Bristol City Council Zero Carbon Heating and Cooling Study

Whole Life Carbon & Cost Appraisal

Revision 02

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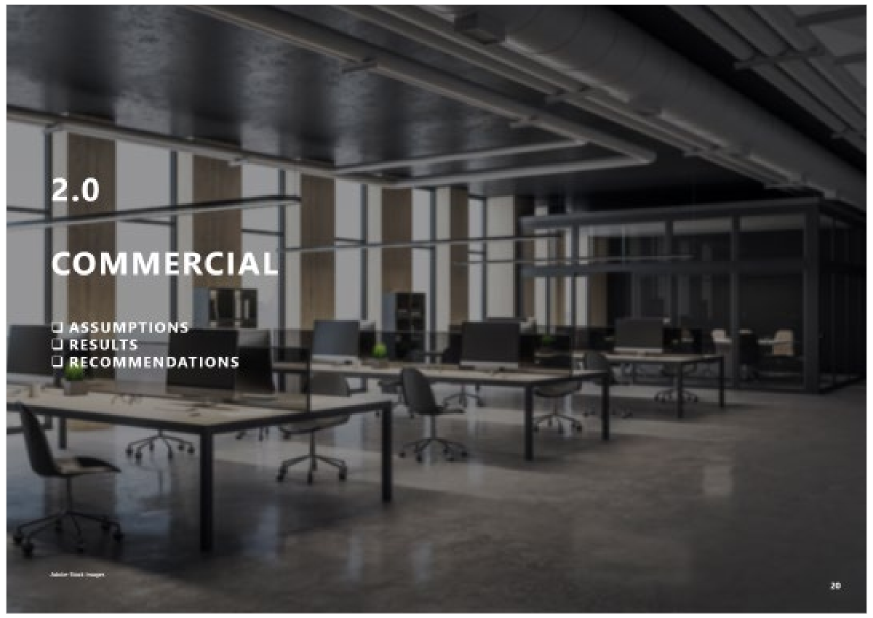

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Glossary

ACH – Air change

AHU – Air Handling Unit

ASHP – Air Source Heat Pump

BCO – British Council for Offices

BEIS – Department for Business, Energy and Industrial Strategy

BREEAM – Building Research Establishment's Environmental Assessment Method

CAPEX – Capital Expenditures

CFC – Chlorofluorocarbons

CHW – Chilled water

CIBSE – Chartered Institute of Building Services Engineers

CO2 – Carbon Dioxide

COP – Coefficient of Performance

DB – Dry Bulb

DfP – Design for Performance

DHN – District Heat Network

DHW – Domestic Hot Water

DX – Direct Expansion

EER – Energy Efficiency Ratio

EPD – Environmental Product Declaration

EUI – Energy Usage Intensity

F-Gas – Fluorinated gas

FCU – Fan Coil Unit

GHG – Greenhouse gas

GIA – Gross Internal Area

GLA – Greater London Authority

GWP – Global Warming Potential

HCFC – Hydrochlorofluorocarbons

HFO – Hydrofluoroolefins

HFC – Hydrofluorocarbons

HIU – Heat Interface Unit

HP – Heat pump

HVAC – Heating Ventilation and Air Conditioning

HVRF – Hybrid Variable Refrigerant Flow

HW – Hot water

LCC – Life cycle cost

LEED – Leadership in Energy and Environmental Design

LETI – London Energy Transformation Initiative

NABERS – National Australian Built Environment Rating System

NIA – Net Internal Area

NZC – Net Zero Carbon

MCWB – Mean Coincident Wet Bulb

MEP – Mechanical Electrical and Public Health

MVHR – Mechanical Ventilation with Heat Recovery

ODP – Ozone Depletion Potential

OPEX – Operating Expenses

POU – Point of Use

PV – Photovoltaic

REPEX – Replacement expenditure

RIBA – Royal Institute of British Architects

RICS – Royal Institute of Chartered Surveyors

SFP – Specific Fan Power

TFA – Trifluoroacetic Acid

TFA – Treated Floor Area

TRY – Test Reference Year

UKGBC – UK Green Building Council

UNEP – United Nations Environment Program

VLT – Visible Light Transmission

VRF – Variable Refrigerant Volume

VRV – Variable refrigerant volume

WLC – Whole Life Carbon

WSHP – Water Source Heat Pump

EXECUTIVE SUMMARY

Executive Summary

Bristol is targeting city wide net zero emissions by 2030 and a key part of the city-wide strategy involves the decarbonisation of heat. The heat supply decarbonisation approach essentially involves prioritising district heating in denser areas of the city and the use of building level heat pumps where district heating is not feasible. This strategy is based around the need for a decarbonised heat supply for both new and existing buildings.

Current Local Plan policy BCS14 Sustainable Energy includes a heat hierarchy that developers are expected to use for the selection of heating and cooling generation systems. The 2019 consultation Local Plan review policy CCS2 also includes proposed heating and cooling hierarchies. There is a need to review and potentially update these to reflect Bristol City Council's strategic decarbonisation proposals, the projected decarbonisation of the electricity grid, emerging regulation, voluntary net zero standards produced by UKGBC and LETI, and whole life carbon considerations. Note that for strategic decarbonisation reasons, BCC's policy is that connection to district heating will remain at the top of the hierarchy; this study will inform the case-by-case application of applying the strategic requirement.

The purpose of this study is to support the implementation of current Bristol City Council (BCC) Local Plan policy and provide part of the evidence base for the new Local Plan in relation to heating and cooling system hierarchies. The work considered whole life analysis of various heating and cooling system options based on residential and commercial office developments that are typical of those found in central Bristol.

The study was based on two archetype buildings selected from Buro Happold's project portfolio that were considered to be characteristic of those expected in Bristol: an office building in the region of 10,000m^2 and a mid-rise apartment building with around 40 units.

The study considered 'current practice' office and apartment building designs that would be compliant with current Bristol planning policy in terms of energy and renewables contribution (BCS14, BCS15), and those that align with emerging 'best practice' standards such as the UKGBC and LETI.

Conceptual designs for each heating and cooling system variant were developed and preliminary plant selections were made to enable quantification of embodied carbon and acquisition of granular performance data at a range of part load and external ambient conditions, as well as to inform the lifecycle cost model.

Operational energy simulations were undertaken to predict operational carbon emissions for each option and projections for decarbonisation of the UK electrical grid and Bristol's heat network were included in the models.

The heating and cooling system variants studied are shown in the table (right).

Key findings and policy recommendations for each building type are summarised in the subsequent pages. However, in general, decarbonisation of the UK electricity grid and the heat network mean that embodied carbon is perhaps the most critical consideration in a building's whole life carbon. In respect of heating and cooling systems, the choice of refrigerant is shown to be particularly pertinent and also equipment replacement cycles.

Adopting best practice design standards in line with LETI/UKGBC was shown to have a major impact on operation carbon and lifecycle costs, but a less significant impact on embodied carbon as it tended not to have a major impact on the quantity or size of equipment selected.

Commercial Office Operational Energy Model

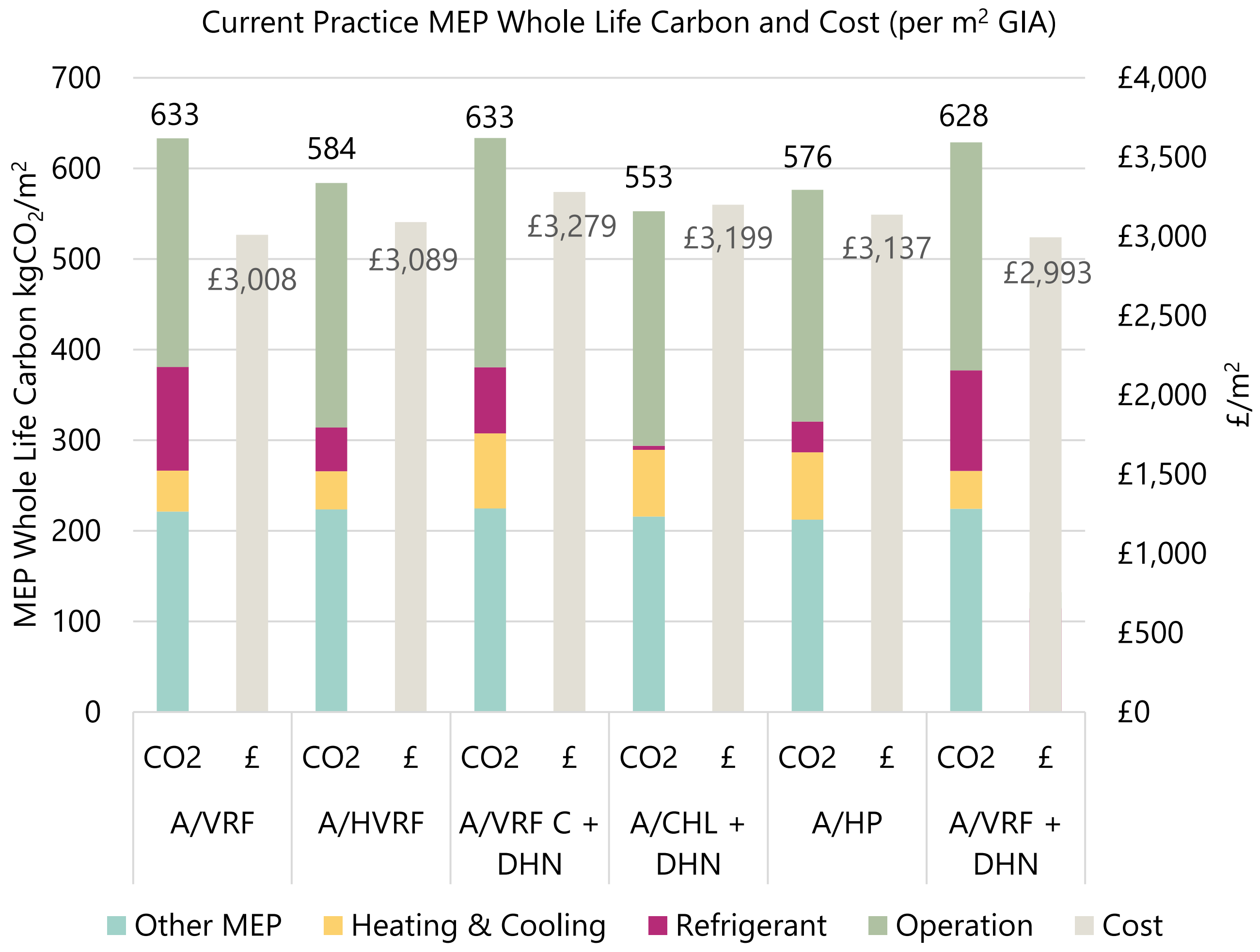
	Description	Notation
Building Performance	Base building *Local planning criteria BCS14 and BCS15, and BCO compliant*	A
	Best practice building *UKGBC and LETI guidance, and BCO compliant*	B
Commercial Office Options	VRF heating and cooling, DHW from ASHP and local direct electric POU	VRF
	Hybrid VRF heating and cooling (i.e. hydronic system in occupied spaces then refrigerant system to outdoor units)	HVRF
	Hydronic heating with district heating connection, VRF cooling	VRF C + DHN
	Hydronic heating with district heating connection, hydronic cooling with central chiller	CHL + DHN
	Hydronic heating and cooling with central heat recovery heat pump/chiller and top-up air source heat pumps and chillers	HP
	VRF heating and cooling, district heating connection for DHW	VRF + DHN
Apartment Building Options	District heating connection, no cooling	DHN
	Shared condenser loop system with central air source heating and local water-to-water heat pumps providing heating, no cooling	AmbHP
	District heating connection for heat, local split system cooling unit	DHN + DX
	Hydronic communal heating system from central air source heat pump, no cooling	HTHP
	Shared condenser loop system with central air source heating and cooling and local water-to-water heat pumps providing heating and cooling	AmbHP + C

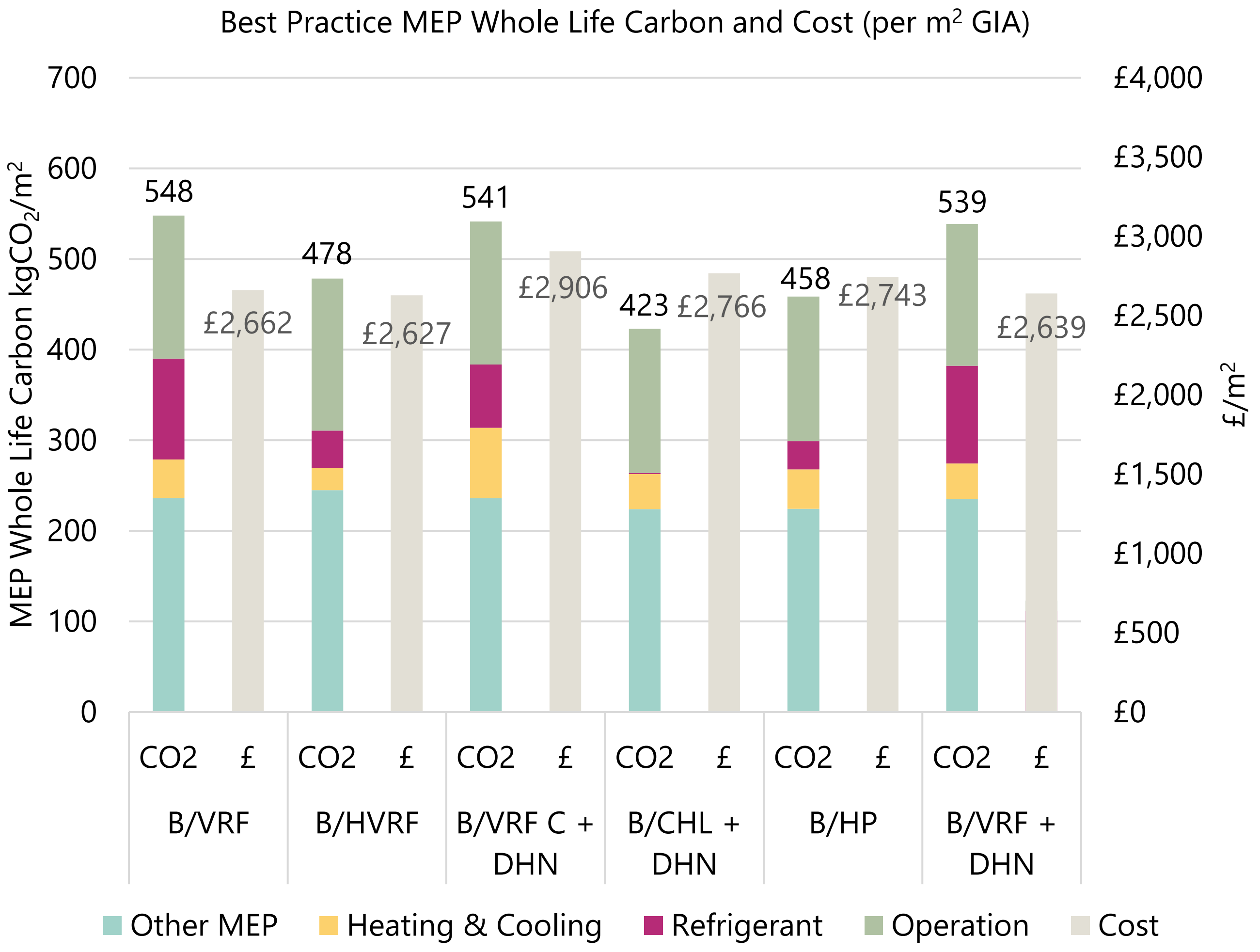
Executive Summary | Commercial

The below charts summarise the MEP whole life carbon and costs of the commercial options studied. The key findings as a result of this study have been summarised below.

Key findings

1. The chiller with DHN system option results in the lowest whole life carbon (noting that the DHN plant itself is outside of the boundary of the embodied carbon assessment.) Generally, systems that distribute heat utilising refrigerants result in the highest whole life carbon, whilst hydronic based systems (including HVRF), result in the lowest. The driving factor is the volume and types of refrigerant used.
2. Significant whole life carbon improvements are achieved through strategies to reduce demands by designing in line with best practice standards e.g. LETI. The implementation of such measures has a larger impact on whole life MEP (17% reduction) and operational energy costs (12% reduction) than the type of heating and cooling system.
3. Embodied carbon is shown to be the main driver for differences in whole life carbon amongst options, especially due to differences in refrigerants and terminal units in heating and cooling systems. Refrigerant impacts increase with volume and associated GWP. Due to the repeating nature of terminal units, minor unit differences can cause significant overall impacts.
4. Connection to the DHN results in lower embodied carbon due to the embodied carbon assessment boundary for a building and the unavailability of ultra-low GWP refrigerant for efficient heating plant. Additionally, the operational carbon is similar (+1%) to the other options based on BCC's projections for the carbon emission factor of the DHN.
5. VRF systems have the lowest whole life MEP costs (~4% less than hydronic systems) and systems with DHN connections result in a 1-2% increase in whole life MEP costs.
6. There is little correlation between the relative performance of systems options in Part L compliance modelling and operational energy modelling. In particular, the Part L models overstate the benefit of VRF based systems compared to hydronic systems. The introduction of a DHN connection for a given system shows a reduction in carbon in the compliance modelling, as opposed to a marginal net increase in the operational carbon modelling.
7. MEP systems and refrigerants are responsible for 20-30% of the total embodied carbon.
8. Centralised systems (e.g. central heat pumps) are shown to result in 18% less MEP related embodied carbon compared to zonal systems (e.g. VRF), with the exception of HVRF. This equates to 6% less of the total embodied carbon.


Current Practice MEP Whole Life Carbon and Cost (per m² GIA)


Best Practice MEP Whole Life Carbon and Cost (per m² GIA)

__A__ – Current practice, __B__ – Best practice, __VRF__ - VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

Executive Summary | Commercial and Other Non-Residential

Policy recommendations

The following recommendations are for buildings with a peak heating/cooling demand larger than 100-150kW (this is based on the smallest high efficiency, low GWP chiller size typically available). Sensitivity analysis has shown that variations in efficiency levels do not compromise the proposed hierarchy.

Heating and cooling hierarchy (condition-based)

- If a district heat connection is available then:
    - DHN connection is prioritised for both space heating and DHW
    - Chillers with ultra-low GWP refrigerants prioritised for cooling
- If there is no district heat connection available then:
    - Hydronic and hybrid VRF systems prioritised

Reduction in energy

- Reduction in peak demand is a good predictor of reducing overall annual energy demand and whole life carbon (mainly a reduction in operational carbon).
- Aiming to achieve LETI EUI targets would ensure that stakeholders partake in tenant power reduction activities; vital for overall net zero commitments.
- Accurate heating and cooling equipment performance data is essential for operational energy modelling but also challenging to obtain due to current regulations (detailed reports are not mandatory). A requirement to report comprehensive in-use energy demands would be welcomed for the following reasons:
    - Provide feedback and accountability to design teams, planning applicants, landlords, and tenants
    - Develop an increased understanding of real-world system performance that could form part of a shared database which is generally lacking in the industry
    - Encourage manufacturers to provide accurate performance data to support early stage design

Recommended metrics, compliance, and enforcement

- The relationship between operational and embodied carbon is complex and challenging to generalise. The equipment and information available is changing due to evolving market and regulatory requirements. Requiring whole life carbon assessments as part of the planning process can form a holistic view on carbon performance and help applicants make informed decisions on projects. This would be more effective than relying on Part L alone.
- A pre-commencement condition could be included to update the carbon assessments highting reasons for any changes. In addition to this, a certain percentage of applications could be audited by an independent competent person.
- Part L is not a good indicator for predicting operational carbon. It is recommended that operational energy modelling is conducted in line with a recognised modelling methodology, such as TM54 and BREEAM GN32. A simplified method might be appropriate for small developments.
- If EUI targets are adopted, systems that are connected to the DHN will need to adjust their DHN energy by a correction factor to represent the generation efficiency of the DHNs heat generation plant.
- In the current climate, clients are likely to be prepared to sacrifice on CAPEX for 'greener' credentials as this supports the marketability of buildings. It is therefore important to standardise the metrics used by clients to ones that represent the actual whole life carbon which include:
    - Accurate estimations of projected operational energy with a process to verify these through metering.
    - Demonstrating that a building is NZC after following the carbon reduction hierarchy (prioritise operational and embodied, and carbon offsetting is a last resort)

Reduction of embodied carbon

Use of high GWP refrigerants or multiple refrigerant-based systems results in a significant increase in embodied carbon for heating and cooling systems. Adoption of the following refrigerant hierarchy is recommended:

- Design for no refrigerant (DHN connection, no cooling)
- Minimise quantity of refrigerant (using water as a distribution medium)
- Select low impact refrigerants prioritising ultra-low <50 GWP where possible and no greater than 750 GWP
    - Consider tying policy to requirements of BREEAM Pol 01 one credit threshold of ≤ 1000 $kgCO_2e/kW$ cooling capacity, with a further update to the two credit target of ≤ 100 $kgCO_2e/kW$.
- Restrict refrigerant leakage (implement detection, monitoring and maintenance regimes)

Considerations for other building typologies

Small commercial buildings

Where natural ventilation is viable for cooling (such as a small office), then a connection to the DHN should be prioritised.

Generally, smaller buildings that require cooling (below 100-150kW peak loads) could consider zonal systems (such as VRF) as centralised hydronic systems may be cost prohibitive at this scale. In order to reduce refrigerant leakages in these instances, it is proposed that systems that utilise low refrigerant charges and low GWPs, and that limit refrigerant distribution are prioritised, such as HVRF. For local systems, such as for a IT room or small retail high street shop, a split/multi split unit utilising low GWP (<750) refrigerants would likely be permissible given the minimal refrigerant charge.

Schools

It is expected that in most cases, natural ventilation will be sufficient for cooling. In these cases, connection to the DHN should be prioritised. IT rooms may require a split/multi split unit for local cooling (with low GWP refrigerants).

In the event where space cooling is also required, potentially for acoustic or air quality reasons, a zonal system, such as the HVRF system should be considered for primary schools to reduce refrigerant volumes and distribution. For secondary schools that require cooling, the loads are likely to be sufficient to warrant the utilisation of a centralised hydronic system along with the DHN where possible.

Large commercial and higher education buildings

For larger developments, centralised hydronic systems should be prioritised, connected to the DHN where possible. This generally follows recommendations made for the commercial building in this study. Options to connect to a local site heat network or generate heating/cooling simultaneously may be considered, but a whole life carbon assessment is encouraged to be undertaken during the decision making process.

Executive Summary | System Evaluation Summary for Commercial

Category	Commercial Office Options											
	VRF heating and cooling, DHW from ASHP and local direct electric POU		Hybrid VRF heating and cooling (i.e. hydronic system in occupied spaces then refrigerant system to outdoor units)		Hydronic heating with district heating connection, VRF cooling		Hydronic heating with district heating connection, hydronic cooling with central chiller		Hydronic heating and cooling with central heat recovery heat pump/chiller and top-up air source heat pumps and chillers		VRF heating and cooling, district heating connection for DHW	
	VRF		**HVRF**		**VRF C + DHN**		**CHL + DHN**		**HP**		**VRF + DHN**	
	Rating	Comments	Rating	Comments	Rating	Comments	Rating	Comments	Rating	Comments	Rating	Comments
Whole life carbon (MEP)	**+5%**	High whole life carbon due to refrigerants	**-3%**	Hybrid VRF reduces refrigerant volumes	**+5%**	Lower refrigerants but increase in terminal units	**-8%**	Least amount of equipment and refrigerants	**-4%**	Heat recovery systems increase refrigerant volumes	**+5%**	High whole life carbon due to refrigerants
Whole life cost (MEP)	**-4%**	Lowest equipment and operation costs	**-1%**	Low equipment costs but higher operational costs (lower efficiency)	**+5%**	Additional terminal units increase CAPEX but low operation costs	**+3%**	Slight premium to utility bills with a DHN connection	**+1%**	Increase in CAPEX, OPEX and REPEX for hydronic systems	**-4%**	Lowest equipment and operation costs
Compliance model results	**-5%**	Part L assumes less energy use for VRF systems	**-3%**	Slightly lower seasonal efficiency compared to standard VRF	**-7%**	Cooling only VRF more efficient than standard VRF in cooling mode	**+11%**	DHN has favourable CO_2 emissions and chillers more efficient	**+17%**	Lower efficiencies assumed for cooling but higher for heating	**-13%**	VRF space heating is more efficient than DHN
Ability to meet potential future standards	All options studied have a similar potential to meet future standards											
Useability, operation and maintenance	Refrigerants increase maintenance requirements						Reduced amount of plant due to connection to DHN		Addition of plant and complexity of controls		Refrigerants increase maintenance requirements	
Potential constraints or impacts the selection of the option may have on the wider building design	Electric heaters may be required where the installation of a dedicated VRF system is cost prohibitive (e.g. back of house)				Incompatibility between VRF and the DHN for space conditioning; extra terminal units (FCU & trench units)		Provision for a heat substation and compliance with BCC heat network technical specifications		Design flow and return temperatures could dictate size of distribution and terminal units		Electric heaters may be required where the installation of a dedicated VRF system is cost prohibitive (e.g. back of house)	
Comfort for occupants	All options have mechanical heating and cooling via fan coil units (convective) so are broadly similar											
Impacts on the wider environment (e.g. cold pluming, urban heat island)	Noise and visual mitigation required for rooftop heat pumps. Heat pumps can contribute to cold pluming and urban heat island effects due to heat acquisition and rejection. DHN would have a similar effect as it is largely heat pump lead and therefore would displace the impacts to another location											
Extent to which systems are 'future climate ready'	System replacement required. Oversizing VRF systems adversely impacts performance						Future climate provisions can easily by making expansion provisions				System replacement required. Oversizing VRF systems adversely impacts performance	

*ratings are based on the percentage differences from the average for the current practice results (A). Therefore a negative (-) result represents an improvement in carbon/cost.

BURO HAPPOLD

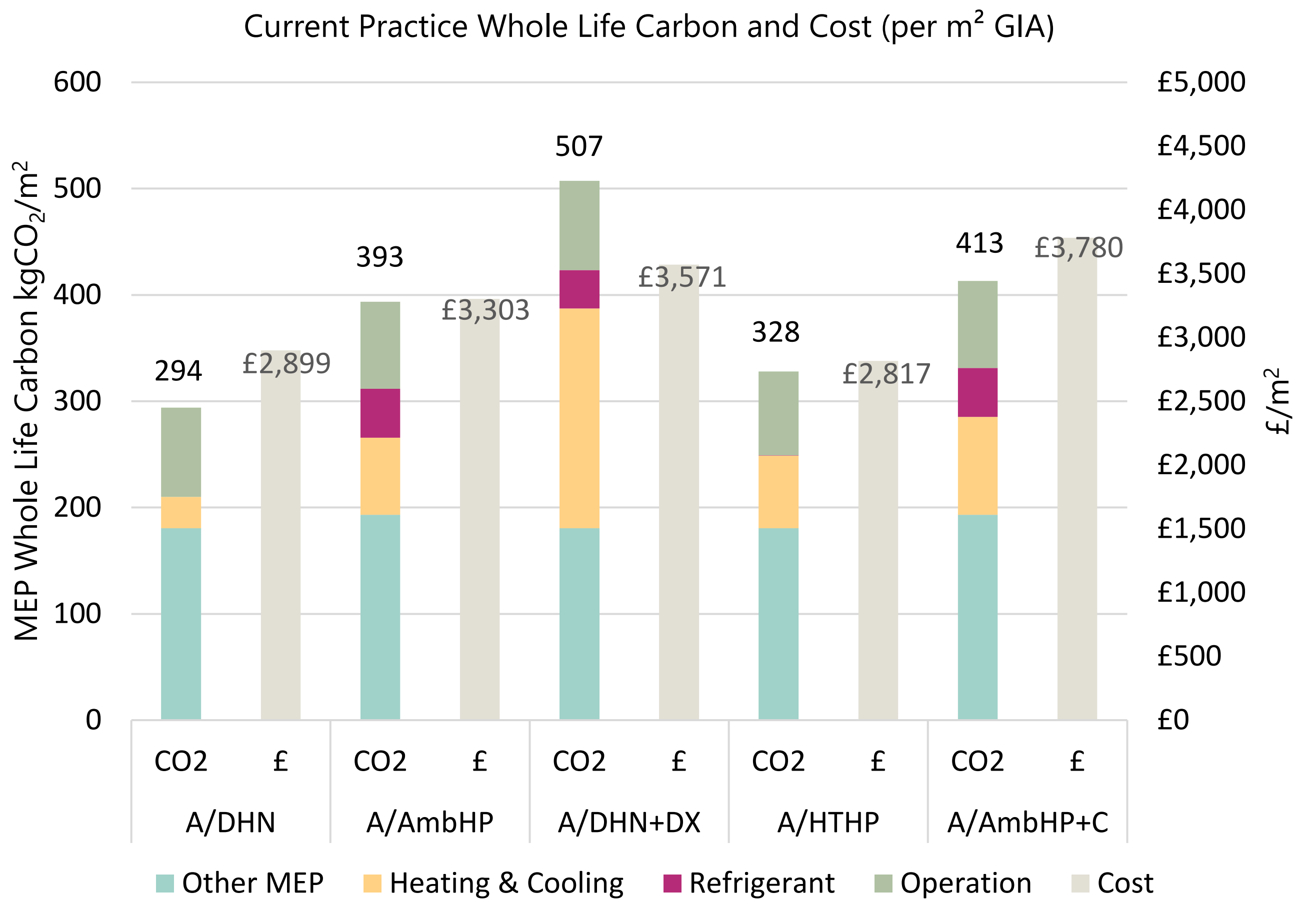
__A__ – Current practice, __B__ – Best practice, __VRF__ – VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

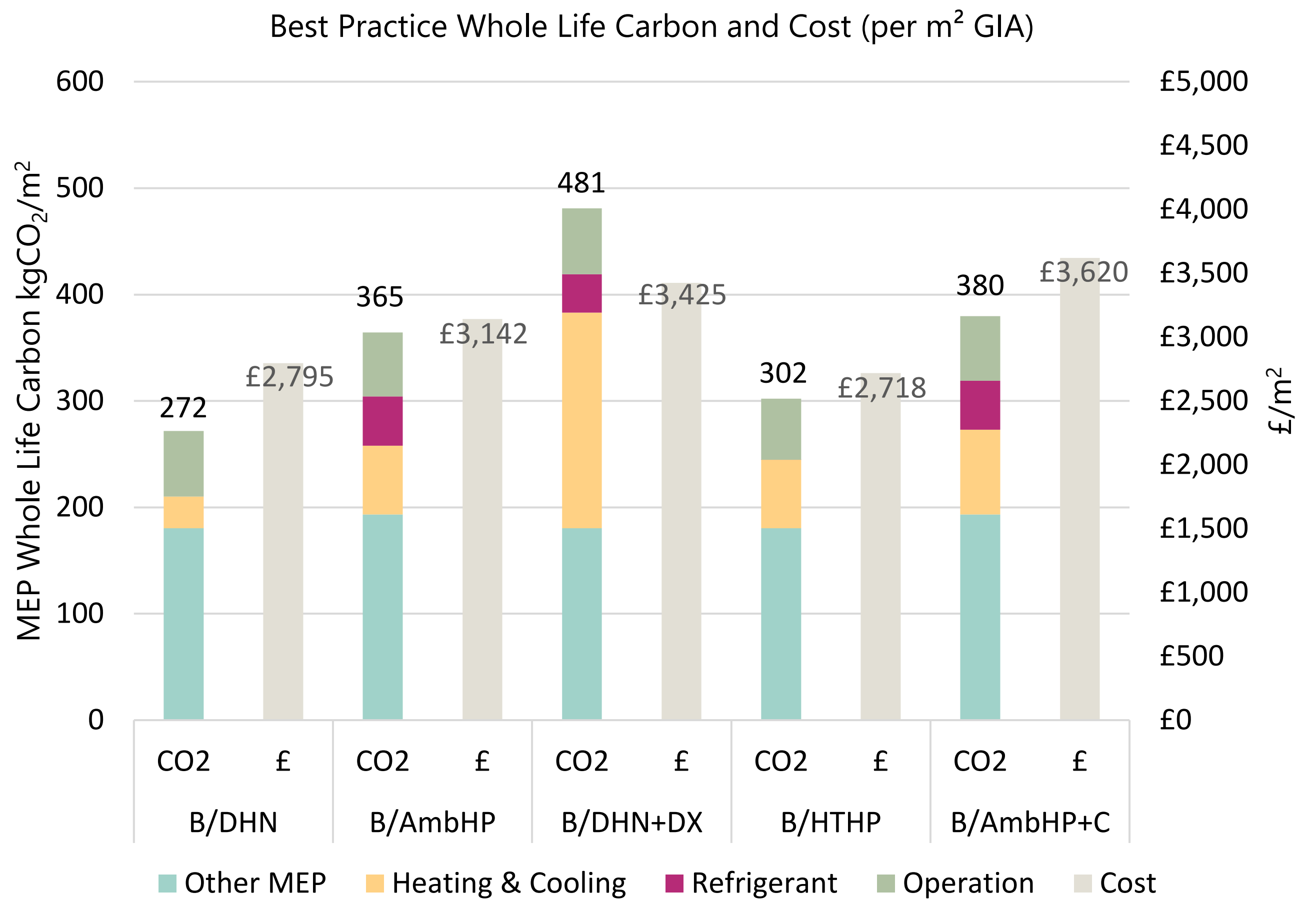
Executive Summary | Residential

The below charts summarise the MEP whole life carbon and costs of the residential options studied. The key findings as a result of this study have been summarised below.

Key findings

1. District heat networks are the lowest whole life carbon system option and also deliver close to the lowest whole life cost. It is noted that this is based on the building forming the boundary of the embodied carbon assessment.
2. High-temperature heat pumps with ultra-low GWP refrigerants are the lowest whole life cost option and also deliver close to the lowest whole life carbon.
3. Operational carbon for all systems types is comparable but embodied carbon has the largest impact on whole life carbon over a 60 year period.
4. Operational energy has a larger impact on whole life cost than carbon (due to grid decarbonisation) but replacement costs (REPEX) have the largest impact overall.
5. Options with decentralised heating and cooling generation equipment were found to have higher costs than systems with heat exchangers for each apartment and a centralised heat source. This is primarily due to higher capital costs for these systems, which then feeds through into higher replacement costs.
6. For heat pump systems the refrigerant type selected has a large impact on whole life carbon. F-Gas regulations will restrict the availability and use of high GWP refrigerants.
7. Best practice building and fabric design has a significant impact on operational carbon, providing a reduction of ~20% compared to current practice, compared to a ~5% variance between system types. However, the impact on whole life carbon is reduced. Regardless, the shift towards best practice design remains important for driving down peak loads and unlocking efficient systems operating at lower temperatures.
8. Systems with heating and/or cooling generation equipment for each dwelling tend to have higher embodied, and therefore whole life, carbon than fully centralised systems.
9. Addition of comfort cooling and separate systems for heating and cooling generally results in higher whole life carbon and cost so should be avoided. The majority of the impact is associated with the embodied carbon and CAPEX/REPEX of the additional equipment instead of operational energy consumption.
10. Management and monitoring of high-temperature heat network losses are important for achieving low EUI targets. Losses become a larger proportion of the annual heating load for best practice buildings with ultra-low heating demand and low return temperatures become increasingly hard to achieve.
11. Design and operation of network pumping equipment are particularly important for ambient loop systems where small ΔT drives high flow rates. Systems must cater for low-load scenarios using a jockey pump.


Current Practice Whole Life Carbon and Cost (per m² GIA)


Best Practice Whole Life Carbon and Cost (per m² GIA)

__A__ – Current practice, __B__ – Best practice, __DHN__ - District heating connection, no cooling, __AmbHP__ – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, __DHN + DX__ - District heating connection for heat, local split system cooling unit, __HTHP__ – High temperature central air source heat pump, no cooling, __AmbHP + C__ - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

Executive Summary | Residential

Policy recommendations

Reduction of operational carbon

Comparing results for the current and best practice buildings demonstrates that reduction in peak demand is a necessary precursor for reducing annual energy consumption and whole life carbon. Adoption of the proposed 15 or 20kWh/m^2 space heating demand target (on a block average basis, calculated using PHPP) is recommended.

It has been demonstrated that it is possible to meet the proposed EUI targets of 35 or 40 kWh/m^2/year (excluding renewable energy contribution) for all system types included in the study. Adoption of these targets (on a block average basis, calculated using PHPP) is recommended.

A methodology has been proposed to calculate a proxy coefficient of performance to apply to DHN thermal energy consumption to allow for direct comparison of EUI with other options and proposed targets. The DHN 'efficiency' factor should be calculated alongside the network carbon and primary energy factors, using the same information and updated at the same frequency.

Accurate performance data for equipment is essential for operational energy modelling but also challenging to obtain. Similarly, the way in which people use energy in their homes is highly variable. This means accurate prediction of operational energy is difficult whereas metered data provides insight into real world performance. A requirement to report anonymised in-use energy demands at a building scale is recommended.

Reduction of embodied carbon

New homes should be designed to be comfortable in future climate scenarios or futureproofed for adaptation to minimise the risk of high carbon and high cost systems needing to be installed from the outset or retrofitted in the future. Where comfort cooling is proven to be necessary, the system selected should be able to provide both heating and cooling to minimise quantities of equipment.

Use of high GWP refrigerants or multiple refrigerant-based systems results in a large increase in embodied carbon for heating and cooling systems. Adoption of the following refrigerant hierarchy is recommended:

- Design for no refrigerant (DHN connection, no cooling)
- Minimise quantity of refrigerant (using water as a distribution medium)
- Select low impact refrigerants prioritising ultra-low <50 GWP where possible and no greater than 750 GWP
  - Consider tying policy to requirements of BREEAM Pol 01 one credit threshold of ≤ 1000 kgCO2e/kW cooling capacity, with a further update to the two credit target of ≤ 100 kgCO2e/kW.
- Restrict refrigerant leakage (implement detection, monitoring and maintenance regimes)

Decentralised (individual dwelling) heating and cooling generation equipment tends to result in higher embodied carbon than centralised (communal / district) systems. Giving priority to district or communal heating networks through adoption of the energy hierarchy is recommended.

Condition-based energy hierarchy

To guide developments to adopt cost effective, low whole life carbon systems, the following energy hierarchy is recommended.

- If a district heat network connection is available then:
  - ➢ DHN connection is prioritised
- If no district heat network connection is available but there is potential for future connection then:
  - ➢ Centralised, high-temperature heat pump systems with ultra low GWP refrigerant is prioritised
- If cooling is required (for areas or occupants at risk of high heat stress such as where natural ventilation is not possible) then:
  - ➢ Ambient loop with reversible heat pumps is prioritised

Policy will need to recognise potential hierarchy conflicts and provide advice on suitable alternatives, for example where DHN connection is available or planned but cooling is required.

Metrics, compliance and enforcement

Carrying out whole life carbon assessments early in the design process will provide a holistic view of carbon performance which can help applicants make informed decisions on their projects. Assessment of whole life carbon impacts at the planning stage, including MEP operational and embodied carbon, and refrigerant impacts is recommended.

Use of pre-commencement or pre-occupation conditions to require an update to any carbon assessments carried out at planning stage, where changes are explicitly highlighted would help to improve enforcement and are recommended. In addition, a percentage of applications should be audited by a qualified independent third party.

Considerations for other building typologies

Low density residential

District and communal heat networks tend to be less cost effective and more carbon intensive due to longer distribution lengths and higher losses for low density developments suggesting individual dwelling systems will be favoured. In this case, the results suggest that heat pump systems with low-GWP refrigerant should be prioritised over direct electric systems in order to minimise operational carbon and cost. The form and density of these types of dwellings tend to lend themselves well to natural ventilation strategies so the requirement for comfort cooling to address summer thermal comfort is reduced.

High density residential and towers

The results from this study suggest that more equipment in each home tends to result in higher whole life carbon and cost regardless of efficiency. It is expected that this rule will scale in proportion to the number of dwellings connected to the same system as the form and thermal demand profile of each dwelling is similar but there is increased diversity for the central plant or building connection. This means the issue of increased embodied carbon and cost will be exacerbated for large developments. Connection to high temperature district or communal heating networks, is therefore strongly favoured to avoid having heat pump equipment in each dwelling.

Co-located living

Systems tend to be centrally managed and controlled as the domain of each occupant is limited, and units frequently change hands. In this case, centralised systems are very well suited such as the central AHSP or DHN options analysed in this study.

Executive Summary | System Evaluation Summary for Residential

Category	Apartment Building Options									
	District heating connection, no cooling		Shared condenser loop system with central air source heating and local water-to-water heat pumps providing heating, no cooling		District heating connection for heat, local split system cooling unit		Hydronic communal heating system from central air source heat pump, no cooling		Shared condenser loop system with central air source heating and cooling and local water-to-water heat pumps providing heating and cooling	
	DHN		**AmbHP**		**DHN + DX**		**HTHP**		**AmbHP+C**	
	Rating	Comments	Rating	Comments	Rating	Comments	Rating	Comments	Rating	Comments
Whole life carbon (MEP)	-19%	Lowest carbon - least equipment and refrigerant	-4%	Individual dwelling systems increase refrigerant and equipment	+30%	Highest carbon - Duplication of heating and cooling systems	-9%	Low carbon - Minimal equipment and low impact refrigerants	+2%	Individual dwelling systems increase refrigerant and equipment
Whole life cost (MEP)	-11%	Low cost - good operational performance and minimal equipment	+1%	Good operational performance but expensive equipment replacement	+9%	High cost - additional cooling system	-14%	Lowest cost - good operational performance and minimal equipment	+15%	Highest cost - expensive equipment replacement and cooling emitters
Compliance model results	-42%	BCS14 compliant. SAP 2012 carbon factors favour CHP	+1%	BCS14 compliant. SAP 2012 carbon factors penalise electric-based systems	-36%	BCS14 compliant. SAP 2012 carbon factors favour CHP	+71%	SAP 2012 carbon factors penalise electric-based systems	+7%	BCS14 compliant. SAP 2012 carbon factors penalise electric-based systems
Ability to meet potential future standards	All system options are compatible with future standards. Best practice building fabric design may be required									
Useability, operation and maintenance	Minimal in-dwelling and on-site plant with DHN connection		Individual in-dwelling and central on-site heat pumps increase maintenance requirement		Reduced heating plant in-dwelling and on-site with DHN connection, but cooling system adds complexity.		Minimal in-dwelling plant but on-site heat pump will require maintenance		Individual in-dwelling and central on-site heat pumps increase maintenance requirement, fan coil units add further complexity	
Potential constraints or impacts the selection of the option may have on the wider building design	Heat network connection from underground requires coordination with and disruption of surrounding area. Corridor purge ventilation required to remove heat gains from pipework		Central heat pump plant space will be required on the roof		Heat network connection impacts as per DHN option. Balcony or wall space required for outdoor unit of split system		Central heat pump plant space will be required on the roof. Corridor purge ventilation required to remove heat gains from pipework		Central heat pump plant space will be required on the roof. Deeper ceiling void required for fan coil units	
Comfort for occupants	Natural ventilation strategy must be futureproofed for future climate		Natural ventilation strategy must be futureproofed for future climate		Comfort cooling ensures summer thermal comfort if natural ventilation is limited		Natural ventilation strategy must be futureproofed for future climate		Comfort cooling ensures summer thermal comfort if natural ventilation is limited	
Impacts on the wider environment (e.g. cold pluming, urban heat island)	Minimal impact as no on-site generation plant		Mitigation required for acoustic and visual impact of rooftop heat pumps		Mitigation required for acoustic and visual impact of balcony- or wall-mounted outdoor split units. Heat rejection contributes to UHI		Mitigation required for acoustic and visual impact of rooftop heat pumps		Mitigation required for acoustic and visual impacts of rooftop heat pumps and risk of cold pluming from heat rejection impact. Heat rejection contributes to UHI	
Extent to which systems are 'future climate ready'	No changes or adaptation anticipated for operation in future climate conditions		No changes or adaptation anticipated for operation in future climate conditions		Cooling system capacity may need to be increased for more extreme hot summer weather events		No changes or adaptation anticipated for operation in future climate conditions		Cooling system capacity may need to be increased for more extreme hot summer weather events	

*ratings are based on the percentage differences from the average for the current practice results (A). Therefore a negative (-) result represents an improvement in carbon/cost.

__A__ – Current practice, __B__ – Best practice, __DHN__ - District heating connection, no cooling, __AmbHP__ – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, __DHN + DX__ - District heating connection for heat, local split system cooling unit, __HTHP__ – High temperature central air source heat pump, no cooling, __AmbHP + C__ - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

Executive Summary | Refrigerants

As the UK heavily invests in heat pumps to move away from its dependency from gas with a net zero 2050 outlook, there will be an inherent increase in the use of refrigerants for heating our buildings. The potential impact that this could have on the atmosphere in respect of refrigerant emissions, and ways to mitigate this, are explored in this report.

The GWP value is used to provide a global warming potential comparison to CO_2. If CO_2 has a global warming potential of 1, and a common HFC, such as R410a has a GWP of 2088, this means R410a is >2,000 times more potent/harmful than CO_2.

In the EU and the UK, the Fluorinated Gas (F-Gas) regulation controls the installation, servicing, sale, and decommissioning of fluorinated gases. After the UK's exit from the EU regulatory framework, the UK Government has reaffirmed its commitment to implementing F-gas phase down targets, closely aligned to the EU. This is considered to be the most influential piece of legislation driving the switch to lower GWP refrigerants.

The phase down of HFCs is designed to steadily reduce the global warming potential of all gases placed on the market in refrigeration, heat pumps and air conditioning equipment in the UK is phasing down HFCs by 79% by 2030 from the average use between 2009 to 2012.

A study has been carried out to compare the relative impact on whole life carbon of the refrigerant for each of the heat pump systems included in this report.

Key findings

1. Exploring the impact of utilising R410A instead of R32 resulted in a ~30% increase in MEP embodied carbon for the commercial building and a 36% increase for the apartment building.
2. Systems that have a high charge, potential leakage, and use refrigerant for their distribution (such as VRF) are likely to have the higher refrigerant emissions. Mitigating measures are limited due to lack of availability of ultra-low GWP refrigerant technology alternatives, inherently higher quantities of refrigerant and increased handling of refrigerant elements during site work.
3. Centralised systems have the greatest opportunity for using low GWP refrigerants. If a centralised system is not feasible and discrete/zonal systems are used, close attention should be paid to the refrigerant types available.
4. Refrigerant leakage rates are frequently underestimated or understated in comparison to values indicated in studies by DECC, CIBSE and USA EPA.

The graph to the right demonstrates the range of refrigerant leakage impacts per system type (identified by other studies and summarised in TM65).

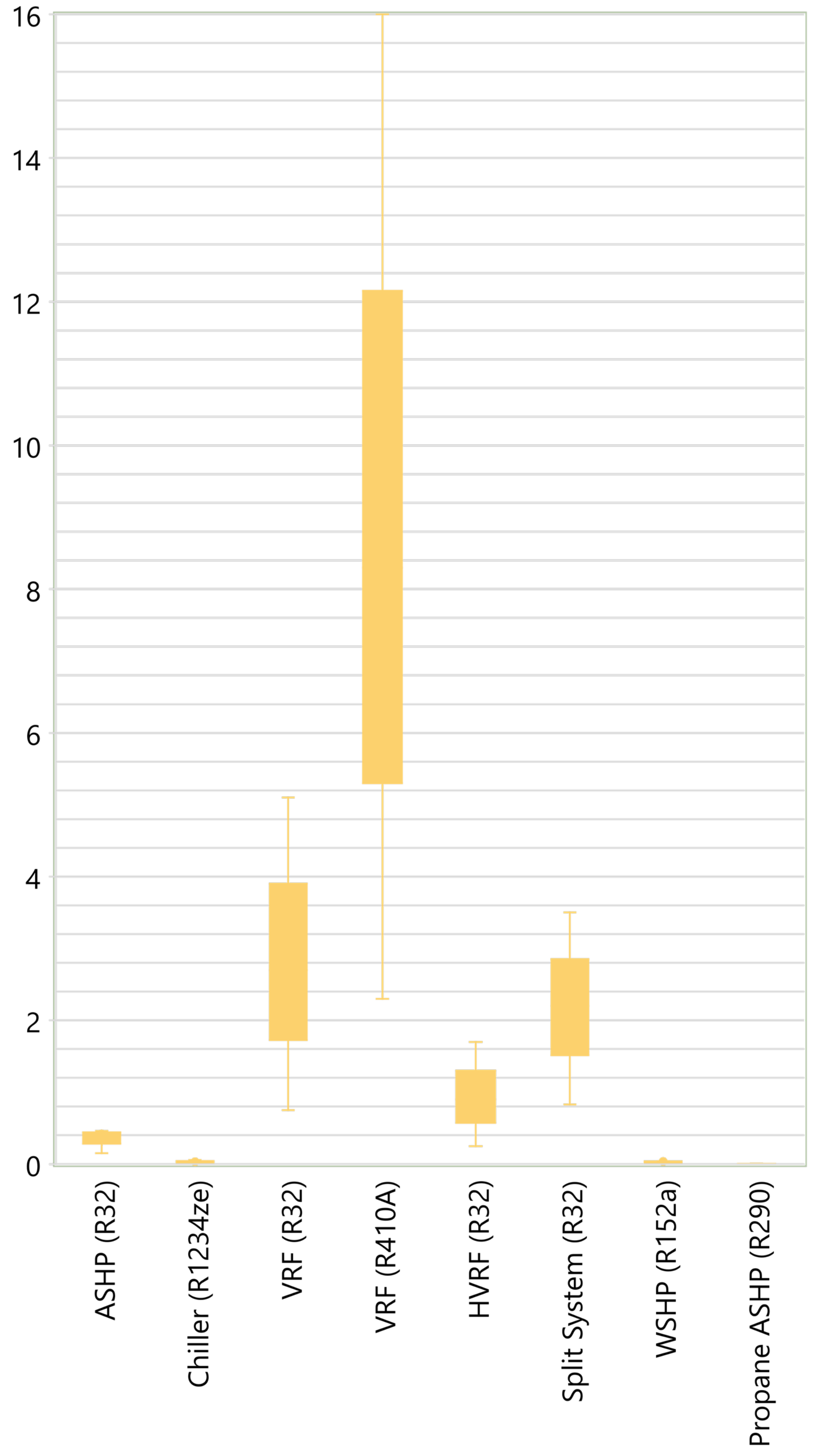
Policy recommendations

Use of high GWP refrigerants or multiple refrigerant-based systems results in a large increase in embodied carbon for heating and cooling systems. Adoption of the following refrigerant hierarchy is recommended:

- Design for no refrigerant (DHN connection, no cooling)
- Minimise quantity of refrigerant (using water as a distribution medium)
- Select low impact refrigerants prioritising ultra-low <50 GWP where possible and no greater than 750 GWP
    - Consider tying policy to requirements of BREEAM Pol 01 one credit threshold of ≤ 1000 kgCO2e/kW cooling capacity, with a further update to the two credit target of ≤ 100 kgCO2e/kW. Tying to BREEAM will ensure policy alignment with guidance.
- Restrict refrigerant leakage (implement detection, monitoring and maintenance regimes)

Proper installation, maintenance, and decommissioning should be carried out as mitigating leakage is what ultimately determines the impact the system refrigerant will have on the atmosphere. Key leakage mitigation measures have been provided in this report and should also be adopted as policy requirements. These include: ensuring that installers/contractors follow manufacturer guidance and procedures, monitoring systems, and recovering 100% of refrigerants (or as close to this as possible).

It is recommended that the average leakage rates shown for specific system types as identified in leakage studies by DECC, CIBSE and USA EPA in Appendix K, be used when assessing the potential impact of a system being designed. Lower leakage rates should be used only if strict leakage mitigation measures such as leak detection (can be demonstrated by targeting relevant Pol 01 BREEAM credits) are adopted.



Leakage Range Emissions (tonnesCO_2/kW) Systems Comparison

1.0

INTRODUCTION

☐ INTRODUCTION
☐ CONTEXT
☐ METHODOLOGY

Introduction

The purpose of this study is to support the implementation of current Bristol City Council Local Plan policy and provide part of the evidence base for the new Local Plan in relation to heating and cooling system hierarchies. The work considered whole life analysis of various heating and cooling system options based on residential and commercial office developments that are typical of those found in central Bristol, shifting the narrative away from a purely Building Regulations compliance based approach.

Scope

Specifically, this study examines the implications of buildings adopting different heating and cooling systems in terms of whole life carbon, whole life cost, impact on the wider environment, and operation and maintenance. There is currently little information on the whole life impacts of different heating and cooling systems that takes account of projected grid decarbonisation. Fossil fuel based systems are excluded from the study as the upcoming revisions to the Bristol Local Plan will not allow them and Government policy means new homes cannot use them from 2025.

The quantitative aspects of the study are focused on offices and apartment buildings, which are the two main typologies of development submitted for planning within the district heating priority area. Based on information provided by Bristol City Council, office developments in central Bristol are commonly in the region of 10,000m^2, and apartment buildings tend to be mid-rise and comprised of around 40 units. The study considers buildings constructed to current performance standards as well as emerging net zero standards. While the study is focused on these two building typologies, the applicability of the findings to other typologies is also considered qualitatively.

The study considered ‘current practice’ office and apartment building designs that would be compliant with the current Bristol planning policy in terms of energy and renewables contribution (BCS14, BCS15), and those that align with emerging ‘best practice’ standards such as the UKGBC and LETI and proposed energy standards for the revised 2024 Local Plan. These are referred to as Scenario A and B respectively (next page). Impacts of future weather data are also tested.

It is not the intent of the study to assess different energy efficiency measures outside of the heat and cooling generation, delivery, and distribution systems. The scope boundary for the embodied carbon assessment of the various system options is drawn around the building itself and as such upstream embodied carbon of the district heat network is not assessed. Embodied carbon impacts on the building structure and envelope of the different variants modelled are not quantified.

District heat network (DHN) embodied carbon boundary

The embodied carbon associated with the DHN has not been included in the study for the following reasons:

- The boundary of embodied carbon assessments for buildings suggests this would not be included in planning applications
- The DHN is a key part of Bristol’s strategy to decarbonise heat for existing buildings and consequently the infrastructure would be in place irrespective of an individual new development.
- Increased number of connections could increase the diversity of loads on the DHN. Therefore, the uplift in the energy centre plant capacity would be significantly lower than the given building load (CIBSE CP1 estimates a 30% reduction).

Archetype buildings

The study was based on a commercial office and apartment building archetypes selected from Buro Happold’s UK project portfolio that were similar to the architecture expected in central Bristol. The archetypes selected are real projects that are in the latter stages of design, and as such the plant space, distribution and architectural designs are realistic and fully developed.

System Options

Heating and cooling system options

In order for this study to remain relevant in time for the expected date of the updated Local Plan policy in 2024, all electric systems have been selected along with low GWP refrigerant based derivatives of existing technologies. All electric systems can reduce whole life operational carbon compared to fossil fuel alternatives due to the rapid decarbonisation of the grid. In addition to this, F-Gas regulations are expected to phase out high GWP refrigerants. Comfort cooling may be more common in future buildings due to climate change. This study does not assess the merits of naturally ventilated buildings against those with comfort cooling and is focused on situations where cooling is present. The energy and cooling hierarchies in the revised Local Plan will place natural ventilation before cooling in the hierarchy. Furthermore, the impact of connecting to the district heat network (DHN) is also explored. The options considered are summarised in the table to the right, along with the notations that will be used throughout the report.

Commercial office

The all-electric options for commercial offices can be categorised into two main options: variable refrigerant flow (including HVRF) or hydronic based technologies. However, ultimately these two technologies are essentially heat pump derivates where they both fundamentally take advantage of the refrigeration cycle. The main difference is the volume of refrigerant in the system due to refrigerant being the distribution medium instead of water, the design implications of each, and their corresponding seasonal efficiencies.

Apartment building

The apartment building study is principally based on variations of centralised hydronic heating systems. In cognisance of future climate projections, cooling is considered for two of the options studied.

	Description	Notation
Building Performance	Base building *Local planning criteria BCS14 and BCS15, and BCO compliant*	A
	Best practice building *UKGBC and LETI guidance, and BCO compliant*	B
Commercial Office Options	VRF heating and cooling, DHW from ASHP and local direct electric POU	VRF
	Hybrid VRF heating and cooling (i.e. hydronic system in occupied spaces then refrigerant system to outdoor units)	HVRF
	Hydronic heating with district heating connection, VRF cooling	VRF C + DHN
	Hydronic heating with district heating connection, hydronic cooling with central chiller	CHL + DHN
	Hydronic heating and cooling with central heat recovery heat pump/chiller and top-up air source heat pumps and chillers	HP
	VRF heating and cooling, district heating connection for DHW	VRF + DHN
Apartment Building Options	District heating connection, no cooling	DHN
	Shared condenser loop system with central air source heating and local water-to-water heat pumps providing heating, no cooling	AmbHP
	District heating connection for heat, local split system cooling unit	DHN + DX
	Hydronic communal heating system from central air source heat pump, no cooling	HTHP
	Shared condenser loop system with central air source heating and cooling and local water-to-water heat pumps providing heating and cooling	AmbHP + C

Context

Bristol is targeting city wide net zero emissions by 2030 and a key part of the city-wide strategy involves the decarbonisation of heat. The heat supply decarbonisation approach essentially involves prioritising district heating in denser areas of the city and the use of building level heat pumps where district heating is not feasible. This strategy is based around the need for a decarbonised heat supply for both new and existing buildings.

Current Local Plan policy BCS14 Sustainable Energy includes a heat hierarchy that developers are expected to use for the selection of heating and cooling generation systems. The 2019 consultation Local Plan review policy CCS2 also includes proposed heating and cooling hierarchies. There is a need to review and potentially update these to reflect Bristol City Council's strategic decarbonisation proposals, the projected decarbonisation of the electricity grid, emerging regulation, voluntary net zero standards such as RIBA, UKGBC and LETI, and whole life carbon considerations. Note that for strategic decarbonisation reasons, BCC's policy is that connection to district heating will remain at the top of the hierarchy; this study will inform the case-by-case application of applying the strategic requirement.

UK Climate Change Policy commitments

In 2019 the UK became the first major economy in the world to pass laws to end its contribution to global warming by 2050. The target will require the UK to bring all greenhouse gas emissions to net zero by 2050, compared with the previous target of at least 80% reduction from 1990 levels. The interim targets are now at least a 57% reduction by 2030 and 78% reduction by 2035.

The UK Green Building Council (UKGBC) highlight, that to meet the UK's net zero emissions target, all sectors of the economy must rapidly decarbonise by 2050. Steep cuts in energy demand are required as soon as possible in order to achieve a net zero economy by 2050 and sectors cannot simply rely on decarbonisation of the grid as a viable solution. To transition towards net zero, UKGBC have included interim energy use intensity (EUI) targets for buildings [in kWh/m²(GIA)/yr.] of: 130 from 2020, 90 from 2025, 70 from 2030 and 55 from 2035.

Electricity grid decarbonisation

In the run up to COP26, the UK has announced an advanced timeline for decarbonisation of the grid, bringing it forward from 2050 to 2035. The transition away from gas fired heating to heat pump based solutions is the route map to net zero being followed for many buildings. However, projections indicate that a demand reduction on the grid of 60% will be required to support grid decarbonisation, and therefore a strong focus on energy efficiency remains critical to delivering the UK's net zero ambition. This is because the national energy demand needs to match the limited national renewables capacity to achieve net zero carbon.

Bristol City Council Net Zero commitment

In July 2019, Bristol made a commitment to become a carbon neutral city by 2030. This bold and ambitious target is for greenhouse emissions from both direct use of fossil fuels and electricity in the city (Scopes 1 and 2) and from the emissions caused by the production of goods and services which are consumed by the city's residents and businesses (Scope 3). The proposed roadmap to net zero is set out in the 'Bristol One City Climate Strategy'. A fundamental part of the strategy is the decarbonisation of heat and the complete phase out of gas fired plants. Delivering a near-zero carbon district heat network across central Bristol and widespread adoption of heat pump technology is at the core of delivering on this aspect of the strategy. It follows that this study is focused on the assessment of these technologies.

F-gas regulations

F-gas regulation includes a method of forcing end users to move away from using high global warming potential (GWP) gases closer to ultra low GWP gases (<50) in stationary refrigeration, air conditioning and heat pump equipment by rapidly limiting how much gas can be placed on the market each year as part of a continually reducing quota system. After the UK's exit from the EU regulatory framework, the UK Government has reaffirmed its commitment to implementing F-gas phase down targets, closely aligned to the EU.

The phase down of HFCs is designed to steadily reduce the global warming potential of all gases placed on the market in refrigeration, heat pumps and air conditioning equipment in the UK is phasing down HFCs by 79% by 2030 from the average use between 2009 to 2012.

The GWP is used to provide a global warming potential comparison to CO_2; CO_2 has a global warming potential of 1, where a common HFC, such as R410a with a GWP of 2008 is >2,000 times more potent/harmful than CO_2.

Refrigerants can form a significant component of a building's whole life carbon.

Building Regulations Part L - 2022 update

On 15 December 2021, the government announced changes to the building regulations to help the UK deliver net zero. This includes a requirement for new homes to produce around 30% less CO_2 than current standards, and a 27% reduction in emissions from other new buildings. At the time of preparing this study, updated Part L compliance software reflecting the associated changes to the National Calculation Methodology (NCM) was not available. The comparisons made in this study are therefore based around the existing Part L 2013 compliance methodology. How future BCC planning policy will be shaped to accommodate the new Part L will need to be considered separately, should the intention be to incorporate any Part L related energy targets.

Building Regulations - Residential Overheating

Approved Document O was published on 15 December 2021 as part of the government's plans to deliver net zero. It covers overheating mitigation requirements for new residential buildings. It requires designers and developers to demonstrate to the building control body that all practicable passive means of limiting unwanted solar gains and removing excess heat have been used first before adopting mechanical cooling complying with future weather files (DSY1 2020 High 50th). It is possible that the introduction of formal overheating limits for all new residential buildings may see an increase in the use of cooling in dwellings going forward in the face of the changing climate, particularly in the southeast of the UK, and on sites where for instance external noise levels are an issue. Some common residential cooling systems are covered in this study.

Emerging voluntary net zero standards and guidance

There are a number of emerging voluntary net zero standards and guidance documents. The most widely referenced of these are by LETI, UKGBC and RIBA. These standards propose targets for both operational and embodied carbon.

The LETI Climate Emergency Design Guide and UKGBC Building the Case for Net Zero have been used to inform the configuration and performance of fabric and MEP systems for the best practice design cases presented in this study.

Methodology Overview

Heating and cooling systems design philosophy

In developing our assumptions, we have tried to adopt the mindset of a developer, i.e. finding the simplest and most economic ways of complying with each requirement.

Approach to other mechanical and electrical services

Building services design outside of heating and cooling generation and distribution is developed to be consistent between options for clear comparisons. These designs are based on projects from our portfolio along with the use of pro-rata allocations.

Design weather data

Weather file of Cardiff TRY 2020 High 50th percentile used for operational energy modelling. The same weather files were used for the base and best practice building cases.

Design conditions for system sizing were based on the ASHRAE 2017 Bristol Weather Centre datasheet.

Current and future weather standards

As part of a sensitivity analysis, future weather files were also used to assess the impact of future climates. The weather files used were Cardiff 2050 Medium 50th percentile and 2080 Low 50th percentile.

Conceptual system design

A loads model was generated in IES VE Apache to determine heating and cooling loads based on the building envelope, use, and external ambient conditions (ASHRAE). This was repeated for both the base and best practice buildings. These loads were then used to size the heating and cooling systems along with BCO guidance and CIBSE Code of Practice for District Heating.

Part L compliance modelling

Part L compliance modelling was undertaken on the office and apartment buildings to demonstrate compliance with current Bristol planning policy in respect of energy (BCS14, BCS15). This also gives the opportunity to compare the Energy Use Intensity (EUI) figures predicted by the operational energy modelling with the Part L compliance modelling predictions, which may assist Bristol City Council with policy definitions around EUI.

Operational energy modelling

Operational energy modelling was undertaken on the archetypes to determine a 'realistic' estimate of performance and in-use energy consumption for each system option. This included consideration of plant performance at part-load and different external ambient conditions based on the instantaneous hourly demands predicted by the energy model. This differs from a Part L compliance based approach which generally considers static SCOP and ESEER values derived under standard test conditions to represent plant performance.

While every effort has been made to make the operational energy modelling emulate real world performance, it is acknowledged that it is unlikely to represent all of the intricacies of performance once built. It is hoped that the shift to a Design for Performance based culture will provide greater availability of actual measured system performance data that can be fed into future policy updates.

Embodied carbon modelling

Embodied carbon modelling has been undertaken in OneClick using the available EPD libraries[1] and manufacturer's TM65 forms[2]. The boundary of embodied carbon assessment is in the MEP systems within the building itself. Upstream embodied carbon associated with the district heat network is not considered. Embodied carbon of the non-MEP elements have not been calculated, although appropriate benchmark values are used to contextualise the contribution of the MEP systems. Changes to embodied carbon from upgrading the building envelope performance arising from following best practice design standards are not included in the scope of this study.

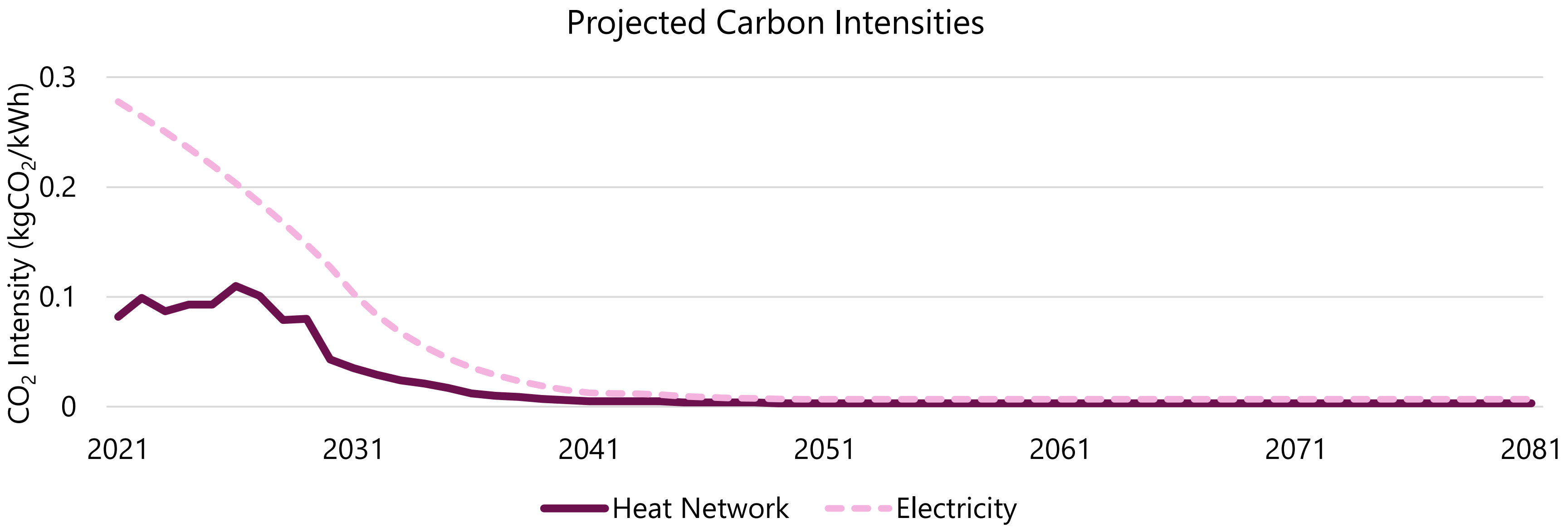
Cost modelling

Life Cycle Costs have been prepared in line with PD 15686:2008 considering the following costs related to the MEP systems only: Construction costs, maintenance costs, utility costs. Lifecycle intervals were based on CIBSE Guide M 2020.

Grid and district heat decarbonisation model

The BEIS 2021 long run marginal projections for grid electricity carbon intensity have been used to calculate whole life operational carbon. Bristol City Council provided the projected carbon intensity for the district heat network. This is shown in the graph, alongside the grid decarbonisation projections. Going forward, the district heat network becomes increasingly dominated by heat pump based technology and therefore has a similar curve profile to the grid, albeit having a carbon intensity 2-3 times lower owing to the COP of the heat pumps.

	Design conditions (ASHRAE)	Operational energy conditions (TRY)
Summer condition (99.6%)	30.6 °C DB @18.9 °C MCWB	28.5 °C DB @21.6 °C MCWB
Winter condition (0.4%)	-1.9 °C DB (Jan)	-2.5 °C DB (Jan)
Annual mean	N/A	11.2 °C DB



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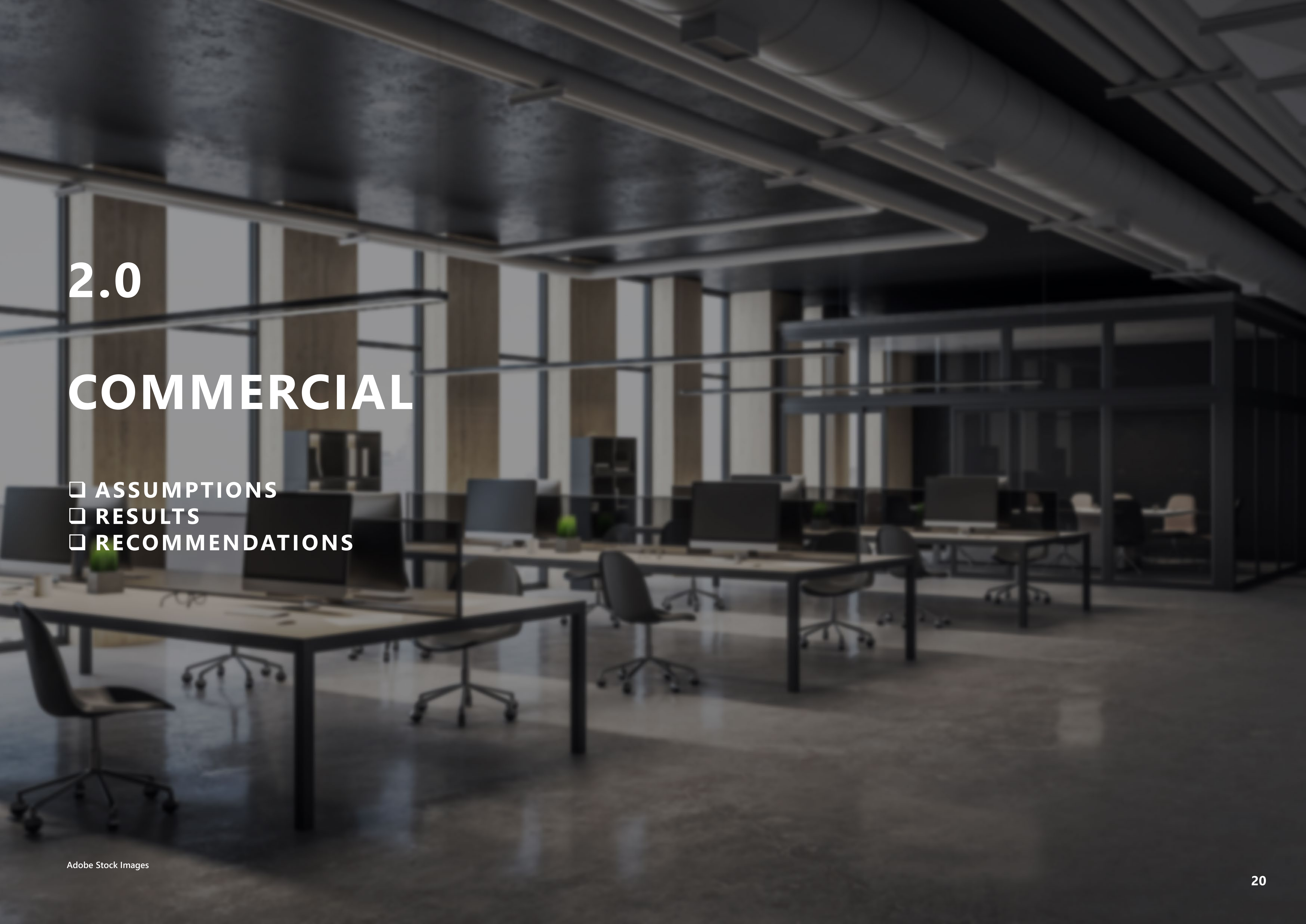
[1] OneClick EPD library: LCA Database of Building products

[2] TM65 Manufacturer Form: https://www.cibse.org/TM65/manufacturerform



2.0

COMMERCIAL

- ☐ ASSUMPTIONS
- ☐ RESULTS
- ☐ RECOMMENDATIONS

Adobe Stock Images

Assumptions | Archetype

Archetype

The study has been based on a real speculative office development that is in the later stages of design targeting, BREEAM Outstanding and NABERS UK rating of 5 stars.

The layout is a standard office arrangement - a central core surrounded by lettable space. The lower ground floor has showers, parking and utility spaces. The ground floor has a reception, some office area and retail units. The retail is separately serviced and not included in the analysis.

Base building (modified archetype)

Area

The archetype building was used as a basis to construct the base office building for this study. To represent a typical office in Bristol, the archetype building was modified resulting in an NIA of 8,925m^2 and a GIA of 12,475m^2, net to gross of 1.40. This includes the omission of the car park to improve the net to gross ratio and the adjustment of changing rooms, cycle and bin store areas, and lift quantities to a provision that is appropriate for the smaller building (reduced number of occupants).

Fabric

Part L compliance modelling was carried out on the base building to ensure that the envelope performance was sufficient to meet Bristol City Council planning energy policy (BCS14,15). For the 'best practice' variants these are modified in line with UKGBC/LETI recommendations.

Conceptual designs

Conceptual designs for each studied heating and cooling system option were developed for the base building and best practice building, along with schedules for equipment capacities/sizes and quantities for all systems including electrical and public health systems, which are available in appendix B. A 10% margin has been added to the calculated capacities in line with typical design practice.

Fixed parameters

Certain parameters have been fixed across all elements of the study:

- Building massing and layout (as described above)
- Occupancy density: *10m^2/person*
- Hours of operation: *based on NABERS UK profiles*[1]

Base building (modified archetype) built in IESVE

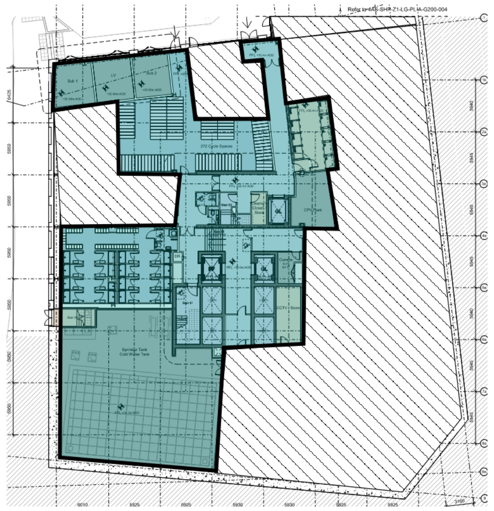
Area: 8,925m^2 (NIA) and 12,475m^2 (GIA), 1.40 net-to-gross

Envelope: Double glazed façade, glazing ratio 57%, 5 floors

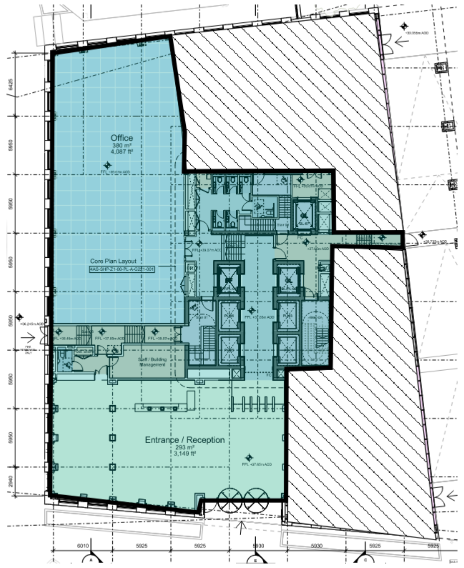
System: Simultaneous heating and cooling functionality, Central AHUs, Fan coil (and trench heaters where required) terminal units, Centralised DHW for showers and POU for wash-hand basins (all centralised with DHN options)

Design: CAT A (standard open plan office arrangement), BCO

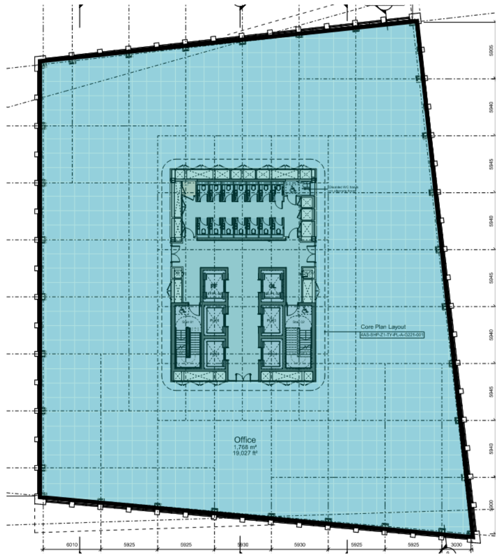
Density: 10m^2/person



Basement (without car park)



Ground floor (without retail)



Office floor (levels 1-5)

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[1] NABERS UK provides a reliable energy efficiency rating system for office buildings in the UK by measuring and reporting on in-use energy and includes a process of reviewed design for performance. NABERS UK Guide to Design for Performance.

Assumptions | Current and Best Practice Designs

This section outlines the differences between current and best practice building based on UKGBC/LETI. Further details can be found in the technical appendix.

Central plant

For the hydronic systems, the chilled water temperatures were elevated to 14F/18R (Flow and Return temperatures) in the best practice design from 10F/16R in the current practice scenario. The design loads and building fabric performance were sufficient to enable fan coil unit (FCU) selections to be based on these flow temperature regimes, although in situations where this is driving a significant increase in the number/size of terminal units, a chilled water temperature reset based on high external temperature/enthalpy should be considered to avoid averse embodied carbon impacts. A relaxation in internal design temperature in peak summer could also be considered.

The specific fan power (SFP) of the central AHUs was reduced from 1.4 W/(l/s) in the current practice design to 1.2 W/l/s in the best practice design. This typically requires velocities of 1.5m/s through the AHUs, maximum velocities of ~5m/s in the main risers, and ~4m/s for on floor distribution. An allowance for increased ductwork material and AHU size/weight were included in the embodied carbon assessment.

Fabric

Fabric improvements were drawn from UKGBC and LETI guidance. The glazing ratio was reduced from 57% in the current practice design to 40% in the best practice design. The U-value of the curtain wall was reduced from 1.4W/m²K to 1.2W/m²K.

Air permeability was improved from 3m^3/h.m^2@50Pa in the current practice design to 1.5m^3/h.m^2@50Pa in the best practice design in line with UKGBC guidance.

External motorised blinds were included in the best practice design to enable the use of low energy fan coils running on elevated chilled water temperatures, without increasing the size/quantity of terminal units. External motorised blinds are commonly found on commercial buildings across much of Europe.

Mixed mode ventilation was not introduced for the best practice design in this instance due to the added cost and complexity on top of the motorised external blinds that had been introduced, and the proposed measures were essentially sufficient to meet the best practice EUI target.

Servers

UKGBC guidance makes the case that cloud based solutions should be favoured over local servers. According to the guidance, cloud based operations are significantly more efficient with handling requests from an operational and embodied energy and carbon standpoint, based on a study by Berkeley Labs. The current practice design assumes landlord and tenant server equipment in line with standard provisions. For the best practice case, tenant servers have been omitted, but landlord servers have been maintained for the operation of the building.

Tenant equipment and lighting

For the best practice case, a reduction in background lux levels from 500lux to 300lux have been implemented, where activities requiring higher lux levels are supplemented with task lighting. It has been suggested that power over ethernet (PoE) has the opportunity to further reduce lighting power densities. Therefore a density of 4.5W/m^2 has been assumed in line with UKGBC, LETI, and GOV Net Zero Annex.

Design small power loads have been reduced from 20W/m^2 (BCO[1]) in the current practice case to 9W/m^2 in the best practice design as proposed in LETI guidance. This is a significant reduction but conceivable for an occupant density of 10m^2/person, assuming a reduction in printers, increased use of cloud computers, low energy laptops, and potentially reducing the number of monitors per person.

Set points

The only modification to set points has been a slight relaxation to the winter set point from 21°C to 20°C as per LETI and UKGBC guidance. The summer set point has not been relaxed, as the best practice design configuration could maintain normal operating temperatures, and a mixed mode system was not included (under future climate scenarios and/or in the southeast of the UK this may be more necessary). It is acknowledged that there may be some incompatibility with current thermal comfort standards referenced by rating schemes such as BREEAM with setpoint relaxation, which will hopefully be addressed in future versions.

Terminal units

Fan coil units (FCUs) have been utilised for both heating and cooling for each option, with the exception of the addition of unfanned trench heater units for the VRF cooling with hydronic (DHN) heating option studied. FCUs are a standard office cooling solution.

