Pembroke College

Decarbonisation Plan

20/11/23

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ISSUE HISTORY

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1	29/03/23	Draft for comment
2	30/03/23	Submission for Salix
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Engineer (Initials)	Role
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PR	Project Manager

PEMBROKE COLLEGE DECARBONISATION

The purpose of this study is a plan to reduce carbon emissions of the College. This is done both by reducing energy demands and by replacing fossil fuels with electricity that can be decarbonised. Indeed in the case of Pembroke, electricity is already decarbonised – Pembroke currently purchases electricity with a Renewable Energy Guarantee of Origin (REGO). Gas fired heating and hot water are then the main cause of carbon emissions for most buildings which explains the reason for focussing on this.

The heating energy consumption of all the buildings in the College estate have been studied by looking at the monthly meter readings and carrying out a heat loss calculation. This has been used to analyse the effect of various fabric and glazing improvements in reducing the heat loss.

Various options have been proposed to look at ways of replacing the use of gas to provide the heat. This is generally some form of heat pump or direct electric heating.

All the proposals will reduce the carbon emissions of the College, and are given budget costs. The costs and carbon savings for each measure have been scored according to the cost per tonne saved over a 30 year program.

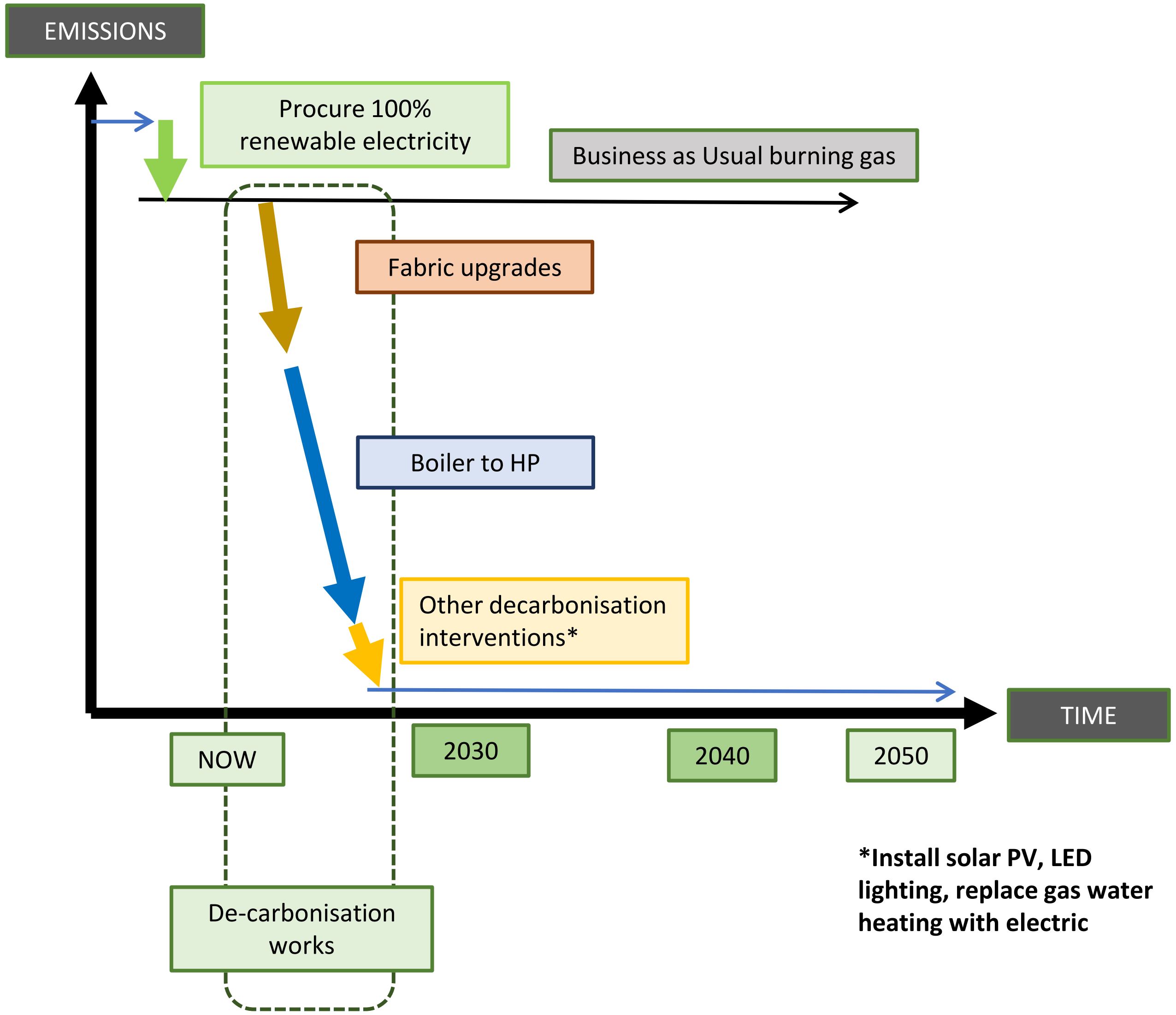
The interventions are likely to require planning consent and listed building consent on the relevant buildings. This process has already begun at the Dining Hall and GAB.

Electrical issues

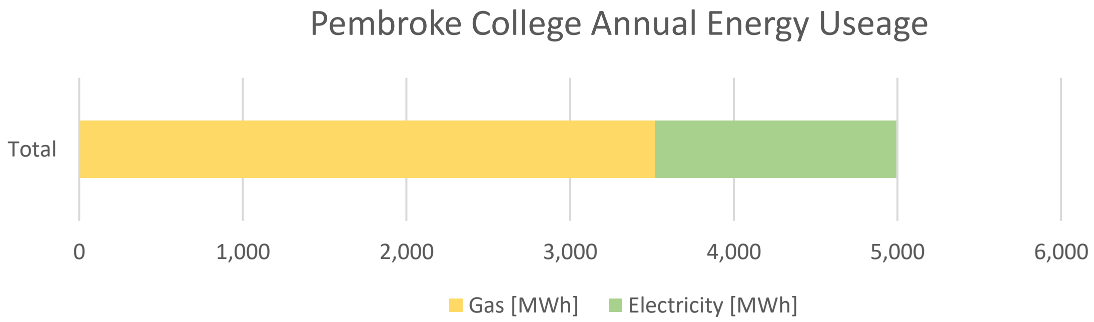
As the electricity grid decarbonises towards 2050, electrifying the heating and hot water will begin to have a larger impact on reducing the emissions of the building and is the most important aspect of the transition to being net zero carbon. This will increase the electrical demand of the various sites. This has been reviewed.

The decarbonisation journey

The graphic shows how the decarbonisation journey will work. The emissions will go down with passive insulation measures to the building fabric. Replacing the gas with an electric heat pump will reduce the carbon emissions further. It is the government's intention to decarbonise the grid over the next 30 years to zero, although Pembroke College already purchases Renewable Electricity.



***Install solar PV, LED lighting, replace gas water heating with electric**

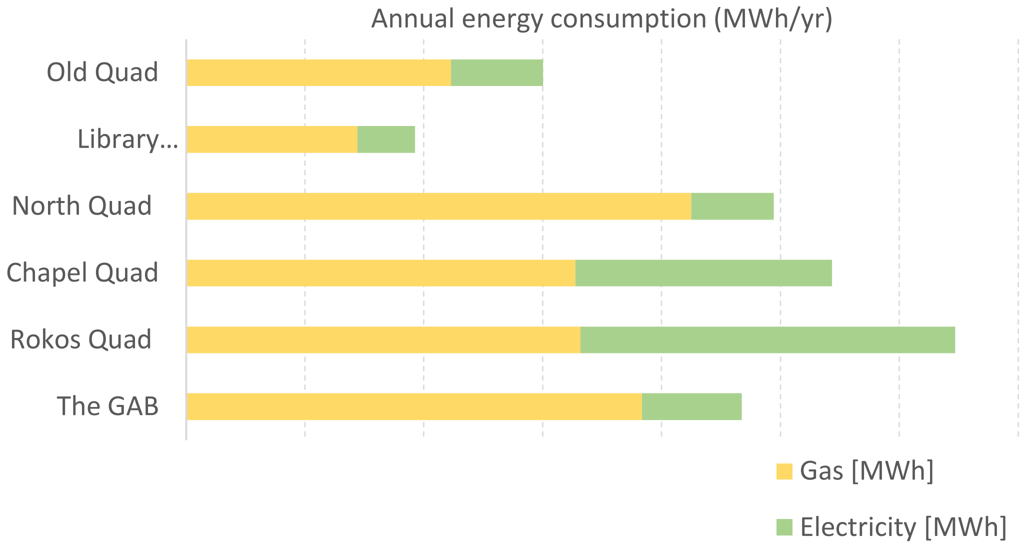


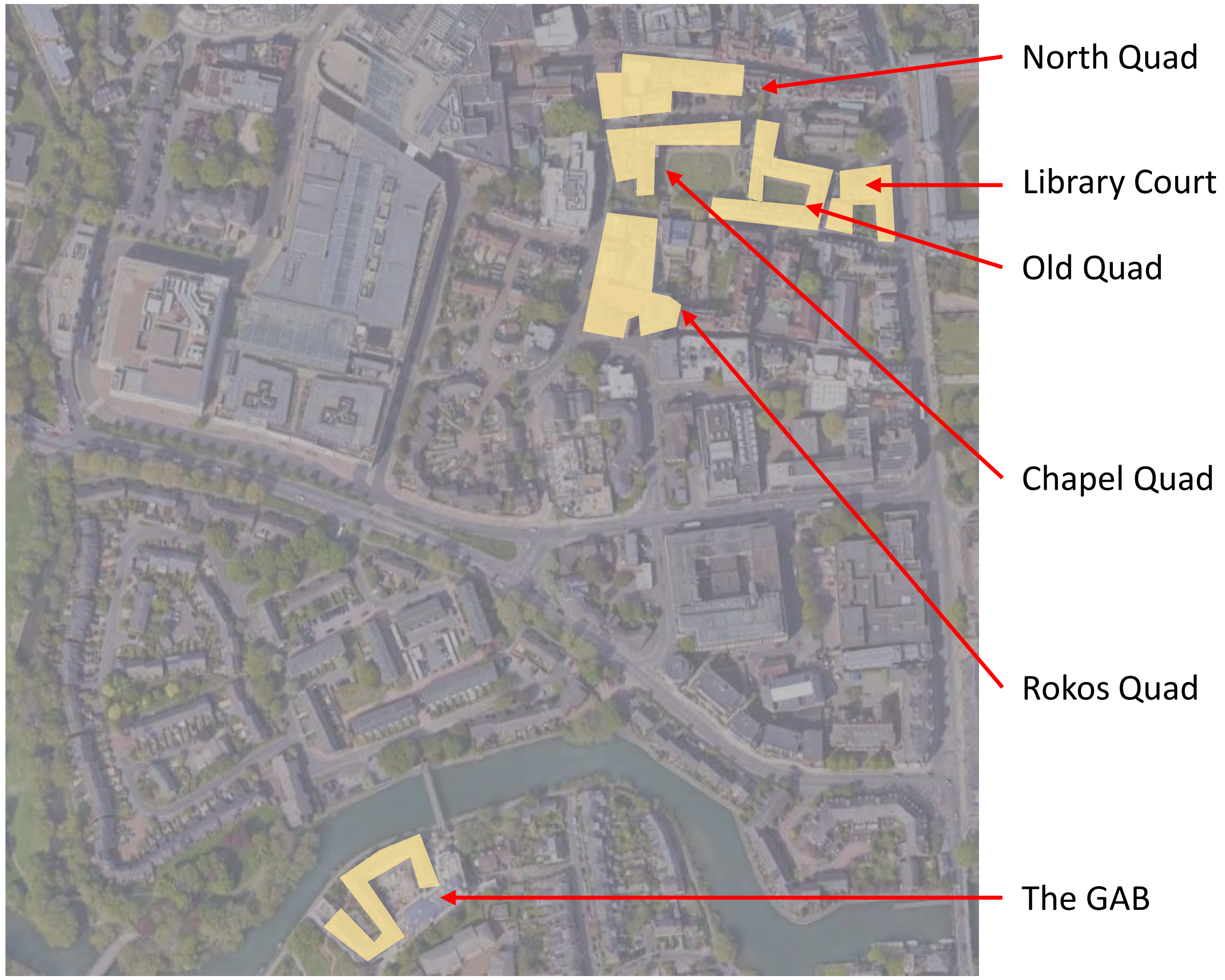
PEMBROKE COLLEGE

Pembroke College is located in the centre of Oxford and is surrounded on all sides by low rise buildings. The site is approximate 14,000 m^2 and is densely occupied with a mixture of historic and modern buildings. The existing buildings are generally for student and staff accommodation, academic teaching and research, and administration. A significant proportion of the older buildings are listed, although many have been adapted from their original layouts.

To the South of the main site lies the Geoffrey Arthur Building (The GAB). The GAB consists of student accommodation. It was originally built in the 1980's but has recently undergone refurbishment in order to reduce the building's energy consumption. It is currently having its heat provision decarbonised

There is also a new GAB building, which is new and coming to completion. It has excellent fabric standards but is initially gas heated. Its heating system is designed for future use with air source heat pumps.





INTRODUCTION

Pembroke College main site has a range of building types arranged around various quads.

Old quad: The buildings of the Old Quad date back to the 16th Century and are Grade 1 listed. They are three storeys, solid walled, with timber roofs. Windows are single glazed in various frames and in various arrangements of sash and casement. These are predominently used as administration and teaching buildings.

Chapel quad: The buildings were built in the 18th & 19th Century and are generally stone or brick construction. There is single glazing across the quad, including ornate stain glass windows in the Chapel & dining hall. The quad does contain some accommodation

North quad: The buildings are a diverse mix of ages including 17th century rubble wall, timber, and more modern brick constructions. The buildings typically pre-date cavity wall and are expected to be generally solid walled and uninsulated. However, the MacMillian building is a relatively modern building constructed in the 1970s. These are predominately residential spaces.

Old quad	Walls:	Stone, some lined internally	Total footprint (gross internal area): 3000m^2 
	Windows:	Timber framed, single glazed. Some secondary glazing	
	Roof:	Timber frame with some insulation	
	Floor:	Combination of suspended timber and solid on grade	
	Ventilation:	via opening windows	
	Typical heat provision:	Direct electric radiators	
	Typical hot water provision:	Local electric storage heaters	
Chapel quad	Walls:	Blockwork wall with pre-cast rainscreen cladding	Total footprint (gross internal area): 2560m^2 
	Windows:	uPVC framed double glazing	
	Roof:	Pre-cast concrete with some insulation	
	Floor:	Combination of timber framed and solid	
	Ventilation:	via opening windows	
	Typical heat provision:	Gas fired heating system with radiators	
	Typical hot water provision:	Central calorifiers fed by gas fired boilers	
North quad	Walls:	Mostly solid brickwork	Total footprint (gross internal area): 2800m^2 
	Windows:	A mix of timber single glazed, with some secondary glazing and some double glazed UPVC.	
	Roof:	Timber framed with insulation at ceiling level	
	Floor:	Combination of timber suspended and solid floors	
	Ventilation:	via opening windows	
	Typical heat provision:	Gas fired heating with radiators	
	Typical hot water provision:	Local calorifiers fed by gas fired boilers	

INTRODUCTION

Surrounding the heart of the college there are further quads. The Geoffrey Arthur Building (GAB), is located on a site to the South of the College by the river.

Rokos quad: Built in 2013 the Rokos buildings are insulated, airtight and doubled glazed. There is little scope to improve the building fabric cost effectively. However, Albion house, another 1970's building, is assumed to be a cavity wall construction with older double glazing. The Rokos contains some teaching and conference spaces but is predominantly residential.

Library Court: The library is a 1970's building with solid walls (assumed) and single glazing. The Almshouses & masters lodging are early 16th century buildings with solid walls, timber roofs & single glazing.

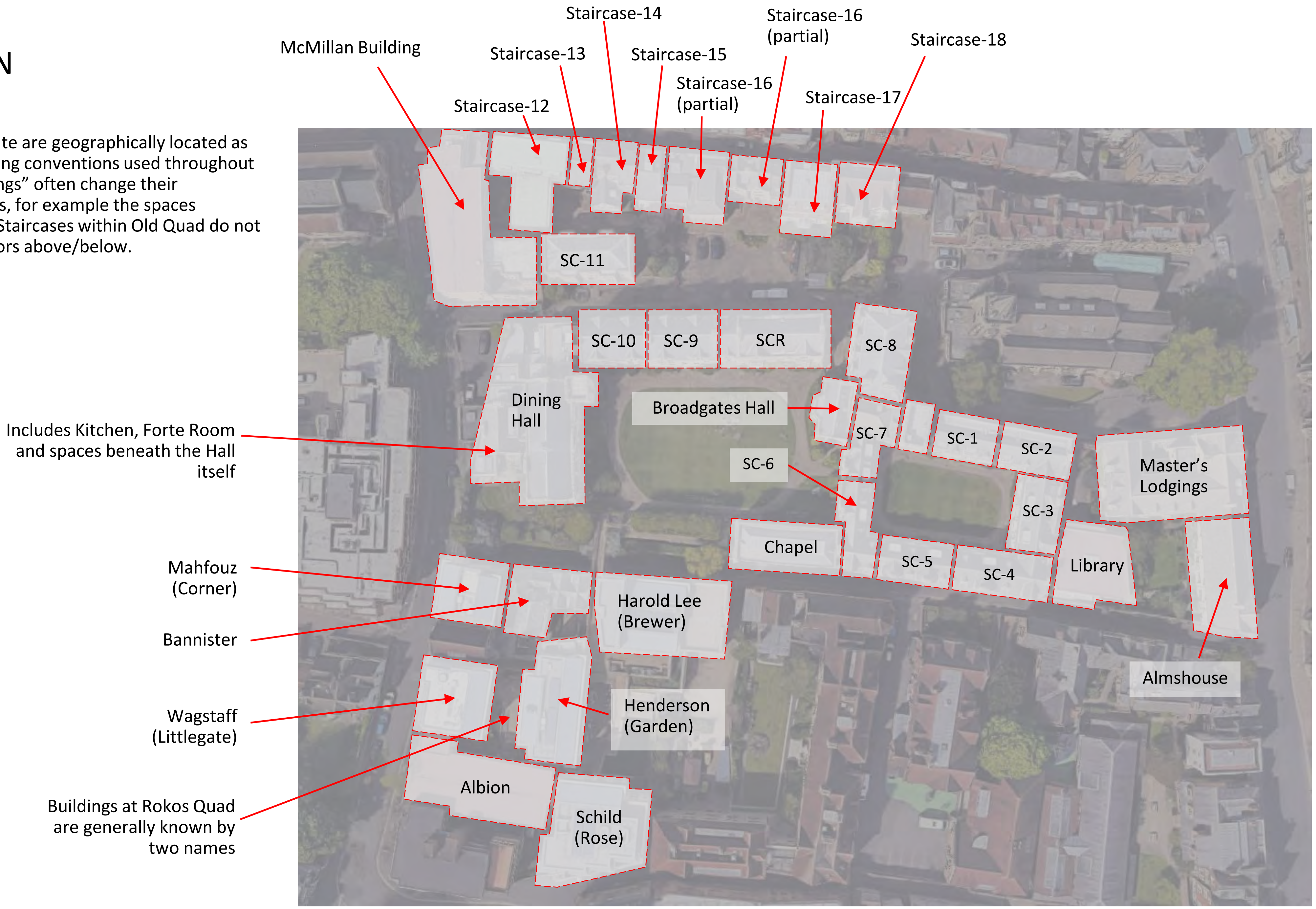
The GAB: Away from the main site is the Geoffrey Arthur Building (GAB). A collection of residential spaces. The GAB has cavity walls with some insulation, consistent with 1980's building regulations, and has recently been upgraded with high performance double glazing.

Rokos quad	Walls:	Stone/block cavity walls with insulation	Total footprint (gross internal area): 6360m^2 
	Windows:	Timber framed, double glazed. Some secondary glazing	
	Roof:	RC slabs with insulation above	
	Floor:	Insulated in line with age of building	
	Ventilation:	Mechanically ventilated with heat recovery	
	Typical heat provision:	LTHW underfloor heating fed by GSHP with gas boiler for peak loads	
	Typical hot water provision:	Central calorifiers fed by solar thermal and gas boilers	
Library quad	Walls:	Blockwork wall with pre-cast rainscreen cladding	Total footprint (gross internal area): 1840m^2 
	Windows:	uPVC framed double glazing	
	Roof:	Pre-cast concrete with some insulation	
	Floor:	Concrete slabs with minimal insulation	
	Ventilation:	via opening windows	
	Typical heat provision:	Gas fired heating system with radiators	
	Typical hot water provision:	Central calorifiers fed by gas fired boilers	
The GAB	Walls:	Cavity walls with blockwork inner leaf and stone outer	Total footprint (gross internal area): 3280m^2 
	Windows:	Largely timber framed double glazing	
	Roof:	Timber framed with insulation at ceiling level	
	Floor:	Beam and block floor, some modest insulation above	
	Ventilation:	via opening windows	
	Typical heat provision:	Gas fired heating with radiators	
	Typical hot water provision:	Local calorifiers fed by gas fired boilers	

INTRODUCTION

The buildings at the main site are geographically located as set out here, with the naming conventions used throughout this document. The “buildings” often change their boundaries at various floors, for example the spaces accessed from the various Staircases within Old Quad do not necessarily line up with floors above/below.

SC = Staircase



Includes Kitchen, Forte Room and spaces beneath the Hall itself

Buildings at Rokos Quad are generally known by two names

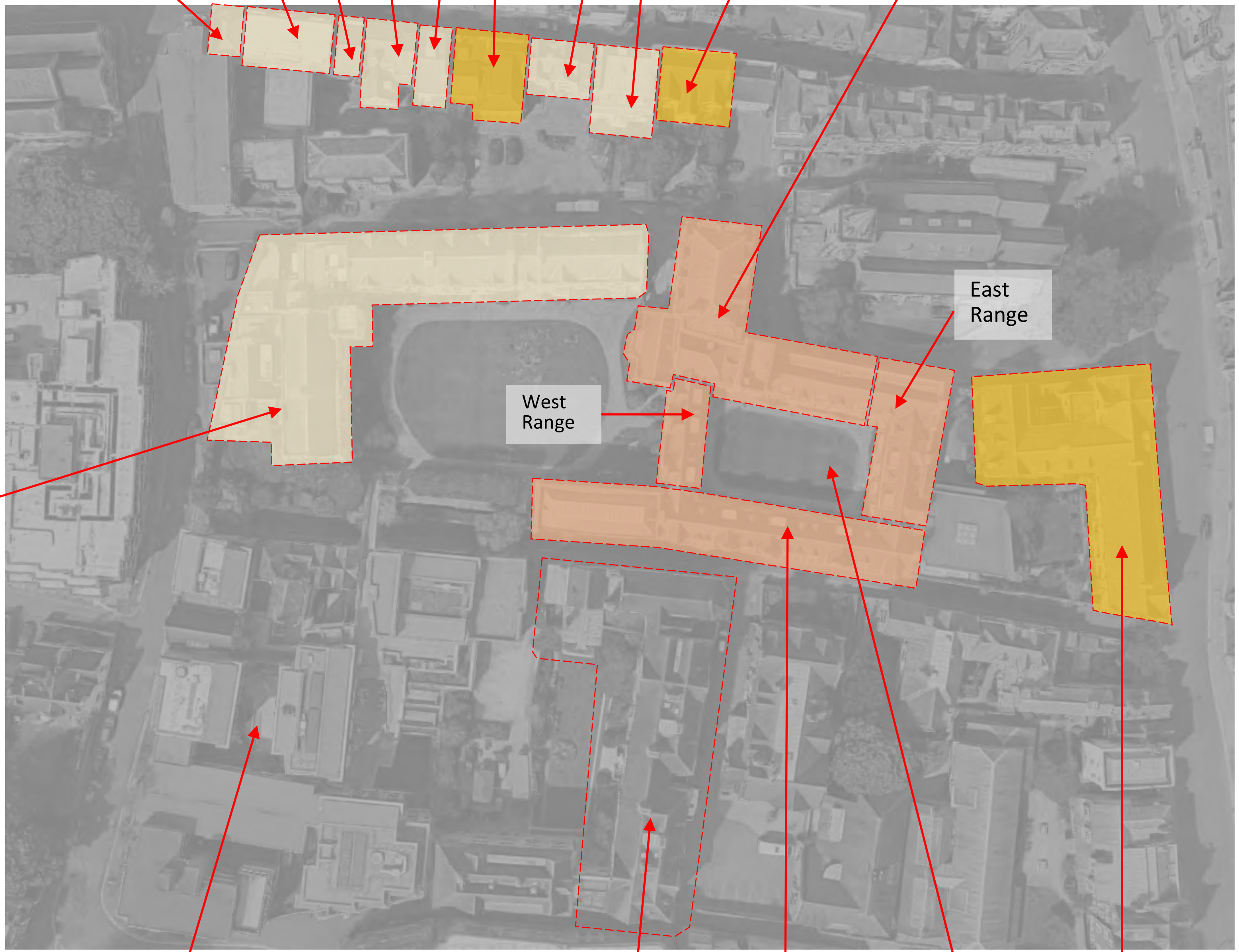
HERITAGE CONSTRAINTS

Many of the buildings at Pembroke have heritage significance and are either listed or within the curtilage of listed buildings (including parts of the historic Oxford City Walls)

This puts constraints on what energy efficiency interventions can be made and these constraints can be unique to each building depending on its particular heritage features.

