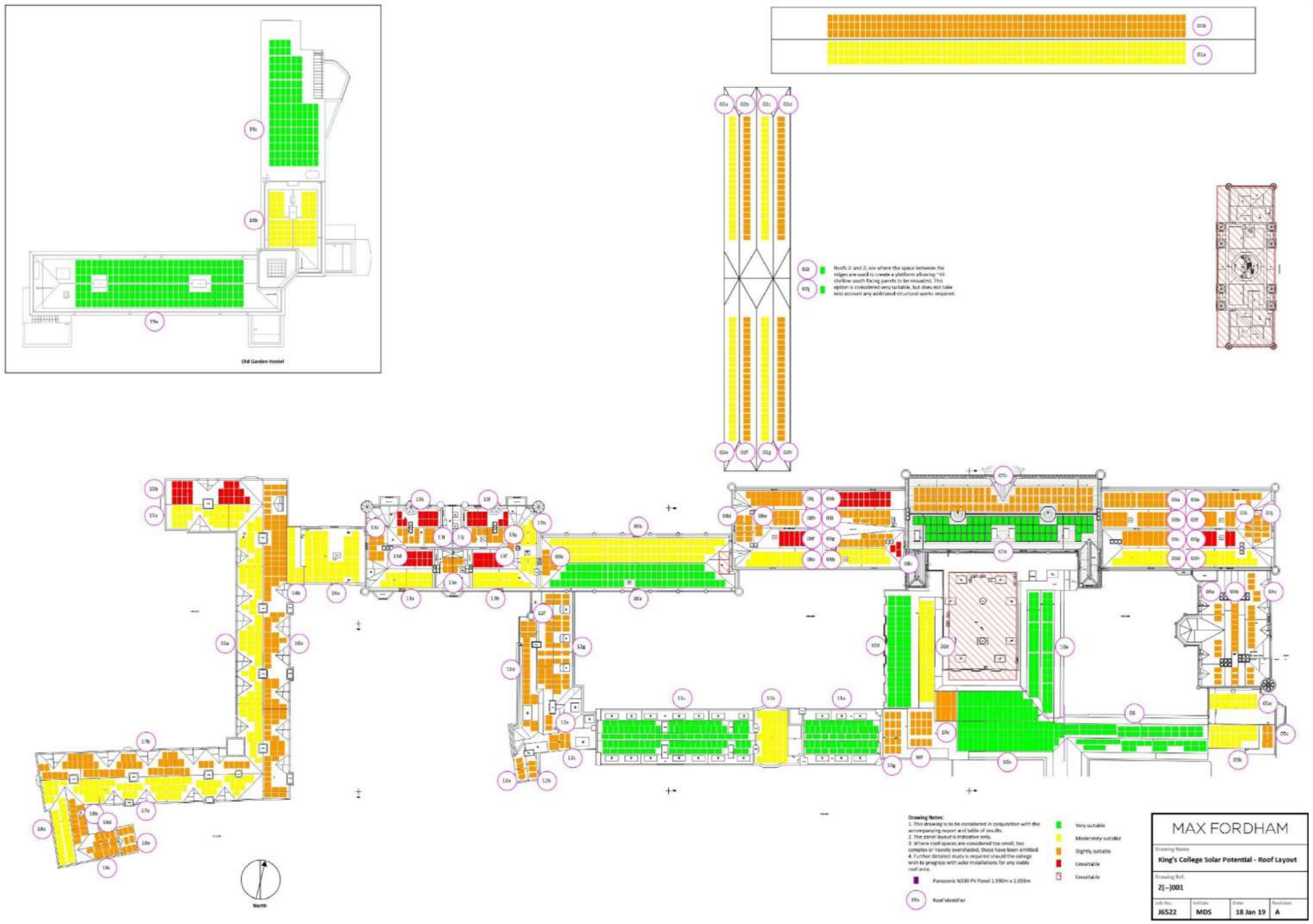


Figure 39

Table 10

Roof ID	Estimated Number of Panels	Orientation	Inclination	Shading	Effective panel area (m²)	Annual Irradiance (kWh/m²)	Shading Factor	Potential kWp	Annual PV Output (kWh/yr)	CAPEX PV (£)	Elec import offset (£/yr)	Simple payback (yrs)	CO2 saving (kgCO2e/yr)
REC Panel: Chapel South Slope	240	S	Shallow	Modest	442	937	0.800	96.0	71,962	£104,448	£9,571	10.9	15,277
REC Panel: Chapel North Slope	240	N	Shallow	Modest	442	612	0.800	96.0	38,400	£104,448	£5,107	20.5	8,152

9.2 Solar Thermal

Not considered further on the basis of the 2019 study

9.3 Wind

Wind Turbines at scale have significant electrical generation potential.