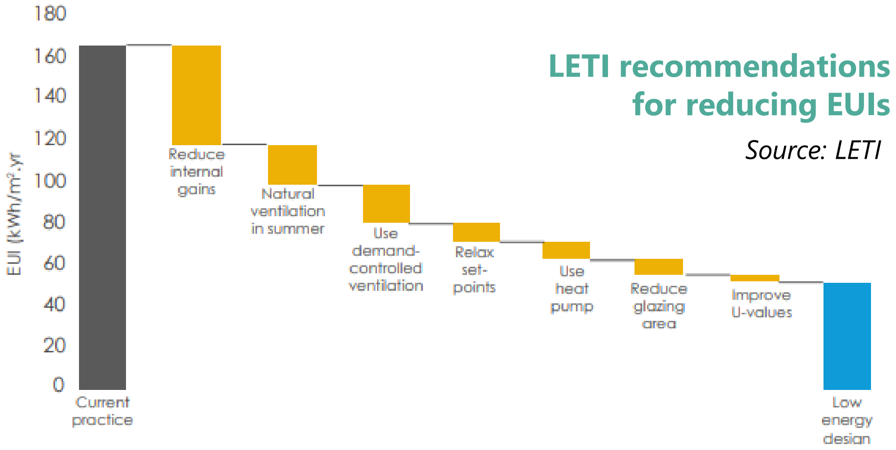
For the current practice design, the hydronic FCUs had an SFP of 0.19W/l/s. In the best practice case, a low energy FCU was used, which had an SFP of 0.1W/l/s. The VRF systems FCU SFPs were 0.25W/l/s for standard VRF and 0.42W/l/s for Hybrid VRF, based on data provided by the manufacturers. The SFP of the VRF terminal units was unchanged for the best practice case.

Domestic hot water

The base building already had high efficiency showerheads (~6l/min flow rates) and therefore there was limited opportunity to reduce domestic hot water loads resulting in ~5.5l/person/day in total. Wastewater heat recovery on the showers was not included but could potentially be considered. A reduction of distribution temperatures e.g. through the use of dosing systems was also not considered, as it adds a potential safety risk if not operated and maintained correctly. Distribution losses were set at 6W/m for the current practice design, which is typically achieved by following the British Standard for insulation. Losses were reduced to 5W/m for the best practice, assuming an enhanced insulation thickness.

Renewables

In line with UKGBC and LETI guidance, solar PV was maximised. The allowance of 400m^2 of PV roof area was increased to 800m^2. High efficiency panels (22.7%) were assumed; 400W per panel with a roof utilisation rate of 75%. Electrical losses were taken as 15%. This arrangement covered 40% of the roof area.



LETI recommendations for reducing EUIs

Source: LETI

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[1] *British Council for Offices (BCO) provides a range of best practice guides and research publications for the commercial property sector. BCO Guide to Specification*

BURO HAPPOLD

Overview of Options | VRF and HVRF

This section describes the **VRF** and **HVRF** system options.

VRF Heating and Cooling, DHW from ASHP and local POU

Hybrid VRF Heating and Cooling (i.e. hydronic system in occupied spaces then refrigerant system to outdoor units)

Systems

VRF (variable refrigerant flow): these systems use refrigerant as the heating and cooling medium.

HVRF (hybrid VRF): similar to VRF, where refrigerant is used as the heating and cooling medium, but after the branch controller to the indoor unit utilises water as the medium.

Space heating and cooling

Discrete systems have been designed where each system has the ability to supply simultaneous heating and cooling (also known as heat recovery VRF units). The building floorplates were split into quadrants for the VRF systems and halves for the HVRF systems. This was due to the maximum number of connectable indoor units per system.

Per system there is:

- an outdoor unit (OU) that is required to either acquire or reject heat
- a branch controller (BC) to provide local heat recovery to enable simultaneous heating and cooling
- an indoor unit (IU) to provide heating/cooling to the space

For the VRF systems using R32 refrigerant, the maximum number of indoor units connectable to an outdoor unit is 9. This is why each discrete VRF system serves one quadrant. On the other hand, 35 units can be connected to the HVRF system. However, due to limitations on capacity per outdoor unit, this is typically not achievable and therefore the HVRF OU serves 18 units in the current practice but is able to serve 35 units in the best practice case. It is understood that the number of units that can be connected to the standard VRF R32 unit will be increased in future product releases.

Domestic hot water (DHW)

A dedicated air source heat pump (ASHP) was introduced to provide hot water for showers. The remainder of the DHW is generated through the use of point of use (POU) electric heaters due to the low demand. VRF linked DHW water heaters do exist but are not often used.

Ventilation

As each system is discrete, air handling units (AHUs) with integrated refrigerant based heat pumps were selected. These essentially work the same as the VRF system but with the added benefit of recovering heat from the return air. These are available as packaged units and eliminate the need for additional heating and cooling plant.

A thermal wheel has been assumed for general ventilation AHUs for heat recovery and a plate heat exchanger assumed for the WC and changing room AHU.

Electric resistance frost coils have been selected to protect the AHU's internal components.

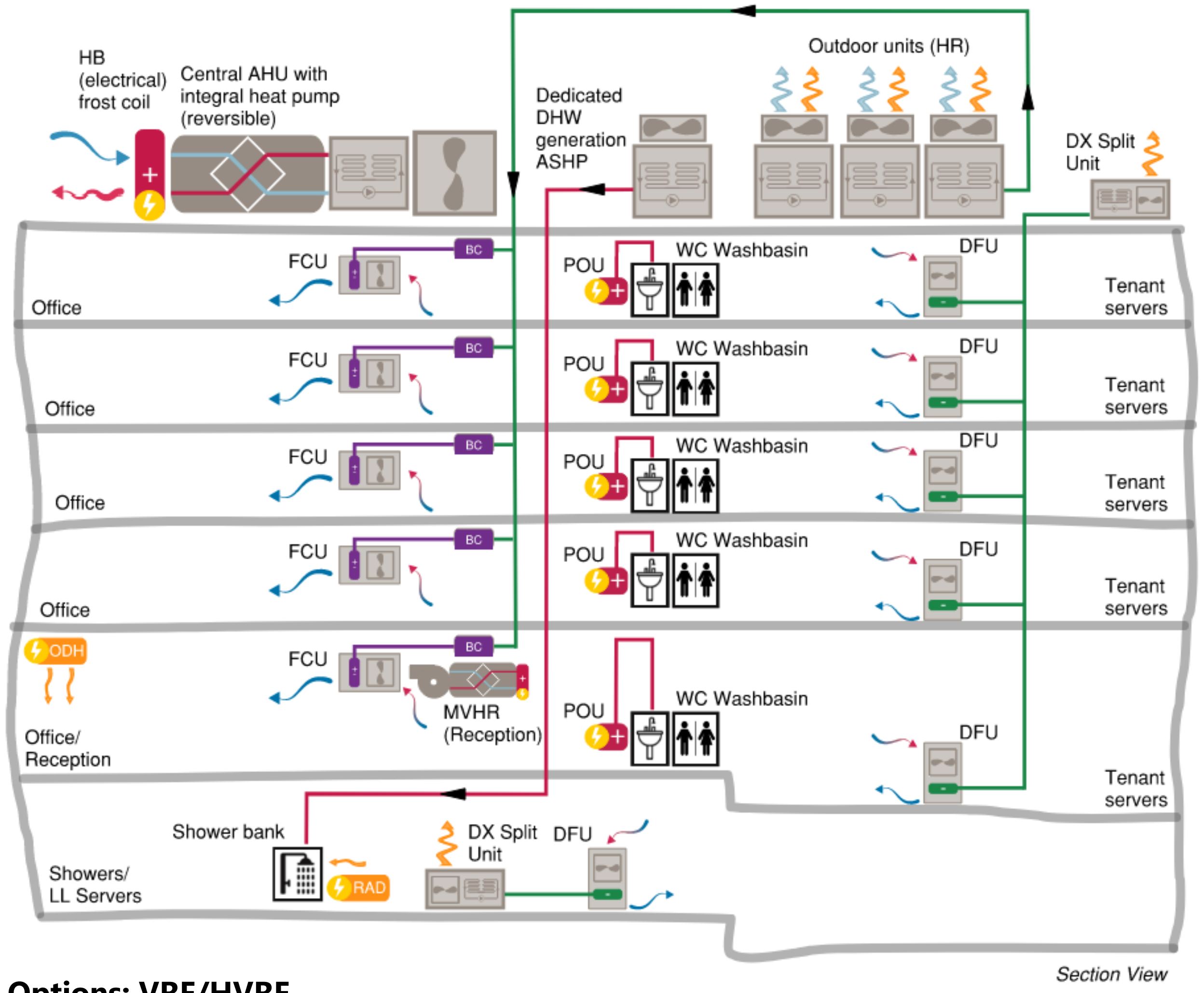
Other systems

Tenant and landlord server rooms are cooled by dedicated direct expansion (DX) split units. Refrigerant is used as the medium to transfer heat.

DX (direct expansion) split unit: A coil that rejects heat is located outside (on the roof or inside the car park) and a coil that sits on the other side of the compressor absorbs heat inside the building. Refrigerant is used as the medium to transfer heat.

An allocation of one DX unit per floor has been made to cover landlord and tenant areas.

Electrical resistance heaters are used for back of house heating and overdoor heaters (ODH).



Options: VRF/HVRF

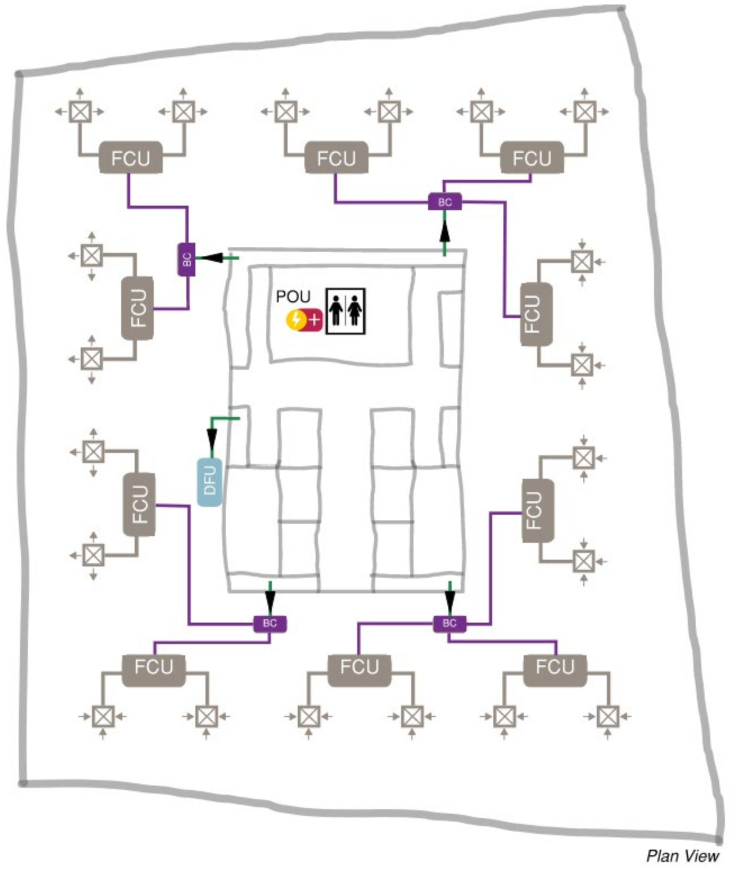
Key

🟩 Refrigerant

🟪 Refrigerant/water (Heating/cooling)

🟥 DHW

DHW: Domestic hot water
FCU: Fan coil unit
BC: Branch controller
POU: Point of use
DFU: Down flow unit
AHU: Air handling unit
HB: Heater battery
ASHP: Air source heat pump
DX: Direct expansion
LL: Landlord
ODH: Over door heater
RAD: Radiator



Overview of Options | Hydronic Heat Pumps

This section describes the **HP** system option.

Hydronic heating and cooling with central heat recovery heat pump/chiller and top-up air source heat pumps and chillers

Systems

This system utilises a number of different types of heat pumps (HP) to deliver hydronic heating and cooling.

ASHP (HR) (air source heat pump with heat recovery): these units provide simultaneous heating and cooling, heating only or cooling only. This unit was sized to cover the base heating load of the building as they operate most efficiently with a simultaneous load. Dedicated heating only or cooling only plant tends to be more efficient when there is no simultaneous load.

Air Cooled Chillers: These meet any additional cooling demand.

ASHPs (heating only): These meet any additional heating demand.

Centralised system

The above heat pumps work together to provide heating and cooling to the centralised hot and chilled water loops in the building. These loops are then distributed to all equipment that requires heat. Systems have been designed to operate with a flow and return temperature of 45/40 °C for hot water systems and 10/16 °C for chilled water. In the best practice building, the chilled water temperatures are elevated to 14/18 °C to maximise efficiency.

As the system is centralised, this provides the opportunity to recover heat across all systems, unlike the VRF which is limited to each discrete system.

Space heating and cooling

Space heating and cooling is provided by 4-pipe fan coil units (FCUs) served from the main hot and chilled water networks.

Domestic hot water (DHW)

As the hot water loop temperatures are too low for DHW generation (where at least 65 °C is required for a storage system), a WSHP is introduced to elevate the hot water flow and return temperatures to 65/60 °C.

WSHP (water source heat pump): Delivers 65 °C water using the 45 °C hot water circuit served by the central air source heat pump as the source. Often called a 2nd stage heat pump as the water is heated in two stages.

The 2nd stage heat pump feeds a calorifier which is used to generate DHW for the showers. The remainder of the DHW for sinks is generated by point of use (POU) electric heaters, as the low demand makes a central generation approach inefficient due to the pipework heat losses incurred.

Ventilation

The heating, cooling, and frost coils within the air handling units (AHUs) are connected to the central chilled and hot water loops.

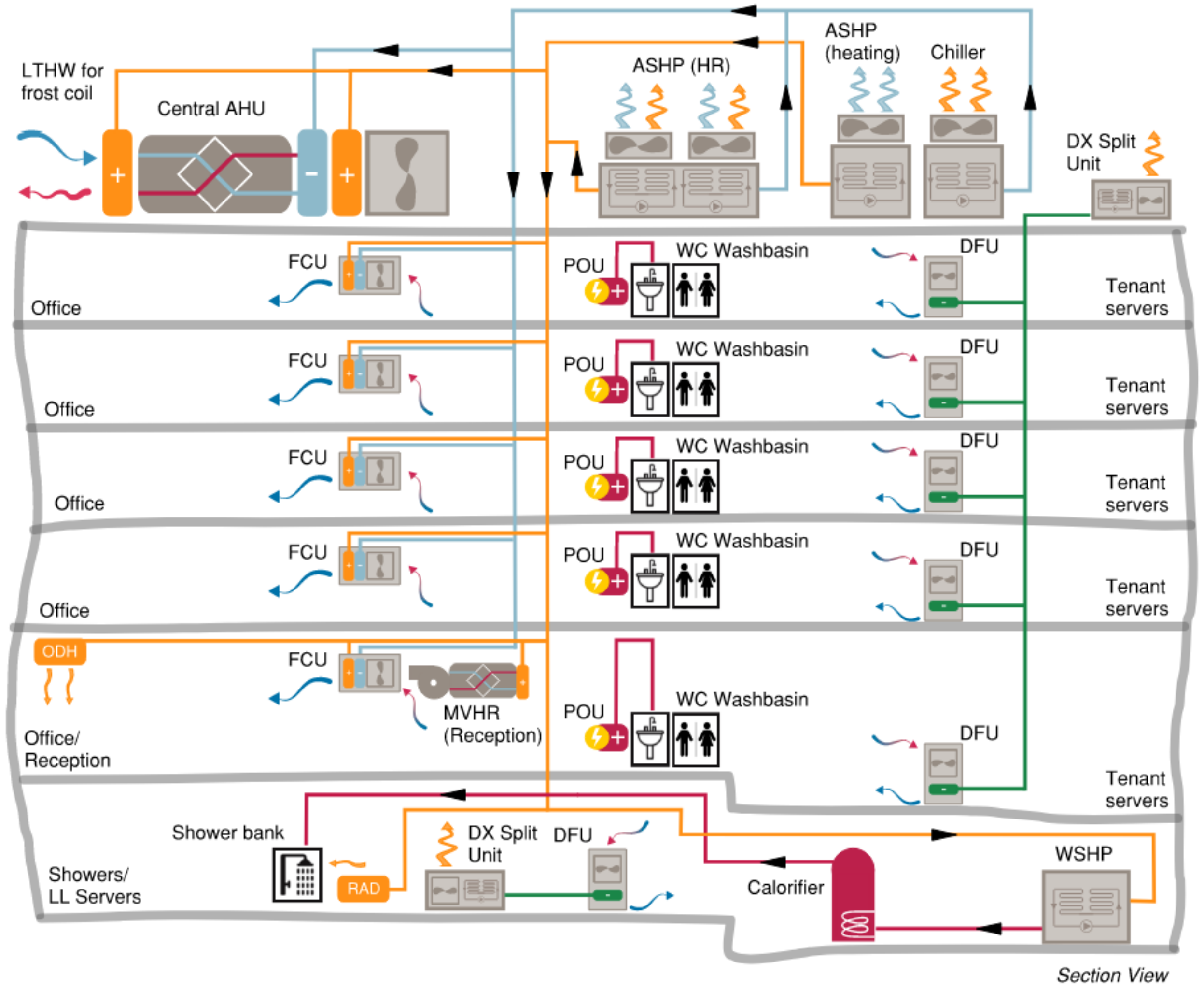
A thermal wheel has been assumed for general ventilation AHUs for heat recovery and a plate heat exchanger assumed for the WC and changing room AHU.

Other systems

Tenant and landlord server rooms are cooled by dedicated direct expansion (DX) split units. An allocation of one per floor has been made.

DX (direct expansion) split unit: A coil that rejects heat is located outside (on the roof or inside the car park) and a coil that sits on the other side of the compressor absorbs heat inside the building. Refrigerant is used as the medium to transfer heat.

Heating for overdoor heaters (ODH) and back of house radiators are provided by the centralised hot water loop.

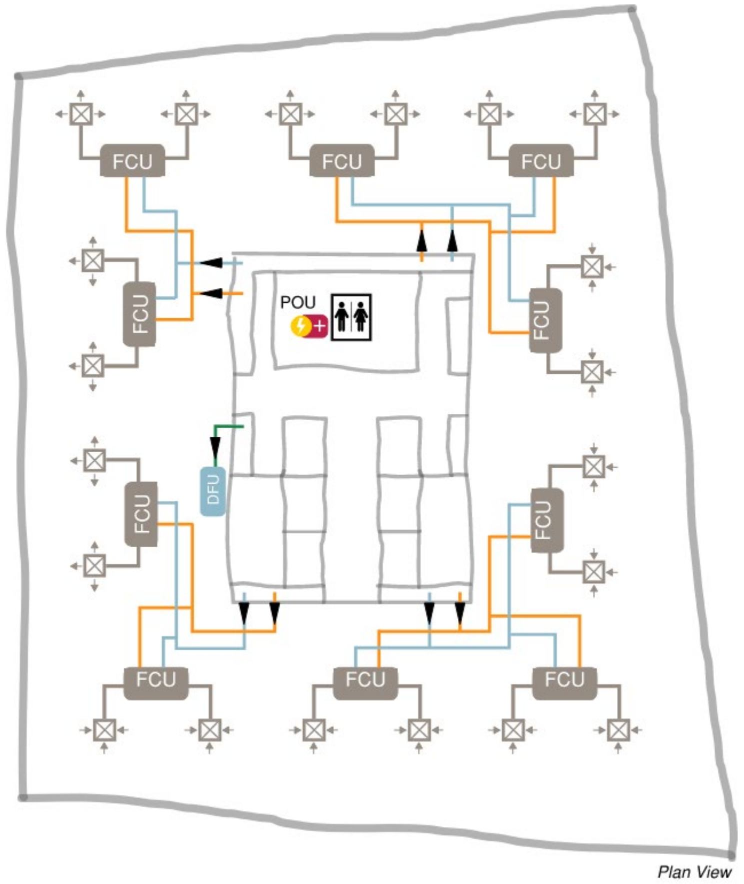


Option: HP

Key

🟦	CHW
🟧	LTHW
🟥	DHW/Boosted temperature
🟩	Refrigerant

DHW: Domestic hot water
FCU: Fan coil unit
POU: Point of use
DFU: Down flow unit
AHU: Air handling unit
LTHW: Low temperature hot water
CHW: Chilled water
WSHP: Water source heat pump
POU: Point of use
DX: Direct expansion
ODH: Over door heater
RAD: Radiator
HR: Heat recovery



BURO HAPPOLD

Overview of Options | DHN Variants

This section describes the **VRF C + DHN**, **CHL + DHN** and **VRF + DHN** system options as derivatives of the previous options.

District heat network (DHN) options have also been considered for both VRF based, and hydronic options. The extent of the DHN use varies with each of these options where either it supplies heat for both general heating and DHW or only DHW. Hot water and 'boosted' temperature loops are generated by exchanging heat through a plate heat exchanger. Connections to the DHN were designed in compliance with the Bristol Heat Networks Technical Specification v12 (provided by BCC).

Domestic hot water

For **all systems** that are connected to the DHN, it has been assumed that a centralised DHW strategy is adopted, meaning that point of use heaters for office washrooms are omitted. The remainder of the DHW system is the same as before where a calorifier is used.

VRF C + DHN

Hydronic heating with district heating connection, VRF cooling

This system utilises a cooling only VRF system (VRF C) (also known as a heat pump VRF system) which is similar to the previously discussed VRF system but without the simultaneous heating and cooling capability. Therefore the branch controllers have been removed. other than this, the design of discrete systems is the same.

Heating is provided from the district via a plate heat exchanger based on 45 °C flow. Trench heaters are used in the offices. This hot water loop also feeds AHU coils, radiators, and over door units.

Cooling only integrated heat pumps are used in the AHUs to temper the incoming fresh air.

CHL + DHN

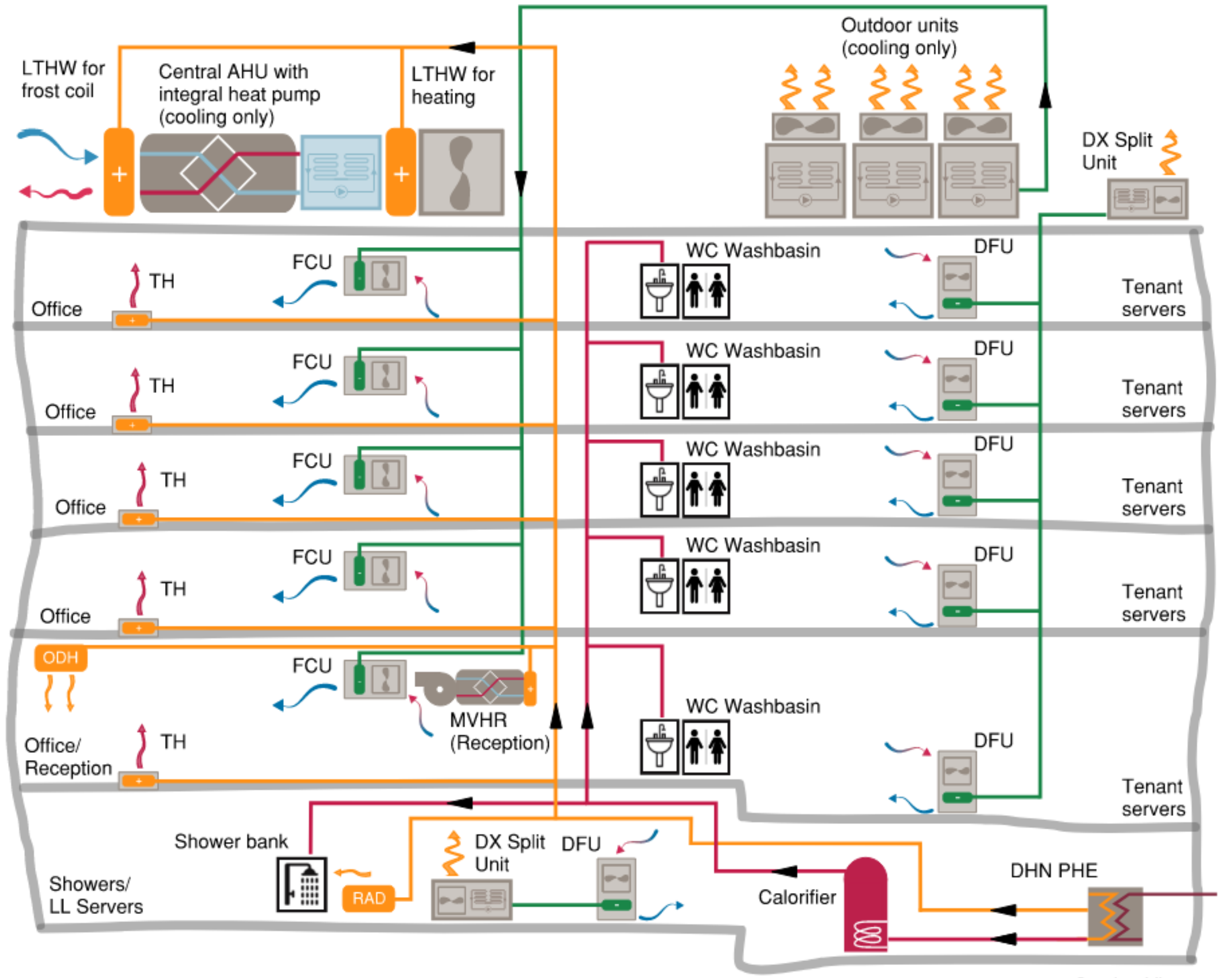
Hydronic heating with district heating connection, hydronic cooling with central chiller

This system is similar to the HP option (page 24), but with the replacement of all heating plant (ASHPs and WSHPs) with the DHN i.e. all other considerations are the same.

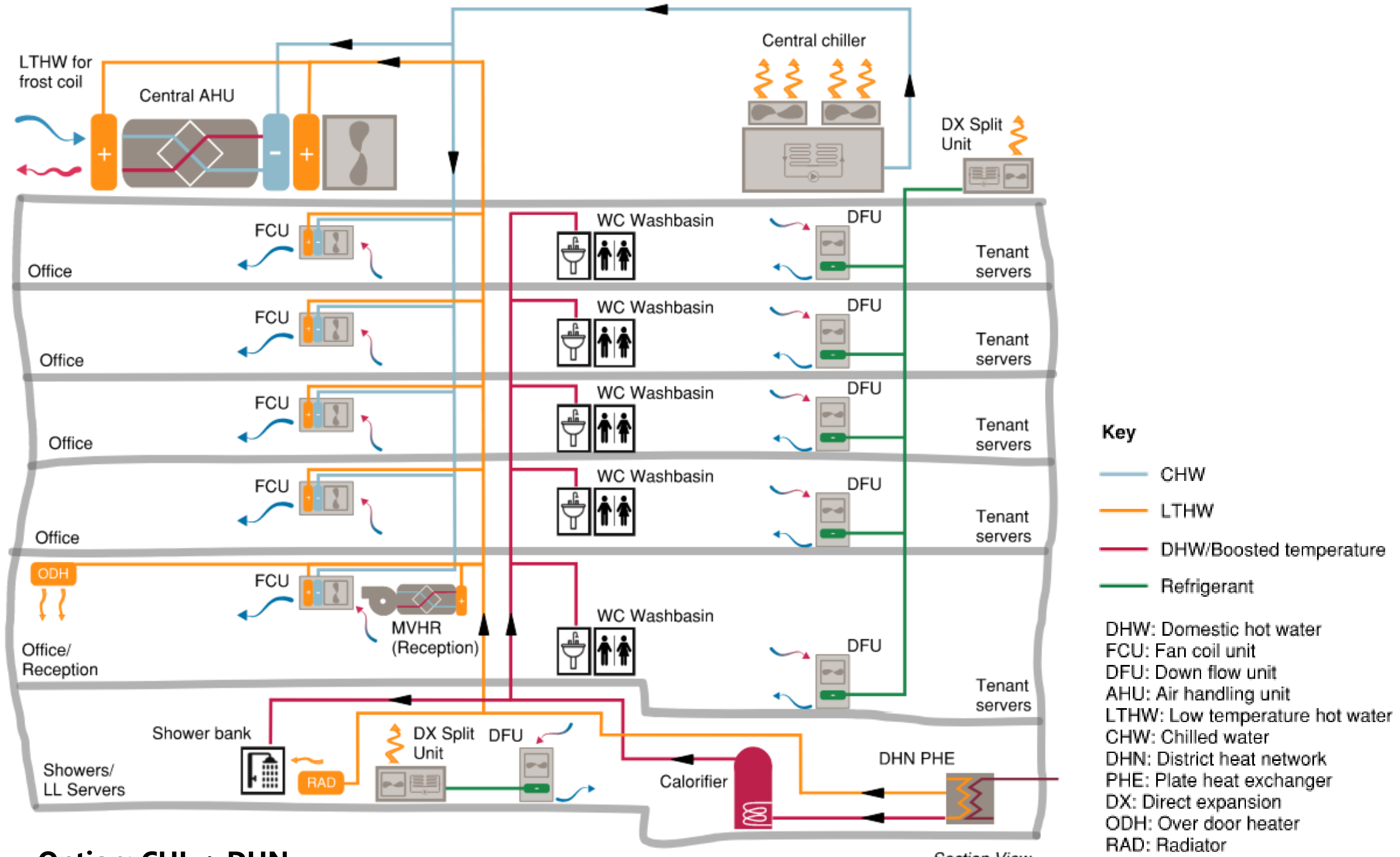
VRF + DHN

VRF heating and cooling, district heating connection for DHW

This is a similar system to the VRF option (page 23), but where the DHW systems are replaced with a centralised DHW system served from the DHN similar to the two options below (separate system sketch not provided).



Option: VRF C + DHN



Option: CHL + DHN

BURO HAPPOLD

Overview of Options | Summary

A summary of the strategies adopted for each heating and cooling demand is summarised below. The following table also includes the assumed refrigerants for each system.

Changes to refrigerants

The Net Zero agenda and the F-Gas legislation means manufacturers are speeding up the transition to lower GWP refrigerants. R410a and other refrigerants with high GWPs are expected to be phased out entirely, initially using refrigerant charge thresholds (under 3kg by 2025 for single split systems). This study, therefore, adopts refrigerants with <750 GWP to ensure it has forward looking applicability in terms of the 60 year whole life carbon analysis.

Not all heating and cooling technologies modelled in the study are currently commercially available with refrigerants that have a GWP <750. Where this was the case, selections were made based on existing products, and then the refrigerant was upgraded to a low GWP alternative. Specifically, this applied to:

- AHUs with integral heat pumps which were switched from R410a to R32
- Hydronic heat recovery heat pumps which were switched from R410a to R32
- The 2nd Stage WSHP for DHW which was switched from R134a to R152a as research suggested easy replacement.

In general, manufacturers contacted were planning on releasing products with GWP <750 in the near future. The refrigerant chapter of this study gives an example of the impact that the use of a R410a based VRF system (rather than R32) would have on the whole life carbon results.

Option	Space Cooling	Space Heating	AHU	AHU Frost coil	DHW Wash Hand Basins	DHW Shower	Server Cooling	Back of House Heating	Reception Over Door Heaters
VRF	VRF (heat recovery)	VRF (heat recovery)	Integrated HP (reversible)	Electrical frost coil	Point of use water heater	Dedicated ASHP heat source	Dedicated Split DX units	Electrical radiators	Electrical overdoor heater
	R32	R32	R32	None	None	R32	R32	None	None
HVRF	Heat recovery HVRF	Heat recovery HVRF	Integrated HP (reversible)	Electrical frost coil	Point of use water heater	Dedicated ASHP heat source	Dedicated Split DX units	Electrical radiators	Electrical overdoor heater
	R32	R32	R32	None	None	R32	R32	None	None
VRF C + DHN	VRF (cooling only)	DHN	Integrated HP (cooling only) and DHN heating	Hydronic frost coil (DHN)	Centralised DHW (DHN)	DHN heat source	Dedicated Split DX units	Radiators (DHN)	Hydronic overdoor heater (DHN)
	R32	None	R32	None	None	None	R32	None	None
CHL + DHN	Chiller	DHN	Cooling by chiller and heating by DHN	Hydronic frost coil (DHN)	Centralised DHW (DHN)	DHN heat source	Dedicated Split DX units	Radiators (DHN)	Hydronic overdoor heater (DHN)
	R1234ze	None	None	None	None	None	R32	None	None
HP	Chiller and ASHP (heat recovery)	ASHP (reversible) and ASHP (recovery)	Central HPs	Hydronic frost coil (HP)	Point of use water heater	2nd stage WSHP heat source	Dedicated Split DX units	Radiators (HP)	Hydronic overdoor heater (HP)
	R1234ze	R32	None	None	None	R152a	R32	None	None
VRF + DHN	VRF (heat recovery)	VRF (heat recovery)	Integrated HP (reversible)	Electrical frost coil	Centralised DHW (DHN)	DHN heat source	Dedicated Split DX units	Electrical radiators	Electrical overdoor heater
	R32	R32	R32	None	None	None	R32	None	None

__A__ – Current practice, __B__ – Best practice, __VRF__ - VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

Energy Modelling

Methodology overview

The current and best practice buildings were built in IES VE. Internal gains, space conditions, operation profiles, and construction information were inputted and the heating and cooling systems modelled in Apache HVAC. Where IES was not capable of modelling certain systems, an excel based model was utilised. The models were run using the Cardiff TRY 2020 50th High weather file. A 20% uplift in energy consumption predicted from the energy model was applied to account for non-ideal operation, commissioning issues, construction defects etc.

Breakdown of energy modelling methodology

Operational profiles

Profiles for equipment, lighting and occupancy were derived from the NABERS UK DfP Modelling Guide. Domestic hot water demand profiles were taken from a similar NABERS DfP project within the Buro Happold project portfolio.

Reception main door infiltration

A general background infiltration rate was applied in the perimeter zones in the thermal model. The rate was based on the correlation between design air permeability ($m^3/hr.m^2@50Pa$) and the infiltration rate (ACH) given in CIBSE Guide A Table 4.15. Average values were used for energy prediction and peak vales for load sizing. Infiltration around the main entrance was accounted for using the bulk airflow modelling engine within IESVE (Macroflo) using an assumed opening profile with peaks in the morning, lunchtime and evening when the doors were expected to have the highest usage.

Lighting controls

Energy savings from daylight linking were accounted for using lux sensors placed in each zone linked to the Radiance calculation engine within IESVE. Allowances for presence and absence detection controls were made in the lighting profiles.

External Blinds

For the best practice case, external blinds were assumed to bring peak loads within the capacity of the low energy fan coil system, and so that additional FCUs would not be required, which would have an adverse impact on embodied carbon. Blinds were controlled based on external incident solar flux. The blinds were deployed when the external incident solar flux exceeded $350W/m^2$.

HVAC system modelling

A plant model for each system was constructed in IES ApacheHVAC; each AHU and FCU was modelled explicitly at a component level. A variable speed drive was applied to AHU fans and 2-speed control logic has been applied to FCUs. FCUs operate to maintain the zone temperature setpoints. Setbacks were applied outside of scheduled hours. Outdoor air ventilation was configured as demand controlled, based on zone CO_2 readings with a 800ppm +/-100 control band. Ventilation plant was scheduled off outside of occupied hours. A frost coil setpoint of 3°C was used.

Where appropriate to the system type the hydronic loops were explicitly modelled. Due to limitations in the IESVE modelling software the central plant attached to the hydronic loops was modelled using a spreadsheet model. The hourly loads on the hydronic loops obtained from IESVE were inputted along with manufacturers tables of performance data to compute hourly efficiencies.

For VRF systems, a standard VRF performance curve set from the (limited) IESVE library was used. Exploratory simulations indicated that the LG performance curves gave the best agreement with the performance data at specific operating conditions that was provided by the VRF manufacturer were used on the project. Defrost energy was allowed for as a 15% derating factor of the outdoor unit performance.

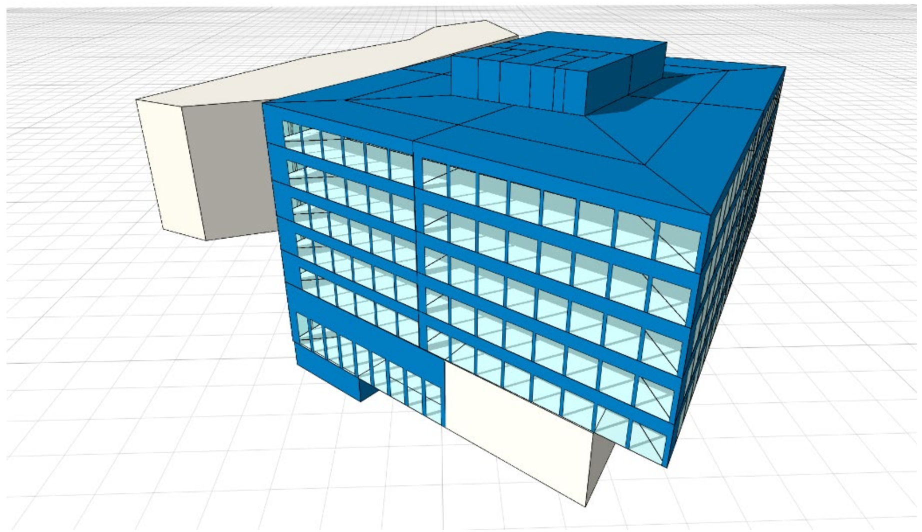
Generally, granular performance data for VRF systems is hard to come by. Manufacturers are not obliged to test these systems at conditions other than those required to generate the SCOP and ESEER values as defined by European Norms i.e. 2.5-7.5m piping lengths, and a very limited combination of part loads and external ambient conditions. This information is not sufficient to carry out detailed operational modelling and therefore the study resorted to utilising IES LG VRF performance curves. This is somewhat unsatisfactory for design engineers, as the lack of performance data inhibits the designer's ability to make fully informed decisions and predictions of real world operational energy. While the testing requirements for hydronic systems (chillers, heat pumps etc) in respect of generating SCOPs and ESEERs are similar, granular performance data at a full range of external ambient conditions is generally available from many manufacturers.

Excel-based plant models

Central plant performance and controls logic for hydronic systems was modelled in MS Excel by post processing the loads on the hydronic loops extracted from IESVE ApacheHVAC. Demands on each item of central plant were calculated on an hourly basis. Energy input to each piece of equipment was determined based on the external ambient conditions and part load performance data provided by manufacturers. Pumping energy calculations were carried out based on the loop loads and the selected pump sets for each circuit.

DHW load profiles were developed in excel based on the expected usage frequencies and flow rates per plumbing fixture. Standing losses from the tank and pipework were accounted for. The DHW loads were then allocated to the relevant hydronic loops.

Miscellaneous power (lifts, etc.) were computed in excel based on manufacturer data, CIBSE guidance and previous projects.



Embodied Carbon Modelling

Methodology

The online software for calculating Whole Life Carbon, OneClick, was used as it has an extensive and constantly updated Environmental Product Declaration (EPD) library and provides the required data granularity required for the study, including emissions due to refrigerant leakage and end of life recovery, transport emissions, equipment lifespans and categorisation of equipment by RICS category.

Information base

MEP equipment embodied carbon quantification is not as well developed as it is for structural components and there is somewhat limited EPD availability.

In the last year, CIBSE has issued a technical memorandum, TM65, to outline current MEP embodied carbon calculation best practice. Included in this publication was the introduction of TM65 manufacturer forms, which provide a less onerous way to provide product specific embodied carbon data compared to traditional EPDs. This provided an additional source of embodied carbon data from manufacturers that would be commonly specified in the UK but did not yet have the data in EPD format, and therefore available on OneClick. Some of the major equipment for this study, such as the ASHPs, split units, and VRF, were input into OneClick from TM65 forms provided by Mitsubishi, as it was deemed this was likely to provide the most accurate estimate of embodied carbon. Typically TM65 forms average higher embodied carbon when compared to EPDs to account for lack of granular information in some aspects of manufacturing (accounted for in the form of a multiplied coefficient based on equipment complexity) – so although they were deemed more accurate from the overall standpoint, this should be considered when considering the total embodied carbon footprint of the MEP. When exact product TM65 manufacturer forms was not available, inputs into OneClick were scaled by product weight, as it has been demonstrated to be the most accurate way to do so (CIBSE TM65).

While ventilation, domestic pipework, and cooling and heating pipework were calculated based on actual quantities arising from the conceptual system design process undertaken, in the case of electrical distribution and infrastructure a Generic EPD was used, using an approved average from other buildings and attributing it to the study on a per m² GIA basis. The only MEP related exclusion from the model was the diesel powered generator due to a lack of any similar EPD available in TM65 form or in available libraries.

Embodied carbon modelling inputs

The systems for each commercial building scenario were split into their respective RICS category, with the exception of Lifts which were included in Electrical Installations. Inclusions for the study with their respective RICS category are outlined in the table to the right:

Non heating and cooling related systems were included to consider the building as a whole, and gain insight into the proportion of heating and cooling embodied carbon when compared to the whole life cycle of the building. In order to do so an office building of a similar build up and proportion was used on a m²/GIA basis to estimate the embodied carbon of all other building elements (substructure, superstructure, façade, and internal finishes – external areas excluded).

Key considerations for differences between scenario A and B are the ventilation system, which to be compliant with Future Building Standard SFPs are larger by approximately 10%, a predominantly cloud based system and therefore less servers in the latter (including the respective size of the cooling system), and the increased provision of photovoltaic panels in a future scenario. Other differences will be due to a proportion in reduction of cooling and heating loads in a better building fabric and more energy efficient (due to lower internal gains) scenario.

Equipment lifespans contribute significantly to MEP embodied carbon, included in the Replacement phase (B4). Lifespans were assumed in line with CIBSE Guide M. For VRF systems it was assumed that corresponding pipework would also be replaced as during main equipment replacement this would typically also be replaced due to pipe cleaning and maintenance requirements (Mitsubishi Electric).

For the purpose of the main study an average leakage rate was assumed based on studies undertaken for respective system types which have been collated in CIBSE TM65 (See Appendix K).

RICS Category	Description
5.1 Sanitary Installations	WHB's, Toilets, and Showers with associated ancillaries
5.3 Disposal Installations	Above Ground Drainage and Rainwater Pipework (PVC)
5.4 Water Installations	Domestic water pipework (Copper), Cold water distribution (storage tank and booster system), cat5 break tank, Sprinkler system (tank, pumps, and distribution), Hot water cylinders, point of use water heaters
5.5 Heat Source	ASHPs, VRFs, HVRFs, WSHPs, Chillers, Outdoor Units (ACC), Refrigerant pipework (copper, with the exception of a part of HVRF pipework which is PVC), Plate Heat Exchangers (PHEs)
5.6 Space Heating and Air Conditioning	Heat emitters, FCUs, equipment associated with heat source systems, overdoor heaters, trench heaters, CRAC indoor units, LTHW and CHW pipework and insulation.
5.7 Ventilation	AHUs, VAVs, MVHRs, extract fans, smoke extract system, ductwork with insulation, attenuators, VCDs, fire dampers, supply and extract grilles
5.8 Electrical Installations	Lighting, PV panel system, Lifts, Transformer, Server Racks, Small power/IT/Comms/Fire safety distribution

Cost Modelling

Scope and cost boundaries

The Life Cycle Cost (LCC) plan has been prepared by Currie & Brown in line with PD 15686:2008, 'Standardised Method for Life Cycle Costing' and the following cost categories *(see tree diagram below):*

Construction costs

Only MEP costs are considered. It is assumed that the rest of the building construction costs are consistent in every option. Quantifying the cost of the enhanced fabric performances for meeting future 'best practice' designs in line with UKGBC/LETI etc were outside the scope of the study.

Maintenance costs

Major replacement costs - scheduled replacement of major systems and components. This will form the detailed asset life cycle replacement cost programme.

Minor replacement (excludes any repairs and maintenance costs) - Minor replacement relates to the unscheduled replacement of parts prior to the scheduled replacement and the end of their service life.

Maintenance relates to planned preventative and/or reliability centred maintenance and is excluded in these costs.

Operation and occupancy costs

Cleaning costs – excluded based on the assumption it is similar for each option.

Utilities costs - electricity and/or Heat Network Connections associated with the building.

Occupancy costs – excluded based on the assumption it is similar for each option.

End of life costs – this includes demolition, transport, waste processing and disposal emissions.

The LCC plan considers these utilities and end of life costs, as provided and relevant to the project.

The period of analysis for this elemental LCC plan is 60 years post construction, for which a 3.5% discount rate will be applied, in-line with HM Treasury 'The Green Book' for years 0-30, and 3% for years 31-60. Both the Real Cost as well as the Discounted Cost are calculated in the LCC Plan. For ease of reference all comparisons in this report will be based on the Real cost.

Methodology

Major and minor replacement

The major replacement costs are based on the initial capital costs.

These are then adjusted using a scale of replacement as relevant to the item and indicative of the level of replacement required at each interval. A reference service life (interval) is then allocated to each item indicating the point at which an intervention is required for an item during the period of analysis. A replacement uplift is then applied to the capital cost to derive a replacement cost per item.

This then calculates the cost per interval per item to generate the life cycle replacement costs over a 60-year period.

Operations

The utilities have been calculated using utility consumption information applied to utility rates provided by Bristol City Council's Energy Service.

The DHN Fixed charge includes allowance for the REPEX for the District Heat Network. This REPEX is therefore not shown separately.

- DHN Connection Fees: £450/kW (included in the capital cost)
- DHN Variable consumption charge: 5.5p/kWh
- DHN Fixed charge: £45/kW

The electricity usage charge is assumed to be 15.6p/kWh.

This process/ methodology enabled the derivation of the following:

1. Outline LCC plan for the MEP cost of the building
2. Replacement strategy.
3. Yearly utility charges

Assumptions

The capital costs are based on current market rates.

The major and minor replacement costs are based on the capital costs.

Lifecycle intervals are based on CIBSE Guide M 2020 Appendix.

Generally, no on-costs have been applied to the capital cost rates used within the LCC plans. However, for M&E services, the cost of M&E subcontractor preliminaries and testing and commissioning have been added to the capital cost of services.

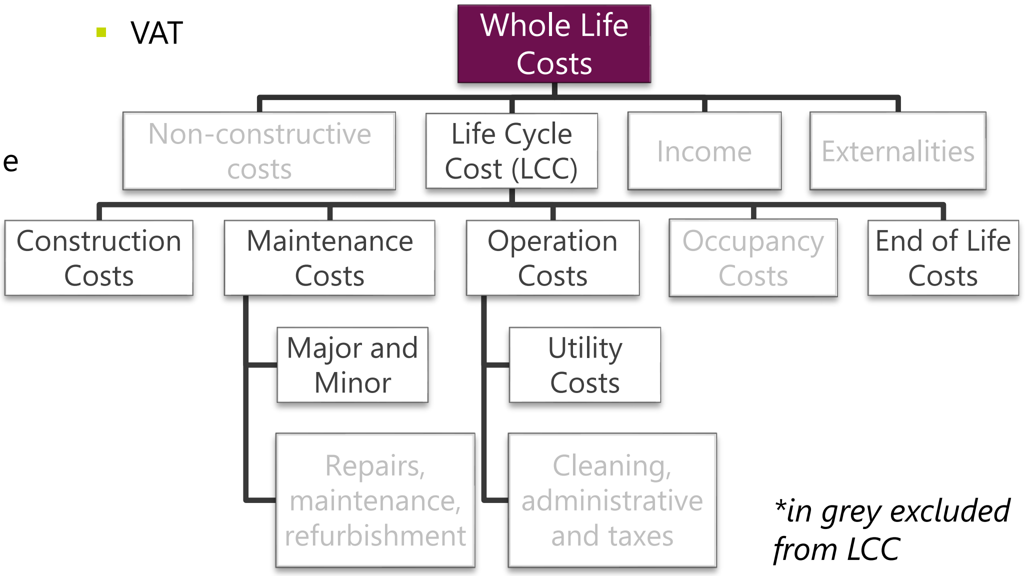
It is assumed that inflation rates will be the same for all the costs and are therefore ignored.

Exclusions

The following have been excluded from the LCC Options Appraisal:

- Construction on-costs inc. main contractor's preliminaries, overheads and profits, design/project fees, risk and inflation except where the percentage of MEP cost vs total construction costs are calculated.
- Replacement and maintenance on-costs
- Inflation for LCC and energy price indexing
- Administration costs
- Risk/ contingency
- Capital allowances
- VAT

Whole Life Costs Scope Tree Diagram



**in grey excluded from LCC*

Part L Compliance

Part L2A calculations have been carried out for each of the building design and system options to demonstrate that each is compliant with the requirements with Building Regulations Part L2A 2013 and Bristol Core Strategy Policy BCS14.

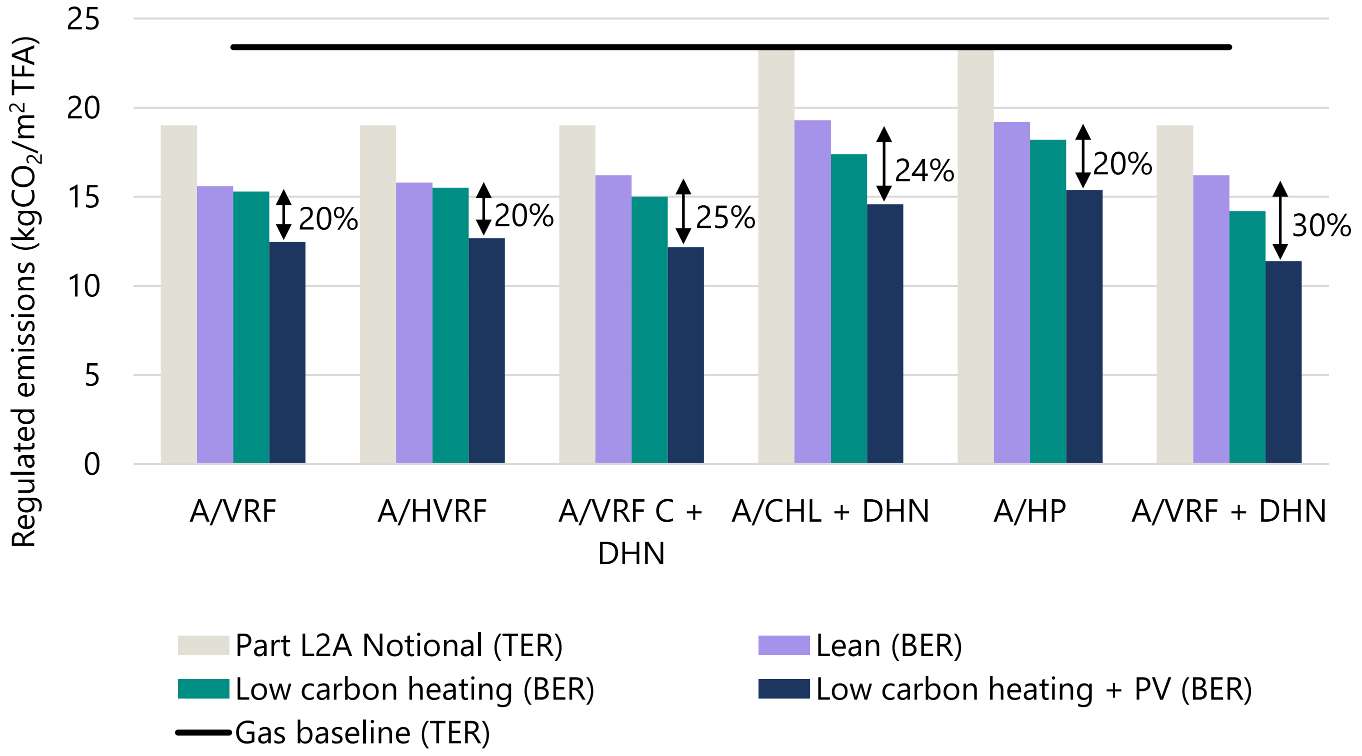
All values shown are calculated using NCM carbon factors which implies that there is no accounted benefit of the decarbonisation of the grid.

The results shown in the chart (also tabulated to the right) demonstrate that all scenarios deliver a reduction in residual regulated CO_2 emissions through solar PV equal or greater than the 20% required in Bristol Core Strategy (2011) Policy BCS14.

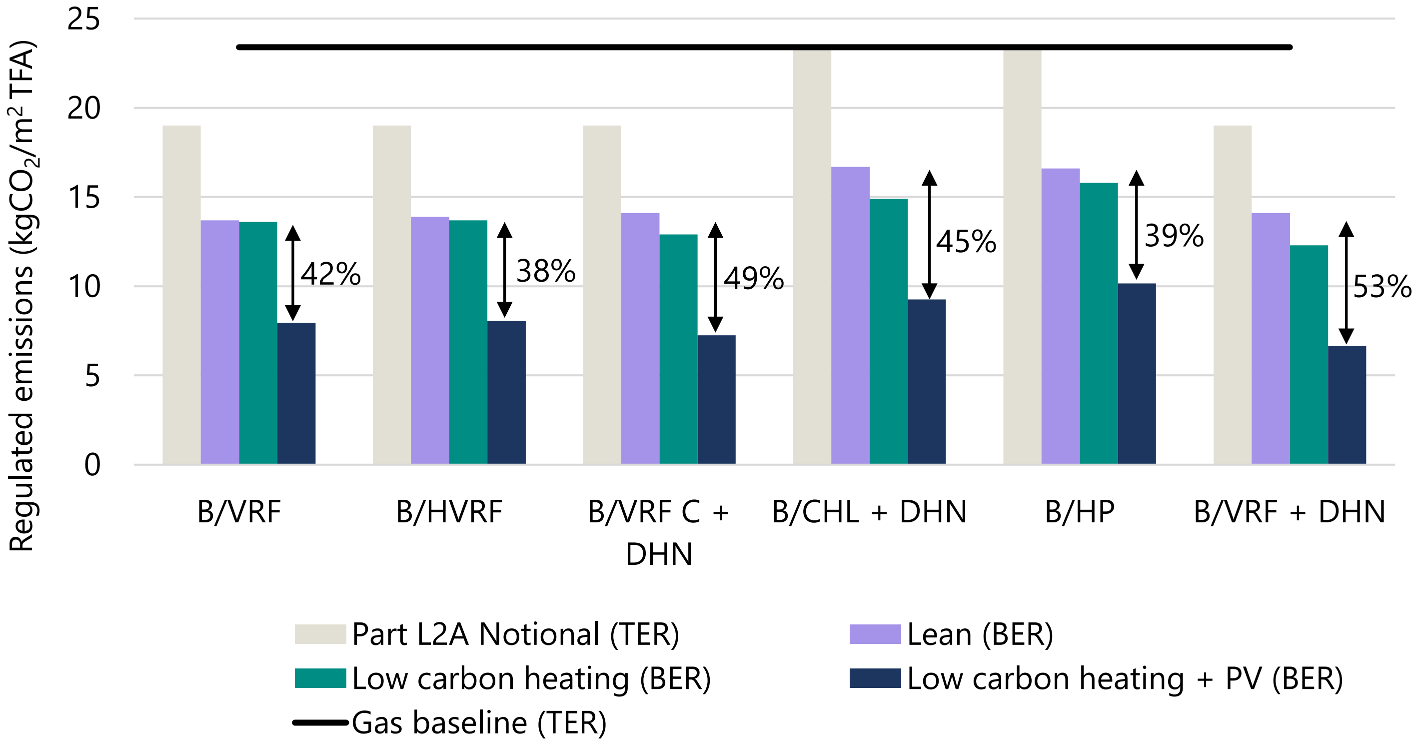
VRF and HVRF options are shown to have the lowest regulated carbon emissions whereas hydronic systems have the highest. The DHN seems to help reduce regulated emissions due to the network carbon intensity of 0.145kgCO_2/kWh provided by BCC. Therefore, it is shown that VRF + DHN is the best option in terms of compliance. When comparing to the operational carbon results (page 33), the compliance model seems to overestimate the differences between VRF and hydronic systems and the overall efficiency of the HVRF system, as can be seen overleaf.

System Options		Notional Compliance Baseline	Lean (energy efficiency measures)	Onsite heat pump renewables	Onsite PV renewables	Residual CO_2 reductions %
Current Practice	A/VRF	19.0	15.6	15.3	12.5	20%
	A/HVRF	19.0	15.8	15.5	12.7	20%
	A/VRF C + DHN	19.0	16.2	15	12.2	25%
	A/CHL + DHN	23.4	19.3	17.4	14.6	24%
	A/HP	23.4	19.2	18.2	15.4	20%
	A/VRF + DHN	19.0	16.2	14.2	11.4	30%
Best Practice	B/VRF	19.0	13.7	13.6	8.0	42%
	B/HVRF	19.0	13.9	13.7	8.1	42%
	B/VRF C + DHN	19.0	14.1	12.9	7.3	49%
	B/CHL + DHN	23.4	16.7	14.9	9.3	45%
	B/HP	23.4	16.6	15.8	10.2	39%
	B/VRF + DHN	19.0	14.1	12.3	6.7	53%

Current Practice Part L Compliance



Best Practice Part L Compliance



__A__ – Current practice, __B__ – Best practice, __VRF__ - VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

Operational Energy Results (EUI)

Energy usage intensities (EUIs) have been calculated for each option as a result of the operational energy modelling. As per LETI definitions on-site renewable energy generation is not included in the EUI calculation.

As shown in the graphs, there is a substantial reduction in EUI between the current and best practice building (~30%), principally owing to reductions to tenant lighting and equipment power, as well as solar loads. This shows that UKGBC interim targets are achievable only when extensive demand reduction strategies are employed. To achieve the 'Paris Proof' targets (LETI) further reduction strategies such as mixed mode operation, enhancements to lighting and plug power monitoring would also need to be explored. It can also be observed that DHW does not significantly change between current and best practice buildings as there are limited intervention opportunities available other than increasing pipework and vessel insulation.

Even though the annual cooling demand is significantly more than the heating and DHW demand (~x2), from an energy consumption standpoint (for non DHN connected systems) they are of an almost similar magnitude due to cooling generation being fundamentally more efficient. Amongst options with a DHN connection, heating and DHW are shown to increase significantly but this is because the thermal energy is compared to the electrical energy which is not a valid comparison. This is generally why the DHN options are seen to incur the highest EUIs. As shown on the operational carbon charts (page 33) the elevated EUIs of the DHN options do not translate to higher operational carbon. To address this, a DHN EUI correction factor has been proposed (page 34).

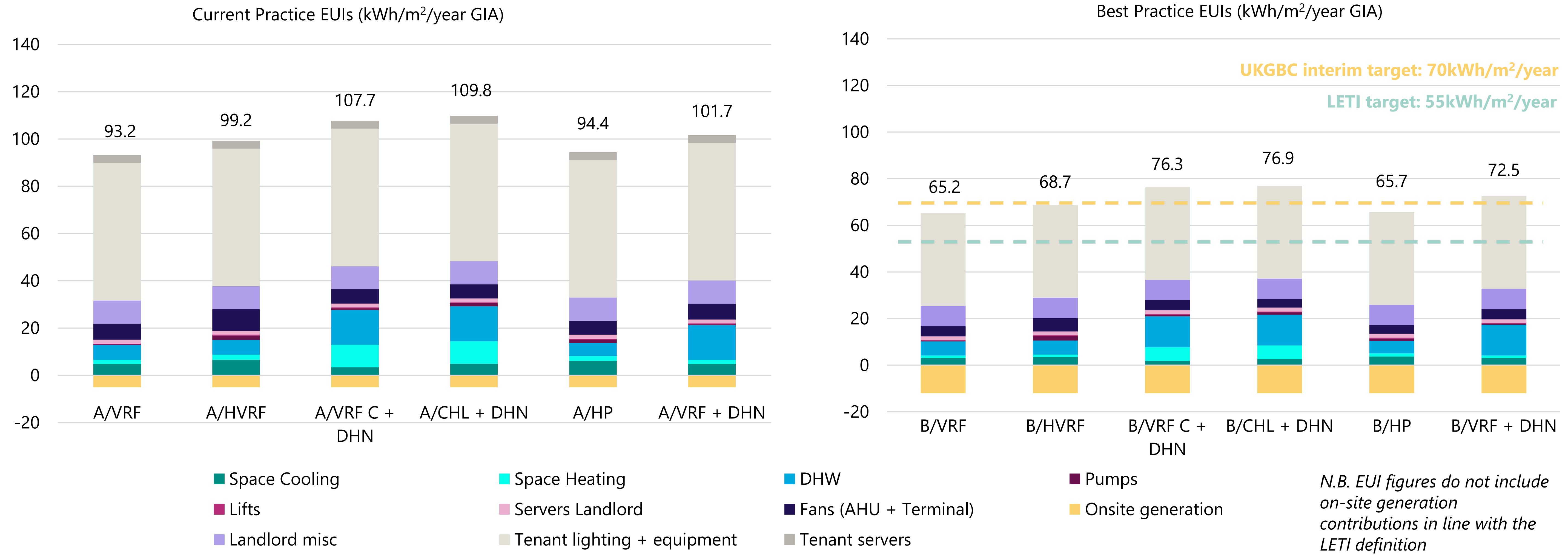
Pumps and lifts contribution to the overall EUI is minor. A taller building would, however, potentially incur higher pumping and lift energies.

Fans energies (AHU and terminal) are appreciable and tend to surpass cooling energy consumption across all options.

Servers and landlord miscellaneous (lighting, extract fans, common power, etc.) energies are appreciable and can almost reach a similar magnitude as the heating and cooling energy.

Unsurprisingly, tenant equipment and lighting amount to the majority of the load in both current and best practices illustrating its importance to meet EUI targets.

Across the options, after applying a suitable correction to DHN connected systems (page 34), it is shown that the HVRF system is the least efficient system overall for heating and cooling. The VRF C + DHN results in the highest cooling efficiency. Generally however, all the system options have a similar total EUI after applying a DHN correction, resulting in a relative range of 6% amongst options.



N.B. EUI figures do not include on-site generation contributions in line with the LETI definition

__A__ – Current practice, __B__ – Best practice, __VRF__ - VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

Operational Energy Results (EUI) | Heating, Cooling & DHW

Focus on heating, cooling, & DHW

The below charts allow for specific heating, cooling, DHW comparisons between the systems in terms of EUIs. A DHN correction factor has been applied to allow direct comparisons between options based on the methodology set out on page 34.

Overall, the relative range between system options for heating and cooling EUIs are ~34%, with a reduction of ~32% from current to best practice options.

Space cooling efficiencies are shown to remain relatively constant across the system options apart from VRF C +DHN which has been shown to be ~30% more efficient in cooling than the VRF system.

Space heating is relatively consistent apart from for DHN connected systems which are higher as generating higher temperature water and distributing it across the city returns a lower efficiency than the on-site heat pumps. DHW is more consistent as the on-site generation via point of use water heaters and 2nd stage heat pumps achieves a similar efficiency to the DHN.

The AHU fan energy is not presented, but FCU terminal fans can amount to 40-50% of the total fan energy demand. This is reduced to 17% when the low SFP FCUs are adopted (SFP of 0.1). Pumping is shown to increase for hydronic based systems.

The HVRF system has resulted in the highest energy requirements principally due to increases to branch controller pumping and terminal unit fan energy demands.

Office energy breakdown

The proportions of the calculated EUI has been compared with the LETI energy breakdowns *(shown in the pie charts to the right).*

The small power and lighting loads are higher, and this results in an overall reduction in heating loads. This could be accredited to differing diversity values applied and the form of the building studied (deep plan vs shallow plan). Higher internal gains have also resulted in higher cooling loads in the building.

Ventilation fans are lower in the study results. This could be because of the approach to sizing the AHUs (based on BCO/undiversified occupancy) which results in significant part load operation based on the applied occupancy diversity of ~70%. The space CO_2 setpoint is 800ppm which could be higher than the LETI assumptions.

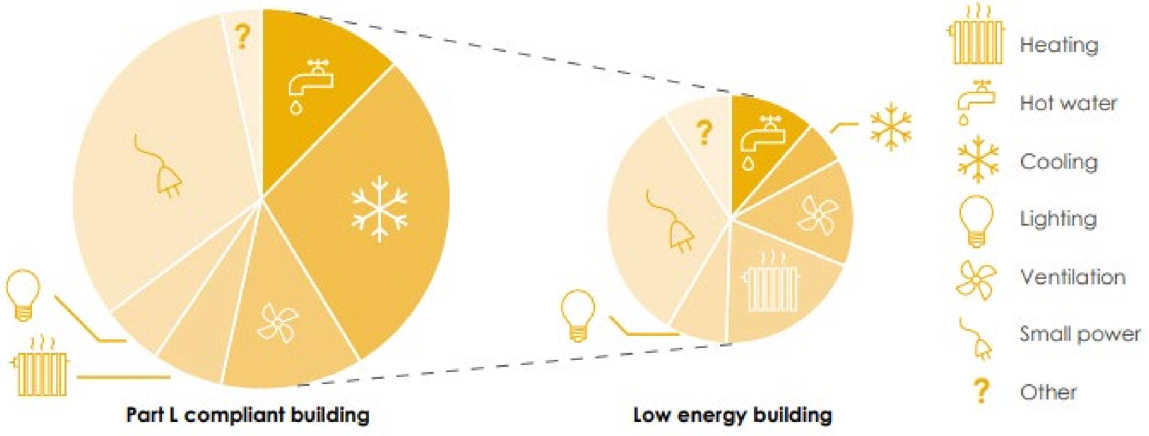
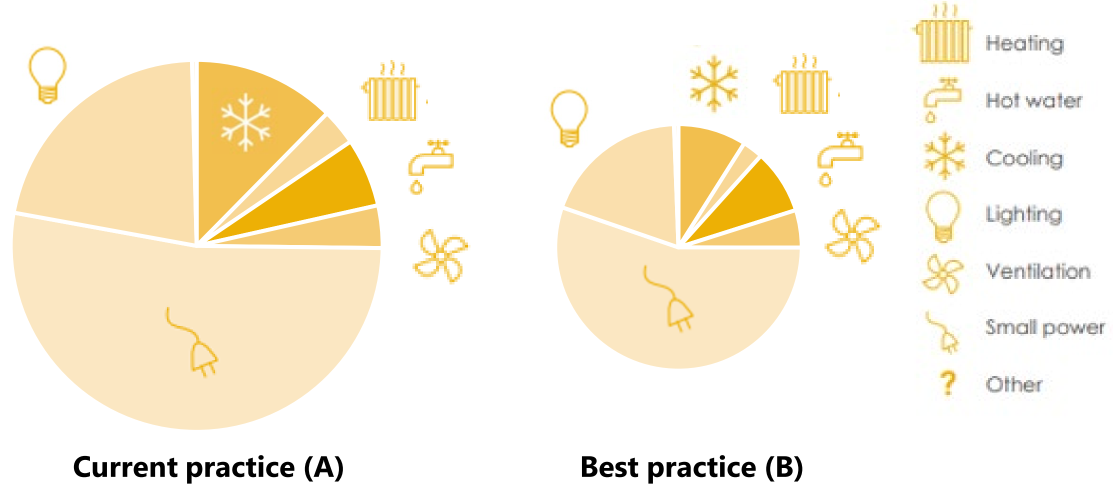
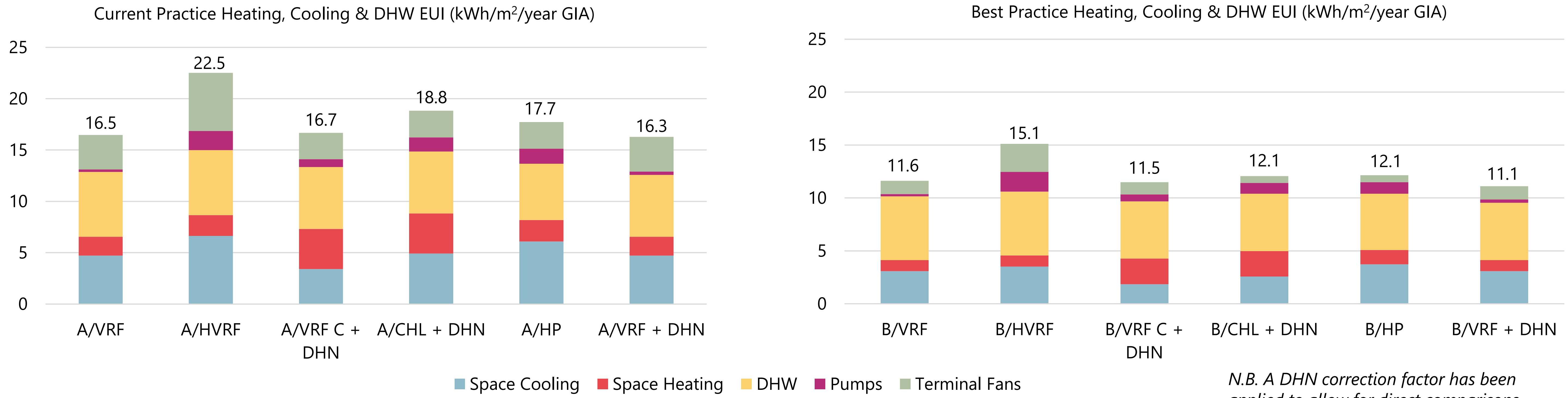


Figure 1.8 - Office energy breakdown

Source: LETI



Recreated for study



N.B. A DHN correction factor has been applied to allow for direct comparisons based on page 34

__A__ – Current practice, __B__ – Best practice, __VRF__ - VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

Operational Carbon Results

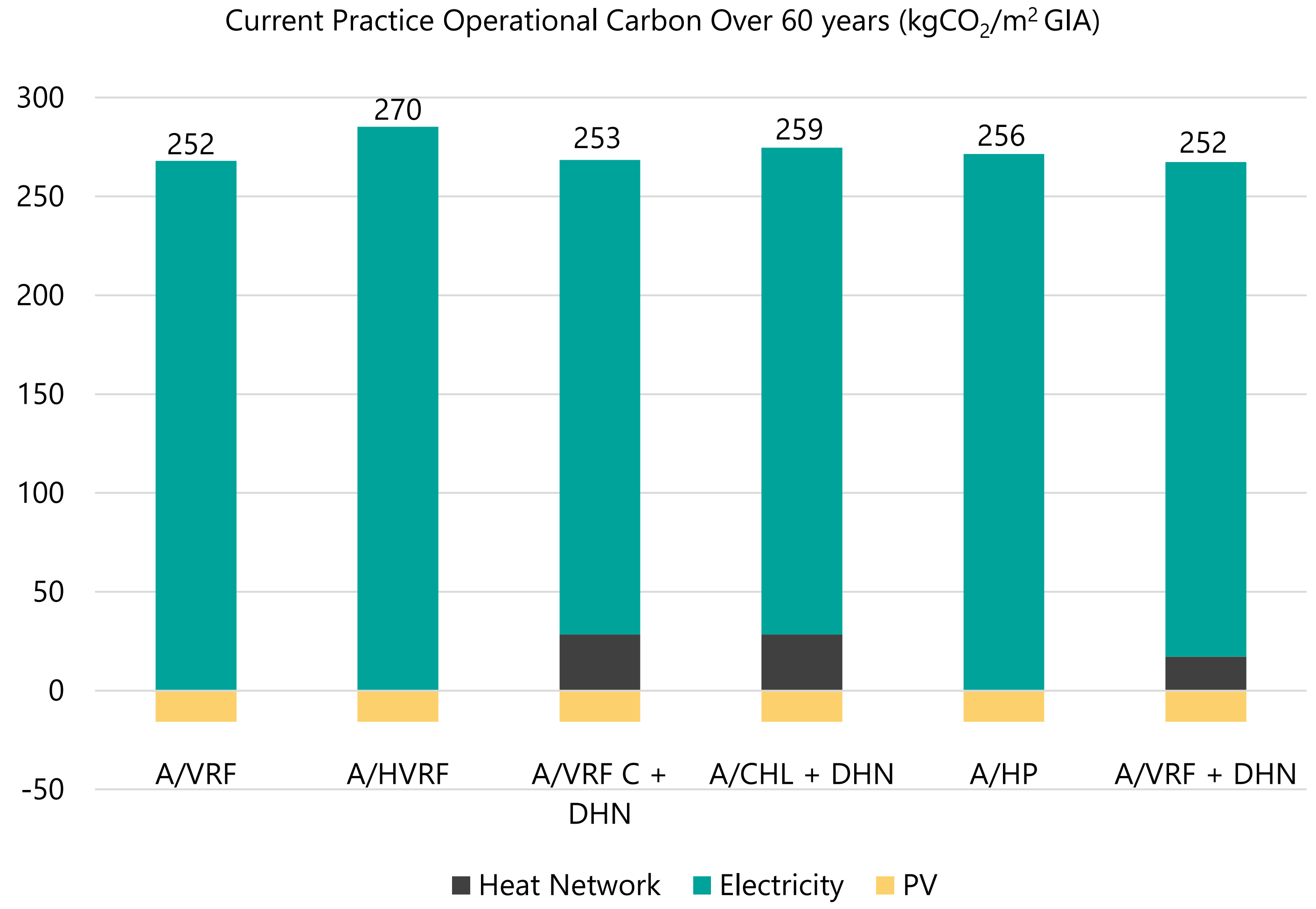
From the EUIs, corresponding operational carbon figures over 60 years were calculated incorporating the decarbonisation of the grid.

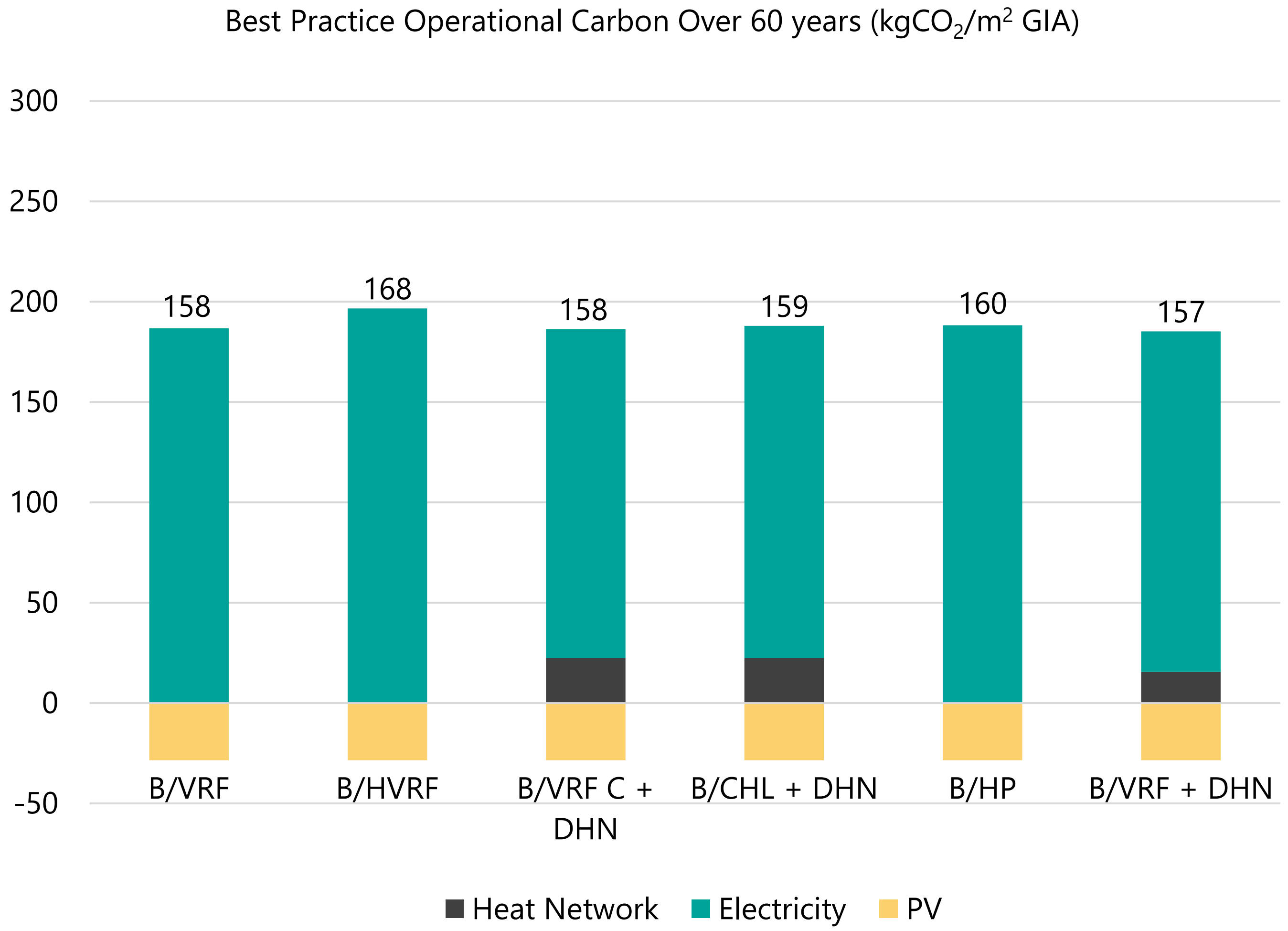
Similar to the EUI figures, the best practice building incurs significantly lower operational carbon compared to the current practice building ~38% reduction. Across system options, and in contrast to the EUI figures, options seem generally interchangeable from an operational carbon point of view. This is shown with a minor variance in results where the difference between the best and worst option is 7%. A portion of this variance could be attributed to the expected margin of error associated with energy modelling.

This range is shown to be double using the EUI metric directly ~17% between the best and worst option which would suggest that the EUI metrics do not directly correspond to the operational carbon, mainly due to the DHN connections. A proposal on how this could be addressed is explored on page 34. After the adjustments are made however, a similar relative range is observed at 6%.

The split between electricity and DHN usage has been presented visually on the graphs. As shown the majority of usage is electric-based for options that are connected to the DHN, re-affirming that non-heating loads are dominant in commercial buildings.

As established from the EUI charts, conventional VRF based systems are shown to incur the least operational carbon. However, due to the minor variances between options presented, the combination of best practice considerations are shown to be more important in reducing the operational carbon rather than the choice of system (in respect of the systems studied).





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DHN EUI Correction

As discussed in the previous operational energy and carbon results sections, the EUI figures are not representative of the operational carbon for DHN connected systems. The reason for this is because the EUI represents the metered energy figures (in kWh) and does not distinguish between the type of fuel (in this case electricity and the heat network). Therefore the heat network EUI is seen to be penalised as this does not take into account the coefficient of performance of the upstream DHN equipment (principally heat pump based systems).

Therefore for benchmarking and policy targeting purposes, if an EUI target is set, it is recommended that an EUI correction is applied for DHN connected schemes.

In this regard, it is suggested that a 'factor' is applied to the energy consumed from the DHN. This factor would essentially represent the long term projected efficiency of the DHN's heat generation plant. This has been calculated to be **~2.44** (or to be directly multiplied by 0.41) over a 60 year period from 2021 based on the decarbonisation projections of the electrical grid from BEIS and the DHN projections from BCC.

Methodology

This factor was calculated by utilising the carbon intensity of the DHN grid for a given electricity grid carbon intensity projection until 2081 (page 19). The resulting total carbon emissions for 1kWh from the electrical grid was divided by the associated carbon emissions of 1kWh of district network heat over the 60 year period.

$$\frac{Carbon\ emissions\ of\ 1kWh\ of\ electricity\ over\ 60\ years}{Carbon\ emissions\ of\ 1kWh\ of\ DHN\ heat\ over\ 60\ years} = \mathbf{2.44}$$

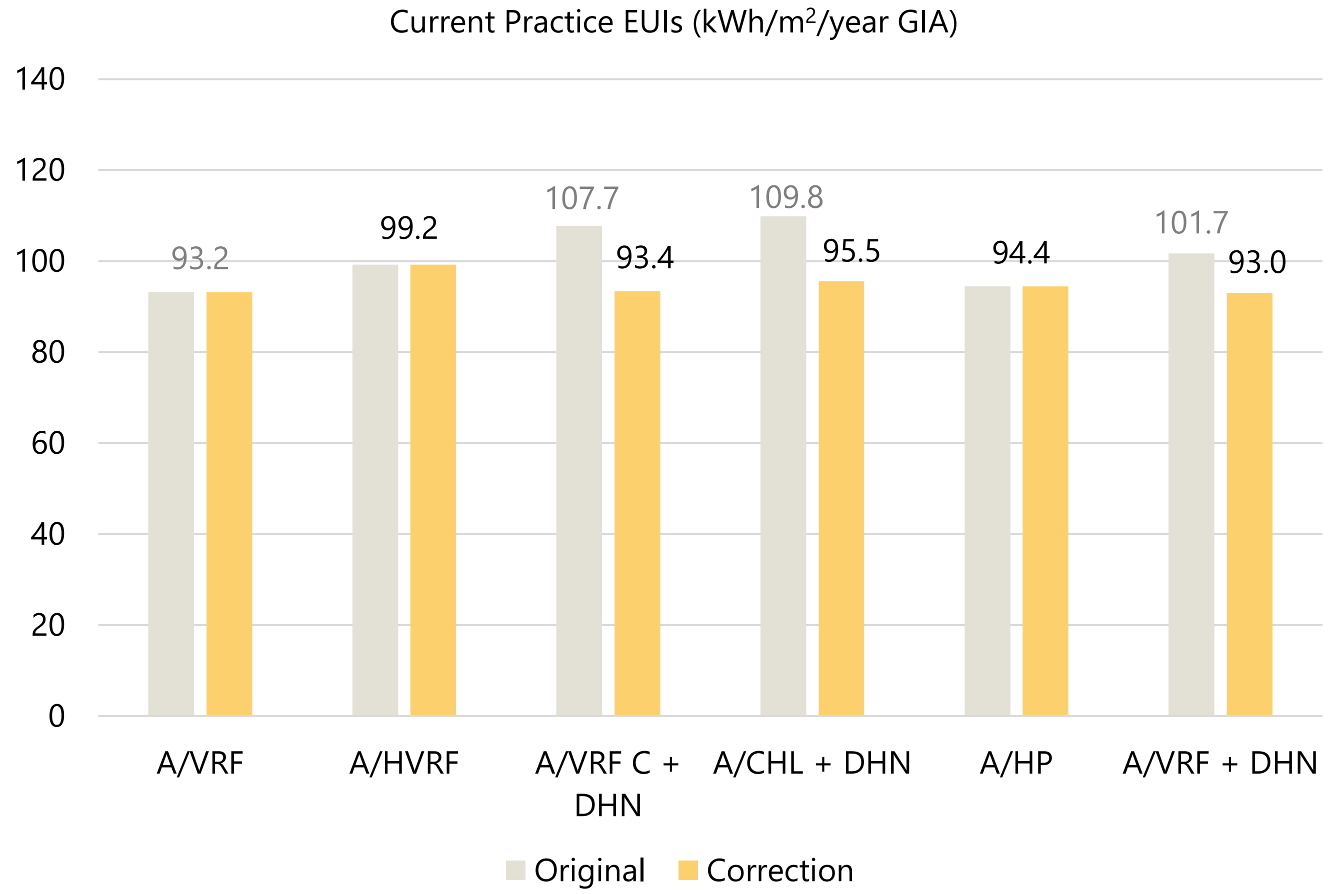
This essentially calculates the electricity equivalence of the heat supplied by the DHN enabling direct operational carbon calculations and comparisons. This factor can be calculated/updated and issued periodically.