Working sensitively within the heritage constraints of buildings will often make any interventions more expensive to deliver.

Only the listed buildings are shown here, not other parts of listed context such as walls.



28 Pembroke Street – Part of McMillan Building?

Staircase-12

Staircase-13

Staircase-14

Staircase-15

Staircase-16 (partial)

Staircase-16 (partial)

Staircase-17

Staircase-18

North Range including “Library”, Broadgates Hall and North Wing

The majority of Chapel Quad is Grade-II listed, and described as the “Back Quadrangle” in the National Heritage List

🟧 Grade-I Listed

🟨 Grade-II* Listed

▨ Grade-II Listed

⬜ Listed Building outside e of Pembroke College

Rokos is not listed, but may be deemed to be within the listed curtilage of the neighbouring Grade-II* listed Campion Hall

Grade-II* listed Campion Hall (outside of Pembroke College)

South Range including Chapel

The Masters Lodgings and Almshouse together are Grade-II* Listed

It is not clear to us where the demarcations between the different listings are for Old Quad, and how they relate to staircases. However, the entirety of Old Quad (including the Chapel, Broadgates Hall and the North Wing) is Grade-I listed.

CARBON CONTEXT

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. 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 oil and gas generation, while nuclear, wind and solar do not burn fossil fuels and are deemed carbon neutral. The grid is a mix of generators and its overall carbon intensity is an aggregate of its constituent generators' carbon intensity. As coal has been all but shut down and more renewables have come on line, the average is falling as shown on the graph. The government has set out an ambition to continue this reduction until it is largely 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. Pembroke College already does this.

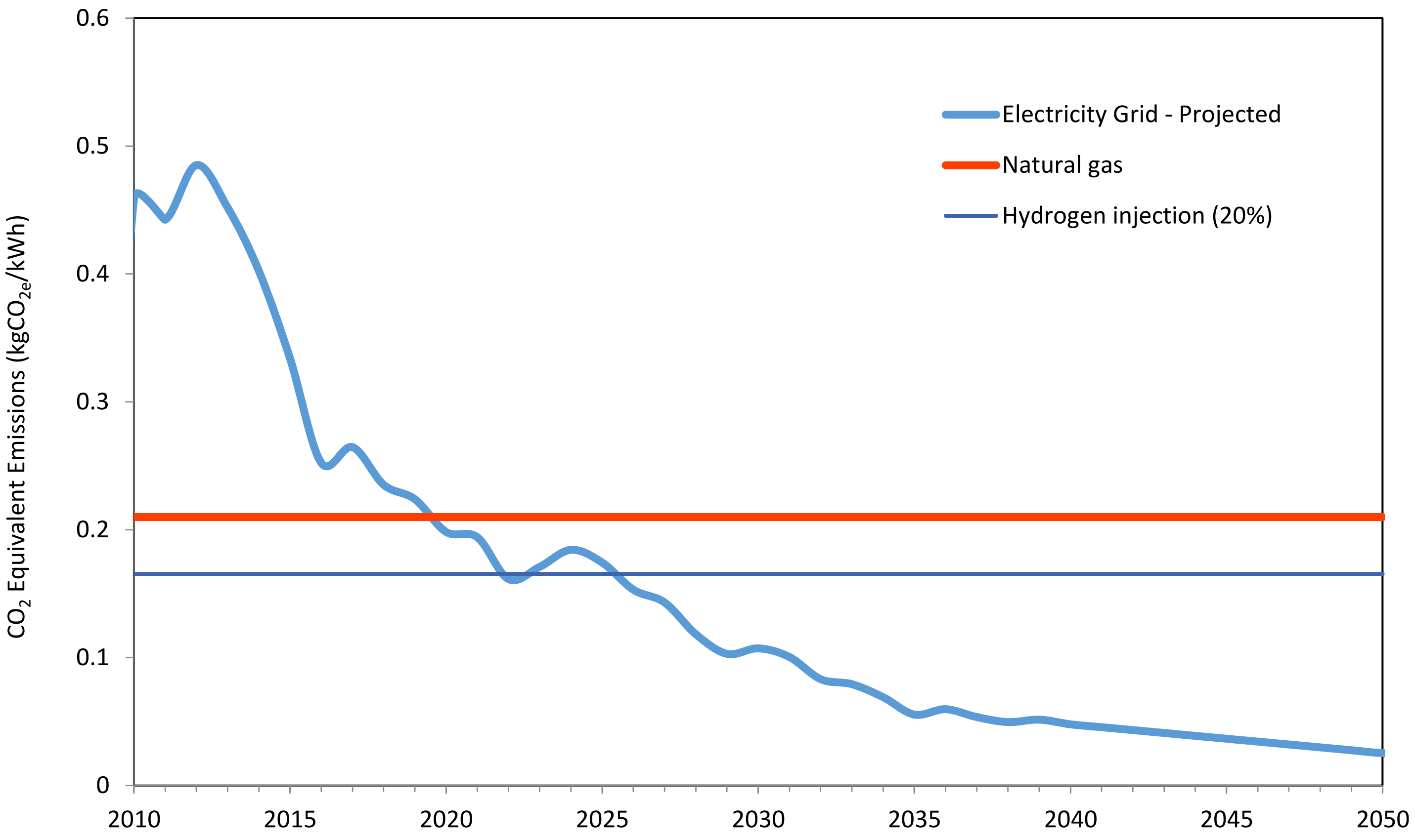
Gas

"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.

Decarbonisation

We would always now recommend that clients look to move heat production from gas to electricity. Hydrogen might be available in a gas grid but it will be in the future and expensive.

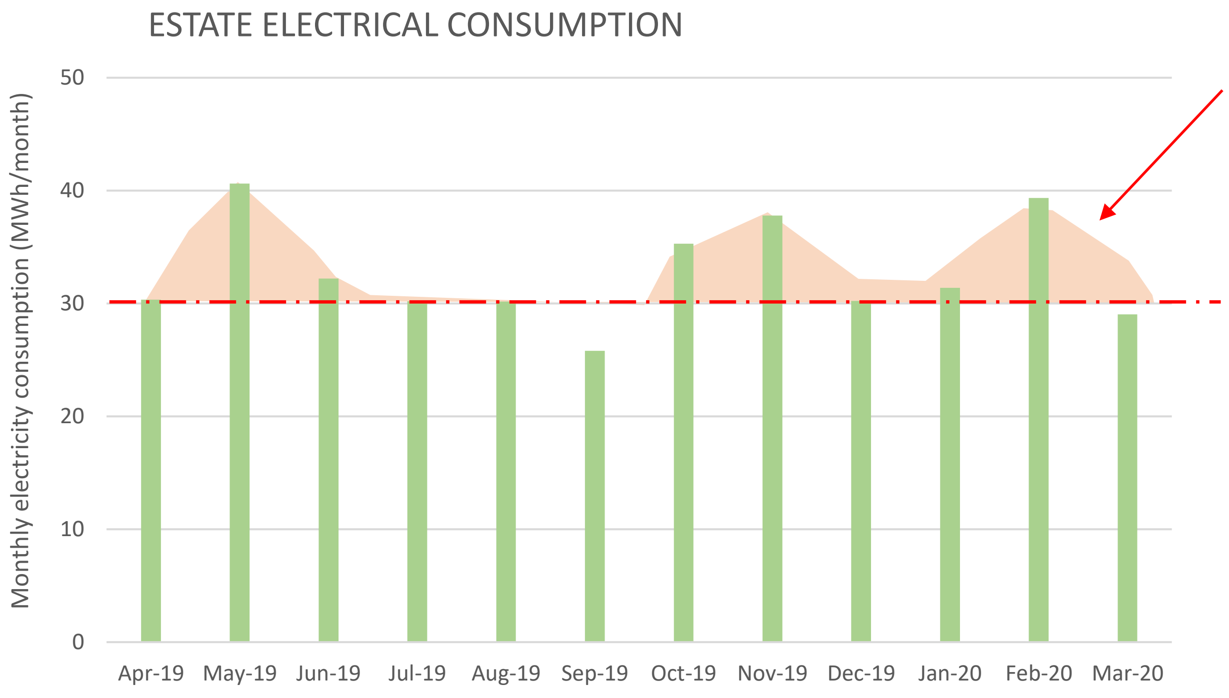


OVERALL ENERGY DEMAND

We have analysed historical energy consumption data which the College has provided to assess which buildings consume the most energy. We have also taken readings from electrical sub-meters on switchgear, where this is available, in order to infer annual electrical usage for buildings which do not have their own utility meters.

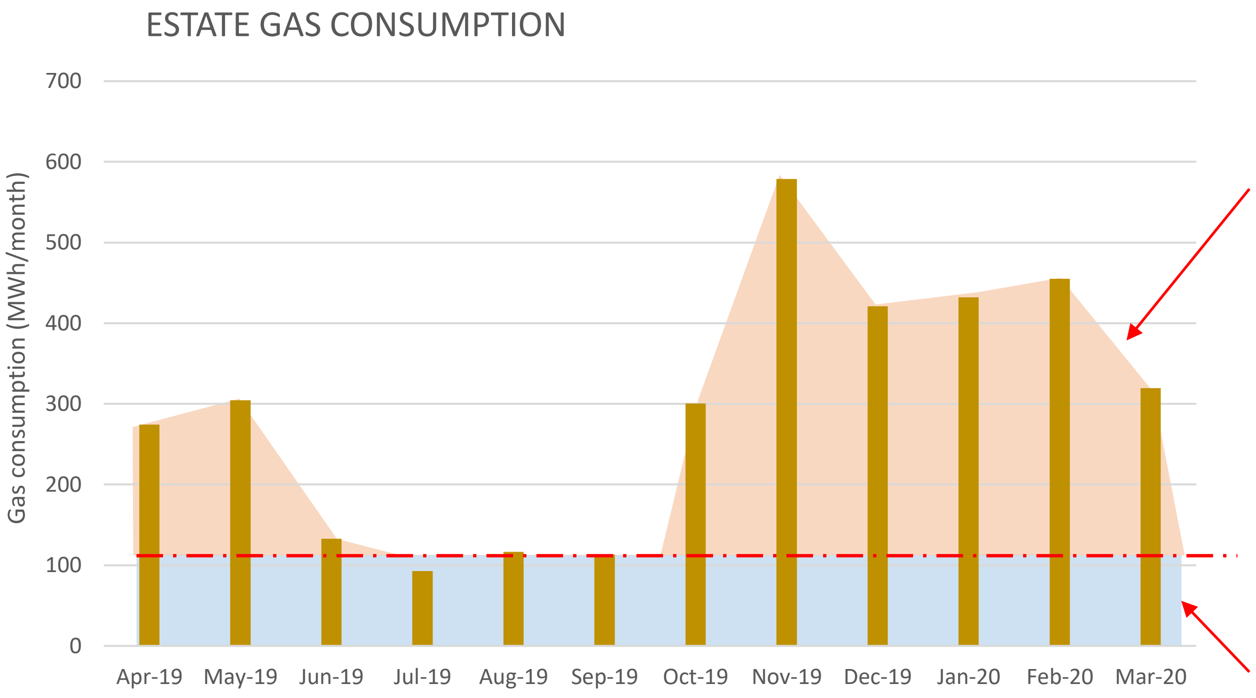
Utility data for the year 2019-2020 was chosen as this was the most recent data for the building in normal use that was not affected by reduced occupancy as a result of Covid-19.

Electrical sub-meter data was recorded by Max Fordham during site visits and used to determine the proportional electricity consumption of buildings served from the same utility meter.



Seasonally varying part of electrical consumption inferred as space heating

Baseline electrical load (ie everything except for space heating)



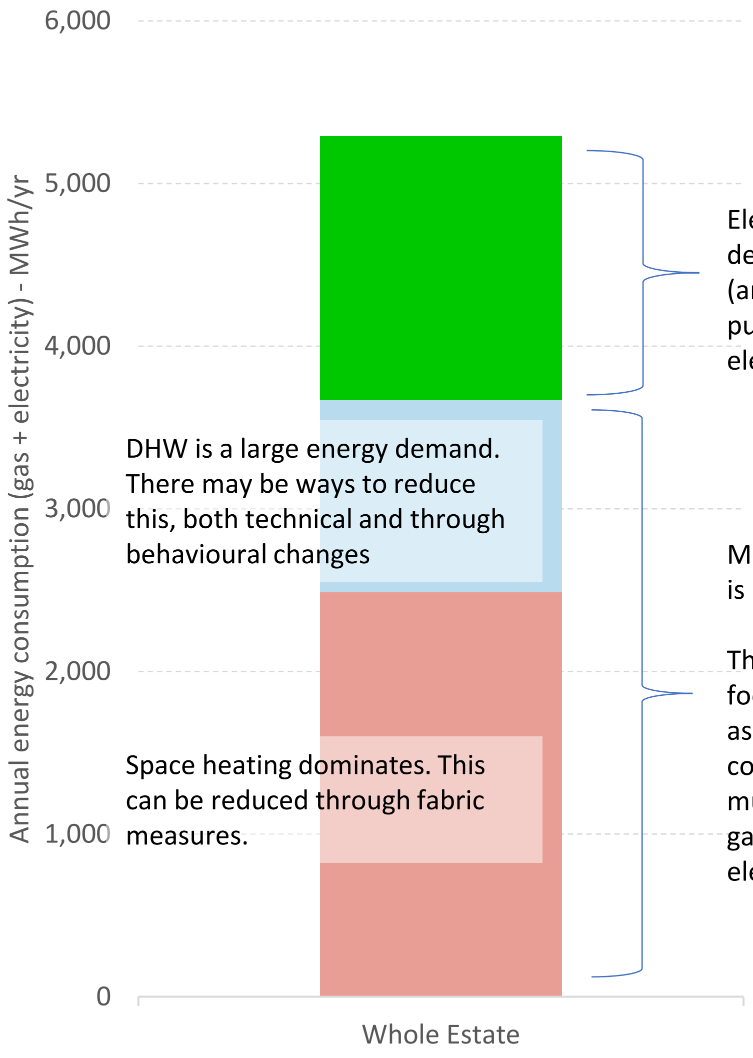
Seasonally varying part of gas consumption inferred as space heating

Baseline DHW and distribution loss

Consistent baseline gas consumption inferred as Domestic Hot Water demand (because there is no gas use which is neither heating nor hot water in the Estate)

OVERALL ENERGY DEMAND

A breakdown of the overall energy demand of the estate is shown here, together with breakdowns of the five main areas.



Electricity is decarbonising already (and Pembroke purchase zero carbon electricity)

DHW is a large energy demand. There may be ways to reduce this, both technical and through behavioural changes

Most heating and hot water is produced with gas.

The main longterm carbon footprint is energy associated with gas combustion. This can be reduced through fabric measures.

Space heating dominates. This can be reduced through fabric measures.

The main longterm carbon footprint is energy associated with gas combustion. This can be much reduced by replacing gas-fired boilers with electrical plant

A portion of this bar contributes to space heating from the ground source heat pump

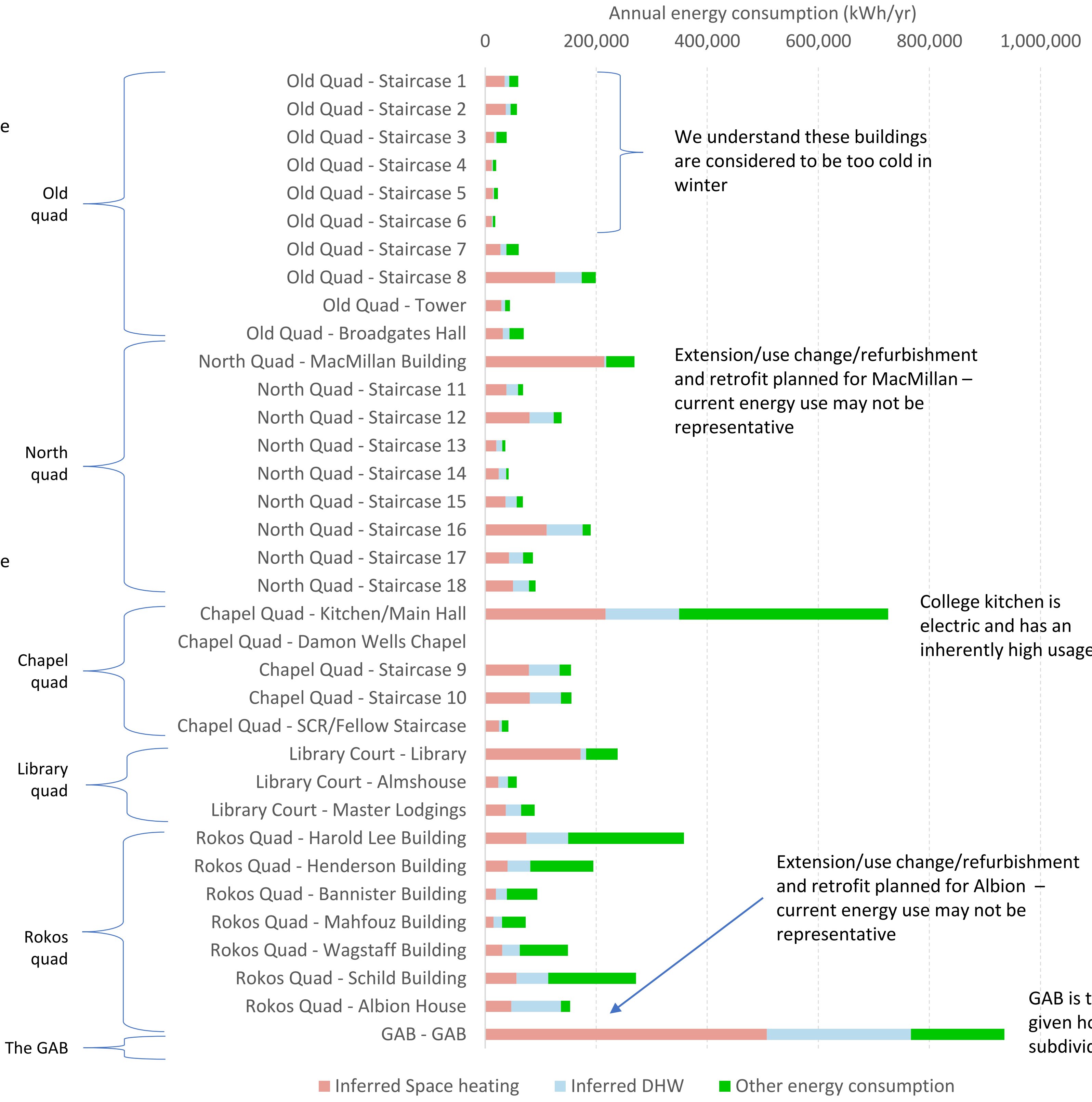
4.2 ENERGY DEMAND BY BUILDING

Energy consumption per building is shown here, derived from meter readings.

Where multiple buildings are served from a single meter, we have:

- pro-rata'd the space heating demands based on the building fabric and construction
- pro-rata'd the domestic hot water based on the occupancy/usage
- pro-rata'd the "other" energy demands based only on floor area

Buildings with low DHW loads are more expensive to decarbonise. This is because fabric works are generally more expensive than heat pumps. A high DHW load represents more carbon impact for any heat pump proposed in a building



We understand these buildings are considered to be too cold in winter

Extension/use change/refurbishment and retrofit planned for MacMillan – current energy use may not be representative

College kitchen is electric and has an inherently high usage

Extension/use change/refurbishment and retrofit planned for Albion – current energy use may not be representative

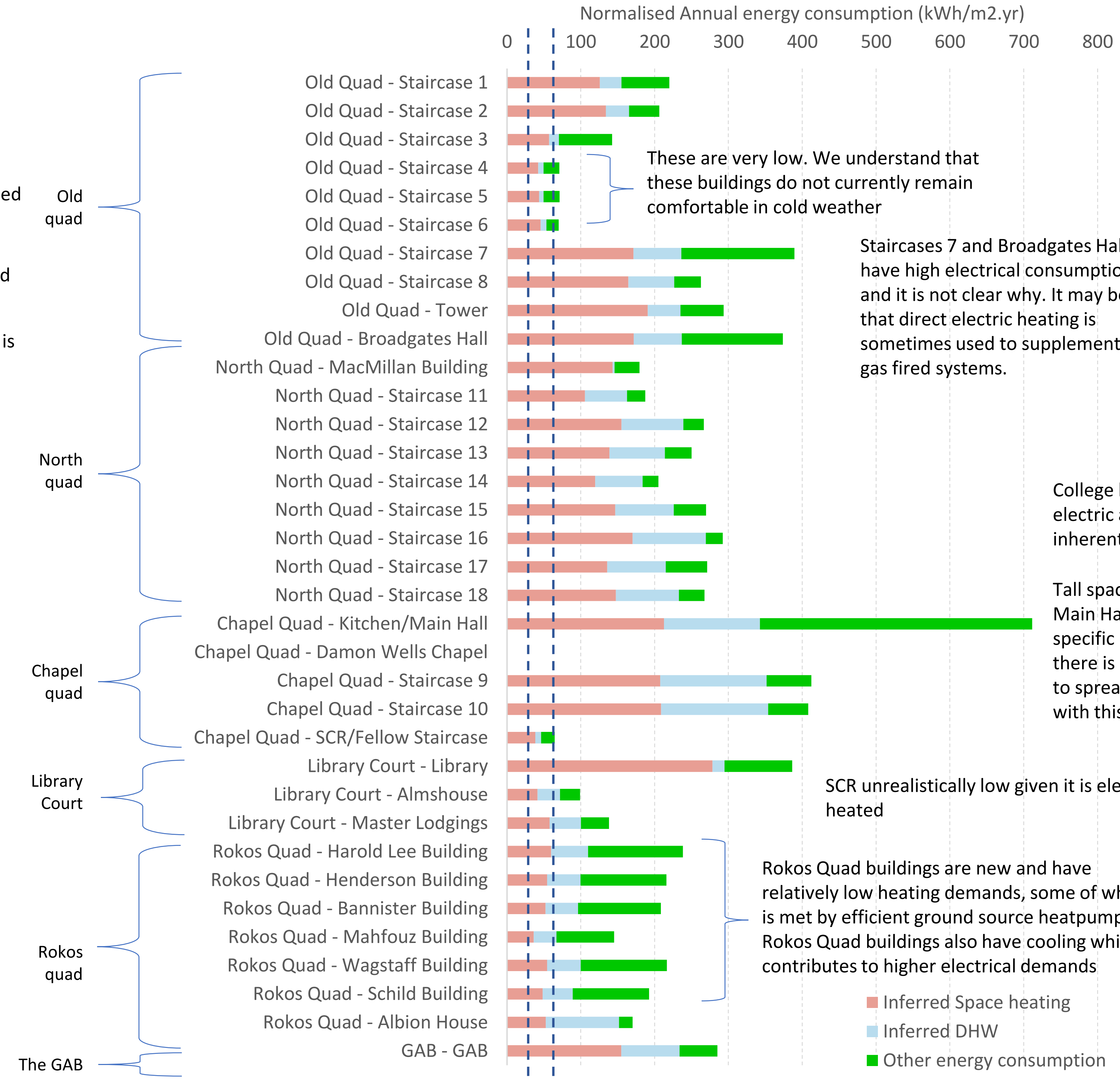
GAB is the largest building, given how they have been subdivided

4.3 NORMALISED ENERGY DEMAND BY BUILDING

Energy consumption per building is shown here, but normalised by floor area. This gives an indication of which buildings are most and least energy efficient.