Figure 40 shows the area of wind turbine required to generate sufficient electricity to meet the annual demand for the base case and energy reduction scenarios.

Despite the potential for electricity generation, a large turbine is not considered feasible or appropriate on a site within the centre of Cambridge, nor is there any further land under the ownership of the College where this is considered so.

Figure 40
Scale of turbine – 52.9m in diameter - Enercon E-53

Table 12

Maximum Power Output	Diameter (m)	Example Turbine	Annual Energy Capture (MWh) for the Annual Average Wind speeds:
			5.5 m/s
100 kW	24	Norvento nED-100	220
800 kW	52.9	Enercon E53	1,521
1 MW	61	EWT DW61	1,832

As per the solar panel exercise, the number of turbines in Table 11 below represent what would be required for the whole college energy demand assuming heating is produced by electric heat pumps.

Table 11

	Diameter (m)	Number of turbines required
Base	52.9	3
Scenario 1	52.9	2
Scenario 2	52.9	1
Scenario 3	52.9	1

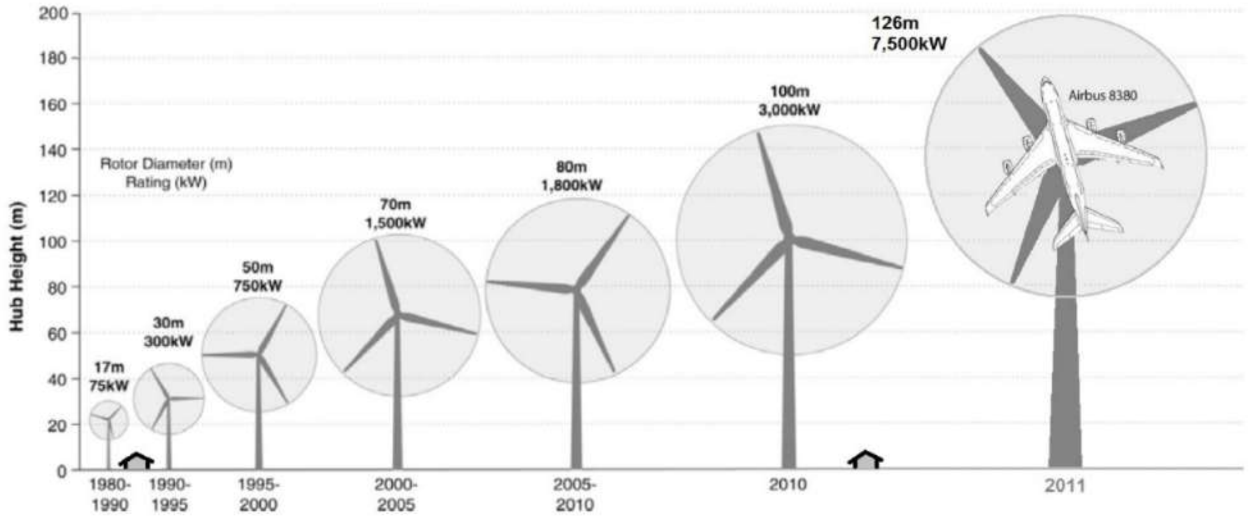


Figure 41

MAX FORDHAM

10.0 CARBON EMISSIONS

10.1 Carbon Emissions Reduction

Every tonne of carbon emissions saved has value. Establishing an accurate understanding of that value is complex. A 2018 German study estimated that the emission of each tonne of CO_2 causes environmental damage worth 180 euros. National Grid have reported using a carbon price of £45/tonne in their comparative cost benefit analysis of projects. The UK GBC recommends using a value of £70/tonne when costing carbon offsets. The London Plan requires a value of £95/tonne to be adopted for planning applications.