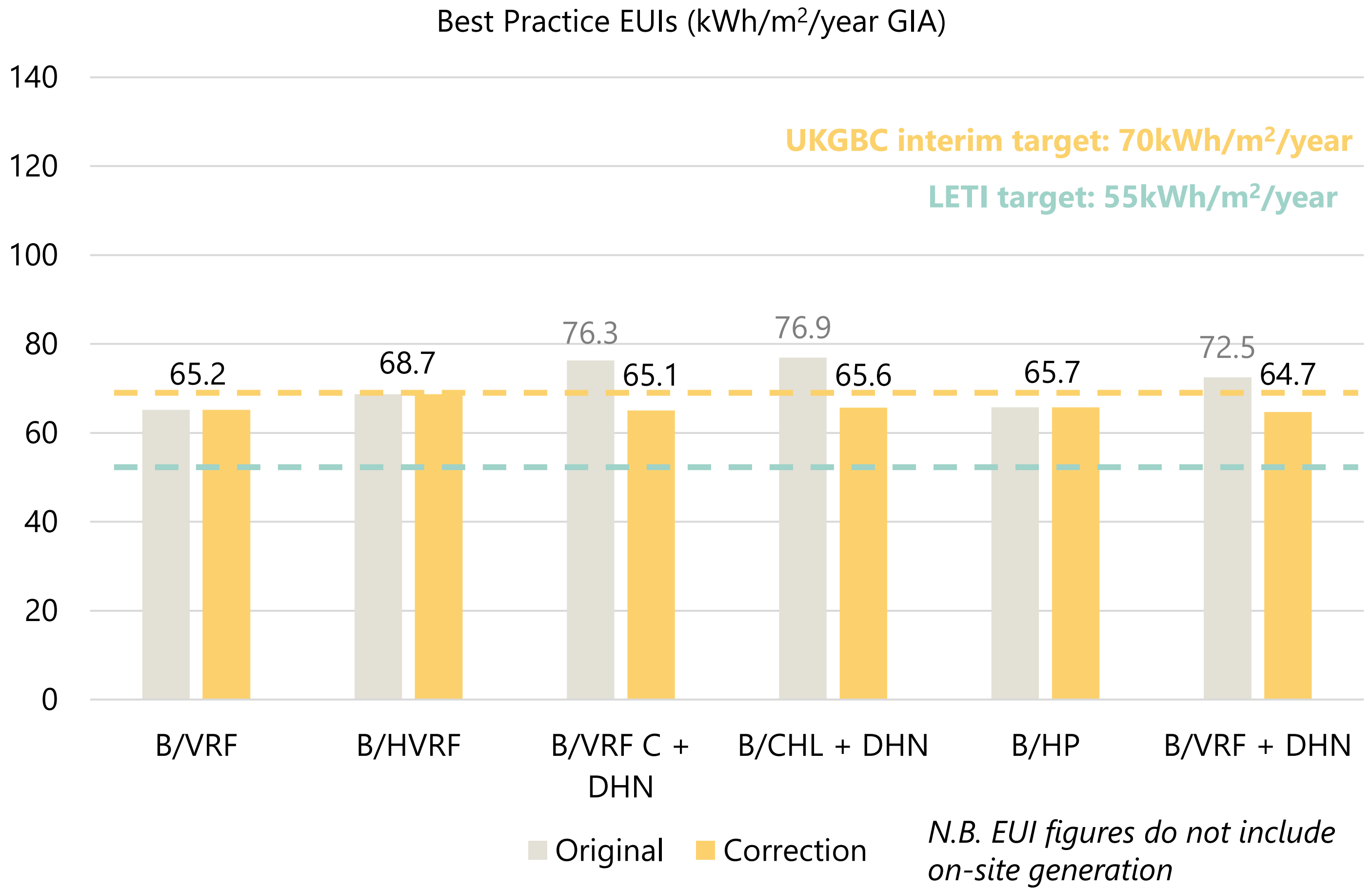
Post-DHN-correction EUI results

After the corrections have been made, it is shown that the system rankings follow the operational carbon rankings. This is an important comparison, as the EUIs now act as a direct indicator for operational carbon emissions. In addition to this, the remainder of the benchmarking process remains the same for simplicity.

A general reduction of ~15% has been observed for the DHN connected systems for the total calculated EUI. As for only the heating, cooling, DHW associated EUI (page 32), the correction has resulted in a reduction of ~40-50%.

As shown (based on a factor of 2.44), all the system options are now meeting the UKGBC interim target. HVRF is now shown to result in the highest EUI in line with the operational carbon results.





N.B. EUI figures do not include on-site generation contributions in line with the LETI definition

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Embodied Carbon Results

The results from the embodied carbon study can be visualised in the following graphs. While the future building scenario (B), generally results in lower embodied carbon, the increased PV included in the Electrical Installations minimises this gap. Refrigerant leakage has also contributed significantly to the results, putting VRF based systems at the top of the embodied carbon list. Refrigerant leakage aside, the HP option would perform the worst for equipment embodied carbon, due to the number of systems and therefore equipment involved. The heating and cooling systems, excluding refrigerant, account for a range of 11%, in the case of B/VRF, to 30%, as is for A/HP. In both cases the DHN system is the best performing as it requires the least building side infrastructure.

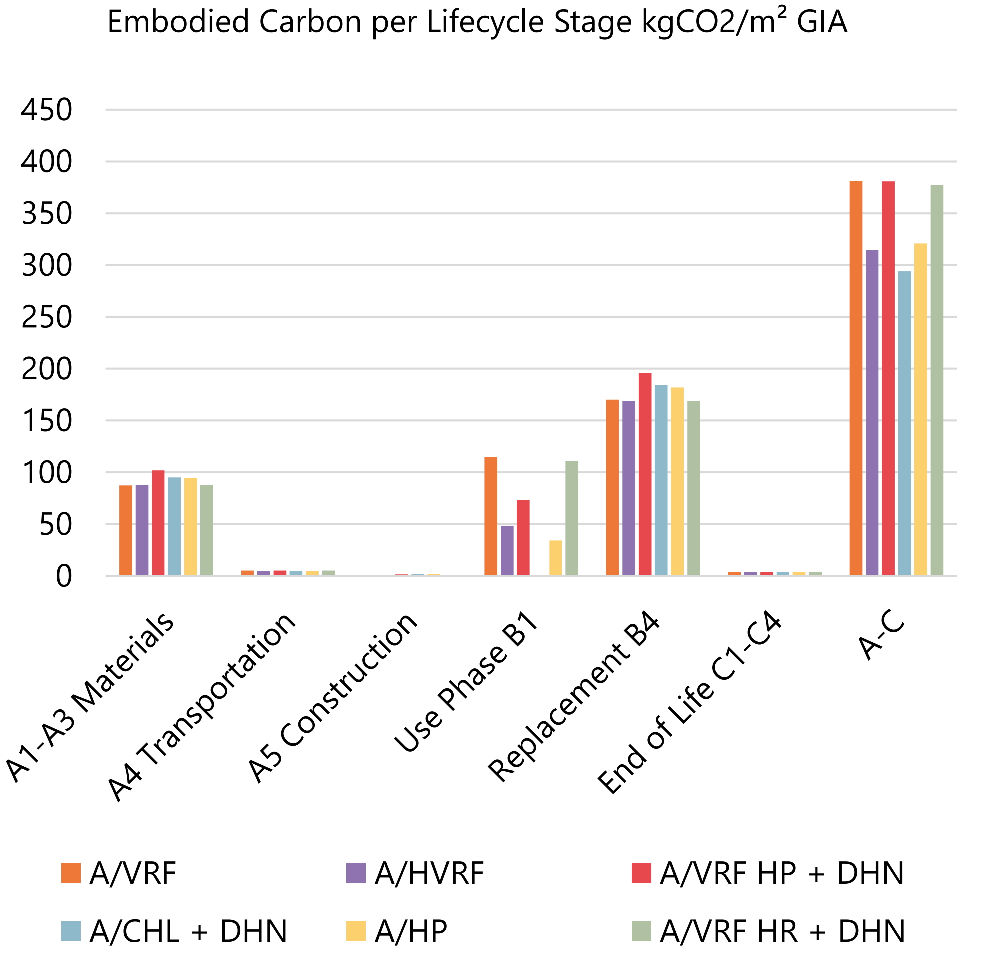
The bar chart to the right shows that Replacement (B4) accounts for nearly twice as much embodied carbon as Materials (A1-A3). This highlights the importance that MEP equipment lifespans have on the whole life carbon of a building. With circular economy principles wherein the lifespan is extended and only what is necessary is replaced within equipment, this value could be significantly reduced.

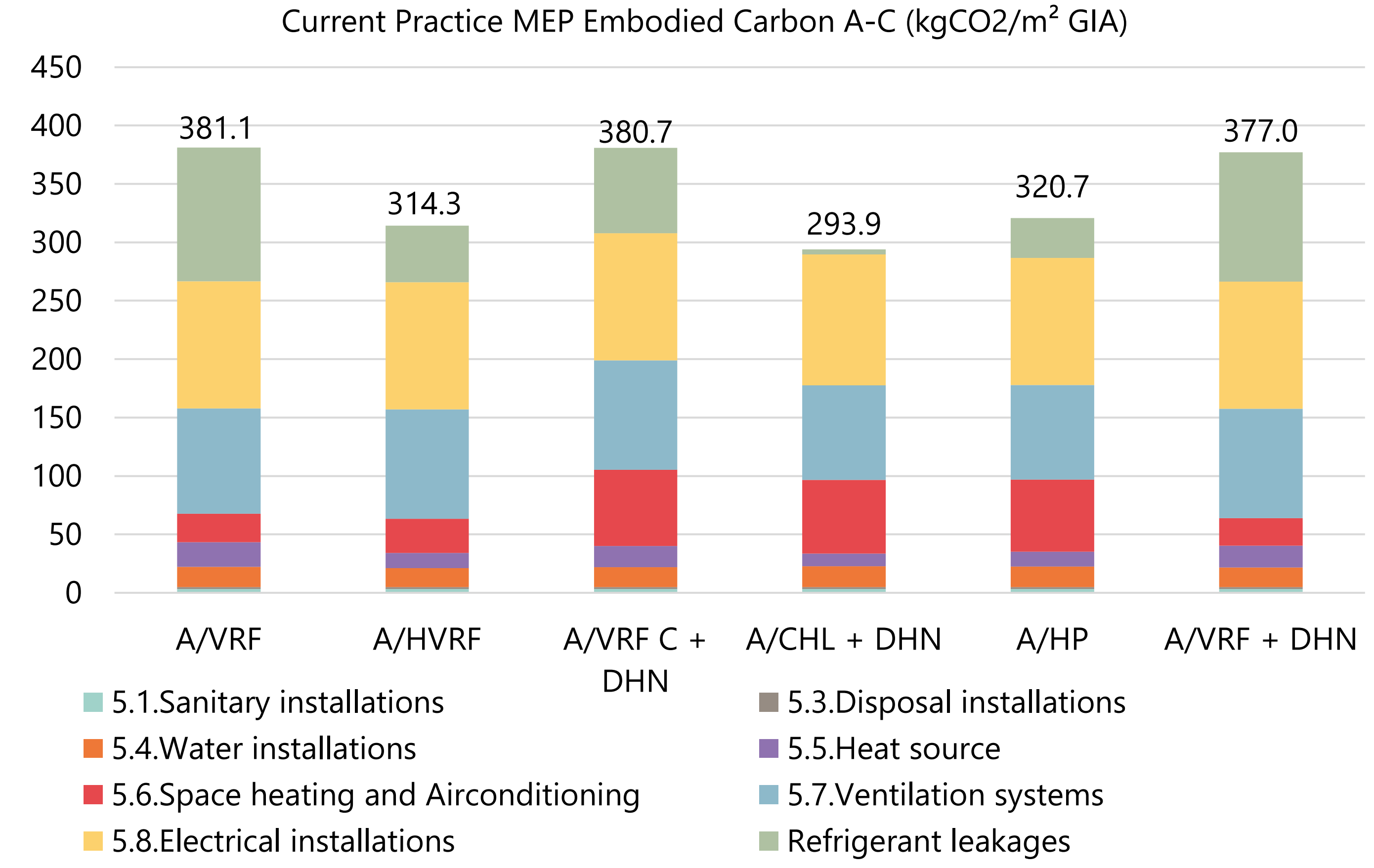
Refrigerant leakage variance is explored in the Refrigerant section of this report, on page 90, to understand what impact more or less controlled leakage prevention measures may have.

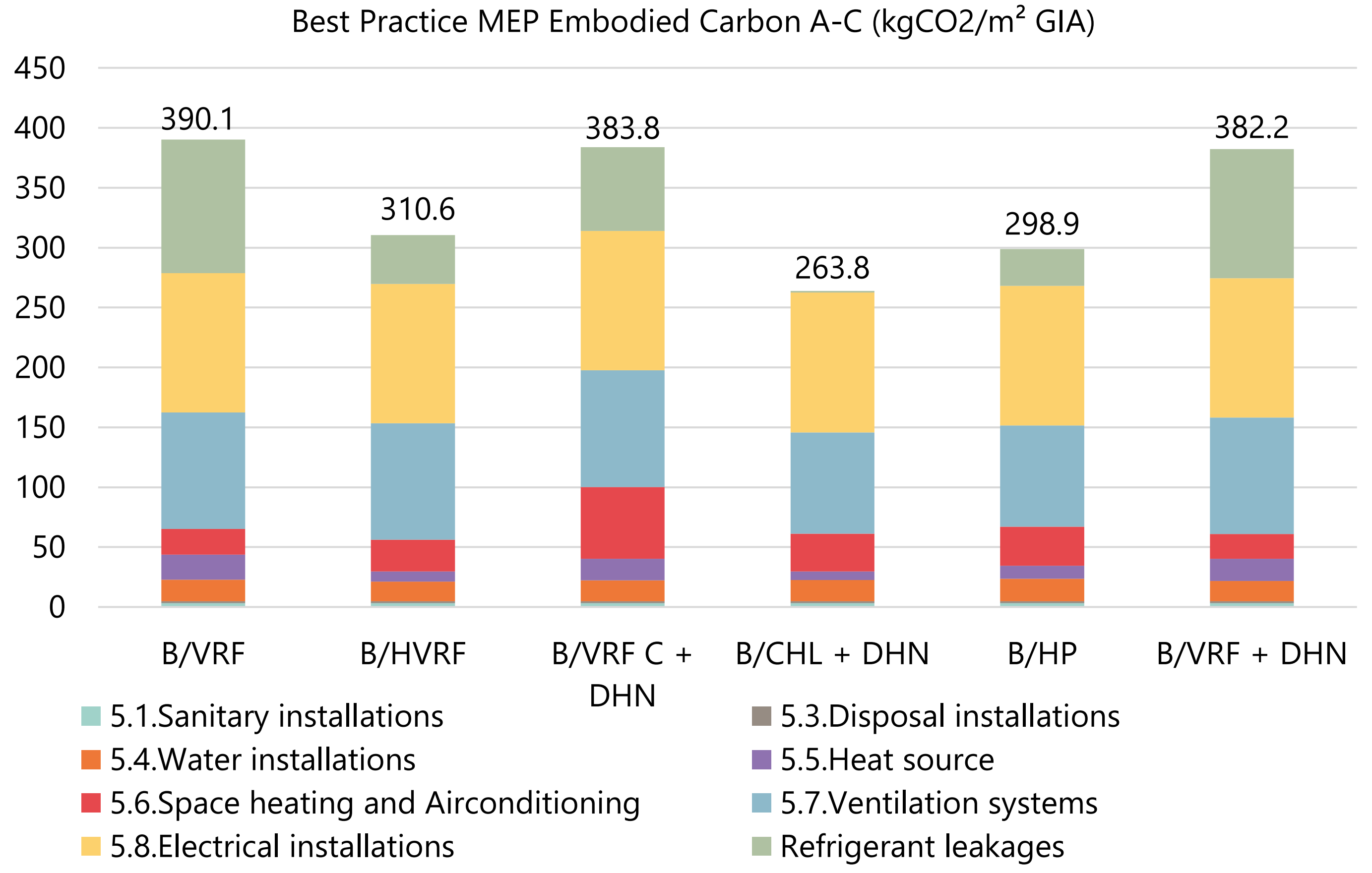
Top 7 contributors to the embodied carbon, in order of average contribution, are as follows:

1. Electrical distribution
2. Ventilation ductwork
3. Refrigerant
4. Space heating and cooling terminals (FCU's, trench heaters, etc.)
5. Heating and Cooling generation equipment (ASHP's, VRF, etc.)
6. Lighting
7. Photovoltaic panels

Heating and Cooling only equipment embodied carbon is analysed on the next page.


Embodied Carbon per Lifecycle Stage kgCO2/m² GIA


Current Practice MEP Embodied Carbon A-C (kgCO2/m² GIA)


Best Practice MEP Embodied Carbon A-C (kgCO2/m² GIA)

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Embodied Carbon Results

The below graphs show the current practice and best practice systems and how they perform only with regards to heating and cooling equipment. The impact of refrigerant in lifecycle phase B1 is clear, making VRF systems that would otherwise be relatively low embodied carbon into the worst performing systems.

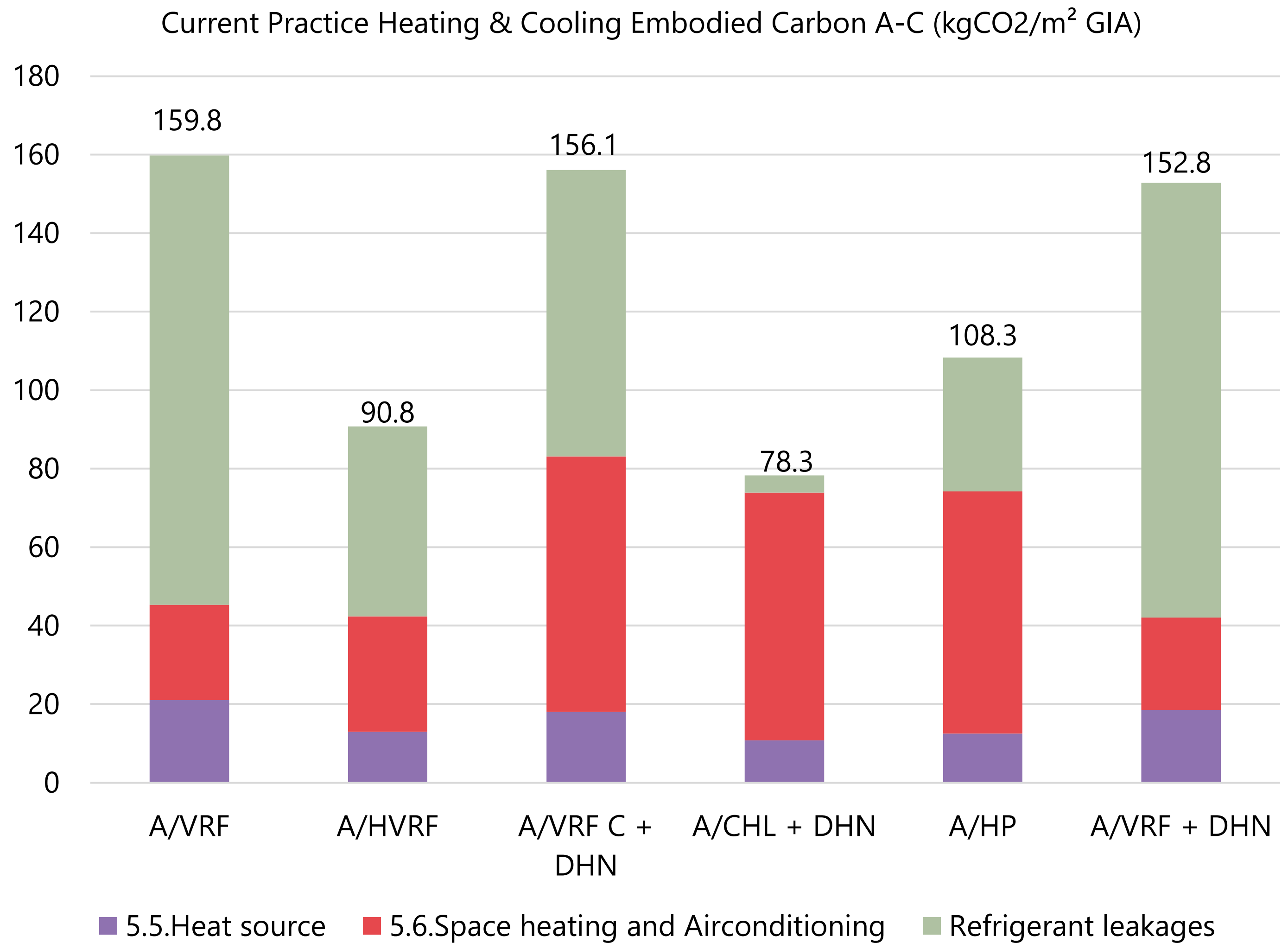
The HVRF and CHL + DHN systems between common and best practice scenarios demonstrate the biggest savings as in these cases it was possible to reduce the pieces of equipment, and weights of the 4-pipe FCUs, to deliver the best practice loads. For centralised systems this is more likely to be possible with load reductions.

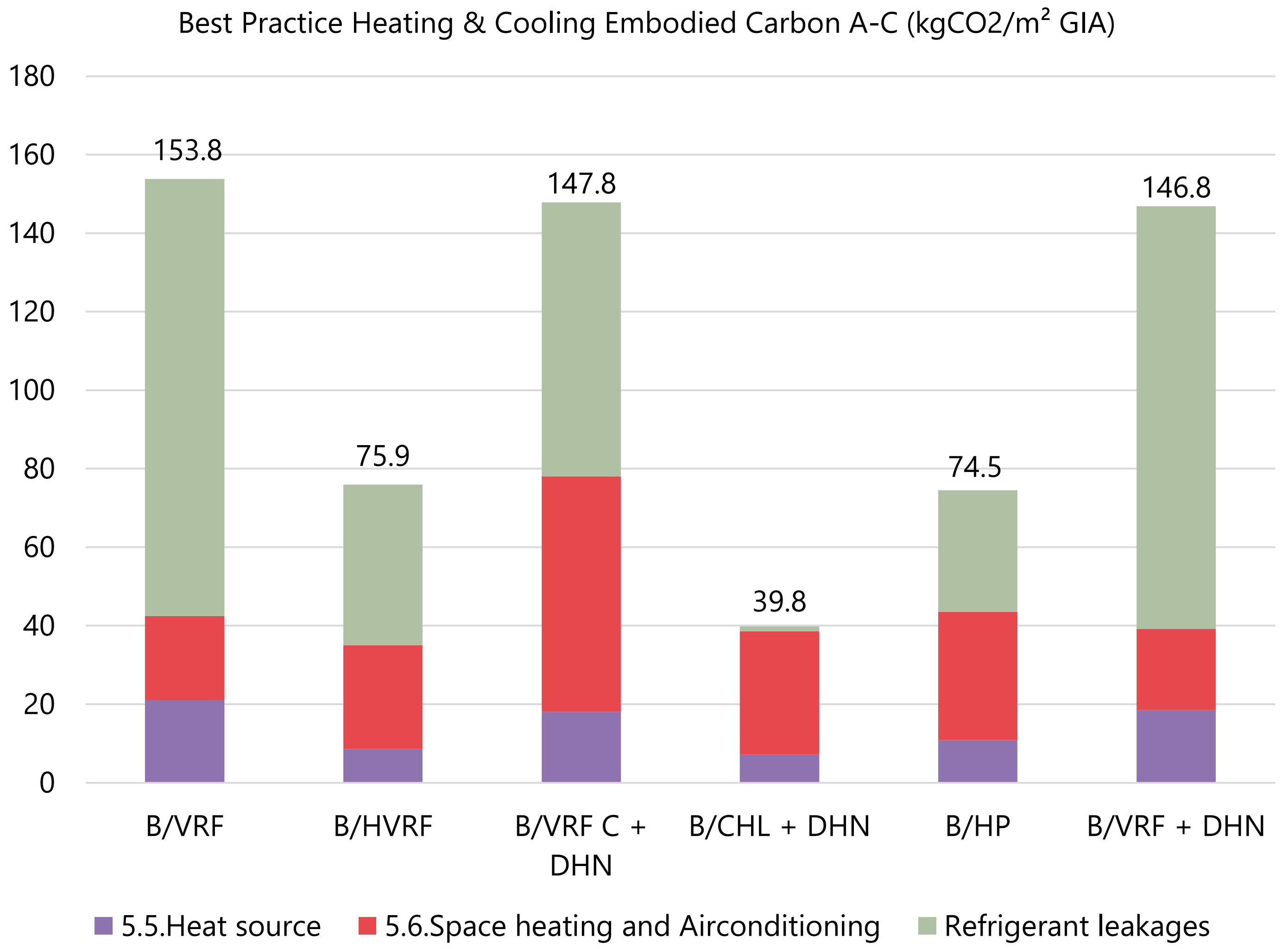
Discrete systems on the other hand (VRF in this case), as can be observed in these graphs, do not reduce in number and therefore the embodied carbon of the common and best practice system performs much more similarly compared to the centralised hydronic systems. Sizing is also affected by load diversity wherein decentralised systems need to be sized to room load whereas centralised systems will account for diversity – particularly solar gain. There is also a limitation in that available VRF FCU components for the system did not change in selection between the two scenarios, whereas the hydronic system FCU weights could be much lighter in best practice. Refrigerant based systems also tend to have more limitations attributed to the number of maximum connections or maximum refrigerant pipe length. In this case, this was largely due to the specified unit being R410A and R32 dual-compatible – when an R32 only unit is available this will allow for more connection flexibility.

HVRF systems, having predominantly hydronic pipework, do not have the same connection number limitations. However, the 5.6 values for the HVRF can be noted as higher, as HVRF components were found to be heavier when compared to the VRF equivalents.

The small difference between current and best practice scenarios is determined by the reduction in pipework sizes.

For VRF systems, there is a limitation to what is available on the market. For example, heat recovery VRF units are only available in larger capacities compared to cooling only VRF systems (R32 smaller units not available yet but it is something manufacturers are working towards).


Current Practice Heating & Cooling Embodied Carbon A-C (kgCO2/m² GIA)


Best Practice Heating & Cooling Embodied Carbon A-C (kgCO2/m² GIA)

A *– Current practice,* ***B*** *– Best practice,* ***VRF*** *– VRF Heating and Cooling with a dedicated DHW ASHP,* ***HVRF*** *– Hybrid VRF with a dedicated DHW ASHP,* ***VRF C + DHN*** *– Cooling only VRF with DHN for heating,* ***CHL + DHN*** *– chiller with DHN for heating,* ***HP*** *– hydronic heat pump only system with heat recovery unit,* ***VRF + DHN*** *– VRF Heating and Cooling and DHN for DHW only*

Embodied Carbon LETI and GLA Comparison

The pie charts to the right compare a typical MEP proportion from the study to the GLA typical Office A-C embodied carbon breakdown, and LETI's medium office building embodied carbon breakdown. It is worth noting that MEP embodied carbon information is ever increasing, and therefore inclusions into the Bristol City Council study are likely to be more detailed and inclusive compared to studies carried out in 2020 and prior.

The other building elements of the Bristol City Council study were calculated on a per GIA basis from a similar project (size and build). The superstructure and finishes element is inclusive of facades, integral partitions, stairs and ramps, the frame, and the roof., but considers a shell and core building, and therefore excludes FFE.

The GLA's anticipated whole life embodied carbon benchmark for a typical commercial office is between 1300-1500 $kgCO_2/m^2$ GIA, with LETI estimating 1000 $kgCO_2/m^2$ GIA, which aligns with the study's average result of approximately 1160 $kgCO2/m^2$ GIA.

The tables to the right show the MEP embodied carbon $kgCO_2/m^2$ comparing extrapolated LETI and GLA business as usual and aspirational values, for A1-A3 (Cradle to Gate) and A-C (Cradle to Grave) respectively. Comparison with the GLA shows that from A-C the BCC study compares more with the business as usual GLA result, however it should be noted that the GLA only considers refrigerants for one of its benchmarking sources from which it averages since we have determined that this is a significant contributing factor. This may be due to refrigerant emissions and lifespans. For example, using RICS lifespans would have less granularity and longer lifespans for equipment when compared with CIBSE Guide M values, particularly since the results align very closely with the LETI expected A1-A3 values for Best Practice.

The pie charts compare the overall proportion of MEP to the rest of the building, showing MEP as contributing similarly to what would be expected by LETI. Though this study did not alter information for other building elements between scenarios, this nonetheless demonstrates an alignment with best practice guidance studies.

A slightly higher embodied carbon result is expected as the granularity and accuracy of MEP embodied carbon studies increase.

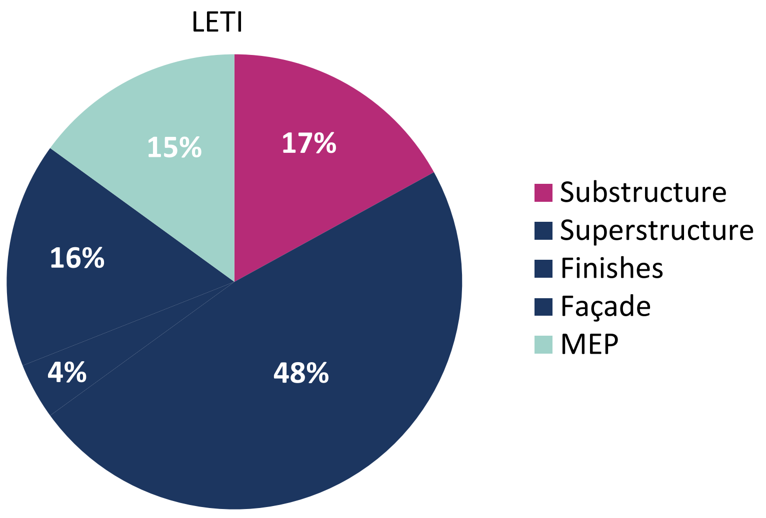
When compared with residential buildings, office buildings have traditionally had more MEP intensive strategies due to the requirement for cooling to counteract internal heat gains and high glass ratios. It would be expected that this discrepancy between "older" and "newer" strategies is less likely. In office buildings than with residential – a comparison which can be made if comparing with the residential study results on page 66.

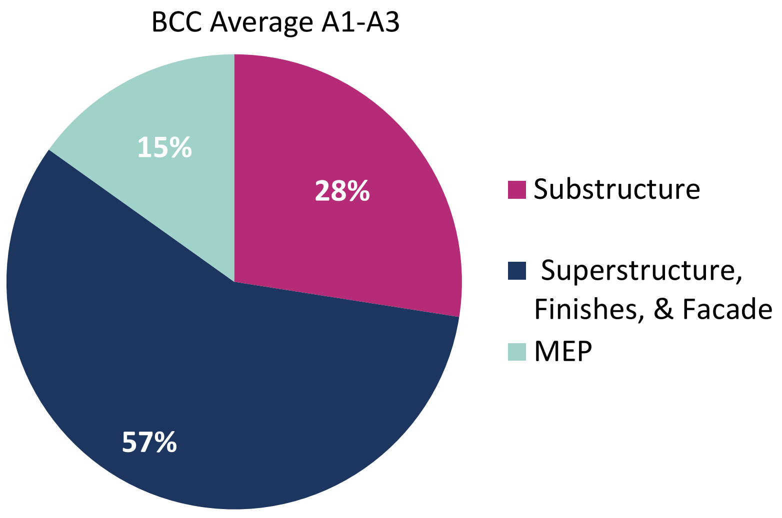
MEP Embodied Carbon $kgCO_2/m^2$ Cradle to Grave (A-C)

	GLA Business as Usual	GLA Aspirational	BCC Study (B/Average)
MEP Embodied Carbon	281	171	338

MEP Embodied Carbon $kgCO_2/m^2$ Cradle to Gate (A1 - A3)

	LETI Business As Usual	LETI Best Practice	BCC Study (B/Average)
MEP Embodied Carbon	150	90	93





Costing Results

MEP related costs can amount to ~25% of the total CAPEX, ~50% of the total of REPEX, and ~65% of the total OPEX.

There is an average cost reduction of ~£4,500,000 (~12% of whole life MEP costs) from the current to best practice building. The main contributing factor for the reduction is the OPEX costs which are linked closely to the EUI figures (without the DHN correction factor applied as presented on page 31).

The VRF options have the lowest whole life cost due to lower CAPEX and post completion costs (~4% reduction). Generally, the variances in options between best and worst amount to a 10% difference in relation to the MEP whole life costs, equating to 5% in whole building whole life costs.

Capital expenditure (CAPEX)

MEP capital costs are similar between current and best practice buildings meaning that a reduction in capacity does not have a significant impact on the upfront MEP cost (~2% decrease). Notable reductions in CAPEX are only observed when equipment is omitted entirely.

Across the options, VRF systems have the lowest CAPEX (3-5% lower than hydronic), and generally options with the DHN are shown to result in a ~3% increase in CAPEX due to connection fees. These fees contribute towards the capital costs of heating plant and distribution to provide heat to the building.

VRF C + DHN is the most expensive because of the doubling up of terminal equipment (FCUs + trench units) with the addition of the DHN connection fees.

Post completion costs (REPEX and OPEX)

The REPEX (replacement expenditure) is affected by the number of plant items/equipment installed and is a major driver for whole life costs due to the magnitude and repetition of payments. System options such as HP and VRF C + DHN have the most equipment and therefore incur the highest costs. There is no cost link to the volume of refrigerant utilised. The relative range in REPEX is ~8%.

In terms of the OPEX (operational expenditure) the real difference between the options are the utility costs and the DHN annual fixed charge. The relative range in OPEX is ~16% disadvantaging systems connected to the DHN. This is because maintenance and replacement costs of the DHN are captured within the utility bills which has been shown to increase by 8-15% mainly due to the annual fixed charge. This could impact the rentability of a commercial property as even though DHN connected systems can eliminate heating plant, the replacement of such major plant is usually not passed onto tenants as this work is carried out during non-tenanted periods.

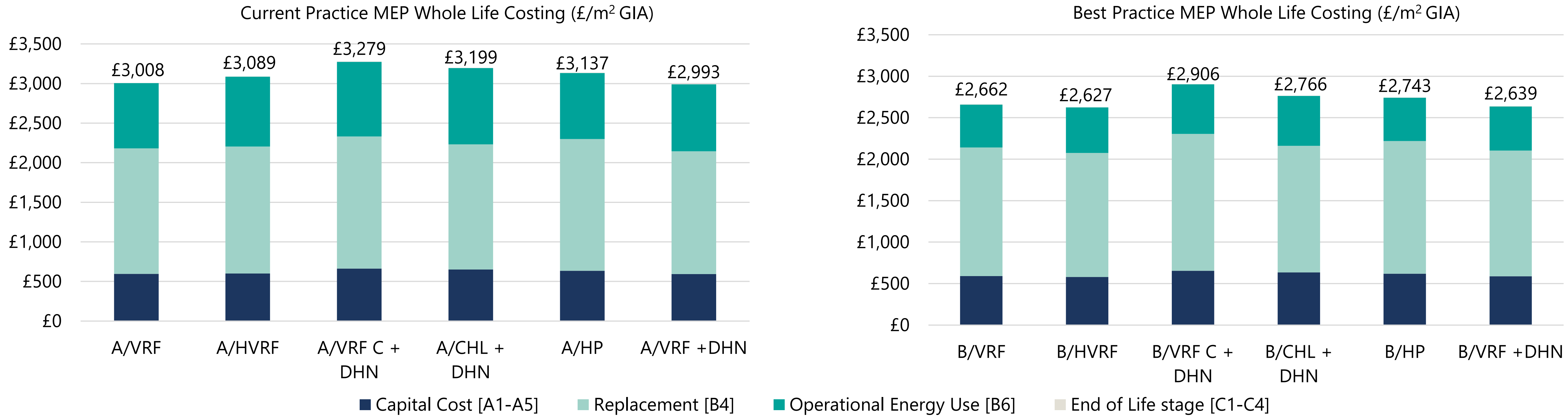
On the other hand, considering the total post completion costs (REPEX and OPEX) the DHN only incurs a 2% increase. Post completion costs result in a relative range of 9% amongst options.

End of life

End of life involves the act of deconstructing and managing disposal and processing. Therefore options with the highest material volumes can incur the highest costs. VRF C + DHN has the highest end of life costs due to the highest volume of overall materials (doubling up on terminal units). Also, handling of refrigerants can increase end of life costs.

Client engagement

Depending on the planned future engagement of the client with the building, the importance of these factors varies. For developers looking for a quick turnaround, CAPEX becomes an important factor that doesn't take the whole life cost or carbon into account. However, to sell the building they will require 'green' credentials and are seen to sacrifice on CAPEX to achieve them. For long term engagements however, REPEX and OPEX would be considered, which means that there would be a link to operational carbon, but there are no obvious links with embodied carbon as refrigerant based systems are usually more affordable. However, a link could be made when considering the cost of carbon offsets which has not been included in the scope of this study.



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Whole Life Carbon and Costing

The below graphs summarise the whole life cost and carbon for all the commercial options studied for MEP elements only.

From a whole life carbon for MEP systems, the major drivers are the type and volume of refrigerant used, along with the annual demand of the building. Therefore hydronic systems incur the least MEP whole life carbon (10-16% less than VRF systems), and a reduction in annual demand associated with the best practice design approach reduced MEP whole life carbon proportionally by ~17% for all options, mainly due to reductions in operational carbon.

Differences between current and best practice options

The embodied carbon per system does not change drastically between current and best practice scenarios but there are a few notable drivers for observed variances. Reductions in capacity of main plant have the least impact, whereas if plant is omitted entirely this provides a noticeable difference, where the reduction in overall refrigerant is the main driver. Finally, the hydronic systems were able to utilise a lighter fan coil unit once the space loads were reduced providing significant embodied carbon reductions.

Significant improvements to operational carbon can be observed with the reduction of annual demands (~38% reduction in operational carbon). This is mainly due to the reduction in tenant power followed by improvements to the façade, and in some scenarios, elevated chilled water temperatures. The improvements to operational carbon are linked to the significant reductions in OPEX. This is an important consideration for rental prices.

Differences amongst options

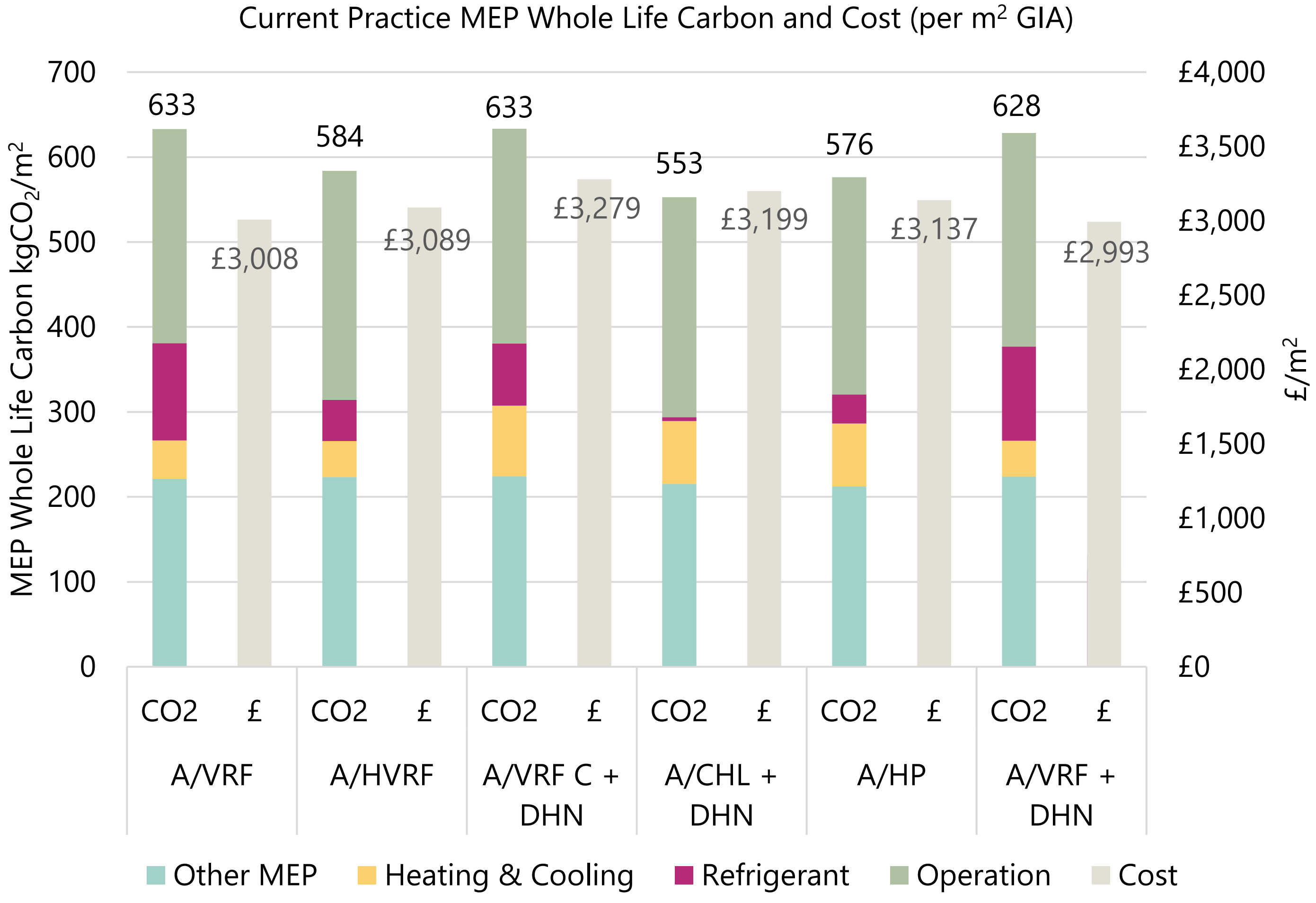
The VRF options (not including HVRF) all have similar associated whole life carbon but with varying whole life costs, which are due to the cost of trench units and DHN associated fees. These systems also incur the highest whole life carbon despite using R32.

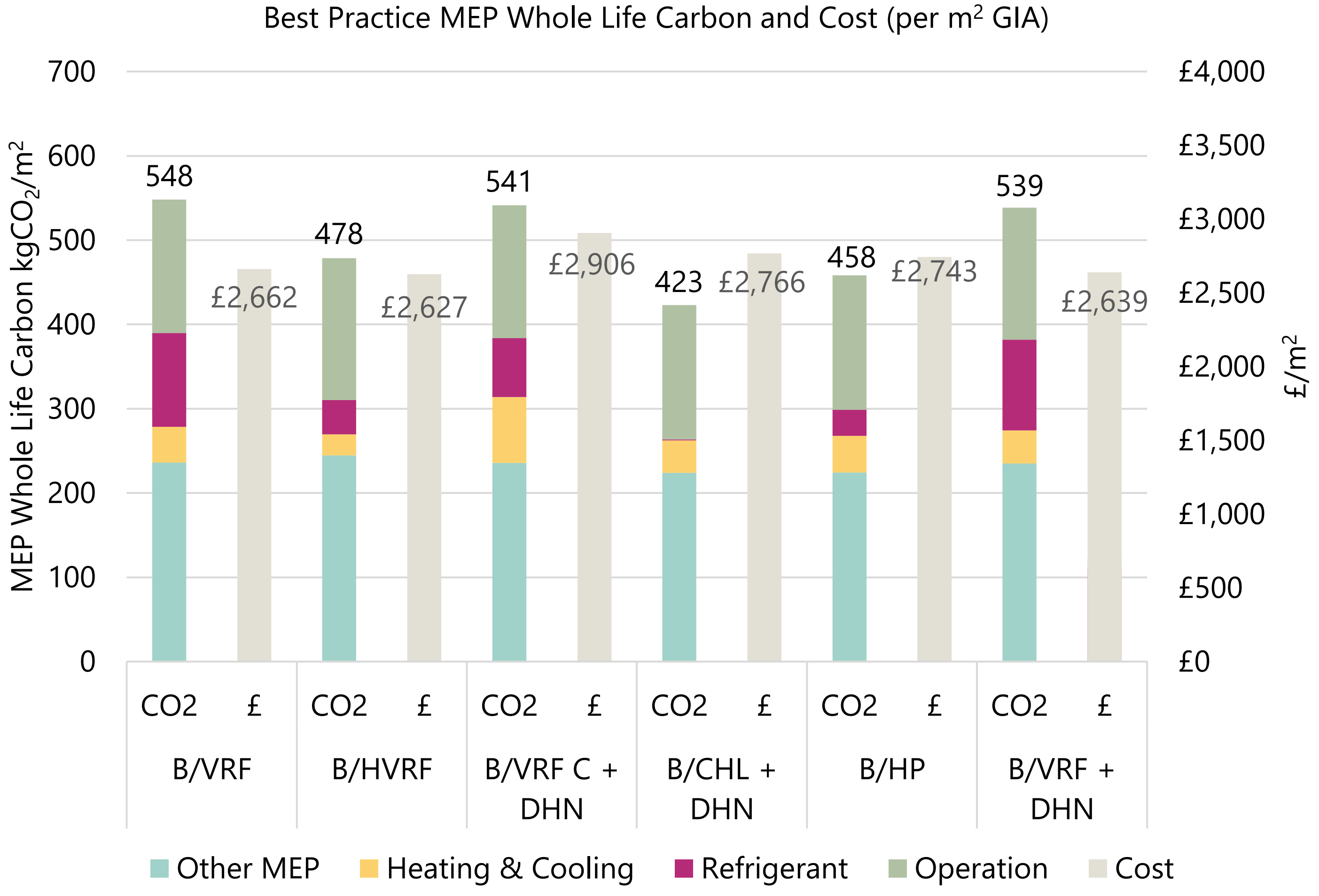
Operational carbon is generally similar across all options due to the fact that fundamentally all of these systems are derivatives of heat pump technologies including the DHN, which is essentially being transitioned to heat pumps.

The VRF systems have the lowest whole life MEP costs (~4% less than hydronic) and systems with DHN connections can induce a 1-2% increase to whole life MEP costs.

Summary

Across the options, it is shown that CHL + DHN results in the least whole life carbon. The VRF C + DHN system has a high cost and carbon due to the doubling of terminal units in addition to DHN costs. Adopting best practice design targets along with the use of ultra low GWP refrigerants, results in the most impactful reductions to whole life carbon.


Current Practice MEP Whole Life Carbon and Cost (per m² GIA)


Best Practice MEP Whole Life Carbon and Cost (per m² GIA)

__A__ – Current practice, __B__ – Best practice, __VRF__ - VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

Whole Life Carbon and Costing

Context to the whole building

The below graphs summarise the whole life cost and carbon for all the commercial options studied which includes benchmark estimations for non-MEP elements to provide context for the whole building carbon and costs.

As shown, the entirety of the MEP elements (embodied and operational) can make up 45% of the whole life carbon given a decarbonising grid. The MEP materials contribute 21% to the total, of which 17-25% is for heating/cooling systems, whilst refrigerant leakages can make up, up to 9% of the total depending on the type and volume of refrigerant in the system.

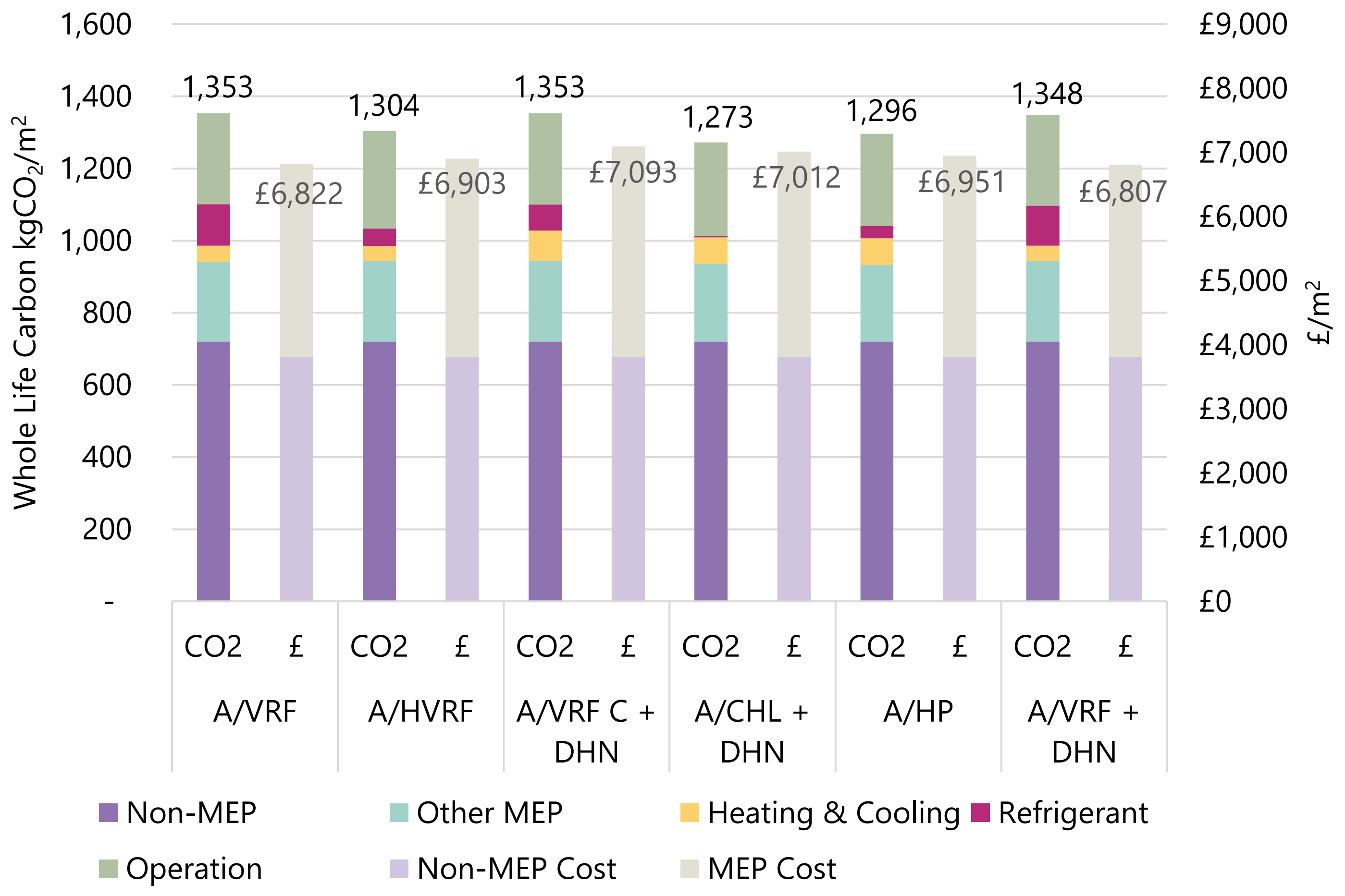
The whole life carbon results represent a percentage relative range of 6% amongst system options for the current practice scenarios and 10% for the best practice scenarios.

The best practice design approach of reducing annual demands results in a ~8% proportional reduction in whole life carbon across all options (mainly due to reductions in operational carbon) with a ~6% reduction in whole life costs (mainly due to reductions in OPEX).

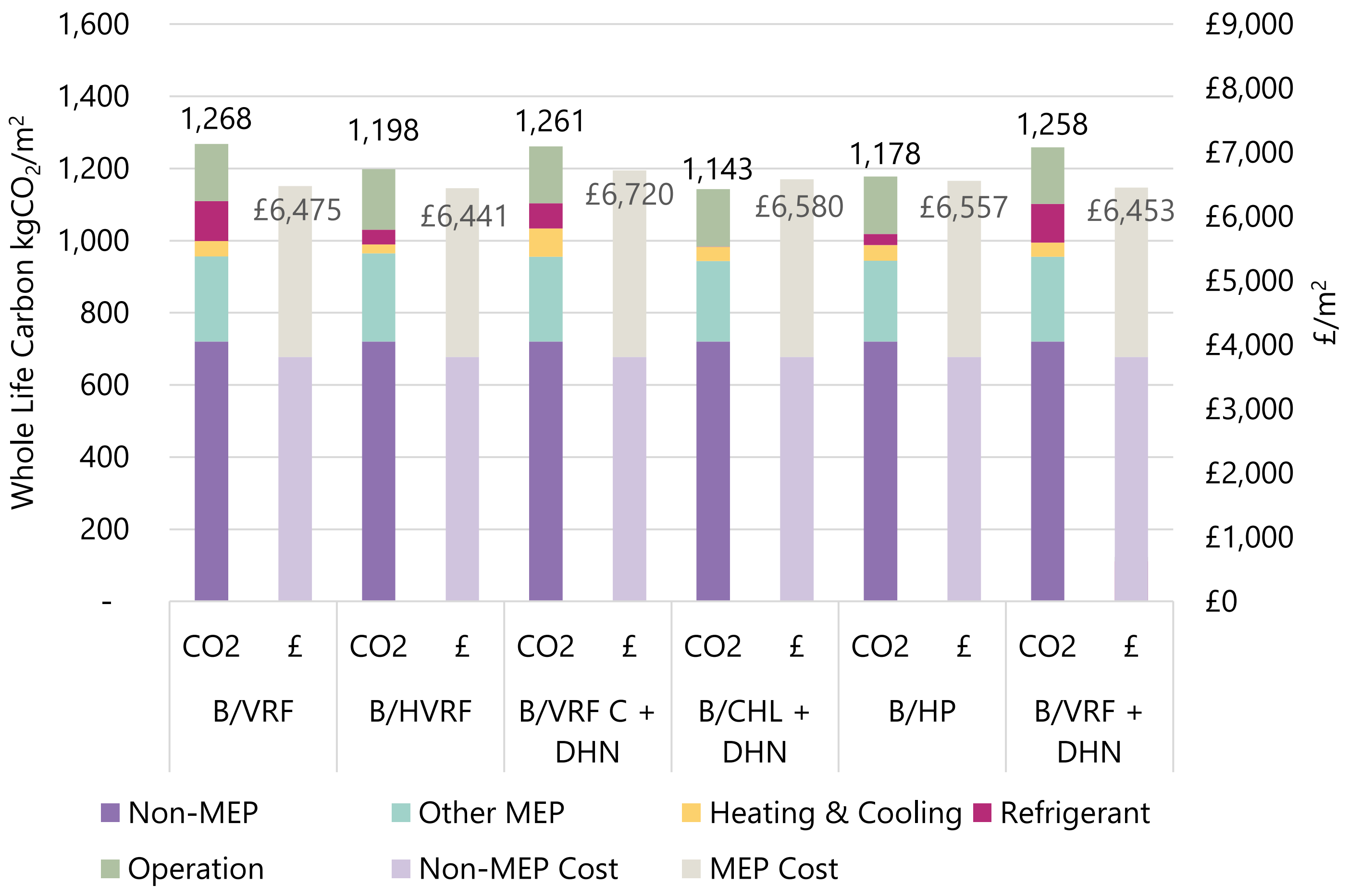
Whole life costs show a reasonable difference between options where variances are captured between a relative cost range of ~4% favouring VRF systems.

The whole building whole life carbon also reveals that hydronic systems can result in 4-7% less whole life carbon compared to VRF systems, but cost 1-2% more in terms of whole life costs.

Current Practice Whole Life Carbon and Cost (per m^2 GIA)



Best Practice Whole Life Carbon and Cost (per m^2 GIA)



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System Evaluation Summary | Commercial

The charts on this page summarise the variation in performance between each system scenario for each of the carbon emissions metrics; Part L2A compliance, operational carbon and whole life carbon.

The graphs show the relative reduction/improvement (shown as a negative bar) or increase/shortfall (shown as a positive bar) in carbon emissions for each system with respect to the mean average of all systems for the current and best practice scenarios respectively. As such, the 0% level indicates the average performance, the most negative bar is the best performing, lowest carbon system and the most positive bar is the worst performing, highest carbon system.

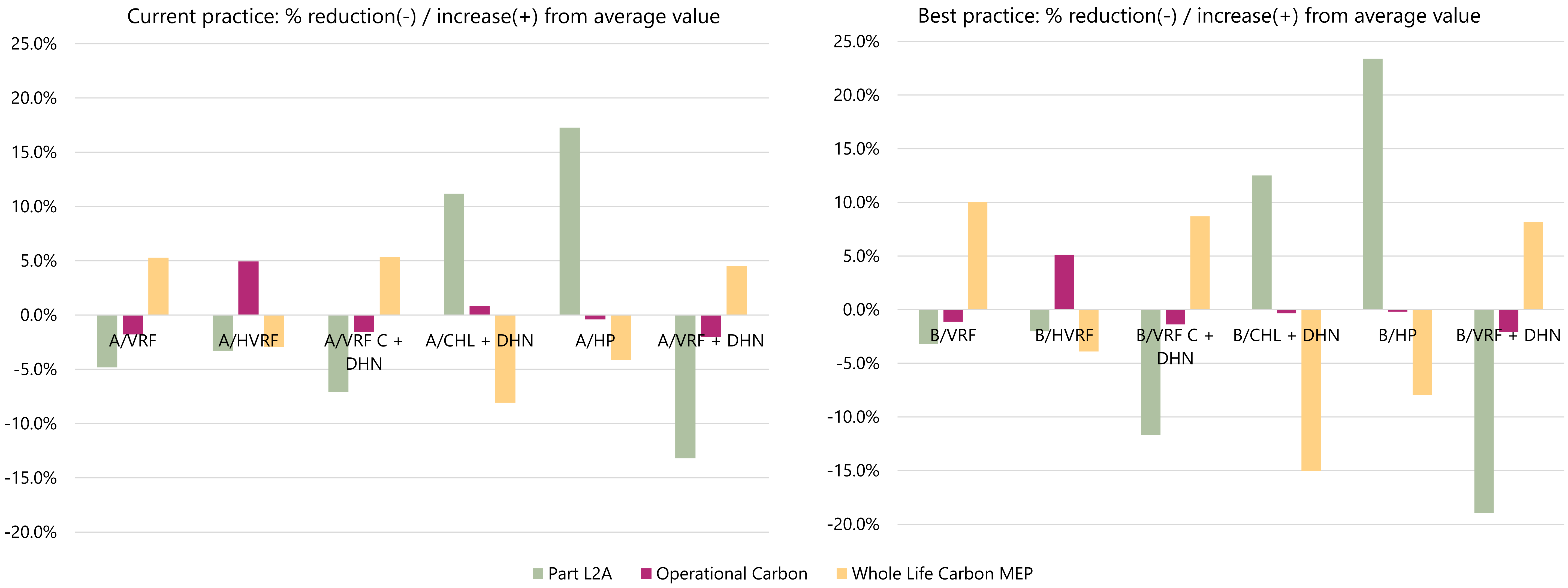
The Part L2A compliance results show the greatest variation between system options from the average, ranging from -19% reduction for VRF + DHN option to +23% increase for the HP option. As discussed previously, Part L favours VRF systems in terms of expected CO_2 emissions and the connection to the DHN provides a benefit to heating generation associated carbon emissions due to the network carbon intensities provided by BCC.

In contrast, the calculated operational energy shows smaller variation between system options ranging from -2% reduction for the VRF options to +5% increase for the HVRF option which is shown to be an outlier in terms of operational carbon emissions.

The whole life carbon results are different again with a notable variation ranging from -15% reduction for CHL + DHN to +10% increase for the VRF options, mainly due to refrigerants.

Between the current and best practice graphs, the trends discussed are similar. However, for the best practice case, systems that are connected to the DHN for compliance are shown to provide an additional benefit. This could be due to an increase in the weighting of DHW generation, caused by an improvement to the fabric, where the DHN is favoured for compliance as it is shown to result in less carbon emissions.

The trends for operational carbon are almost identical between the two scenarios. Therefore, changes to the extent of whole life carbon variance are due to embodied carbon. Differences include changes to terminal unit weights, and refrigerant volumes and GWPs.



__A__ – Current practice, __B__ – Best practice, __VRF__ – VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

System Evaluation Summary | Commercial

<table>
<tr><th rowspan="4">Category</th><th colspan="12">Commercial Office Options</th></tr>
<tr><th colspan="2">VRF heating and cooling, DHW from ASHP and local direct electric POU</th><th colspan="2">Hybrid VRF heating and cooling (i.e. hydronic system in occupied spaces then refrigerant system to outdoor units)</th><th colspan="2">Hydronic heating with district heating connection, VRF cooling</th><th colspan="2">Hydronic heating with district heating connection, hydronic cooling with central chiller</th><th colspan="2">Hydronic heating and cooling with central heat recovery heat pump/chiller and top-up air source heat pumps and chillers</th><th colspan="2">VRF heating and cooling, district heating connection for DHW</th></tr>
<tr><th colspan="2">VRF</th><th colspan="2">HVRF</th><th colspan="2">VRF C + DHN</th><th colspan="2">CHL + DHN</th><th colspan="2">HP</th><th colspan="2">VRF + DHN</th></tr>
<tr><th>Rating</th><th>Comments</th><th>Rating</th><th>Comments</th><th>Rating</th><th>Comments</th><th>Rating</th><th>Comments</th><th>Rating</th><th>Comments</th><th>Rating</th><th>Comments</th></tr>
<tr><td>Whole life carbon (MEP)</td><td>+5%</td><td>High whole life carbon due to refrigerants</td><td>-3%</td><td>Hybrid VRF reduces refrigerant volumes</td><td>+5%</td><td>Lower refrigerants but increase in terminal units</td><td>-8%</td><td>Least amount of equipment and refrigerants</td><td>-4%</td><td>Heat recovery systems increase refrigerant volumes</td><td>+5%</td><td>High whole life carbon due to refrigerants</td></tr>
<tr><td>Whole life cost (MEP)</td><td>-4%</td><td>Lowest equipment and operation costs</td><td>-1%</td><td>Low equipment costs but higher operational costs (lower efficiency)</td><td>+5%</td><td>Additional terminal units increase CAPEX but low operation costs</td><td>+3%</td><td>Slight premium to utility bills with a DHN connection</td><td>+1%</td><td>Increase in CAPEX, OPEX and REPEX for hydronic systems</td><td>-4%</td><td>Lowest equipment and operation costs</td></tr>
<tr><td>Compliance model results</td><td>-5%</td><td>Part L assumes less energy use for VRF systems</td><td>-3%</td><td>Slightly lower seasonal efficiency compared to standard VRF</td><td>-7%</td><td>Cooling only VRF more efficient than standard VRF in cooling mode</td><td>+11%</td><td>DHN has favourable CO_2 emissions and chillers more efficient</td><td>+17%</td><td>Lower efficiencies assumed for cooling but higher for heating</td><td>-13%</td><td>VRF space heating is more efficient than DHN</td></tr>
<tr><td>Ability to meet potential future standards</td><td colspan="12">All options studied have a similar potential to meet future standards</td></tr>
<tr><td>Useability, operation and maintenance</td><td colspan="6">Refrigerants increase maintenance requirements</td><td colspan="2">Reduced amount of plant due to connection to DHN</td><td colspan="2">Addition of plant and complexity of controls</td><td colspan="2">Refrigerants increase maintenance requirements</td></tr>
<tr><td>Potential constraints or impacts the selection of the option may have on the wider building design</td><td colspan="4">Electric heaters may be required where the installation of a dedicated VRF system is cost prohibitive (e.g. back of house)</td><td colspan="2">Incompatibility between VRF and the DHN for space conditioning; extra terminal units (FCU & trench units)</td><td colspan="2">Provision for a heat substation and compliance with BCC heat network technical specifications</td><td colspan="2">Design flow and return temperatures could dictate size of distribution and terminal units</td><td colspan="2">Electric heaters may be required where the installation of a dedicated VRF system is cost prohibitive (e.g. back of house)</td></tr>
<tr><td>Comfort for occupants</td><td colspan="12">All options have mechanical heating and cooling via fan coil units (convective) so are broadly similar</td></tr>
<tr><td>Impacts on the wider environment (e.g. cold pluming, urban heat island)</td><td colspan="12">Noise and visual mitigation required for rooftop heat pumps. Heat pumps can contribute to cold pluming and urban heat island effects due to heat acquisition and rejection. DHN would have a similar effect as it is largely heat pump lead and therefore would displace the impacts to another location</td></tr>
<tr><td>Extent to which systems are ‘future climate ready’</td><td colspan="6">System replacement required. Oversizing VRF systems adversely impacts performance</td><td colspan="4">Future climate provisions can easily by making expansion provisions</td><td colspan="2">System replacement required. Oversizing VRF systems adversely impacts performance</td></tr>
</table>

*ratings are based on the percentage differences from the average for the current practice results (A). Therefore a negative (-) result represents an improvement in carbon/cost.

*A – Current practice, **B** – Best practice, **VRF** – VRF Heating and Cooling with a dedicated DHW ASHP, **HVRF** – Hybrid VRF with a dedicated DHW ASHP, **VRF C + DHN** – Cooling only VRF with DHN for heating, **CHL + DHN** – chiller with DHN for heating, **HP** – hydronic heat pump only system with heat recovery unit, **VRF + DHN** – VRF Heating and Cooling and DHN for DHW only*

Simultaneous Loads

An assessment on the appropriateness of heat recovery between heating and cooling circuits for the current practice office building was carried out.

Building profile

The building is cooling dominated due to the high internal gains and low air permeability of the envelope. The majority of heating loads originate from overdoor heaters, WC AHU heating, and DHW for showers. Server cooling is on dedicated DX units and therefore do not contribute to the base cooling load. As the loads are dispersed across multiple systems, this would suggest that heat recovery opportunities exist principally with centralised HVAC systems.

This is supported by VRF system dynamic simulations, where the systems are set up discretely, and the results show that the outdoor units essentially switch between cooling or heating only modes without utilising their heat recovery functionality.

The ratio of simultaneous demand for each 24 hour day was calculated and plotted [1] to showcase the simultaneous load potential (1 representing maximum simultaneous potential whilst 0 representing no potential). This shows that over a 24 hour period, there are instances in the shoulder seasons when the heating demands match the cooling demands, signifying the potential for simultaneous generation. However, very large thermal stores would be needed to load shift across a 24-hour period. In relation to the modelling completed with 1-hour thermal storage, 36% of the annual heating load was met in simultaneous mode. While this suggests reasonable potential exists, the whole life carbon benefits are questionable.

Simultaneous heat pump performance

As shown in the chart below, the heating efficiencies are significantly increased with a simultaneous cooling load, but at the cost of a lower cooling efficiency in comparison to a high performance chiller.

As the building does not have high heating demands the benefit of heating in simultaneous mode is cancelled out by the reduction in performance of the cooling system. It was found that a system without heat recovery functionality was worse only by an additional 1.2kgCO_2/m^2 over its 60 year life time (<0.5% increase to the operational carbon).

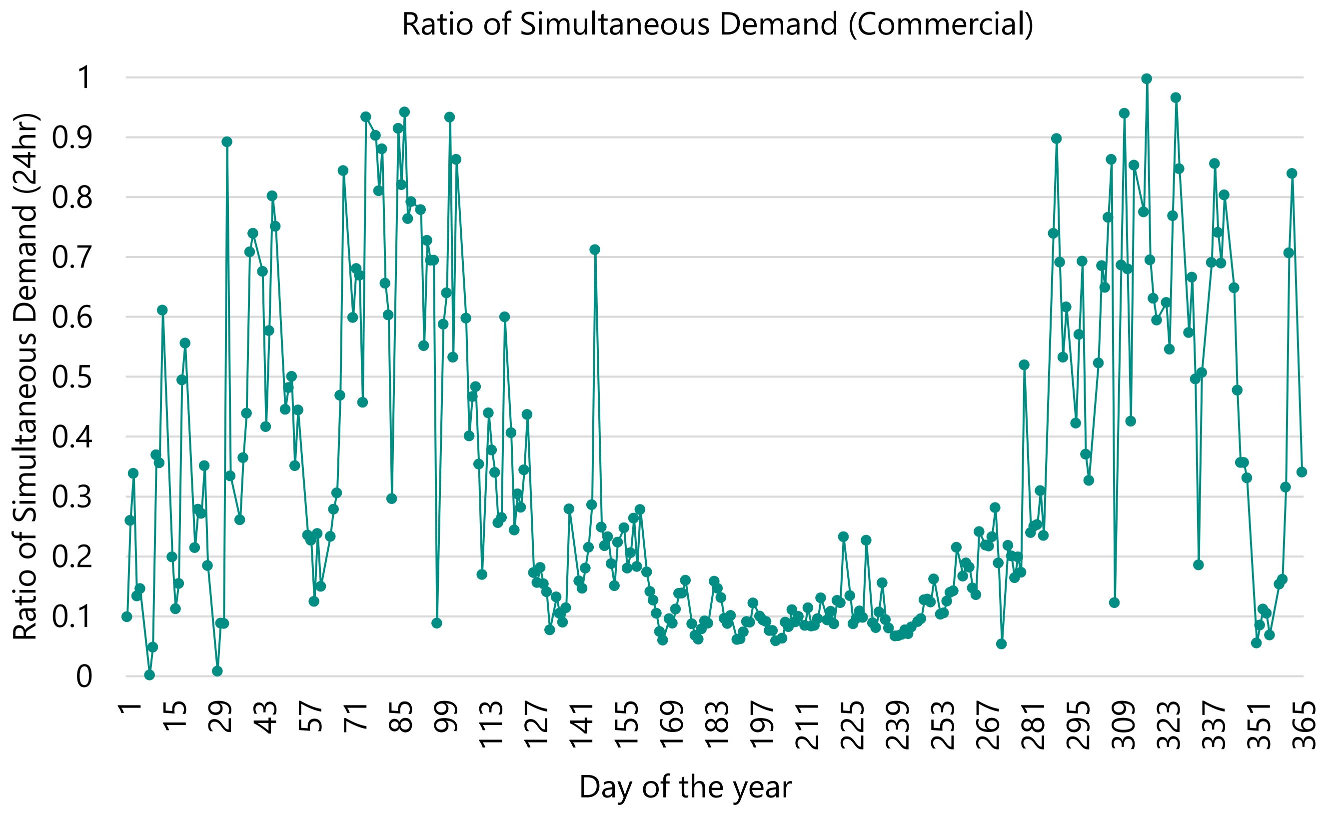
Based on this exercise, simultaneous heating and cooling generation seem to be more beneficial in systems within a heating dominated building.

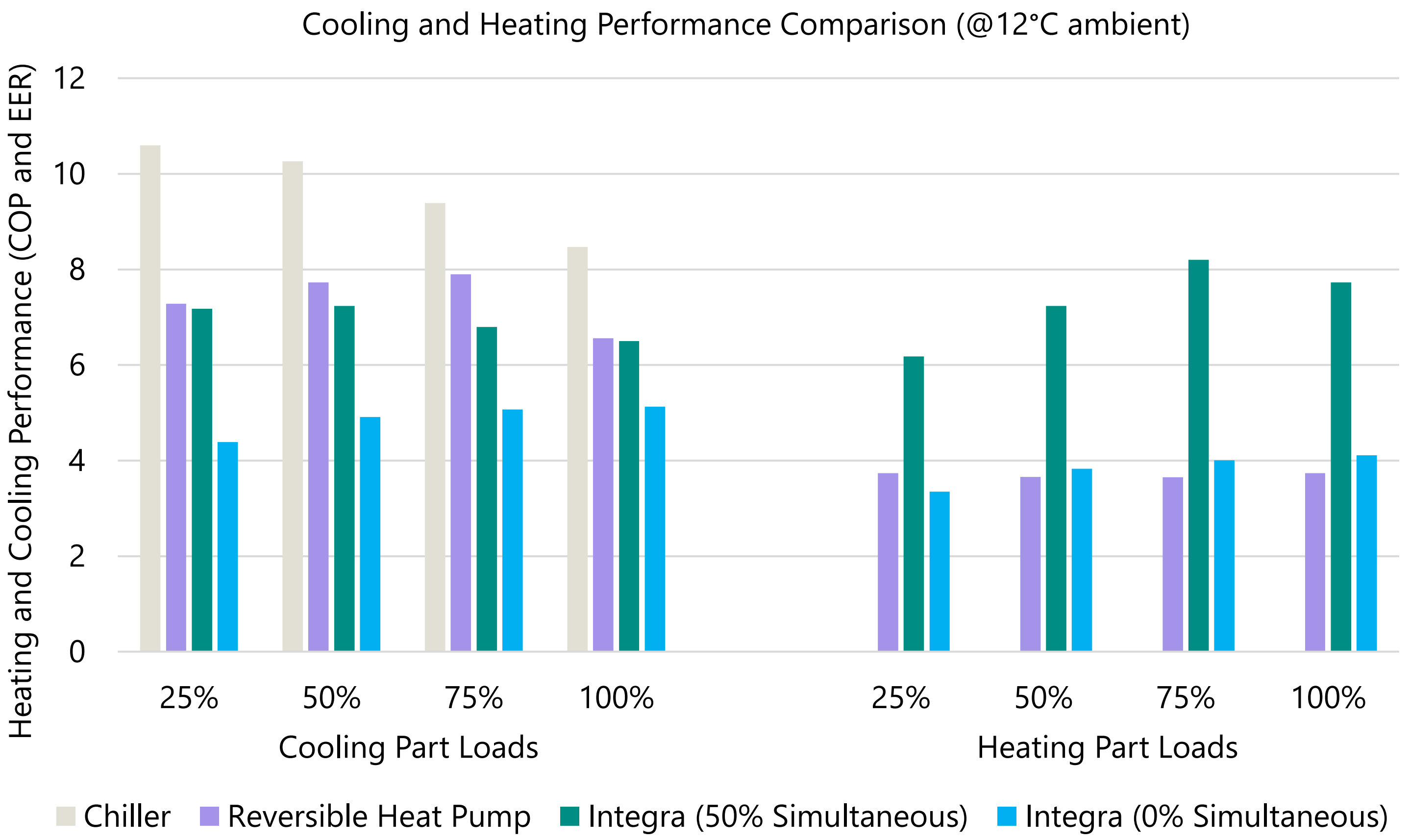
Embodied carbon emissions

When this is compared to the embodied carbon with a system without heat recovery, this results in a reduction of 14.3kgCO_2/m^2, mainly due to a reduction in refrigerant (90% of the reduction). This is because simultaneous units are not currently available with ultra-low GWP refrigerants (e.g. R1234ze). And when this is combined with the DHN, further reducing on-site plant, this results in an overall reduction of 30.0kgCO_2/m^2 (difference in heat source and refrigerant between A/CHL + DHN & A/HP page 36). The embodied costs are therefore likely to outweigh the operational benefits for commercial offices in most situations.

Further considerations

The potential for simultaneous heating and cooling can be considered where there are sufficient heating loads. Buildings with a closed plan layout including multiple meeting rooms, or with large retail/catering spaces could potentially increase the heating load enough to warrant a heat recovery system.





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[1] Byrne et al. the ratio of simultaneous demand was calculated according to the methodology outlined in this scientific paper

Sensitivity Analysis | Future Climate

Future climate impact on results

The operational models were also run on the Cardiff 2050 Medium 50th percentile and 2080 Low 50th percentile weather files in addition to the 2020 High 50th percentile weather file (used as the base for the operational modelling).

These additional runs illustrate the sensitivity of the results to predicted future climate scenarios.

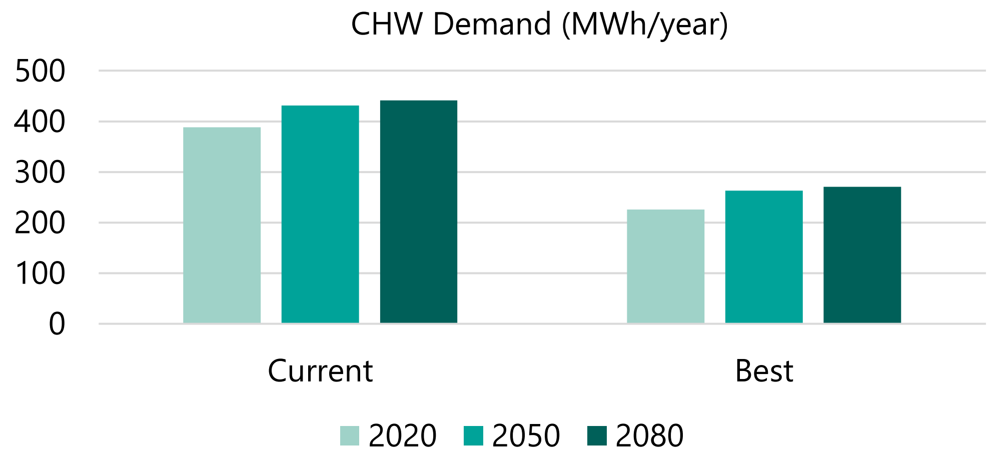
As expected, the cooling demands increased with the warmer weather whilst reductions in heating demands occurred. When comparing the changes to EUI and operational carbon, it was found the impact was generally marginal, resulting in a net increase in EUI of ~0.2-0.4kWh/m²/year. This is not sufficient enough to make a notable difference across options or to impact the conclusions of the study. This represents a net change of <1% of the total energy.

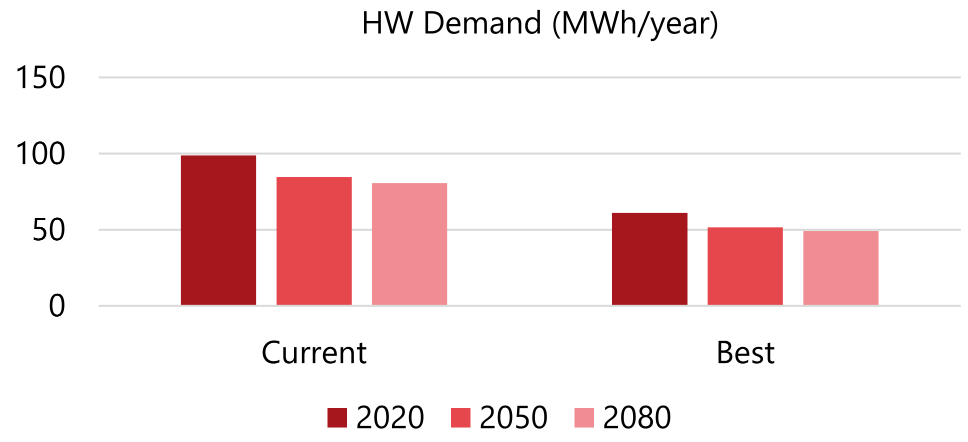
The below charts highlight these changes between the different weather files and how it impacts the current and best practice buildings. Across the options, there may be slight variations but ultimately these variations will be in this order of magnitude. Therefore results from one option only (HP) have been presented to illustrate the observed changes.

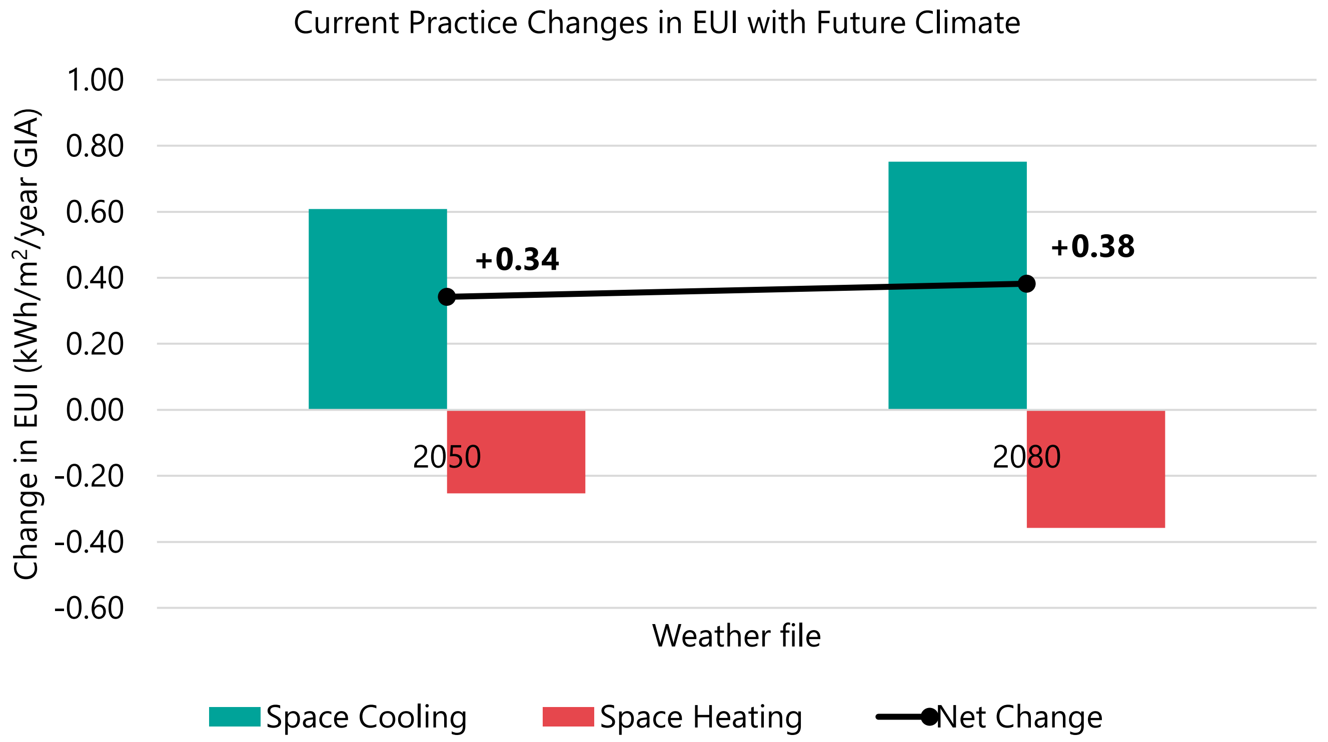
It was identified that only the heating and cooling parameters would be affected by the warming climate. It was found that fan energies were broadly unchanged and therefore not reported in the charts below. In both cases, the 2080 weather results in a 16% cooling related energy demand increase whilst the space heating energy demand is reduced by 25%.