Also shown are some benchmarks for space heating only. LETI (Low Energy Transformation Initiative) are an organisation who have produced benchmarks for retrofitted buildings which are intended to align with a UK wide NZC society.

The Passivhaus Institute have a standard for retrofit (called EnerPHit), which is more onerous. Generally, we do not advocate EnerPHit because of the high cost and high disruption – in our view decarbonising more of the estate is greater impact than decarbonising fewer buildings more completely.



These are very low. We understand that these buildings do not currently remain comfortable in cold weather

Staircases 7 and Broadgates Hall have high electrical consumption and it is not clear why. It may be that direct electric heating is sometimes used to supplement the gas fired systems.

College kitchen is electric and has an inherently high usage

Tall spaces such as the Main Hall have high specific heat losses – there is less floor area to spread the load over with this sort of metric

SCR unrealistically low given it is electrically heated

Rokos Quad buildings are new and have relatively low heating demands, some of which is met by efficient ground source heatpumps. Rokos Quad buildings also have cooling which contributes to higher electrical demands

Passivhaus EnerPHit benchmark for space heating in retrofit buildings – 25kWh/m^2.yr

LETI Benchmark space heating demand for retrofit heritage buildings – 60kWh/m^2.yr

GAS CONSUMPTION, HEATING ZONING

The annual gas consumption and boiler room zoning for the majority of the estate is as shown here.

We understand that some buildings which appear to have reasonable gas consumption performance are thermally uncomfortable, such as Staircases 1-2.

Staircases 2-6, the SCR Staircase and the Chapel are all heated with direct electric radiators.

🟧 Gas consumption >200 kWh/m2.yr

🟨 Gas consumption 100-200 kWh/m2.yr

🟩 Gas consumption <100 kWh/m2.yr

⬚ Zone served by boiler room

🟫 Boiler room

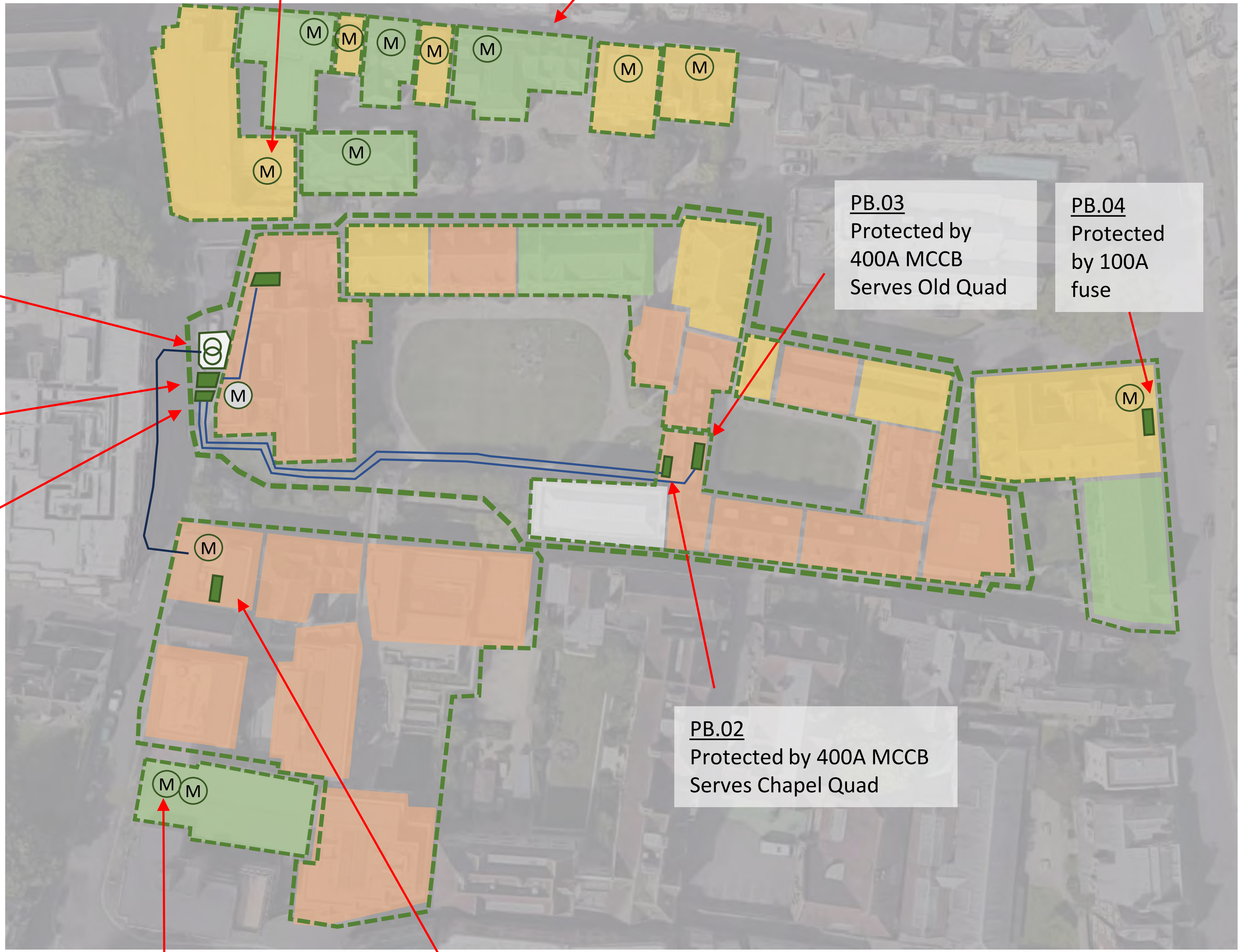
ELECTRICAL CONSUMPTION AND ZONING

The relative electric consumption for each building is shown here, along with main electric infrastructure including panelboards, swichpanels and metered utility connections.

Each separate utility electrical supply has different supply characteristics and is a completely separate electrical system.

Supply size to McMillan building unknown. Used to serve Dining Hall/Kitchen. Assumed to be 160A

Utility connections to North Quad Staircases from Pembroke St. Sizes and capacities unknown but assumed to be either 63A or 100A single phase connections



Main site SSE Owned Substation.
Capacity unknown.
Serves Chapel Quad, Old Quad and Rokos Quad

Main site switchgear
Protected by 800A MCCB

PB.01
Protected by 630A MCCB
Serves Dining Hall

PB.03
Protected by 400A MCCB
Serves Old Quad

PB.04
Protected by 100A fuse

PB.02
Protected by 400A MCCB
Serves Chapel Quad

Albion
100A three phase supply, 2No. meters

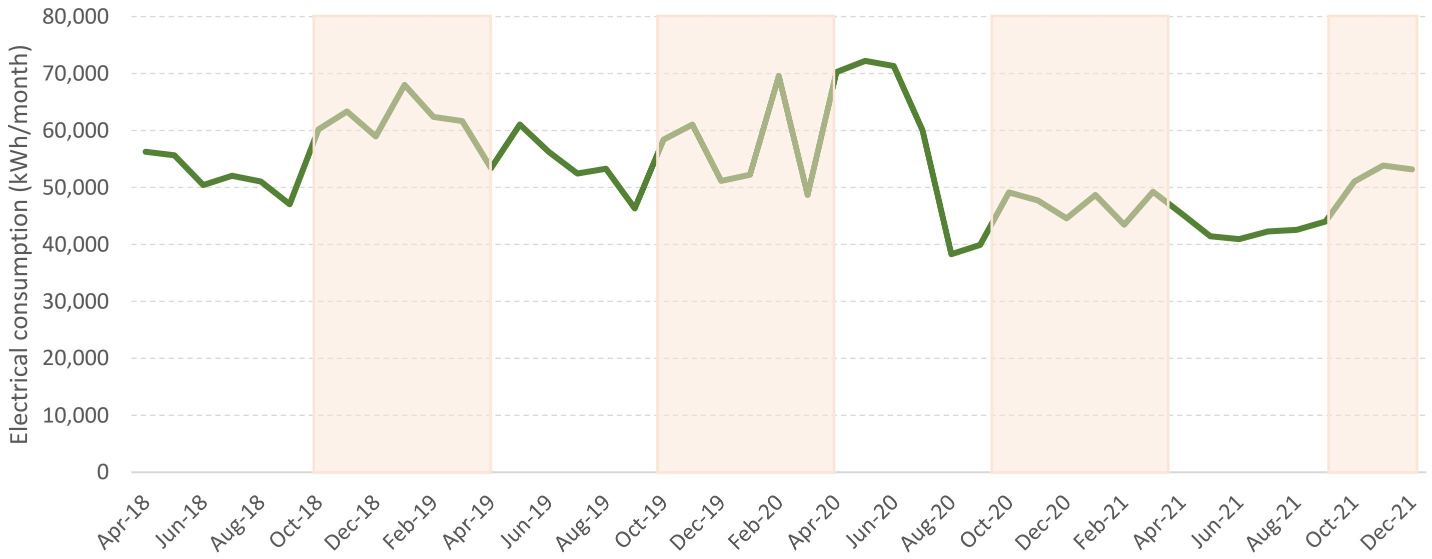
Rokos Switchgear
Served from substation on St Ebbe's St.

Protected by 630A MCCB
Loaded to 120kVA

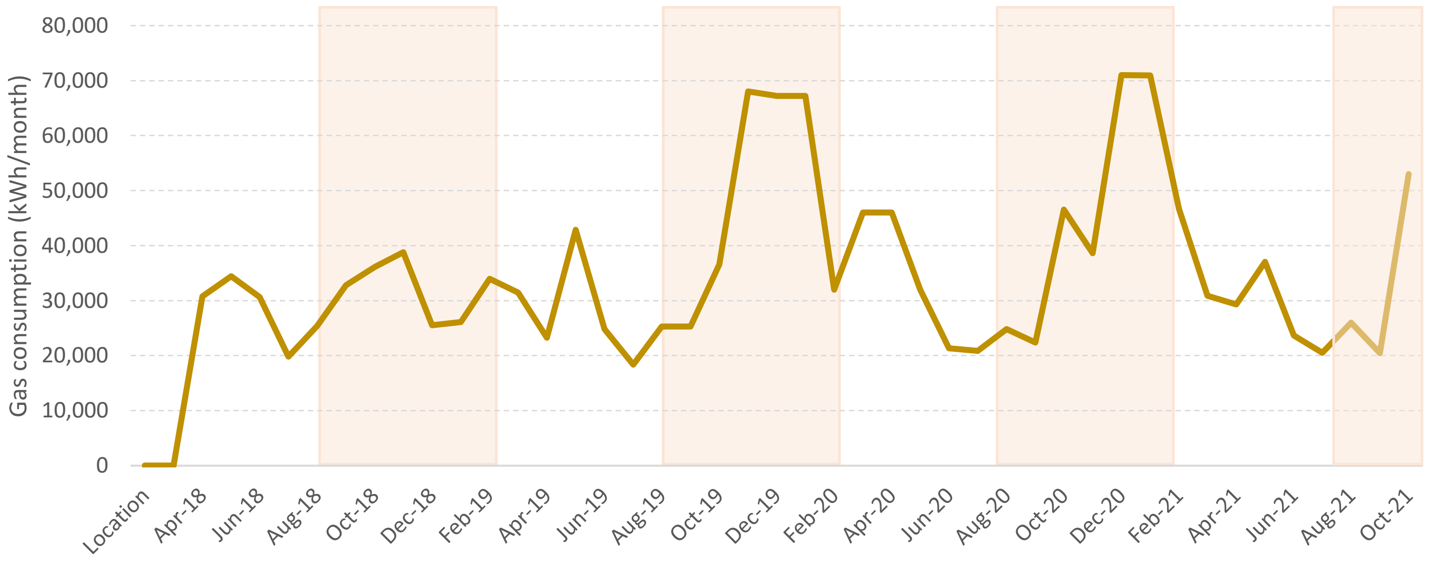
- 🟧 Elec consumption >60 kWh/m2.yr
- 🟨 Gas consumption 30-60 kWh/m2.yr
- 🟩 Gas consumption <30 kWh/m2.yr
- ⬚ Zone served by meter/panelboard/switchpanel
- ■ Switchgear or panelboard

ELECTRICALLY HEATED BUILDINGS

Rokos electrical meter does not display any clear seasonal demand. It is not possible to reasonably ascribe some portion of the electrical demand to the GSHP. Meanwhile the gas meter for the same group of buildings displays the seasonality expected for gas heated buildings. We expect that the gas fired boilers are meeting some proportion of the space heating load, with the ground source heat pump meeting the remainder.



2018-2019 winter
electrical load
slightly higher



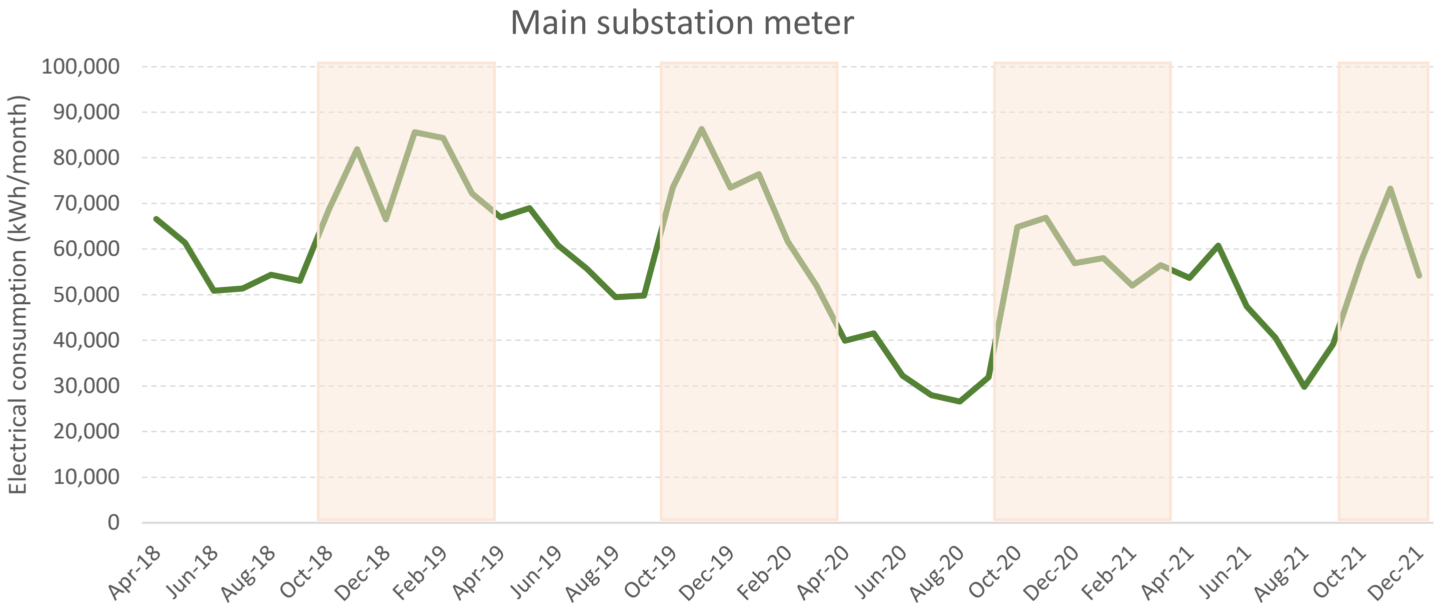
Gas load not
particularly high
winter 2018-2019

Seasonal gas load
as expected in gas
heated buildings

ELECTRICALLY HEATED BUILDINGS

We have monthly history from the main meter at the substation which gives some view of the seasonality of the electrical demand for much of the site.

This energy use is submetered. However, this gives granularity in space but not in time. So it is not possible to properly ascribe electrical energy to the electrically heated buildings. We have taken a reasonable view based on the bulk seasonality, and the size and construction of the electrically heated buildings.



5. DECARBONISATION STRATEGY

Heat for space heating is dominant across most buildings in the Pembroke. Replacing gas-fired heating plant with electric plant both reduces carbon emissions now and puts buildings on a pathway to decarbonisation. The general approach is to:

- reduce demands by improving the buildings' fabric
- replace boilers with heat pumps

Fabric improvements can be expensive and disruptive. Not all heating systems can be used effectively by a heatpump.

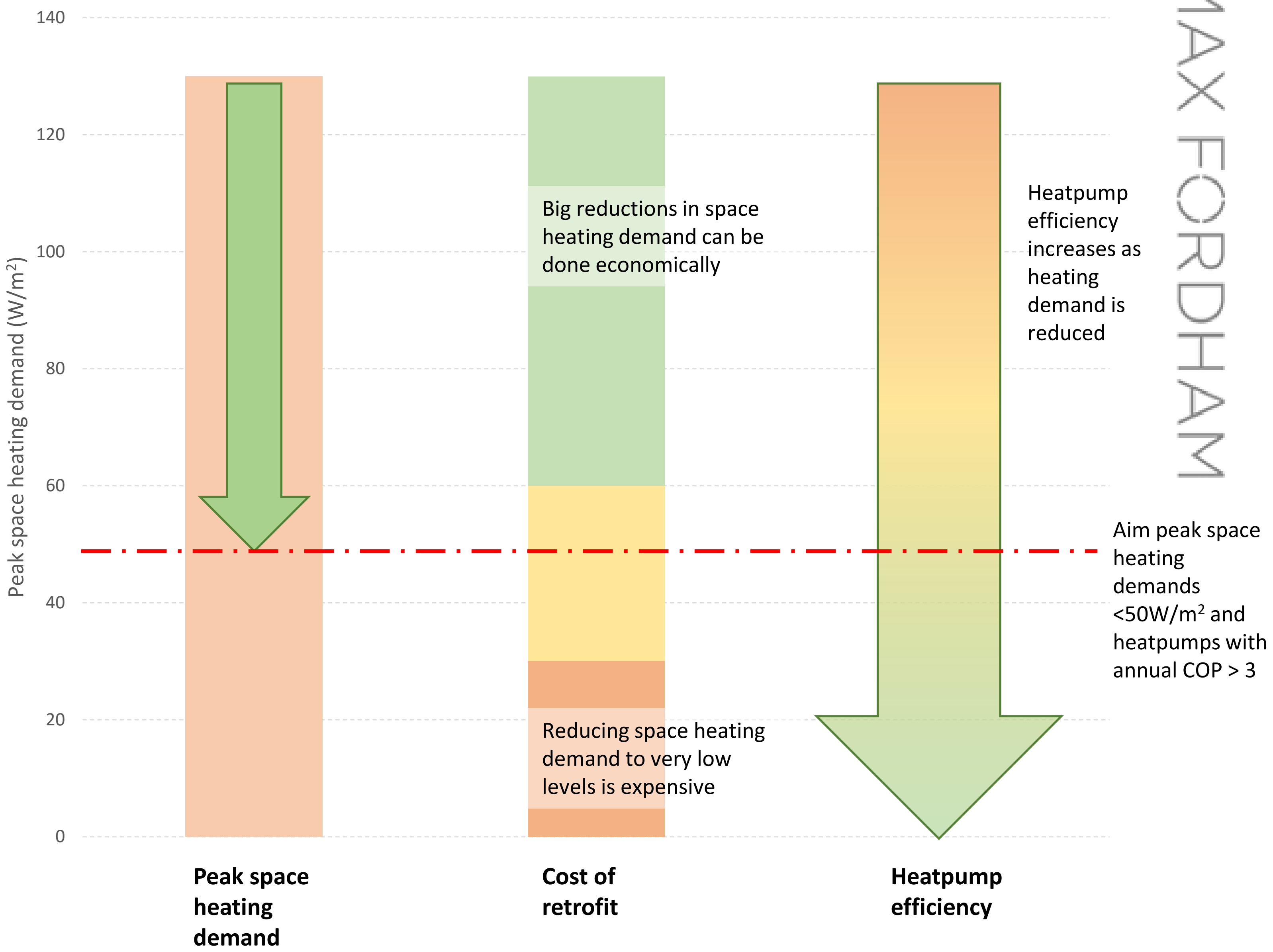
The extent of fabric improvements for any building will depend on:

- the cost and disruption of the improvements
- the reduction in peak and annual space heating demand achieved by the fabric intervention
- the resulting peak heating load and whether it can be met with either a new or repurposed heatpump led heating system.
- Balancing the ambition for energy reduction with heritage constraints and the sensitivities of the buildings at Pembroke

Electricity is an expensive fuel whereas gas is relatively cheap. The ratio of gas price to electricity price is greater than the ratio of gas boiler efficiency to heatpump efficiency.

We would aim to reduce annual heating demand enough that decarbonisation does not increase ongoing annual fuel costs. This is done by:

- reducing demand directly
- reducing demand enough to maintain heatpump efficiency.



Big reductions in space heating demand can be done economically

Reducing space heating demand to very low levels is expensive

Heatpump efficiency increases as heating demand is reduced

Aim peak space heating demands <50W/m^2 and heatpumps with annual COP > 3

FABRIC PERFORMANCE

The heat loss through the building envelop is measured as a U-value in watts/m2 per degree K. [W/m2K]

Older buildings tend to have higher U-value elements [poorer insulation]. The elements can be changed or supplemented with more insulation to reduce the U-values. The upper bar chart indicates typical values.

Single glazed windows have a high U-value and changing them to modern double glazing will result in a big reduction. However changing older double glazed units for newer ones would have a lower reduction.