The charts illustrate the significant cumulative effect on reducing carbon emissions by implementation of the 3-part decarbonisation strategy:

1. Energy demand reduction by improving the buildings fabric performance. Double glazing and roof insulation
2. Electrification by changing over to heat pumps for heating and domestic hot water. The effect of implementing heat pumps for heating appears relatively small but this is due to the energy demand for space heating having already been dramatically reduced by the fabric improvement measures.
3. On-site renewable electricity generation. The reduction of carbon emissions achieved by using on-site renewably generated electricity from PV array.

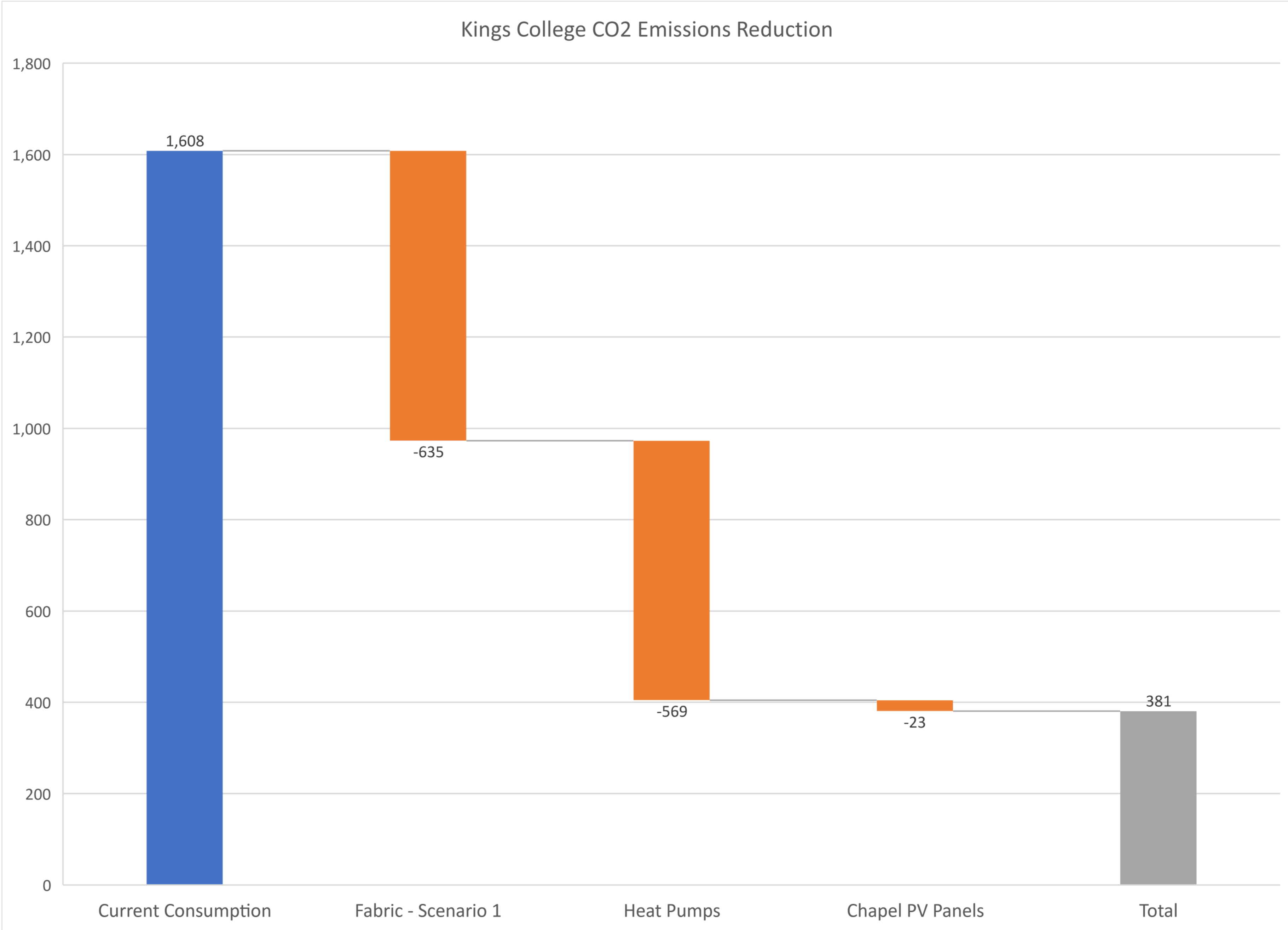


Figure 42

10.2 Offsetting

As you increase the fabric improvement the energy required to heat the building is greatly reduced, helping reduce your carbon and running cost.