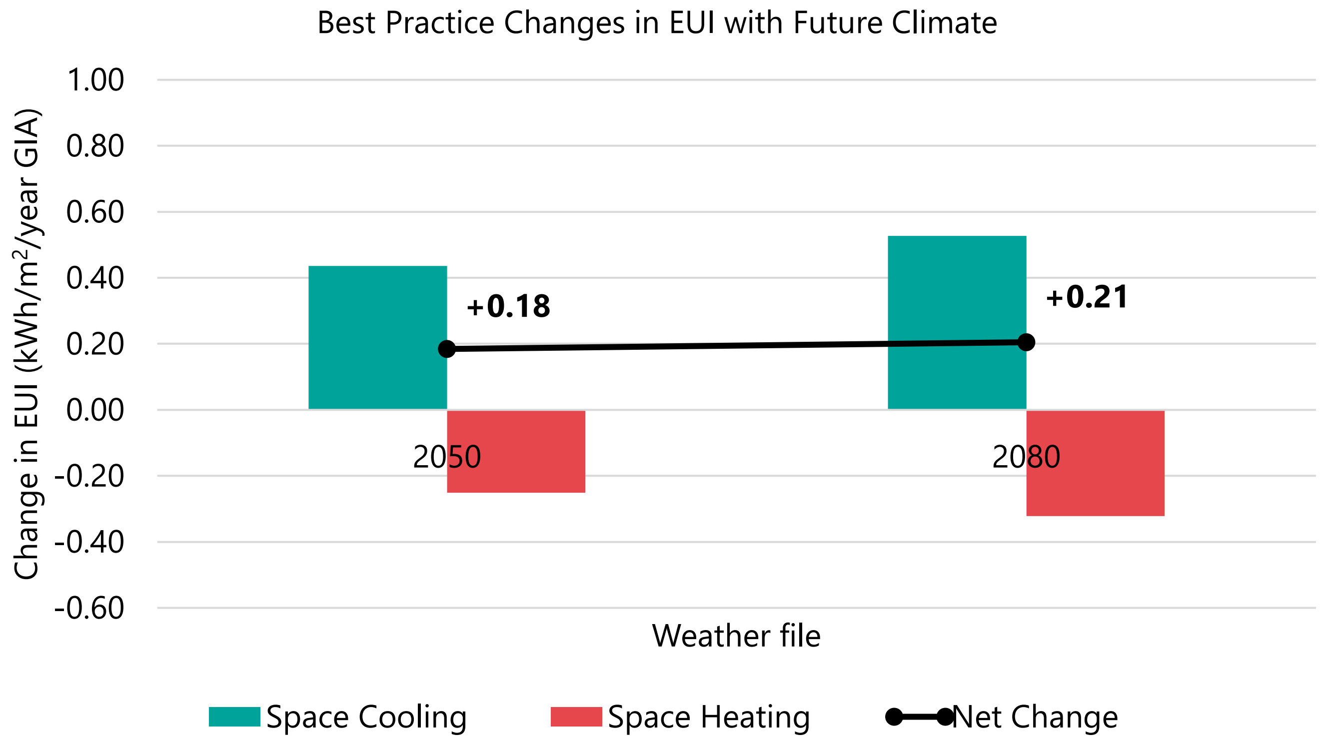
It is possible that a mixed mode approach could benefit from warmer ambient conditions as this could increase the number of hours viable for natural ventilation. With the climate change scenarios considered, a ~20% increase in number of natural ventilation hours is possible; this increase represents ~4% of the total occupied hours. Of course the extent of utilisation/benefits depends on site suitability (e.g. acoustics, building form, location and air quality) and the assumption that the façade design addresses solar gain suitably.

In terms of performance, the cooling seasonal efficiencies for the case modelled were largely unaffected, with only minor degradations in performance observed. The heating systems showed an increase in seasonal efficiency due to rising temperatures (~10% in 2050).









Sensitivity Analysis | Plant Efficiencies EUI

Primary plant efficiencies impact on EUI

The entirety of the results generated is based on manufacturer data. Without the ability to validate the performance figures, lies a level of uncertainty. It is assumed that figures provided from the manufacturers represent the top end of the achievable performance and therefore performance figures have been adapted to a 10%, 30%, and 50% degradation to illustrate the impact of inefficiencies on the overall EUIs. As these inefficiencies are all related to electricity use, the operational carbon would increase proportionally. The below charts utilise the DHN EUI corrected figures (page 34).

Systems that are connected to the DHN are less affected by overall primary plant inefficiencies because the efficiency of the DHN is out of the control of the designer/installer/building operator. This is shown as a flatter line across different inefficiencies. Assumed efficiencies are maintained for the DHN as it is in the DHN operator's best interest to ensure continual efficient heat generation.

As outlined on page 90 VRF systems could be prone to high efficiency degradation factors as the efficiency of the system is dependant on maintaining the operating volume of refrigerant in the system. In cases where refrigerant leakage rates are high, these degradation scenarios may be realised. The risk of this increases with the volume of refrigerant (charge) in the system and if it is used as a means of heat distribution.

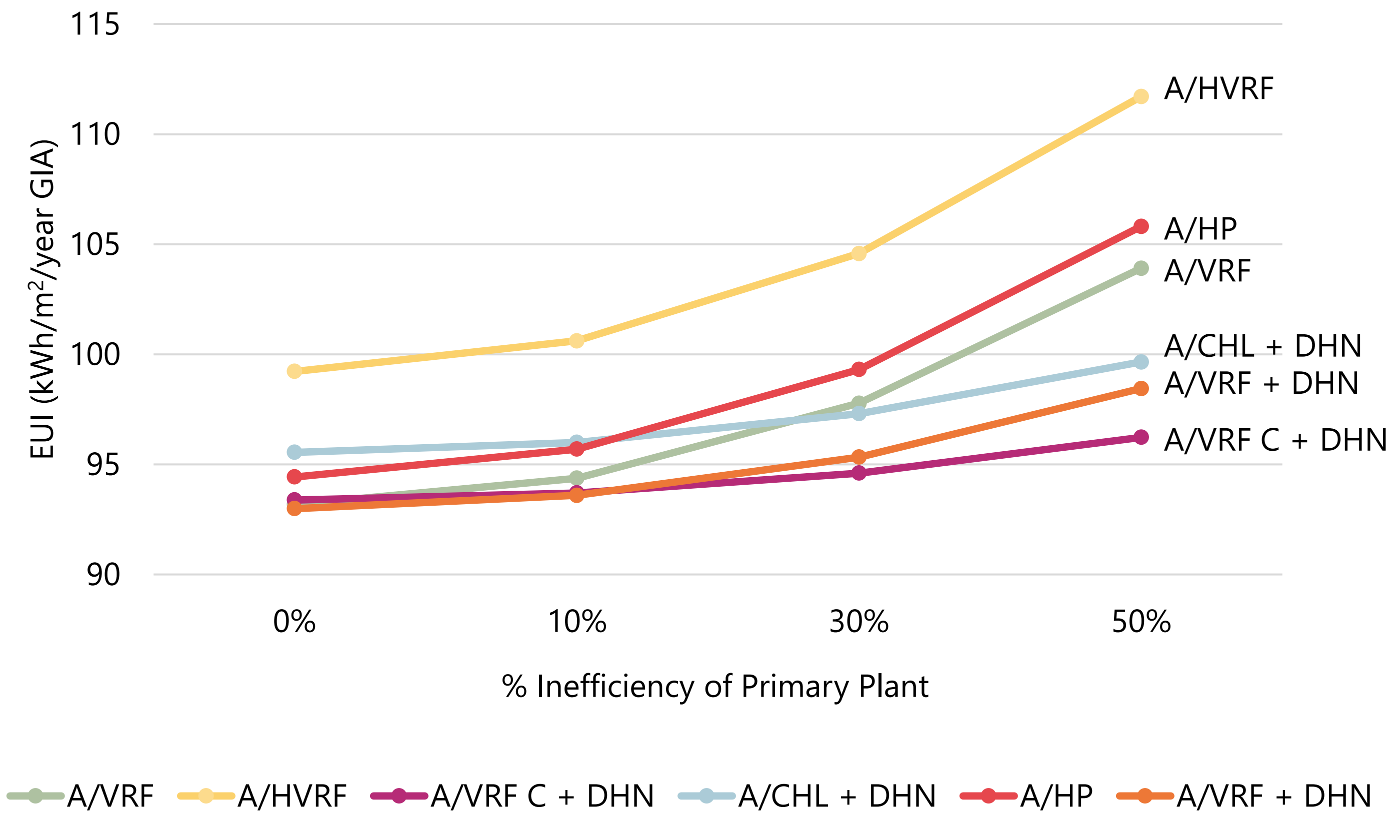
The inherent assumed efficiencies play a part in determining how much they are affected by performance degradation. For example, it was identified that HVRF was the least efficient system and therefore incurs the highest penalty for further inefficiencies.

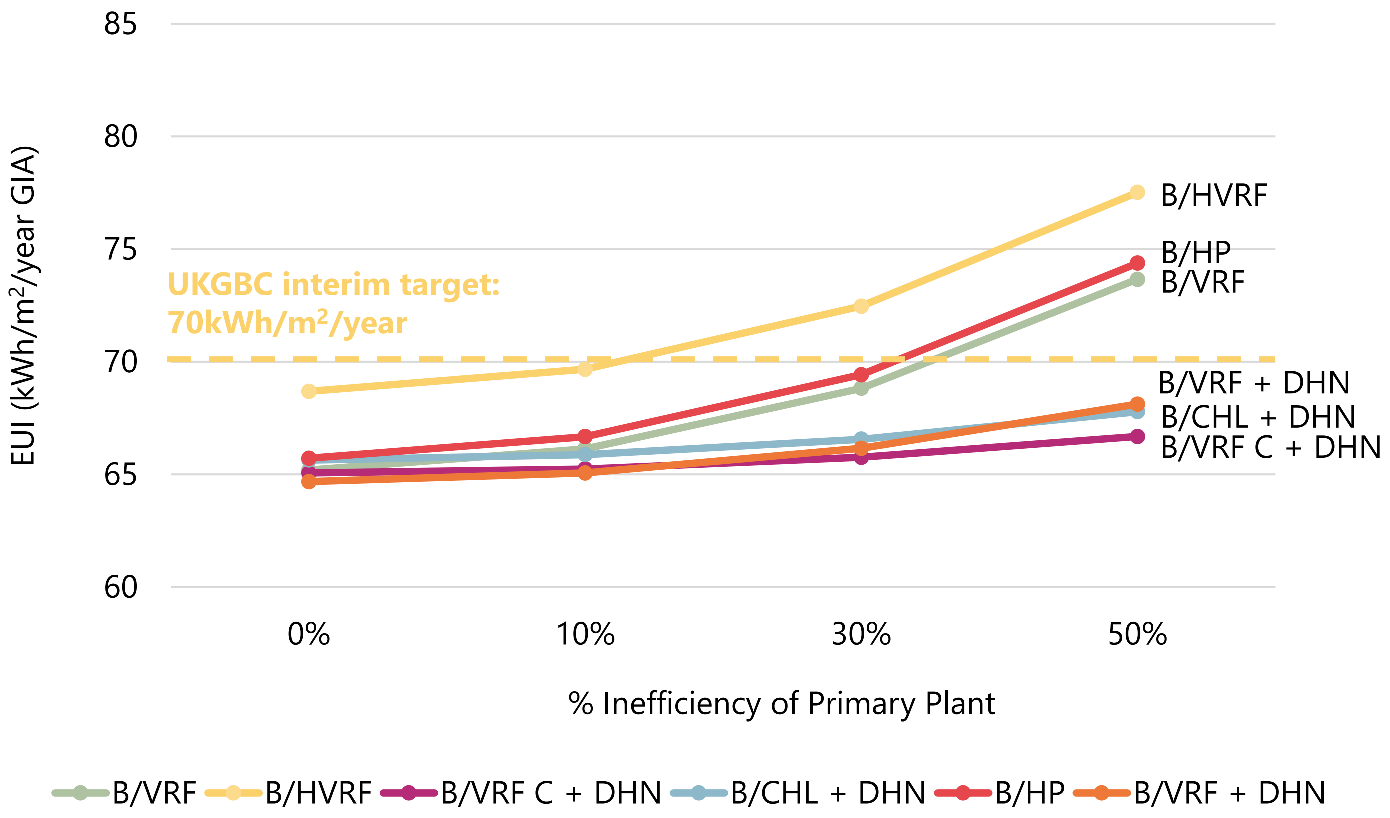
On the other hand, these charts show the sensitivity of plant efficiencies on the overall operational performance. A 10% decrease in efficiency could represent minor discrepancies in assumptions and is shown to increase the EUI by <1.5 kWh/m^2/year in the current practice building and no more than 1 kWh/m^2/year for the best practice. This would represent an overall 2% uplift in operational carbon.

With a substantial reduction of 30% in seasonal efficiencies, could start to compromise achieving UKGBC interim targets as an uplift of 4 kWh/m^2/year is observed for the best practice case. However, for a DHN connected system, the EUI figures are less affected and therefore a DHN connection could become favourable in reducing the risk of increased EUIs due to potential off-axis plant performance.

Off-axis plant performance refers to operation scenarios that divert from the expected operation of the plant, such as increases to resistance in the system, discrepancies in performance of the plant from testing to actual conditions, and ineffective system controls.

Finally, a major reduction of 50% can result in notable detrimental increases to the EUI and is provided for illustrative purposes only. However, that said. it does show that even extremely under performing primary plant only affects the overall EUI by ~12% in the worst case which is reduced down to ~5% increase if connected to the DHN.


Current Practice Changes in EUI with Primary Plant Inefficiency


Best Practice Changes in EUI with Primary Plant Inefficiency

N.B. A DHN correction factor has been applied to allow for direct comparisons based on page 34

__A__ – Current practice, __B__ – Best practice, __VRF__ – VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

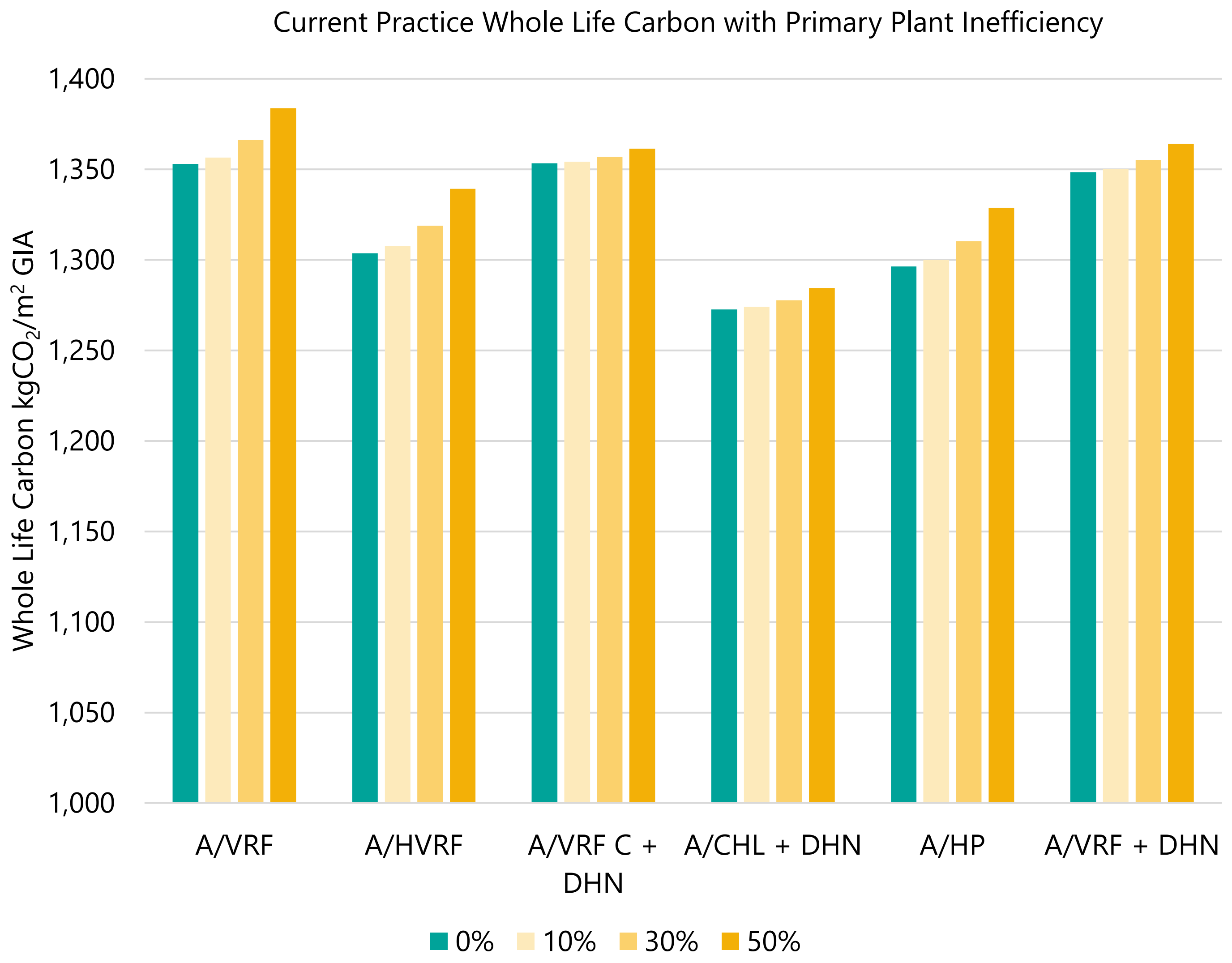
Sensitivity Analysis | Plant Efficiencies Whole Life Carbon

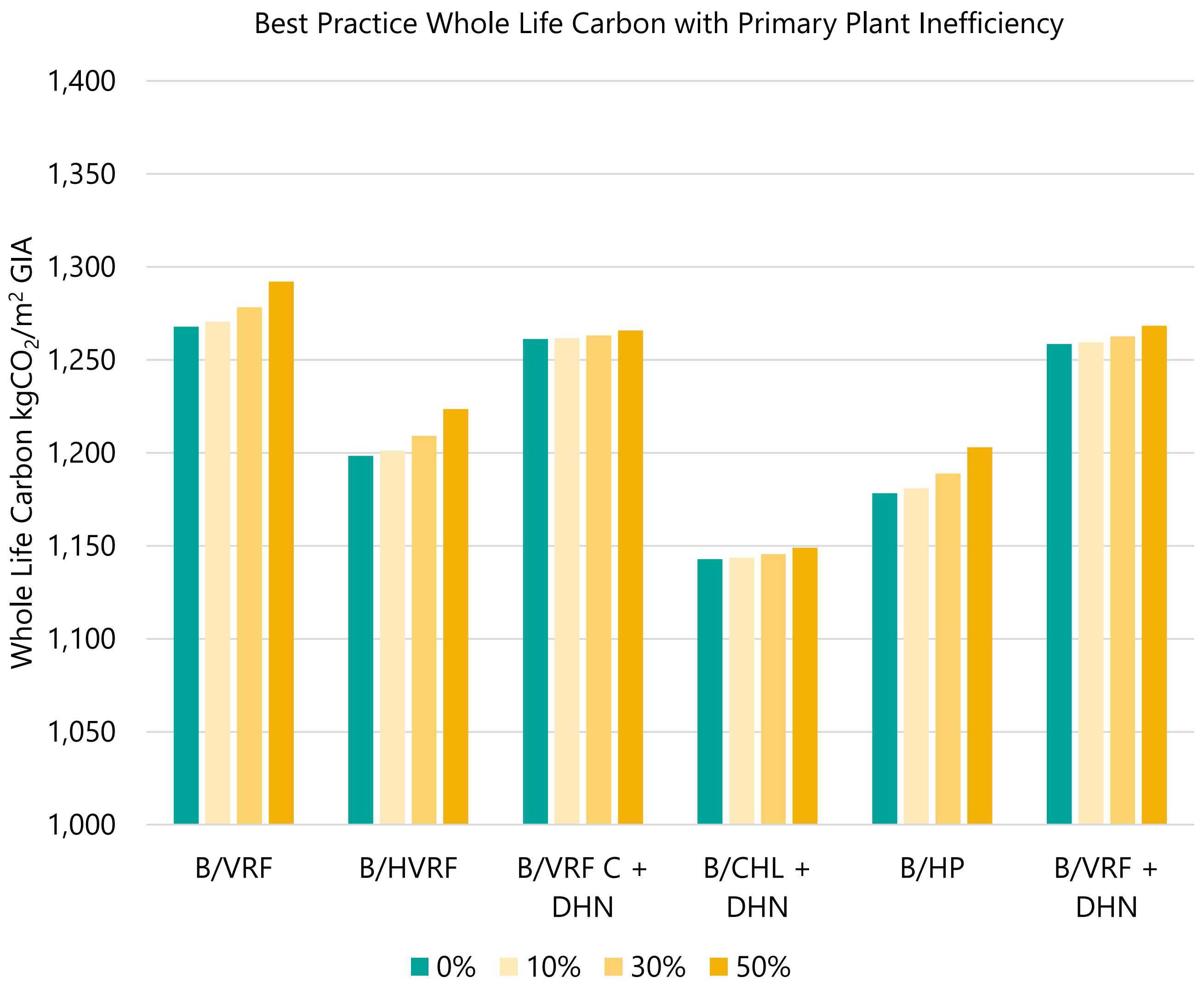
Primary plant efficiencies impact on whole life carbon

The graphs below summarise the impact on whole life carbon with changes to the primary plant efficiencies. As shown the CHL + DHN option still incurs the least whole life carbon even with a 50% inefficiency. VRF options are still ranked as the systems with the highest total whole life carbon.

Generally, this shows that the plant inefficiency does not impact the choice of system, as the conclusions made on the whole life carbon and costs section (page 40) still hold true. The worst performing HP and HVRF systems (50% inefficiency) are still better than VRF.

The below graphs can also be used to cross-compare scenarios where the plant performance is below manufacturers quoted data, but not necessarily by a uniform amount. There is often most scepticism around the quoted performance of VRF systems. Moreover it is often difficult to obtain granular performance data outside of standard test conditions from manufacturers. Such data seems to be more widely available for hydronic chillers and heat pumps allowing more satisfactory predictive modelling to be undertaken. This tends to reinforce the preferencing of hydronic systems, particularly the connection to the DHN. It is expected that the DHN plant will be more optimally operated due to the significant commercial incentive involved.





BURO HAPPOLD

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Sensitivity Analysis | Grid Decarbonisation

Grid decarbonisation scenarios

The results are heavily linked to the decarbonisation of the electricity grid. The current BEIS projections predict rapid decline in grid carbon intensities over the next 10-15 years. This section explores the impact of slower rates of decarbonisation of the grid. The BEIS projected carbon grid intensities were modified to generate different decarbonisation scenarios. As the DHN has planned to electrify its heat source, its decarbonisation rate is assumed to move proportionally with the grid in this analysis. The following two derivative projections were created:

1. **Late:** A delayed decarbonisation of the grid assuming minimal intervention in the short-term, but with a rapid decrease after 25 years (same rate as the current projection)
2. **Shortfall:** A decarbonisation shortfall, where the overall target has not been met (reaching a grid intensity of 0.05 kgCO2/kWh as opposed to 0.007 kgCO2/kWh).

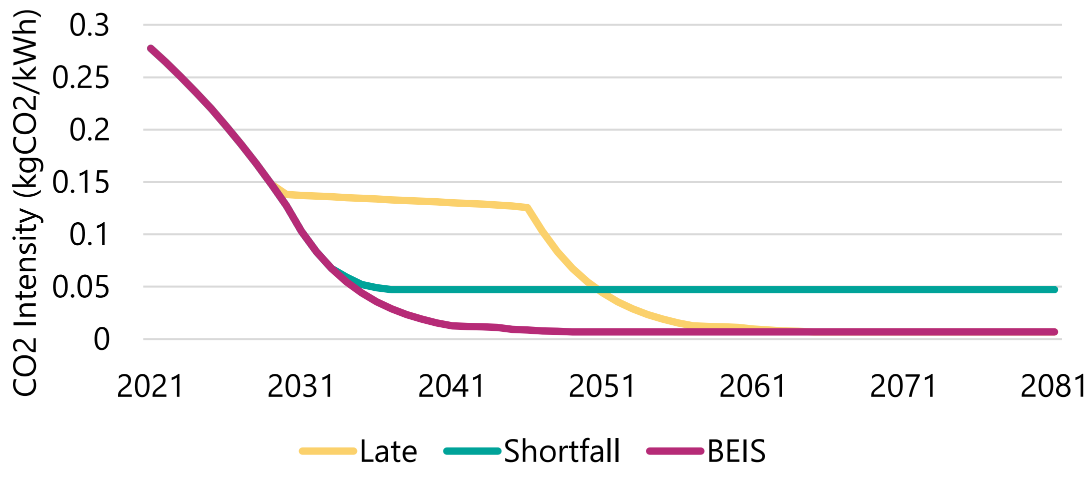
These two alternate projections are captured in the graph to the right alongside the BEIS long run marginal used in the study.

The operational carbon of all of the options has been calculated and is presented in the graphs. As shown, the failure to deliver a decarbonised grid, both immediately and in terms of the extent of decarbonisation, result in a significant increase to operational carbon in similar orders of magnitude. Compared to the BEIS figures, these scenarios would result in an increase of around 65% in the operational carbon for current and best practices. However, because the best practice building had started with significantly less operational carbon, the net increase in terms of carbon is substantially less than the current practice projection. Pursuing best practice design through policy both aids decarbonisation of the grid and provides resilience against a shallower decarbonisation trajectory.

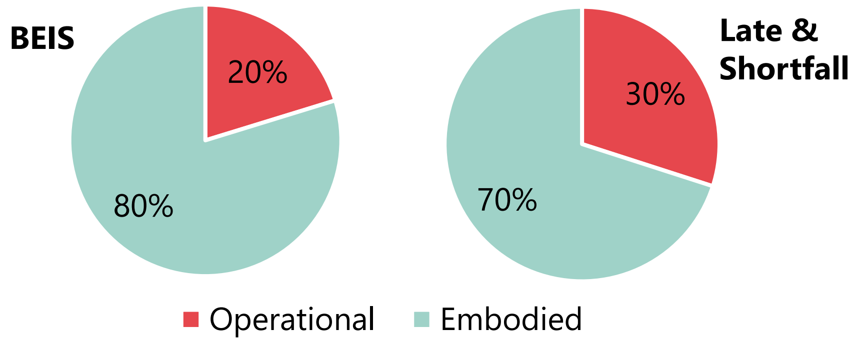
It can also be observed that the 'late' projection of the best practice building is the same as the 'BEIS' projection of the current practice building.

These projections have also changed the operational carbon contribution to the whole life carbon across all options. A general 10% increase in contribution has been noted which equates to an average increase of 15% to the WLC for each option. This would suggest that efficiencies for demand reduction would become more critical.

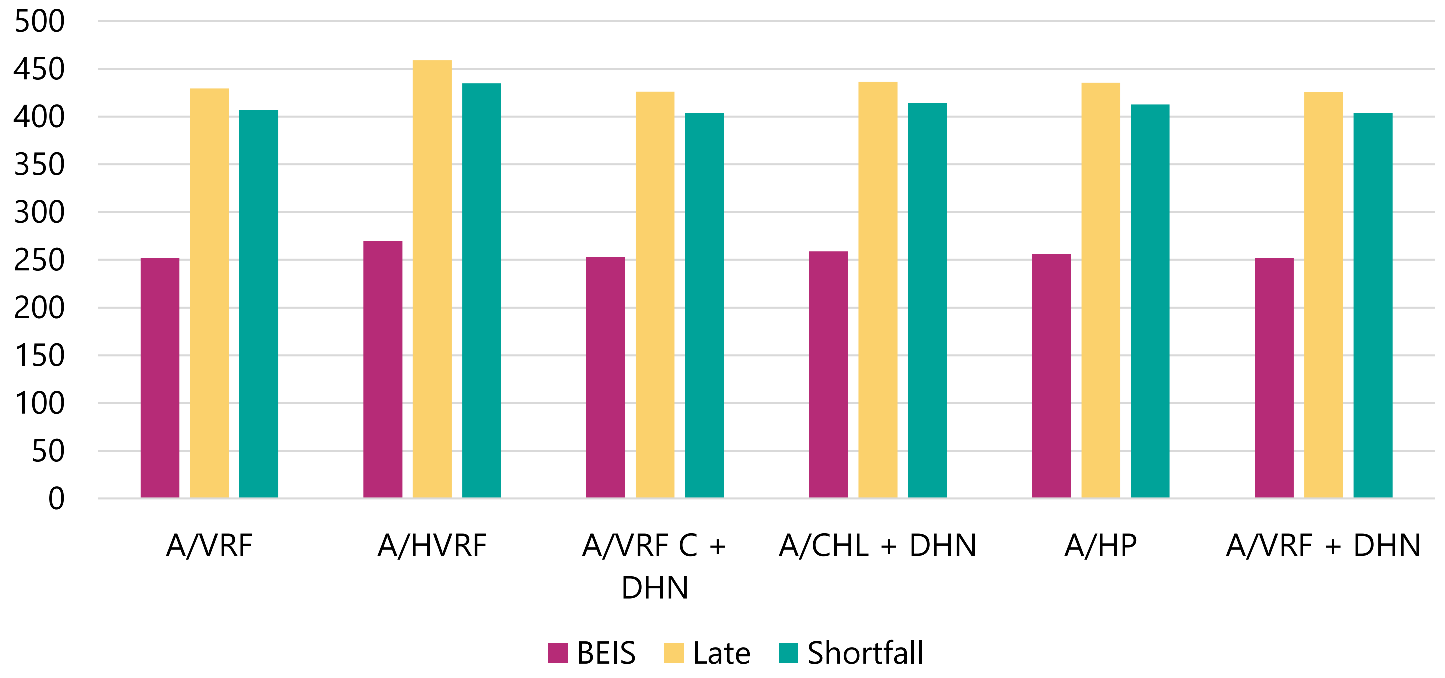
Electricity Grid Decarbonisation Scenarios



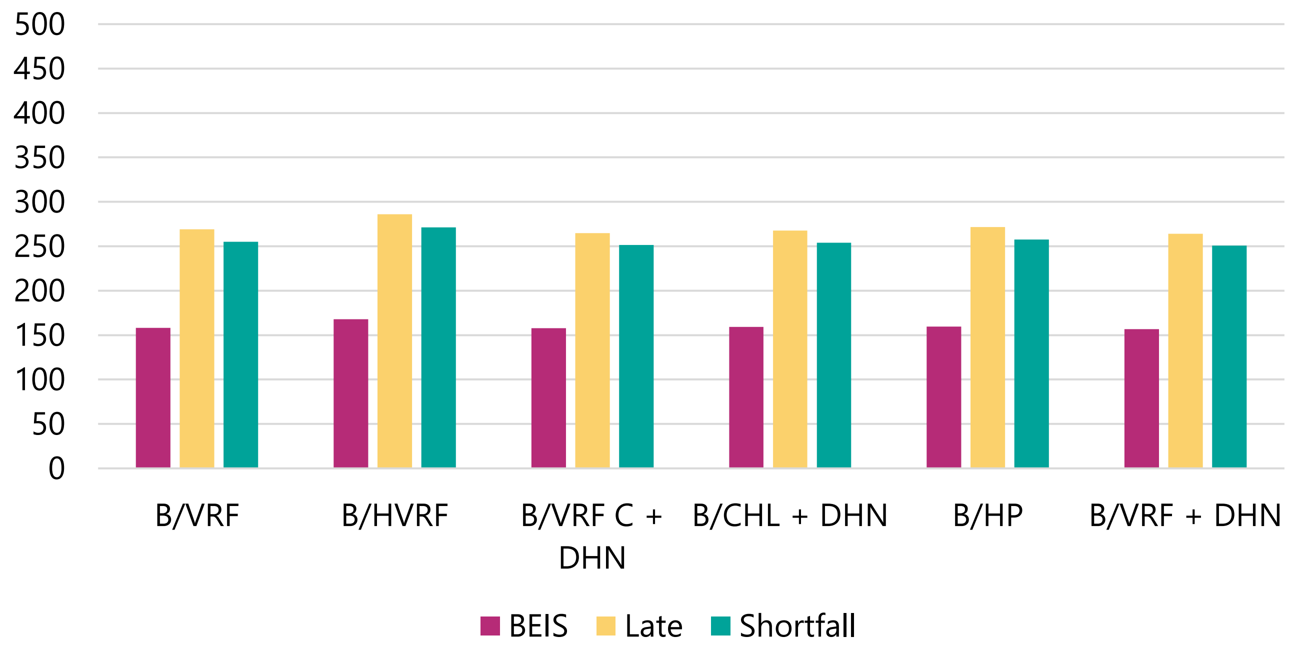
Operational carbon comparison to whole building embodied carbon with changes to decarbonisation projections



Current Practice Operational Carbon (kgCO$_2$/m^2 GIA)



Best Practice Operational Carbon (kgCO$_2$/m^2 GIA)



__A__ – Current practice, __B__ – Best practice, __VRF__ – VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

Key Findings & Policy Recommendations

The scope of the study considered changes in heating and cooling strategies based on heat pump technologies (refrigerant, hybrid and hydronic) and connections to the district heat network (DHN), taking into account the decarbonisation of the grid. In addition to this, these options were then adapted to a building following emerging net zero carbon standards (LETI, UKGBC, and RIBA).

Key findings

1. The chiller with DHN system option results in the lowest whole life carbon. Generally, systems that distribute heat utilising refrigerants result in the highest whole life carbon, whilst hydronic based systems (including HVRF), result in the lowest. The driving factor is the volume and types of refrigerant used.
2. Significant whole life carbon improvements are achieved through strategies to reduce demands by designing in line with best practice standards e.g. LETI. The implementation of such measures has a larger impact on whole life MEP (17% reduction) and operational energy costs (12% reduction) than the type of heating and cooling system.
3. Embodied carbon is shown to be the main driver for differences in whole life carbon amongst options, especially due to differences in refrigerants and terminal units in heating and cooling systems. Refrigerant impacts increase with volume and associated GWP. Due to the repeating nature of terminal units, minor unit differences can cause significant overall impacts.
4. Connection to the DHN results in lower embodied carbon due to the embodied carbon assessment boundary for a building and the unavailability of ultra-low GWP refrigerant for efficient heating plant. Additionally, the operational carbon is similar (+1%) to the other options based on BCC's projections for the carbon emission factor of the DHN.
5. VRF systems have the lowest whole life MEP costs (~4% less than hydronic systems) and systems with DHN connections result in a 1-2% increase in whole life MEP costs.
6. There is little correlation between the relative performance of systems options in Part L compliance modelling and operational energy modelling. In particular, the Part L models overstate the benefit of VRF based systems compared to hydronic systems. The introduction of a DHN connection for a given system shows a reduction in carbon in the compliance modelling, as opposed to a marginal net increase in the operational carbon modelling.
7. MEP systems and refrigerants responsible for 20-30% of the total embodied carbon.
8. Centralised systems (e.g. central heat pumps) are shown to result in 18% less MEP related embodied carbon compared to zonal systems (e.g. VRF), for the exception of HVRF. This equates to 6% of the total embodied carbon.

Policy recommendations

The following recommendations are for buildings with a peak heating/cooling demand larger than 100-150kW (this is based on the smallest higher efficiency chiller size typically available). Flexibility to consider zonal systems such as VRF (with low GWP) is likely to be appropriate for small buildings with low cooling loads. Sensitivity analysis has shown that variations in efficiency levels do not compromise the proposed hierarchy.

Heating and cooling hierarchy (condition-based)

- If a district heat connection is available then:
    - ➢ DHN connection is prioritised for both space heating and DHW
    - ➢ Chillers with ultra-low GWP refrigerants prioritised for cooling
- If there is no district heat connection available then:
    - ➢ Hydronic and hybrid VRF systems prioritised

Reduction in energy

- Reduction in peak demand is a good predictor of reducing overall annual energy demand and whole life carbon (mainly a reduction in operational carbon).
- Aiming to achieve LETI EUI targets would ensure that stakeholders partake in tenant power reduction activities; vital for overall net zero commitments.
- Accurate heating and cooling equipment performance data is essential for operational energy modelling but also challenging to obtain due to current regulations (detailed reports are not mandatory). A requirement to report comprehensive in-use energy demands would be welcomed for the following reasons:
    - Provide feedback and accountability to design teams, planning applicants, landlords, and tenants
    - Develop an increased understanding of real-world system performance that could form part of a shared database which is generally lacking in the industry
    - Encourage suppliers to provide accurate performance data to support early stage design

Recommended metrics, compliance, and enforcement

- The relationship between operational and embodied carbon is complex and challenging to generalise. The equipment and information available is changing due to evolving market and regulatory requirements. Requiring whole life carbon assessments as part of the planning process can form a holistic view on carbon performance and help applicants make informed decisions on projects. This would be more effective than relying on Part L alone.
- A pre-commencement condition could be included to update the carbon assessments highting reasons for any changes. In addition to this, a certain percentage of applications could be audited by an independent competent person.
- Part L is not a good indicator for predicting operational carbon. It is recommended that operational energy modelling is conducted in line with a recognised modelling methodology, such as TM54 and BREEAM GN32. A simplified method might be appropriate for small developments.
- If EUI targets are adopted, systems that are connected to the DHN will need to adjust their DHN energy by a correction factor to represent the generation efficiency of the DHN's heat generation plant.
- In the current climate, clients are likely to be prepared to sacrifice on CAPEX for 'greener' credentials as this supports the marketability of buildings. It is therefore important to standardise the metrics used by clients to ones that represent the actual whole life carbon which include:
    - Accurate estimations of projected operational energy with a process to verify these through metering.
    - Demonstrating that a building is NZC after following the carbon reduction hierarchy (prioritise operational and embodied, and carbon offsetting is a last resort)

Key Findings & Policy Recommendations

Reduction of embodied carbon

Use of high GWP refrigerants or multiple refrigerant-based systems results in a significant increase in embodied carbon for heating and cooling systems. Adoption of the following refrigerant hierarchy is recommended:

- Design for no refrigerant (DHN connection, no cooling)
- Minimise quantity of refrigerant (using water as a distribution medium)
- Select low impact refrigerants prioritising ultra-low <50 GWP where possible and no greater than 750 GWP
    - Consider tying policy to requirements of BREEAM Pol 01 one credit threshold of ≤ 1000 $kgCO_2e/kW$ cooling capacity, with a further update to the two credit target of ≤ 100 $kgCO_2e/kW$.
- Restrict refrigerant leakage (implement detection, monitoring and maintenance regimes)

Further considerations

Elimination of heat recovery functionality:

- The study has shown that for commercial offices, the additional equipment needed to enact heat recovery across heating and cooling circuits is unlikely to return a whole life carbon benefit.
- Significant reductions to embodied carbon of VRF systems are possible with reversible units (no heat recovery). These systems utilise less overall refrigerant, do not require branch controllers, and are more efficient for heating and cooling.
- It is generally accepted that simpler systems inherently have lower embodied carbon and are more robust.

Introduction of mixed mode:

- Energy saving potentials of mixed mode strategies could be explored in terms of whole life carbon along with its feasibility for most future new builds.

General rules of thumb

- Following best practice energy reduction measures has the most impact on limiting whole life carbon
- Selecting lower GWP and volumes of refrigerants can provide significant embodied carbon savings amongst system options
- Holistic energy reduction strategies are required to achieve emerging net zero EUI targets (including tenant power, and heating and cooling)
- Lower whole life carbon options attract higher CAPEX and OPEX

3.0

APARTMENT BUILDING

- ☐ ASSUMPTIONS
- ☐ RESULTS
- ☐ RECOMMENDATIONS

Adobe Stock Images

Assumptions | Archetype

Archetype

The study has been based on a real mid-rise, medium density residential development in London that is in the later stages of design.

Base building

The building selected is a typical size, form and layout for a mid-rise residential development in Bristol consisting of 39no. dwellings across 5no. stories, with around 8 apartments per floor. Dwellings are mostly 2-bed with some 1-bed apartments ranging from 54m^2 to 92m^2 NIA. No modification of the archetype was therefore needed.

The dwellings sit above a level of commercial retail and ancillary spaces as is typical for new build residential schemes, however, these elements have not been included within this study as they are assumed to be serviced separately.

Fabric

Part L1A compliance modelling was carried out on the base building to ensure that the envelope performance was sufficient to meet Bristol City Council planning energy policy (BCS14,15). For the 'best practice' variants these are modified in line with LETI, AECB and Passivhaus guidelines.

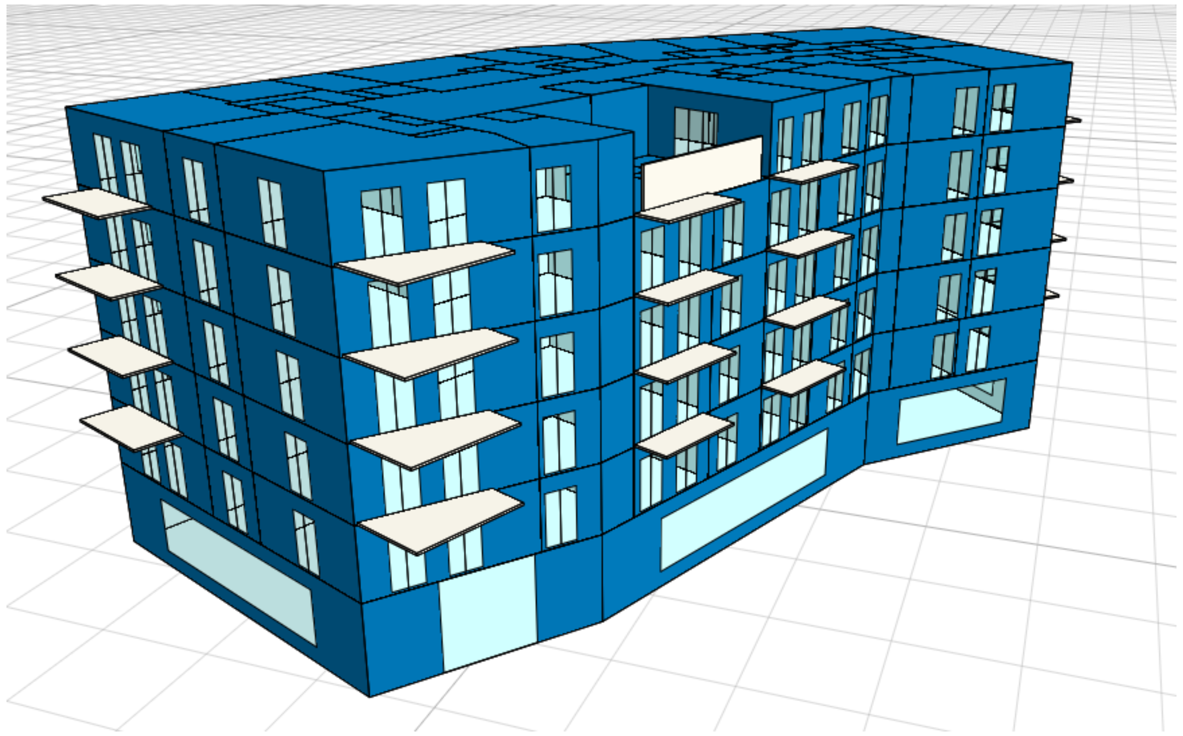
Conceptual designs

Conceptual designs for each studied heating and cooling system option were developed for the base building and best practice building, along with schedules for equipment capacities/sizes and quantities for all systems including electrical and public health systems.

Fixed parameters

Certain parameters have been fixed across the base and best practice buildings:

- Building massing and layout
- Household composition, occupancy use profile and density
- External design conditions for system sizing
- Internal design conditions including set point temperatures and ventilation fresh air rates
- Window opening logic



Thermal model of the archetype building

Size: 39no. units, 2,861 m^2 NIA, 3,541.3m^2 GIA

Envelope: double-glazed, opaque U-values < 0.18W/m^{2}K

System: CHP-led district heat network and MVHR with openable windows for natural ventilation

Performance target: London Plan 2016 compliant >35% improvement over Part L1A 2013 notional building

Thermal comfort: Meets CIBSE TM59 thermal comfort criteria for Heathrow 2020 DSY1 weather file

Dwelling type	Count	Floor area NIA (m²)			
		Total	Mean average	Minimum	Maximum
1B2P	15	840.3	56.0	53.9	69.5
2B4P	24	2020.7	84.2	74.1	91.9
Total	39	2861.0	-	-	-

Assumptions | Current & Best Practice Buildings

RIBA, UKGBC and LETI have set EUI targets of 35-40 kWh/m²/year (GIA) to achieve net zero carbon targets for residential apartment buildings. The Cornwall Council Climate Emergency Technical Evidence Base (Etude, 2021) demonstrates that these targets are technically feasible for the residential buildings including mid-rise flats.

To assess the impact of demand reduction and the feasibility of achieving EUI targets, the study considers two building design scenarios;

- **Current practice (Option A):** compliant with Part L1A 2013 and current Bristol City Council Core Strategy policy BCS14
- **Best practice (Option B):** in line with LETI, UKGBC and Passivhaus guidance, expected to meet or exceed Future Homes Standard requirements

The figure to the right from the LETI Climate Emergency Design Guide, sets out a series of example design measures to successfully achieve low energy use intensities in dwellings.

Glazing ratio

The glazing design of the current practice building has been assumed to be as per the archetype building as it complies with the Part L1A 2013 fabric energy efficiency criterion. The glazing ratio of the best practice building has been adapted to align with LETI design guidance by reducing the glazing height.

Building fabric

The building fabric design specification for the current practice building, as shown in the table to the right, has been relaxed from the archetype design to align more closely to the Part L 2013 notional building. The best practice building fabric specification has been selected to align with industry best practice guidance.

Appliances and lighting

The Cornwall Council Climate Emergency Technical Evidence Base (Etude, 2021) identifies a potential reduction in energy use from appliances and lighting through selecting more efficient equipment and fittings. For the purposes of this study, the energy use for the current building is assumed to be 1,700 kWh/dwelling/year and 1,250 kWh/dwelling/year for the best practice building, regardless of dwelling size. The reduction principally comes from high efficiency appliances.

Building services

The building services strategy was maintained for both cases. This includes mechanical ventilation with heat recovery which may not always be considered necessary for compliance with current minimum standards but was included in the archetype building design so has been retained.

Renewables

Provision of a high-efficiency photovoltaic array on the south-facing, pitched roof of the building is included for both cases.

Best practice building key characteristics:

- Lower glazing ratio ~20% of façade area
- Triple glazing ~1.0 W/m²K
- Enhanced solid element U-values by ~25%
- Enhanced thermal bridging detailing
- Enhanced air tightness target
- Lower appliance and lighting energy use

Recommendations for reducing EUIs in residential buildings (LETI, 2020)

Parameter		Units	Current practice	Best practice
Wall u-value		W/m².K	0.18	0.15
Roof u-value		W/m².K	0.15	0.10
Floor u-value		W/m².K	0.15	0.10
Window u-value (including frame)		W/m².K	1.40	1.00
Door u-value		W/m².K	1.40	1.00
Glazing g-value			0.40	0.50
Infiltration	Air tightness target	m³/hr/m² @ 50Pa	3.0	<1.0
	In-use air exchange	ACH	0.40	0.35
Thermal bridging	Compliance input	W/m²K	Calculated with ACD ψ-values, Y~0.17	Calculated with bespoke and ACD ψ-values, Y~0.05
	In-use heating demand	kWh/m².yr	5.0	3.0
	Adjusted wall u-value	W/m².K	0.48	0.31
Glazing percentage of façade area			28%	20%
Energy for appliances, lighting, fans and pumps		kWh/dwelling/year	1,700	1,250

BURO HAPPOLD

Overview of Options | District Heat Network (DHN)

District heat networks are a key part of Bristol City Council's decarbonisation strategy and are given highest priority in the Heat Hierarchy defined in the Bristol City Council Core Strategy Policy BCS14. This study considers two scenarios where district heat network is the main heat source to the building.

System description

Heating and hot water

The district heat network delivers heat to the building via a plate heat exchanger, typically located at ground floor or basement level. Secondary pipework distributes heat from the DHN connection throughout the building, through risers and corridor ceiling voids, to a heat interface unit (HIU) within each dwelling. The HIU is designed to provide heat instantaneously for both space heating and domestic hot water in the dwelling. There is no hot water or thermal storage either in dwellings or centrally in the building. Radiators have been assumed as the space heating emitters in both DHN cases.

Cooling

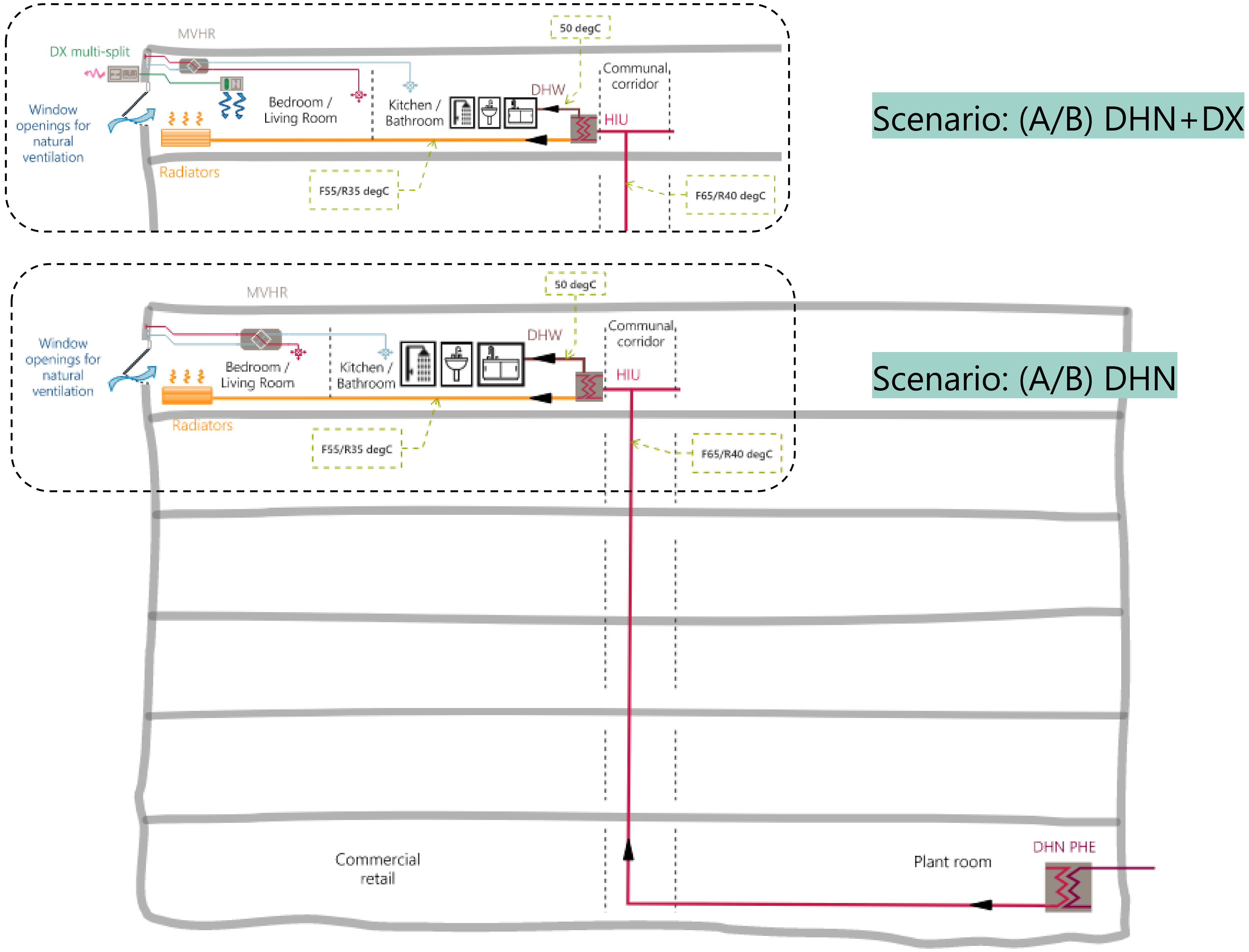
A variant of the DHN system option includes a multi-split heat pump for each dwelling to provide comfort cooling to living rooms and bedrooms. It has been assumed that the outdoor unit for each dwelling would be located on the dwelling balcony with indoor fan coil units located in each room where cooling is provided. An alternative design could be to locate all outdoor units on the roof but this would require prior planning to identify a suitable route for refrigerant pipework. Locating the plant within the occupant's domain models a retrofit scenario where a cooling system has been added to mitigate overheating risk.

Temperature regime

The system flow and return temperatures of 65°C flow / 40 °C return have been selected in accordance with the Bristol Heat Networks Technical Specification in all cases.

Network heat losses

The secondary pipework has been assumed to be fully insulated in accordance with the requirements of CIBSE CP1 Heat Networks: Code of Practice for the UK 2020 to ensure the efficient operation of the network and minimise overheating risk for communal corridors.



Scenario: (A/B) DHN+DX

Scenario: (A/B) DHN

Key

- Refrigerant
- LTHW tertiary
- LTHW secondary
- District heat network
- DHW/Boosted temp

DHW: Domestic hot water
MVHR: Mechanical ventilation with heat recovery
LTHW: Low temperature hot water
HIU: Heat interface unit
DX: Direct expansion
DHN: District heat network
PHE: Plate heat exchanger

Overview of Options | High-temperature Heat Pump

Air source heat pumps provide an all-electric alternative to gas combustion plant for on-site communal heating systems. This study considers a single scenario where high-temperature heat pumps are the main heat source to the building.

ASHP delta T (ΔT)

Most air source heat pumps can only operate with a narrow temperature differential (between flow and return pipework), typically no more than ΔT = 5°C. However, there are commercially available heat pumps, typically for large-scale application, that operate at higher temperature differentials. These are typically characterised by using multiple compressor-stages and alternative refrigerants such as propane, isobutane, ammonia, or CO_2. The heat pump assumed for this study was a duel-compressor unit, where the first compressor using propane makes the initial rise of temperature, then a second compressor using isobutane raises the flow temperature to the desired level.

Futureproofing

This heat pump system intentionally shares many characteristics with the district heat network options to ensure it can be adapted for connection to a heat network in the future. This model captures the scenario where a scheme is designed and built in a location where a heat network is either planned or likely to exist in the future but is not due to be completed in time for the building's occupation. Previously this scenario would be designed to include a gas combustion plant, but using heat pumps instead is preferable as it removes the need for a gas connection to the site and delivers lower on-site carbon emissions.

System description

Heating and hot water

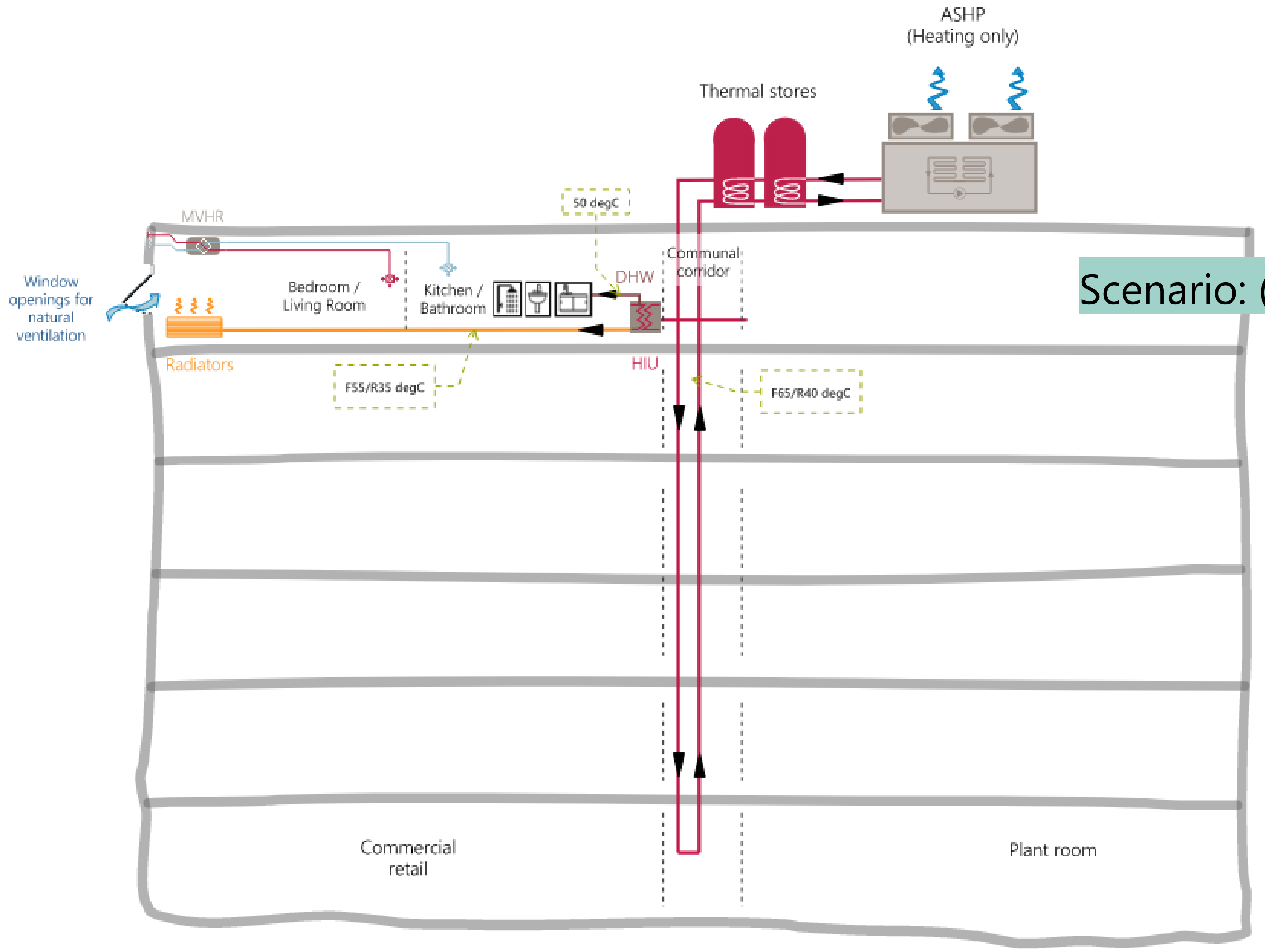
Communal air source heat pump plant, typically located on the roof of the building, generates heat which is sent to either thermal stores or the communal heating loop. Secondary pipework distributes heat throughout the building, through risers and corridor ceiling voids, to a heat interface unit (HIU) within each dwelling. The HIU is designed to provide heat instantaneously for both space heating and domestic hot water in the dwelling. There is no hot water storage in dwellings. Radiators have been assumed as the space heating emitters.

Temperature regime

The system flow and return temperatures of 65°C flow / 40 °C return have been selected in accordance with the Bristol Heat Networks Technical Specification in all cases. These temperatures have been selected to ensure compatibility with a future district heat network connection.

Network heat losses

The secondary pipework has been assumed to be fully insulated in accordance with the requirements of CIBSE CP1 Heat Networks: Code of Practice for the UK 2020 to ensure the efficient operation of the network and minimise overheating risk for communal corridors.



Scenario: (A/B) HTHP

Key

- LTHW tertiary
- LTHW secondary
- DHW/Boosted temp

DHW: Domestic hot water
MVHR: Mechanical ventilation with heat recovery
LTHW: Low temperature hot water
HIU: Heat interface unit
ASHP: Air-source heat pump

Overview of Options | Ambient Loop

Air source heat pumps provide an all-electric alternative to gas combustion plant for on-site communal heating systems. This study considers two scenarios with an 'ambient loop' style system, where central air source heat pumps are the main heat source to the building, in combination with secondary stage water-source heat pumps in each dwelling.

Ambient loop

One of the key drawbacks of conventional heat networks is the risk of high heat losses from water stored at high temperatures in distribution pipework and thermal stores, an issue which is exacerbated in buildings with low heat demand and long distribution routes. An alternative solution is to distribute heat at significantly lower temperatures (~25°C), close to the internal air temperature to minimise heat losses, then elevate the water temperature as required close to where the demand is and only when it is needed. The central, near-room temperature distribution pipework is commonly referred to as an 'ambient loop'.

System description

Heating and hot water

Communal air source heat pump plant, typically located on the roof of the building, generates heat to maintain the ambient loop at the target temperature of 25°C. Within each dwelling, a secondary water-source heat pump uses the ambient loop as a heat source and generates hot water to the required temperatures for either space heating or hot water. The system includes a hot water cylinder within each dwelling to provide domestic hot water on demand. Radiators have been assumed as the space heating emitters for the heating only option, see below for an option with cooling.

Cooling and heat recovery

A variant of the ambient loop system option is to use reversible heat pumps to provide comfort cooling to living rooms and bedrooms. In this scenario, the in-dwelling heat pumps reject heat to the ambient loop and the central ASHP works to keep the loop at 25°C by rejecting heat to the atmosphere. For the reversible heat pump cooling system option only, the emitters in the room have been assumed to be fan coil units for both heating and cooling.

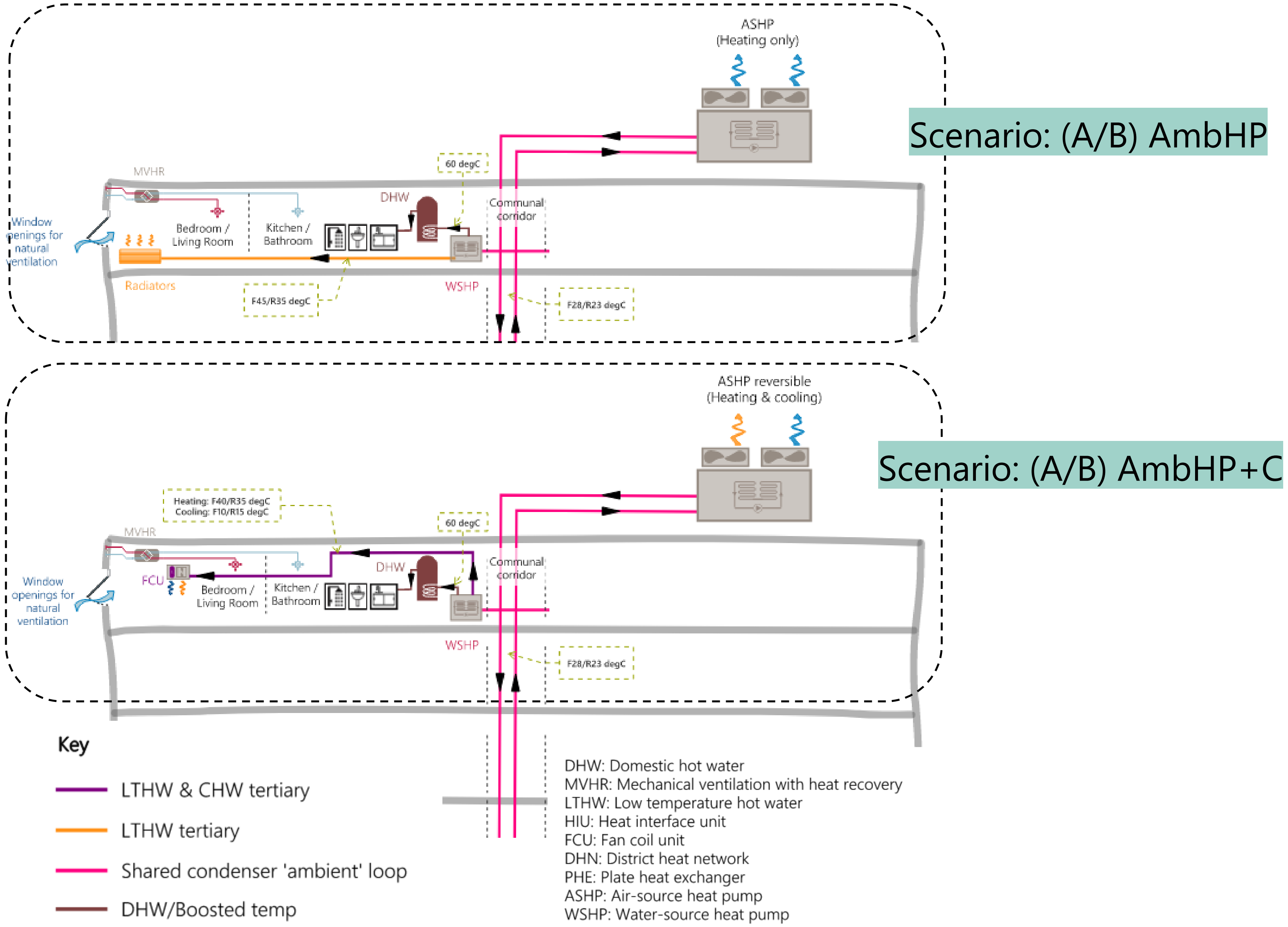
The shared water loop for both heating and cooling provides the opportunity for heat recovery throughout the building. For example, where some dwellings are in cooling mode, but others have a domestic hot water load, so heat is simultaneously rejected to and extracted from the loop meaning the temperature of the loop will remain stable such that the central ASHP is not required.

Temperature regime

The system flow and return temperatures have been selected in accordance with the 'Design Guidance for Diversity Factors for Ambient Temperature Networks using the Zeroth Energy System', by Wallace Whittle in collaboration with TÜV SÜD for Glen Dimplex Heating & Ventilation.

Network heat losses

The ambient loop distribution pipework has been assumed to be fully insulated to the same degree as traditional heat networks, as calculated in accordance with the requirements of CIBSE CP1 Heat Networks: Code of Practice for the UK 2020.



DHW: Domestic hot water
MVHR: Mechanical ventilation with heat recovery
LTHW: Low temperature hot water
HIU: Heat interface unit
FCU: Fan coil unit
DHN: District heat network
PHE: Plate heat exchanger
ASHP: Air-source heat pump
WSHP: Water-source heat pump

Energy Modelling

Methodology used

Calculation of the annual energy consumption and operational carbon has been carried out using a dynamic thermal simulation model and manual post-processing of the results in an Excel spreadsheet based model of the heating and cooling plant. The approach used does not strictly follow an existing published methodology (such as NABERS used for the commercial office study), as there isn't currently any such methodology available. However, the results have been calibrated and benchmarked against existing studies where PHPP has been used, including the Cornwall Council Climate Emergency Technical Evidence Base (Etude 2021).

Heat pump efficiency data

Part-load performance data for a range of external ambient conditions has been provided by heat pump manufacturers. These values are used to provide a more accurate estimate of the energy consumed by the heat pump as opposed to using the annual Seasonal Coefficient of Performance (SCOP) figure, calculated to BS EN 14825, as commonly applied in Part L compliance calculations. With this method it is possible to take into account the efficiency of the unit depending on the design temperature regime, the amount of load seen, and the external air temperature at that moment.

Occupancy

The occupancy density and use profile assumed within the dwellings has been estimated using the findings of the published paper *Developing English domestic occupancy profiles* (V. Aragon et al., 2017) in conjunction with an analysis of typical demographics for the wards where new build flats would most likely be built, provided by Bristol City Council. The resulting occupancy typologies cover the following four typical household categories:

1. Working, no dependents (home working)
2. Working, no dependents (working elsewhere)
3. Retired, no dependents
4. Working family

The assumed occupancy density and profiles have been used to adjust assumptions and benchmark figures such as;

- Heating and cooling operating schedules
- Domestic hot water consumption
- Energy use from appliances, lighting, fans and pumps
- Window opening

Domestic hot water

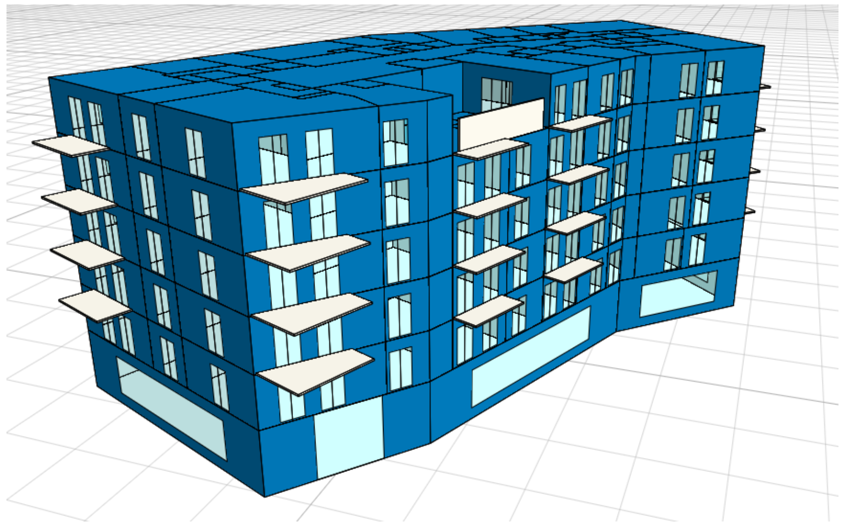
Annual hot water demand has been calculated in accordance with the findings of the Energy Saving Trust report *Measurement of Domestic Hot Water Consumption in Dwellings* (2008). The annual demand has been translated into hourly load profiles, one for weekdays and another for weekends, for each occupancy type.

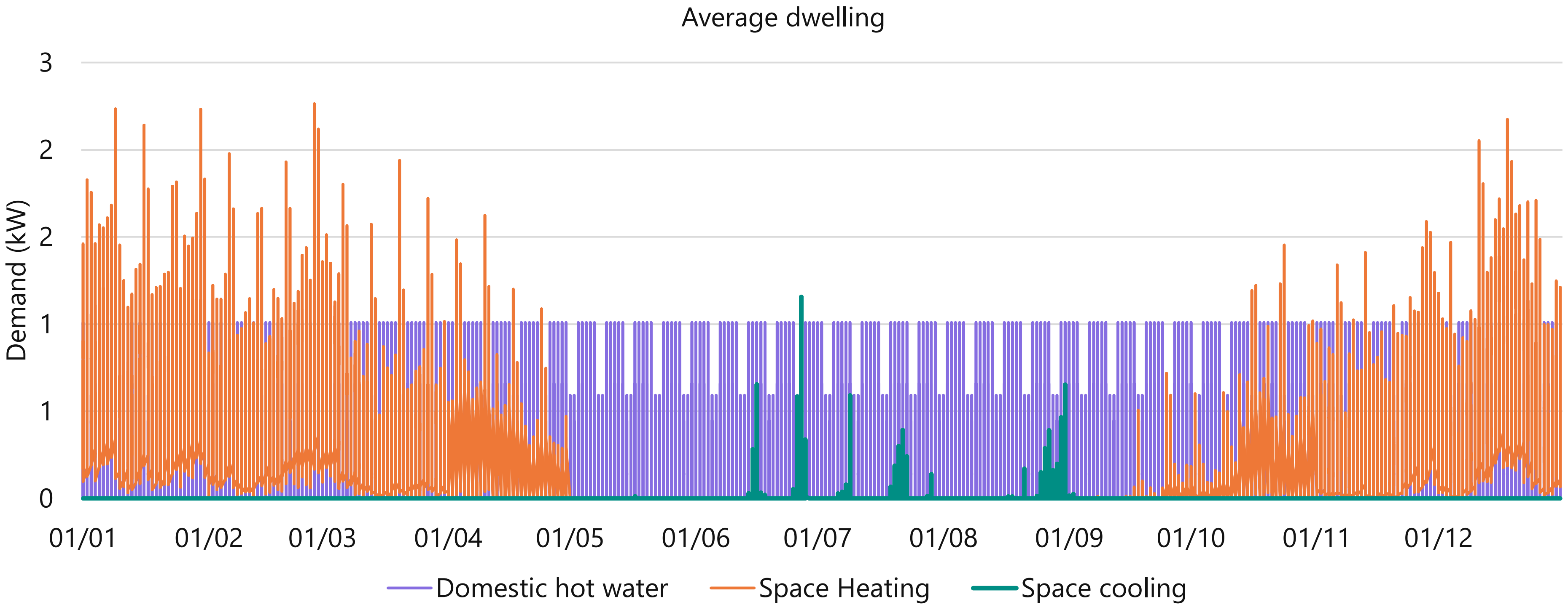
Dynamic thermal simulation

IES Virtual Environment Apache dynamic simulation was used to calculate the hourly space heating and cooling demand profile for each dwelling, for both the current and best practice building scenarios. Space heating demand and appliance/lighting power demands showed good alignment with the annual demands given for a similar apartment building in the Cornwall Council Climate Emergency Technical Evidence Base (Etude 2021).

Excel-based plant model

Each of the outputs from the calculations described above were then collated to calculate the central and in-dwelling plant performance using an excel based model with hourly time steps. The calculation included logic to define the way in which the plant would operate depending on the conditions at each time-step. In this way, the calculation accounts for varying equipment efficiency due to load and external ambient temperature, the inclusion of thermal storage, and potential for heat recovery.





Embodied Carbon Modelling

Methodology

As with the commercial building study, the online software for calculating Whole Life Carbon, OneClick, was used as it has an extensive and constantly updated Environmental Product Declaration (EPD) library and provides the required data granularity needed for the study, including emissions due to refrigerant leakage and end of life recovery, transport emissions, equipment lifespans, and categorisation of equipment by RICS category.

Information Base

As mentioned earlier, MEP equipment embodied carbon quantification is not as well developed as it is for structural components and there is somewhat limited EPD availability.

In the last year, CIBSE has issued a technical memorandum, TM65, to outline current MEP embodied carbon calculation best practice. Included in this publication was the introduction of TM65 manufacturer forms, which provide a less onerous way to provide product specific embodied carbon data compared to traditional EPDs. This provided an additional source of embodied carbon data from manufacturers that would be commonly specified in the UK but did not yet have the data in EPD format, and therefore available on OneClick. Some of the major equipment for this study, such as the ASHPs, and split DX units, were input into OneClick from TM65 forms provided by Mitsubishi, as it was deemed this was likely to provide the most accurate estimate of embodied carbon. Similarly, for Heat Interface Units (HIUs), an embodied carbon value from the recently published TM65.1 on residential building MEP embodied carbon, likely from a non publicly available TM65 manufacturer form provided to CIBSE, was used. Typically TM65 forms average higher embodied carbon to account for lack of granular information in some aspects of manufacturing, so although they were deemed more accurate from the overall standpoint, this should be taken into account when considering the embodied carbon footprint of the MEP.

While ventilation, domestic pipework, and cooling and heating pipework were calculated based on actual quantities arising from the conceptual system design process undertaken, in the case of electrical distribution and infrastructure a Generic EPD was used, using an approved average from other buildings and attributing it to the study on a per m² GIA basis. The only MEP related exclusion from the model was the diesel powered generator due to a lack of any similar EPD available in TM65 form or in available libraries.

Embodied Carbon modelling inputs

The systems for each residential building scenario were split into their respective RICS category, with the exception of lifts which were included in 'Electrical Installations'. Inclusions for the study with their respective RICS category are outlined in the table to the right.

Non-heating and cooling related systems were included to consider the building as a whole, and gain insight into the proportion of heating and cooling embodied carbon when compared to the whole life cycle of the building. In order to do so a residential apartment building of a similar build and proportion was used on a m²/GIA basis for other building element embodied carbon (substructure, superstructure, façade, and internal finishes – external areas excluded).

When exact product TM65 information was not available, the schedule inputs into OneClick were scaled to EPDs by product weight, as it has been demonstrated to be the most accurate way to do so (CIBSE TM65), generating a small difference between scenarios. Where TM65 information was used, however, the selection of residential products would often not change with a small change in capacity (ex: the DX system selection), and therefore the size and embodied carbon of the equipment would remain the same.

Refrigerants for this study were those used by the selected equipment, with the exception of the ambient loop system. The proprietary ambient loop system is currently only available with R410a, this study has changed this to R32 to reflect the impact of F-gas regulations by the time the Local Plan is adopted. The impact of this is explored on page 90.

System	Selection	Refrigerant
WSHP	4 kW_{th} (heating and cooling, originally R410A)	R32
ASHP	300 kW_{th} (heating and cooling)	R32
Propane ASHP	200 kW_{th} (heating only)	Propane
DX Unit	4 kW (cooling only)	R32

RICS Category	Description
5.1 Sanitary Installations	WHBs, toilets, showers and baths, with associated ancillaries
5.3 Disposal Installations	Above-ground drainage and rainwater pipework (PVC)
5.4 Water Installations	Domestic water pipework (PVC), Cold water distribution (storage tank and booster system), cat5 break tank, sprinkler system (tank, pumps, and distribution), hot water cylinders, point of use water heaters
5.5 Heat Source	ASHPs, VRFs, WSHPs, chillers, outdoor units (ACC), heat interface units (HIUs), plate heat exchangers (PHEs), AHUs with integrated HPs
5.6 Space Heating and Air Conditioning	Heat emitters, FCUs, equipment associated with heat source systems, DX indoor units, LTHW and CHW pipework and insulation.
5.7 Ventilation	MVHRs, smoke extract system, ductwork with insulation, attenuators, VCDs, fire dampers, supply and extract grilles
5.8 Electrical Installations	Lighting, PV panel system, lifts, transformer, small power/IT/comms./fire safety distribution

Cost Modelling

Scope and cost boundaries

The Life Cycle Cost (LCC) plan has been prepared by Currie & Brown in line with PD 15686:2008, 'Standardised Method for Life Cycle Costing' and the following cost categories *(see tree diagram below)*:

Construction costs

Only MEP costs are considered. It is assumed that the rest of the building construction costs are consistent in every option. Quantifying the cost of the enhanced fabric performances for meeting future 'best practice' designs in line with UKGBC/LETI etc were outside the scope of the study.

Maintenance costs

Major replacement costs - scheduled replacement of major systems and components. This will form the detailed asset life cycle replacement cost programme.

Minor replacement (excludes any repairs and maintenance costs) - Minor replacement relates to the unscheduled replacement of parts prior to the scheduled replacement and the end of their service life.

Maintenance relates to planned preventative and/or reliability centred maintenance and is excluded in these costs.

Operation and occupancy costs

Cleaning costs – excluded based on the assumption it is similar for each option.

Utilities costs - electricity and/or heat network connections associated with the building.

Occupancy costs – excluded based on the assumption it is similar for each option.

End of life costs – this includes demolition, transport, waste processing and disposal emissions.

The LCC plan considers these utilities and end of life costs, as provided and relevant to the project.

The period of analysis for this elemental LCC plan is 60 years post construction, for which a 3.5% discount rate will be applied, in-line with HM Treasury 'The Green Book' for years 0-30, and 3% for years 31-60. Both the real cost as well as the discounted cost are calculated in the LCC Plan. For ease of reference all comparisons in this report will be based on the real cost.

Methodology

Major and minor replacement

The major replacement costs are based on the initial capital costs.

These are then adjusted using a scale of replacement as relevant to the item and indicative of the level of replacement required at each interval. A reference service life (interval) is then allocated to each item indicating the point at which an intervention is required for an item during the period of analysis. A replacement uplift is then applied to the capital cost to derive a replacement cost per item.

This then calculates the cost per interval per item to generate the life cycle replacement costs over a 60-year period.

Operations

The utilities have been calculated using utility consumption information applied to utility rates provided by Bristol City Council's Energy Service.

The DHN Fixed charge includes allowance for the REPEX for the District Heat Network. This REPEX is therefore not shown separately.

- DHN Connection Fees: £450/kW (included in the capital cost)
- DHN Variable consumption charge: 5.5p/kWh
- DHN Fixed charge: £45/kW

The electricity usage charge is assumed to be 15.6p/kWh.

This process/ methodology enabled the derivation of the following:

1. Outline LCC plan for the MEP cost of the building
2. Replacement strategy.
3. Yearly utility charges

Assumptions

The capital costs are based on current market rates.

The major and minor replacement costs are based on the capital costs.

Lifecycle intervals are based on CIBSE Guide M 2020 Appendix.

Generally, no on-costs have been applied to the capital cost rates used within the LCC plans. However, for M&E services, the cost of M&E subcontractor preliminaries and testing and commissioning have been added to the capital cost of services.