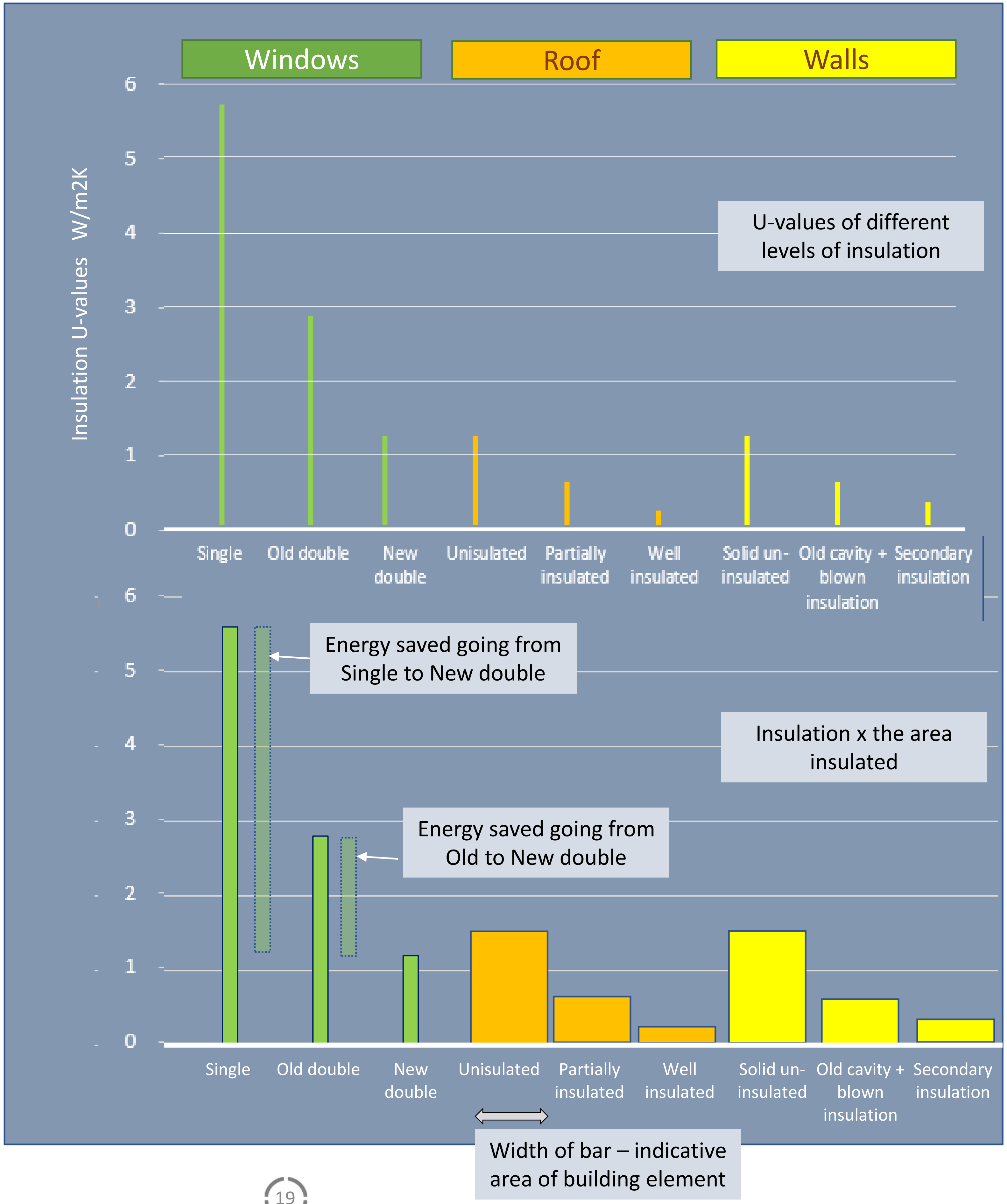
Given that the cost of the new window would be the same for irrespective of the condition of the existing one, the replacement of the single glazed unit gives more value for money.

This logic can be applied to a greater or lesser extent to the roof and walls. Applying rolls of loft insulation is comparatively cheap as it is simply added to the roof without disturbing any of the other building elements. Adding cavity wall insulation to an empty cavity is also relatively cheap. However adding a secondary layer to a wall internally or externally means adding another finishing layer to the building that is more costly.

The overall effect of changing the level of insulation of an element across the building envelope will vary according to the area of that element. The lower bar chart opposite is an area weighted analysis of the total heating energy being lost through that element given the relative insulation level and proportion of the building it covers.

It is possible to reduce the U-value (and heat loss) of a window by a large amount (ie, >80%). It is not generally possible to reduce the U-value (and heat loss) of a wall by as much (ie, 40-50% may be achievable).

However, walls and roof are a much larger area of thermal envelope in buildings such as those at Pembroke. Improvements to walls and roofs can lead to larger benefits, despite the improvements themselves being much more incremental.



U-values of different levels of insulation

Energy saved going from Single to New double

Insulation x the area insulated

Energy saved going from Old to New double

Width of bar – indicative area of building element

EXISTING BUILDING FABRIC

	Wall performance	Roof performance	Ground performance	Glazing performance	Airtightness	NOTES
Old Quad - Staircase 1	🟧	🟧	🟨	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed
Old Quad - Staircase 2	🟧	🟧	🟨	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed
Old Quad - Staircase 3	🟧	🟧	🟨	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed
Old Quad - Staircase 4	🟧	🟧	🟨	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed
Old Quad - Staircase 5	🟧	🟧	🟨	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed
Old Quad - Staircase 6	🟧	🟧	🟨	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed
Old Quad - Staircase 7	🟧	🟧	🟨	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed
Old Quad - Staircase 8	🟧	🟧	🟨	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed
Old Quad - Tower	🟧	🟧	🟧	🟧	🟧	Solid stone walls, timber roof with slate tiles, suspended floors? Single glazed
Old Quad - Broadgates Hall	🟧	🟧	🟧	🟧	🟧	Solid stone walls, timber roof with slate tiles, suspended floors? Single glazed
North Quad - MacMillan Building	🟧	🟧	🟨	🟨	🟧	Uninsulated Cavity walls, flat roof with modest insulation, solid floor, double glazed
North Quad - Staircase 11	🟧	🟧	🟧	🟧	🟧	Solid stone or brick walls, timber roof with slate tiles, suspended floors? Single glazed
North Quad - Staircase 12	🟧	🟧	🟧	🟧	🟧	Solid stone or brick walls, timber roof with slate tiles, suspended floors? Single glazed
North Quad - Staircase 13	🟧	🟧	🟧	🟧	🟧	Solid stone or brick walls, timber roof with slate tiles, suspended floors? Single glazed
North Quad - Staircase 14	🟧	🟧	🟧	🟧	🟧	Solid stone or brick walls, timber roof with slate tiles, suspended floors? Single glazed
North Quad - Staircase 15	🟧	🟧	🟧	🟧	🟧	Solid stone or brick walls, timber roof with slate tiles, suspended floors? Single glazed
North Quad - Staircase 16	🟧	🟧	🟧	🟧	🟧	Solid stone or brick walls, timber roof with slate tiles, suspended floors? Single glazed
North Quad - Staircase 17	🟧	🟧	🟧	🟧	🟧	Solid stone or brick walls, timber roof with slate tiles, suspended floors? Single glazed
North Quad - Staircase 18	🟧	🟧	🟧	🟧	🟧	Solid stone or brick walls, timber roof with slate tiles, suspended floors? Single glazed
Chapel Quad - Kitchen/Main Hall	🟧	🟧	🟧	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed stained glass
Chapel Quad - Damon Wells Chapel	🟧	🟧	🟧	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed stained glass
Chapel Quad - Staircase 9	🟧	🟧	🟨	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed
Chapel Quad - Staircase 10	🟧	🟧	🟨	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed
Chapel Quad - SCR/Fellow Staircase	🟧	🟧	🟨	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed
Library Court - Library	🟧	🟧	🟨	🟨	🟧	Uninsulated Cavity walls, flat roof with modest insulation, solid floor, double glazed
Library Court - Almshouse	🟧	🟧	🟨	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed
Library Court - Master Lodgings	🟧	🟧	🟨	🟧	🟧	Solid stone walls, timber roof with slate tiles, solid floors? Single glazed
Rokos Quad - Harold Lee Building	🟩	🟩	🟩	🟩	🟩	Recent buildings built to good fabric standards - have heat recovery ventilation and cooling
Rokos Quad - Henderson Building	🟩	🟩	🟩	🟩	🟩	Recent buildings built to good fabric standards - have heat recovery ventilation and cooling
Rokos Quad - Bannister Building	🟩	🟩	🟩	🟩	🟩	Recent buildings built to good fabric standards - have heat recovery ventilation and cooling
Rokos Quad - Mahfouz Building	🟩	🟩	🟩	🟩	🟩	Recent buildings built to good fabric standards - have heat recovery ventilation and cooling
Rokos Quad - Wagstaff Building	🟩	🟩	🟩	🟩	🟩	Recent buildings built to good fabric standards - have heat recovery ventilation and cooling
Rokos Quad - Schild Building	🟩	🟩	🟩	🟩	🟩	Recent buildings built to good fabric standards - have heat recovery ventilation and cooling
Rokos Quad - Albion House	🟧	🟨	🟨	🟨	🟧	Uninsulated Cavity walls, flat roof with modest insulation, solid floor, double glazed
GAB	🟨	🟨	🟨	🟩	🟨	Uninsulated Cavity walls, timber roof with slate tiles and loft insulation, suspended beam+block floor, double glazed

FABRIC PERFORMANCE - GLAZING

The original windows for the older buildings will be single glazed and have a high heat loss. They can be replaced with newer windows systems with a lower heat loss.

There are many options for window replacement with a wide range in cost, technical performance and heritage sensitivity. What is appropriate as a decarbonisation measure will depend on the particularities of the building in question.

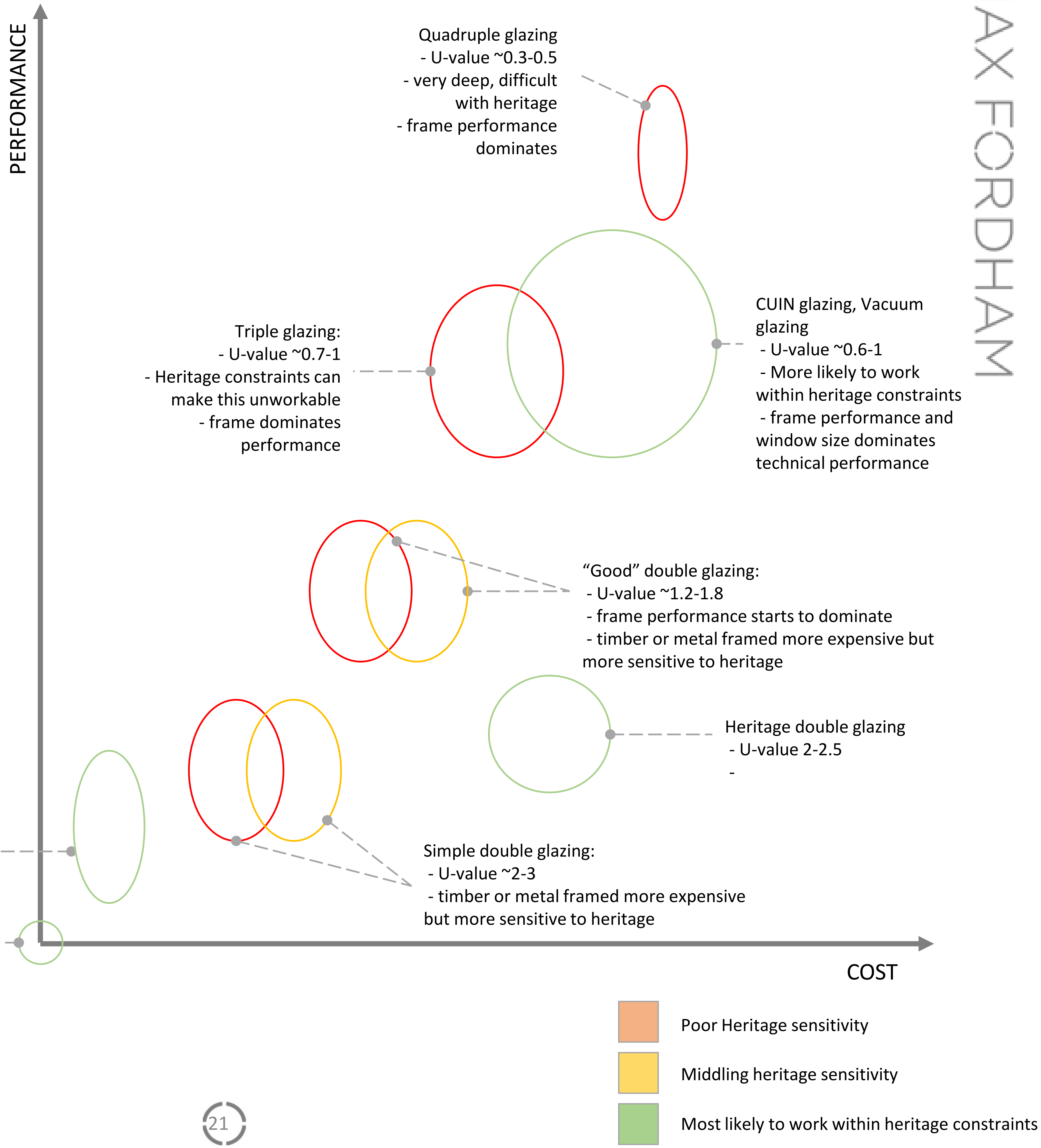
Where buildings are listed and historic, the heritage constraints must be respected. The historic single glazing often has inherent heritage value and replacement is largely unacceptable. Secondary glazing is then the only real option and even then may not be acceptable to Historic England or the Oxford City Council Planning Heritage team.

Compared to replacement glazing, secondary glazing has some limitations:

- it must be closed to work properly, which relies on people's behaviour
- it can reduce the amenity of a room if it makes a window sill unusable.

Thicker glazing systems generally need larger frames which are more contentious in a heritage context.

Generally, given the cost, benefit and heritage constraints, we propose secondary glazing with single panes for the older buildings, and replacement windows with triple glazing for the newer buildings which are not listed.



Quadruple glazing
- U-value ~0.3-0.5
- very deep, difficult with heritage
- frame performance dominates

CUIN glazing, Vacuum glazing
- U-value ~0.6-1
- More likely to work within heritage constraints
- frame performance and window size dominates technical performance

Triple glazing:
- U-value ~0.7-1
- Heritage constraints can make this unworkable
- frame dominates performance

"Good" double glazing:
- U-value ~1.2-1.8
- frame performance starts to dominate
- timber or metal framed more expensive but more sensitive to heritage

Heritage double glazing
- U-value 2-2.5
-

Simple double glazing:
- U-value ~2-3
- timber or metal framed more expensive but more sensitive to heritage

Simple secondary glazing:
- U-value ~3 but requires people to use it properly

Single glazing (will always be existing)
- U-value ~5.5

🟧 Poor Heritage sensitivity

🟨 Middling heritage sensitivity

🟩 Most likely to work within heritage constraints

FABRIC CONSTRAINTS

Every building facade interacts with its external environment throughout the year. Two notable instances of this are the transport of heat and moisture. The typical mechanisms throughout the seasons are illustrated opposite.

Uninsulated masonry walls allow both heat and moisture to flow quite well, they are also stored and buffered as well because of the thermal and moisture capacity of the materials.

Adding insulation to a wall changes this mechanism. The purpose of insulation is to reduce heat flow. Insulation reduces moisture flow as well, some more than others.

Consistent exposure to high moisture levels resulting from insulation can result in slow, but certain damage to the building in the long term. This is why it is important to undertake a risk assessment for moisture for any retrofit.

Some parameters when undertaking this type of analysis can vary significantly by project, or is simply unknown in detail. Below are some elements which can change the dynamics of heat and moisture.

- The hygrothermal properties of masonry being used
- Any rendering on the façade
- Paints that are vapour resistant
- Orientation which changes sun and rain exposure
- Geometrical features such as overhangs
- Building height which effects wind and rain exposure
- Façade colour which effects solar absorptivity
- Internal moisture load (No. of people & activity etc)
- Any cavities that are existing or will be put in place after insulating, and how much this will be ventilated.

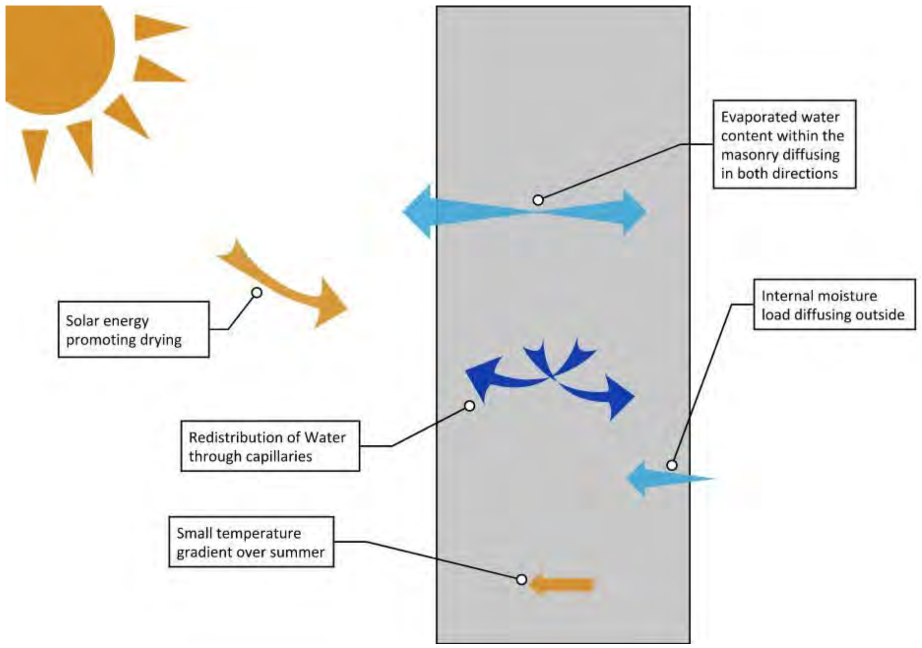
We have assessed some potential insulation approaches for each case based on generic material properties for stone.

This is to establish a baseline insulation approach with some expected thermal performance that can be costed. Outline considerations of moisture risk have informed the fabric improvement options presented in this report in a couple of ways:

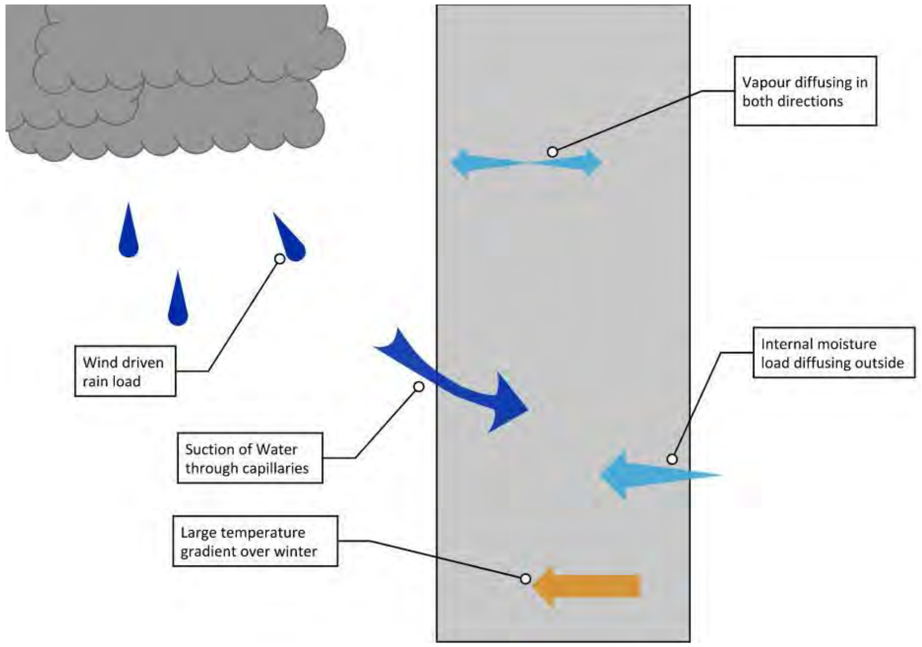
- the type of insulation considered
- the maximum amount of insulation

Practically, this limits the achievable U-Value of an internally insulated wall.

Drying Event – Occurs more in summer



Wetting Event – Occurs more in winter



VENTILATION

How much air does a person need?

In the winter outside air that comes into the College needs heating to warm up and so it uses heating energy.

Occupants do require a certain amount of ventilation to provide fresh air for CO2, moisture and other smell removal. Fresh air also dilutes airborne viruses to reduce the risk of spreading Covid and other airbourne diseases.

The buildings themselves also require ventilation to manage moisture and prevent deterioration of the building fabric.

Buildings should be reasonably well sealed to keep the heat in in the winter when it is not in use, and have controlled openings to provide adequate ventilation for the occupants when the building is in use.

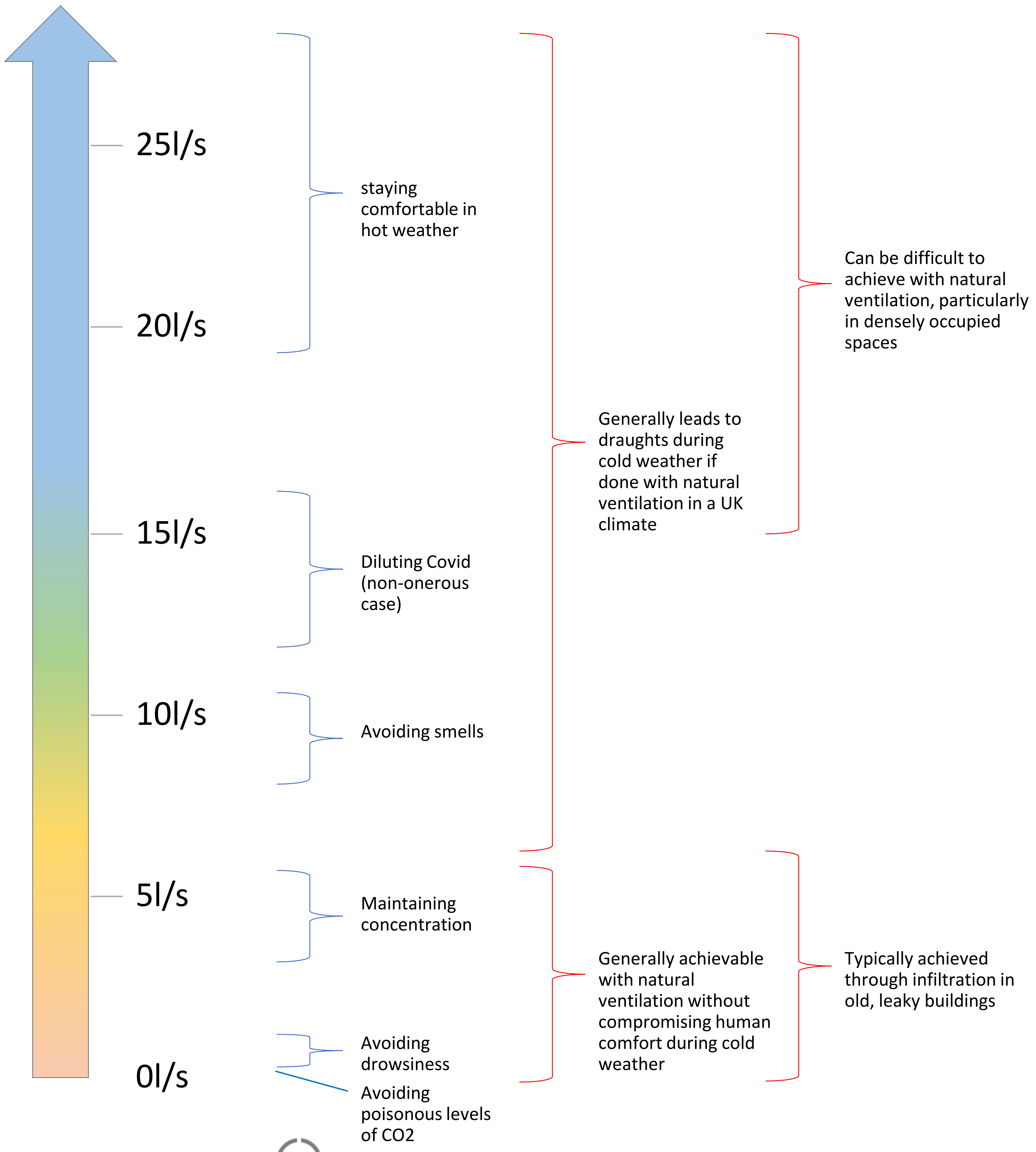
Generally older buildings are not particularly well sealed around the window and door frames. Any work to the fabric should improve the airtightness of these elements with draught stripping. However the windows should be capable of being opened in a graded way to allow the right amount of air into the rooms to suit the occupant’s needs. To avoid draughts the openings should be high up so the incoming air can mix with the room air before reaching the occupants.