What you can't generate, can be offset to a certain degree.

Without a fully zero carbon electricity tariff, to be fully Net Zero carbon under the heat pump energy strategy, some level of offsetting would be required. Offsetting costs reduce with higher performing building as the operational carbon emissions are lower. Offsetting costs are variable, but the UK Green Building Council recommends using a value of £80/tonne/year

10.3 Residual Carbon Emissions

Beyond 2022, the proportion of national grid electricity produced from renewable sources will continue to increase. The beneficial reduction in carbon emissions because of purchase of grid electricity as the only fuel source, over the next 28 years up to 2050, is illustrated.

For Kings College, the residual carbon emissions are predicted to be 24 Tonne of CO2/annum by 2040 and 11 Tonne of CO2/annum by 2050 (the national net zero carbon target).

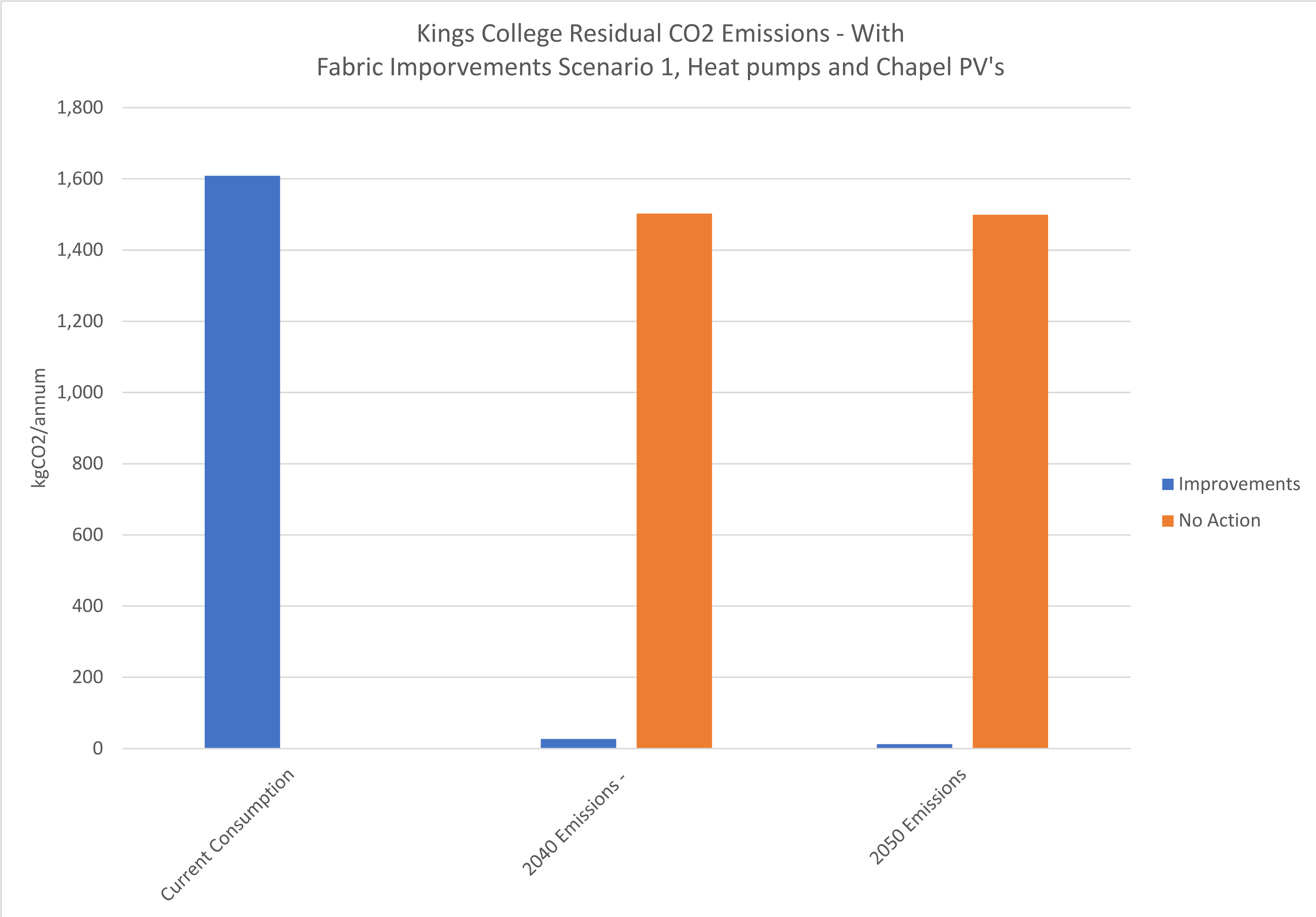


Figure 43

11.0 ONGOING FUEL COSTS

A direct comparison of the energy strategies can be found below. They represent the carbon and running cost of each option against that level of fabric improvement.