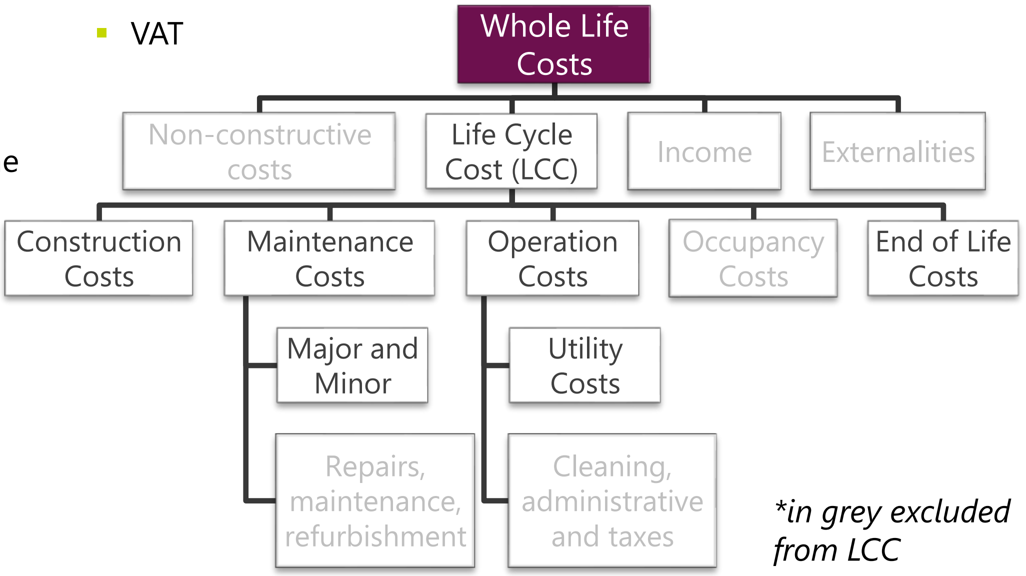
It is assumed that inflation rates will be the same for all the costs and are therefore ignored.

Exclusions

The following have been excluded from the LCC Options Appraisal:

- Construction on-costs inc. main contractor's preliminaries, overheads and profits, design/project fees, risk and inflation except where the percentage of MEP cost vs total construction costs are calculated.
- Replacement and maintenance on-costs
- Inflation for LCC and energy price indexing
- Administration costs
- Risk/ contingency
- Capital allowances
- VAT

Whole Life Costs Scope Tree Diagram



**in grey excluded from LCC*

Part L Compliance

SAP 2012 calculations have been carried out for each of the building design and system options to demonstrate that each is compliant with the requirements of Building Regulations Part L1A 2013 and Bristol Core Strategy Policy BCS14. The results can also be interpreted to estimate the performance against Part L1 2021.

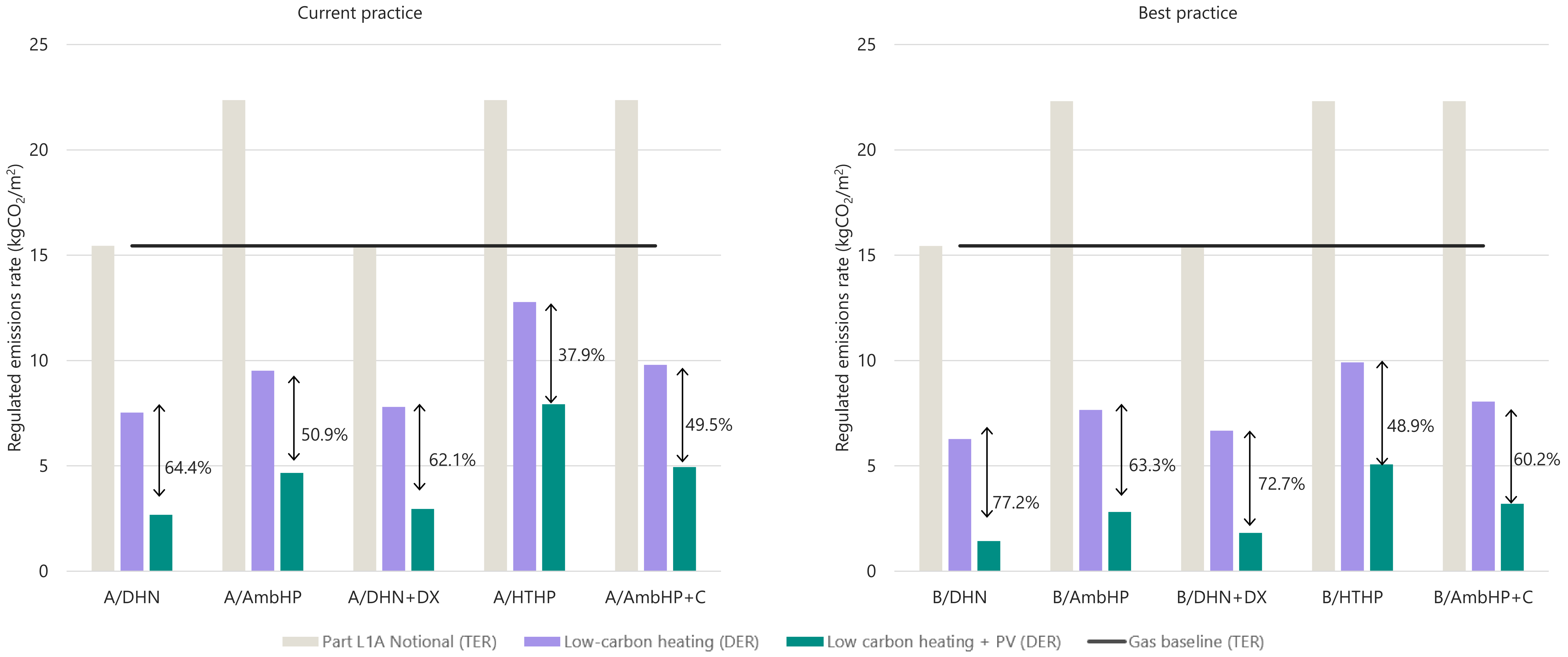
All values shown are calculated using SAP 2012 carbon factors so no benefit from electricity grid decarbonisation is accounted for.

The results, shown in the figures below, demonstrate that all scenarios deliver a reduction in regulated CO_2 emissions with respect to the Part L1A 2013 Notional Building for a gas boiler system, indicated as a black line on the graphs. All options deliver a significant improvement against their respective TER, indicated as a light grey bar in the graphs.

Similarly, all scenarios deliver a reduction in regulated CO_2 emissions through PV greater than the 20% required in Bristol Core Strategy (2011) Policy BCS14.

District heat network options have the lowest regulated carbon emissions whereas the high-temperature heat pump is estimated as the highest. This is the opposite of the findings of the operational carbon calculations.

Summary tables of the Part L1A compliance results including the actual and notional building carbon (DER & TER) and fabric energy efficiency (DFEE & TFEE) for each system and building design option are included in the appendices of this report.



__A__ – Current practice, __B__ – Best practice, __DHN__ - District heating connection, no cooling, __AmbHP__ – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, __DHN + DX__ - District heating connection for heat, local split system cooling unit, __HTHP__ – High temperature central air source heat pump, no cooling, __AmbHP + C__ - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

Energy Demand

Space heating, space cooling, and domestic hot water thermal demand, as well as in-dwelling electricity demand (from appliances, lighting, fans & pumps), has been calculated for each dwelling. The figures below show the demand breakdown by end use for dwellings with the lowest, highest, and average total demand values of all dwellings for both the current and best practice building scenarios.

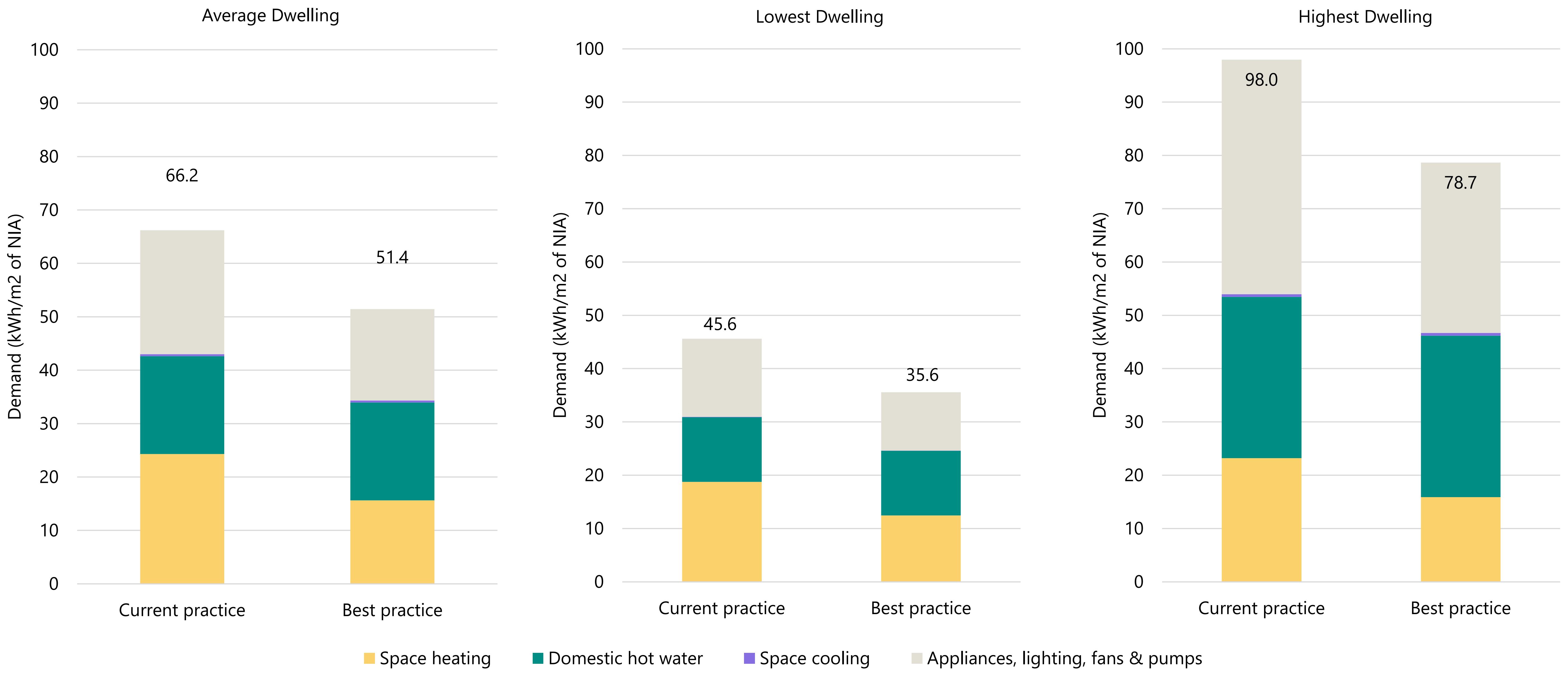
Space heating demand varies in relation to dwelling form, orientation, and occupancy characteristics. Irrespective of these variables, a significant reduction in space heating demand is seen between the current and best practice scenarios. For the current practice building, only 28% of dwellings achieve the proposed heating demand target of <20 kWh/m^2, compared to 87% of dwellings for the best practice building. None of the dwellings for the current practice building scenario and only 41% of dwellings for the best practice building scenario achieve a heat demand <15 kWh/m^2.

Domestic hot water demand varies greatly depending on occupancy use patterns and density. No change in hot water consumption has been assumed between current and best practice scenarios.

Space cooling demand is very small as the dwellings are already designed to minimise the risk of overheating and natural ventilation from openable windows has been included in the modelling.

Energy use from appliances, lighting, fans and pumps is a large and highly variable demand, driven by occupant density and behaviour. This demand can also have a knock on impact on the space heating and cooling demand.

Summary tables of the space heating, domestic hot water, space cooling, and electrical demand for the lowest, average, and highest dwellings in both the current and best practice building scenarios are included in the appendices of this report.



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Operational Energy Results

Annual energy usage intensities (EUIs) in kWh/m^2 of dwelling GIA have been calculated for each option to provide comparison between building design and system options as well as targets proposed by RIBA, UKGBC and LETI.

The results indicate that the high-temperature heat pump option has the lowest EUI whilst the DHN with DX cooling has the highest.

EUIs vary significantly between DHN and heat pump-based system options because the heat demand from the DHN has no efficiency factor applied meaning a direct comparison is difficult.

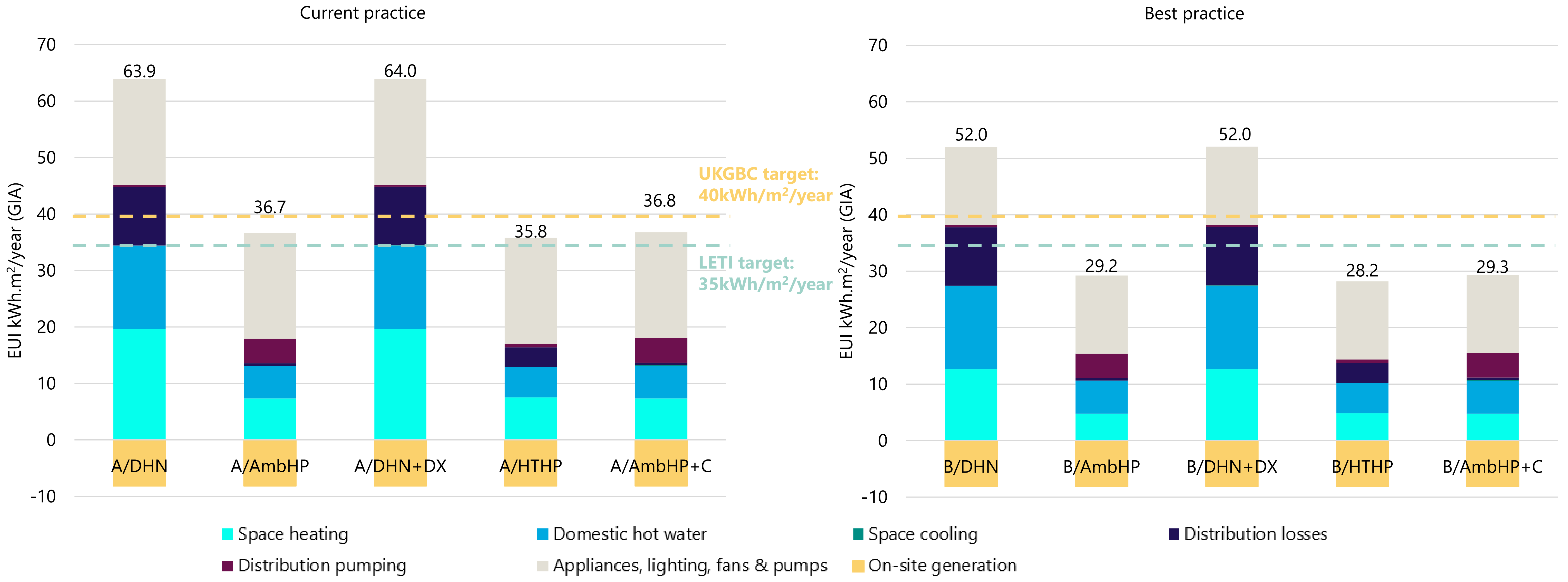
For the current practice building, none of the system options achieve the proposed LETI EUI target of <35 kWh/m^2/year, (excluding renewable energy contribution) whereas each of the heat pump-based system options (AmbHP & HTHP) meet the <40 kWh/m^2/year target. Heat pump-based system options meet both EUI targets for the best practice building but DHN systems do not because no efficiency is applied to the DHN heat. A methodology to enable more direct comparison of EUI performance is proposed on page 63.

As shown in the figures below, there is a major reduction in energy use between the current and best practice buildings due to the significant reduction in annual demands as a result of reduction in energy use for appliances, lighting, fans and pumps as well as lower space heating demand.

Energy consumption from network heat losses is a significant load for system options with high-temperature distribution, representing on average 16% and 19% of the total EUI (excluding renewable energy generation) for the current and the best practice building scenarios respectively. Conversely, pumping energy is large for ambient loop systems due to lower temperature differentials, representing on average 12% and 15% of the total EUI (excluding renewable energy generation) for the current and the best practice building scenarios respectively. Note that heat losses for DHN options are calculated as heat demand so do not account for generation efficiency whereas pumping energy is direct electricity consumed.

Between each system option there is an energy use balance between generation efficiency, heat losses and pumping. The lowest overall option will depend on the specific characteristics of the building such as size, form and heat demand profile. Energy consumption from each of these use types can be limited through good design practices.

Summary tables of the EUI breakdown by end use for the average dwelling for each system type in both the current and best practice building scenarios are included in the appendices of this report.



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Operational Energy and Carbon Results

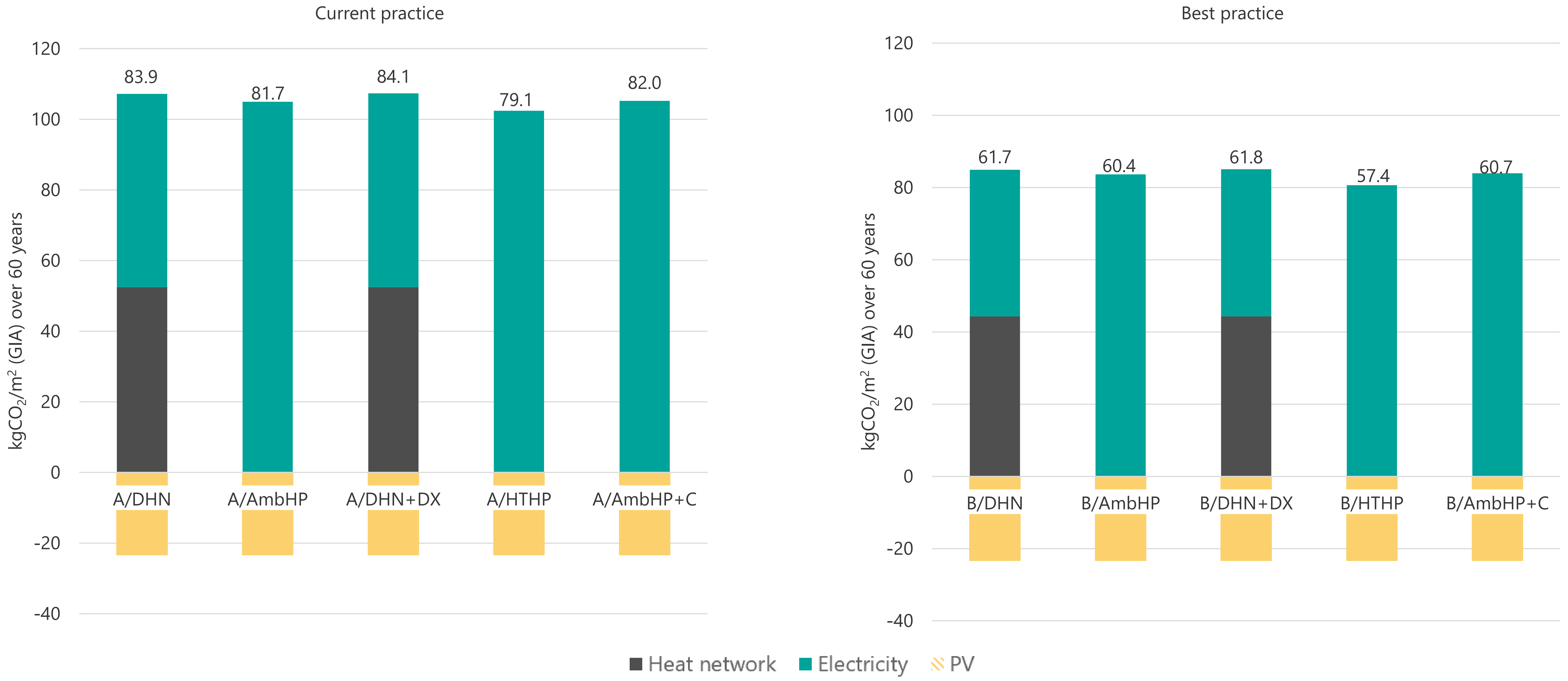
Operational carbon over a period of 60 years has been calculated using the energy use intensity figures and carbon intensity projections for DHN and grid electricity, incorporating the decarbonisation of the grid for each option.

As shown in the figures below, there is a significant reduction in carbon of ~26% (excluding renewable energy generation) between the current and best practice buildings due to the significant reduction in annual demands as a result of reduction in energy use for appliances, lighting, fans and pumps as well as lower space heating demand.

Despite the higher energy use intensity for heat from DHN identified on the previous page, the lower carbon intensity of heat from DHN in comparison to grid electricity results in very similar carbon emissions from all system options with only a ~5% uplift (excluding renewable energy generation) in emissions between the lowest (HTHP) and the highest (DHN+DX) options.

In agreement with the EUI results, the operational carbon results indicate that the high-temperature heat pump option has the lowest operational carbon emissions, whilst the DHN with DX cooling has the highest.

Summary tables of the carbon emissions breakdown by fuel for the average dwelling for each system type in both the current and best practice building scenarios are included in the appendices of this report.



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DHN EUI Correction

As discussed in the previous operational energy and carbon results sections, the EUI figures are not representative of the operational carbon for DHN connected systems. The reason for this is because the EUI represents the metered energy figures (in kWh) and does not distinguish between the type of fuel (in this case electricity and the heat network). Therefore the heat network EUI is seen to be penalised as this does not take into account the coefficient of performance of the upstream DHN equipment (principally heat pump based systems).

Therefore for benchmarking and policy targeting purposes, if an EUI target is set, it is recommended that an EUI correction is applied for DHN connected schemes.

In this regard, it is suggested that a 'factor' is applied to the energy consumed from the DHN. This factor would essentially represent the long term projected efficiency of the DHN's heat generation plant. This has been calculated to be **~2.44** (or to be directly multiplied by 0.41) over a 60 year period from 2021 based on the decarbonisation projections of the electrical grid from BEIS and the DHN projections from BCC.

Methodology

This factor was calculated by utilising the carbon intensity of the DHN grid for a given electricity grid carbon intensity projection until 2081 (page 19). The resulting total carbon emissions for 1kWh from the electrical grid was divided by the associated carbon emissions of 1kWh of district network heat over the 60 year period.

$$\frac{Carbon\ emissions\ of\ 1kWh\ of\ electricity\ over\ 60\ years}{Carbon\ emissions\ of\ 1kWh\ of\ DHN\ heat\ over\ 60\ years} = \mathbf{2.44}$$

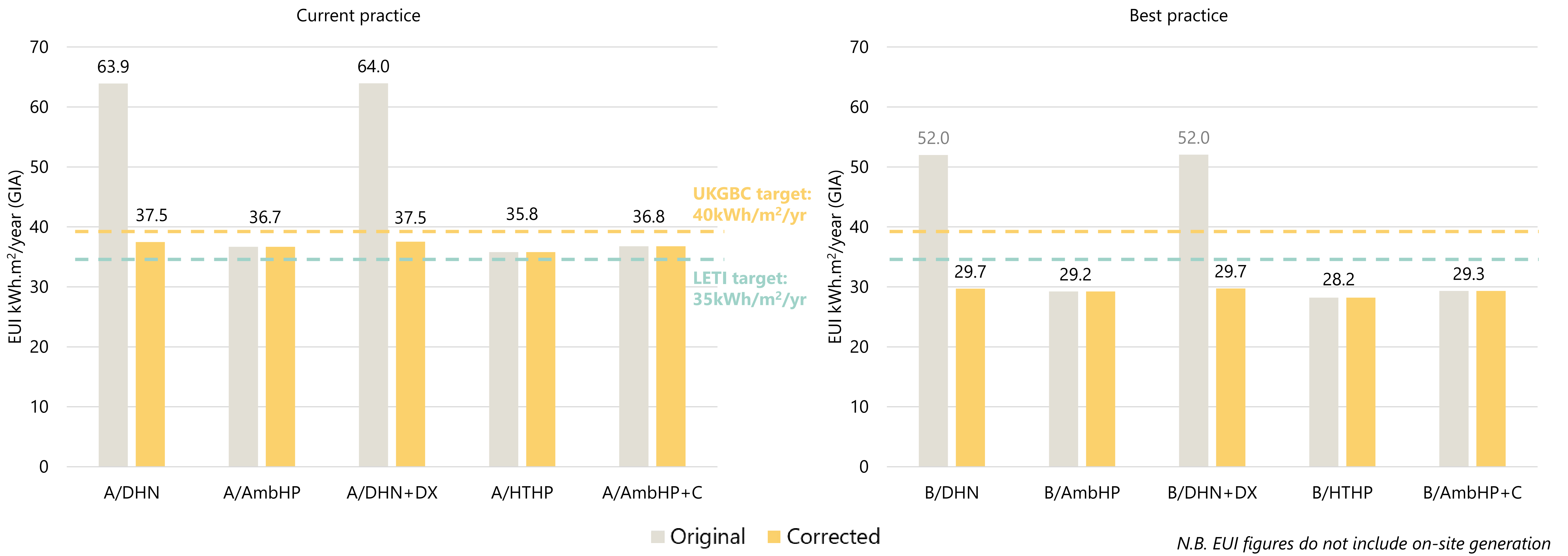
This essentially calculates the electricity equivalence of the heat supplied by the DHN enabling direct operational carbon calculations and comparisons. This factor can be calculated/updated and issued periodically.

Post-DHN-correction EUI results

The hierarchy of performance of each system remains unchanged after adjustment of the DHN energy but all options are significantly closer with only up to 1.7kWh/m^2/year difference between the lowest and highest options, representing a ~5% uplift.

A general reduction of 41-43% has been observed for the DHN connected systems for the total calculated EUI for the current and best practice buildings respectively.

As shown (based on a factor of 2.44), all the system options now meet the UKGBC target for the current practice building and all system options meet the LETI target for the best practice building.



N.B. EUI figures do not include on-site generation contributions in line with the LETI definition

A *– Current practice,* ***B*** *– Best practice,* ***DHN*** *- District heating connection, no cooling,* ***AmbHP*** *– Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling,* ***DHN + DX*** *- District heating connection for heat, local split system cooling unit,* ***HTHP*** *– High temperature central air source heat pump, no cooling,* ***AmbHP + C*** *- Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.*

Embodied Carbon Results

The results from the residential apartment building embodied carbon study can be visualised in the bar graphs below. The best practice building scenario does not make a significant difference, to the embodied carbon results due to the size of heating and cooling equipment not changing with a small reduction in capacity – DHW demand is the principal driver here.

Refrigerant leakage contributes significantly to the ambient loop systems, as well as the DX. The former is explored in the Refrigerant section of this report, on page 90, as for this study it was assumed the systems use R32 as a lower GWP alternative to R410A. Refrigerant leakage (use phase) will also be explored in line with the commercial study.

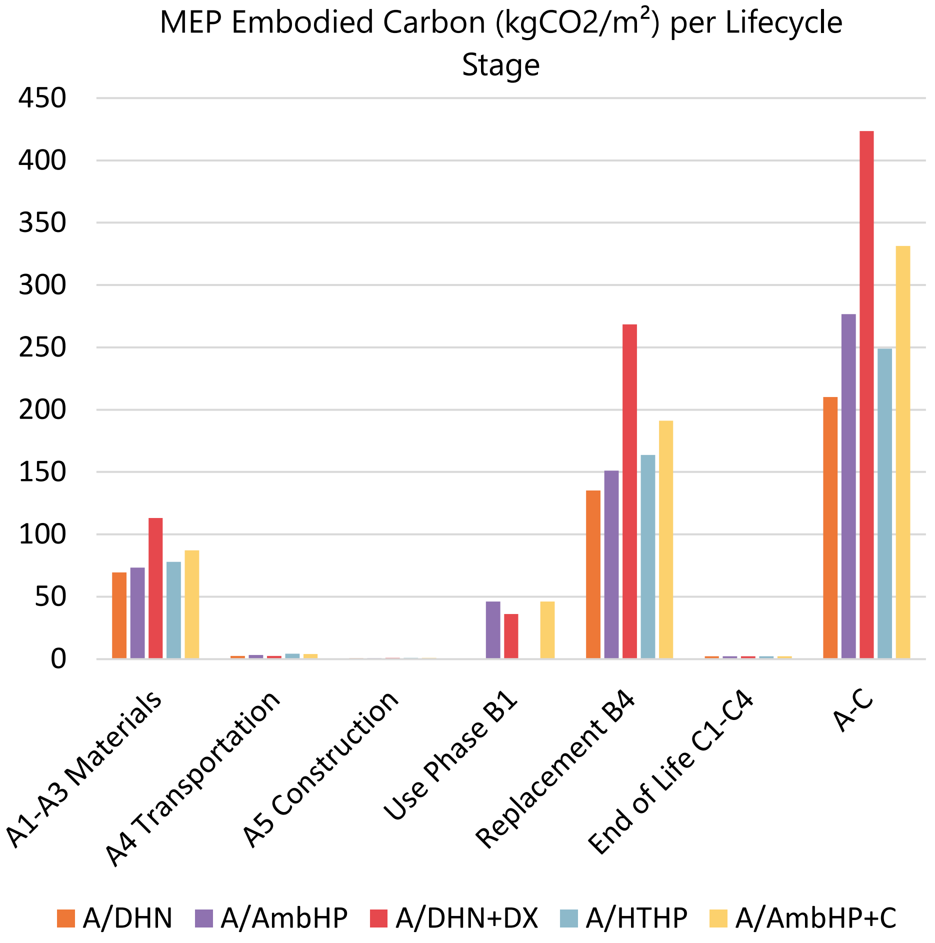
The district heat network system alone is the least intensive with regard to embodied carbon, however when combined with the DX system this is the worst performing system due to the doubling up of emitters (hydronic heating and DX fan coils). Across the heating and cooling systems account for a range of 15% (B/DHN) to 50% (A/DHN+DX) of the MEP embodied carbon.

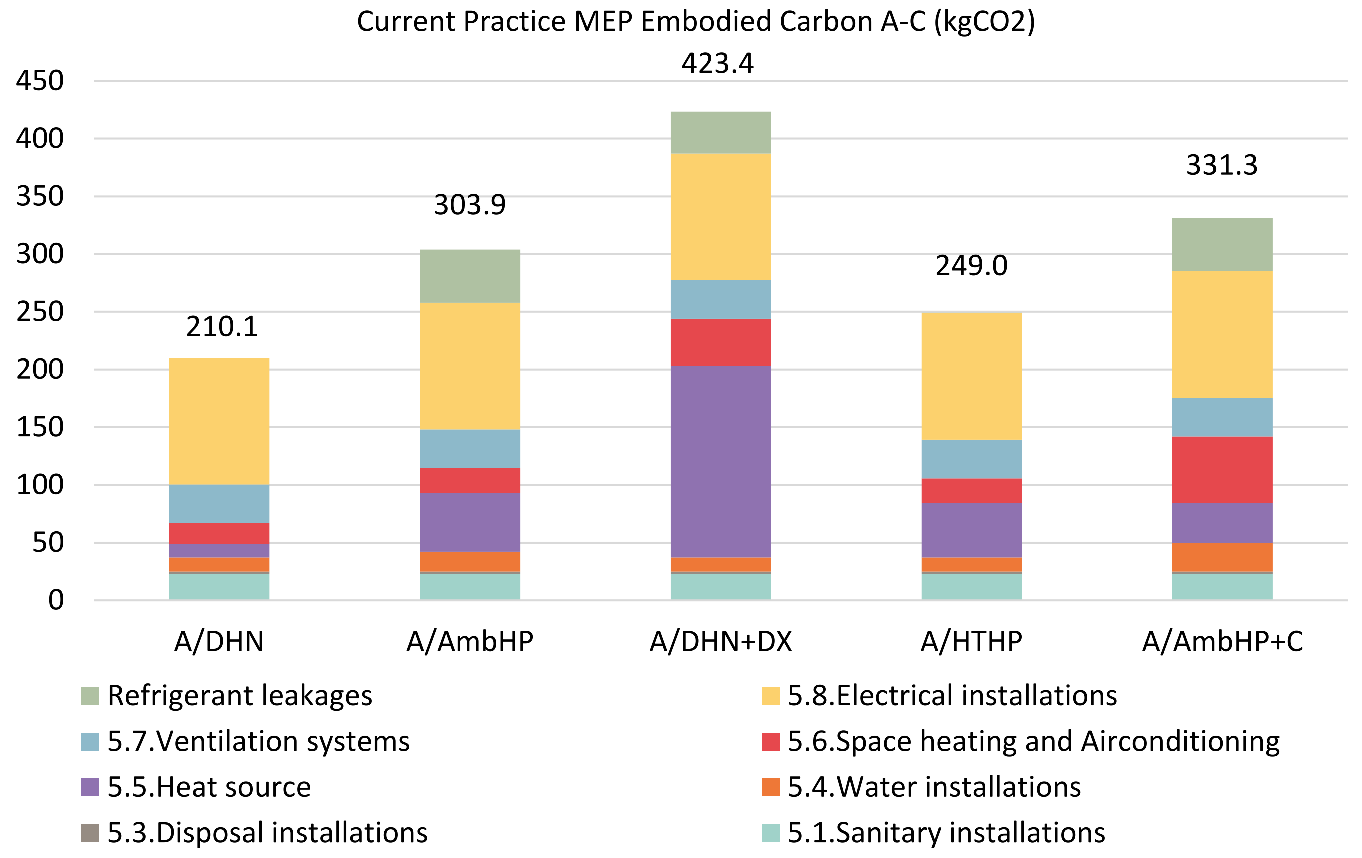
The bar chart to the right shows that Replacement (B4) contributes approximately twice as much as Materials (A1-A3), highlighting the importance that MEP equipment lifespans have on the whole life carbon of a building. As mentioned in the commercial study section, circular economy principles to prolong service lifespans should be strongly considered to mitigate this.

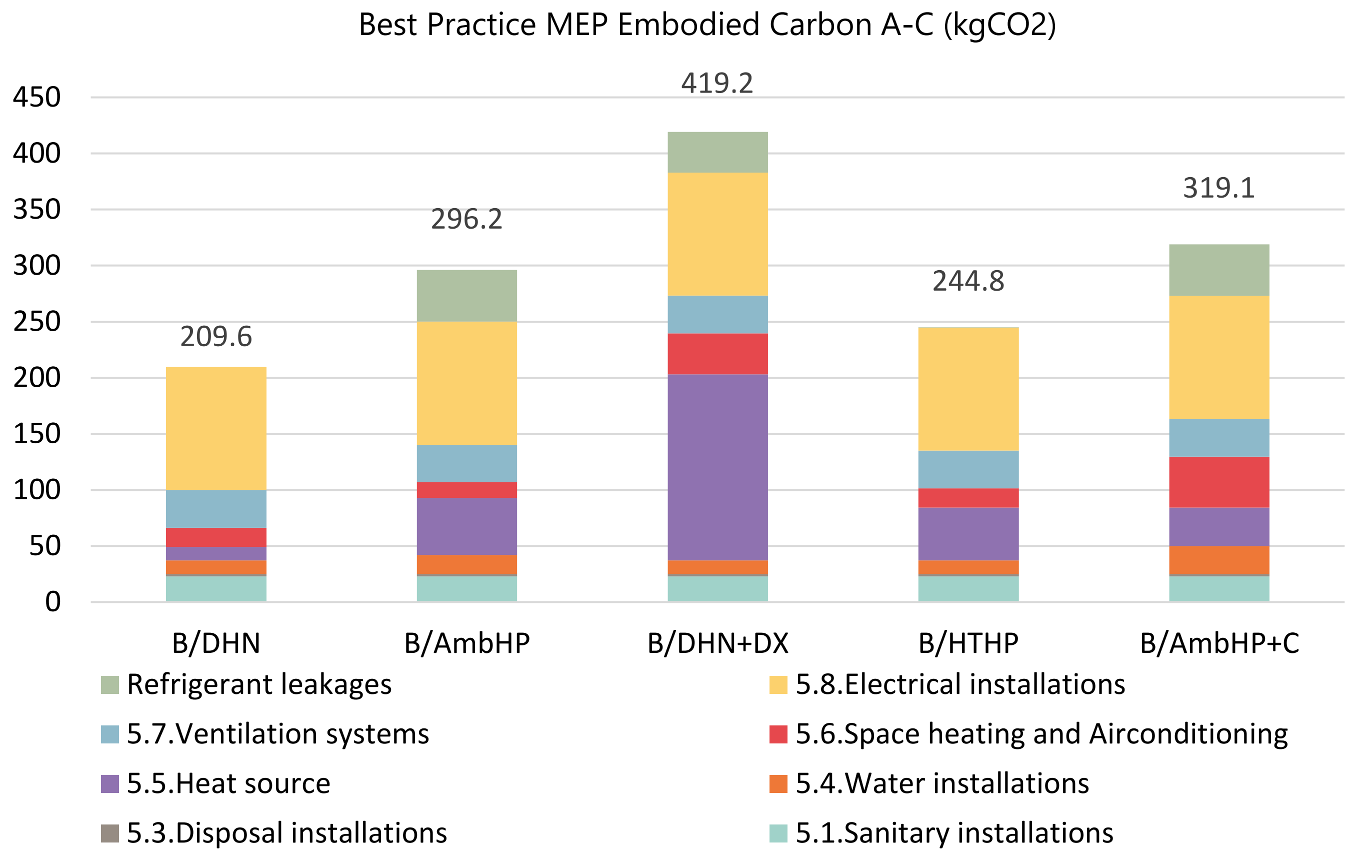
Top 7 contributors to the embodied carbon, in order of average contribution, are as follows:

1. Electrical distribution
2. Heating and Cooling generation equipment (ASHPs, VRF, etc.)
3. Refrigerant
4. Photovoltaic panels
5. Space heating and cooling terminals (FCUs, trench heaters, etc.)
6. Lighting
7. Sanitary equipment (WHBs, WCs, showers, baths)

The embodied carbon comparison for only heating and cooling systems can be found on the next page.







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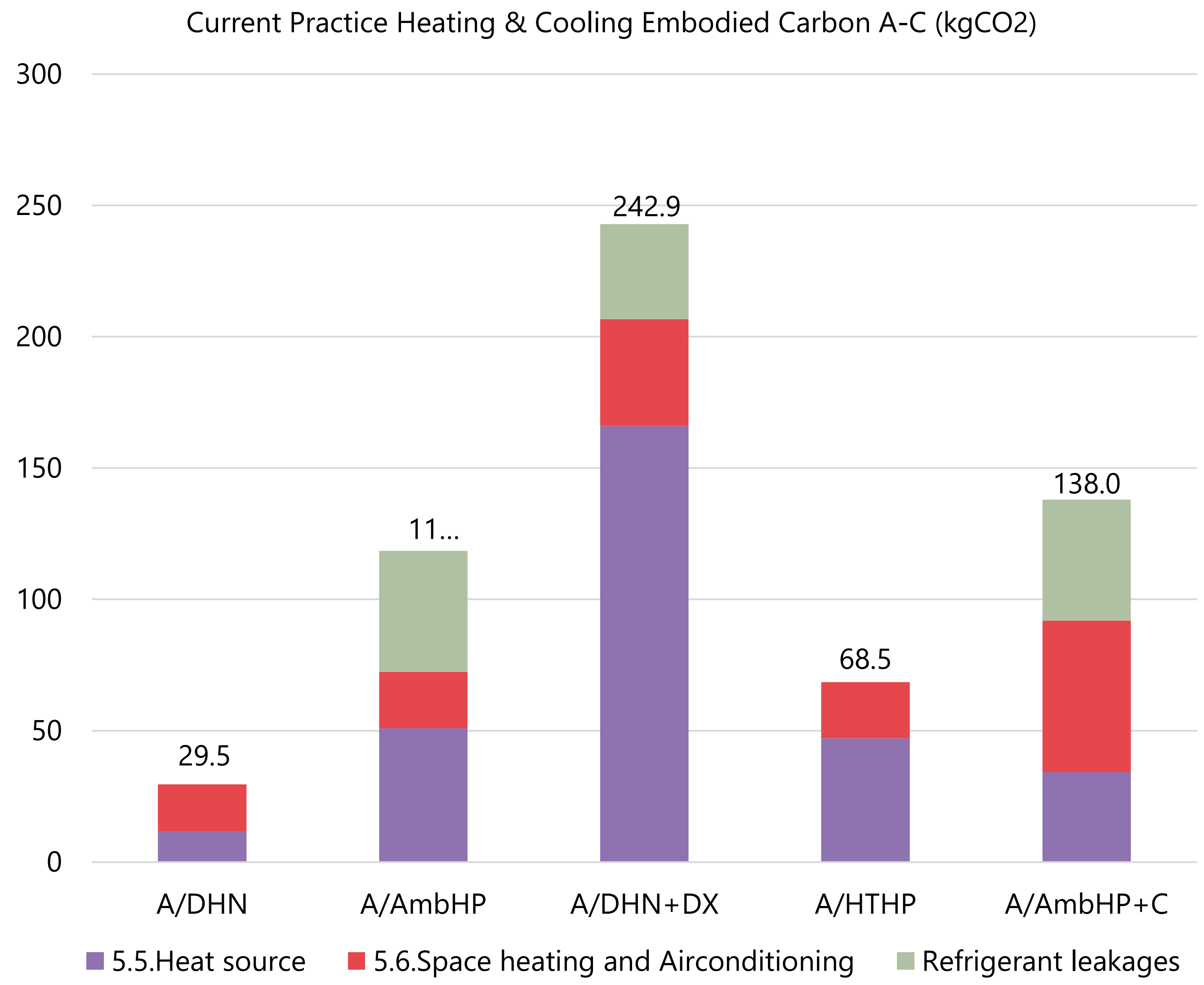
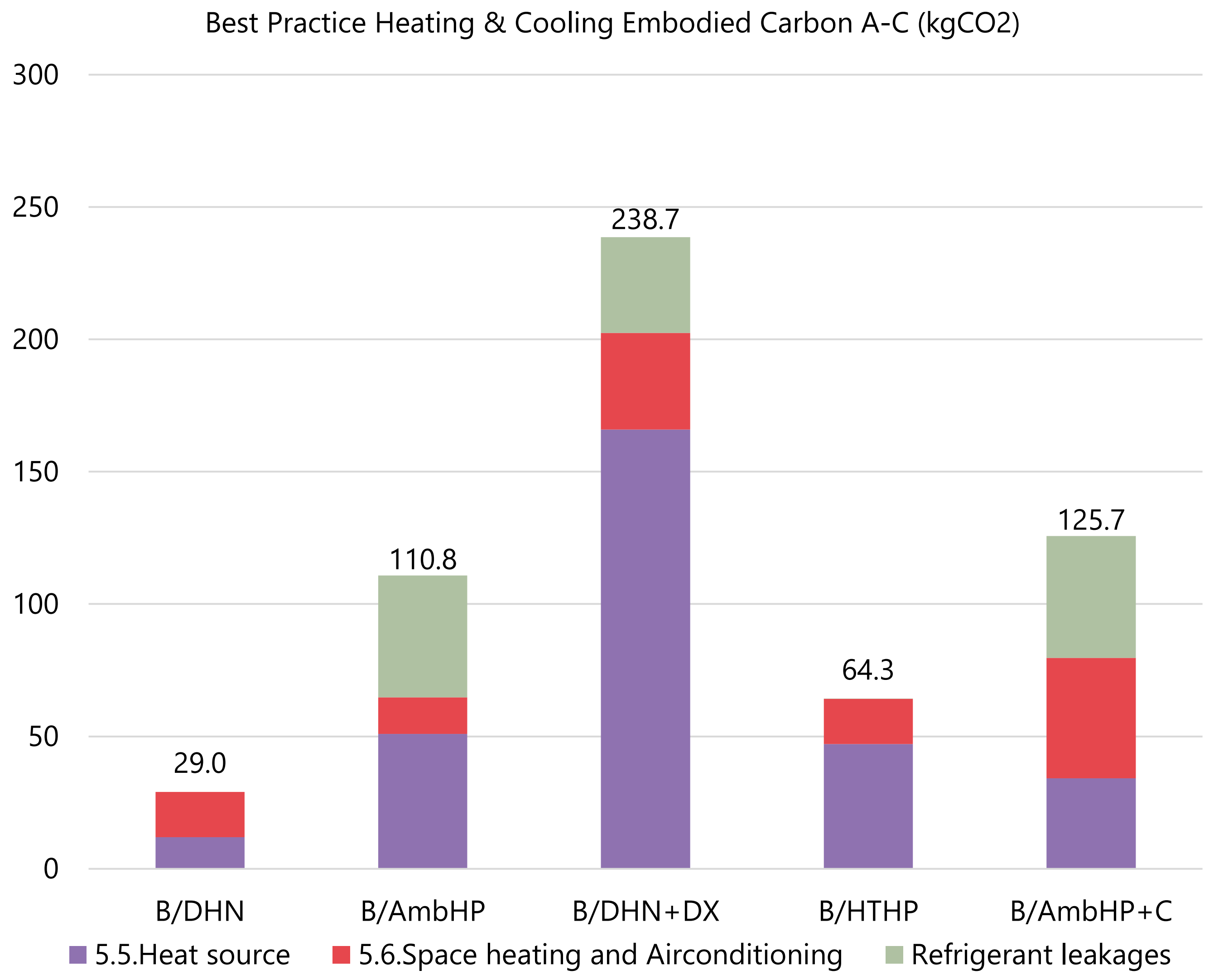
Embodied Carbon Results

The bar charts below show the current practice and best practice systems and how they perform only with regards to heating and cooling equipment only. In these, the increase in embodied carbon due to the amount of required equipment for the system strategy in the DHN + DX scenario is even clearer. This scenario has been modelled as it is a likely scenario with retrofit housing, this should therefore be considered in conjunction with a wider appreciation for building reuse and reduction of structures embodied carbon.

The impact of refrigerant makes the most difference to the Ambient loop heat pump option (AmbHP) which would be performing second best were it not for the leakage emissions. As is explored in the refrigerant section of this report on p. 90, this system was modelled using R32 rather than R410A which the currently available system actually uses, therefore the impact of refrigerant could be an even greater contributor in this case.

The propane heat pump (HTHP) and DHN systems perform best as they require the least amount of equipment and do not have high refrigerant charges or GWPs to consider.





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Embodied Carbon LETI and GLA Comparison

The pie charts to the right compare a typical MEP proportion from the study to the GLA typical apartment A-C embodied carbon breakdown, and LETI's medium scale apartment building embodied carbon breakdown. It is worth noting that MEP embodied carbon information is ever increasing, and therefore inclusions into the Bristol City Council study are likely to be more detailed and inclusive compared to studies done in 2020 and prior.

The non-MEP elements of the Bristol City Council study were calculated on a per GIA basis from a similar project (size and build). The superstructure and finishes element is inclusive of FFE, facades, integral partitions, stairs and ramps, the frame, and the roof.

The GLA's anticipated whole life embodied carbon benchmark for a typical apartment or hotel building is between 1,050-1,250 kgCO2/m^2 GIA, which aligns with the study's average result of approximately 1,050 kgCO2/m^2 GIA.

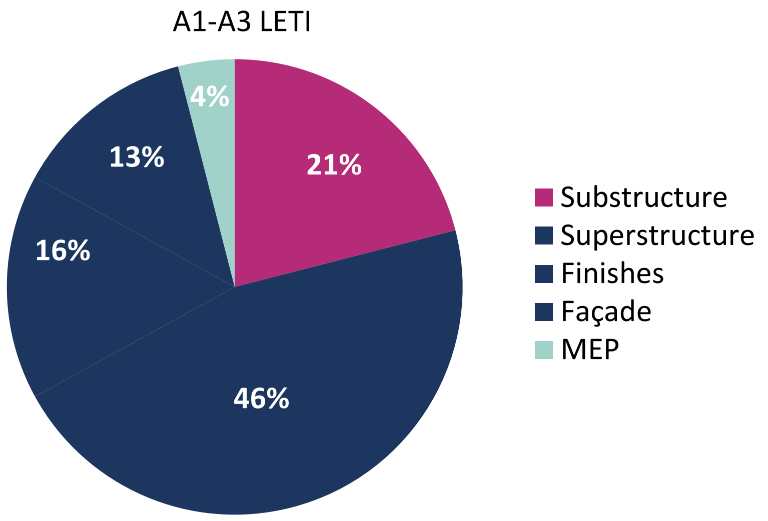
The tables to the right show the MEP embodied carbon kgCO2/m^2 comparing extrapolated LETI and GLA business as usual and aspirational values for apartment buildings, for A1-A3 (Cradle to Gate) and A-C (Cradle to Grave) respectively. Comparison with the GLA shows that from A-C the BCC study averages higher, even when considering the lowest embodied carbon system, namely the DHN. This is likely in large due to refrigerant emissions and lifespans as suggested in the commercial section since the GLA only considers them for one of its benchmarking sources from which it averages. It is likely also that the concept of building services and space conditioning in apartment buildings has changed in the last few years towards a more services-heavy approach, for example, the use of MVHRs and PV. This reasoning can also be applied to the LETI comparison table as the BCC study is more than twice as much. It is worth noting, however, that in the most recent TM65 publication on residential MEP embodied carbon, the modelled heating and cooling systems ranged between 20 and 33 kgCO2/m^2 for communal systems, excluding ventilation, water, and electrical systems. This suggests that as previously hypothesised, as MEP embodied carbon knowledge becomes more granular, the impact that it has on whole building lifetime carbon will become more evident.

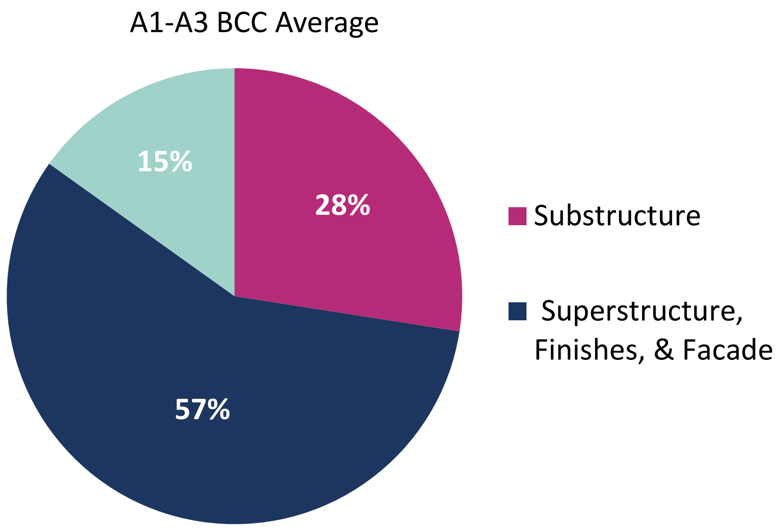
The breakdowns in the charts show that the study has a higher embodied carbon proportion when compared to the benchmarks. This is likely due to both the inclusion of more detail, as well as the MEP-intensive strategies that have been modelled in the study - as previously suggested. This may also be due to assumed lifespans of equipment. For example, if using RICS lifespans, this will have less granular and longer lifespans for equipment when compared with CIBSE Guide M values.

LETI assumptions suggest residential MEP should be a smaller proportion of the whole building, however, this study's results show a similar proportion to the commercial building due to the aforementioned MEP intensive strategies.

MEP Embodied Carbon kgCO2/m^2 Cradle to Grave (A-C)			
	GLA Business as Usual	GLA Aspirational	BCC Study (B/Average)
MEP	193	115	299

MEP Embodied Carbon kgCO2/m^2 Cradle to Gate (A1 - A3)			
	LETI Business As Usual	LETI Best Practice	BCC Study (B/Average)
MEP	32	20	83





Costing Results

MEP related costs amount to ~35% of the entire building life cycle cost. Of the MEP costs ~22% is CAPEX, ~64% is REPEX and ~14% is OPEX.

On average across all system types, the best practice building has a whole life cost for MEP related items of ~£474,300 lower than the current practice building, a ~4% reduction. Most of the cost saving is realised in the OPEX which is closely linked to the EUI values.

The high temperature heat pump options have the lowest whole life cost due to lower REPEX and OPEX. The ambient loop options have the highest whole life cost driven by high CAPEX and REPEX. The estimated whole life cost uplift between the highest and lowest options was ~34% at £3.4M.

Capital expenditure (CAPEX)

MEP capital costs are similar between base and best practice buildings meaning that a reduction in capacity does not have a significant impact on overall costs (~2% decrease).

Across the options, high-temperature heat pump systems have the lowest CAPEX and generally, the ambient loop options have the highest CAPEX due to the inclusion of WSHP units in each dwelling. This is exacerbated for the ambient loop options with cooling due to the need for more expensive fan coil units in dwellings instead of radiators.

Traditionally, developers in the private sector would aim for the lowest capital expenditure possible, however recently, they are focussing on sustainability and net zero carbon at an increasing rate to be able to advertise their buildings. Therefore, according to these trends increases to the CAPEX are not entirely detrimental to net zero objectives.

Replacement expenditure (REPEX)

The replacement cost is the largest contributor to the whole life cost and has the greatest variation between all options. Therefore the cost, quantities, and service life of installed equipment strongly influence whole life cost.

DHN options without cooling have the lowest REPEX as the amount of equipment within dwellings is minimal and there is limited central plant within the building boundary. Note that the REPEX for replacement of the DHN plant is accounted for within the OPEX for this study, as the cost will be passed to the consumer through connection, unit or standing charges. Ambient loop systems have the highest REPEX driven by the inclusion of WSHP units in each dwelling.

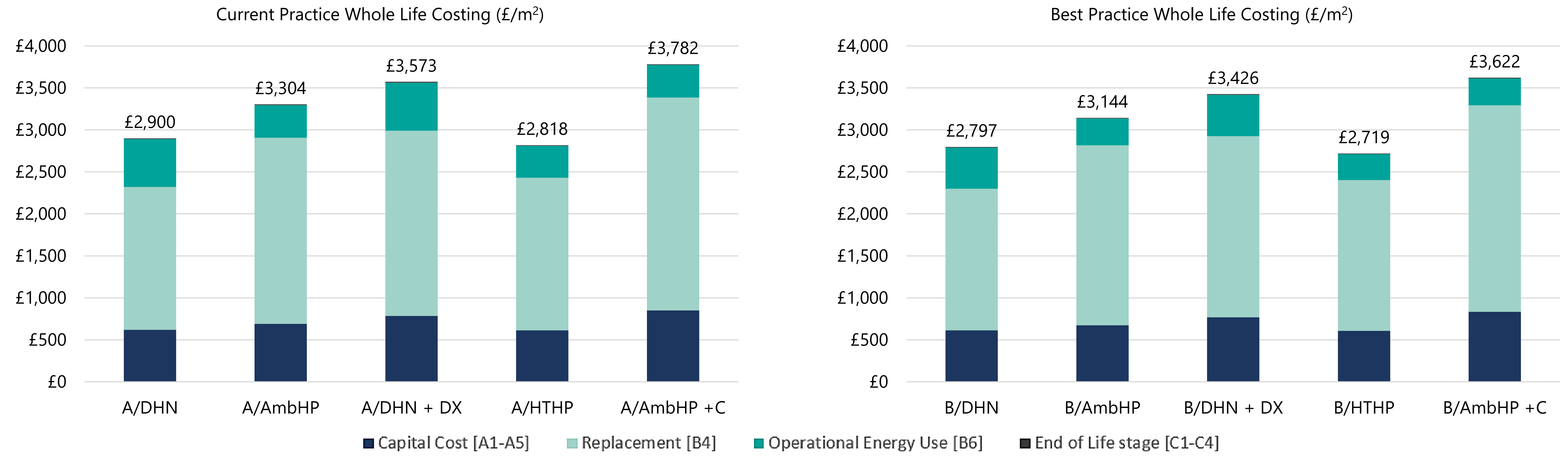
Overall, the addition of cooling leads to an increase in REPEX due to the introduction of additional quantity or cost of equipment.

Operational expenditure (OPEX)

The OPEX is tied to the operational energy demand and DHN related costs (e.g. unit and standing charges). It is shown that options with DHN connections have significantly higher operating costs due to associated fees. High-temperature heat pump systems have the lowest OPEX despite having lower generation efficiency in comparison to the ambient loop option because of the cost of increased pumping energy for the ambient loop.

End of life

End of life involves the act of deconstructing and managing disposal and processing. Therefore options with the highest material volumes can incur the highest costs. DHN + DX has the highest end of life costs due to the highest volume of overall materials (doubling up on space heating and cooling plant). Handling of refrigerants can also increase end of life costs.



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Whole Life Carbon and Costing

Results of the operational carbon, embodied carbon and costing have been combined to calculate the whole life carbon and cost for each system scenario for the current practice and best practice building options.

MEP-related elements only

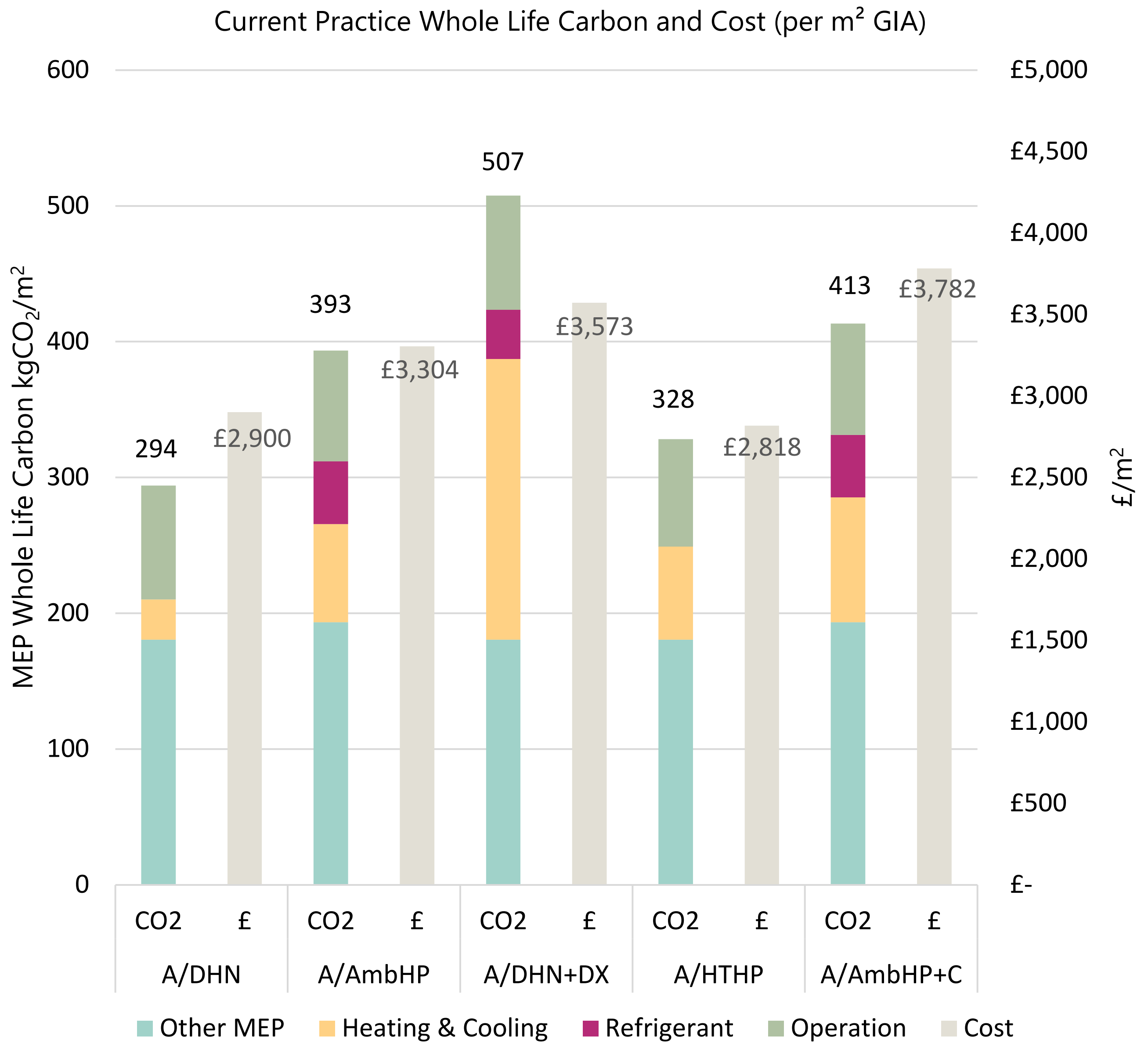
In all options the embodied carbon and whole life cost of the building elements other than the building services are maintained constant for all iterations so have been excluded from the figures below but are shown on the following page.

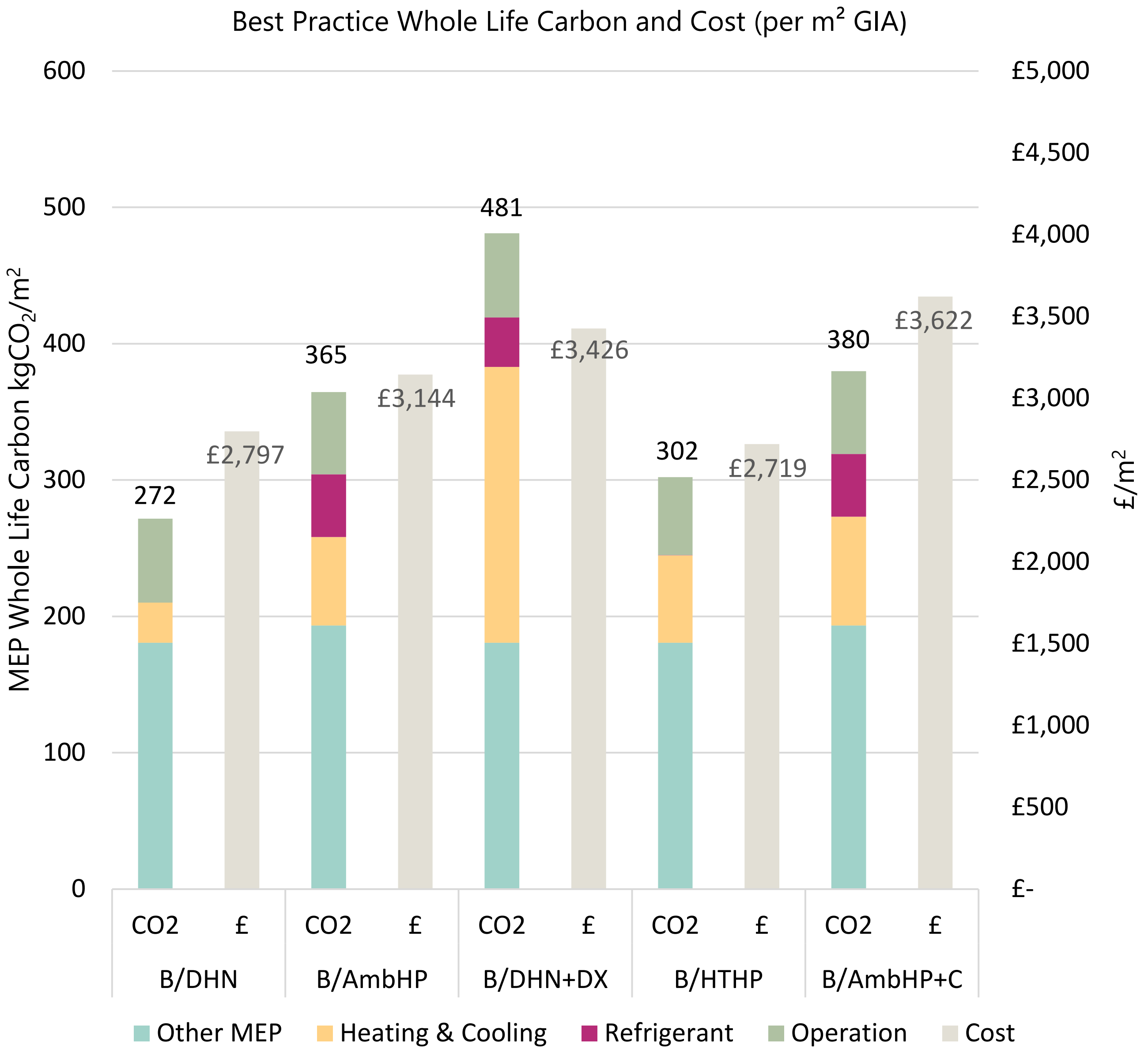
Embodied carbon of the 'Other MEP' only changes to account for a change in hot water cylinder for the ambient loop systems.

The highest whole life carbon is the DHN+DX option, driven by the high embodied carbon of the additional cooling equipment. The lowest whole life carbon is the DHN option due to significantly lower heating and cooling equipment embodied carbon. There is a 73-77% uplift in whole life carbon of MEP-related elements between the lowest and highest system options for the current and best practice scenarios respectively.

The highest whole life cost is the AmbHP+C option driven by the high capital and replacement cost despite low operating costs. The lowest whole life cost is the HTHP option because of a combination of low capital, replacement, and operational cost outlay. The DHN option is marginally higher whole life cost with only a 3% increase. There is a 34-33% uplift in whole life cost of MEP-related elements between the lowest and highest system options for the current and best practice scenarios respectively.

Summary tables of the whole life carbon emissions breakdown by element for the average dwelling for each system type in both the current and best practice building scenarios are included in the appendices of this report.





A – Current practice, B – Best practice, DHN - District heating connection, no cooling, AmbHP – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, DHN + DX - District heating connection for heat, local split system cooling unit, HTHP – High temperature central air source heat pump, no cooling, AmbHP + C - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

Whole Life Carbon and Costing

Results of the operational carbon, embodied carbon and costing have been combined to calculate the whole life carbon and cost for each system scenario for the current practice and best practice building options.

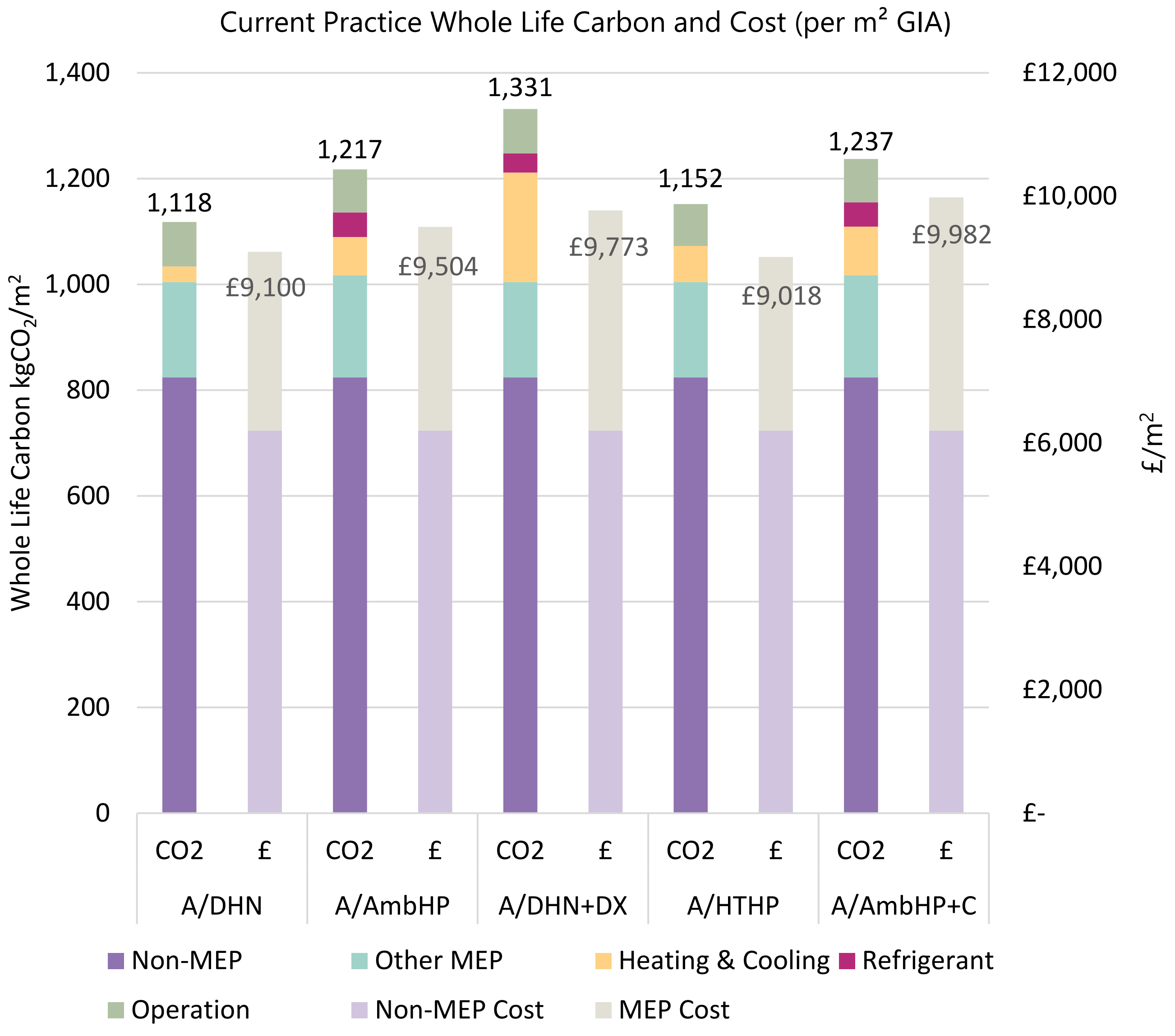
Context of the whole building

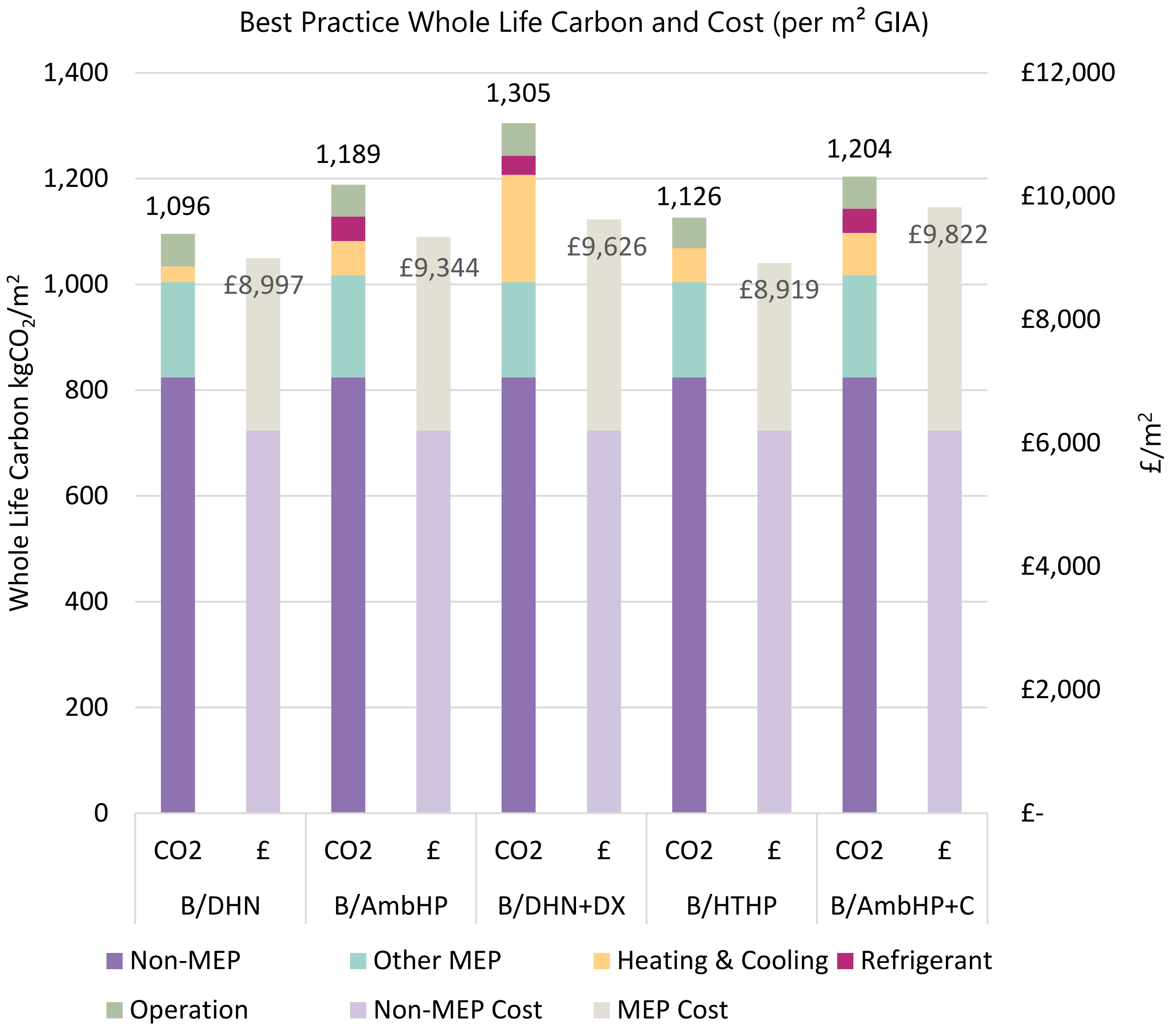
To set the findings of the whole life carbon and cost analysis for MEP-related elements in the context of the whole building, the figures below summarise the whole life cost and carbon for all the residential options studied which includes benchmark estimations for non-MEP elements.

There is a ~19% uplift whole life carbon for all building elements between the lowest and highest system options for both the current and best practice scenarios.

There is an 11-10% uplift in whole life cost for all building elements between the lowest and highest system options for the current and best practice scenarios respectively.

Summary tables of the whole life carbon emissions breakdown by element for the average dwelling for each system type in both the current and best practice building scenarios are included in the appendices of this report.


Current Practice Whole Life Carbon and Cost (per m² GIA)


Best Practice Whole Life Carbon and Cost (per m² GIA)

*A – Current practice, **B** – Best practice, **DHN** - District heating connection, no cooling, **AmbHP** – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, **DHN + DX** - District heating connection for heat, local split system cooling unit, **HTHP** – High temperature central air source heat pump, no cooling, **AmbHP + C** - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.*

System Evaluation Summary | Apartments

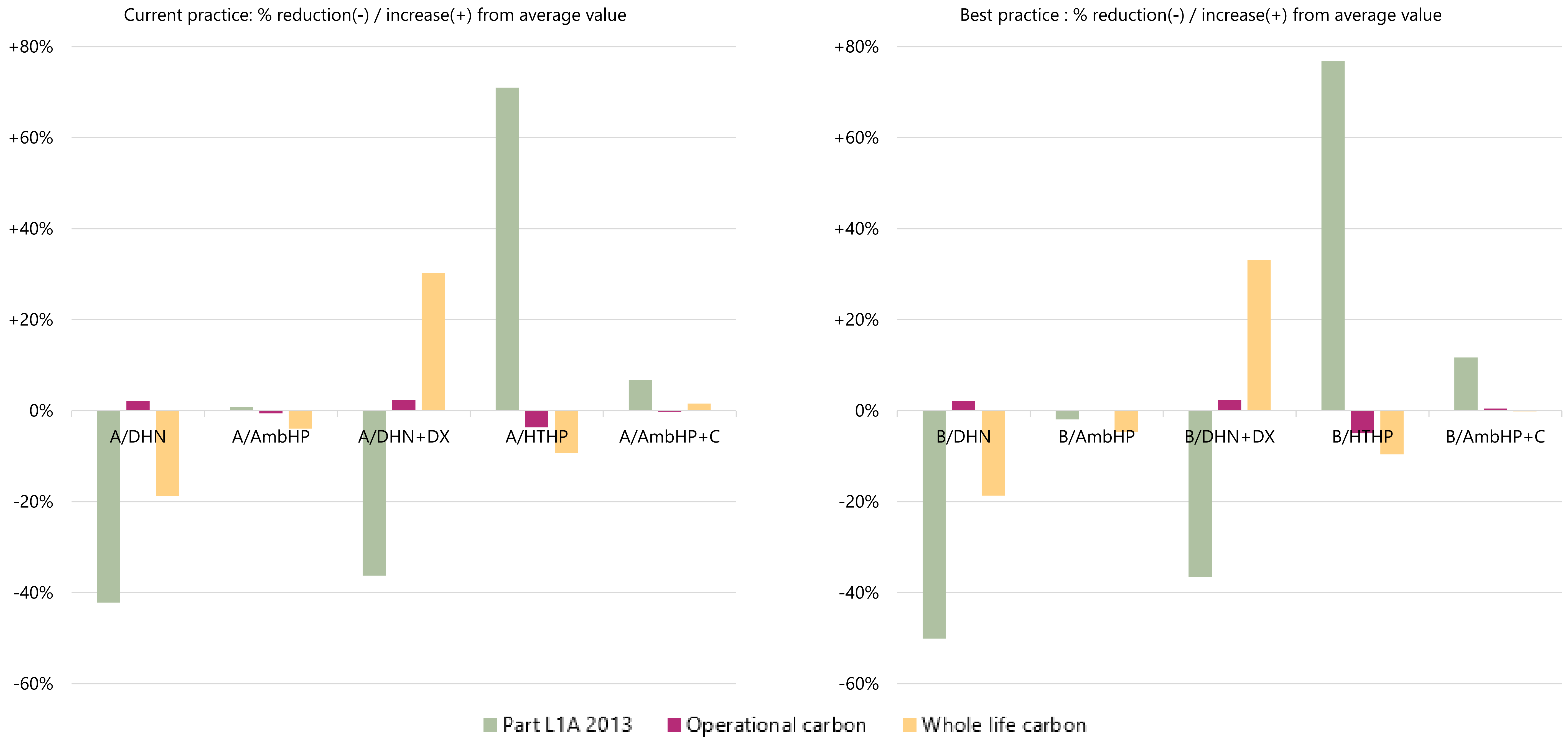
The charts on this page summarise the variation in performance between each system scenario for each of the carbon emissions metrics; Part L1A 2013 compliance, operational carbon and whole life carbon.

The graphs show the relative reduction/improvement (shown as a negative bar) or increase/shortfall (shown as a positive bar) in carbon emissions for each system with respect to the mean average of all systems for the current and best practice scenarios respectively. As such, the 0% level indicates the average performance, the most negative bar is the best performing, lowest carbon system and the most positive bar is the worst performing, highest carbon system.

The Part L1A 2013 compliance results show the greatest variation between system options from the average, ranging from -50% reduction for DHN to +77% increase for the HTHP options.

In contrast, the calculated operational energy shows smaller variation between system options ranging from -5% reduction for HTHP to +2% increase for the DHN+DX options.

The whole life carbon results are different again with a notable variation ranging from -19% reduction for DHN to +33% increase for the DHN+DX options.



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System Evaluation Summary | Residential

Category	Apartment Building Options									
	District heating connection, no cooling		Shared condenser loop system with central air source heating and local water-to-water heat pumps providing heating, no cooling		District heating connection for heat, local split system cooling unit		Hydronic communal heating system from central air source heat pump, no cooling		Shared condenser loop system with central air source heating and cooling and local water-to-water heat pumps providing heating and cooling	
	DHN		**AmbHP**		**DHN + DX**		**HTHP**		**AmbHP+C**	
	Rating	Comments	Rating	Comments	Rating	Comments	Rating	Comments	Rating	Comments
Whole life carbon (MEP)	**-19%**	Lowest carbon - least equipment and refrigerant	**-4%**	Individual dwelling systems increase refrigerant and equipment	**+30%**	Highest carbon - Duplication of heating and cooling systems	**-9%**	Low carbon - Minimal equipment and low impact refrigerants	**+2%**	Individual dwelling systems increase refrigerant and equipment
Whole life cost (MEP)	**-11%**	Low cost - good operational performance and minimal equipment	**+1%**	Good operational performance but expensive equipment replacement	**+9%**	High cost - additional cooling system	**-14%**	Lowest cost - good operational performance and minimal equipment	**+15%**	Highest cost - expensive equipment replacement and cooling emitters
Compliance model results	**-42%**	BCS14 compliant. SAP 2012 carbon factors favour CHP	**+1%**	BCS14 compliant. SAP 2012 carbon factors penalise electric-based systems	**-36%**	BCS14 compliant. SAP 2012 carbon factors favour CHP	**+71%**	SAP 2012 carbon factors penalise electric-based systems	**+7%**	BCS14 compliant. SAP 2012 carbon factors penalise electric-based systems
Ability to meet potential future standards	All system options are compatible with future standards. Best practice building fabric design may be required									
Useability, operation and maintenance	Minimal in-dwelling and on-site plant with DHN connection		Individual in-dwelling and central on-site heat pumps increase maintenance requirement		Reduced heating plant in-dwelling and on-site with DHN connection, but cooling system adds complexity.		Minimal in-dwelling plant but on-site heat pump will require maintenance		Individual in-dwelling and central on-site heat pumps increase maintenance requirement, fan coil units add further complexity	
Potential constraints or impacts the selection of the option may have on the wider building design	Heat network connection from underground requires coordination with and disruption of surrounding area. Corridor purge ventilation required to remove heat gains from pipework		Central heat pump plant space will be required on the roof		Heat network connection impacts as per DHN option. Balcony or wall space required for outdoor unit of split system		Central heat pump plant space will be required on the roof. Corridor purge ventilation required to remove heat gains from pipework		Central heat pump plant space will be required on the roof. Deeper ceiling void required for fan coil units	
Comfort for occupants	Natural ventilation strategy must be futureproofed for future climate		Natural ventilation strategy must be futureproofed for future climate		Comfort cooling ensures summer thermal comfort if natural ventilation is limited		Natural ventilation strategy must be futureproofed for future climate		Comfort cooling ensures summer thermal comfort if natural ventilation is limited	
Impacts on the wider environment (e.g. cold pluming, urban heat island)	Minimal impact as no on-site generation plant		Mitigation required for acoustic and visual impact of rooftop heat pumps		Mitigation required for acoustic and visual impact of balcony- or wall-mounted outdoor split units. Heat rejection contributes to UHI		Mitigation required for acoustic and visual impact of rooftop heat pumps		Mitigation required for acoustic and visual impacts of rooftop heat pumps and risk of cold pluming from heat rejection impact. Heat rejection contributes to UHI	
Extent to which systems are 'future climate ready'	No changes or adaptation anticipated for operation in future climate conditions		No changes or adaptation anticipated for operation in future climate conditions		Cooling system capacity may need to be increased for more extreme hot summer weather events		No changes or adaptation anticipated for operation in future climate conditions		Cooling system capacity may need to be increased for more extreme hot summer weather events	

*ratings are based on the percentage differences from the average for the current practice results (A). Therefore a negative (-) result represents an improvement in carbon/cost.