In the summer the ventilation needs to be sufficient to maintain comfort conditions which means a much greater amount of opening than the winter. The windows should be capable of being left open at night to allow the building to cool down.

MVHR [Mechanical ventilation with heat recovery] is a system that makes use of the outgoing air to pre-heat the incoming ventilation air. It involves the installation of ductwork to connect all the spaces to an air handling plant. For it to be viable the building must be well sealed so that most of the air can be channelled through the system. If much of the ventilation needs are met with uncontrolled ventilation, the MVHR will add to the ventilation load and not offer an advantage.

MVHR is also generally space intensive and difficult to implement in existing buildings.

Improvements to walls and particularly windows need to be mindful of the ventilation requirements of a space.



25l/s

20l/s

15l/s

10l/s

5l/s

0l/s

staying comfortable in hot weather

Diluting Covid (non-onerous case)

Avoiding smells

Maintaining concentration

Avoiding drowsiness

Avoiding poisonous levels of CO2

Generally leads to draughts during cold weather if done with natural ventilation in a UK climate

Generally achievable with natural ventilation without compromising human comfort during cold weather

Can be difficult to achieve with natural ventilation, particularly in densely occupied spaces

Typically achieved through infiltration in old, leaky buildings

THERMAL COMFORT

Several of the buildings are reported to be thermally uncomfortable in cold weather.

Where this is the case, fabric improvements will generally improve matters. However, where fabric improvements improve thermal comfort they may not also improve energy performance

Within these buildings there are various aspects of the existing arrangement which impact thermal comfort and we have seen several of these in the Dining Hall.

The “felt” temperature of a space depends on:

- Air temperature
- Air velocity
- The temperature of surrounding surfaces

All of these affect the rate at which people transfer heat to their surroundings. Higher air velocities are perceived as draughts as more heat is convectively transferred away. Cooler surrounding surfaces increases radiative heat transfer from people, and is part of why it often feels colder clear night skies or inside caves.

The following mechanisms make the space feel colder than the air temperature. All of these can be mitigated by various fabric measures.

•A space is draughty when doors are open

•The inner surface of the windows is cold, creating downdraughts. This is likely masked by the effect of the main draughts at present

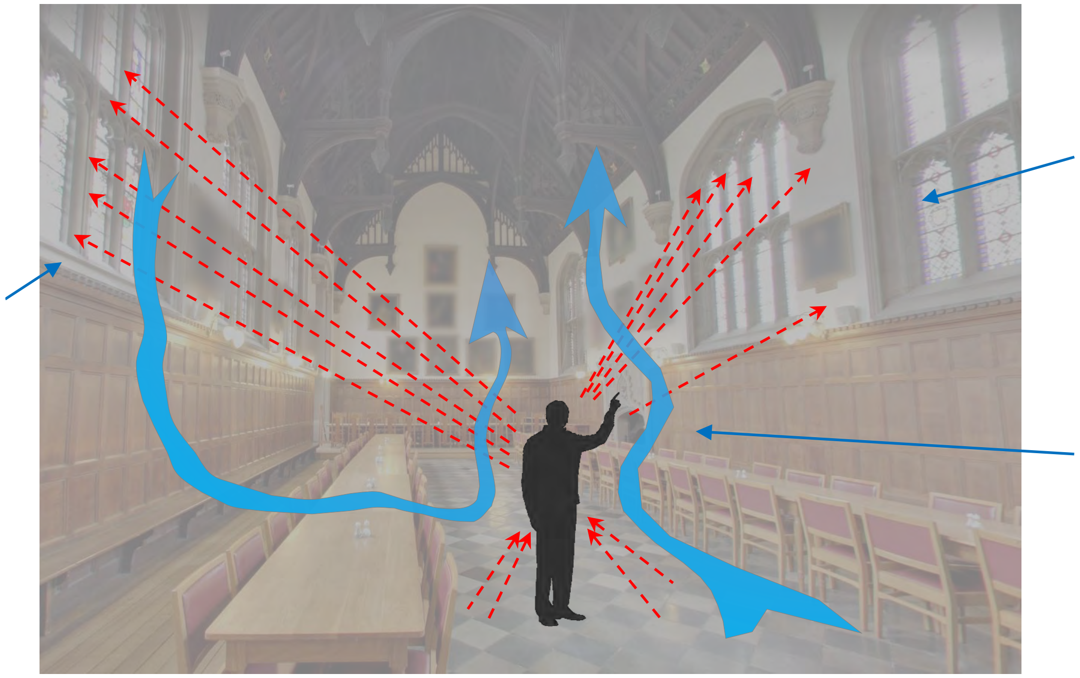
•The inner surface of the windows is cold, so people will radiatively lose heat to them

•The inner surface of the walls is cool, so people will radiatively lose lots of heat to them. This is less of an impact than the windows and is a benefit during the summer

These can be mitigated by various fabric proposals

Conceptually, these are illustrated in the context of the Dining Hall.

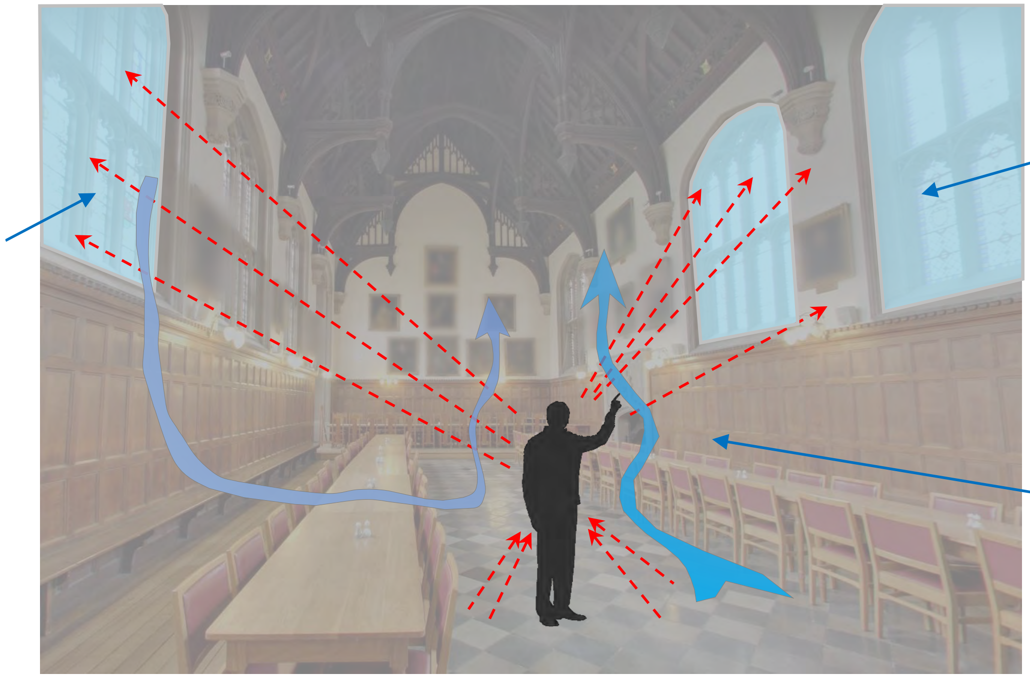
We understand that the buildings which currently have wintertime thermal comfort issues are the Main Hall and Staircases 3-6.



Cold windows creates down-draught which increases draughtiness

Lots of radiant heat to cold windows

Draughty space – lots of convective heat loss from people



Inner surface of window is less cold -down-draughts reduced

Less radiant heat transfer to windows as inner surfaces less cold

Space less draughty

FABRIC IMPROVEMENTS – COST EFFECTIVENESS

Given the heritage constraints, the fabric improvements which may be possible are set out here. Some are not cost effective in the context of reducing the College's carbon footprint. This is particularly the case in buildings which are already electrically heated (carbon reductions shown here assume grid electricity, rather than zero carbon electricity)

In buildings where there are wintertime thermal comfort issues, it is likely that fabric improvements will not reduce energy use, but instead improve comfort – for example instead of a heat emitter working to its full capacity to deliver 17C internally, it will be able to work to its full capacity to deliver 21C internally.

Nevertheless, it is clear that some fabric improvements represent better value than others. This has informed which ones we are proposing.

There are various fabric improvements which are technically possible. Fabric improvements generally offer many benefits:

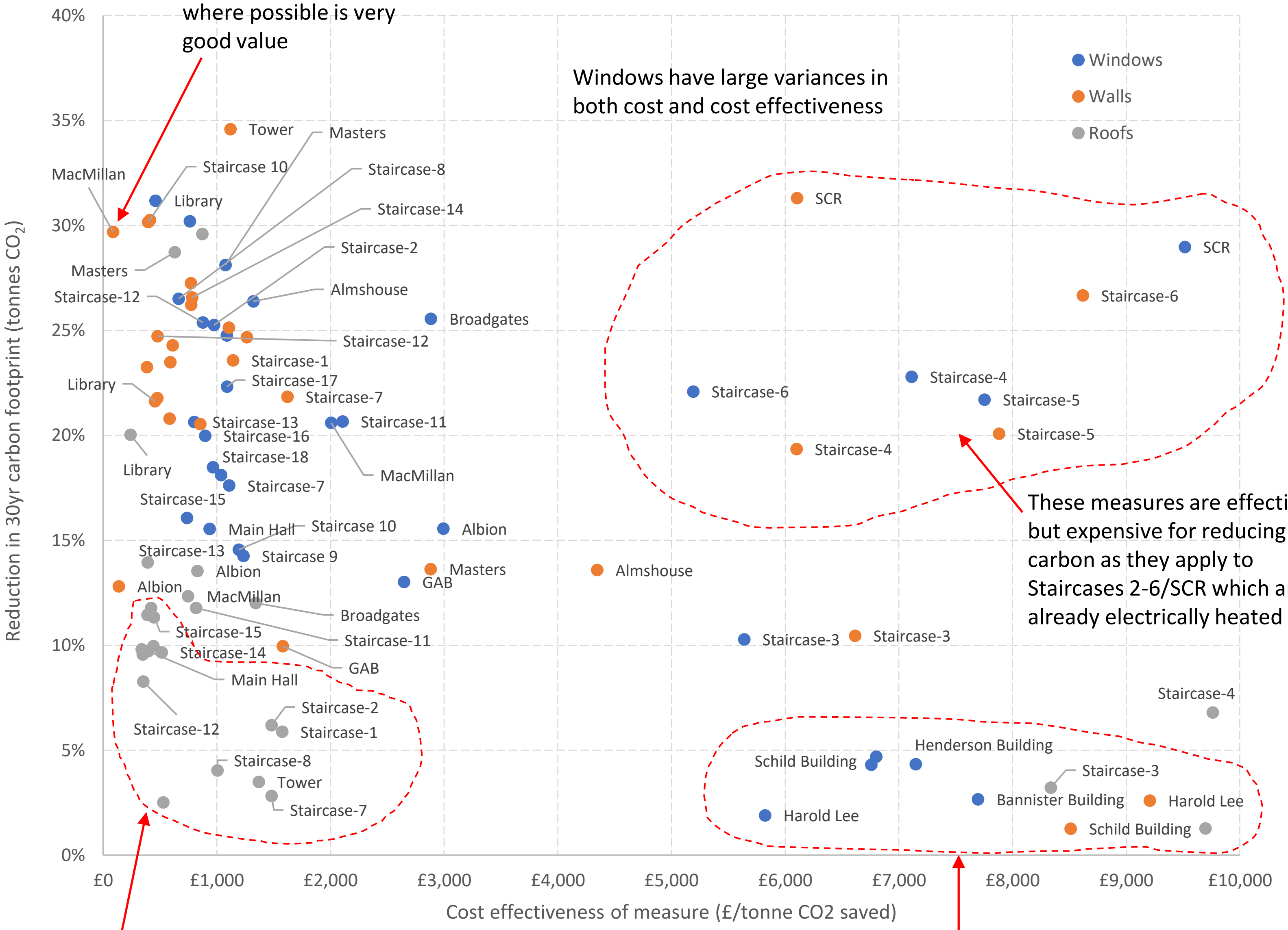
- reduced energy demands
- improved thermal comfort
- smaller mechanical installations
- improved solar control in a world which is getting warmer
- (potentially) improved conservation of existing building fabric

Ordinarily fabric improvements reduce the space heating demands of a building and improve its energy performance.

Where spaces are currently thermally uncomfortable, fabric improvements are unlikely to lead to any improvement in energy performance. Instead, the spaces will become more comfortable. For comparative purposes, the carbon/energy benefits shown here assume equivalent thermal comfort

Cost effectiveness for electrically heated buildings here assumes grid carbon intensity. With electrically heated buildings this is very high. With Pembroke's zero carbon electricity tariff, the cost effectiveness at reducing carbon becomes infinite.

Cavity wall insulation where possible is very good value



Windows have large variances in both cost and cost effectiveness

These measures are effective but expensive for reducing carbon as they apply to Staircases 2-6/SCR which are already electrically heated

Roofs are typically good value, particularly where they can be done internally without works to a building's weathertightness

These measures are all expensive and ineffective because Rokos already has good fabric

PROPOSED FABRIC IMPROVEMENTS

Given what is cost effective, the following fabric improvements are generally proposed. However, all fabric improvement is relatively expensive and disruptive to do.

Building	Window Improvements	Wall insulation	Roof insulation	Reduction in annual space heating load	Reduction in peak space heating load	Reduction in 30yr carbon footprint (tonnes CO2)	Reduction in 30yr carbon footprint (tonnes CO2)	Total cost (£)	Normalised cost (lifetime carbon saved - £/tonne)
Old Quad - Staircase 1	Y - secondary		Y - loft	45%	33%	88	29%	£ 108,223	£ 1,229
Old Quad - Staircase 2	Y- secondary		Y - loft	44%	32%	90	30%	£ 100,996	£ 1,119
Old Quad - Tower			Y- loft	4%	2%	8	3%	£ 11,204	£ 1,369
Old Quad - Staircase 3	Y- secondary		Y- loft	43%	31%	14	13%	£ 89,395	£ 6,577
Old Quad - Staircase 4	Y- secondary		Y- loft	47%	35%	12	28%	£ 96,181	£ 8,116
Old Quad - Staircase 5	Y - secondary		Y- loft	44%	32%	13	27%	£ 113,084	£ 8,751
Old Quad - Staircase 6	Y- secondary		Y- loft	40%	29%	10	26%	£ 63,608	£ 6,339
Old Quad - Staircase 7	Y- secondary		Y- loft	37%	26%	56	20%	£ 66,808	£ 1,189
Old Quad - Staircase 8	Y- secondary		Y- loft	47%	34%	326	30%	£ 238,340	£ 730
Old Quad - Broadgates Hall			Y- loft	14%	10%	38	12%	£ 51,262	£ 1,342
North Quad - MacMillan Building	Y- replacement	Y – cavity	Y – re-roof	61%	47%	780	55%	£ 751,854	£ 963
North Quad - Staircase 11	Y- replacement	Y - internal	Y- loft	69%	56%	160	43%	£ 316,394	£ 1,976
North Quad - Staircase 12	Y- replacement	Y- internal	Y- loft	67%	54%	324	42%	£ 285,257	£ 882
North Quad - Staircase 13	Y- replacement	Y- internal	Y- loft	66%	52%	79	40%	£ 63,788	£ 804
North Quad - Staircase 14	Y- replacement	Y- internal	Y- loft	64%	51%	95	40%	£ 105,431	£ 1,110
North Quad - Staircase 15	Y- replacement	Y- internal	Y- loft	67%	54%	148	41%	£ 137,807	£ 930
North Quad - Staircase 16	Y- replacement	Y- internal	Y- loft	67%	54%	445	41%	£ 402,988	£ 906
North Quad - Staircase 17	Y- replacement	Y- internal	Y- loft	66%	53%	171	38%	£ 182,318	£ 1,064
North Quad - Staircase 18	Y- replacement	Y- internal	Y- loft	69%	56%	207	41%	£ 215,557	£ 1,044
Chapel Quad - Kitchen/Main Hall	Y- replacement			34%	24%	449	16%	£ 420,000	£ 936
Chapel Quad - Damon Wells Chapel			Y- loft	30%	21%	0	0%	£ 37,100	-
Chapel Quad - Staircase 9			Y- loft	17%	11%	82	10%	£ 28,270	£ 347
Chapel Quad - Staircase 10			Y- loft	18%	12%	85	10%	£ 28,641	£ 338
Chapel Quad - SCR/Fellow Staircase			Y- loft	8%	5%	5	5%	£ 48,156	£ 10,024
Library Court - Library	Y- replacement	Y - cavity	Y – re-roof	62%	49%	644	53%	£ 350,924	£ 545
Library Court - Almshouse	Y- secondary		Y- loft	58%	44%	143	51%	£ 170,362	£ 1,192
Library Court - Master Lodgings	Y- secondary		Y- loft	58%	45%	227	52%	£ 212,515	£ 937
Rokos Quad - Harold Lee Building				0%	0%	0	0%	£ -	-
Rokos Quad - Henderson Building				0%	0%	0	0%	£ -	-
Rokos Quad - Bannister Building				0%	0%	0	0%	£ -	-
Rokos Quad - Mahfouz Building				0%	0%	0	0%	£ -	-
Rokos Quad - Wagstaff Building				0%	0%	0	0%	£ -	-
Rokos Quad - Schild Building				0%	0%	0	0%	£ -	-
Rokos Quad - Albion House		Y - cavity	Y- re-roof	56%	42%	158	18%	£ 110,918	£ 703
GAB				0%	0%	0	0%	£ -	-

Electric buildings – carbon saving cost effectiveness is high, but these buildings have thermal comfort issues to address

New buildings with reasonable fabric standards – not cost effective to improve particularly

ELECTRIFICATION OF HEAT

A large component of the decarbonisation is to use electricity that can be generated from renewables [wind, solar] instead of gas for the provision of heat.

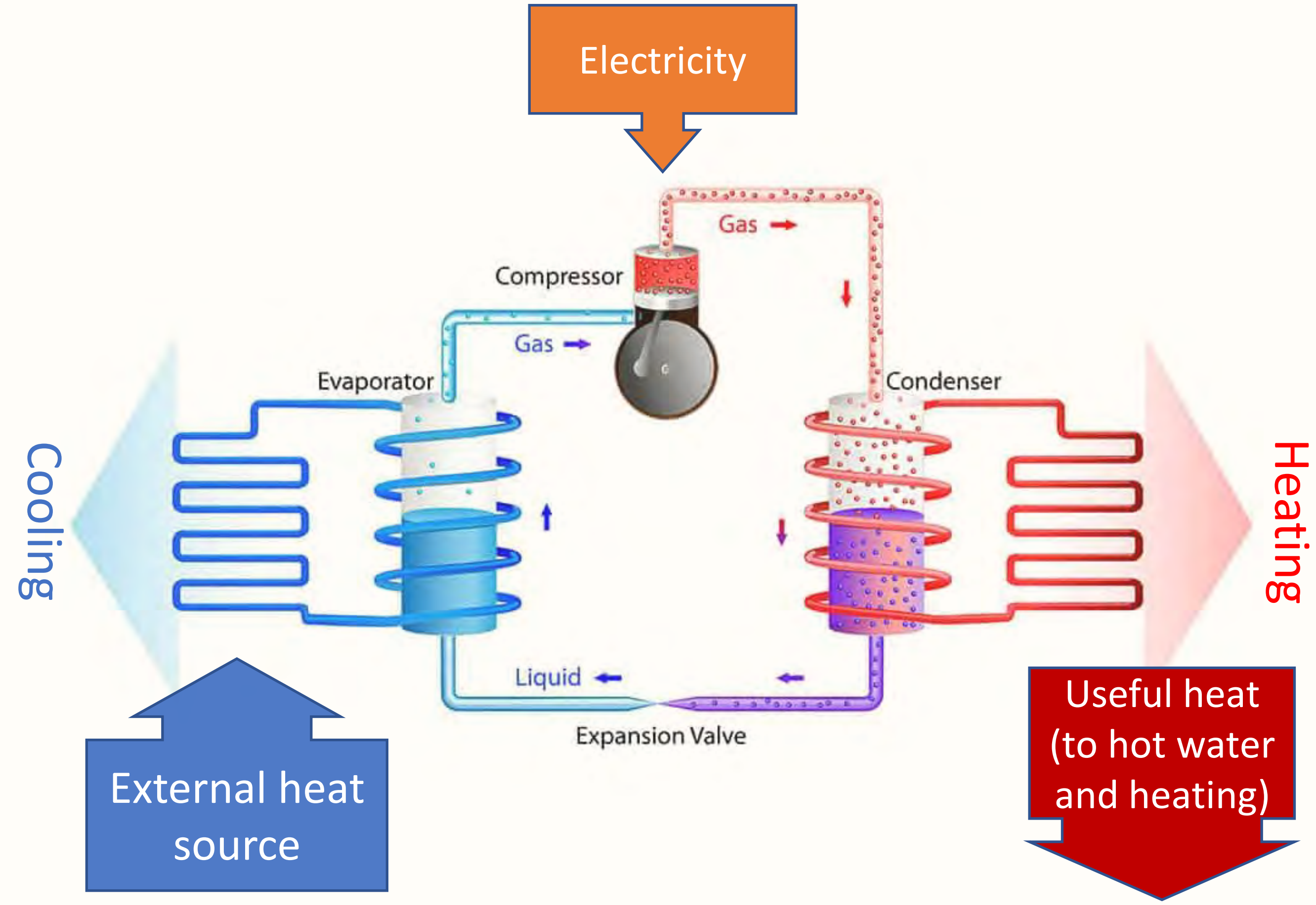
The simplest way to use electricity to provide heat is with direct electric heating (eg, electric radiators or immersion heaters in hot water cylinders).

Rather than use electricity directly in an electric heater, electricity can be used to drive a compressor in a Heat Pump that produces 2 to 4 times more heat than the electricity consumed. This works by taking heat out of a cold source such as the air or ground and “pumping” up to a warmer useful temperature to heat water and the buildings.

The efficiency of a heatpump is characterised by its “Coefficient of Performance” [COP]. This is the ratio of useful heat to electrical energy input:

COP = useful heat output (kW) / electricity consumption (kW)

For most refrigeration cycles, the COP depends on the source and output temperatures. A warmer source temperature leads to higher efficiencies. The temperature of most heat sources used for heatpumps varies throughout the year. This means that the COP also varies throughout the year. To account for this, annual performance of a heatpump is characterised by its Seasonal Coefficient of Performance [SCOP]. A real SCOP is building specific because it depends when the demands for heat occur in relation to the source temperature.



Electricity

External heat source

Useful heat (to hot water and heating)

Basic Heat Pump schematic

REFRIGERANT TECHNOLOGY

All heat pumps need a refrigerant that efficiently moves heat around the cycle through the mechanisms of evaporation and condensing at different pressures.

Successful refrigerants that were efficient, non-toxic, non-flammable and worked at a reasonable pressure were shown to damage the ozone layer and have been banned. These have been replaced with others that are not damaging but have a global warming potential [GWP] measured by comparison to CO_2, that can be significant for the carbon footprint of a development based on the risk of it releasing to the atmosphere.

There are various “new” refrigerants on the market that look to address this. Some of these low GWP refrigerants are Per- and polyfluoroalkyl substances (PFAS), which persist for a long time in the environment. These PFAS refrigerants are more or less likely to be banned in the future because of their environmental impact beyond GWP

Other “new” refrigerants are “natural”, and have limited environmental impact but have other issues such as flammability.