Costs are based on the existing costs of energy purchased by the college.

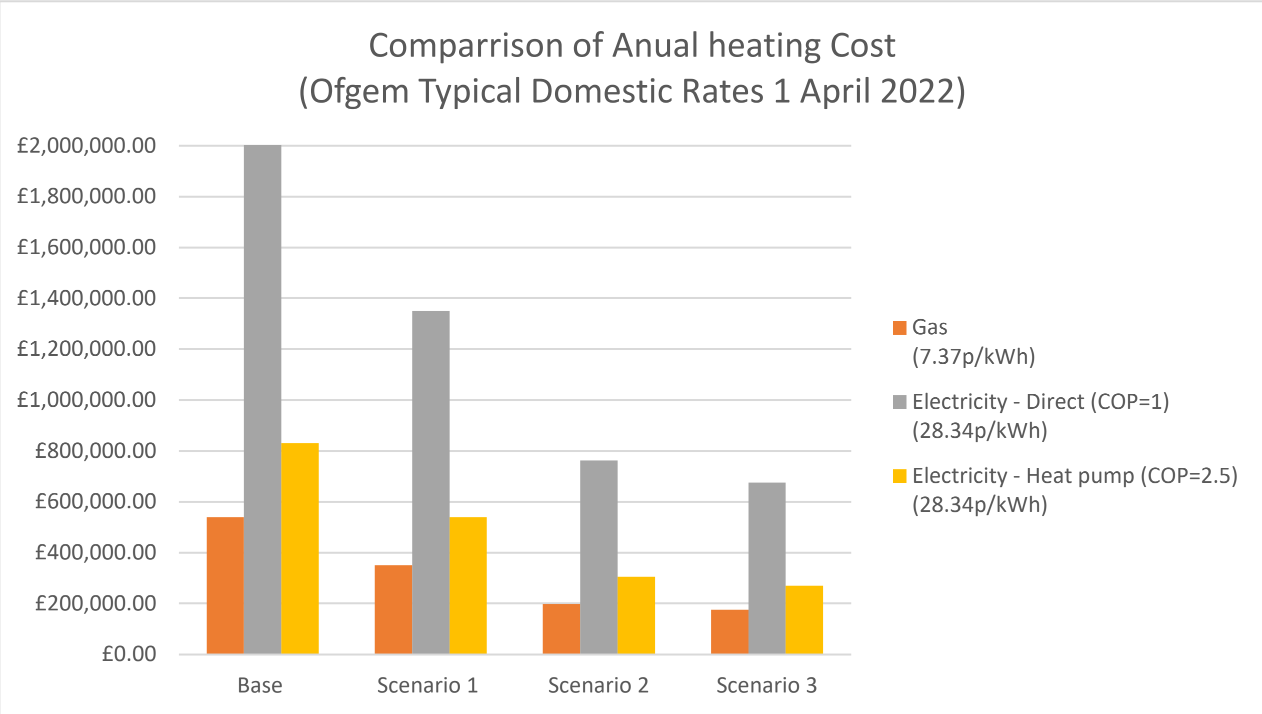


Figure 44

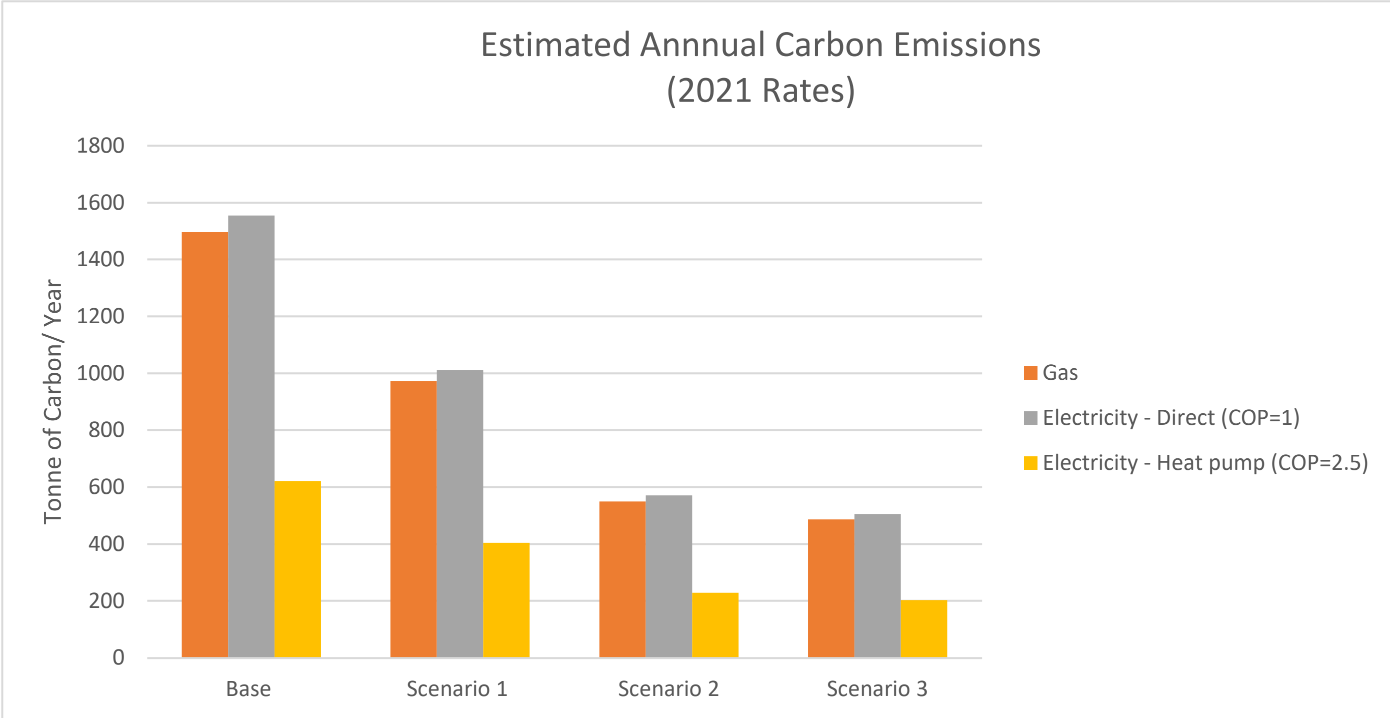


Figure 45

12.0 ELECTRICITY STORAGE

12.1 Electricity

As is the nature of renewables the energy is not always produced when needed or demand is not always there. This then leads to question if the energy can be easily stored and used when needed. Large Lithium-Ion batteries can be used to store excess electricity. However, on a large scale such as the king's college estate, this is not always a viable solution due to size, cost, and environmental impact. It becomes more suitable to sell back to the grid.

Figure 46

MAX FORDHAM

13.0 SUMMARY

The report and analysis sets out a route to Zero Carbon for the King's College estate.

It has considered the potential to reduce heat loads by improving building fabric performance and taken a balanced view of what is likely to be possible given the architectural and heritage significance of many of the buildings. It has showed how the heating loads may be transferred from fossil fuels onto electricity, a decarbonising energy source, and how electricity may be used efficiently to provide that heat. Based on some earlier work to assess the electricity generation capacity of the college roofs it has illustrated the contribution that PV generation could make to the overall energy usage and the scale of renewable generation that would be needed to generate sufficient energy to meet the annual need. It has also mentioned the increase in electricity supply capacity that would be needed to support the electrification of the heat loads.

Reduction in heat loads, implementation of heat pumps and renewable electricity generation all have a part to play in achieving net zero carbon.

Fabric improvements are needed to allow the implementation of heat pumps which minimise the increase in electricity supply capacity.

Renewable electricity generation projects may be implemented quickly, have relatively short payback periods and create carbon savings while the grid carbon intensity decreases. Beyond the point where grid supplied electricity is carbon neutral, renewable generation has relevance in decreasing costs associated with importing electricity and supporting capacity in the transition to a smart grid. The largest and most impactful current opportunity is the implementation of PVs in conjunction with the replacement of the lead roof of the chapel which has the potential to reduce the college carbon emissions by an average of 23 tonnes a year over the next 30 years.