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Sensitivity Analysis | Heat Network Losses

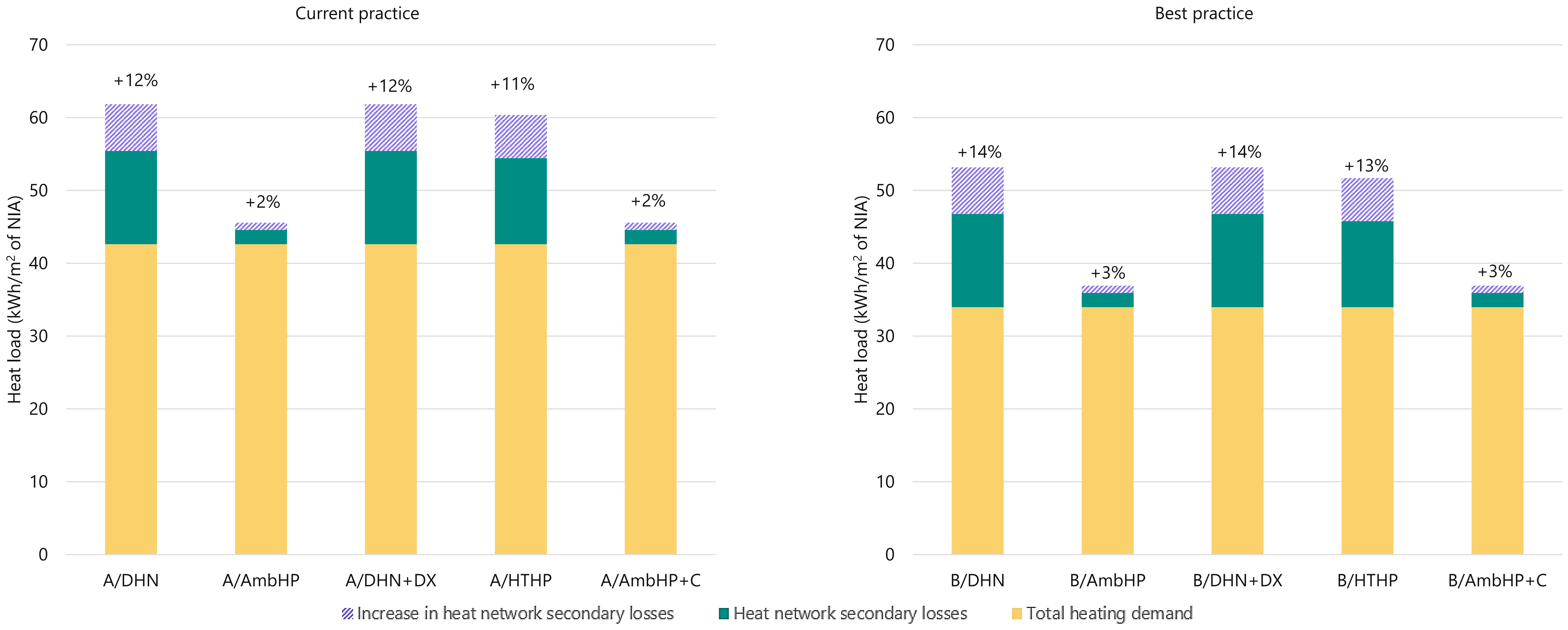
To assess the relative impact of excessive heat losses from heat network distribution pipework, the energy use and whole life carbon of a high loss / 'poor practice' scenario has been calculated and compared to the 'good practice' case.

Losses have been estimated using the guidance and calculation methodology set out in CIBSE CP1 Heat Networks: Code of Practice for the UK (2020).

The 'good practice' losses case assumes pipework insulation of 50mm phenolic foam (λ=0.025) to give a pipework heat loss of 0.16 W/m/K according to CIBSE Guide C: Reference Data (2007). For an ambient internal air temperature of 20°C, this equates to 5.2 W/m for the DHN options.

The 'poor practice' losses case assumes pipework insulation of 50mm mineral fibre (λ=0.040), which is equivalent to 25mm of phenolic foam, to give a pipework heat loss of 0.24W/m/K. For an ambient internal air temperature of 20°C, this equates to 7.8 W/m for the DHN options.

The results shown in the figures below indicate that the poor practice losses scenario has a large impact on the total building heat load for high temperature distribution systems (DHN & HTHP) but much less so for ambient loop systems (AmbHP). For the high temperature systems, the additional losses represent an uplift of the total building heat load of 11-12% for the current practice building and 13-14% for the best practice building.



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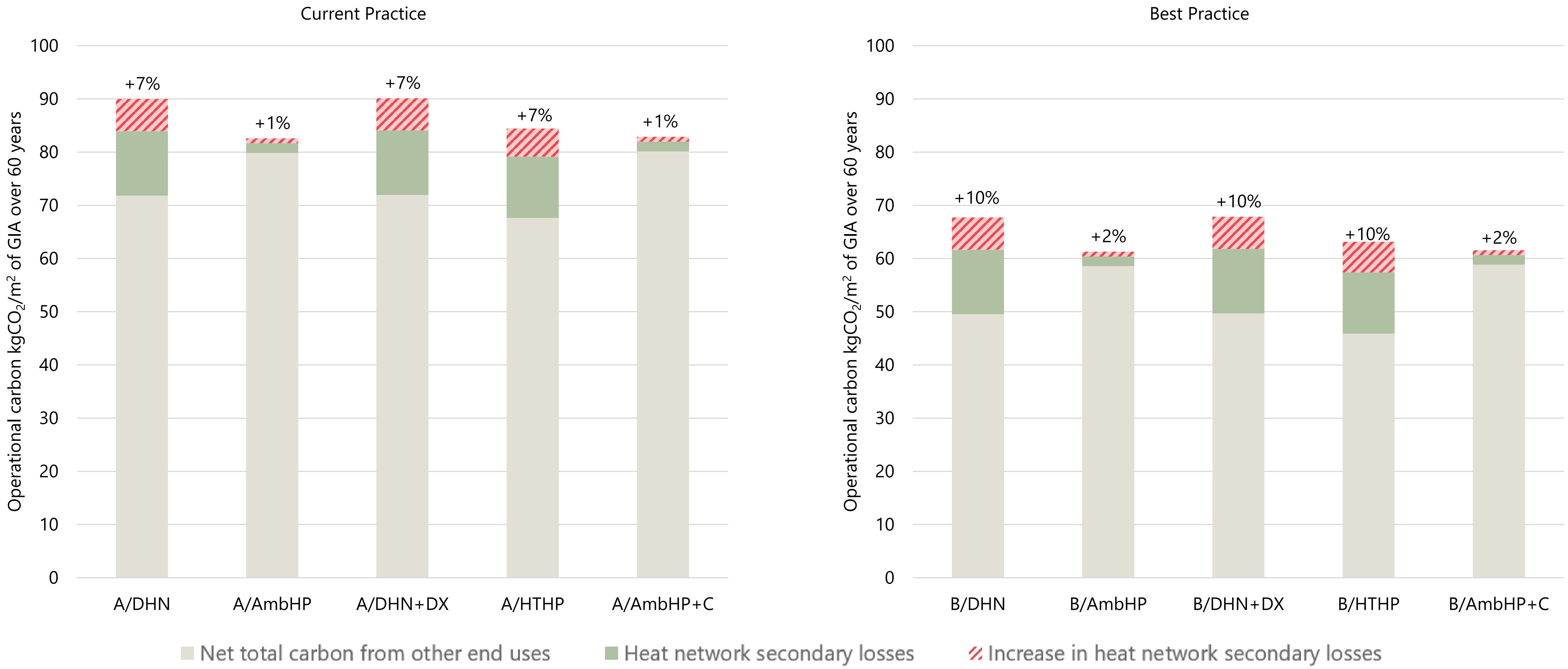
Sensitivity Analysis | Heat Network Losses

The results of the operational carbon assessment, shown in the figures below, indicate that the increase in heat losses has a considerable impact on net (including reduction from PV) operational carbon.

The impact of 'poor practice' insulation is significantly more pronounced for high temperature systems (DHN and HTHP), resulting in a 7-10% increase in operational carbon over a 60 year lifespan for the current and best practice building scenarios respectively.

The increase in carbon due to additional losses is sufficient to alter the hierarchy of the results as the ambient loop systems become the lowest operational carbon options. AmbHP is the lowest and DHN+DX is the highest with a 9-11% uplift in operational carbon emissions between them for the current and best case scenarios respectively.

Despite the notable impact on operational carbon, the increase has a limited impact on the whole life carbon. The carbon associated with the additional heat losses in the poor practice scenario results in an uplift in whole life carbon of up to 2% for MEP-related elements and 0.5% for the whole building for high temperature distribution systems.



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Sensitivity Analysis | Heat Pump Efficiency

To assess the relative impact of the efficiency of operation of heat pumps on the energy use and whole life carbon, the results for a 'poor performance' scenario has been calculated and compared to the 'as designed' scenario previously reported on.

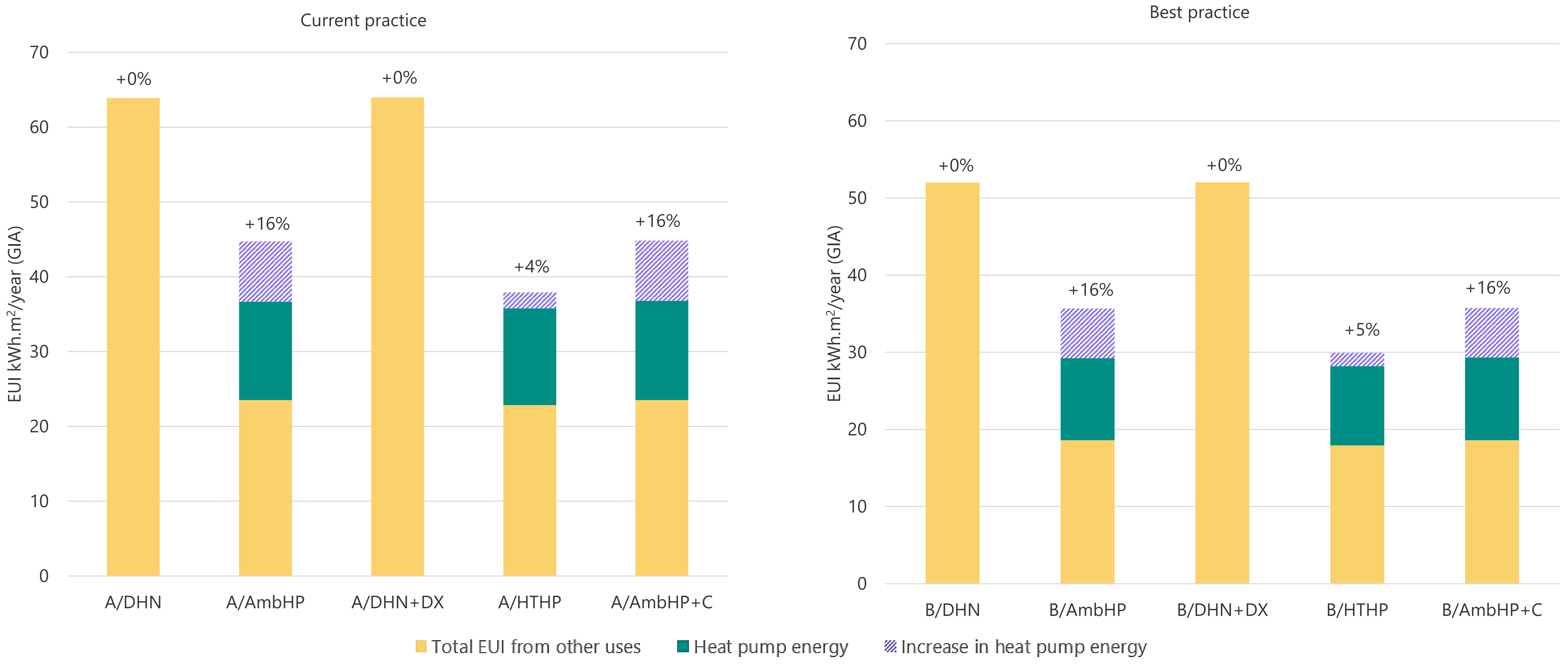
The 'as designed' scenario uses part-load COP values for a range of external temperature conditions as provided by heat pump manufacturers.

The 'poor performance' scenario accounts for situations where heat pumps do not operate as efficiently as intended such as; where equipment does not perform in line with quoted performance data at standard test conditions, lower performance units are specified, when operating to a higher temperature regime or when maintenance routines are neglected. The performance values for this scenario have been estimated by de-rating the manufacturer declared values. The in-dwelling WSHP seasonal efficiency has been reduced by up to 60% as it is expected that these will be the most variable, with calculated SCOP values ranging from 7.0 to 2.8. The central ASHP for the ambient loop system performance has been reduced by 8% on average with calculated SCOP values ranging from 3.8 to 4.2. The high-temperature ASHP performance has been reduced by 14% with SCOP values ranging from 2.3 to 2.7.

The results shown in the figures below indicate that the poor performance scenario has a large impact on the total building EUI, particularly for ambient loop systems (AmbHP) but much less so for high-temperature heat pump systems (HTHP).

For the ambient loop scenarios, the reduction in performance represents an uplift in EUI of 16% for both current practice and best practice buildings.

For the high temperature heat pump system, the reduction in performance represents an uplift in EUI of 4% for the current practice building and 5% for the best practice building.



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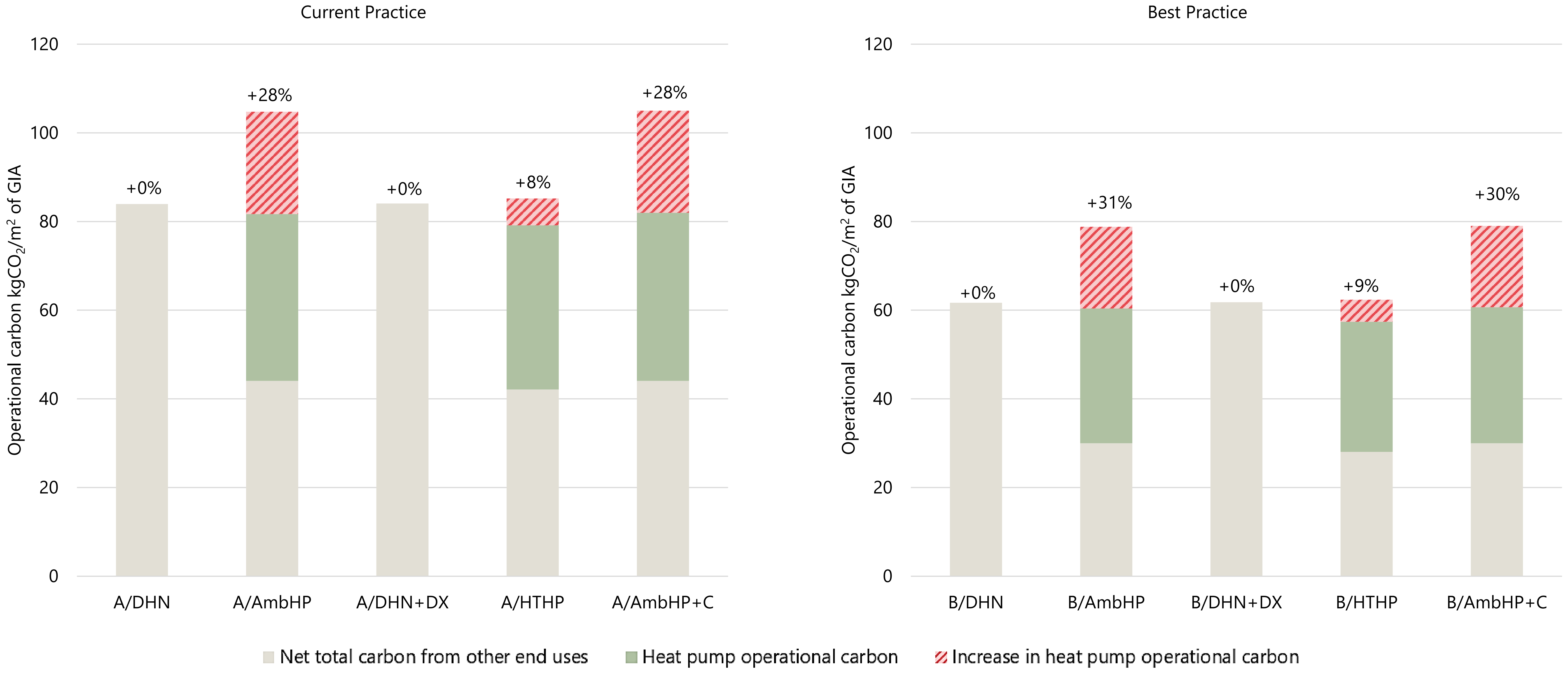
Sensitivity Analysis | Heat Pump Efficiency

The results of the operational carbon assessment, shown in the figures below, indicate that the reduction in heat pump performance has a considerable impact on net (including reduction from PV) operational carbon.

The impact of the 'poor performance' scenario is significantly more pronounced for ambient loop systems (AmbHP), resulting in a 28-31% increase in operational carbon over a 60 year lifespan for the current and best practice building scenarios respectively.

The increase in carbon due to the reduction in heat pump performance is sufficient to alter the hierarchy of the results as the DHN systems become the lowest operational carbon options. DHN is the lowest and AmbHP+C is the highest with a 25-28% uplift in operational carbon emissions between them for the current and best case scenarios respectively.

Despite the notable impact on operational carbon, the increase has a limited impact on the whole life carbon. The carbon associated with the reduction in heat pump performance in the poor performance scenario results in an uplift in whole life carbon of up to 5.5% for MEP-related elements, and 2% for the whole building for high temperature distribution systems.



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Sensitivity Analysis | Future Climate

Future climate impact on results

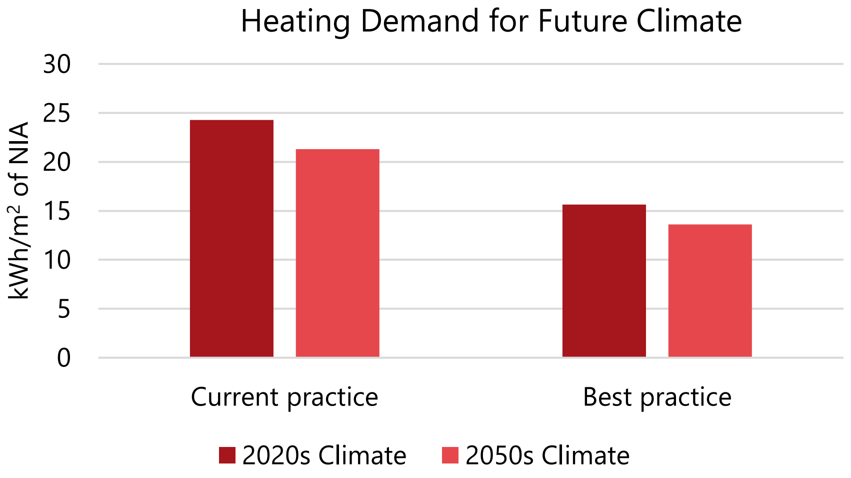
The operational models for a selection of cases were also run on the Cardiff 2050 Medium 50th percentile weather file in addition to the 2020 High 50th percentile weather file (used as the base for the operational modelling). These additional runs illustrate the sensitivity of the results to predict future climate scenarios.

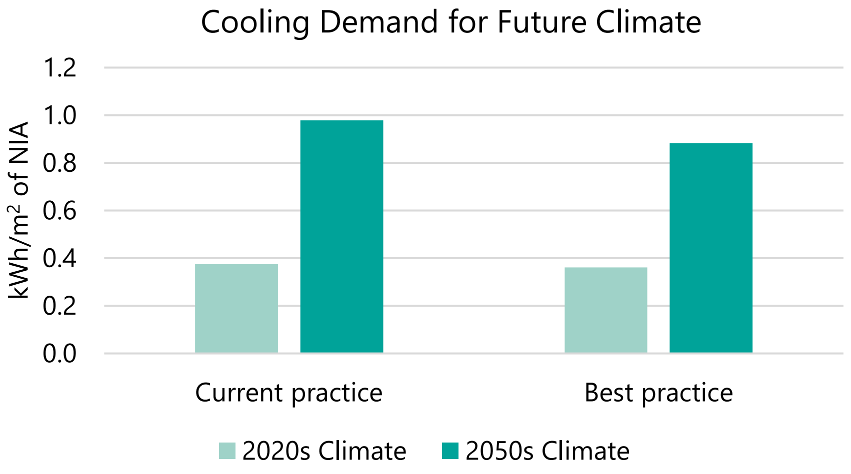
Both DHN+DX and ambient loop systems have been included in the future climate test to understand the impact of a warming climate on whole life carbon. The two system options have been tested for both the current and best practice building.

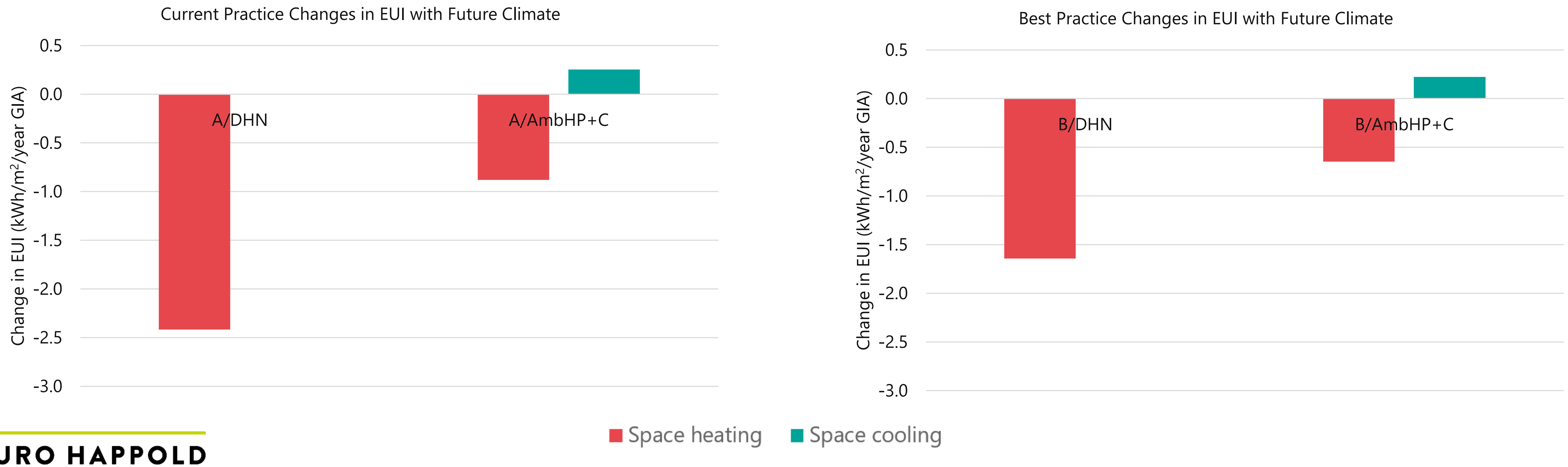
As to be expected for a warming climate, the cooling demands increased for the future climate scenario whilst reductions in heating demands occurred during winter. The figures on this page, show a small reduction in annual heating demand of ~12% and an uplift in annual cooling demand of ~150% for both the current and best practice buildings. Whilst the proportional increase in cooling is large, the actual increase in annual load remains small at ~0.6kWh/m^2.

The reduction in heating demand significantly outweighs the increase in cooling and results in a net decrease in EUI, the impact of which is seen more for DHN options where the reduction constitutes ~4% reduction in comparison to ~2% for ambient loop systems. This reduction in energy use translates to a similar reduction in operational carbon with a decrease of 2% and 3% for DHN and ambient loop options respectively. The relatively small reductions in operational carbon represent an even smaller reduction in whole life carbon at 0.2% and 0.1% for DHN and ambient loop options respectively.

Overall, the warmer climate results in a reduced annual heating load and subsequent EUI and operational carbon decrease, but the impact on whole life carbon is marginal as this is dominated by embodied carbon. The decrease in operational carbon in future climate scenarios does not impact the WLC sufficiently to alter the overall hierarchy.







Sensitivity Analysis | Grid Decarbonisation

Grid decarbonisation scenarios

The results are heavily linked to the decarbonisation of the electricity grid. The current BEIS projections predict rapid decline in grid carbon intensities over the next 10-15 years. This section explores the impact of slower rates of decarbonisation of the grid. The BEIS projected carbon grid intensities were modified to generate different decarbonisation scenarios. As the DHN has planned to electrify its heat source, its decarbonisation rate is assumed to move proportionally with the grid in this analysis. The following two derivative projections were created:

1. **Late:** A delayed decarbonisation of the grid assuming minimal intervention in the short-term, but with a rapid decrease after 25 years (same rate as the current projection)
2. **Shortfall:** A decarbonisation shortfall, where the overall target has not been met (reaching a grid intensity of 0.05 kgCO2/kWh as opposed to 0.007 kgCO2/kWh).

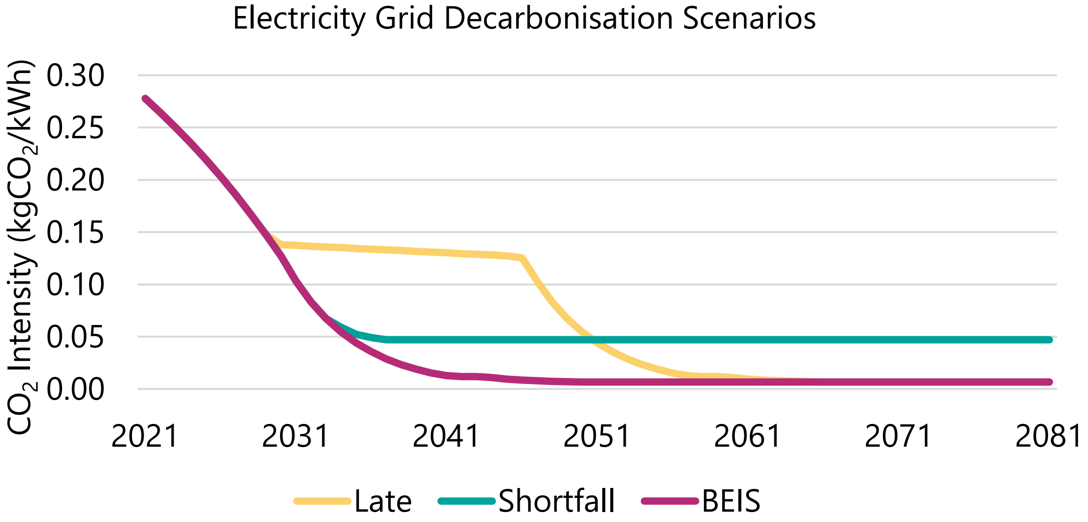
These two alternate projections are captured in the line graph (top right) alongside the BEIS long run marginal used in the study. The operational carbon of each decarbonisation scenario has been calculated and is presented in the bar charts (below) for each system and building design option. The relative difference in operational carbon for each decarbonisation scenario is also compared to the overall MEP-related embodied carbon in the pie charts (centre right).

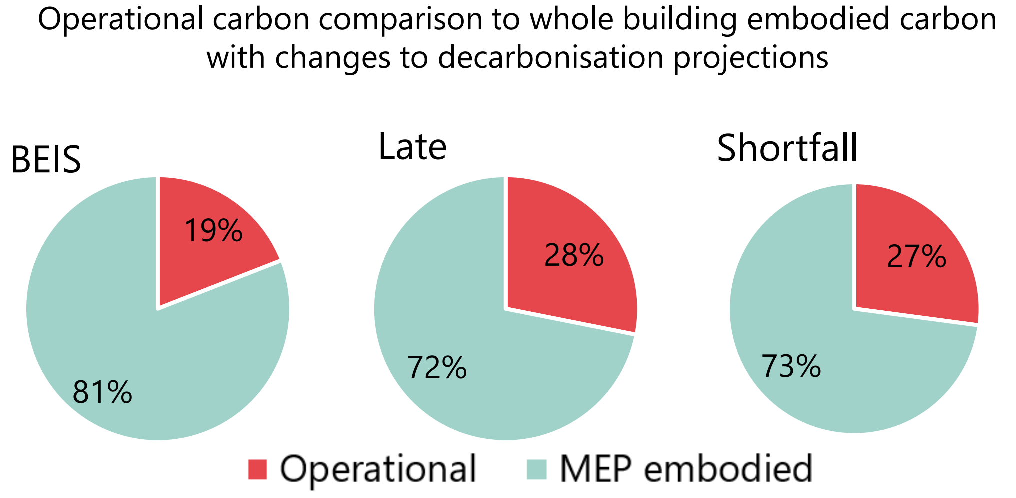
Compared to the BEIS figures, these scenarios would result in an increase of between 59-67% in the operational carbon for current and best practice scenarios.

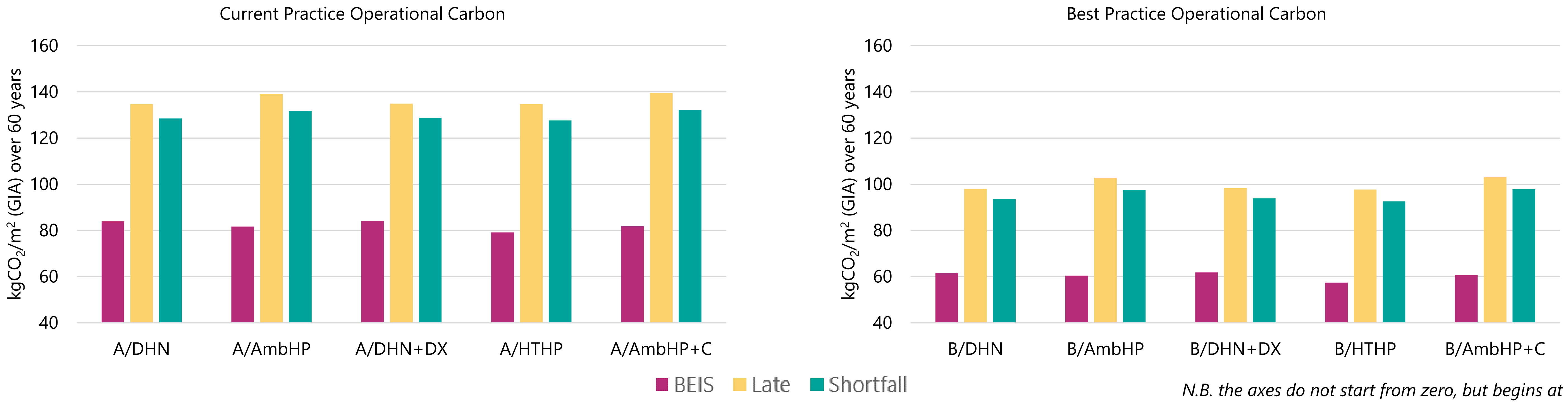
Because the best practice building had started with significantly lower operational carbon, the net increase in terms of carbon is substantially less than the current practice projection. Pursuing best practice design through policy, both aids decarbonisation of the grid and provides resilience against a shallower decarbonisation trajectory.

In scenarios where decarbonisation is delayed or reduced, the carbon intensity of the DHN options decrease and the ambient loop options increase with respect to each other, driven by the proportion of grid electricity consumed.

These projections have also increased the operational carbon contribution to the whole life carbon for the entire building by 3-4% on average across all options. The increase in operational carbon in lower decarbonisation scenarios does not impact the whole life carbon sufficiently to alter the overall hierarchy.







N.B. the axes do not start from zero, but begins at 40kgCO$_2$/m^2 to better allow for visual comparisons.

A *– Current practice,* ***B*** *– Best practice,* ***DHN*** *- District heating connection, no cooling,* ***AmbHP*** *– Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling,* ***DHN + DX*** *- District heating connection for heat, local split system cooling unit,* ***HTHP*** *– High temperature central air source heat pump, no cooling,* ***AmbHP + C*** *- Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.*

Key Findings & Policy Recommendations

The scope of the study considered changes in heating and cooling strategies based on heat pump technologies (high-temperature and ambient loop) and connections to the district heat network (DHN), taking into account the decarbonisation of the electricity grid. In addition to this, these options were then adapted to a building following emerging net zero carbon standards (LETI, UKGBC, and RIBA).

Key Findings

- District heat networks are the lowest whole life carbon system option and also deliver close to the lowest whole life cost. It is noted that this is based on the building forming the boundary of the embodied carbon assessment.
- High-temperature heat pumps with ultra-low GWP refrigerants are the lowest whole life cost option and also deliver close to the lowest whole life carbon.
- Operational carbon for all systems types is comparable but embodied carbon has the largest impact on whole life carbon over a 60 year period.
- Operational energy has a larger impact on whole life cost than carbon (due to grid decarbonisation) but replacement costs (REPEX) have the largest impact overall.
- Options with decentralised heating and cooling generation equipment were found to have higher costs than systems with heat exchangers for each apartment and a centralised heat source. This is primarily due to higher capital costs for these systems, which then feeds through into higher replacement costs.
- For heat pump systems the refrigerant type selected has a large impact on whole life carbon. F-Gas regulations will restrict the availability and use of high GWP refrigerants.
- Best practice building and fabric design has a significant impact on operational carbon, providing a reduction of ~20% compared to current practice, compared to a ~5% variance between system types. However, the impact on whole life carbon is reduced. Regardless, the shift towards best practice design remains important for driving down peak loads and unlocking efficient systems operating at lower temperatures.
- Systems with heating and/or cooling generation equipment for each dwelling tend to have higher embodied, and therefore whole life, carbon than fully centralised systems.
- Addition of comfort cooling and separate systems for heating and cooling generally results in higher whole life carbon and cost so should be avoided. The majority of the impact is associated with the embodied carbon and CAPEX/REPEX of the additional equipment instead of operational energy consumption.
- Management and monitoring of high-temperature heat network losses are important for achieving low EUI targets. Losses become a larger proportion of the annual heating load for best practice buildings with ultra-low heating demand and low return temperatures become increasingly hard to achieve.
- Design and operation of network pumping equipment are particularly important for ambient loop systems where small ΔT drives high flow rates. Systems must cater for low-load scenarios using a jockey pump.

Policy Recommendations

Reduction of operational carbon

Comparing results for the current and best practice buildings demonstrates that reduction in peak demand is a necessary precursor for reducing annual energy consumption and whole life carbon. Adoption of the proposed 15 or 20kWh/m^2 space heating demand target (on a block average basis, calculated using PHPP) which is recommended.

It has been demonstrated that it is possible to meet the proposed EUI targets of 35 or 40 kWh/m^2/year (excluding renewable energy contribution) for all system types included in the study. Adoption of these targets (on a block average basis, calculated using PHPP) is recommended.

A methodology has been proposed to calculate a proxy coefficient of performance to apply to DHN thermal energy consumption to allow for direct comparison of EUI with other options and proposed targets. The DHN 'efficiency' factor should be calculated alongside the network carbon and primary energy factors, using the same information and updated at the same frequency.

Connection to the Bristol Heat Network delivers very similar operational carbon performance to local heat generation technologies. Based on BCC's projections for the carbon emission factor and the long term decarbonisation strategy of the Bristol Heat Network, arguments that connection to the heat network disadvantages developments from achieving net zero operational carbon are not credible.

Accurate performance data for equipment is essential for operational energy modelling but also challenging to obtain. Similarly, the way in which people use energy in their homes is highly variable. This means accurate prediction of operational energy is difficult whereas metered data provides insight into real world performance. A requirement to report anonymised in-use energy demands at a building scale is recommended.

Further policy recommendations continued on the next page.

Key Findings & Policy Recommendations

Reduction of embodied carbon

Decentralised (individual dwelling) heating and cooling generation equipment tends to result in higher embodied carbon than centralised (communal / district) systems. Giving priority to connection to district or communal heating networks through adoption of the proposed energy hierarchy identified on this page is recommended.

To minimise the risk of high carbon and high cost systems needing to be installed from the outset or retrofitted in the future, new homes should be designed to ensure summer thermal comfort in future climate scenarios or futureproofed for adaptation. Where comfort cooling is proven to be necessary, the system selected should be able to provide both heating and cooling to minimise quantities of equipment.

Use of high GWP refrigerants or multiple refrigerant-based systems results in a large increase in embodied carbon for heating and cooling systems. Adoption of the following refrigerant hierarchy is recommended:

- Design for no refrigerant (DHN connection, no cooling)
- Minimise quantity of refrigerant (using water as a distribution medium)
- Select low impact refrigerants prioritising ultra-low <50 GWP where possible and no greater than 750 GWP
    - Consider tying policy to requirements of BREEAM Pol 01 one credit threshold of ≤ 1000 kgCO2e/kW cooling capacity, with a further update to the two credit target of ≤ 100 kgCO2e/kW.
- Restrict refrigerant leakage (implement detection, monitoring and maintenance regimes)

Condition-based energy hierarchy

To drive developments to adopt cost effective, low whole life carbon systems, the following energy hierarchy is recommended.

- If a district heat network connection is available then:
    - ➢ DHN connection is prioritised
- If no district heat network connection is available but there is potential for future connection then:
    - ➢ Centralised, high-temperature heat pump systems with ultra low GWP refrigerant prioritised
- If cooling is required (for areas or occupants at risk of high heat stress such as where natural ventilation is not possible) then:
    - ➢ Ambient loop with reversible heat pumps is prioritised

Policy will need to recognise potential hierarchy conflicts and provide advice on suitable alternatives:

- DHN connection is available or planned but cooling is required.
    - ➢ Avoid duplication of heating and cooling generation and emitter plant e.g. DX
    - ➢ Consider DHN connection for space heating and hydronic cooling system with central chiller plant

Metrics, compliance and enforcement

The relationship between operational carbon and the embodied carbon of heating and cooling systems is complex and difficult to generalise. The equipment in the market and the information available regarding operational and embodied performance is changing due to market and regulatory requirements.

Carrying out whole life carbon assessments early in the design process will provide a holistic view of carbon performance which can help applicants make informed decisions on their projects. It will also help to develop a better evidence base for future policy and will encourage the industry to provide more detailed information to designers/applicants. Assessment of whole life carbon impacts at the planning stage, including MEP operational and embodied carbon, and refrigerant impacts is recommended.

Use of pre-commencement or pre-occupation conditions to require an update to any carbon assessments carried out at planning stage, where changes are explicitly highlighted would help to improve enforcement and are recommended. In addition, a percentage of applications should be audited by a qualified independent third party.

General rules of thumb

- Operational carbon reduction is delivered most effectively through passive design measures i.e. adopting best practice building design
- Embodied carbon reduction is delivered most effectively by reducing quantum of heat pump equipment e.g. design out need for cooling
- Whole life cost reduction is delivered most effectively by reducing the frequency or cost of equipment replacement

4.0

OTHER BUILDING TYPOLOGIES

- ☐ RESIDENTIAL
- ☐ RETAIL
- ☐ EDUCATION

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Other Non-residential Buildings

The recommendations of the study have been qualitatively extrapolated to provide guidance on the heating and cooling strategies that should be adopted for other non-residential building typologies. The below assumes that equipment with low GWP (<750) refrigerants are used in all cases.

Smaller office buildings

For smaller office buildings (<3,500m^2), natural ventilation is likely to be an option due to shallower floorplates and this can eliminate the cooling system. If this solution is viable and there is a DHN connection available to the site, this should be prioritised. If cooling is required, a zonal solution (such as VRF) is likely to be the most practicable and affordable solution, with central hydronic systems likely to be cost prohibitive at this scale. Systems that have low refrigerant charges and low GWPs should be prioritised, such as HVRF, and therefore is the most favourable option from a whole life carbon standpoint. Packaged heat pump heat recovery AHUs should be considered for ventilation systems.

Medium-scale retail units

It is expected that most retail units of this scale will require cooling. A zonal solution (such as VRF) is likely to be the most practicable and affordable solution (also due to fit-out frequencies), with central hydronic systems likely to be cost prohibitive at this scale. Therefore, it is expected that HVRF is the most favourable out of the practically acceptable options from a whole life carbon standpoint. Where significant refrigerated cabinets are provided, opportunities for heat recovery from these units should be considered. Packaged heat pump heat recovery AHUs should be considered for ventilation systems.

Small-scale retail units

For small retail units, such as local convenience stores and boutique shops, a split/multi-split solution is likely to be the most practicable and affordable solution, with central hydronic systems likely to be unviable and cost prohibitive at this small scale. Small stores will likely benefit from short distribution pipework lengths with similar load profiles across indoor units meaning that larger and more adaptable zonal systems that require higher refrigerant volumes, such as VRF, are not necessary. Natural ventilation or packaged heat pump heat recovery AHUs should be considered for ventilation systems.

Larger retail stores and shopping centres

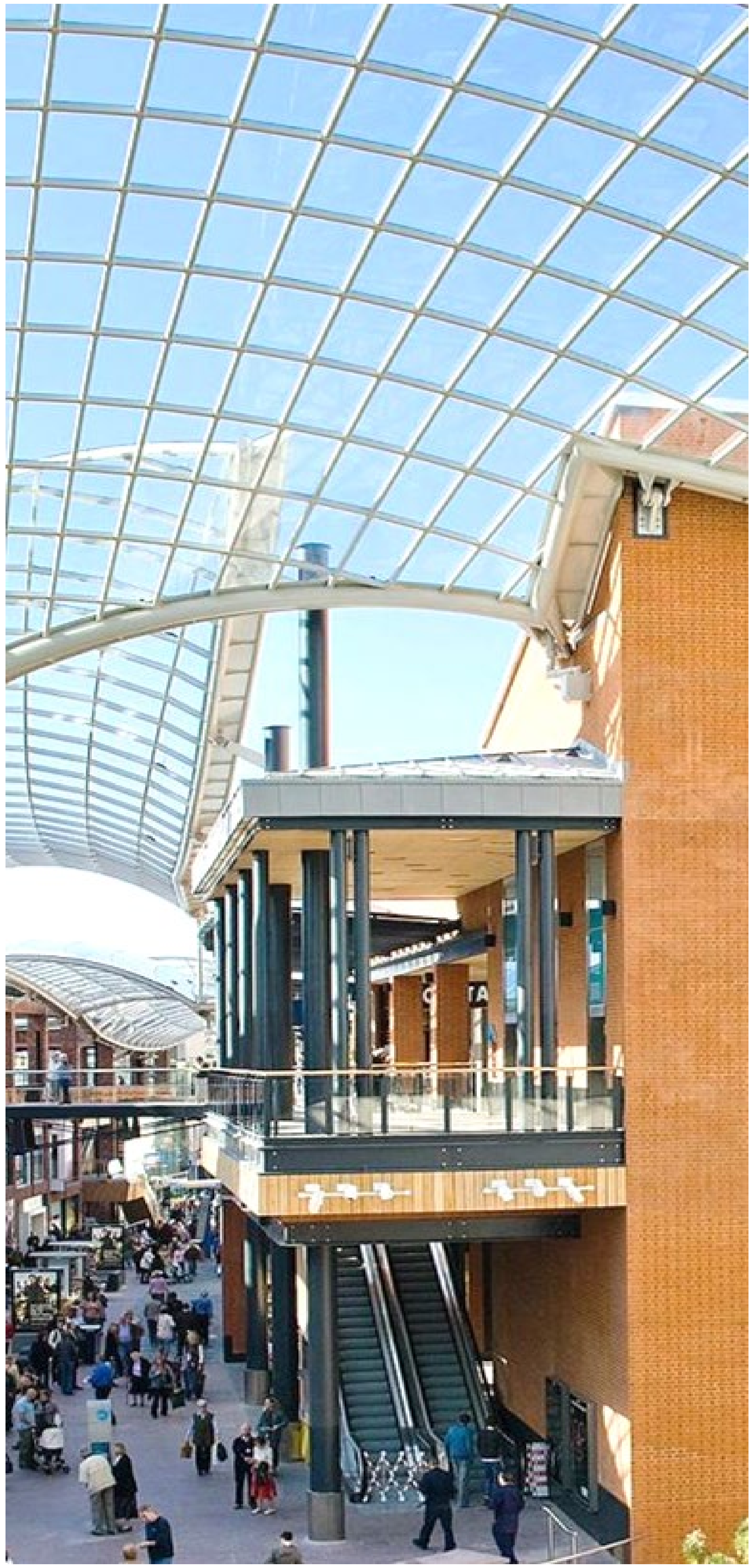
Larger retail stores should follow a similar philosophy to the commercial office development in the study. The scale should be sufficient to warrant a central hydronic system. Connection to the district heat network should be given first priority, followed by hydronic heat pumps. Hydronic systems are expected to offer the advantage of being easier to adapt when tenancy changes, which can be relatively frequent in the retail environment. Moreover, there is a higher likelihood that a VRF system would be completely replaced rather than adapted at the end of a tenancy, which would worsen whole life carbon. Shopping malls should consider central plant with heat recovery or an ambient loop.

Schools

The approach for schools is likely to utilise natural ventilation and therefore could eliminate cooling. If there is a DHN connection available to the site, this should be prioritised. Otherwise, a central standard heat pump running on low flow temperatures, with a 2nd-stage heat pump for hot water is likely to be the best solution. The widespread use of cooling in a school is not expected to be required. Local split/multi split cooling to IT classrooms is likely to be appropriate but the refrigerant must have a low GWP. Packaged heat pump heat recovery AHUs should be considered for peak lopping in AHUs. In the rare event that a primary school requires cooling, e.g. due to significant acoustic or air quality issues, a zonal system such as VRF would be the most appropriate solution due to the expected scale. In this instance reducing the refrigerant volume, distribution, and leakage must be prioritised and would likely be best achieved with a HVRF system. As for secondary schools that require cooling, the loads are likely to be sufficient to warrant the utilisation of a centralised hydronic heating and cooling system along with the DHN where possible.

University buildings

Where a university has a campus energy network it is likely that connecting to this would be the default option, where a credible plan for decarbonisation of the campus network can be provided. Where no campus network exists, a similar philosophy to that used for the commercial office building considered in this study is excepted to be appropriate, as university buildings are typically of a scale that makes central hydronic heating and cooling appropriate i.e. if there is a DHN connection available, this should be prioritised, followed by a central heat pump/chiller solution. The potential for simultaneous heating and cooling load in a university building may be greater than an office depending on its particular function. University buildings have longer operational hours, therefore EUIs are expected to be significantly higher than for an office. During the decision making process, a whole life carbon assessment could be undertaken to take into account the resultant whole life carbon of each option.



Other Residential Typologies

The recommendations of the study have been qualitatively extrapolated to provide guidance on the heating and cooling strategies that should be adopted for other residential building typologies. The below assumes that equipment with low GWP refrigerant is used in all cases.

Low density residential (bungalows, houses, and low-rise flats)

Individual dwellings and smaller apartment buildings have a higher form factor (i.e. more exposed heat loss area per internal floor area) meaning that they will tend to have a higher heating demand and peak load per m^2. In this case, the performance of the building fabric is likely to have more impact on the EUI and whole life carbon and cost than the results of this study indicate, so designs will need to tend towards the 'best practice' building to achieve EUI targets.

District and communal heat networks tend to be less cost effective and more carbon intensive due to longer distribution lengths and higher losses for low density developments suggesting individual dwelling systems will be favoured. In this case, the results suggest that heat pump systems with low-GWP refrigerant should be prioritised over direct electric systems in order to minimise operational carbon and cost.

The form and density of these types of dwellings tend to lend themselves well to natural ventilation strategies so the requirement for comfort cooling to address summer thermal comfort is reduced. Where comfort cooling is necessary, the system selected should be able to provide both heating and cooling to minimise quantities of equipment

Suitable system types could include:

- ASHP (low-GWP refrigerant) linked to hydronic system, providing space heating and domestic hot water
- Exhaust-air heat pump (EAHP) (low-GWP refrigerant) linked to hydronic system, providing space heating, and domestic hot water
- Multi-split ASHP (low-GWP refrigerant) to provide space heating via fan coil units and hot water via cylinder

High density and residential towers

The results from this study suggest that more equipment in each home tends to result in higher whole life carbon and cost regardless of efficiency. It is expected that this rule will scale in proportion to the number of dwellings connected to the same system as the form and thermal demand profile of each dwelling is similar but there is increased diversity for the central plant or building connection. This means the issue of increased embodied carbon and cost will be exacerbated for large developments. Connection to high temperature district or communal heating networks, is therefore strongly favoured to avoid having heat pump equipment in each dwelling.

Conversely, high density developments are more likely to require comfort cooling to mitigate the risk of overheating and heat stress due to limitations on natural ventilation, such as noise, air pollution, and security. In this case, the results of the study suggest that an ambient loop system would be the preferred option in terms of whole life carbon with the additional benefit of avoiding additional heat gains from distribution pipework in the building.

Co-located living (student residences and long-stay hospitality)

These buildings are similar to dwellings in the way in which they are used by occupants and so have a similar demand profile. However, the systems tend to be centrally managed and controlled as the domain of each occupant is limited, and units frequently change hands. Because of this residents are typically not billed based on metered energy use btu instead it is included as part of a service charge. In this case, centralised systems are very well suited such as the central AHSP or DHN options analysed in this study. CO_2 heat pumps (or similar) which operate at high temperature differentials are well suited to meet the high temperatures required for hot water systems.

Cooling is not frequently provided and should be discouraged but where it is required a communal system is again most appropriate. To minimise the amount of equipment provided in each unit a communal chiller water loop and central chiller plant would be appropriate.

5.0

REFRIGERANTS

- ☐ F-GAS
- ☐ COMPARISONS
- ☐ RECOMMENDATIONS

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Introduction to Refrigerants

As the UK heavily invests in heat pumps to move away from its dependency from gas with a Net Zero 2050 outlook, there will be an inherent increase in the use of refrigerants for heating our buildings. Moreover, the number of cooling devices in use globally is estimated to increase from 3.6 billion to 9.5 billion by 2050, according to a report by the United Nations Environment Programme (UNEP) and the IEA (cit. BBC). The potential impact that this could have on the atmosphere in respect of refrigerant emissions, and ways to mitigate this, are explored in this section.

Refrigerant leakage has contributed significantly to the built environment's carbon footprint to date. Today, refrigerants used in HVAC systems equate to circa 396 kilotons globally. In the UK, operational leakage in 2020 would represent about 70,000kg of refrigerant lost, representing about 130,000 tonnes of CO2e (according to The Centre for Air Conditioning and Refrigeration Research, London Southbank University), a figure which is likely to rise with more extreme temperature peaks due to climate change.

Fluorinated Gas (F-Gas) emissions had originally been on an upward trend, but there has been a decrease of 5% since the 2014 EU F-Gas Regulation has been put in place in the UK.

Most UK-specific data until recently has been part of EU data collection, its recorded quantities since 1990 outlined in Figure 5.1.

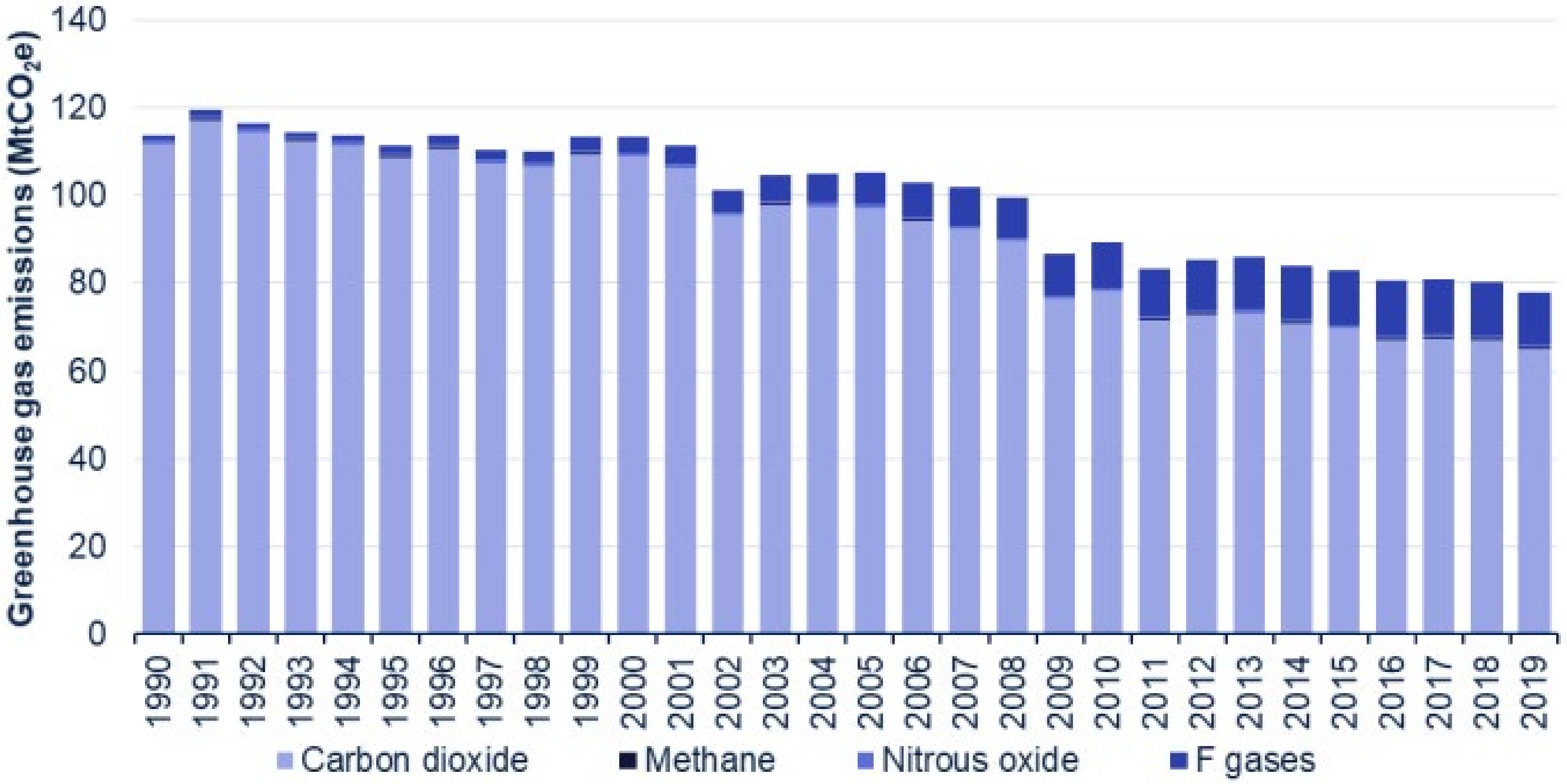


Figure 5.1 - Greenhouse gas emissions trend (1990-2019) (Source: Final UK greenhouse gas emissions national statistics)

Introduction to Refrigerants

Refrigerants available and most widely used today in air conditioners and heat pumps include HFOs with ultra-low GWP (0-10), some mixtures of HFCs, and HFOs with medium GWP values (450-750), and one HFC, R-32, with a medium GWP value (675). Before the introduction of these were CFCs (1920-1970s) and HCFCs, which have both been disbanded due to their destructive impact on the ozone layer identified by UNEP. This led to new types of refrigerant coming to market: HFCs. such as R-134a and R-410a slowly replacing Freon (R-12) and R22. However, substitution by HFCs did not address the very high Global Warming Potential (GWP) of these gases. In 1997, several countries ratified the Kyoto Protocol to reduce greenhouse gas emissions (GHG), which drew attention to this aspect but did not create a mechanism to address it. Unfortunately, this means HFCs are still widely used in existing systems.

The most recently developed refrigerants, HFOs, are natural/hydrocarbon options. The European Union introduced its F-Gas Regulation in 2014, limiting the volume of HFCs used to reduce GWP of fluorinated gases. More recently in 2016, the Kigali amendment to the Montreal Protocol set a strict timeline to phase out HFCs; first in high-income countries and then in low-income countries by 2030. As a result, new refrigerants with lower GWP and without Ozone Depletion Potential (ODP), such as HFOs recommended by the new F-Gas Regulation (e.g. R-1234ze, R-1233zd, R-1234yf) are now more widely available on the market, as well as other natural/hydrocarbons options (e.g. ammonia, CO2, water, propane). As a result, progress has been made moving away from higher GWP refrigerants to low and ultra-low ones by manufacturers, supported by more of the component supply chain and as demanded by end users. For example, the shift from the widely used VRF refrigerant R410A (GWP 2088) to R32 (GWP 675) in split units and small chillers/heat pumps, as well as ultra-low GWP HFOs and low-GWP HFO blends in larger chillers. There are natural alternatives to HFCs: for chiller and heat pump applications, the common ones are ammonia (R717), propane (R290) and CO2 (R744). The standard classifications for refrigerants revolve around toxicity (A or B – non-toxic or toxic) and flammability (1, 2L, 2 or 3 – non-flammable to highly flammable), as defined in ISO 817. CO2 is an A1 refrigerant, so neither toxic nor flammable. Ammonia (B2L) is toxic but exhibits low flammability. Propane (A3) is non-toxic, but highly flammable.

As HFCs are being phased out, it is essential to find ways to replace them in existing systems, as it was with R22 (HCFC) with R410a or R12 (CFC) with R134a being used in the same equipment, with only a small loss of performance.

It is expected that during the new Bristol Local Plan implementation period, HFOs and other hydrocarbon options will become more readily available commercially due to the push of EU legislation as well as that on whole life carbon affecting future offsetting requirements. As noted earlier, this is why the study has been based on equipment using refrigerants with a GWP <750.

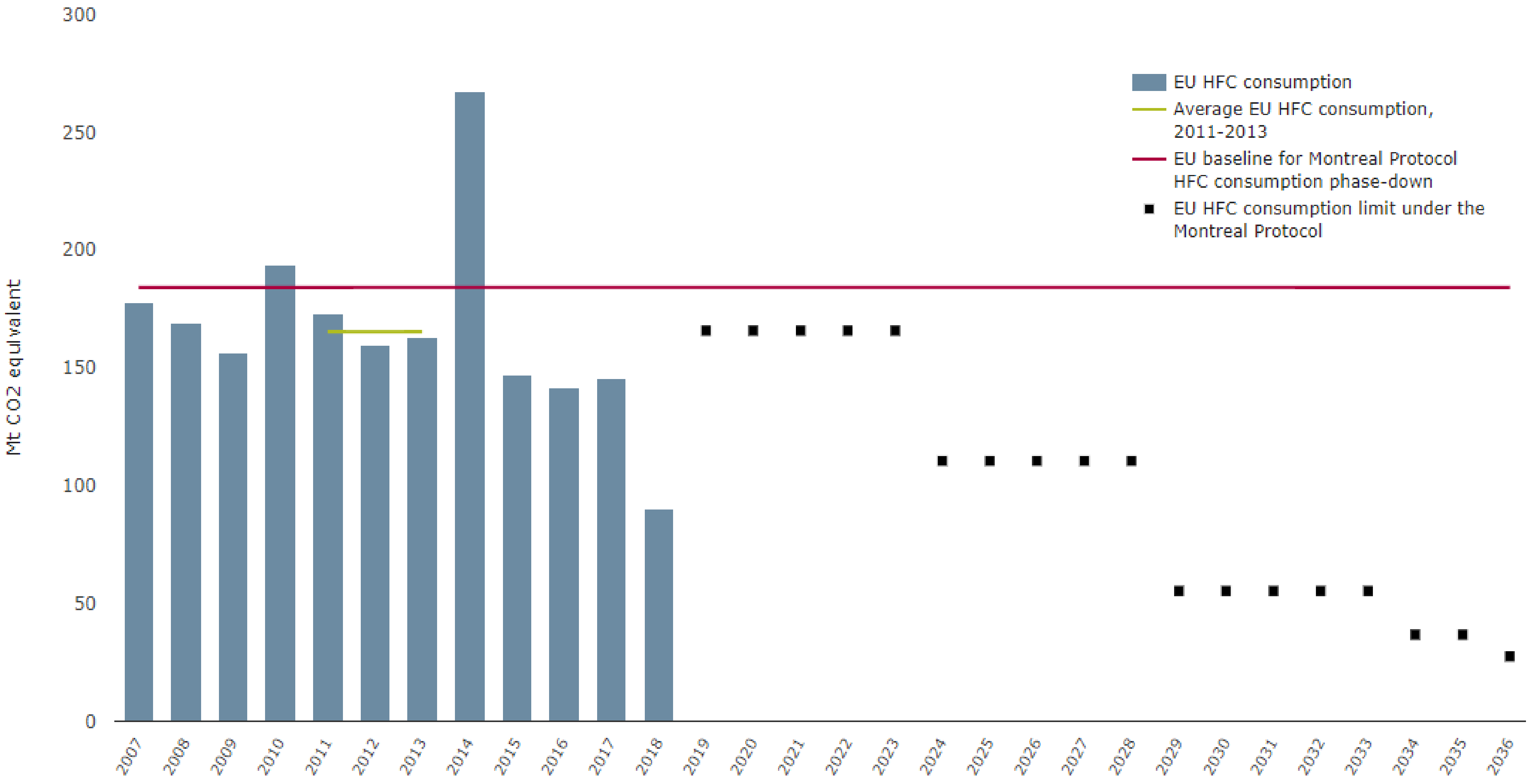
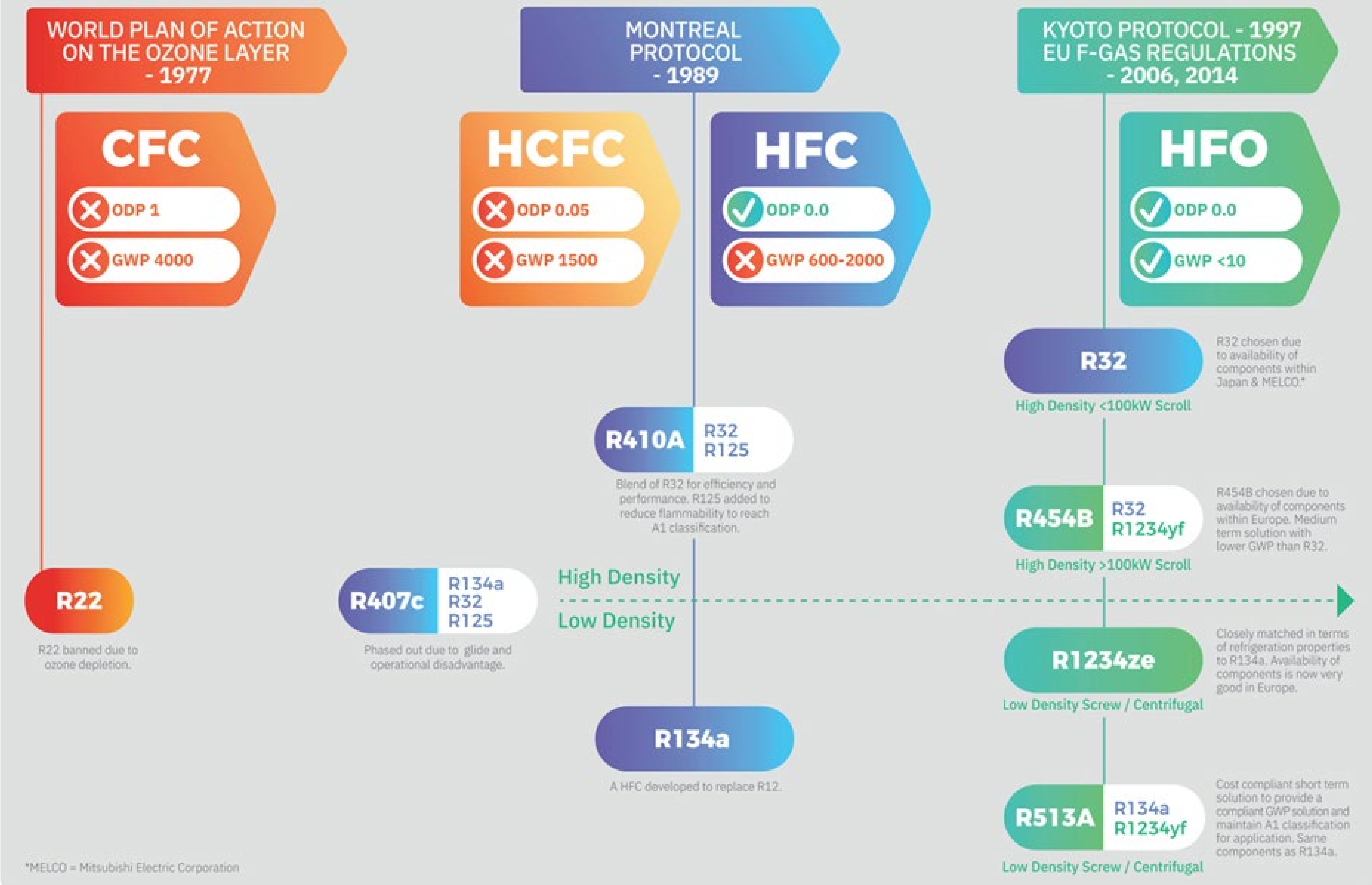


Figure 5.2— EU progress towards the worldwide hydrofluorocarbon consumption phase-down under the Montreal Protocol

F-Gas Legislation

When discussing the driving forces behind the shift to lower GWP refrigerants with manufacturers it becomes apparent that without legislation little change would be occurring. In most countries around the world, F-gases (CFCs, HCFCs, HFCs) are regulated by law. Many F-gases, like HCFC gases, are banned. The following timeline shows the historic phasedown of CFC, HCFCs, and some HFCs due to legislation.



R32 chosen due to availability of components within Japan & MELCO.*

Blend of R32 for efficiency and performance. R125 added to reduce flammability to reach A1 classification.

R454B chosen due to availability of components within Europe. Medium term solution with lower GWP than R32.

R22 banned due to ozone depletion.

Phased out due to glide and operational disadvantage.

Closely matched in terms of refrigeration properties to R134a. Availability of components is now very good in Europe.

A HFC developed to replace R12.

Cost compliant short term solution to provide a compliant GWP solution and maintain A1 classification for application. Same components as R134a.

*MELCO = Mitsubishi Electric Corporation

Figure 5.3 - Refrigerant Legislation History (Source: Mitsubishi Electric)

F-Gas Legislation

In 2016 the Kigali Amendment to the Montreal protocol was signed making the goal to achieve over 80% reduction in HFC consumption by 2047. The impact of the amendment aims to avoid up to 0.5 °C increase in global temperature by the end of the century.

Due to the phase out and phase down of existing refrigerants, and the associated increase in cost, a black market has formed trading in HCFC refrigerants. Designers should include in their specifications and remind clients to only obtain refrigerants from a reputable source. The international standard that dictates specific requirements for electrical heat pumps, air conditioners and dehumidifiers up to a certain refrigerant charge limit is IEC 60335-2-40.

In the EU and the UK, the Fluorinated Gas (F-Gas) regulation controls the installation, servicing, sale, and decommissioning of fluorinated gases. Despite Brexit, as part of its commitment to comply with EU F-Gas Regulation, the UK is phasing down HFCs by 79% by 2030 from the average use between 2009 to 2012. This is considered to be the most influential piece of legislation driving the switch to lower GWP refrigerants.

The phase down of HFCs is designed to steadily reduce the global warming potential (GWP) of all gasses placed on the market in refrigeration, heat pumps and air conditioning in the EU. The target is to reduce the CO2 equivalent of all gasses in use to 21% of the baseline by 2030. Individual producers and importers will receive a progressively reducing quota based on their 2009-12 baseline. The costs of HFC refrigerants have seen a rise in excess of 400% between 2016 and 2020 with this set to continue as we reach further quota thresholds.

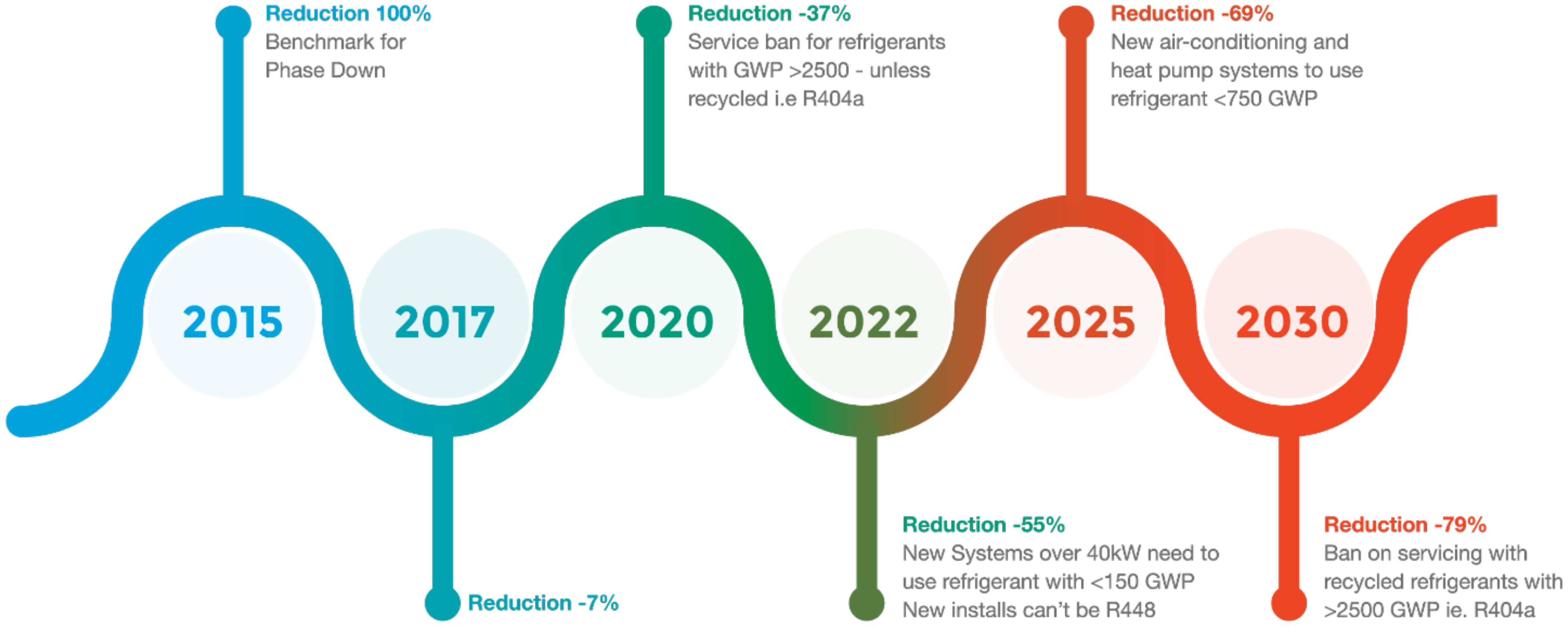


Figure 5.4 - F-Gas Phase Down (Source: Isentra.net))

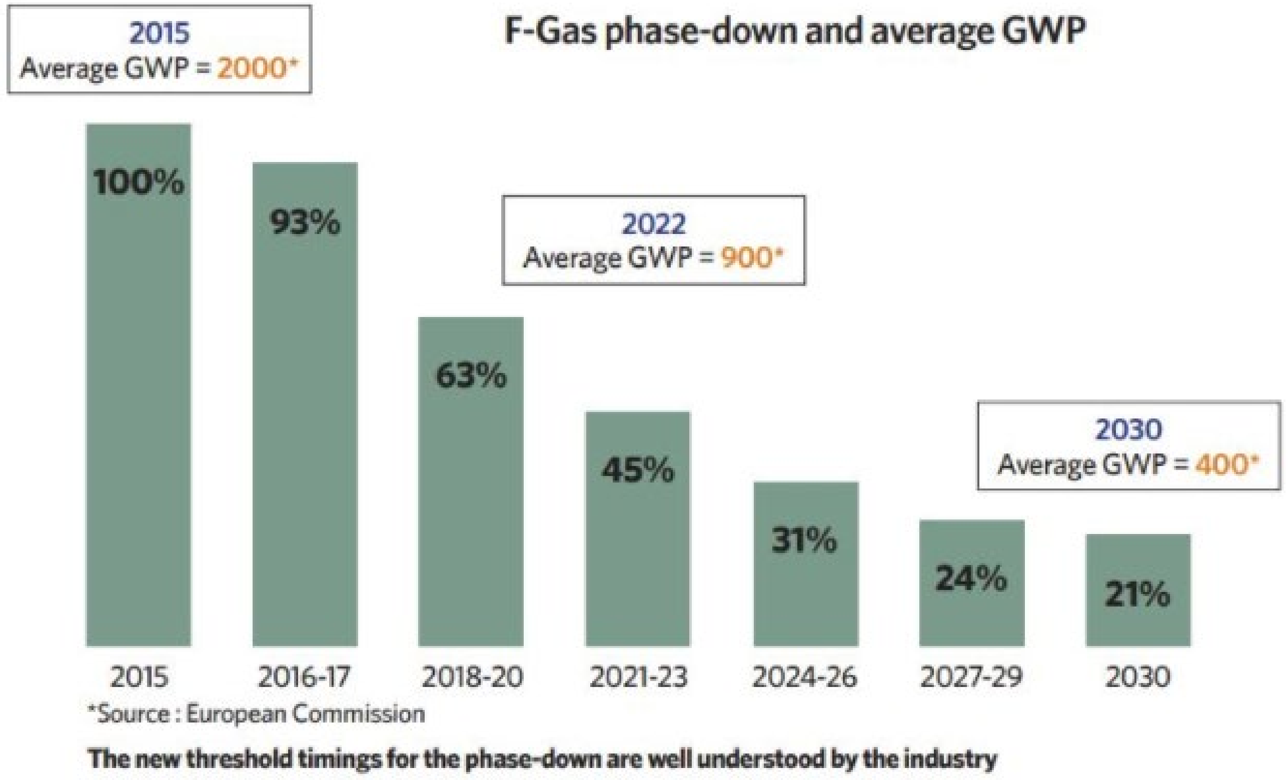


Figure 5.5 - F-Gas phase-down and average GWP (Source: CIBSE Journal, 2021)

F-Gas Legislation

As of 1 January 2020 refrigerants with a GWP greater than 2,500 have already been banned. Other refrigerants have not been banned, however they have limits in some situations. The following limits apply to new refrigerant applications:

- Single split air conditioners with a refrigerant charge below 3kg (individual apartment split units are typically under this threshold, normally closer to 1kg, or in the case of the commercial split units 2.3kg)
    - GWP limit of 750 from 2,025
    - Portable air conditioners GWP limit: 150
- No limit on single split above 3kg
- No limit on multi split/VRV systems
- Stationary refrigeration equipment
    - From 2020: a ban on refrigerants with GWP > 2,500
    - From 2022: GWP limit of 150 on multipack centralized refrigeration systems for commercial use with a capacity of 40 kW or more
    - Except for cascade systems where the primary refrigerant circuit has a GWP limit of < 1,500

A summary of the limits found on the UK government website can be found in the table to the right.

This is not a ban on any particular type of F-gas, but by limiting the total GWP of the F-gases in equipment it is expected that the gases with the highest GWP will be eliminated from the market first. As of April 2018, the new Fluorinated Greenhouse Gases Enforcement Regulation in Great Britain (http://www.legislation.gov.uk/uksi/2018/98/made) enables regulators in England and Scotland to issue civil penalties up to £200,000 to operators breaching the requirements of the Regulation. An EU quota allocation mechanism has been made, with the first phase-down step accomplished in 2016 with quotas reduced by 7% compared to the baseline. The quota system mechanism assigns quotas to producers and importers of bulk gases in order to achieve the required phase down. This quota system post-Brexit has become part of the UK F-gas regulations, and can be applied for through the government F-gas website.

If a project is seeking compliance with a certification scheme, or if future policy refers to a certification scheme as best practice, this may also have an impact on refrigerant choice. The certifications that consider refrigerants in some form include:

- BREEAM New Construction 2018 - 3 credits maximum are available for "Pol 01 Impact of Refrigerant" if no refrigerant is used within the installed plant or systems or if refrigerant used comply with 3 different requirements. If there is no refrigerant use one automatically achieves 3 credits. 2 credits can be achieved if the emissions are under ≤100 CO_2-eq/kW or have a GWP ≤10. 1 credit if the system's using refrigerants have a DELC of ≤1,000kgCO_2-eq/kW cooling and heating capacity.
- LEED - 1 credit is available for "Enhanced Refrigerant Management".

However, it is worth noting that any certification schemes requiring embodied carbon targets and thresholds will need to consider refrigerant choice as part of a greater strategy.

Type of F-gas	Banned uses	GWP	Date of ban	Exceptions from the ban
F-gases banned in new products				
HFCs and PFCs	Non-confined direct evaporation systems (where refrigerant can escape into the atmosphere).	All	Banned now	None
HFCs	Domestic fridges and freezers	Above 150	Banned now	None
HFCs	Stationary refrigeration equipment	Above 2,500	Banned now	Systems that cool products to below -50 degrees Celsius
HFCs – will mainly affect HFC134a, HFC245fa, HFC365mfc	Refrigerators and freezers for commercial use (hermetically sealed equipment)	Above 150	From 2022	None
Any F-gas	Multipack centralised refrigeration systems for commercial use with a rated capacity of 40 kW or more. (Product storage, display or dispensing in retail and food services to sell to end users.)	Above 150	From 2022	Primary refrigerant circuit of cascade systems with fluorinated greenhouse gases that have a Global Warming Potential (GWP) of less than 1,500.
Air Conditioning and Heat Pump systems: F-gases banned in new products				
HFCs	All new cars	Above 150	Banned now	None
HFCs	Movable air conditioning equipment (user can move it between rooms)	Above 150	Banned now	None
All F gases	'Single split' systems that contain less than 3kg of refrigerant. (A system with one cooling coil connected to a remote condensing unit.)	Above 750	From 2025	Larger air-conditioning or heat pump systems, such as chillers or larger split systems

Refrigerant Embodied Carbon

The following considers refrigerants in their current legislative context looking forward to the rise of more readily available low GWP technologies, highlighting what current system limitations and opportunities there are in central plant, VRF, and residential systems.

Overarching Refrigerant Options

Based on legislation and the impact on the environment, going forward the best refrigerant options for use in Bristol are the following, in descending order of GWP impact:

- **Natural/hydrocarbon substances – GWP < 5** are Ammonia (R717), CO2 (R744), and Propane (R290). These natural refrigerants less likely to have unintended consequences, as they are known substances. Today, their use is aspirational for most sectors since products are not widely available to enable their selection. With pressure from the industry, it is expected that manufacturers will increase the range of applications that can use these refrigerants.
- **HFOs – GWP < 10** are alternative low GWP refrigerants that are currently available commercially such as R1234ze, R1234yf, R1233zd.
- **HFCs - GWP < 750** are refrigerants that have a GWP between 450-750. Most major manufacturers will now offer systems using refrigerants with a GWP <750. R32 falls within this parameter and is an HFC refrigerant that is a Class A (non-toxic) refrigerant listed in ISO817. It is not explosive, and it is also extremely difficult to ignite. Because of it being sub 750 GWP, R32 is the most readily available refrigerant for many systems and is often used in lower GWP mixes with HFOs. Details of some of the most common refrigerants are outlined in a table published in 2021 in CIBSE TM65 (replicated here).

Some refrigerant options, as previously mentioned, are refrigerant mixes of the ones listed. Typical Refrigerant applications in different system types as outlined by the US Environmental Protection Agency can be found in Appendix K.

The majority of HFC and HFC/HFO blend refrigerants are classified as A1, with low toxicity and zero flammability. Ammonia, which has been in use for many years, is classified as B2L; R-152a is an A2 refrigerant, and all hydrocarbons are classified as A3 (higher flammability). The main differences between A1 refrigerants, such as R-410A, R-134a, R-407C, and A2L refrigerants such as R-32, HFO R-1234yf and HFO R-1234ze is the ability to propagate a flame. A2L refrigerants will burn, but their burning velocity is below 10cm/s, which is lower than an A3 refrigerant such as R-290 which actually burn explosively when ignited. It is very difficult to ignite 2L gases, but some precautions must be taken to prevent accidental build-up of refrigerant, particularly during charging of systems. All flammable refrigerants will not ignite if the concentration level in a room stays below their lower flammability limit. Safety legislation and standards such as ISO 5149 and EN 378 define requirements to remain far below the lower flammable limit in case of accidental leakage. Ammonia is B2L due to its higher toxicity, however, its distinctive smell is detectable at concentrations well below those considered to be dangerous, and if it does leak, it will rise and dissipate in the atmosphere due to its low density. The industry will need to begin to use the new higher flammability refrigerants as part of the F-Gas phase down process. These new refrigerants can be used safely in a wide range of applications, provided guidance and regulations are observed, and good practice is used.

For the studies in previous chapters refrigerant GWPs lower than 750 were assumed for all options. Where equipment was not commercially available with a GWP <750, conversations with the manufacturers have indicated that in line with F-Gas regulations this will change within in the next few years.

Type	Refrigerant	Ozone depletion potential (kg CFC-11eq) from Montreal Protocol (EPA. online)	Global warming potential over 100 years (kg CO_2eq) (CARB, online)	Toxicity and flammability classification (ASHRAE, 2019)
CFC	R11	1	4750	A1
HCFC	R22	0.055	1810	A1
	R407c	0	1774	A1
HFC	R410a	0	2088	A1
	R134a	0	1430	A1
	R32	0	677	A2L
HFO	R1234yf	0	<1	A2L
	R1234ze (E)	0	1	A2L
Hydrocarbon	R290 (propane)	0	4	A3
Natural	R744 (CO_2)	0	1	A1
	R717 (ammonia)	0	0	B2L
	R718 (water)	0	0	A1

Toxicity and flammability classifications: A1 = no flame propagation; A2L = mildly flammable; A3 = highly flammable; B2L = mildly flammable with medium toxicity concerns.

Figure 5.6: GWP for different Refrigerant types (Source: CIBSE TM65)

Refrigerant Embodied Carbon: Refrigerant Leakage Study

Most refrigerants can be reused in other systems indefinitely and without affecting performance. Factory sealed small volumes can be taken from site and safely discharged, while split systems such as VRF / DX systems need to be drained on site. If reuse is not possible, destruction should happen in an approved facility, equipped to absorb, and neutralise acid gases and other toxic processing products.