High GWP refrigerants have been largely phased out in the retail cold chain sector. This is yet to happen in the building industry but legislation is heading that way. To be ahead of the curve on these issues the proposal is to use CO_2 and propane with appropriate safeguards. This means siting the plant in appropriate places, and designing the heating system to be able to accommodate the refrigeration cycles. However there may be instances where this may not be possible and R32 would need to be used.

The trans critical cycle of CO_2 means that it can produce high temperatures such as 70◦C but requires a low return [>35◦C] to be efficient (i.e. a large temperature difference). This has implications for the design of the heating system, as the flow rates are a significantly lower than with a boiler or certainly other refrigerants that work on very low temperature differences.

Refrigerant	GWP	Other environmental impact	Safety	Comment
R410A	2088	PFAS – on a list of substances likely to be banned	Generally benign (unless installed in very small spaces)	Good but high GWP [Global Warming Potential], being phased out by legislation
R134a	1430	PFAS – on a list of substances likely to be banned	Generally benign (unless installed in very small spaces)	High GWP [Global Warming Potential], being phased out by legislation
R32	675	Currently outside of working definition of “PFAS”	Low flammability rather than no flammability.	Displacing R410A; Widely available equipment
R454c	158	PFAS – on a list of substances likely to be banned	Low flammability rather than no flammability.	A new Refrigerant that is seeking to displace the older chemicals. Equivalent heat pump plant currently on the market tends to be louder with lower efficiency
R1234ze	7	PFAS – on a list of substances likely to be banned	Low flammability rather than no flammability.	We expect this to be phased out in the near future under PFAS bans
R290 (Propane)	4	Minimal	Flammable – constraints on were plant can be sited	Good but constraints around flammability; Less widely available equipment.
R744 (CO2)	1	Minimal	Generally benign (unless installed in very small spaces)	High pressure: thicker pipework etc; Trans critical cycle: Can produce high flow temperatures but requires low return temperatures; Large temperature delta T => low flow and small pipes. Less widely available equipment.
R717 (Ammonia)	0	Minimal	Toxic and flammable	Good but toxic. Generally units are bigger than 1MW and only used in large commercial facilities with high level of maintenance. No central plant of appropriate size at Pembroke
R718 (Water)	0	None	Benign	Plant not currently commercially available for applications in buildings (there is a single R718 chiller we are aware of). Technology appears well suited to very high temperature applications,.

5.3 CHOICES OF HEAT SOURCE

A heatpump needs an external source of heat. Ultimately the source of ambient heat is the sun [setting aside the heat from the earth's nuclear core]. The temperature of the sources will follow the seasons to a greater or lesser extent. Generally the warmer the source is, the more efficient the heatpump.

If heat is taken out of a source it will cool down and the heat needs to be replenished from somewhere. Finally the need for space heating is greatest when it is coldest, but very cold weather doesn't happen often and doesn't represent a large portion of the annual heating load. Meanwhile hot water demand is consistent irrespective of season.

Ambient air is the easiest heat source to access and varies the most seasonally [say -5°C to 35°C]

Open bodies of water such as the river will vary less [say 2°C to 25°C]. There are no convenient open bodies of water available to Pembroke generally, although the GAB is close to a river.

The ground in the UK is around 11°C. If heat is extracted it will cool down and will need to be replaced by conduction from adjacent ground or heat from the surface which is very slow. If the ground is permeable flowing water can extract and transport the heat through the ground and into a heat pump.

Heat pumps are generally split into:

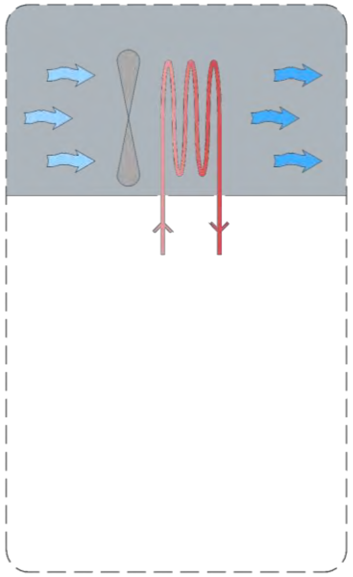
- Air source [ASHP] taking heat from ambient air.
- Water source [WSHP], taking heat from a variety of sources that are reviewed on the chart which follows.

Where a water source is "open loop" it uses an environmental fluid directly, i.e. ground water is pumped into a plantroom and heat extracted before being returned to the ground. "Closed loop" systems involve recirculating a single volume water through a heat source (such as the ground) to extract heat.

Pembroke has several options to choose from, with some only available at some sites

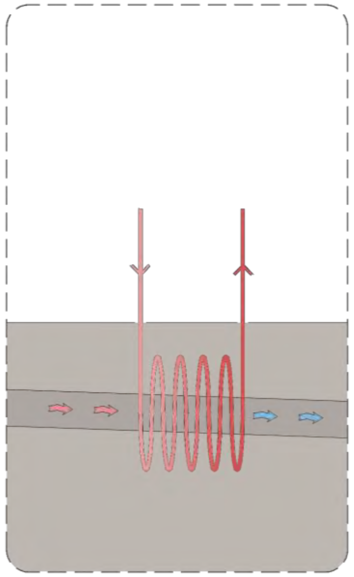
AIR SOURCE

Ambient air is the heat source



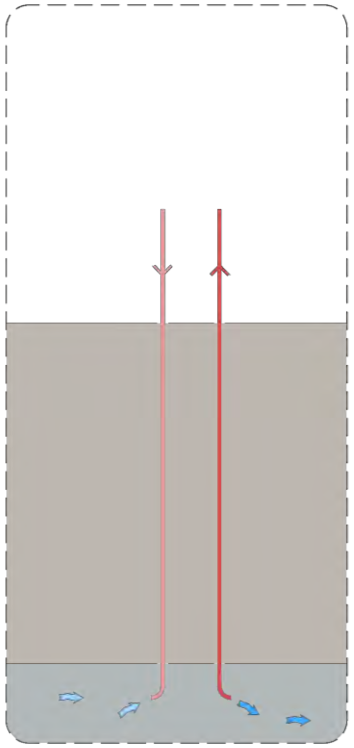
SEWER SOURCE

Sewerage air is the heat source



GROUND SOURCE: OPEN LOOP

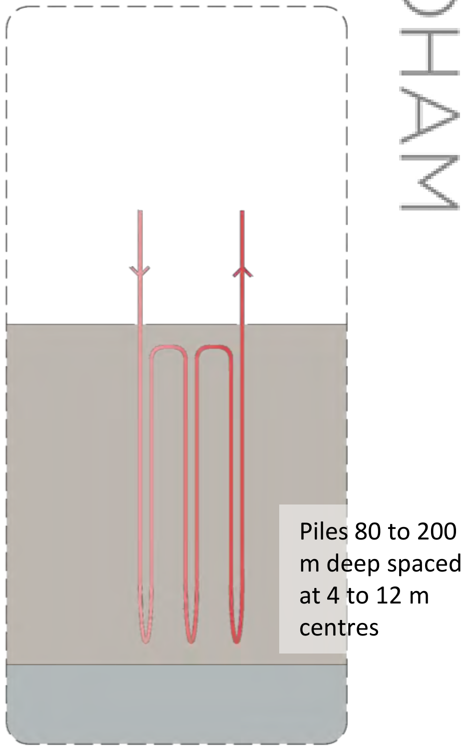
The groundwater is the heat source - directly



Water bearing aquafer

GROUND SOURCE: CLOSED LOOP

The ground is the heat source - indirectly



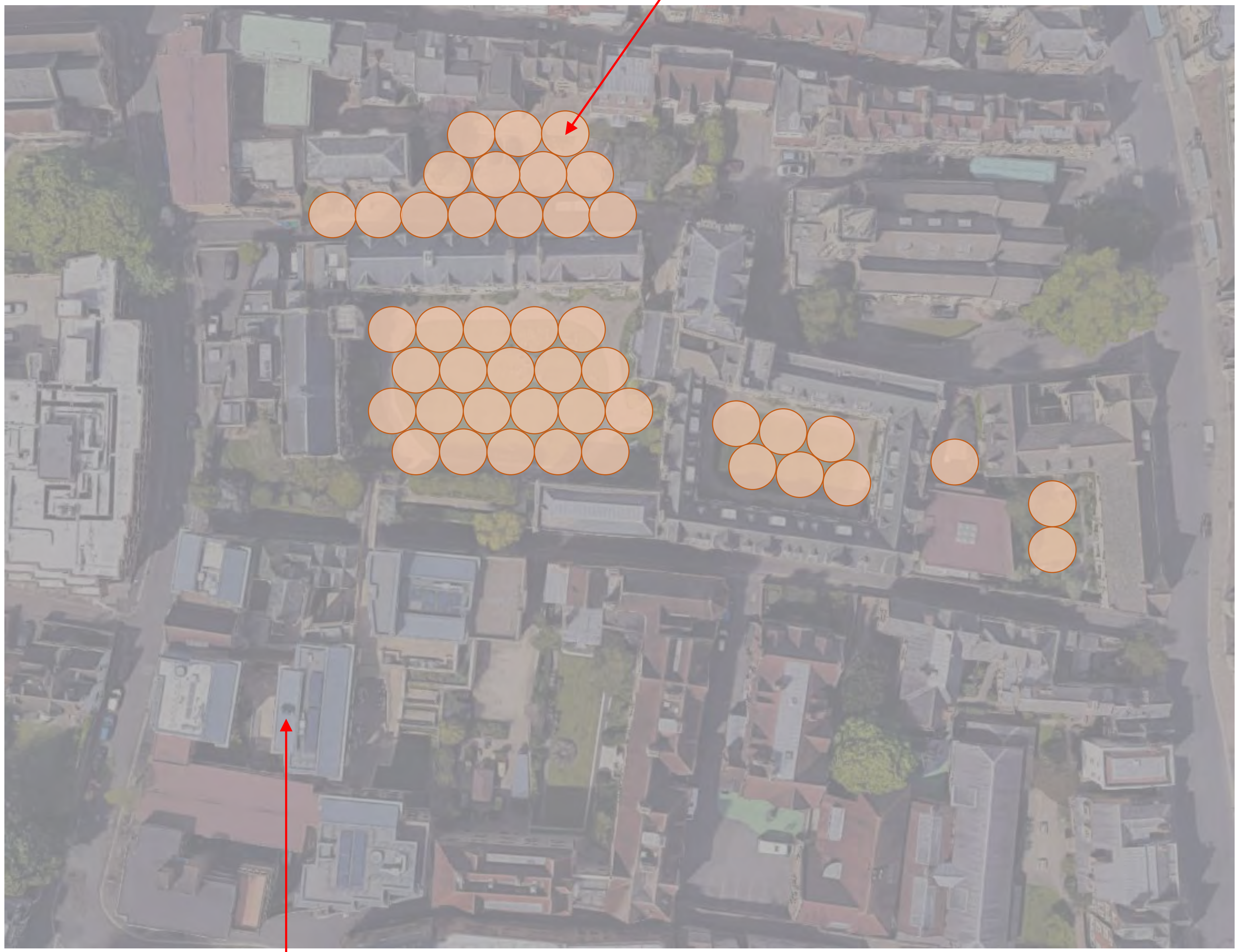
HEAT SOURCES - GROUND

This illustrates the required number of boreholes on the main site assuming that the fabric insulation measures are carried out. More would be required if the fabric upgrades where not as extensive. A ground source array at the main site would not be adequate to completely meet the load and would be expensive.

The advantage of the ground source is that the installation is quiet and discrete once it is installed. However this illustrates the disruption associated with its installation

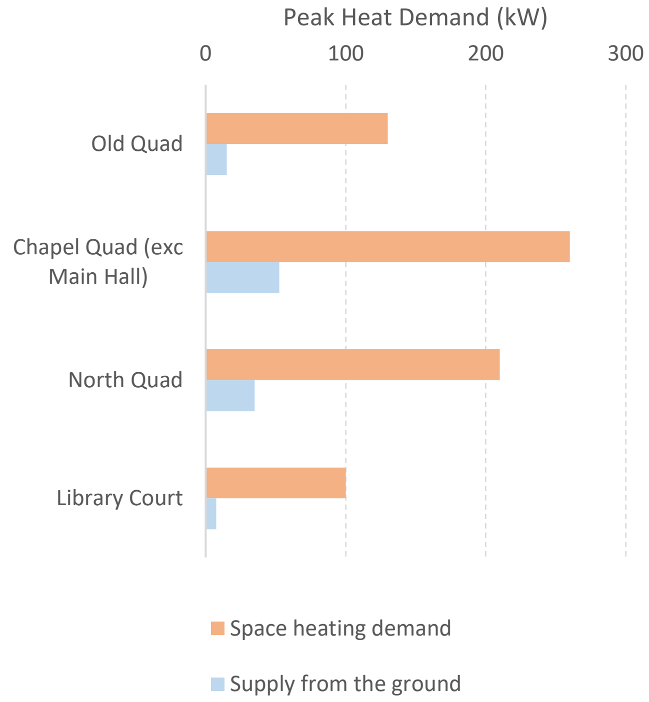
The bore holes would require a piling rig to get to each position. Each pile would take between half a day and a day to complete. There would be a concern that the positioning of the rig if not the drilling of the bore hole would cause damage to the landscaping and archaeology. In addition all the bore holes would need to be connected with pipework that would need to be in trenches across the site. There would likely be archaeological constraints.

Given the level of disruption and the additional costs we are not recommending this as a solution for the College.



80m deep Boreholes
at 6m spacing

Existing ground heat
exchanger at Rokos
Quad is beneath the
buildings



HEAT SOURCES - AIR

An air source heat pump takes heat from the ambient air. As such, the temperature of the heat source varies to a greater degree.

The heat extraction is done with air coils with fans that blow air through the heat exchangers. At times the condensation on the coils freezes and the system needs to go through a defrost cycle.

Unlike the ground source arrays, the air coils need to be outside and be able to circulate air. As such they have greater acoustic issues to deal with.

The physical size of ASHPs can become quite large for larger heat loads. This can necessitate additional structure. In the Main Site's heritage setting, some ASHPs would only be able to be accommodated at roof level and this will likely necessitate additional structure. The access and maintenance requirements need to be addressed as part of their design.

The acoustic issues need to be considered in the siting of the units.

COP

The efficiency will vary and will depend on the machine used, the external air temperature and the heating system temperatures involved.

The air temperature of the heat source varies a lot and the system efficiency will go down when it is cold and the demand is the highest. In better insulated buildings more of the annual load is when it is coldest. However the peak conditions don't occur often.

When air source heatpumps are used, a heating system should be controlled so that the system temperature is minimised while meeting the load at any given time. This maximises efficiency throughout the year and makes a very big difference to the overall performance of the system.

Domestic units have this control build into them.

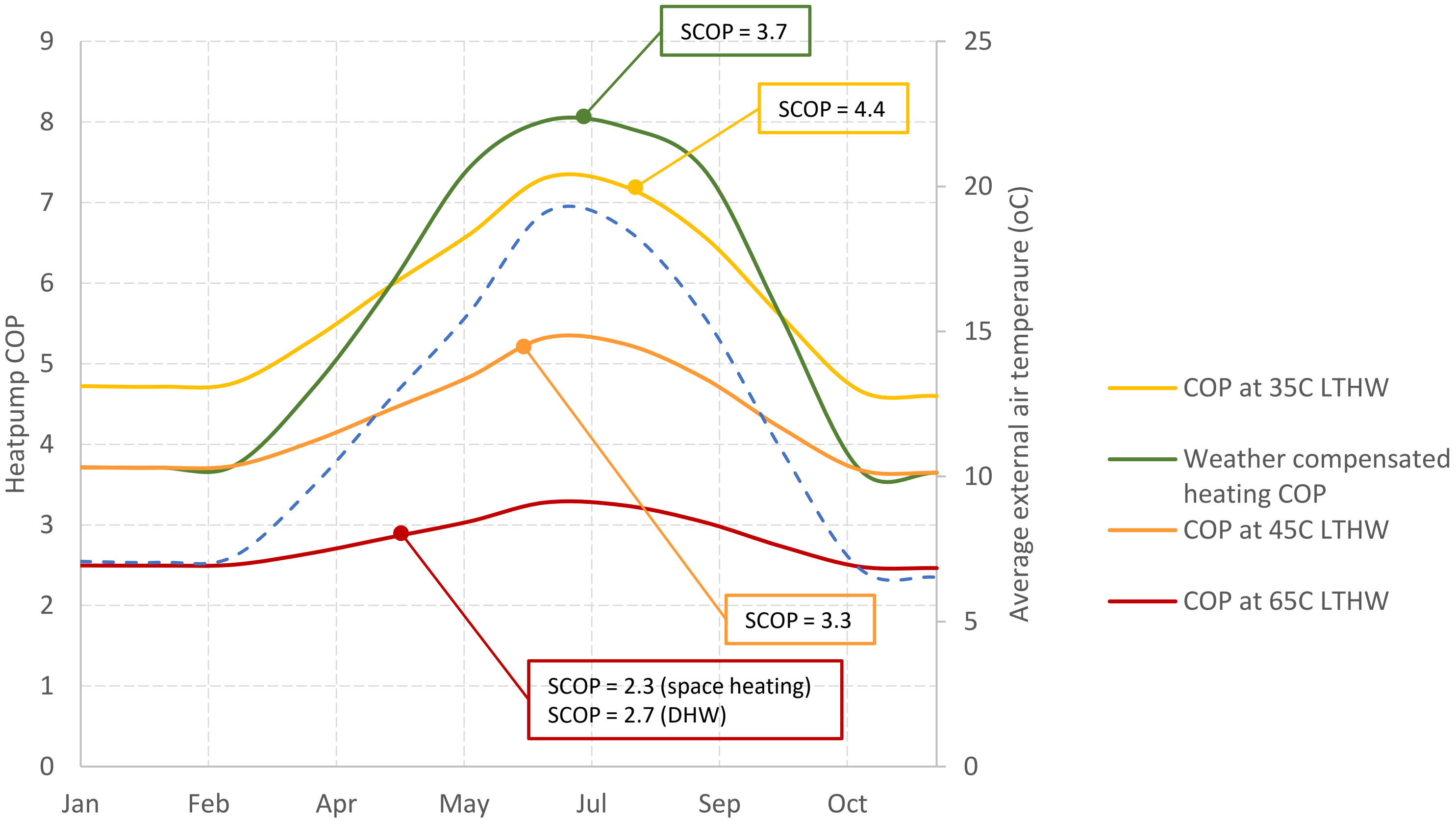
The overall annual efficiency for any particular system depends on the system temperatures, the external temperatures during the year and the building's load profile. This annual efficiency is the "Seasonal Coefficient of Performance" (SCOP)

Various published efficiencies at various mean monthly temperatures for a typical modern propane heatpump are shown opposite. The resulting SCOP when used for space heating in buildings with typical load profiles of buildings at Pembroke in typical Oxford weather are also noted. Real SCOPs would tend to be lower as more of the load happens at colder times within each month, and because manufacturers' published lab-tested efficiencies are rarely achieved in real world buildings

This sensitivity of efficiency to temperature is not so pronounced for some refrigeration technologies such as CO_2.

Domestic 7kW unit

Commercial 40kW unit



5.5 CONCLUSIONS

This study has focused on using an air source as it will be reliable, low maintenance, cost effective and minimises the risk involved in acquiring additional environmental consents. As such it could be installed quickly to take advantage of government grants that tend to be associated with short spending deadlines.

We do not think that the seasonal efficiency of the air source will be significantly worse than a water source. As such, efficiency should not drive the decision of heatpump heat source.

Not all options are practical or available at all sites – for example closed loop ground source systems require large areas of ground whereas sewer source systems require a large sewer.

Site constraints:

- The plant needs to be largely hidden and fit in with the listed building status (for most buildings). Any air source collectors need to be in well ventilated spaces. Plant areas are identified individually for buildings.
- The noise of the plant cannot be too intrusive. The requirements to both the neighbours and the college residents are stringent.
- The air from the air source heat pumps will be cooler than the ambient air and can cause a nuisance to people adjacent to the units.

Engineering constraints:

- The plant needs to quietly circulate enough air to collect enough heat for the needs of the building without causing a nuisance.
- The plant needs to be available to buy.
- The existing pipework installations should be retained as far as possible.
- The efficiency of the system should be as high as possible.
- The refrigerants involved should have a low Global Warming Potential [GWP] and be safe
- The controls should be simple.

Recommendation: Use Air source Heatpumps (ASHP) generally.

	Air source	**Sewer Source**	**Ground source – open loop**	**Ground source – closed loop**
Cold weather efficiency	Lowest (but still reasonable with good system design)	Good	Best	Best: if big enough. [Bad if too small.]
Warm weather efficiency	Best	Good	Good	Good [Bad if too small.]
Local thermal nuisance to people	Potentially high – must be designed and managed	N/A	Only issue if discharging ground water into river.	N/A
Local acoustic nuisance	Potentially high – must be designed and managed	N/A	N/A	N/A
Ecological impact	N/A	N/A	Low	Low
Consents required	Planning consent required generally – applied for already for the Dining Hall and GAB	Needs coordination with sewerage undertaker	High – Consent to extract from ground and recharge water.	N/A
Visual impact	Potentially high – must be designed and managed	N/A	N/A	N/A
Cost	Low	Can be high depending on nature of drainage	Moderate:	Very high, particularly as aquifer limits borehole depth in Oxford
Programme	Very little uncertainty	Time consuming to acquire consents	Time consuming to acquire consents: Trial bore holes required.	Extensive borehole array to drill
Maintenance	Low	High – foulwater heat exchanger needs regular cleaning	Low	Low
Site specific feasibility	Sites for air coils have been identified on the campus.	Sufficiently sized and accessible unlikely to be available	Heavily dependent on local hydrogeology at aquifer, not researched.	Shallow aquifer in Oxford limits borehole depth – insufficient ground area for heat exchanger generally

HEATING METHOD, CARBON, RUNNING COST

Type of heating system:

Electricity is an expensive fuel.

There are various buildings which currently have direct electric heating. With Pembroke's REGO electricity tariff, these could be considered decarbonized already, and even without that are fairly low carbon given the decarbonisation of electricity more widely.

The efficiency / COP of direct electric heating is 100% / 1.

This is far less than that of heatpump based heating systems, where we would look to design the SCOP to be > 300% / 3 in practice.

Extending existing heating systems to serve those areas which are heated with direct electric heaters is then desirable.

This is principally Staircases 2-6 and the SCR Staircase. While the Chapel is also direct electrically heated, it is used much more sporadically. Routes for pipework to serve it are difficult to coordinate while respecting the heritage sensitivity and would be very expensive to implement. As such, we are not recommending extending a wet LTHW heating system to the Chapel.

All else being equal, changing from direct electric to heatpump heating will reduce electricity consumption and reduce loading on the electrical infrastructure.

Heat emitters:

As discussed, the efficiency of heatpumps depends on the source and sink temperatures. The system efficiency varies just as much with sink temperatures as it does with source temperatures and cooler heating systems run more efficiently.

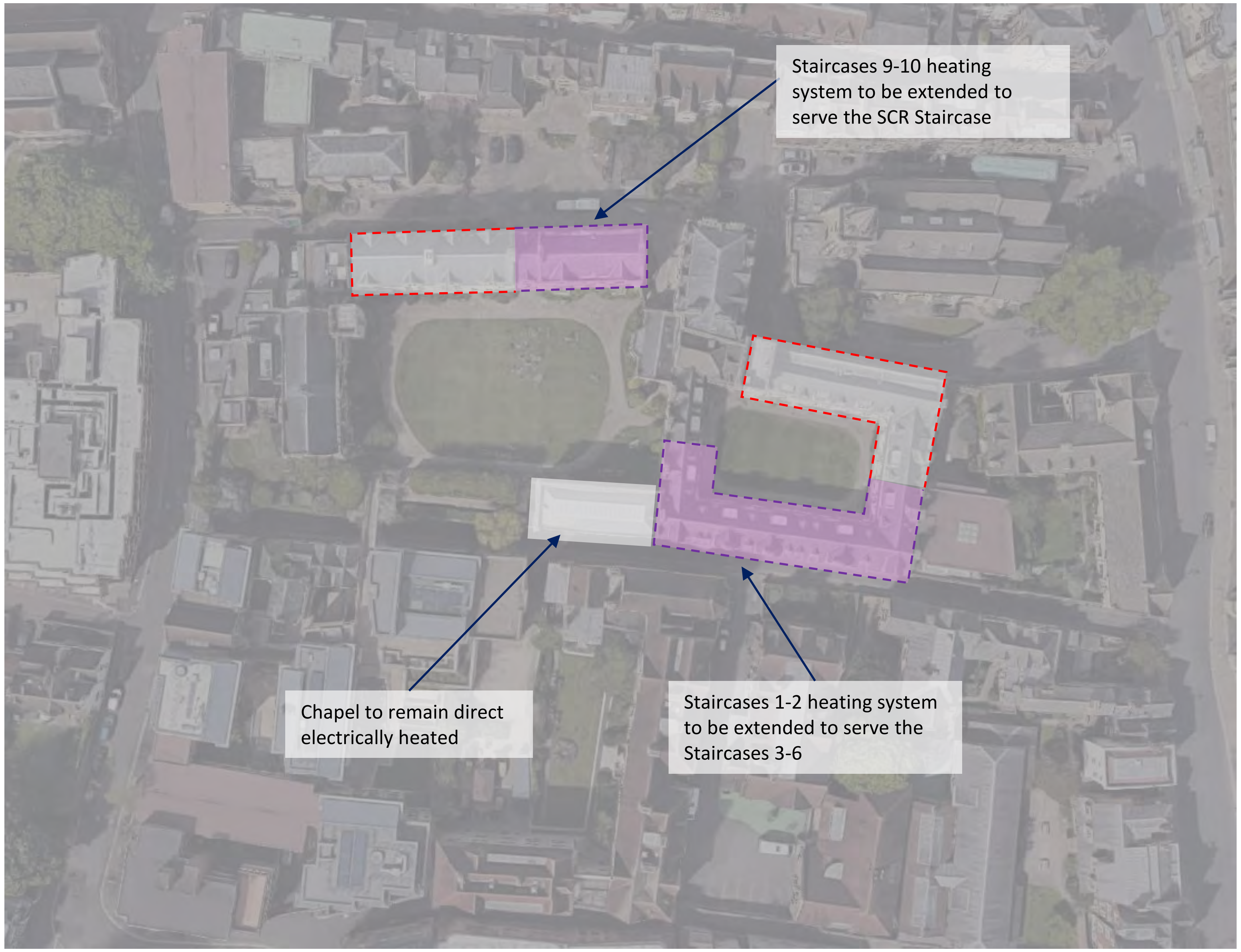
The way to make cooler heating systems work is to have large heat emitters. These can come in various forms:

- Larger radiators
- fan assisted convectors
- underfloor heating

In heritage buildings, increasing the heat emitter size is generally cheaper and less contentious than making fabric improvements and can lead to comparable energy savings.

The heritage buildings at Pembroke pre-date the invention of modern heating systems, which in themselves have little or no heritage value.

However, there will be physical, architectural and aesthetic limits to how large emitters can be. Fabric improvements which reduce heat demand mean that emitters can be large relative to a space's heat demand given these constraints. The design of emitters is part of the detailed design of any piecemeal decarbonization programme

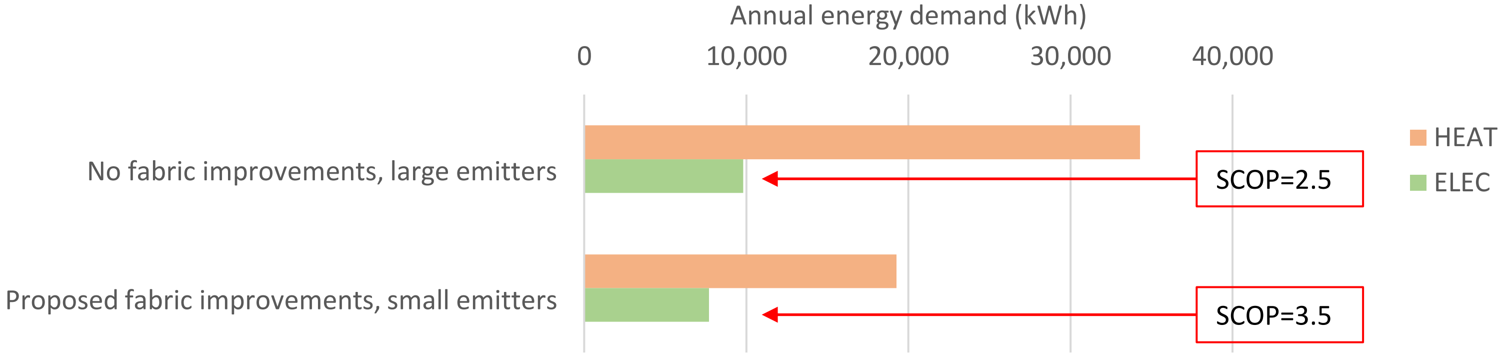


Staircases 9-10 heating system to be extended to serve the SCR Staircase

Chapel to remain direct electrically heated

Staircases 1-2 heating system to be extended to serve the Staircases 3-6

Staircase-2 comparison – fabric vs emitter size



DOMESTIC HOT WATER PROVISION [DHW]

Generally the circulation of the hot water is the highest load compared to the actual water consumed

We suggest that the DHW provision is done as locally as possible.

In spaces with very low or infrequent DHW demands, we recommend that DHW is provided by local point of use direct electric water heaters, avoiding distribution heat loss entirely.

Where the demands are higher and more frequent, we recommend making use of heat pumps to provide the heat. This can either be via the heat pump that does both space heating with DHW or with its own dedicated heat pump.

We are suggesting the use of these smaller heat pumps as it avoids having to run the space heat system in the summer and in any event they will run at different temperatures.

With these Edel water heating ASHPs the air is ducted in and out of the small heat pump that sits on top of the water cylinder. The units are domestic in scale and can be connected to give greater capacity.

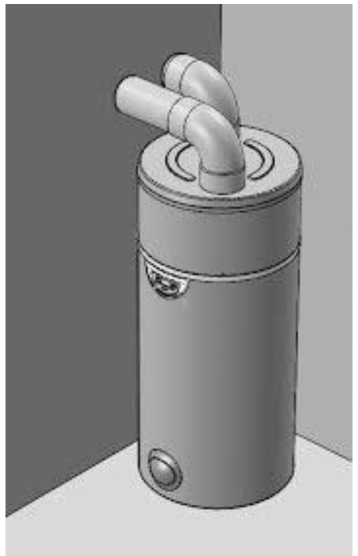
The hot water heating at Pembroke does largely follow the model of several distributed hot water heaters, be they electric, direct gas fired or a calorifier. Providing that there is an adequate supply of air to the space or a flue or window for 150mm diameter ducts, an Edel heatpump can be put in most places.

To work well, the systems these are connected to must have either very low or zero recirculation losses. We would recommend reconfiguring any DHW distribution systems from a recirculating system to a radial distribution system. However, this is generally more intrusive, disruptive and expensive to deliver as it involves works to the pipework distribution within the building which may be concealed and difficult to access.

This is the proposal that is currently designed for the GAB.

We suggest that refurbishment plans for other staircases (eg Staircases 13-15) include space for an Edel heatpump water heater, along with suitable duct routes to outside.

Electrification of DHW in this way could be done as smaller piecemeal projects to the rest of a abuilding.

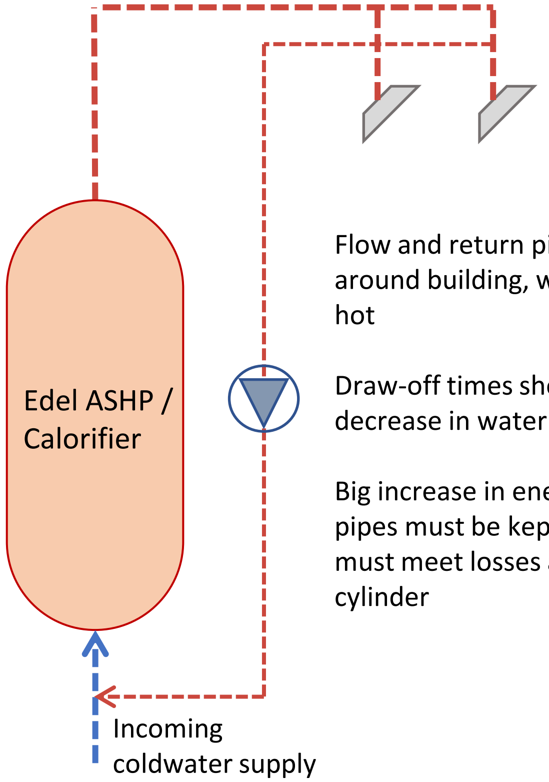


Air Ducts to outside

Heat pump section

Hot water cylinder section

Traditional recirculating DHW system

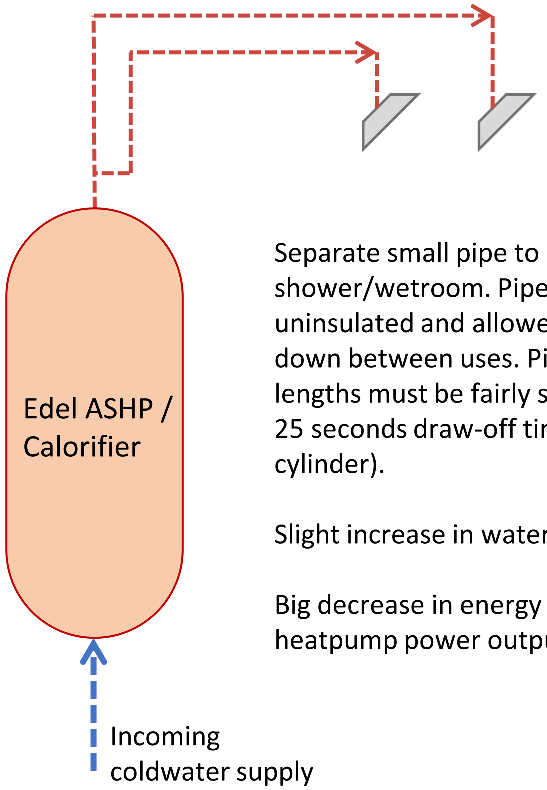


Flow and return pipes distributed around building, with network kept hot

Draw-off times shorter, slight decrease in water use.

Big increase in energy/heat use as pipes must be kept warm. Heatpump must meet losses as well as heat cylinder

Radial DHW system



Separate small pipe to each shower/wetroom. Pipes uninsulated and allowed to cool down between uses. Pipe lengths must be fairly short (20-25 seconds draw-off time from cylinder).

Slight increase in water use

Big decrease in energy use ane heatpump power output (if

ASHP SIZES and POSITIONS

We have largely assumed that buildings are served by their existing plantrooms, with boilers replaced with new ASHPs for space heating only. DHW would be done locally with ducted ASHPs located within plantrooms.

The sizes and positions of ASHPs are indicatively shown here.

We have suggested that some collocated heating systems are combined and centralised, which will offer some resiliency. The degree of this could be increased. However any systems which require higher temperatures to meet their loads should be kept separate. For example, it is expected that SC 9-10+SCR will need to operate at a higher temperature than McMillan because heritage will constrain both fabric improvements and emitter size.

For GAB proposals, see GAB design.

Staircases 11-17:
160kW R290 ASHPs on McMillan Terrace for space heating. ASHP plant connects to 3No. Existing internal plantrooms. Edel ducted ASHPs inside for DHW. Plant installation could be modular to suit phased delivery

Staircase-18
30kW R290 ASHP within shed ASHP area. Edel ASHPs inside for DHW

Staircases 7-8 + Broadgates
90kW R290 ASHPs near shed. PoU water heaters for DHW

Staircases 9-10+SCR:
160kW R290 ASHPs near shed. PoU water heaters for DHW

MacMillan:
Most pragmatic place is on the terrace. Size depends on nature of McMillan extension/retrofit. 70kW to decarbonise current building

Dining:
160kW CO_2 ASHPs on roof for space heating. 15kW R32 ASHP for DHW recirculation

Albion:
Most pragmatic place is on the roof. Size depends on nature of Albion extension/retrofit

Rokos:
150kW propane ASHPs on roof for DHW and peak space heating.
75kW Electric boilers in plantroom to provide peak load assistance to GSHPs

Staircases 1-2 + Tower, and extended system to serve Staircases 3-6
150kW R290 ASHP located on Library Roof

Almshouse and Master's Lodgings:
80kW Propane ASHP located on roof of Library

Library:
30kW R290 ASHP – located on roof

KEY

🟦	New ASHP plant
🟧	Existing boiler plantroom
⬚	Heating system zone
⬚	Extended (new) heating system zone
—	Indicative pipework/controls connection. Routing will need to be designed

ELECTRICAL SUPPLIES FOR DECARBONISED HEAT

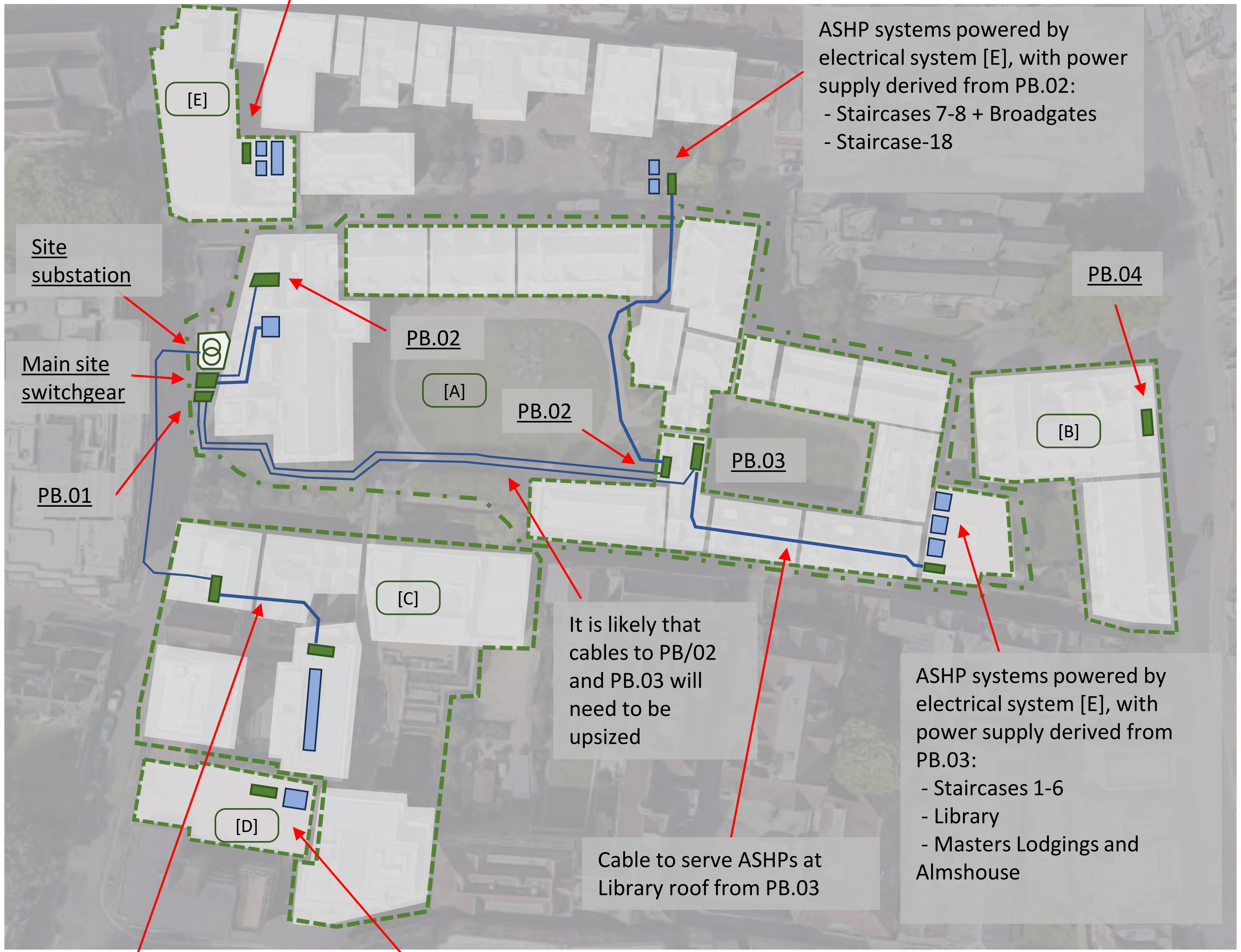
The proposed power supplies to each main heatpump load are shown here.

The relevant electrical installations where these power supplies would be derived from are as follows:

[A]	Main Site	800A
[B]	Almshouse area	100A
[C]	Rokos	630A
[D]	Albion	100A
[E]	McMillan	160A (TBC)
[F]	GAB	400A

It is important not to have two different electrical installations in close proximity, to avoid them becoming entwined where inconsistent earth potentials can cause safety issues This means that where there are multiple heatpump heat sources in the same location, they should be served from the same electrical system. The controls system for a heatpump installation may then be hosted in a different electrical system.

This means that the system serving the Masters Lodgings/Almshouse is better powered from Electrical System [A],



ASHP systems powered by electrical system [E]:
- McMillan
- Staircases 11-17
- Staircases 9-10+SCR

Power supp

ASHP systems powered by electrical system [E], with power supply derived from PB.02:
- Staircases 7-8 + Broadgates
- Staircase-18

It is likely that cables to PB/02 and PB.03 will need to be upsized

ASHP systems powered by electrical system [E], with power supply derived from PB.03:
- Staircases 1-6
- Library
- Masters Lodgings and Almshouse

Cable to serve ASHPs at Library roof from PB.03

New power supply from main Rokos switchpanel to serve decarbonised heat sources in Henderson

Albion heatpumps only within electrical system [D]

ELECTRICAL SUPPLIES FOR DECARBONISED HEAT

The existing loading of the various electrical systems is not known with any certainty.

We have estimated the existing loading based on energy use, size of systems and nature of buildings served. Where possible, we have used maximum demand loadings recorded by electrical meters.

The existing capacity is generally taken as the size of the main protective device on the utility incoming power feed, unless there is another constraint in evidence. There may also be Agreed Maximum Demands which are lower.

Both Rokos Quad and the Main Site supplies are taken from the same SSE owned substation. The loading and capacity of the substation is unknown. It may be that the available capacity to both systems is lower than the sum of their individual supply sizes.

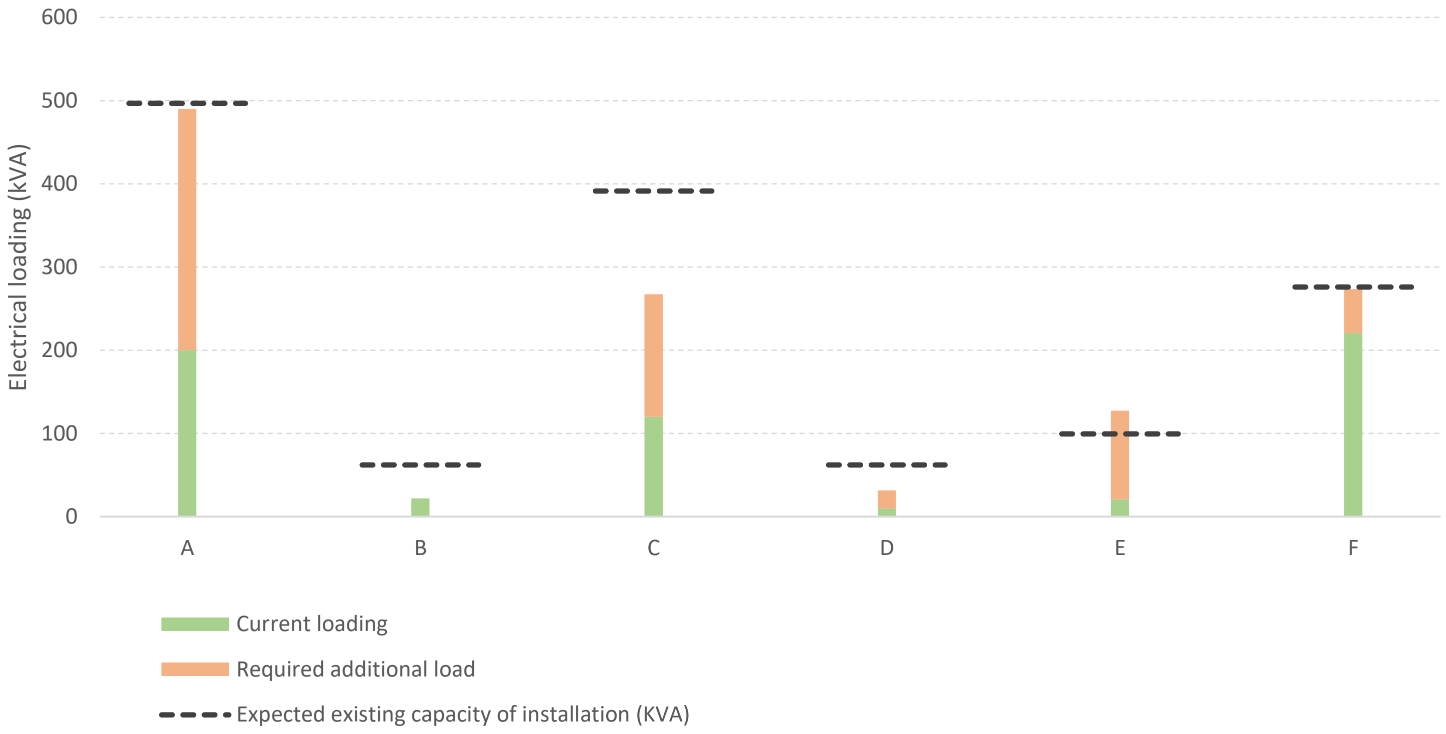
The anticipated additional loading assumes heatpumps are located and sized as set out in this Decarbonisation Plan. This also assumes the fabric improvement measures recommended in this report are taken forward.

The existing capacity, current loading and anticipated additional loading for the five main electrical systems are set out below and opposite.

It is likely that the McMillan building will need its supply size to be increased. The GAB site will need its supply increased when the newly finished buildings are decarbonised.