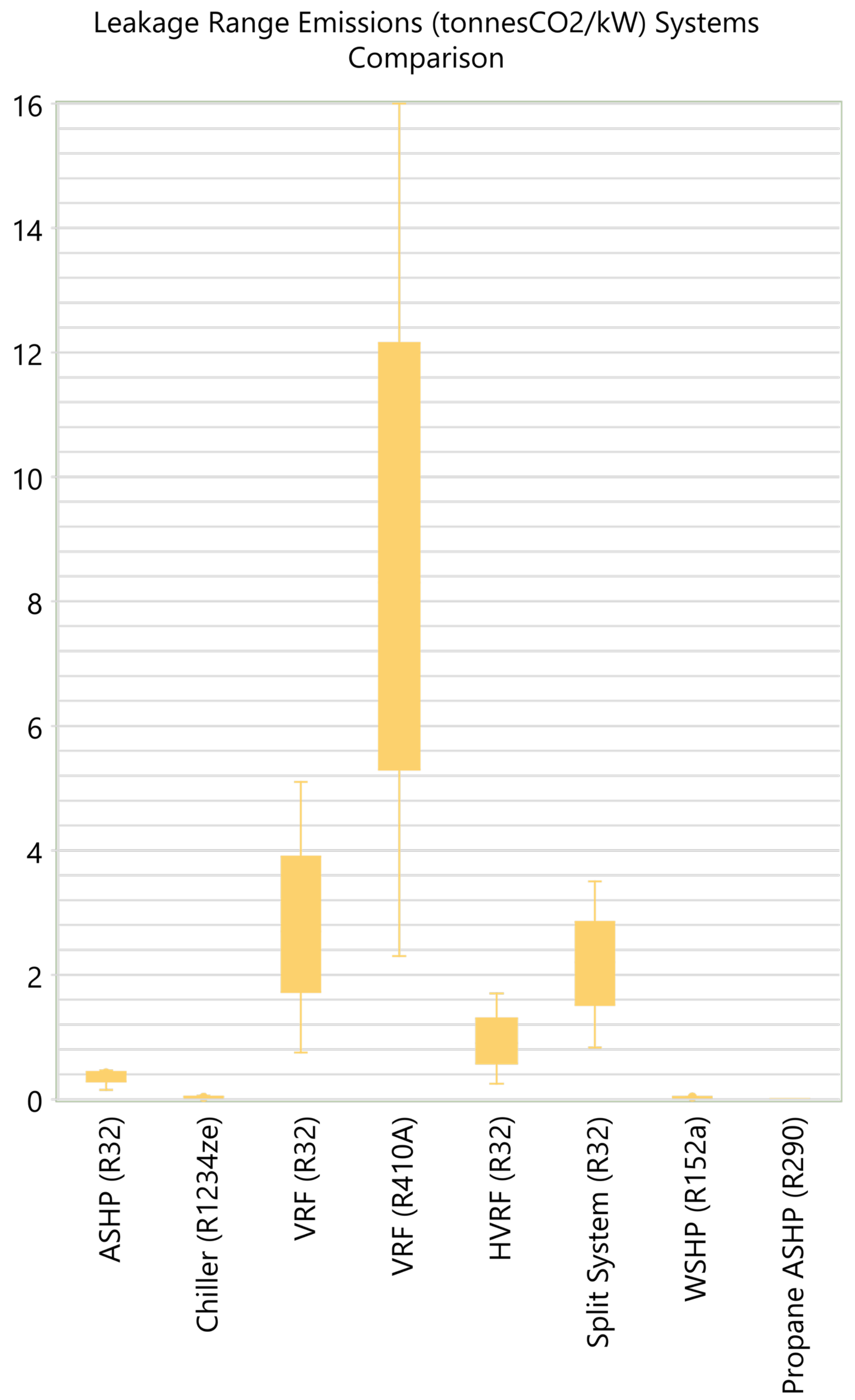
A study from the UK Department of Energy and Climate Change on heat pumps reports that a refrigerant charge reduction of:

- 10% leads to a relative COP reduction of about 3% in heating and 15% in cooling operation
- 40% would reduce the relative COP by around 45% in heating mode and 24% in cooling operation
- 50% is considered catastrophic and the system is unlikely to function properly

A refrigerant can be used throughout the life of an HVAC system. However, there is usually a need for top-up due to leakage as the loss of refrigerant affects the system's performance - 50% leakage is regarded as the breaking point for system performance. Leakage during operation (not commissioning or decommissioning) can occur due to a variety of reasons. The capillary tubes of system evaporator coils can vibrate during system operation causing the tubes to rub against themselves or other components, leading to holes which allow refrigerant to leak. In condenser coils this can occur in their U-bends, which are joined by tubular sheet metal. As the system runs, this tube rubs against the copper condenser coil tubes, forming small holes which allow refrigerant to leak. Reports suggest that leakage rates during the 'use' phase could be between 1% and 10% with an average of 3% subject to recurring maintenance and component ware. During removal at end-of-life stage, leakage rates range from 1% to 3%. Specific system refrigerant leakage reports can be found in Appendix K in a table sourced from CIBSE TM65. Some of the most impactful ways to mitigate refrigerant charge due to leakage include:

- Installation by a registered installer with the manufacturer of the system. This could potentially extend to adding a requirement in specifications for the manufacturer to attend site and confirm all their requirements have been met. This is particularly effective as there is currently a shortage of refrigerant engineers – using manufacturer resources can ensure that the refrigerant is properly installed, maintained, decommissioned, and either reused or destroyed appropriately.
- Maintenance by a registered contractor from the manufacturer of the system.
- Prescriptive procedures for how to recover refrigerants from systems in order to achieve 100% recovery (or as close to it as possible).
- Use system performance monitoring software so that the manufacturer and owner can identify a problem with system performance (which may be related to refrigerant leakage) quickly.
- Refrigerant choices should also consider what research has been done on them. On one hand, HFOs can break down into trifluoroacetic acid (TFA) and hydrofluoric acid and can potentially cause acid rain. However, R-1234ze does not break down into TFA, and some preliminary studies in Australia have found that the substance R-23 is formed (GWP=14,800) when leaked due to photodecomposition. Though this study is just an example of progressing knowledge on different refrigerant types, opting for refrigerants like propane and CO_2 where it is known how they interact with the environment is a better option when possible.

GWP of the refrigerant should not be the only consideration, as the refrigerant charge can determine the overall effect the system could have if a percentage were discharged to atmosphere. For example VRF system refrigerant charge is generally greater than with centralised water-based systems and comes with the added risk that it is inserted on-site under construction conditions. However, coupled with high GWP refrigerants, leakage will contribute significantly to a building's whole life carbon. The graph to the right shows the results of a study undertaken to visualise the effect that refrigerant leakage ranges (identified by other studies and summarised in TM65, summarised in Appendix J) can have in specific system types. The refrigerant type was as per the main study, with the exception of the inclusion of a VRF R410A option to demonstrate the significant emissions that may result, even when considering the lowest leakage rates for VRF. Refrigerant charge was proportional to kW for the system to normalise the results. With the propane ASHP having the least impact due to the low GWP, followed by the R1234ze chiller, the split system result was relatively high due to the charge per kW ratio. Despite the higher charges, the first two demonstrate the importance of using much lower GWP refrigerants. With similar leakage rates, the HVRF has demonstrated the importance of lower refrigerant charges when compared to the VRF. Systems that use refrigerant based distribution have a higher average impact as well as there being a greater risk of much higher impacts if installation and management leads to high leakage rates.



Refrigerant Embodied Carbon: R410A Systems

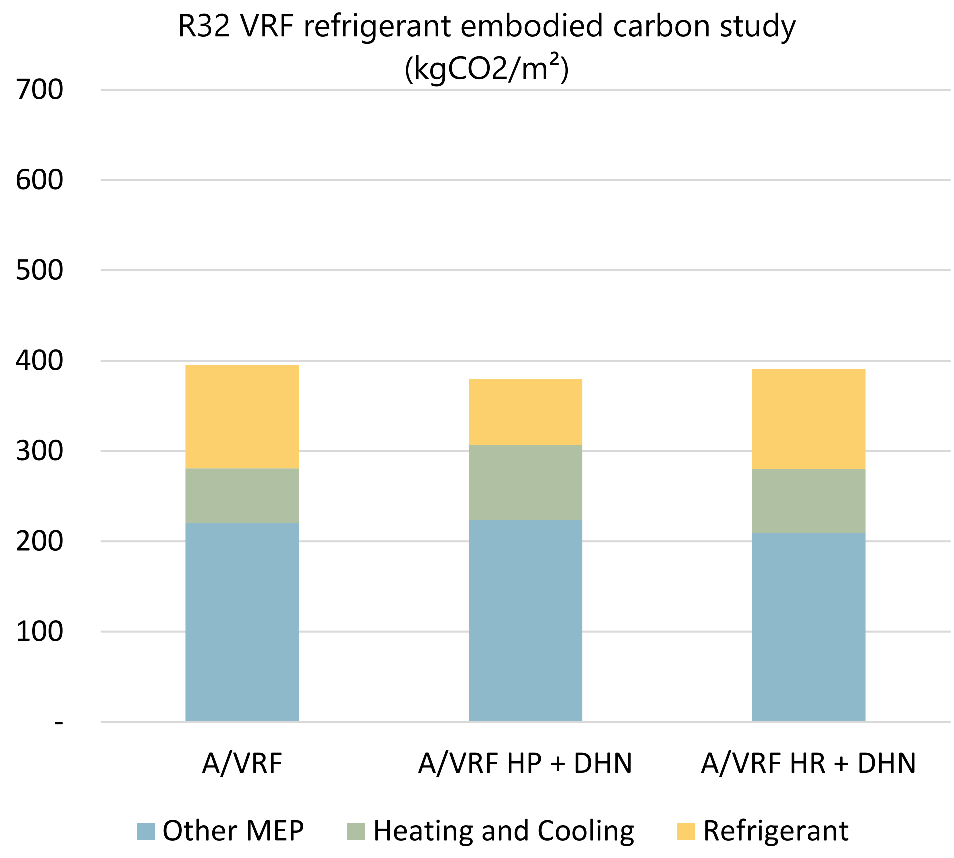
VRF systems are currently the most problematic system when considering refrigerant charge. There are limited reduced GWP options, with the best commercially available refrigerant being R32 (GWP 675). A study was carried out wherein the impact of changing one system within a scenario to R410A, as is widespread currently within the industry, visualising the impact that high GWP has on the total embodied carbon of a system.

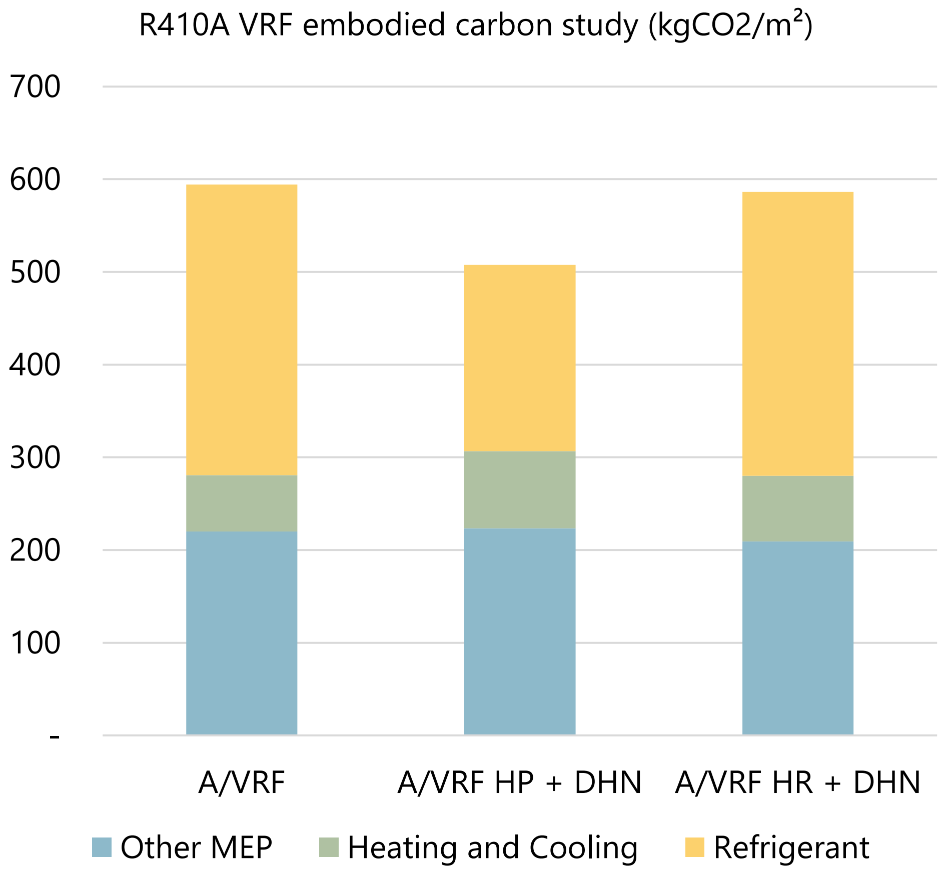
In the case of the commercial building, the VRF was changed to reflect an R410A system as they tend to have high leakage rates, both during construction, use, and decommissioning, and are most commonly found as such in the current industry. The bar charts to the right, visualise the impact this has despite all other systems in the building remaining the same, namely nearly an average 30% increase in embodied carbon with an R410A VRF system. It should be noted that an R410A VRF system currently would be more efficient and require less units, however, given the proportion of heating and cooling embodied carbon to refrigerant, this would not change the results drastically.

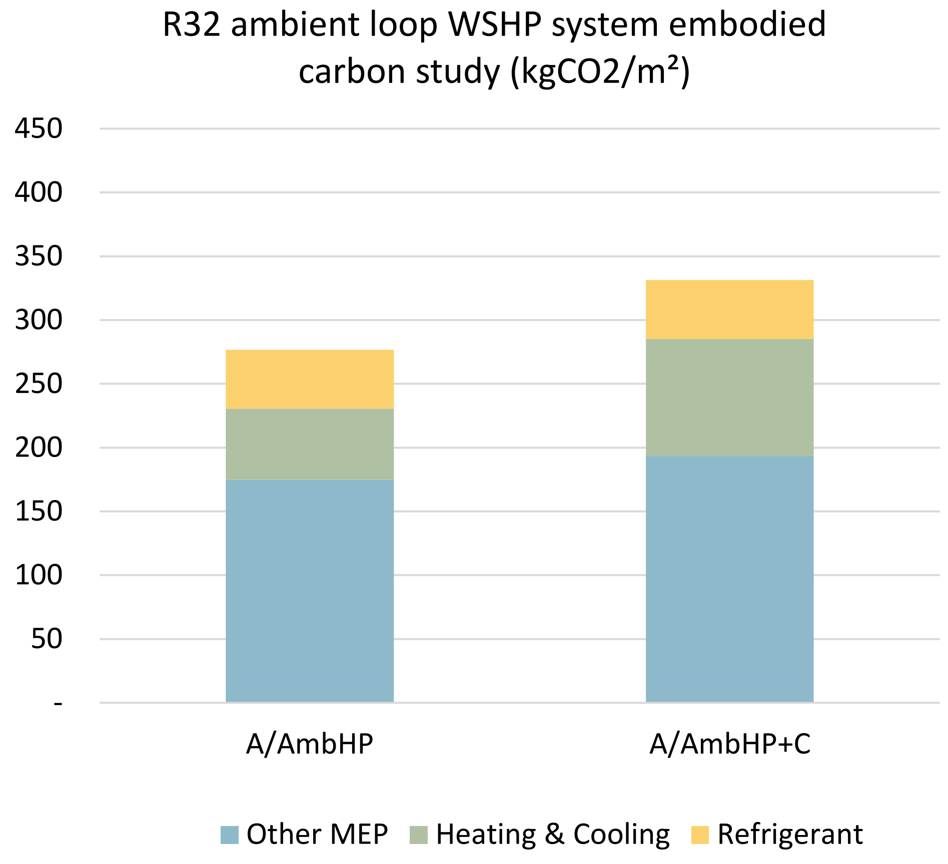
Within the residential building the ambient loop system includes an in-dwelling WSHP, which currently is typically an R410A system. Conversations with the manufacturers are in line with what we expect to occur in the next few years as equipment is modified to cater to lower GWP refrigerants. It should be therefore noted that until this occurs, some ambient loop systems may not be as beneficial. However, as can be seen by comparing the VRF system and the ambient loop WSHP system, typical leakage rates for these systems, and the amount of refrigerant charge implicated means that the ambient loop WSHP system impact with R410A is less, albeit still a significant 36% increase in its own system.

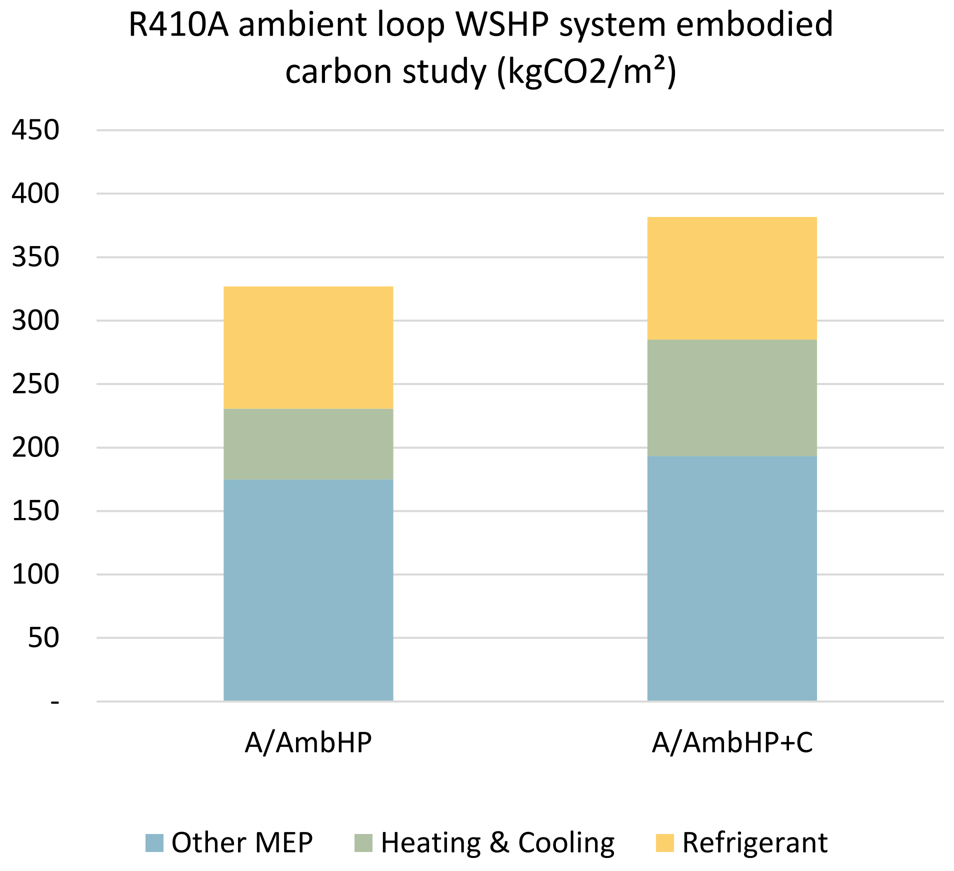
Until the ban on the use of virgin refrigerants with a GWP greater than 750 comes in force in 2025, new units with GWPs over 750 should be avoided, unless it can be proven that the overall warming potential of the whole system is less than a comparable system in the 450-750 band.

In both cases it can be seen that even a lower than 750 GWP refrigerant such as R32 still accounts for a significant proportion of the embodied carbon of the system – it is therefore vital that much lower GWP refrigerant options be considered, and that refrigerant leakage mitigation measures be taken seriously.


R32 VRF refrigerant embodied carbon study (kgCO2/m²)


R410A VRF embodied carbon study (kgCO2/m²)


R32 ambient loop WSHP system embodied carbon study (kgCO2/m²)


R410A ambient loop WSHP system embodied carbon study (kgCO2/m²)

Refrigerant Considerations for Centralised Systems

When specifically considering centralised systems, the following refrigerant options are the most readily available.

In centralised systems the main components that affect refrigerant volume are the heat exchangers. Recently manufacturers have been transitioning towards flooded evaporators and condensers, which increase equipment efficiency but also increase refrigerant volumes. Ways to reduce the refrigerant charge of centralised systems includes considering the selections of equipment that uses microchannel air to refrigerant heat exchangers or alternatively micro plate heat exchangers (for systems below 400kW), which can offer lower refrigerant volumes.

Refrigerant	GWP	Comments
R717 Ammonia	0	Has an ideal GWP performance and one of the best energy efficiency solutions, however, Ammonia is a toxic refrigerant, and it is also flammable at certain concentrations, and therefore needs to be handled with care and systems be designed with safety in mind. Despite this, unlike most other refrigerants, it has a characteristic odour that can be detected by humans even at very low concentrations were it to leak, and is less dense than air, and therefore will dissipate into the atmosphere easily. The cost of ammonia (per kg) is considerably lower than the cost of HFCs. This lends itself particularly to energy centres as they tend to both be high efficiency and high temperature, and the toxicity can be easily managed.
R744 CO_2	1	While not as efficient as ammonia or some HFOs, CO_2 is starting to be found in some residential centralised systems as it can produce high enough temperature for domestic hot water use., and they require a very low return temperature for the refrigerant cycle to work and is therefore well suited for heating cold water up to DHW temperatures. For example, Mitsubishi Electric introduced a high temperature, hot water Ecodan QAHV heat pump, which uses CO_2 as a refrigerant. It can provide water between 55°C and 90°C, eliminating the requirement for a boiler. However, currently the high pressure ratio between the evaporator and the cooler necessarily requires double stage compression for reasonable performance, so natural refrigerants such as Ammonia and Propane, or future CO2 blends, may become more mainstream for commercial applications.
R290 Propane	4	Packaged propane air-cooled refrigerant chillers can be a serious contender when considering low GWP cooling plant for commercial buildings. Propane chillers are not too dissimilar from those that have been used for many years in the building services industry. They have similar designs, dimensions, weight and efficiency, and can be equipped with inverter-controlled capacity to operate effectively across varying loads. Propane is classified as "highly flammable", however this is in high concentrations. All flammable refrigerants will not ignite if the concentration level in a room stays below their lower flammability limit, and therefore if regulations are followed (such as ISO 5149 and EN 378) this risk is mitigated.
HFOs (R1234ze or R1234yf)	<10	There are now many R1234ze or R1234yf (HFOs) units becoming available commercially. R1234ze has near zero environmental impact, with a small reduction in chiller capacity. Energy efficiency performance remains the same, but there is an increase in cost. It is also an A2L refrigerant (like R32), categorising it as 'mildly flammable'. As previously mentioned, these systems are installed in accordance with regulations and good practice, thereby mitigating the risk of this causing any issues. Though currently more expensive, with the progression of the market towards lower GWPs they are becoming more affordable.
HFCs	<750	A short-term solution to lower GWP is offered by R454b, R513a and R32, the first two being blends of R32 with HFO refrigerants which are also seeing increased use to get lower GWPs. For example, R454b (GWP 466) is a blend of R1234yf with R32. Similarly, R513A (GWP 631) is made up of R1234yf and R134a. Both are classed as HFO refrigerants and used commonly in chiller applications as a low GWP option. As these units are often roof mounted, were they to leak, concentrations could be easily controlled. Compared to all other common refrigerants, R32 requires the highest concentration level to cause any adverse health effect.

Refrigerant Considerations for Discrete Systems

For greater control and autonomy residential and some leased office heating and cooling systems tend to be local. The selection of refrigerants available for residential scale systems, within the current legislative context, is more limited than for commercial units for now , but we are aware that manufacturers are working towards making them more interchangeable for future market resilience, so wider choice might be expected in the next few years.

The study on page 90 on VRF systems underlines the propensity they have to having higher leakage emissions. As an alternative, hybrid VRF uses refrigerant in primary routes and switches over to a water-based medium for the final run outs and in fan coil units, additionally making it easier to manage toxicity and flammability risks. This type of system can reduce the refrigerant content by as much as 66% when compared to a traditional VRF system. Combined with the shift from R410a to R32 this can offer a 90% reduction in the whole system refrigerant GWP (as well as being a cheaper refrigerant). This use of water removes the need for any leak detection in occupied spaces (required when using R32) and helps lower annual maintenance costs. Hybrid VRF offers the flexibility that attracts the use of VRF systems, while lowering the global warming potential (GWP) of the system as a whole. Moreover, in the case of renovation or tenant ft-out in multi-tenanted buildings, only the water-based elements need to be altered, which eliminates the leakage risk associated with works to the refrigerant containing parts of the system.

Despite the European F-Gas regulation is a phase down rather than a ban, R410A will still be available but it is incumbent on the industry to use them in lower quantities, which will result in issues with price / supply as was seen in 2018 when the first intermediate F-Gas milestone came into effect. Therefore all refrigerants above 750 GWP have been left off the list in the table to the right.

Refrigerant	GWP	Comments
R290 Propane	4	Easily managed by the very small quantity involved and using products where all the refrigerant containing elements of the system are located externally. It is currently the lowest GWP option available for air source heat pumps (heating and hot water), water source heat pumps (suitable for ambient loop or ground source system), close coupled to hot water cylinders. Propane is classified as “highly flammable”, however this is in high concentrations. All flammable refrigerants will not ignite if the concentration level in a room stays below their lower flammability limit, and therefore if regulations are followed (such as ISO 5149 and EN 378) this risk is mitigated.
R744 CO_2	1	Individual apartment or dwelling CO2 heat pumps are currently not as commercially viable as centralised district heating type versions that provide heat to the whole building. Due to the increase in size and material of CO2 heat pumps individual dwelling versions are not yet available, but may become as heat pump prices become more competitive.
R454C	148	Available from Stiebel Eltron in the UK for residential ASHPs as a longer term and more resilient alternative to R32. Since 2020 these have become more commercially available as a more environmentally friendly refrigerant (GWP<150), additionally providing better COPs to enable higher flow temperatures.
R32	675	Though R32 is above the 150 desired GWP threshold, it is very common in a lot of refrigerant systems, and while other sub 150 GWP refrigerants gain traction, it may be the only option available in certain contexts.

Refrigerant Recommendations

As can be seen in the studies on pages 90 and 91, systems that have a high charge, potential leakage, and use refrigerant for their distribution (such as VRF) are likely to have higher refrigerant emissions. Mitigation is challenging due to the lack of availability of low GWP refrigerant technology alternatives, inherently have higher quantities of refrigerant and site work handling refrigerant elements. Centralised systems have the greatest opportunity for using low GWP refrigerants in offices. Where a centralised system is not feasible and a zonal system is used, close attention should be paid to the refrigerant types. A summary can be found visualised in the table on page 95.

In all scenarios proper installation, maintenance, and decommissioning should be carried out as mitigating leakage is what ultimately determines the impact the system refrigerant will have on the atmosphere. Key leakage mitigation measures should be encouraged through policy and documentation including:

- Installation by a registered installer with the manufacturer of the system. This could potentially extend to adding a requirement in specifications for the manufacturer to attend site and confirm all their requirements have been met.
- Maintenance by a registered contractor with the manufacturer of the system. Avoiding constant over pressurisation of the system is important for this.
- Prescriptive procedures for how to recover refrigerants from systems in order to achieve 100% recovery (or as close to it as possible).
- Use a system performance monitoring software so that the manufacturer and owner can identify a problem with system performance (which may be related to refrigerant leakage) quickly.
- Carrying out research on the latest knowledge pertaining to the refrigerants being considered, as for many refrigerants this is in flux.

National and international legislation means that there is a strong drive for manufacturers to make the shift to lower GWP refrigerants in the next few years and should be reflected in local policy as well to encourage this trend. However, the way we assess refrigerant charge and leakage also needs to be prioritised and carefully assessed during the design stages of our buildings. Often leakage rates considered are much lower than studies show are on average occurring. We would recommend that the average leakage rates shown for specific systems types as identified in leakage studies in Appendix K (p.147) be used when assessing the potential impact of a system being designed. Lower leakage rates should be used only if strict leakage mitigation measures such as leak detection (can be demonstrated by targeting relevant Pol 01 BREEAM credits) as being integrated as part of design and policy to ensure it does not occur.

It also must be appreciated that the lowest emission overall building may not be the one with the lowest refrigerant GWP, though less common. If one wants to demonstrate that the proposed system would perform better than a lower GWP system from a WLC standpoint, relevant studies should be conducted to evidence this. An alternative to limit GWP may also be the approach of LEED's "Enhanced Refrigerant Management" requirements, option 2 (option 1 being no refrigerants with a GWP greater than 50), wherein the combination of all new and existing base building and tenant HVAC & R equipment that serves the project must comply with the following formula:

Where,

LCGWP: Lifecycle Direct Global Warming Potential (kgCO2/kW-year)

ODPr: Ozone Depletion Potential of Refrigerant (0 to 0.2 kg CFC 11/kg r)

For a predefined annual refrigerant leakage rate of 2%, and end of life loss of 10%, for, if not known, a refrigerant charge of 0.65kg per kW of cooling capacity, and a lifespan of 10 years (also if not known). This approach can provide an alternative route to demonstrate the refrigerant emissions of a proposed system. Using this formula/approach for the systems in our study, the only compliant systems would be the low GWP chiller, WSHP, and propane heat pump, demonstrating that R32 cannot be a long term solution. BREEAM's threshold for one credit of 1000 is currently more achievable, with its 100 two credit option which should be considered in future.

The table on the next page outlines key summary points for the different refrigerants covered in this study.

Refrigerant Summary

The below table outlines the summary of refrigerant options (non exhaustive) for different system types in the current legislative context, their benefits and limitations, and applications.

Key	Lower Toxicity	Higher Toxicity
Higher Flammability	A3	B3
Lower Flammability	A2 / A2L	B2 / B2L
No Flame Propagation	A1	B1

Refrigerant Type	Type	GWP	Flammability /Toxicity	Typical System Scale	Typical Application	Benefits	Limitations
Ammonia (R717)	Natural	0	B2L	Energy Centre	Industrial but being explored for commercial and residential applications	Lowest GWP of 0, known for its very high performance in refrigeration cycles.	Not compatible with copper circuits, therefore systems with secondary fluid are used to avoid direct contact together with glycol-water or CO_2. However this complexity and required enhanced procedures for maintenance, mean that ammonia is generally used in larger systems such as industrial, or sports facilities.
CO_2 (R744)	Natural	1	A1	Centralised	High temperature hot water heat pumps for domestic water (and heating in very efficient energy homes)	GWP of 1, lowest GWP classified as A1. Well known as a substance.	Requires high output temperatures and lower return temperatures and therefore is best suited to domestic hot water applications, and requires appropriate infrastructure due to higher working pressures. Combination with space heating can only work in very low energy buildings.
Propane (R290)	Hydrocarbon	3	A3	Centralised	High Temperature Heat Pumps	GWP of 3 with good energy efficiency in most conditions, equal to that of HFCs and with low discharge temperatures.	Cost is low, however due to enhanced safety measures to mitigate flammability it may be more expensive.
R1234ze	HFO	7	A2L	Centralised	Chillers	Presents efficiencies similar to R134a, is already widely available in chillers	Lesser known substance. Has low volumetric capacity and therefore does not work in all ways to replace R134a, but is well suited to chillers
R152a	HFC	124	A2	Centralised	R134a replacement, in blends	Can replace R134a in most cases	Due to its lower yet not very low GWP it is not widely available as a standalone refrigerant and is found most commonly in blends.
R32	HFC	677	A2L	Centralised and Discrete	R410a replacement in chillers, heat pumps, split, and VRF systems	Easily replaceable in R410A systems as a lower GWP option and therefore widely available	Still relatively high GWP when considering future refrigerant GWP ambitions.
R134a	HFC	1430	A1	Centralised	Mostly hot water heat pumps and chillers, as well as small domestic heat pumps	Widely used, classified as A1	High GWP and is being phased out by lower GWP options
R407c	HFC	1770	A1	Centralised	small to medium commercial refrigeration and rooftop systems	Widely used, classified as A2	High GWP and is being phased out by lower GWP options
R410a	HFC	2088	A1	Centralised and Discrete	Widely used in split systems, heat pumps, and VRF systems	Widely used, classified as A1	High GWP and is being phased out by lower GWP options

BURO HAPPOLD

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TECHNICAL APPENDIX

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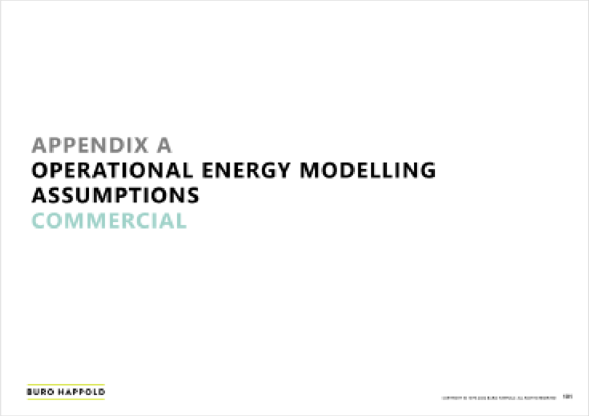
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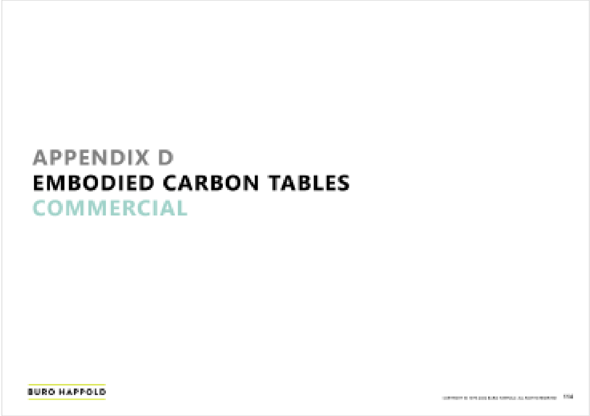
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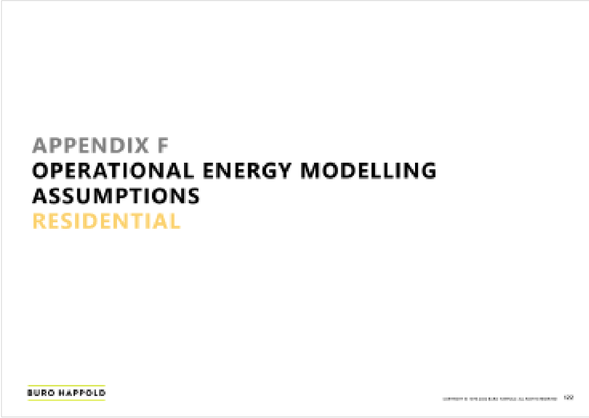
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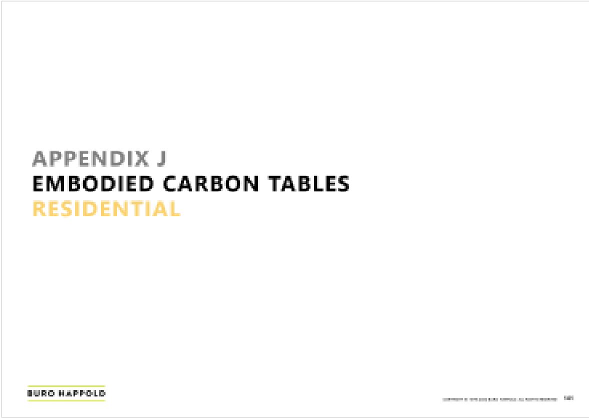
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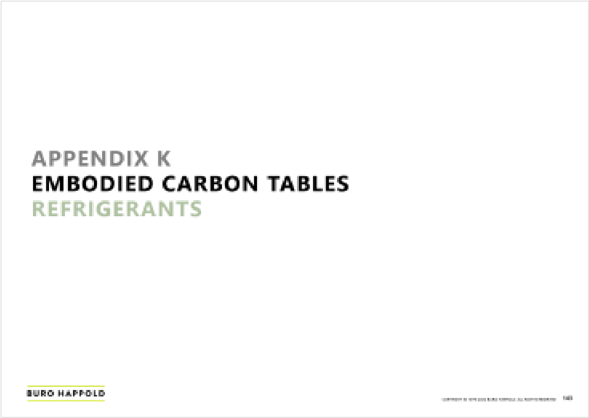
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APPENDIX A
OPERATIONAL ENERGY MODELLING ASSUMPTIONS
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Assumptions | Basis of Design

A basis of design was agreed with BCC which was constructed using current practices (A) in line with BCO and CIBSE Guide A, and a best practice design (B) was set out to achieve LETI and UKGBC targets.

An indiscriminatory glazing ratio has been applied all orientations.

As part of the DfP modelling, a 20% margin has been assumed and applied to calculated energy demands for each category to provide an account of potential building mis-management. This is referred to as the management factor.

Constructions

Building Element	Current Practice U-value (W/m^{2}K)	Best Practice U-value (W/m^{2}K)	References
Floor	0.2	0.12	LETI
External Wall	0.2	0.15	LETI
Roof	0.18	0.12	LETI
Glazing	1.4@ (VLT 0.7 & G 0.3) *Reception G 0.26*	1.2@ (VLT 0.7 & G 0.3) *Reception G 0.26*	LETI

Other Factors	Current Practice	Best Practice	References
Air permeability (m^3/hr/m^2 @50Pa)	3	1.5	LETI
Infiltration rates (ach)	0.15 (Office) 1.0 (Reception)	0.075 (Office) 0.6 (Reception)	CIBSE A
Glazing Percentage %	57%	40%	LETI

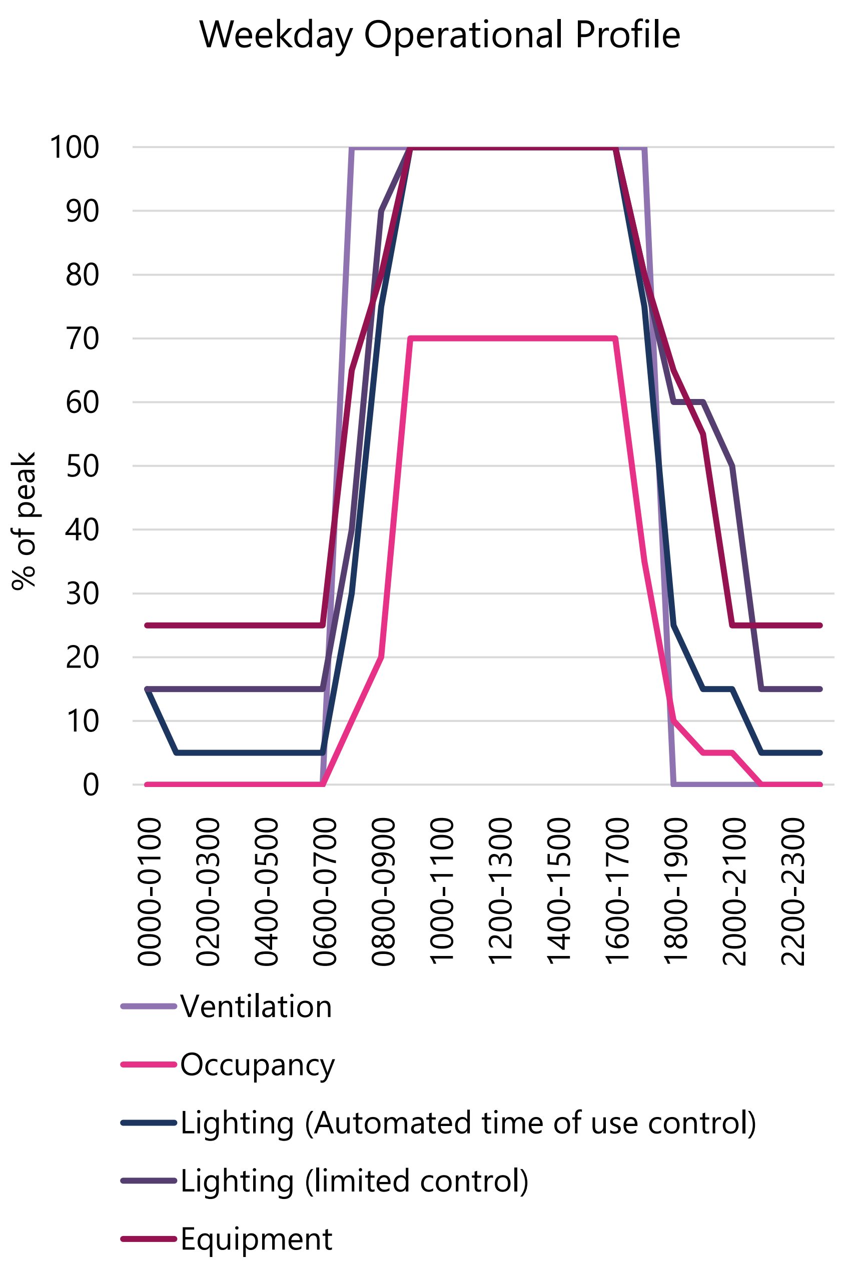
Basis of design

Parameter	Units	Office A	Office B	Reference
Heating set-point temperature (& set-back)	°C	21 (12)	20 (12)	CIBSE A, UKGBC
Cooling set-point temperature (& set-back)	°C	24 (30)		CIBSE A
External ambient CO_2 concentration	ppm	400		
Internal CO_2 set point	ppm	700-900		
Ventilation Off-Coil DB Summer	°C	18 (ramped)		
Ventilation Off-Coil DB Winter	°C	20 (ramped)		
Occupancy density (design)	m^2/person	10		BCO
Ventilation rate (design)	l/s/person	12		BCO
Sensible gain per person (& latent gain per person)	W/person	74 (56)		CIBSE A
Lighting power density	W/m^2	8	4.5	BCO, UKGBC
Lighting illumination levels (offices)	lux	500	300 +task	CIBSE A
Equipment power density - on floor peak	W/m^2	20	9	BCO, UKGBC
Equipment power density – terminal (with div)	W/m^2	17	8	BCO
Equipment power density – central (with div)	W/m^2	12	8	BCO
Equipment power density – operational energy model	W/m^2	11	8	NABERS UK
Ventilation heat recovery effectiveness	%	*80*	*80*	
AHU specific fan power	W/l/s	*1.4*	*1.2*	
Terminal specific fan power	W/l/s	*Variable*	*Variable*	
Comms equipment gains – Landlord	W/m^2 (net)	*0.25*	*0.25*	NABERS UK
Comms equipment gains – Tenant	W/m^2 (net)	*0.5*	*0*	NABERS UK
Domestic hot water demand	l/person/day	*4*	*4*	NABERS UK
DHW distribution losses	W/m	*6*	*5*	
Storage volume (semi instantaneous)	m^3	*0.9-1.2*	*0.9-1.2*	
Storage losses	kWh/l/day	*0.0025*	*0.0025*	
Central plant sizing margin	%	*10%*	*10%*	
Management factor	%	*20%*	*20%*	
Renewable PV allowance	m^2	*400*	*800*	

Operational Profiles | System Profiles

Operational profiles were set using NABERS UK Design for Performance guidance. DHW profiles were taken from another DfP office project undergoing the NABERS rating process.

When the ventilation system is 'off', it is assumed that HVAC systems will be in standby and set back mode.



Workday

Time period	Occupancy	Lighting (Automated time of use control)	Lighting (limited control)	Equipment (Option B in brackets)	Vent
0000-0100	0%	5%	15%	25% (12.5%)	Off
0100-0200	0%	5%	15%	25% (12.5%)	Off
0200-0300	0%	5%	15%	25% (12.5%)	Off
0300-0400	0%	5%	15%	25% (12.5%)	Off
0400-0500	0%	5%	15%	25% (12.5%)	Off
0500-0600	0%	5%	15%	25% (12.5%)	Off
0600-0700	0%	5%	15%	25% (12.5%)	Off
0700-0800	10%	30%	40%	65%	On
0800-0900	20%	75%	90%	80%	On
0900-1000	70%	100%	100%	100%	On
1000-1100	70%	100%	100%	100%	On
1100-1200	70%	100%	100%	100%	On
1200-1300	70%	100%	100%	100%	On
1300-1400	70%	100%	100%	100%	On
1400-1500	70%	100%	100%	100%	On
1500-1600	70%	100%	100%	100%	On
1600-1700	70%	100%	100%	100%	On
1700-1800	35%	75%	80%	80%	On
1800-1900	10%	25%	60%	65%	On
1900-2000	5%	15%	60%	55%	On
2000-2100	5%	15%	50%	25% (12.5%)	On
2100-2200	0%	5%	15%	25% (12.5%)	Off
2200-2300	0%	5%	15%	25% (12.5%)	Off
2300-2400	0%	5%	15%	25% (12.5%)	Off

DHW (Workday, Saturday, Sunday and Holidays)

Time period	Shower Profile Weekday	Toilets Profile Weekday	Toilets DHW Profile Saturday	Toilets DHW Profile Sunday
0000-0100	0%	0%	0%	0%
0100-0200	0%	0%	0%	0%
0200-0300	0%	0%	0%	0%
0300-0400	0%	0%	0%	0%
0400-0500	0%	0%	0%	0%
0500-0600	0%	0%	0%	0%
0600-0700	25%	0%	0%	0%
0700-0800	50%	10%	0%	0%
0800-0900	25%	20%	5%	5%
0900-1000	5%	70%	15%	5%
1000-1100	0%	70%	15%	5%
1100-1200	10%	70%	15%	5%
1200-1300	20%	70%	5%	5%
1300-1400	10%	70%	5%	5%
1400-1500	0%	70%	5%	5%
1500-1600	0%	70%	5%	5%
1600-1700	5%	70%	5%	5%
1700-1800	0%	35%	0%	0%
1800-1900	0%	10%	0%	0%
1900-2000	0%	5%	0%	0%
2000-2100	0%	5%	0%	0%
2100-2200	0%	0%	0%	0%
2200-2300	0%	0%	0%	0%
2300-2400	0%	0%	0%	0%

Operational Profiles | Weekend and Holiday System Profiles

Saturday

0000-0100	0%	5%	15%	25% (12.5%)	Off
0100-0200	0%	5%	15%	25% (12.5%)	Off
0200-0300	0%	5%	15%	25% (12.5%)	Off
0300-0400	0%	5%	15%	25% (12.5%)	Off
0400-0500	0%	5%	15%	25% (12.5%)	Off
0500-0600	0%	5%	15%	25% (12.5%)	Off
0600-0700	0%	5%	15%	25% (12.5%)	Off
0700-0800	0%	5%	15%	25% (12.5%)	Off
0800-0900	5%	40%	25%	25% (12.5%)	Off
0900-1000	15%	40%	40%	25% (12.5%)	On
1000-1100	15%	40%	40%	25% (12.5%)	On
1100-1200	15%	40%	40%	25% (12.5%)	On
1200-1300	5%	15%	25%	25% (12.5%)	Off
1300-1400	5%	15%	25%	25% (12.5%)	Off
1400-1500	5%	15%	25%	25% (12.5%)	Off
1500-1600	5%	15%	25%	25% (12.5%)	Off
1600-1700	5%	15%	25%	25% (12.5%)	Off
1700-1800	0%	5%	15%	25% (12.5%)	Off
1800-1900	0%	5%	15%	25% (12.5%)	Off
1900-2000	0%	5%	15%	25% (12.5%)	Off
2000-2100	0%	5%	15%	25% (12.5%)	Off
2100-2200	0%	5%	15%	25% (12.5%)	Off
2200-2300	0%	5%	15%	25% (12.5%)	Off
2300-2400	0%	5%	15%	25% (12.5%)	Off

Sunday and Holidays

Time period	Occupancy	Lighting (Automated time of use control)	Lighting (limited control)	Equipment (Option B in brackets)	Vent
0000-0100	0%	5%	15%	25% (12.5%)	Off
0100-0200	0%	5%	15%	25% (12.5%)	Off
0200-0300	0%	5%	15%	25% (12.5%)	Off
0300-0400	0%	5%	15%	25% (12.5%)	Off
0400-0500	0%	5%	15%	25% (12.5%)	Off
0500-0600	0%	5%	15%	25% (12.5%)	Off
0600-0700	0%	5%	15%	25% (12.5%)	Off
0700-0800	0%	5%	15%	25% (12.5%)	Off
0800-0900	5%	15%	25%	25% (12.5%)	Off
0900-1000	5%	15%	25%	25% (12.5%)	Off
1000-1100	5%	15%	25%	25% (12.5%)	Off
1100-1200	5%	15%	25%	25% (12.5%)	Off
1200-1300	5%	15%	25%	25% (12.5%)	Off
1300-1400	5%	15%	25%	25% (12.5%)	Off
1400-1500	5%	15%	25%	25% (12.5%)	Off
1500-1600	5%	15%	25%	25% (12.5%)	Off
1600-1700	5%	15%	25%	25% (12.5%)	Off
1700-1800	0%	5%	15%	25% (12.5%)	Off
1800-1900	0%	5%	15%	25% (12.5%)	Off
1900-2000	0%	5%	15%	25% (12.5%)	Off
2000-2100	0%	5%	15%	25% (12.5%)	Off
2100-2200	0%	5%	15%	25% (12.5%)	Off
2200-2300	0%	5%	15%	25% (12.5%)	Off
2300-2400	0%	5%	15%	25% (12.5%)	Off

APPENDIX B
EQUIPMENT SCHEDULES
COMMERCIAL

Schedules | Heating and Cooling Equipment

System	A	B	VRF	HVRF	VRF C + DHN	CHL+ DHN	HP	VRF + DHN	Item/Description	Capacity	Unit	Qty	Comments
Heat/Cool	A		x					x	Outdoor unit VRF	20	kW	22	Simultaneous heating and cooling. 2 per typical office floor. 1 for the GF (office + reception)
Heat/Cool		B	x					x	Outdoor unit VRF	20	kW	22	Simultaneous heating and cooling. 2 per typical office floor. 1 for the GF (office + reception)
Heat/Cool	A			x					Outdoor unit HVRF	35.8	kW	11	Simultaneous heating and cooling. 2 per typical office floor. 1 for the GF (office + reception)
Heat/Cool		B		x					Outdoor unit HVRF	35.8	kW	6	Simultaneous heating and cooling. 2 per typical office floor. 1 for the GF (office + reception)
Heat/Cool	A						x		ASHP - Heating/Cooling	100	kW	1	For base simultaneous load - includes heat recovery. 20% of peak load ~= DHW peak load
Heat/Cool		B					x		ASHP - Heating/Cooling	100	kW	1	For base simultaneous load - includes heat recovery. 20% of peak load ~= DHW peak load
Heat/Cool	A						x		Thermal store for Integra Unit	2200	litres	2	Thermal store to balance out the cooling loads 25kW capacity over an hour
Heat/Cool		B					x		Thermal store for Integra Unit	2200	litres	2	Thermal store to balance out the cooling loads 25kW capacity over an hour
Heat/Cool	A						x		ASHP LTHW	275	kW	2	Dedicated LTHW production ASHP 45F/40R
Heat/Cool		B					x		ASHP LTHW	210	kW	2	Dedicated LTHW production ASHP 45F/40R
Heat/Cool	A	B	x					x	VRF Branch controller	10	port	22	Master Controller
Heat/Cool	A			x					HVRF Master Branch controller	12	port	11	Master Controller
Heat/Cool	A			x					HVRF Sub Branch controller	4	port	21	Sub Controller
Heat/Cool		B		x					HVRF Master Branch controller	12	port	11	Master Controller
Heat/Cool		B		x					HVRF Sub Branch controller	4	port	21	Sub Controller
Heat/Cool	A		x		x			x	VRF FCU	3	kW	185	Refrigerant based FCU + valve sets. Reception units are 5kW (5 units)
Heat/Cool	A			x					HVRF FCU	3	kW	185	Hybrid VRF compatible FCU + valve sets. Reception units are 5kW (5 units)
Heat/Cool		B	x		x			x	VRF FCU	1.5	kW	185	Refrigerant based FCU + valve sets. Reception units are 5kW (5 units)
Heat/Cool		B		x					HVRF FCU	1.5	kW	185	Hybrid VRF compatible FCU + valve sets. Reception units are 5kW (5 units)
Heat/Cool	A					x	x		4 pipe FCU	3	kW	185	4 pipe FCU + valve sets. Reception units are 5kW (5 units)
Heat/Cool		B				x	x		4 pipe FCU	1.5	kW	185	4 pipe FCU + valve sets. Reception units are 5kW (5 units) Low SFP units
Heat/Cool	A		x	x	x	x	x	x	DX Split System Outdoor Unit - Servers	3	kW	8	Dedicated server room split units + pipework. With power inverter
Heat/Cool	A		x	x	x	x	x	x	CRAC Units - Servers	3	kW	8	Dedicated server room split units + pipework
Heat/Cool		B	x	x	x	x	x	x	DX Split System Outdoor Unit - Servers	3	kW	1	Dedicated server room split units + pipework - Cloud based operations - located in the car park. With power inverter
Heat/Cool		B	x	x	x	x	x	x	CRAC Units - Servers	3	kW	2	Dedicated server room split units + pipework

BURO HAPPOLD

__A__ – Current practice, __B__ – Best practice, __VRF__ - VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

Schedules | Heating/Cooling and DHW

System	A	B	VRF	HVRF	VRF C + DHN	CHL+ DHN	HP	VRF + DHN	Item/Description	Capacity	Unit	Qty	Comments
Heat	A				x	x			Plate heat exchanger - LTHW	235	kW	2	2x PHE as per BCC requirements + metering, valve sets, and pumps
Heat		B			x	x			Plate heat exchanger - LTHW	175	kW	2	2x PHE as per BCC requirements + metering, valve sets, and pumps
Cool	A				x				Outdoor unit VRF (cooling only)	20	kW	22	Cooling or heating only
Cool		B			x				Outdoor unit VRF (cooling only)	20	kW	22	Cooling or heating only
Cool	A					x	x		Chillers	250	kW	2	Duty - share. Sized at 50% each. 10F/16R
Cool		B				x	x		Chillers	300	kW	1	Duty only 14F/17R
Heat	A				x				Trench unit heater	965	m	1	Natural convection - 250W/m
Heat		B			x				Trench unit heater	965	m	1	Natural convection - 160W/m
Heat	A		x	x				x	Overdoor heater - Elec	10	kW	2	To be mounted above revolving doors
Heat	A				x	x	x		Overdoor heater - Wet	10	kW	2	To be mounted above revolving doors
Heat		B	x	x				x	Overdoor heater - Elec	5	kW	2	To be mounted above revolving doors
Heat		B			x	x	x		Overdoor heater - Wet	5	kW	2	To be mounted above revolving doors
Heat	A	B	x	x				x	Electric heater panel	1	kW	25	Showers, core, stairs, plant - mix between 0.75kW and 2kW
Heat	A	B			x	x	x		Radiator	1	kW	25	Showers, core, stairs, plant - mix between 0.75kW and 2kW

System	A	B	VRF	HVRF	VRF C + DHN	CHL+ DHN	HP	VRF + DHN	Item/Description	Capacity	Unit	Qty	Comments
DHW	A	B	x	x					ASHP - DHW Generation (01,02)	40	kW	2	For showers only.
DHW	A	B			x	x		x	Plate heat exchanger - DHW	70	kW	2	High temp (65degC) - all DHW + metering, valve sets, and pumps
DHW	A	B					x		WSHP (Water source heat pump)	80	kW	1	For showers only. 2x PHE as per BCC requirements
DHW	A	B			x	x		x	Calorifier - showers + WHB	100	kW	1	1200l capacity each (60min reheat) - Semi Instantaneous
DHW	A	B	x	x			x		Calorifier - showers only	75	kW	1	900l capacity (60min reheat) - Semi Instantaneous
DHW	A	B	x	x			x		Point of use water heater	4.5	l/m	92	For WHB and cleaners sinks only (range of 4 - 6.8l/s), Electric. 10 bar. Instantaneous.

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Schedules | Ventilation

System	A	B	VRF	HVRF	VRF C + DHN	CHL+ DHN	HP	VRF + DHN	Item/Description	Capacity	Unit	Qty	Comments
Vent	A	B	x	x				x	AHU Integrated HP	5.5	m³/s	2	Integrated heat pump, thermal wheel, electrical frost coil (~40kW), variable speed fan, attenuators
Vent	A	B			x				AHU Integrated HP Cooling Only	5.5	m³/s	2	Integrated heat pump, thermal wheel, wet frost coil (~40kW), variable speed fan, attenuators
Vent	A	B				x	x		AHU Wet Coils	5.5	m³/s	2	Wet coils, thermal wheel, variable speed fan, attenuators
Vent	A	B	x	x				x	MVHR (Elec frost)	0.4	m³/s	1	Allocated to the reception. Electrical heater battery (~3kW). Variable speed fan, attenuators
Vent	A	B			x	x	x		MVHR (wet frost)	0.4	m³/s	1	Allocated to the reception. Wet heater battery (~3kW). Variable speed fan, attenuators
Vent	A	B	x	x	x			x	WC AHU Integrated HP	3.5	m³/s	1	Integrated heat pump, plate heat exchanger, electrical frost coil (~20kW), variable speed fan, attenuators
Vent	A	B				x	x		WC AHU Wet Coils	3.5	m³/s	1	Wet coils, plate heat exchanger, wet frost coil (~20kW), variable speed fan, attenuators
Vent	A	B	x	x	x	x	x	x	VAV	0.55	m³/s	26	To include silencer and case cladding for acoustics
Vent	A	B	x	x	x	x	x	x	Office VCDs	60	l/s	185	Balance flow in office/reception system
Vent	A	B	x	x	x	x	x	x	WC VCDs	25	l/s	120	Balance flow in WC system
Vent	A		x	x	x	x	x	x	Ventilation Distribution system	N/A	N/A	N/A	To include ductwork, diffusers/grilles
Vent		B	x	x	x	x	x	x	Ventilation Distribution system	N/A	N/A	N/A	To include ductwork, diffusers/grilles + 10% for increased duct sizes to reduce Pa drop

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Schedules | Other MEP

System	A	B	VRF	HVRF	VRF C + DHN	CHL+ DHN	HP	VRF + DHN	Item/Description	Capacity	Unit	Qty	Comments
Elec	A		x	x	x	x	x	x	Server Racks	N/A	N/A	23	3 per floor + 5 for the landlord. Standard racks
Elec		B	x	x	x	x	x	x	Server Racks	N/A	N/A	5	Landlord only. Standard racks
Elec	A	B	x	x	x	x	x	x	Transformer (HV)	1	MVA	1	To include LV switchgear, metering, distribution boards, power correction, cabling, power supply systems
Fire	A	B	x	x	x	x	x	x	Sprinkler water tank + sprinkler system	185	m^3	1	Sprinkler pipework to serve all floors, including pump sets, zone valves
Fire	A	B	x	x	x	x	x	x	Smoke fans	4	m^3/s	6	For the building (extract fans only) and car park (make up and extract). To include duty standby
Fire	A	B	x	x	x	x	x	x	Fire dampers (vent)	300x600	mm	30	Fire curtain damper for ventilation system crossing fire lines
Elec	A		x	x	x	x	x	x	PV allowance	450	Wp	200	22% efficient solar PV panels (90kWp/400m2 of roof area PV with ballast mounting system) + Inverters, cabling, meters
Elec		B	x	x	x	x	x	x	PV allowance	450	Wp	400	22% efficient solar PV panels (90kWp/400m2 of roof area PV with ballast mounting system) + Inverters, cabling, meters
PH	A	B	x	x	x	x	x	x	Cold water booster system	1.6	l/s	N/A	Booster and pump set (potable water) ~5 bar. Variable speed + meters, pipework, valve sets. No potable tank assumed.
PH	A	B	x	x	x	x	x	x	CAT 5 Break tank and booster	0.25	l/s	2	Basement bin store and rooftop plant ~5 bar. Variable speed. To include break tanks, pipework and valve sets
Elec	A	B	x	x	x	x	x	x	Lighting	12475	m^2 (GIA)	1	Lettable area (reception + office = 9513m2 NIA). LED high efficiency lighting (80-100lm/W) + boards, metering, cables, controls
PH	A	B	x	x	x	x	x	x	Drainage + rainwater piping	N/A	N/A	N/A	Drainage and rainwater to be contained in the cores
Elec	A	B	x	x	x	x	x	x	IT/Comms/Fire Alarm/BMS/Security	N/A	N/A	N/A	Allowance for these electrical systems should be made for the building

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APPENDIX C
COSTING
COMMERCIAL

Costing | Summary of costs

	A/VRF	A/HVRF	A/VRF C + DHN	A/CHL + DHN	A/HP	A/VRF +DHN	B/VRF	B/HVRF	B/VRF C + DHN	B/CHL + DHN	B/HP	B/VRF +DHN
Capital Cost [A1-A5]	£7,438,950	£7,497,050	£8,267,250	£8,126,100	£7,926,925	£7,404,325	£7,374,150	£7,216,650	£8,167,950	£7,900,800	£7,733,225	£7,330,525
Replacement [B4]	£19,765,517	£20,012,017	£20,823,387	£19,723,171	£20,745,107	£19,343,157	£19,345,037	£18,664,457	£20,572,907	£19,043,891	£19,946,152	£18,922,677
Operational Energy Use [B6]	£10,282,360	£10,986,677	£11,764,502	£12,016,698	£10,427,955	£10,539,942	£6,442,558	£6,849,420	£7,461,312	£7,528,545	£6,503,153	£6,618,865
End of Life stage [C1-C4]	£42,000	£42,000	£53,000	£37,000	£37,000	£48,000	£42,000	£42,000	£53,000	£37,000	£37,000	£48,000
Total MEP	**£37,528,827**	**£38,537,744**	**£40,908,139**	**£39,902,970**	**£39,136,987**	**£37,335,424**	**£33,203,746**	**£32,772,528**	**£36,255,169**	**£34,510,237**	**£34,219,530**	**£32,920,067**

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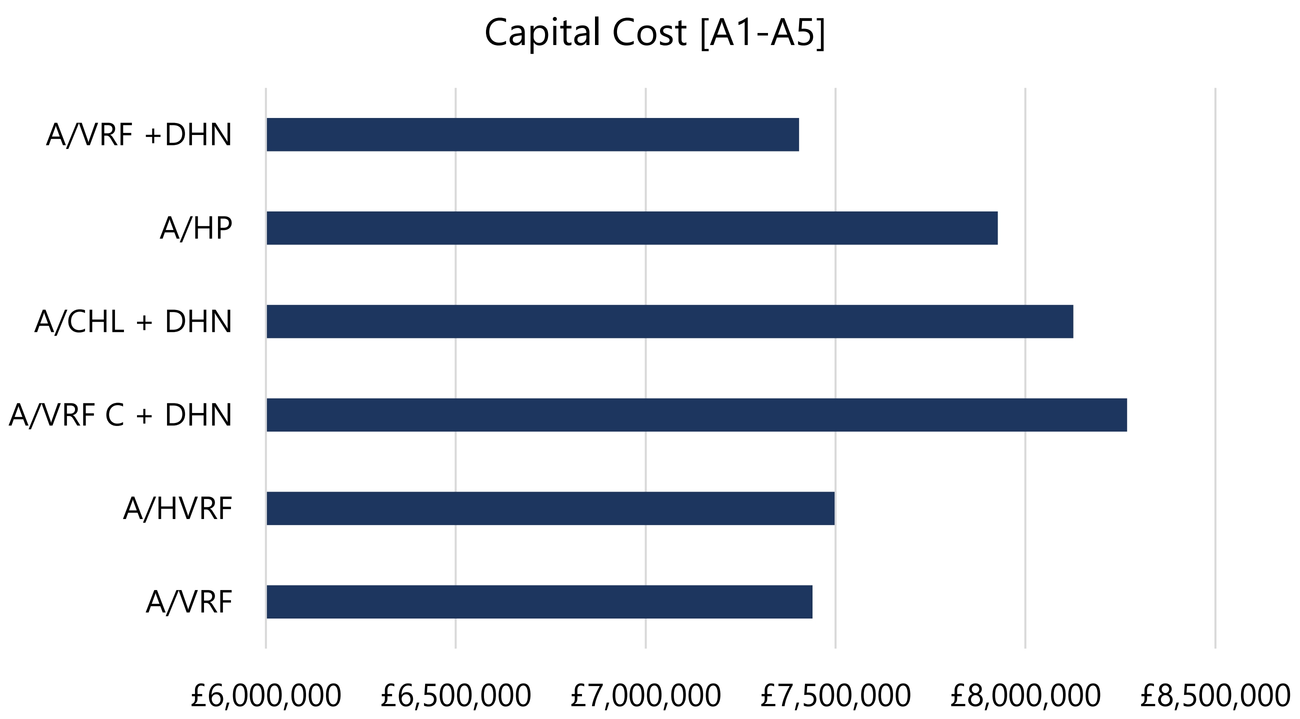
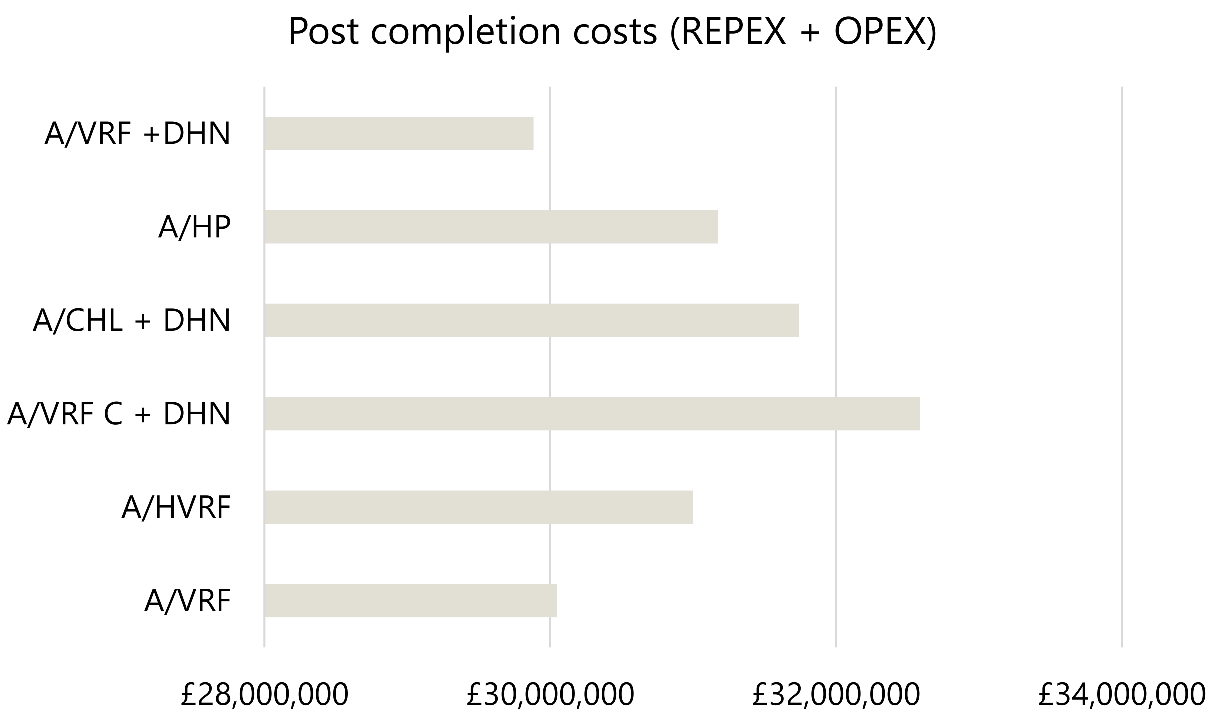
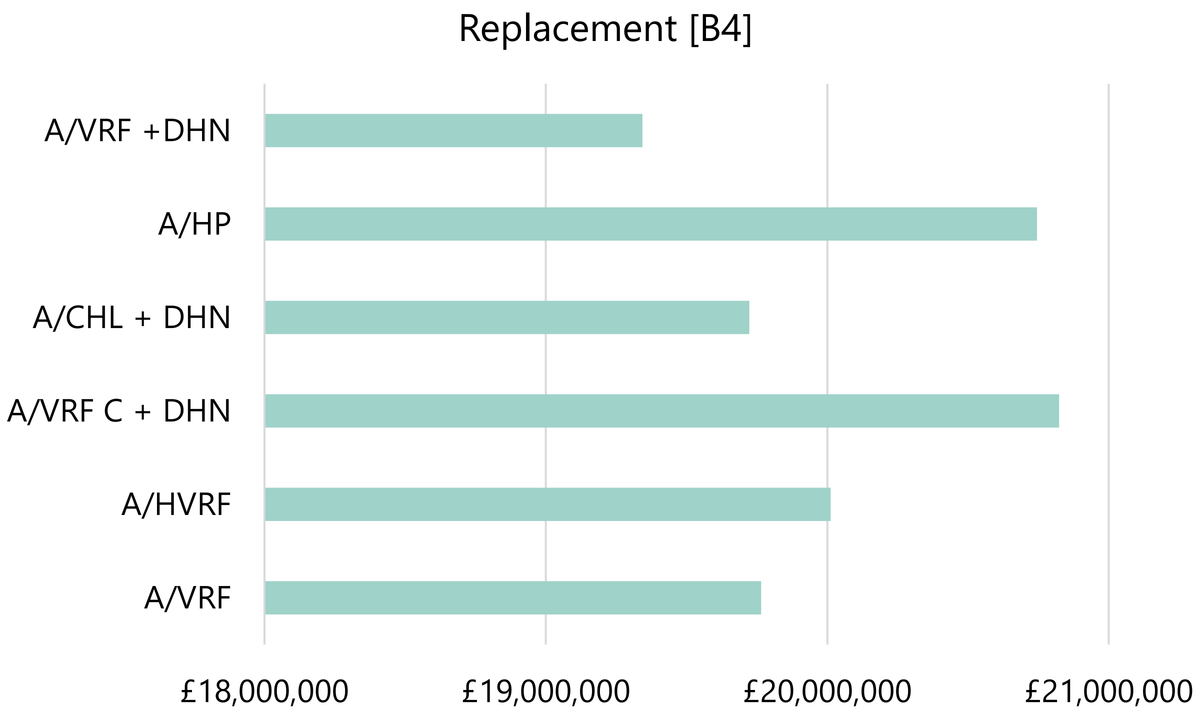
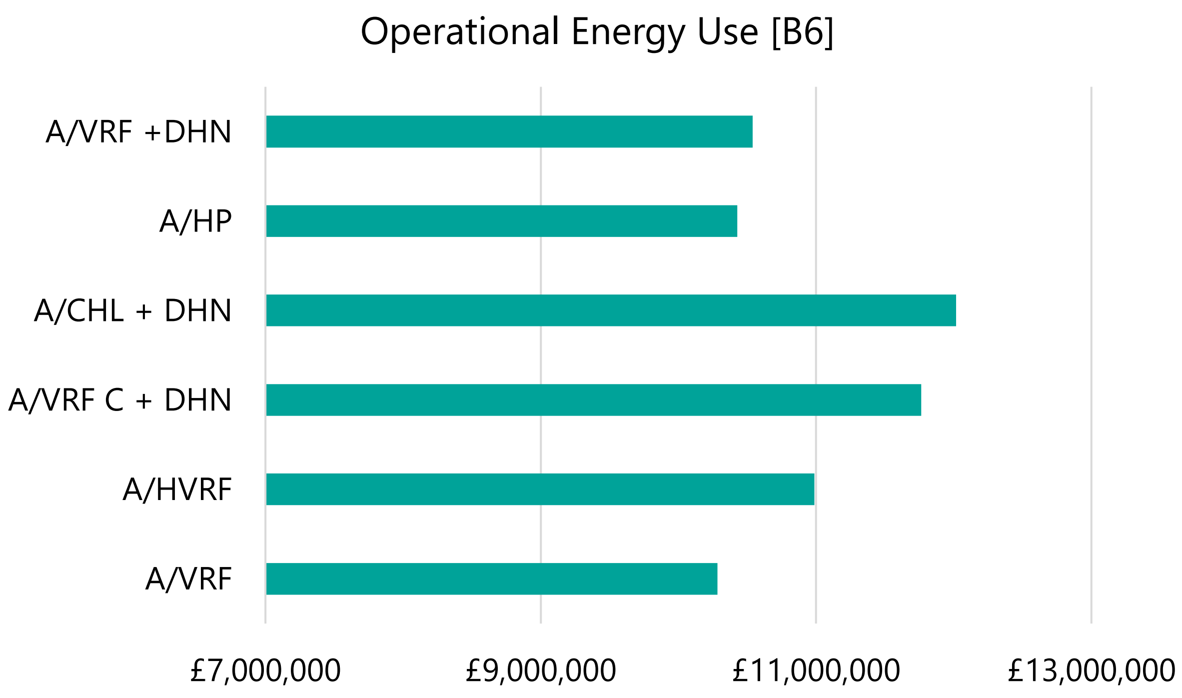
Costing | Current practice comparison



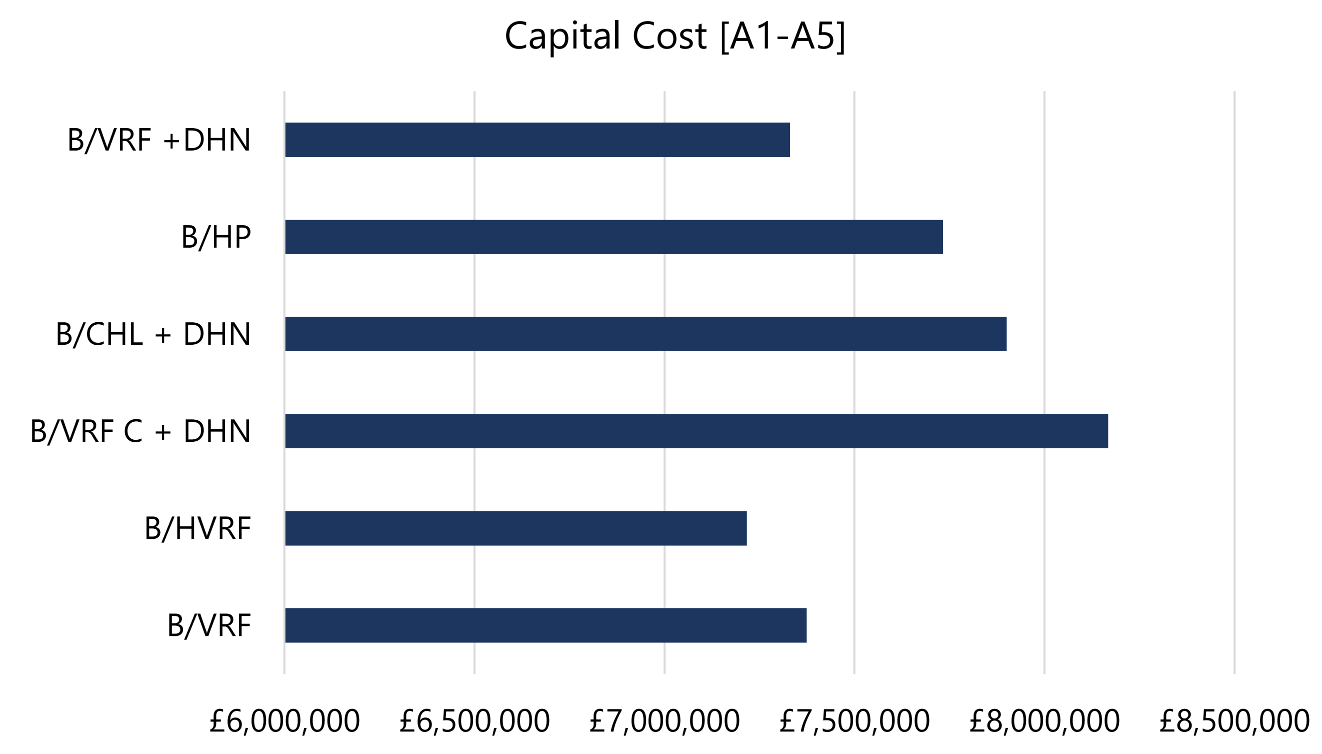


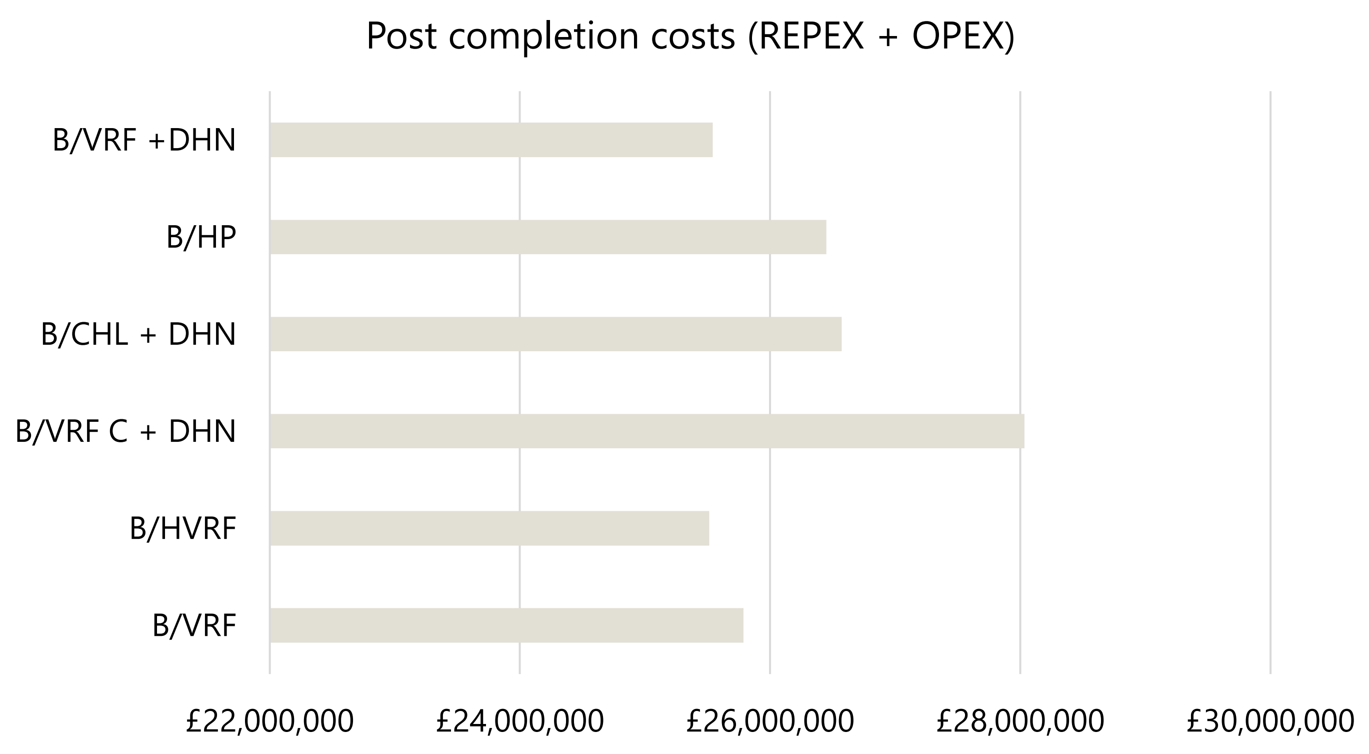


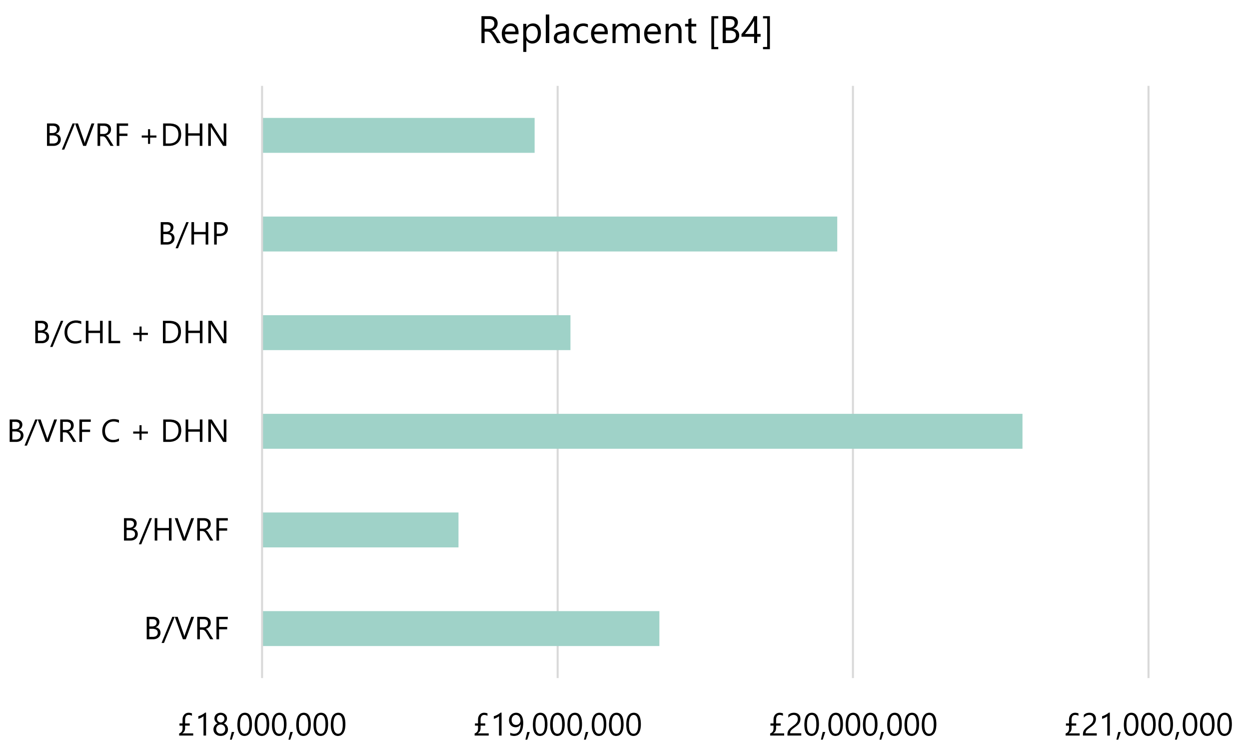


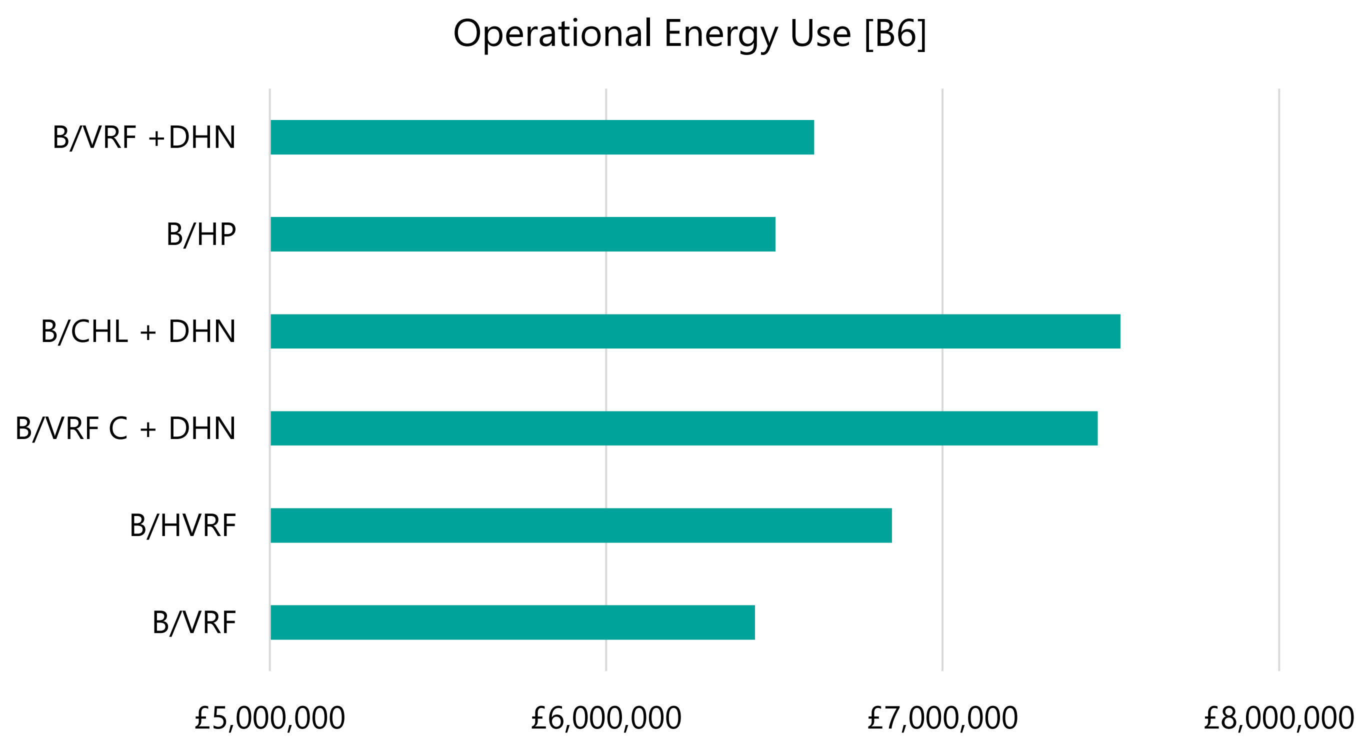
__A__ – Current practice, __B__ – Best practice, __VRF__ - VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