The supply capacity to the main site is marginal. This is another reason for carrying out works which reduce the peak energy consumption of electrically powered heating systems, such as:

- making fabric improvements
- increasing heat emitter sizes
- replacing direct electric heating with heatpump led LTHW systems

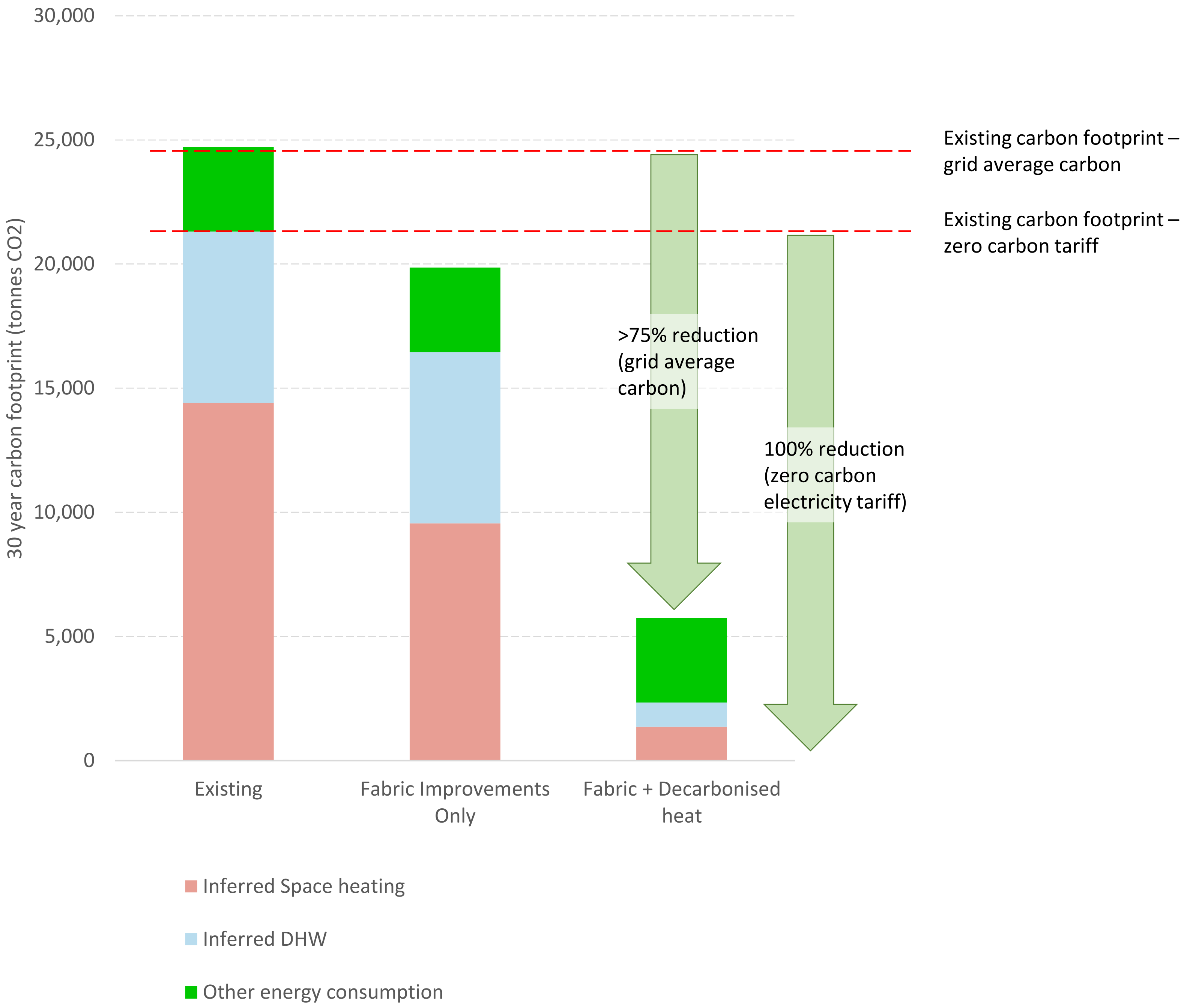


Electrical Zone	Heating systems served	Expected capacity (kVA)	Anticipated existing loading (kVA)	Required additional loading (kVA)
[A] Main Site	Dining Hall Staircases 1-6 Staircases 7-8+Broadgates Library Masters Lodgings + Almshouse	500	200	290
[B] Almshouse	None	62	22	0
[C] Rokos	Rokos Quad	400	120	150
[D] Albion	Albion	62	10	22
[E] McMillan	McMillan Staircases 11-17 Staircases 9-10	100*	21	110
[F] GAB	GAB Staircases 1-18	276	220	45

9. DECARBONISATION – WHOLE ESTATE

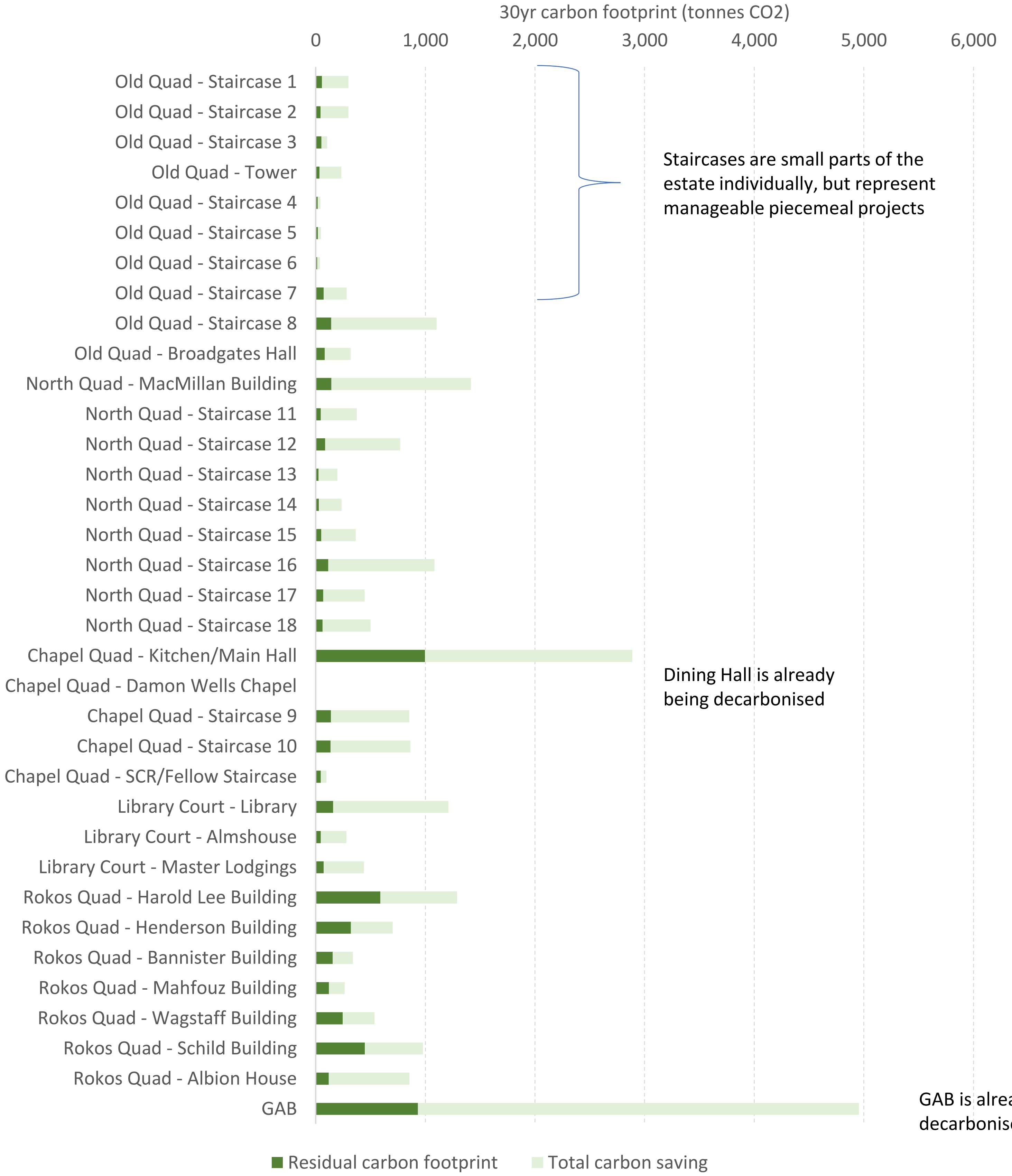
The approaches outlined in this decarbonisation plan would lead to a total reduction in the Pembroke Estate's carbon footprint of just over 75% over 30 years, assuming average grid carbon intensity. However, the College's carbon footprint would become zero as soon as the last gas-fired boiler was decommissioned, given that the College has a zero carbon electricity supply.

Decarbonising the whole estate is a large project. To make it more manageable, it can be broken down into piecemeal projects.



9. DECARBONISATION – WHOLE ESTATE (cont.)

The individual carbon reductions for buildings are shown here, when all proposals are implemented. The residual carbon footprints consider national average grid carbon intensity. Pembroke purchases renewable electricity, so one could equally consider the residual carbon footprints to be zero once fossil fuels are removed.



Staircases are small parts of the estate individually, but represent manageable piecemeal projects

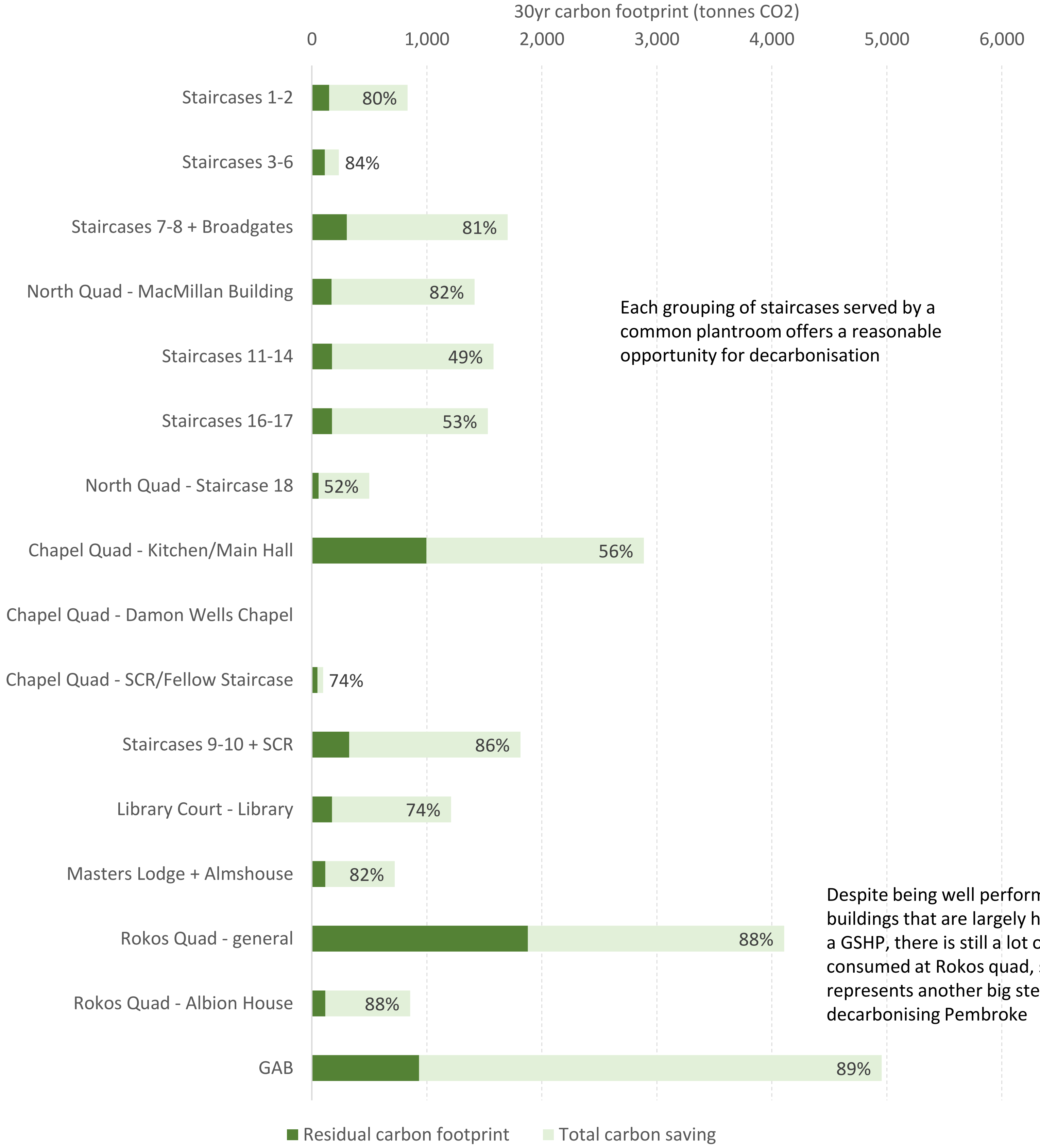
Dining Hall is already being decarbonised

GAB is already being decarbonised

DISCREET PROJECTS

The way that buildings are grouped around distributed heating plantrooms suggests a piecemeal set of projects. Indeed, the first two of these are underway – the GAB and the Dining Hall, with the next phase currently being designed.

The others are set out here.



Each grouping of staircases served by a common plantroom offers a reasonable opportunity for decarbonisation

Despite being well performing buildings that are largely heated with a GSHP, there is still a lot of gas consumed at Rokos quad, so this represents another big step in decarbonising Pembroke

OVERALL ESTATE DECARBONISATION PLAN

The Decarbonisation Plan and its current status is shown here, assuming grid average carbon intensity for electricity.

Phase-1 is decarbonizing the Dining Hall and GAB and this is due to complete by the end of 2023.

Phase-2 is to decarbonize the Rokos Quad and the Old Quad. This project is currently being designed.

Phase-3 looks to be decarbonization of the McMillan and Albion buildings, however the nature of these projects is less clear.

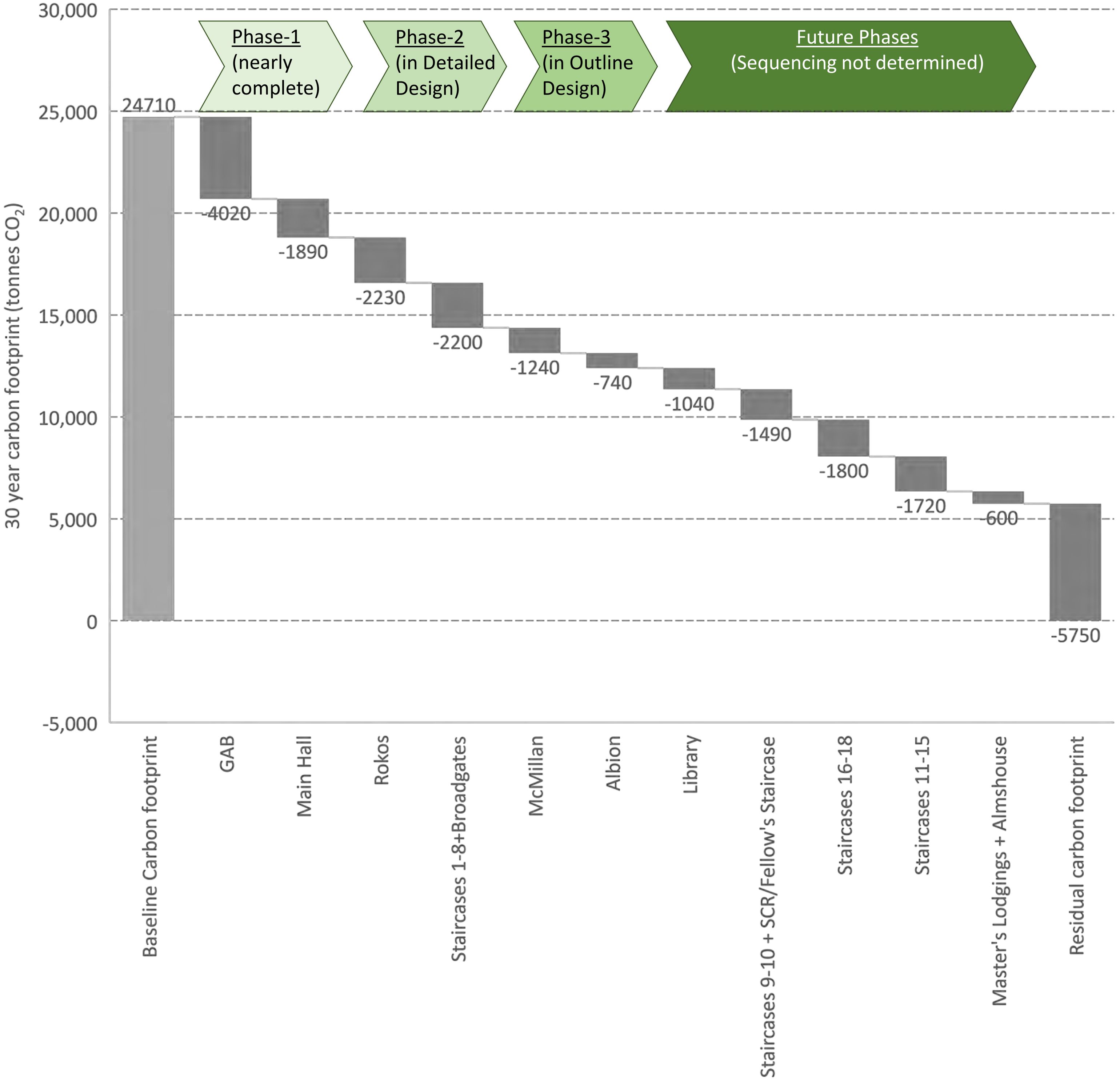
When Phase-1 is complete, the Estate's carbon footprint will have reduced by ~25%

When Phase-2 is complete, the Estate's carbon footprint will have reduced by a further ~20%, for a cumulative reduction of ~45%.

Phase-2
~45% CO_2
reduction
overall

Phase-1
~25% CO_2
reduction

Phase-2
~20% CO_2
reduction



OVERALL ESTATE DECARBONISATION PLAN

The Decarbonisation Plan and its current status is shown here, in the context of Pembroke's zero carbon electricity supply, with the same phasing as previously outlined.

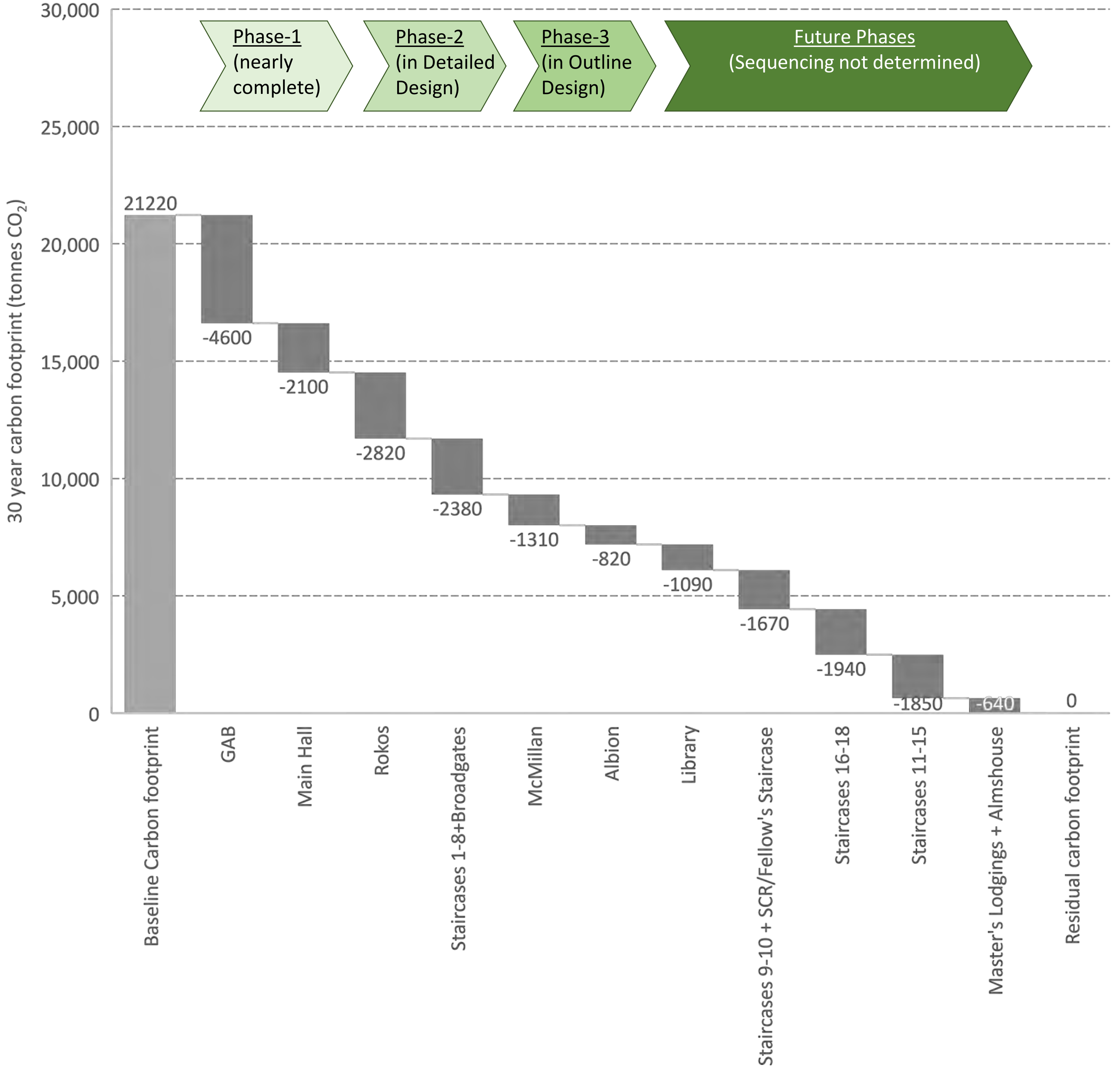
When Phase-1 is complete, the Estate's carbon footprint will have reduced by ~30%

When Phase-2 is complete, the Estate's carbon footprint will have reduced by a further ~25%, for a cumulative carbon reduction of 55%.

Phase-2
~55% CO_2
reduction
overall

Phase-1
~30% CO_2
reduction

Phase-2
~25% CO_2
reduction



PROJECT SCHEDULE

The overall costs and benefits to all the discrete projects are tabulated here. Costs are indicative, are for the decarbonization elements only and represent construction cost rather than total project cost.

The intention of this outline costing is to help define the scope of decarbonization and to help prioritize the delivery of the projects.

The project descriptions here note the main aspects. There would be some supporting works, such as electrical enhancements and a refurbishment of ventilation provision where buildings become more airtight.

Project	Project description	Reduction in peak heating load	Reduction in annual heating load	Cost	Cost effectiveness (£/tonne CO2)	Reduction in CO2 (grid carbon intensity)	Reduction in CO2 (with REGO tariff
GAB	R32 ASHPs for space heating, larger radiators, ducted Edels for DHW	0%	0%	£860,000	£214	81%	100%
Main Hall	CO2 ASHPs for space heating and DHW, additional radiators, additional door	24%	34%	£950,000	£503	65%	100%
Rokos Quad	Additional ASHPs for space heating and DHW, additional electric boiler	0%	0%	£590,000	£265	54%	100%
Staircases 1-8 + Broadgates	ASHPs for space heating. Extended space heating system. Larger radiators. Electric PoU for hot water. Secondary glazing, doors at staircases, loft insulation	27%	38%	£2,157,851	£981	79%	100%
MacMillan	Replacement windows, cavity wall insulation, roof insulation, ASHPs for space heating, ducted Edels for DHW	47%	61%	£930,000	£748	88%	100%
Albion	Replacement windows, cavity wall insulation, roof insulation, ASHPs for space heating. Electric PoU water heating	42%	56%	£180,000	£244	86%	100%
Library	Replacement windows, cavity wall insulation, roof insulation, ASHPs for space heating. Electric PoU water heating	49%	62%	£420,000	£405	86%	100%
Staircases 9-10 + SCR	Loft insulation, larger radiators, ASHPs for space heating.	45%	59%	£1,120,000	£752	82%	100%
Staircases 16-18	Replacement or secondary glazing. Loft insulation. Internal wall insulation, ASHPs for space heating, Edels for DHW	54%	67%	£1,040,000	£579	88%	100%
Staircases 11-15	Replacement or secondary glazing. Loft insulation. Internal wall insulation, ASHPs for space heating, Edels for DHW	54%	67%	£1,210,000	£703	88%	100%
Masters Lodge + Almshouse	ASHPs for space heating. Larger radiators. Edels for hot water. Secondary glazing, loft insulation	45%	58%	£660,000	£1,095	84%	100%