Costing | Best practice comparison









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APPENDIX D

EMBODIED CARBON TABLES

COMMERCIAL

EMBODIED CARBON TABLES – Refrigerant Assumptions

Equipment Type	Description	Refrigerant Type	Refrigerant Weight (kg)	Unit	Total Refrigerant Charge (kg)	annual leakage (%)	end of life recovery (%)	Lifespan (Years)
Integrated HP	AHU with integrated heat pump for heating and cooling	R410a (R32)	23	2	46	3.8	80	15
Integrated HP	AHU with integrated heat pump for cooling only	R410a (R32)	11.2	2	22.4	3.8	80	15
Integrated HP	AHU with integrated heat pump for heating only	R410a (R32)	11.2	2	22.4	3.8	80	15
ASHP	Dedicated ASHP for domestic hot water generation	R407C (R32)	11	2	22	3.8	80	15
WSHP (2nd stage)	2nd stage water source heat pump for domestic hot water generation	R134a (R152a)	7	1	7	3.8	80	15
VRF	VRF system with heat recovery	R32	22.2	22	488.4	5	85	15
HVRF	HVRF system	R32	13.3	11	146.3	5	85	15
HVRF	HVRF system	R32	20.6	6	123.6	5	85	15
Split Unit	Server split cooling system	R32	2.3	8	18.4	5	70	15
DX & CRAC	Server split cooling system	R32	2.3	2	4.6	5	70	15
ASHP	Simultaneous heating and cooling hydronic unit	R410a (R32)	38.4	2	76.8	3.8	80	15
Chiller	Chiller unit	R1234ze	115	2	230	2.5	85	20
Chiller	Chiller unit	R1234ze	125	1	125	2.5	85	20
VRF (cooling only)	VRF heat pump system	R32	14.3	22	314.6	5	85	15
ASHP	Reversible hydronic air source heat pump	R32	50	2	100	3.8	80	15

EMBODIED CARBON TABLES

	System											
	A/VRF	B/VRF	A/HVRF	B/HVRF	A/VRF C + DHN	B/VRF C + DHN	A/CHL + DHN	B/CHL + DHN	A/HP	B/HP	A/VRF + DHN	B/VRF + DHN
5.1.Sanitary installations	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
5.3.Disposal installations	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
5.4.Water installations	17.5	18.0	16.3	16.3	17.3	17.4	18.0	17.7	17.8	18.7	17.0	17.0
5.5.Heat source	21.0	21.0	13.0	8.6	18.0	18.0	10.8	7.2	12.5	10.8	18.5	18.5
5.6.Space heating and Airconditioning	24.3	21.4	29.4	26.5	65.1	60.0	63.1	31.4	61.7	32.7	23.6	20.7
5.7.Ventilation systems	90.2	97.2	93.6	97.1	93.8	97.3	81.0	84.6	81.0	84.5	93.6	97.1
5.8.Electrical installations	108.8	116.4	108.8	116.4	108.8	116.4	111.8	116.9	108.8	116.4	108.8	116.4
Refrigerant leakages	114.4	111.3	48.4	40.8	73.0	69.8	4.4	1.2	34.1	30.9	110.8	107.6
Total kgCO2/m^2 GIA	381.1	390.1	314.3	310.6	380.7	383.8	293.9	263.8	320.7	298.9	377.0	382.2

	Embodied Carbon per Lifecycle Stage (kgCO2/m^2)						
	Scope A1-A3 Materials	Scope A4 Transportation	Scope A5 Construction	Scope Use Phase B1	Scope Replacement B4	Scope End of Life C1-C4	Scope A-C
A/VRF	0.0	5.1	0.9	114.4	170.0	3.5	381.1
A/HVRF	87.9	5.0	0.9	48.4	168.6	3.6	314.3
A/VRF HP + DHN	101.9	5.1	1.4	73.0	195.6	3.7	380.7
A/CHL + DHN	94.9	4.7	1.6	0.0	184.4	3.8	293.9
A/HP	94.8	4.6	1.6	34.1	182.0	3.7	320.7
A/VRF HR + DHN	88.0	5.0	0.9	110.8	168.7	3.6	377.0

__A__ – Current practice, __B__ – Best practice, __VRF__ - VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

APPENDIX E
RESULTS TABLES
COMMERCIAL

EUI, Operational Carbon & Part L2A

EUI (kWh/m^2/year GIA)

	Option	Space Cooling	Space Heating	DHW	Pumps	Lifts	Servers Landlord	Fans (AHU + Terminal)	Onsite generation (PV)	Landlord misc.	Tenant lighting + equipment	Tenant servers	EUI (not including PV)	EUI with DHN correction
Current Practice	A/VRF	4.7	1.8	6.3	0.2	0.4	1.6	6.8	-5.0	9.8	58.2	3.3	93.2	93.2
	A/HVRF	6.6	2.0	6.3	1.9	0.4	1.6	9.0	-5.0	9.8	58.2	3.3	99.2	99.2
	A/VRF C + DHN	3.4	9.5	14.7	0.8	0.4	1.6	6.0	-5.0	9.8	58.2	3.3	107.7	93.4
	A/CHL + DHN	4.9	9.5	14.7	1.4	0.4	1.6	6.0	-5.0	9.8	58.2	3.3	109.8	95.5
	A/HP	6.1	2.1	5.5	1.5	0.4	1.6	6.0	-5.0	9.8	58.2	3.3	94.4	94.4
	A/VRF + DHN	4.7	1.8	14.7	0.3	0.4	1.6	6.8	-5.0	9.8	58.2	3.3	101.7	93.0
Best Practice	B/VRF	3.1	1.0	6.0	0.2	0.4	1.6	4.4	-10.0	8.7	39.7	0.0	65.2	65.2
	B/HVRF	3.5	1.0	6.0	1.9	0.4	1.6	5.7	-10.0	8.7	39.7	0.0	68.7	68.7
	B/VRF C + DHN	1.9	5.9	13.2	0.7	0.4	1.6	4.3	-10.0	8.7	39.7	0.0	76.3	65.1
	B/CHL + DHN	2.6	5.9	13.2	1.0	0.4	1.6	3.8	-10.0	8.7	39.7	0.0	76.9	65.6
	B/HP	3.7	1.3	5.3	1.1	0.4	1.6	3.8	-10.0	8.7	39.7	0.0	65.7	65.7
	B/VRF + DHN	3.1	1.0	13.2	0.3	0.4	1.6	4.4	-10.0	8.7	39.7	0.0	72.5	64.7

Part L2A (kgCO$_2$/m^2 TFA)

	Option	Part L Compliance Baseline	Lean (energy efficiency measures)	Onsite heat pump renewables	Onsite PV renewables	Residual CO$_2$ reductions %
Current Practice	A/VRF	18.7	15.6	15.3	12.5	20%
	A/HVRF	18.7	15.8	15.5	12.7	20%
	A/VRF C + DHN	18.7	16.2	15	12.2	25%
	A/CHL + DHN	23.1	19.3	17.4	14.6	24%
	A/HP	23.1	19.2	18.2	15.4	20%
	A/VRF + DHN	18.7	16.2	14.2	11.4	30%
Best Practice	B/VRF	18.7	13.7	13.6	8.0	42%
	B/HVRF	18.7	13.9	13.7	8.1	42%
	B/VRF C + DHN	18.7	14.1	12.9	7.3	49%
	B/CHL + DHN	23.1	16.7	14.9	9.3	45%
	B/HP	23.1	16.6	15.8	10.2	39%
	B/VRF + DHN	18.7	14.1	12.3	6.7	53%

__A__ – Current practice, __B__ – Best practice, __VRF__ - VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

EUI, Operational Carbon & Part L2A

EUI (kWh/m^2/year GIA)
Cooling, Heating, and DHW only with the DHN Correction Factor Applied (2.44)

	Option	Space Cooling	Space Heating	DHW	Pumps	Fans (Terminal)	Total
Current Practice	A/VRF	4.7	1.8	6.3	0.2	3.4	16.5
	A/HVRF	6.6	2.0	6.3	1.9	5.6	22.5
	A/VRF C + DHN	3.4	3.9	6.0	0.8	2.6	16.7
	A/CHL + DHN	4.9	3.9	6.0	1.4	2.6	18.8
	A/HP	6.1	2.1	5.5	1.5	2.6	17.7
	A/VRF + DHN	4.7	1.8	6.0	0.3	3.4	16.3
Best Practice	B/VRF	3.1	1.0	6.0	0.2	1.2	11.6
	B/HVRF	3.5	1.0	6.0	1.9	2.6	15.1
	B/VRF C + DHN	1.9	2.4	5.4	0.7	1.1	11.5
	B/CHL + DHN	2.6	2.4	5.4	1.0	0.6	12.1
	B/HP	3.7	1.3	5.3	1.1	0.6	12.1
	B/VRF + DHN	3.1	1.0	5.4	0.3	1.2	11.1

Operational Carbon (kgCO_2/m^2 GIA)

	Option	Heat Network	Electricity	Total Operational Carbon
Current Practice	A/VRF	0.0	252.3	252.3
	A/HVRF	0.0	269.5	269.5
	A/VRF C + DHN	28.4	224.4	252.8
	A/CHL + DHN	28.4	230.6	259.0
	A/HP	0.0	255.8	255.8
	A/VRF + DHN	17.2	234.4	251.7
Best Practice	B/VRF	0.0	158.1	158.1
	B/HVRF	0.0	168.0	168.0
	B/VRF C + DHN	22.4	135.3	157.7
	B/CHL + DHN	22.4	136.9	159.3
	B/HP	0.0	159.5	159.5
	B/VRF + DHN	15.5	141.1	156.6

__A__ – Current practice, __B__ – Best practice, __VRF__ - VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

Seasonal Efficiencies

The below lists summarise the inclusions and exclusions from the seasonal efficiency calculation. These were calculated utilising manufacturer performance data and weather data based on the demands computed via simulations.

Domestic hot water includes:

- Central plant generation
- 2nd stage WSHP
- Electrical POU

Hot and chilled water includes:

- AHU and space loads (includes the performance efficiency of the integrated heat pump AHU where applicable)
- Electrical heaters (frost coils and room)

Seasonal efficiencies do not include:

- Pumping
- Fans
- DHN efficiencies (equates to the calculated DHN correction factor of 2.44)
- Detailed server cooling calculations and was assumed to be 3 as this does not impact the options
- Parasitic power

	Option	**Domestic Hot Water**	**Hot Water**	**Chilled Water**
Current Practice	A/VRF	1.5	5.3	8.6
	A/HVRF	1.5	4.6	6.5
	A/VRF C + DHN	*2.4*	*2.4*	11.5
	A/CHL + DHN	*2.4*	*2.4*	7.6
	A/HP	1.7	4.6	6.1
	A/VRF + DHN	*2.4*	5.3	8.6
Best Practice	B/VRF	1.4	5.7	8.1
	B/HVRF	1.4	5.7	7.2
	B/VRF C + DHN	*2.4*	*2.4*	12.9
	B/CHL + DHN	*2.4*	*2.4*	8.4
	B/HP	1.6	4.4	5.8
	B/VRF + DHN	*2.4*	5.7	8.1

*in grey is the DHN correction factor of 2.44 as outlined on page 34

__A__ – Current practice, __B__ – Best practice, __VRF__ - VRF Heating and Cooling with a dedicated DHW ASHP, __HVRF__ – Hybrid VRF with a dedicated DHW ASHP, __VRF C + DHN__ – Cooling only VRF with DHN for heating, __CHL + DHN__ – chiller with DHN for heating, __HP__ – hydronic heat pump only system with heat recovery unit, __VRF + DHN__ – VRF Heating and Cooling and DHN for DHW only

Whole Life Carbon and Cost

	Option	Non-MEP	Other MEP	Heating & Cooling	Refrigerant	Operational	MEP Cost	Non-MEP Cost
	Units	$kgCO_2/m^2$ GIA					£/m² GIA	
Current Practice	A/VRF	*719.9*	221.2	45.3	114.4	252.3	£3,008	*£3,813*
	A/HVRF	*719.9*	223.4	42.3	48.4	269.5	£3,089	*£3,813*
	A/VRF C + DHN	*719.9*	224.5	83.1	72.9	252.8	£3,279	*£3,813*
	A/CHL + DHN	*719.9*	215.5	73.8	4.4	259.0	£3,198	*£3,813*
	A/HP	*719.9*	212.3	74.2	34.1	255.8	£3,137	*£3,813*
	A/VRF + DHN	*719.9*	224.1	42.0	110.7	251.7	£2,992	*£3,813*
Best Practice	B/VRF	*719.9*	236.2	42.4	111.2	158.1	£2,661	*£3,813*
	B/HVRF	*719.9*	244.7	24.9	40.8	168.0	£2,627	*£3,813*
	B/VRF C + DHN	*719.9*	235.8	78.0	69.8	157.7	£2,906	*£3,813*
	B/CHL + DHN	*719.9*	223.9	38.6	1.2	159.3	£2,766	*£3,813*
	B/HP	*719.9*	224.3	43.5	30.9	159.5	£2,743	*£3,813*
	B/VRF + DHN	*719.9*	235.2	39.2	107.6	156.6	£2,638	*£3,813*

*in purple are the non-MEP elements provided for context which were not part of the scope of the study

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APPENDIX F

OPERATIONAL ENERGY MODELLING ASSUMPTIONS

RESIDENTIAL

Assumptions | Occupancy and Operational Profiles

Household composition and use profiles were developed based on a study published in 2017 by V. Aragon et al. of the University of Southampton and BEIS entitled *Developing English domestic occupancy profiles*[1]. This source is considered appropriate as the research has been undertaken with the intent of providing more clarity on dwelling occupancy specifically for use in analysis of energy demand and thermal comfort analysis.

Household composition

Figure 6 of the *Developing English domestic occupancy profiles* paper sets out the findings of the Time Use Survey 2014-15 and the English Housing Survey 2014-15 and defines 11no. discrete household composition groups. For the purposes of this study these have been condensed into 3no. categories with similar occupancy profiles:

1. Working, no dependents
2. Retired, no dependents
3. Working family

Occupancy type distribution

The 3no. household categories identified have been applied to the existing dwelling mix in the building as shown in the table to the right (upper). The assumed peak occupancy density for each household category is also provided.

The table to the right (lower) shows how the mix of household assumed for this study compares to the national average extrapolated from the English Housing Survey (2014-15), as reported in the *Developing English domestic occupancy profiles* paper. The distribution has been adapted from the national average to increase the number of *Working, no dependents* households. This adaptation was based on analysis of typical demographics for the wards where new build flats would most likely be built provided by Bristol City Council.

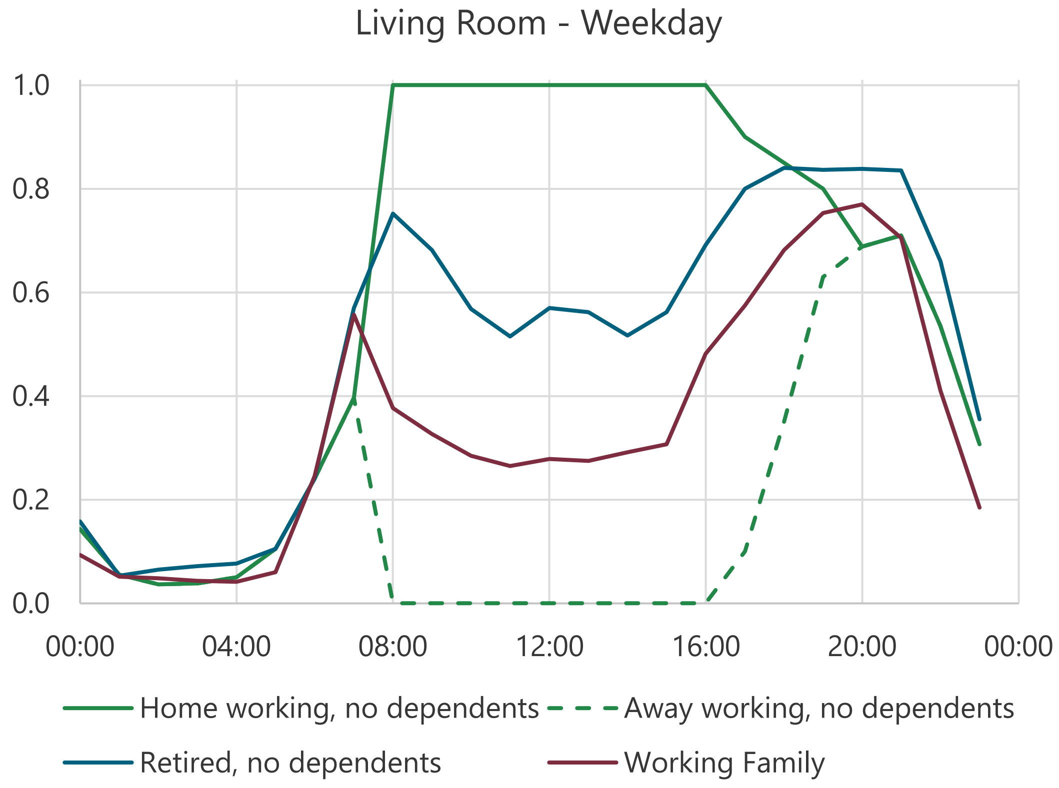
Operation profiles

The *Developing English domestic occupancy profiles* paper produced a set of time-series data for occupancy and activity type. These profiles have been adapted for use within this study with simplifications made such as;

- Profiles for each household composition group within the same category have been averaged to provide a single profile per category
- Time-step reduced to hourly

The line graph to the right provides a visualisation of the resulting profiles with each category shown in colour; *Working, no dependents* in green, *Retired, no dependents* in blue and *Working family* in red. To provide some diversity in the use pattern for the largest category, the *Working, no dependents* profile has been additionally split into two variants, one shown as a dashed line, that average to match the original. One variant represents no occupancy during working hours to model the scenario where occupants are working away from home. The other represents full occupancy during working hours to capture scenarios such as working from home or annual leave.

These profiles are probabilistic so represent the likelihood that occupants within a household will be involved in a particular activity. The heat gains associated with occupancy, lighting and equipment have been modelled to follow these profiles exactly. However, set-point temperatures have been applied when the occupancy probability exceeds 40%. In this way, unique heating schedules are created which mimic how individual apartment occupiers might schedule their systems depending on their requirements.



Architectural dwelling type	No. dwellings	Occupancy type	Occupancy density
1B2P	14	Working, no dependents	50% at 2 adults. 50% at 1 adult
	1	Retired, no dependents	1 adult
2B4P	15	Working, no dependents	50% at 3 adults. 50% at 2 adult
	2	Retired, no dependents	2 adults
	7	Working family	2 adults, 1 child
TOTAL	39		

	% split based on English Housing Survey (2014-15)	% split to be assumed in this study
Working, no dependents	39%	74%
Retired, no dependents	33%	8%
Working family	29%	18%

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[1] https://www.researchgate.net/publication/321344489_Developing_English_domestic_occupancy_profiles

Assumptions | Basis of Design

The basis of design was agreed with Bristol City Council for both the base case and the best practice scenario. For the base case this was based on the original building design which is compliant with BSC14 in 2011 Bristol Core Strategy and the best practice design was defined following LETI, AECB and Passivhaus guidelines.

Building fabric

The building fabric design performance, as typically specified for Part L1A compliance calculations, are shown for both scenarios in the table to the right (upper).

However, these values represent a design target rather than the reality of the building performance once constructed and occupied. To align with other evidence base work referenced by BCC, the annual dynamic thermal model heating demand was calibrated against the results in the Cornwall Council Climate Emergency Technical Evidence Base (Etude, 2021) for an equivalent building typology. The Etude study was based on PHPP modelling which is an empirically validated tool and as such contains adjustment factors that increase the heat demand prediction to account for imperfect construction and operation. To align the dynamic simulation model with the PHPP figures, the following adjustments have been made to the values applied in the dynamic simulation model.

- **Thermal bridging:** In lieu of a method to account for thermal bridging explicitly within the dynamic simulation model, an uplift has been applied to the external wall U-value within the model for each scenario
- **Infiltration:** To account for external air ingress due to imperfect façade connections and the opening of windows and doors by occupants, infiltration rates have been increased beyond standard design values

Internal gains

The heat gain inside the dwellings from occupants, lighting and appliances is based on design assumptions from CIBSE Guide A, PHPP and the Cornwall Council Climate Emergency Technical Evidence Base (Etude, 2021), with reductions applied to avoid the build up of gains from suppressing the space heating demand and peak load in the simulation. The reductions applied have been calibrated against PHPP benchmark values for annual heating demand. Internal gains are set out in the table to the right (lower).

The Cornwall Council Climate Emergency Technical Evidence Base (Etude, 2021) suggests that equipment load tends to be influenced more by occupancy density and use type than by dwelling floor area, on the basis that a similar number of appliances tend to be included in a dwelling regardless of its size.

On this basis the equipment gain has been applied to each dwelling in proportion to the number of hours occupied over the year. This results in a different equipment gain intensity (W/m^2) applied across almost all dwellings.

Parameter		Units	Base case	Best practice
Wall u-value		W/m².K	0.18	0.15
Roof u-value		W/m².K	0.15	0.10
Floor u-value		W/m².K	0.15	0.10
Window u-value (incl frame)		W/m².K	1.40	1.00
Door u-value		W/m².K	1.40	1.00
Glazing g-value			0.40	0.50
Infiltration	Air tightness target	m³/hr/m² @ 50Pa	3.0	<1.0
	In-use air exchange	ACH	0.40	0.35
Thermal bridging	Compliance input	W/m²K	Default, Y=0.15	Calculated, Y<0.04
	In-use heating demand	kWh/m².yr	5.0	3.0
	Adjusted wall u-value	W/m².K	0.48	0.31
Glazing percentage of façade area			28%	20%

Parameter	Units	Base case	Best practice	Reference
Sensible gain per person (& latent gain per person) – Living room	W/person	75 (55)		CIBSE Guide A
Sensible gain per person (& latent gain per person) – Bedroom	W/person	40 (30)		
Lighting power density	W/m²	2.5		
Max equipment power density - Living room	W/m²	14.0	9.6	
Max equipment power density - bedroom	W/m²	5.0	4.5	

Assumptions | Basis of Design

Building systems

Heating and cooling

Space conditioning set points have been applied in accordance with CIBSE Guide A and SAP guidelines and assumptions, as shown in the table to the right (upper). Space conditioning equipment operating schedules depend on the occupancy profile. Heating or cooling will only switch on in the model if the probability a space is occupied exceeds 40% to simulate the high level of control available to occupants using smart hubs and multiple room thermostats.

Ventilation rates and heat recovery

Fresh air provided by the MVHR systems has been modelled using the minimum ventilation rates stipulated in Part F 2013 and an assumed heat recovery efficiency as set out in table to the right (upper). To capture the effect of the heat recovery in the simulation, the supply air temperature was calculated for each timestep based on the temperature differential between the internal and external air.

Domestic hot water

Annual hot water demand has been calculated in accordance with the findings of the report Measurement of Domestic Hot Water Consumption in Dwellings (Energy Saving Trust, 2008). The base hot water usage for each was calculated using the equation:

$$Vol = 36 + 25N$$

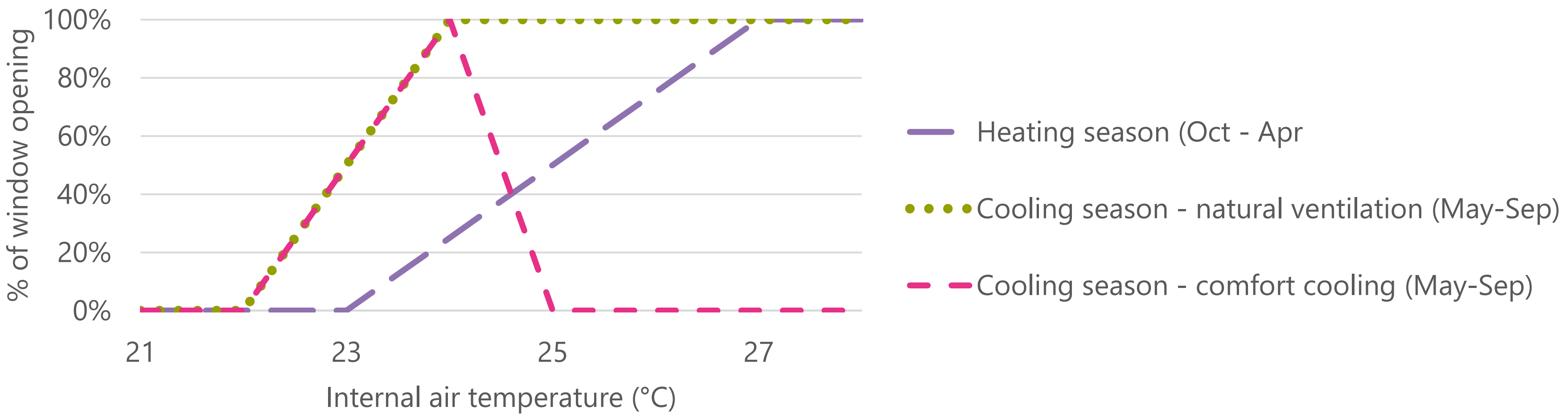
Where *Vol* is the litres of hot water per day and *N* is the number of occupants. Daily demand was then extrapolated across the year and adapted to reflect the occupancy use profile, based on the assumption that more hot water is used when occupants spend more time in the dwelling. This tailored annual demand was then translated into hourly load profiles, one for weekdays and another for weekends, for each occupancy and use type. The average daily hot water load profile for the entire building, aligns closely with the form of the profile from the recorded hot water consumption data as reported by the Energy Saving Trust.

Window opening controls

The archetype building was designed to be naturally ventilated and overheating risk was successfully mitigated in line with CIBSE TM59 assessment methodology. The proposed window opening strategy, as set out in the table (lower) and line graph below, has been applied to the dynamic thermal model to provide passive cooling and fresh air during warmer periods of the year. Although the vision glazing area is reduced between the base case and best practice scenario, the opening free areas applied are the same on the assumption that areas of fixed pane vision glazing would be removed instead of openings.

Parameter	Units	Value	Reference
Heating set-point temperature (& set-back) - Living room	°C	21 (16)	SAP 2021
Heating set-point temperature (& set-back) - Bedroom	°C	18 (16)	CIBSE Guide A
Cooling set-point temperature (& set-back)	°C	25 (30)	CIBSE Guide A
Ventilation supply air rate - 1 bed flat	l/s	13	Part F 2013
Ventilation supply air rate - 2 bed flat	l/s	17	Part F 2013
Ventilation heat recovery effectiveness	%	90	

Room air temperature (°C) at which windows...	...begin to open	...are fully open	...are closed again
Heating season (Oct - Apr	23	27	-
Cooling season - natural ventilation (May-Sep)	22	24	-
Cooling season - comfort cooling (May-Sep)	22	23.5	25



BURO HAPPOLD

APPENDIX G

EQUIPMENT SCHEDULES

RESIDENTIAL

Equipment Schedule

Building level	System	DHN	Amb HP	DHN +DX	HTHP	Amb HP+C	Item/Description	Capacity (Current practice)	Capacity (Best practice)	Unit	Quantity: rationale	Quantity: block total
Central	Public health	x	x	x	x	x	Domestic Cold Water Storage Tank	5	5	m^3	1no. per block	1
Central	Public health	x	x	x	x	x	Residential Sprinkler Tank	9	9	m^3	1no. per block	1
Central	Elec	x	x	x	x	x	Electrical infrastructure	500	500	kVA	1no. per block	1
Central	Elec	x	x	x	x	x	PV allowance	35	35	kWp	1no. per block	1
Central	Fire	x	x	x	x	x	Corridor smoke extract system	-	-		1no. per block	1
Central	Public health	x	x	x	x	x	Diesel backup generator	71	71	kVA	1no. per block	1
Central	LTHW1	x		x			Plate heat exchanger (DHN incomer)	205.5	189.8	kW	1no. per block	1
Central	LTHW1	x		x			LTHW ancillaries: pumpsets, pipework, meters, controls, valves, expansion vessels etc…	-	-		1no. set per block	1
Central	LTHW1				x		ASHP (heating only)	205.5	189.8	kW	1no. per block	1
Central	LTHW1				x		LTHW ancillaries: pumpsets, pipework, meters, controls, valves, expansion vessels etc…	-	-		1no. set per block	1
Central	LTHW1		x				ASHP (heating only)	335.6	320.0	kW	1no. per block	1
Central	LTHW1					x	ASHP (heating and cooling)	335.6	320.0	kW	1no. per block	1
Central	LTHW1		x			x	Ambient loop ancillaries: pumpsets, pipework, meters, controls, valves, expansion vessels etc…	-	-		1no. set per block	1

__A__ – Current practice, __B__ – Best practice, __DHN__ - District heating connection, no cooling, __AmbHP__ – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, __DHN + DX__ - District heating connection for heat, local split system cooling unit, __HTHP__ – High temperature central air source heat pump, no cooling, __AmbHP + C__ - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

Equipment Schedule

Building level	System	DHN	Amb HP	DHN +DX	HTHP	Amb HP+C	Item/Description	Capacity (Current practice)	Capacity (Best practice)	Unit	Quantity: rationale	Quantity: block total
Dwelling	LTHW2/ DHW	x		x	x		Heat interface unit	45	45	kW	1no. per dwelling	39
Dwelling	LTHW2	x	x	x	x		1 Bed Apt - Radiators - bedrooms	0.47	0.26	kW	Number of bedrooms	15
Dwelling	LTHW2	x	x	x	x		1 Bed Apt - Radiators - KLDs	0.95	0.75	kW	Number of KLDs	15
Dwelling	LTHW2	x	x	x	x		2 Bed Apt - Radiators - bedrooms	0.63	0.34	kW	Number of bedrooms	48
Dwelling	LTHW2	x	x	x	x		2 Bed Apt - Radiators - KLDs	1.13	0.89	kW	Number of KLDs	24
Dwelling	LTHW2	x	x	x	x	x	Dwelling LTHW ancillaries: pumps, pipework, meters, controls, valves etc...	-	-		1no. set per dwelling	39
Dwelling	LTHW2					x	Dwelling CHW ancillaries: pumps, pipework, meters, controls, valves etc...	-	-		1no. set per dwelling	39
Dwelling	LTHW2		x				1 Bed Apt - WSHP (from ambient loop, heating only)	4.00	4.00	kW	1no. per dwelling	15
Dwelling	LTHW2		x				2 Bed Apt - WSHP (from ambient loop, heating only)	4.00	4.00	kW	1no. per dwelling	24
Dwelling	LTHW2/ CHW					x	1 Bed Apt - Fan coil units (heating and cooling) - bedrooms	0.98	0.91	kW	Number of bedrooms	15
Dwelling	LTHW2/ CHW					x	1 Bed Apt - Fan coil units (heating and cooling) - KLDs	1.93	1.71	kW	Number of living rooms	15
Dwelling	LTHW2/ CHW					x	2 Bed Apt - Fan coil units (heating and cooling) - bedrooms	0.92	0.84	kW	Number of bedrooms	48
Dwelling	LTHW2/ CHW					x	2 Bed Apt - Fan coil units (heating and cooling) - KLDs	2.67	2.42	kW	Number of living rooms	24
Dwelling	LTHW2					x	1 Bed Apt - WSHP (from ambient loop, heating only)	4.00	4.00	kW	1no. per dwelling	39
Dwelling	LTHW2					x	2 Bed Apt - WSHP (from ambient loop, heating only)	4.00	4.00	kW	1no. per dwelling	39
Dwelling	DHW		x			x	Hot water cylinder	172	172	L	1no. per dwelling	15

__A__ – Current practice, __B__ – Best practice, __DHN__ - District heating connection, no cooling, __AmbHP__ – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, __DHN + DX__ - District heating connection for heat, local split system cooling unit, __HTHP__ – High temperature central air source heat pump, no cooling, __AmbHP + C__ - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

Equipment Schedule

Building level	System	DHN	Amb HP	DHN +DX	HTHP	Amb HP+C	Item/Description	Capacity (Current practice)	Capacity (Best practice)	Unit	Quantity: rationale	Quantity: block total
Dwelling	Vent	x	x	x	x	x	1 Bed Apt - MVHR + ductwork, air supply/extract terminals & louvres	29	29	l/s	1no. per dwelling	15
Dwelling	Vent	x	x	x	x	x	2 Bed Apt - MVHR + ductwork, air supply/extract terminals & louvres	37	37	l/s	1no. per dwelling	24
Dwelling	DX			x			1 Bed Apt - Split cooling outdoor unit	2.90	2.62	kW	1no. per dwelling	39
Dwelling	DX			x			2 Bed Apt - Split cooling outdoor unit	4.43	4.04	kW	1no. per dwelling	39
Dwelling	DX			x			1 Bed Apt - Split cooling indoor units - bedrooms	0.98	0.91	kW	Number of bedrooms	15
Dwelling	DX			x			1 Bed Apt - Split cooling indoor units - KLDs	1.93	1.71	kW	Number of living rooms	15
Dwelling	DX			x			2 Bed Apt - Split cooling indoor units - bedrooms	0.92	0.84	kW	Number of bedrooms	48
Dwelling	DX			x			2 Bed Apt - Split cooling indoor units - bedrooms	2.67	2.42	kW	Number of living rooms	24
Dwelling	DX			x			Dwelling DX ancillaries: refrigerant, pipework, leakage detection, meters, controls, valves etc…	n/a	n/a	kW	1no. set per dwelling	39

__A__ – Current practice, __B__ – Best practice, __DHN__ - District heating connection, no cooling, __AmbHP__ – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, __DHN + DX__ - District heating connection for heat, local split system cooling unit, __HTHP__ – High temperature central air source heat pump, no cooling, __AmbHP + C__ - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

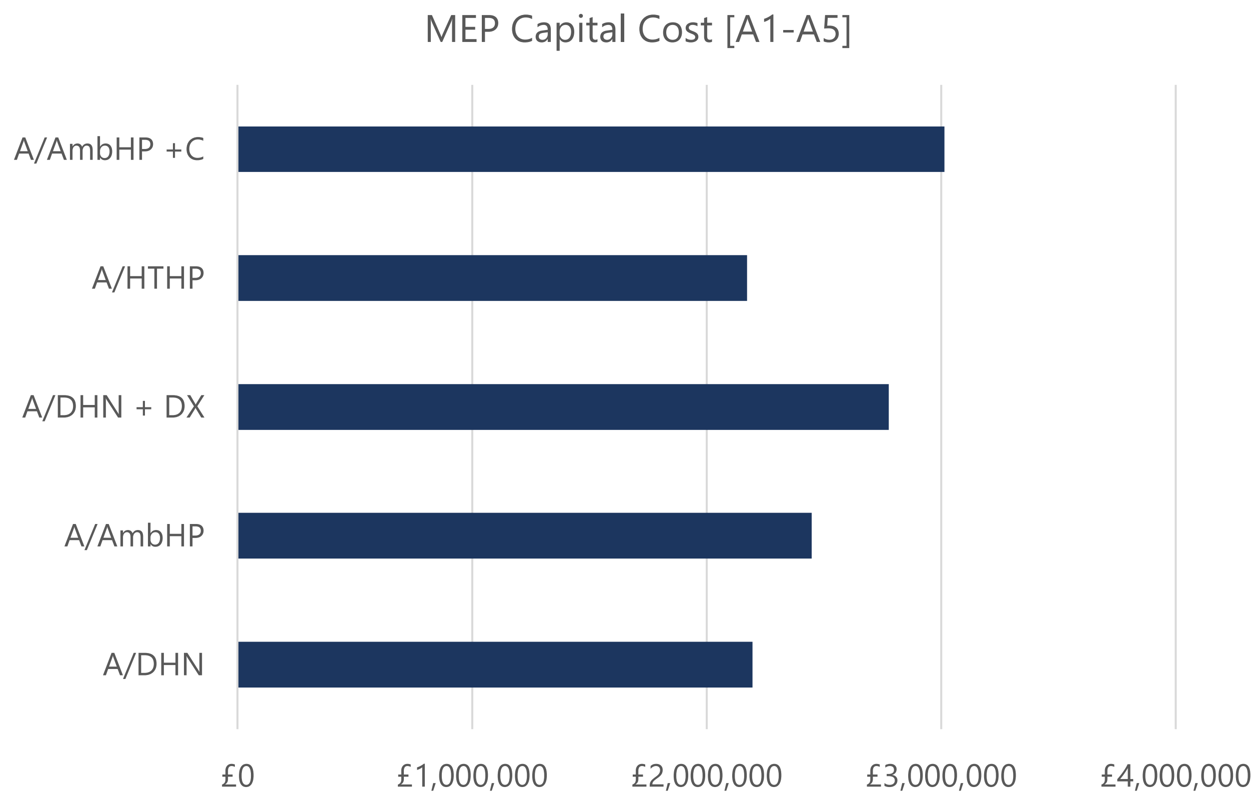
APPENDIX H
COSTING
RESIDENTIAL

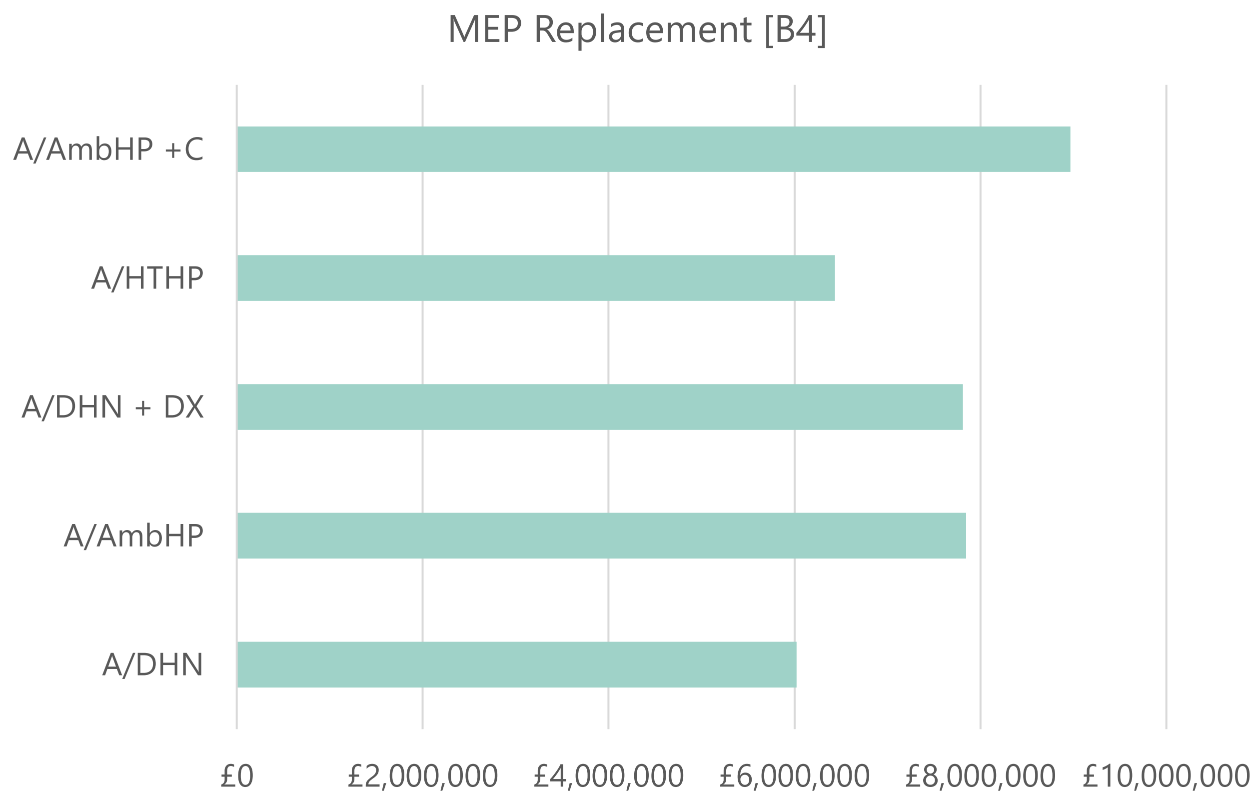
Costing | Summary of MEP costs

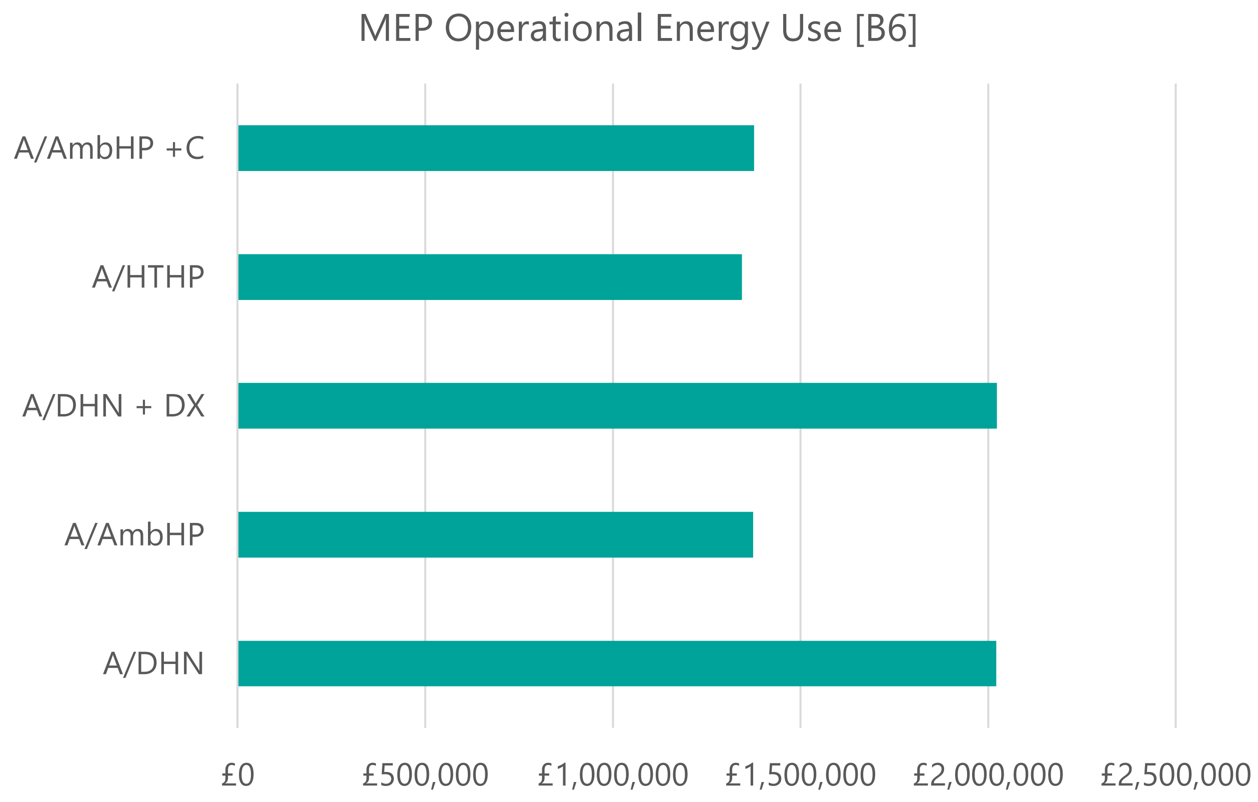
	A/DHN	A/AmbHP	A/DHN + DX	A/HTHP	A/AmbHP +C	B/DHN	B/AmbHP	B/DHN + DX	B/HTHP	B/AmbHP +C
Capital Cost [A1-A5]	£2,196,060	£2,448,270	£2,776,774	£2,171,725	£3,014,075	£2,172,654	£2,385,405	£2,719,468	£2,150,768	£2,949,018
Replacement [B4]	£6,023,022	£7,844,738	£7,813,445	£6,433,982	£8,968,153	£5,967,879	£7,585,543	£7,640,330	£6,355,835	£8,711,592
Operational Energy Use [B6]	£2,021,610	£1,373,662	£2,023,480	£1,343,739	£1,376,467	£1,733,862	£1,126,796	£1,735,733	£1,092,197	£1,130,536
End of Life stage [C1-C4]	£30,000	£35,000	£38,000	£30,000	£35,000	£30,000	£35,000	£38,000	£30,000	£35,000
Total	**£10,270,692**	**£11,701,699**	**£12,651,446**	**£9,979,446**	**£13,393,695**	**£9,904,395**	**£11,132,743**	**£12,133,530**	**£9,628,799**	**£12,826,145**

__A__ – Current practice, __B__ – Best practice, __DHN__ - District heating connection, no cooling, __AmbHP__ – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, __DHN + DX__ - District heating connection for heat, local split system cooling unit, __HTHP__ – High temperature central air source heat pump, no cooling, __AmbHP + C__ - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

MEP Costing | Current practice comparison

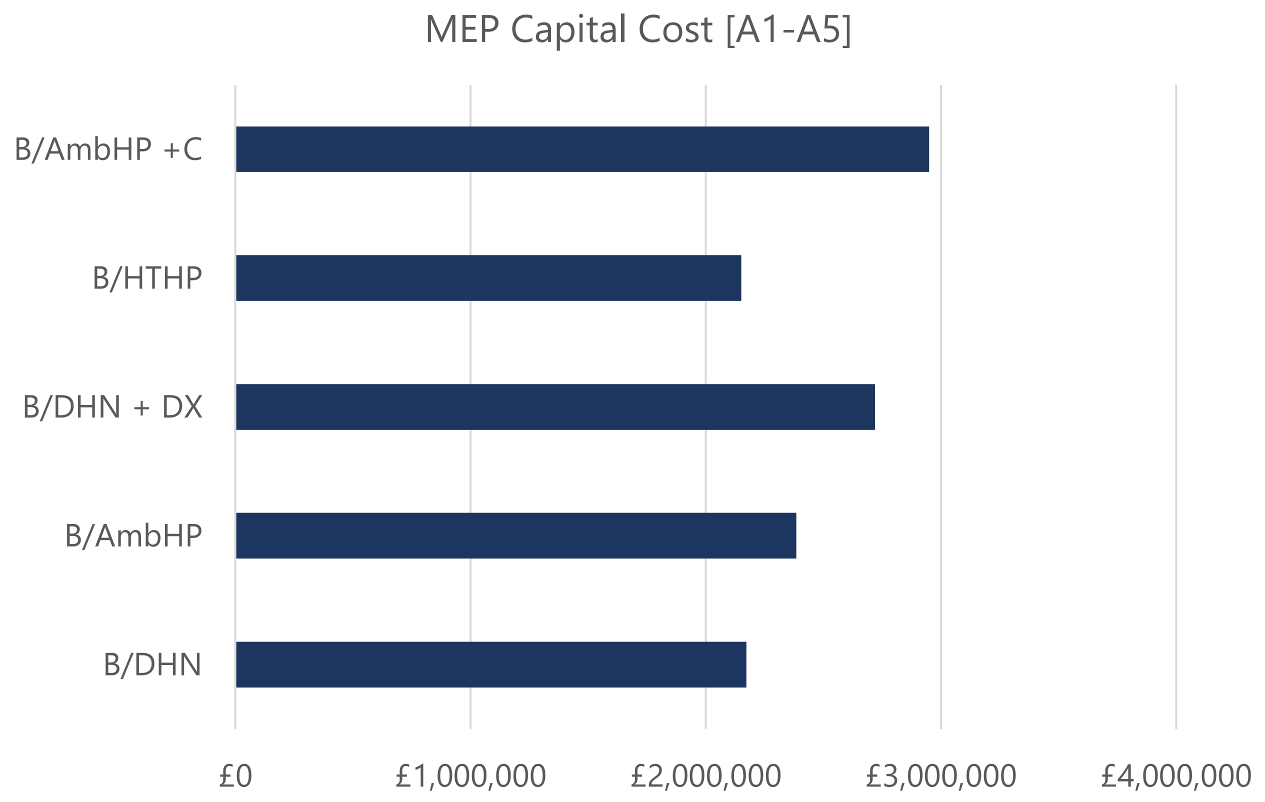


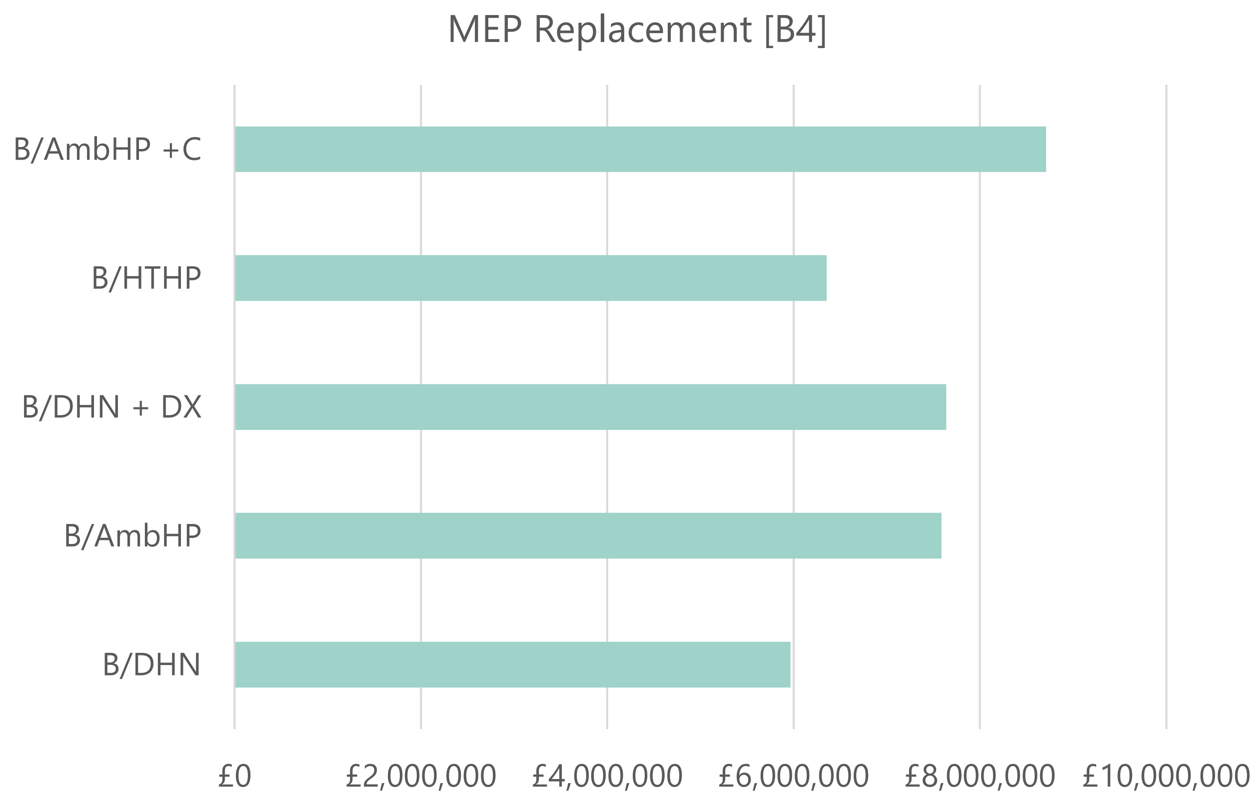


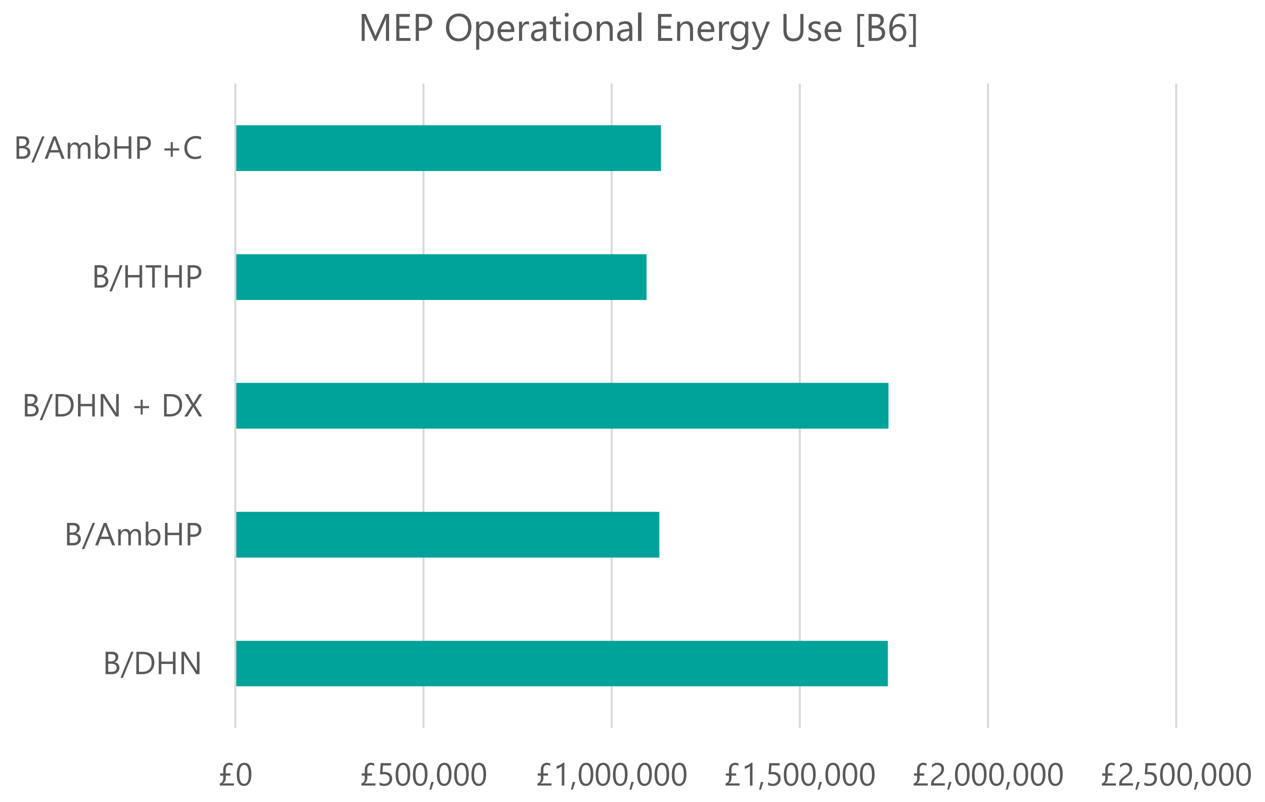


A *– Current practice,* ***B*** *– Best practice,* ***DHN*** *- District heating connection, no cooling,* ***AmbHP*** *– Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling,* ***DHN + DX*** *- District heating connection for heat, local split system cooling unit,* ***HTHP*** *– High temperature central air source heat pump, no cooling,* ***AmbHP + C*** *- Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.*

MEP Costing | Best practice comparison







__A__ – Current practice, __B__ – Best practice, __DHN__ - District heating connection, no cooling, __AmbHP__ – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, __DHN + DX__ - District heating connection for heat, local split system cooling unit, __HTHP__ – High temperature central air source heat pump, no cooling, __AmbHP + C__ - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

APPENDIX I
RESULTS TABLES
RESIDENTIAL

Part L1A 2013

Scenario	Fabric Energy Efficiency			Baseline (gas boiler)		
	DFEE	TFEE	DFEE|TFEE % improvement	DER	TER	DER|TER % improvement
Current practice	35.7	36.6	2.6%	14.5	15.4	5.9%
Best practice	22.5	35.8	37.1%	11.1	15.4	27.9%

Option		Gas baseline ($kgCO_2/m^2$)	Part L1A Notional ($kgCO_2/m^2$)	Low-carbon heating ($kgCO_2/m^2$)	Low carbon heating + PV ($kgCO_2/m^2$)	Carbon reduction from PV ($kgCO_2/m^2$	Carbon reduction from PV as % of low-carbon heating scenario
Current practice	A/DHN	15.4	15.4	7.5	2.7	4.8	64.4%
	A/AmbHP	15.4	22.4	9.5	4.7	4.8	50.9%
	A/DHN+DX	15.4	15.4	7.8	3.0	4.8	62.1%
	A/HTHP	15.4	22.4	12.8	7.9	4.8	37.9%
	A/AmbHP+C	15.4	22.4	9.8	4.9	4.8	49.5%
Best practice	B/DHN	15.4	15.4	6.3	1.4	4.8	77.2%
	B/AmbHP	15.4	22.3	7.7	2.8	4.8	63.3%
	B/DHN+DX	15.4	15.4	6.7	1.8	4.8	72.7%
	B/HTHP	15.4	22.3	9.9	5.1	4.8	48.9%
	B/AmbHP+C	15.4	22.3	8.0	3.2	4.8	60.2%

__A__ – Current practice, __B__ – Best practice, __DHN__ - District heating connection, no cooling, __AmbHP__ – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, __DHN + DX__ - District heating connection for heat, local split system cooling unit, __HTHP__ – High temperature central air source heat pump, no cooling, __AmbHP + C__ - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

Dwelling Energy Demand

Option		Space heating demand (kWh/m²)	Domestic hot water demand (kWh/m²)	Space cooling demand (kWh/m²)	Appliances, lighting, fans & pumps energy (kWh/m²)	Dwelling total (kWh/m²)
Current practice	Lowest	15.8	12.1	0.0	14.7	45.6
	Average	24.3	18.3	0.4	23.2	66.2
	Highest	34.8	30.6	1.1	44.0	98.0
Best practice	Lowest	9.3	12.1	0.0	10.9	35.6
	Average	15.6	18.3	0.4	17.1	51.4
	Highest	25.8	30.6	1.1	32.0	78.7

__A__ – Current practice, __B__ – Best practice, __DHN__ - District heating connection, no cooling, __AmbHP__ – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, __DHN + DX__ - District heating connection for heat, local split system cooling unit, __HTHP__ – High temperature central air source heat pump, no cooling, __AmbHP + C__ - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

Energy Use Intensity

Option		**Space heating energy (kWh/m^2)**	**Domestic hot water energy (kWh/m^2)**	**Space cooling energy (kWh/m^2)**	**Heat network secondary losses energy (kWh/m^2)**	**Heat network pumping energy (kWh/m^2)**	**Appliances, lighting, fans & pumps energy (kWh/m^2)**	**On-site energy generation (kWh/m^2)**	**EUI (excluding PV) (kWh/m^2)**	**EUI with DHN correction (excluding PV) (kWh/m^2)**
Current practice	A/DHN	19.6	14.8	0.0	10.4	0.4	18.7	-8.1	63.9	37.5
	A/AmbHP	7.4	5.8	0.0	0.4	4.3	18.7	-8.1	36.7	36.7
	A/DHN+DX	19.6	14.8	0.1	10.4	0.4	18.7	-8.1	64.0	37.5
	A/HTHP	7.5	5.4	0.0	3.5	0.6	18.7	-8.1	35.8	35.8
	A/AmbHP+C	7.4	5.7	0.2	0.4	4.3	18.7	-8.1	36.8	36.8
Best practice	B/DHN	12.6	14.8	0.0	10.4	0.4	13.8	-8.1	52.0	29.7
	B/AmbHP	4.8	5.8	0.0	0.4	4.3	13.8	-8.1	29.2	29.2
	B/DHN+DX	12.6	14.8	0.1	10.4	0.4	13.8	-8.1	52.0	29.7
	B/HTHP	4.9	5.4	0.0	3.5	0.6	13.8	-8.1	28.2	28.2
	B/AmbHP+C	4.8	5.8	0.1	0.4	4.3	13.8	-8.1	29.3	29.3

__A__ – Current practice, __B__ – Best practice, __DHN__ - District heating connection, no cooling, __AmbHP__ – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, __DHN + DX__ - District heating connection for heat, local split system cooling unit, __HTHP__ – High temperature central air source heat pump, no cooling, __AmbHP + C__ - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

Seasonal Efficiencies

The below lists summarise the inclusions and exclusions from the seasonal efficiency calculation. These were calculated utilising manufacturer performance data and weather data based on the demands computed via simulations. The calculation aligns with the Seasonal Performance Factor H3 defined in the SEPEMO system boundaries.

Seasonal efficiencies include:

- Electricity to heat pump
- Electricity to source fans/pumps
- Electricity to frost protection heater

Seasonal efficiencies do not include:

- Secondary distribution pump power
- Fresh air ventilation fans
- DHN efficiencies

Dwelling WSHP SCOP	**As designed**			**Poor performance**		
Scenario	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**
A/AmbHP	6.67	7.73	7.18	2.56	3.02	2.83
A/AmbHP+C	6.67	7.73	7.18	2.56	3.02	2.83
B/AmbHP	6.44	7.41	6.85	2.54	2.93	2.76
B/AmbHP+C	6.44	7.41	6.85	2.54	2.93	2.76

Central ASHP SCOP	**As designed**	**Poor performance**
Scenario		
A/AmbHP	4.12	3.80
A/HTHP	2.66	2.29
A/AmbHP+C	4.14	3.83
B/AmbHP	4.14	3.85
B/HTHP	2.68	2.29
B/AmbHP+C	4.17	3.89

Whole system SCOP	**As designed**	**Poor performance**
Scenario		
A/AmbHP	2.62	1.62
A/HTHP	2.66	2.29
A/AmbHP+C	2.63	1.63
B/AmbHP	2.58	1.61
B/HTHP	2.68	2.29
B/AmbHP+C	2.59	1.61

__A__ – Current practice, __B__ – Best practice, __DHN__ - District heating connection, no cooling, __AmbHP__ – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, __DHN + DX__ - District heating connection for heat, local split system cooling unit, __HTHP__ – High temperature central air source heat pump, no cooling, __AmbHP + C__ - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

Operational Carbon

Option		Carbon from grid electricity consumption (kgCO2/m2 GIA)	Carbon from district heat network energy consumption (kgCO2/m2 GIA)	Carbon from PV electricity generation (kgCO$_2$/m^2 GIA)	Net total operational energy carbon emissions (kgCO$_2$/m^2 GIA)
Current practice	A/DHN	54.7	52.5	-23.3	83.9
	A/AmbHP	104.9	0.0	-23.3	81.7
	A/DHN+DX	54.9	52.5	-23.3	84.1
	A/HTHP	102.4	0.0	-23.3	79.1
	A/AmbHP+C	105.2	0.0	-23.3	82.0
Best practice	B/DHN	40.6	44.3	-23.3	61.7
	B/AmbHP	83.7	0.0	-23.3	60.4
	B/DHN+DX	40.8	44.3	-23.3	61.8
	B/HTHP	80.7	0.0	-23.3	57.4
	B/AmbHP+C	83.9	0.0	-23.3	60.7

__A__ – Current practice, __B__ – Best practice, __DHN__ - District heating connection, no cooling, __AmbHP__ – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, __DHN + DX__ - District heating connection for heat, local split system cooling unit, __HTHP__ – High temperature central air source heat pump, no cooling, __AmbHP + C__ - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

Whole Life Carbon

Option		Structure	Other MEP	Heating & Cooling	Operation
		(kgCO$_2$/m^2 GIA)			
Current practic	A/DHN	824.0	180.5	29.5	83.9
	A/AmbHP	824.0	174.8	101.8	81.6
	A/DHN+DX	824.0	180.5	242.9	84.0
	A/HTHP	824.0	180.5	68.5	79.1
	A/AmbHP+C	824.0	193.4	138.0	81.9
Best practice	B/DHN	824.0	180.5	29.5	61.6
	B/AmbHP	824.0	174.8	110.8	60.4
	B/DHN+DX	824.0	180.5	238.7	61.8
	B/HTHP	824.0	180.5	64.3	57.4
	B/AmbHP+C	824.0	193.4	125.7	60.6

__A__ – Current practice, __B__ – Best practice, __DHN__ - District heating connection, no cooling, __AmbHP__ – Ambient loop, central air source heat pumps and local water-to-water heat pumps, no cooling, __DHN + DX__ - District heating connection for heat, local split system cooling unit, __HTHP__ – High temperature central air source heat pump, no cooling, __AmbHP + C__ - Ambient loop, central air source heat pumps and reversible local water-to-water heat pumps for heating and cooling.

APPENDIX J
EMBODIED CARBON TABLES
RESIDENTIAL

EMBODIED CARBON TABLES - Residential

Equipment Type	Selection	Refrigerant Type	Refrigerant Weight (kg)	Unit	Total Refrigerant Charge (kg)	Annual Leakage Rate (%)	End of Life Recovery (%)
WSHP (5, 2)	4 kW$_{th}$ (heating and cooling, originally R410A)	R32	1.05	39	40.95	3.8	80
ASHP (5, 2)	300 kW$_{th}$ (heating and cooling)	R32	45.60	2	91.20	3.8	80
ASHP (4)	200 kW$_{th}$ (heating only)	Propane	120.00	1	120.00	3.8	80
DX Unit (Scenario 3)	4 kW (cooling only)	R32	1.16	39	45.24	5.0	70

	System Embodied Carbon Emissions (kgCO$_2$/m^2 GIA)									
	A/DHN	B/DHN	A/AmbHP	B/AmbHP	A/DHN+DX	B/DHN+DX	A/HTHP	B/HTHP	A/AmbHP+C	B/AmbHP+C
5.1.Sanitary installations	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
5.3.Disposal installations	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
5.4.Water installations	12.4	12.4	17.2	17.2	12.4	12.4	12.4	12.4	25.2	25.2
5.5.Heat source	11.6	11.9	50.9	50.9	165.9	165.9	47.1	47.1	34.2	34.2
5.6.Space heating and Airconditioning	18.0	17.1	21.5	13.8	40.8	36.6	21.3	17.1	57.7	45.4
5.7.Ventilation systems	33.6	33.6	33.6	33.6	33.6	33.6	33.6	33.6	33.6	33.6
5.8.Electrical installations	109.7	109.7	109.7	109.7	109.7	109.7	109.7	109.7	109.7	109.7
Refrigerant leakages	0.0	0.0	46.1	46.1	36.2	36.2	0.1	0.1	46.1	46.1

	Embodied Carbon per Lifecycle Stage (kgCO /m^2 GIA)						
	Scope A1-A3 Materials	Scope A4 Transportation	Scope A5 Construction	Scope Use Phase B1	Scope Replacement B4	Scope End of Life C1-C4	Scope A-C
A/DHN	69.4	2.6	0.8	0.0	135.2	2.1	210.1
A/AmbHP	80.6	4.5	0.8	46.1	169.7	2.1	303.9
A/DHN+DX	113.2	2.6	0.8	36.2	268.6	2.1	423.4
A/HTHP	78.0	4.4	0.8	0.1	163.7	2.1	249.0
A/AmbHP+C	87.1	4.0	0.9	46.1	191.1	2.1	331.3

APPENDIX K
EMBODIED CARBON TABLES
REFRIGERANTS

REFRIGERANT EMISSIONS STUDY TABLES

R410A System (kgCO$_2$/m^2 GIA)						
Category	A/VRF	A/HVRF	A/VRF HP + DHN	A/CHL + DHN	A/HP	A/VRF HR + DHN
Other MEP	180.3	182.5	184.6	214.3	205.8	183.2
Heating and Cooling	85.2	82.2	123.1	73.8	88.3	81.9
Refrigerant	313.6	45.1	200.9	0.21	42.3	306

R32 System (kgCO$_2$/m^2 GIA)						
Category	A/VRF	A/HVRF	A/VRF HP + DHN	A/CHL + DHN	A/HP	A/VRF HR + DHN
Other MEP	180.31	182.59	184.67	214.32	205.81	183.21
Heating and Cooling	85.21	82.20	123.11	73.89	88.39	81.90
Refrigerant	114.45	48.39	72.97	4.42	34.12	110.78

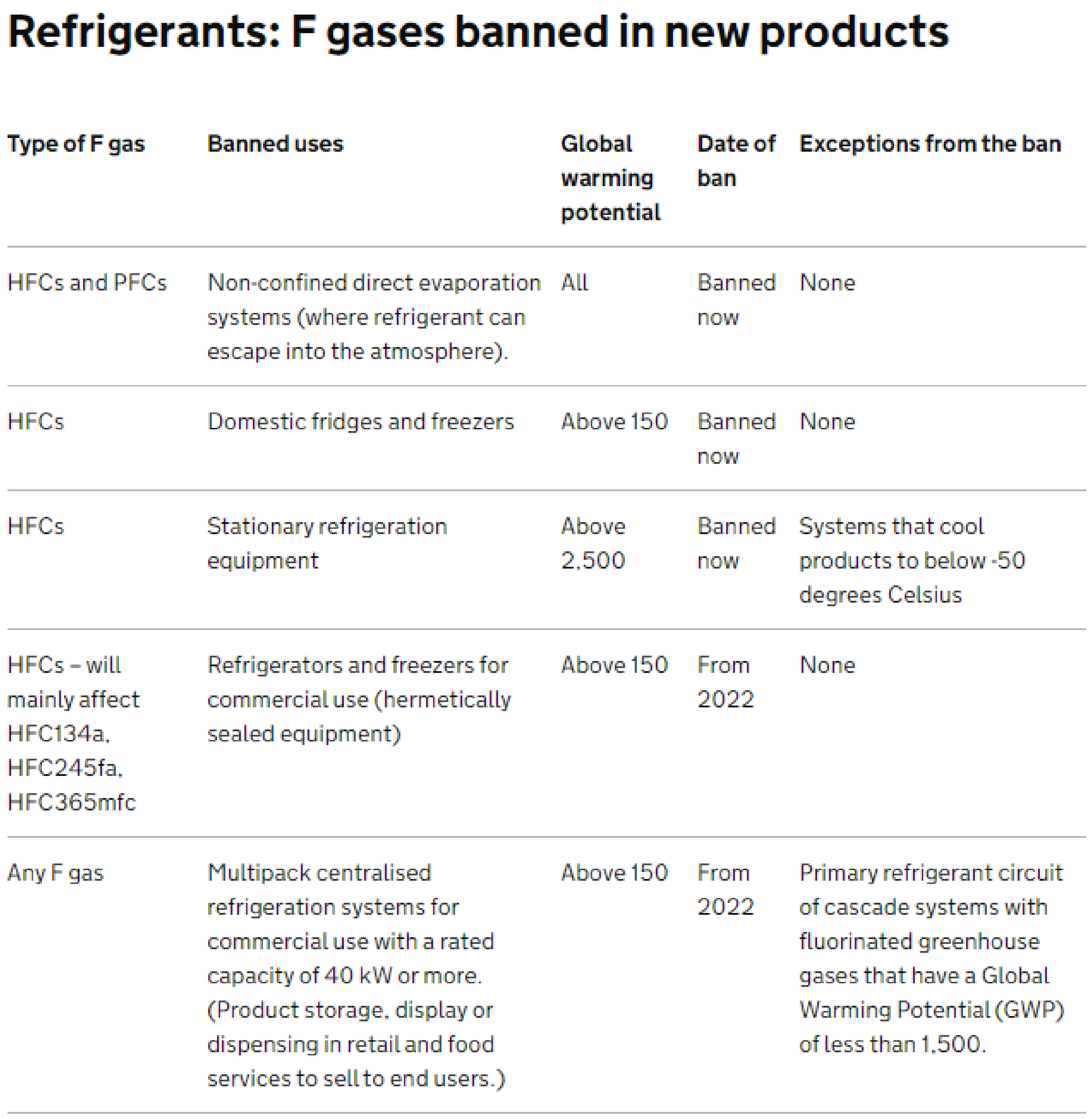
R410A System (kgCO$_2$/m^2 GIA)					
Category	A/DHN	A/AmbHP	A/DHN+DX	A/HTHP	A/AmbHP+C
Heating & Cooling	180.5	174.8	180.5	180.5	193.4
Other MEP	29.5	55.7	206.7	68.4	91.9
Refrigerant	-	96.4	36.2	0.1	96.4

R32 System (kgCO$_2$/m^2 GIA)					
Category	A/DHN	A/AmbHP	A/DHN+DX	A/HTHP	A/AmbHP+C
Heating & Cooling	29.5	55.7	206.7	68.4	91.9
Other MEP	180.5	174.8	180.5	180.5	193.4
Refrigerant	-	46.1	36.2	0.1	46.1

REFRIGERANT EMISSIONS STUDY TABLES

System and refrigerant	Parameters	kW	Refrigerant Charge (kg)	Charge/kW (kg)	GWP	Leakage (%)	End of Life Leakage (%)	CO_2 Emissions (tonnes)
ASHP (R32)	Low	275	50.0	0.18	677	1.0	15	0.15
ASHP (R32)	Medium	275	50.0	0.18	677	3.8	20	0.42
ASHP (R32)	High	275	50.0	0.18	677	5.0	20	0.46
Chiller (R1234ze)	Low	250	115.0	0.46	7	1.0	10	0.013
Chiller (R1234ze)	Medium	250	115.0	0.46	7	2.5	20	0.03
Chiller (R1234ze)	High	250	115.0	0.46	7	5.0	30	0.056
VRF (R32)	Low	20	22.2	1.11	677	1.0	10	0.75
VRF (R32)	Medium	20	22.2	1.11	677	5.0	15	2.7
VRF (R32)	High	20	22.2	1.11	677	10.0	20	5.1
VRF (R410A)	Low	20	22.2	1.11	677	1.0	10	2.3
VRF (R410A)	Medium	20	22.2	1.11	677	5.0	15	8.3
VRF (R410A)	High	20	22.2	1.11	677	10.0	20	16
HVRF (R32)	Low	35.8	13.3	0.37	677	1.0	10	0.25
HVRF (R32)	Medium	35.8	13.3	0.37	677	5.0	15	0.9
HVRF (R32)	High	35.8	13.3	0.37	677	10.0	20	1.7
Split System (R32)	Low	3	2.3	0.77	677	2.0	10	0.83
Split System (R32)	Medium	3	2.3	0.77	677	5.0	30	2.2
Split System (R32)	High	3	2.3	0.77	677	8.0	50	3.5
WSHP (R152a)	Low	80	7.0	0.09	124	1.0	15	0.013
WSHP (R152a)	Medium	80	7.0	0.09	124	3.8	20	0.034
WSHP (R152a)	High	80	7.0	0.09	124	5.0	20	0.042
Propane ASHP (R290)	Low	60	120.0	2.00	3	1.0	15	0.0013
Propane ASHP (R290)	Medium	60	120.0	2.00	3	3.8	20	0.0034
Propane ASHP (R290)	High	60	120.0	2.00	3	5.0	20	0.0042

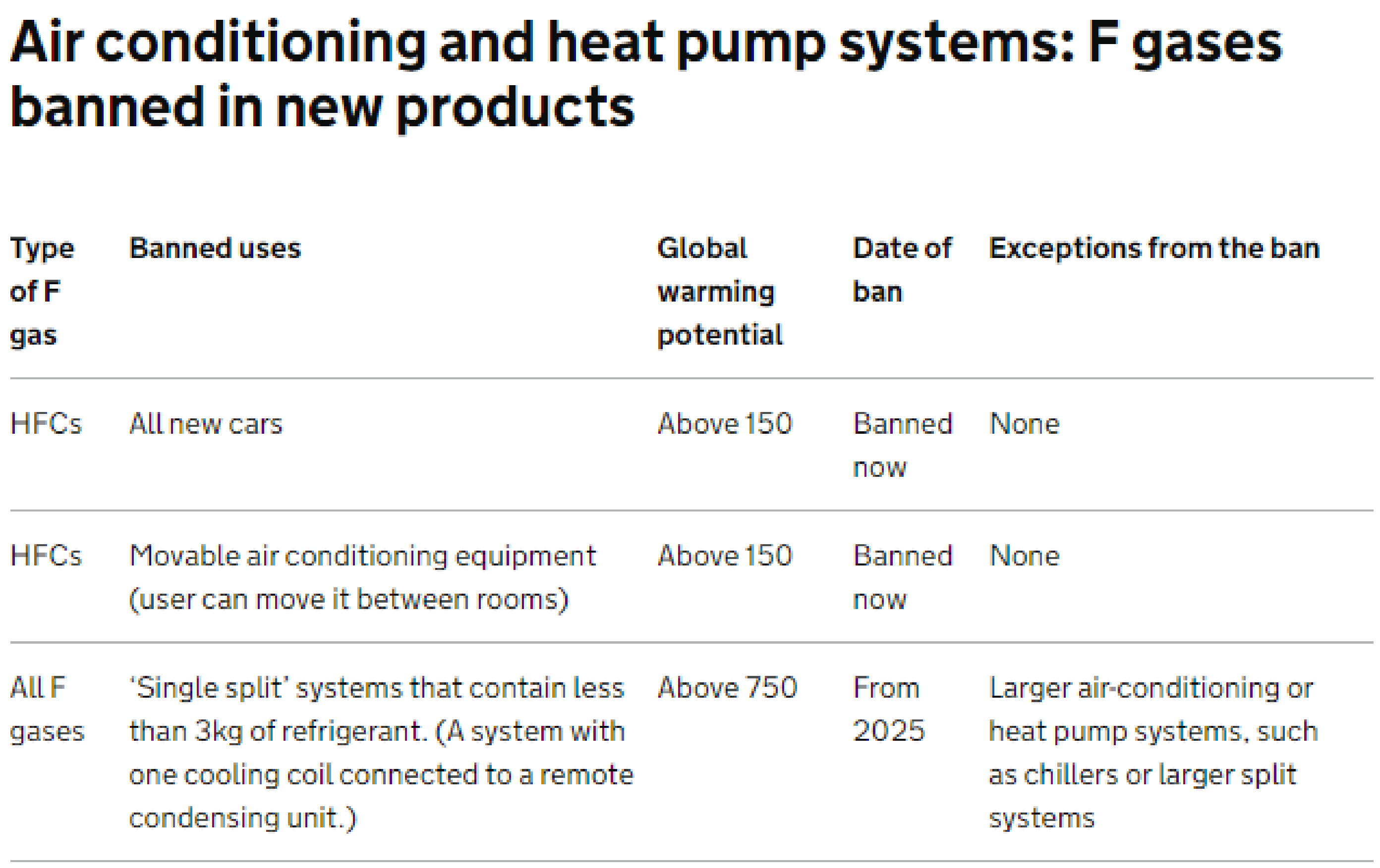
REFRIGERANT EMISSIONS REFERENCE TABLES



Refrigerants: F gases banned in new products

Type of F gas	Banned uses	Global warming potential	Date of ban	Exceptions from the ban
HFCs and PFCs	Non-confined direct evaporation systems (where refrigerant can escape into the atmosphere).	All	Banned now	None
HFCs	Domestic fridges and freezers	Above 150	Banned now	None
HFCs	Stationary refrigeration equipment	Above 2,500	Banned now	Systems that cool products to below -50 degrees Celsius
HFCs – will mainly affect HFC134a, HFC245fa, HFC365mfc	Refrigerators and freezers for commercial use (hermetically sealed equipment)	Above 150	From 2022	None
Any F gas	Multipack centralised refrigeration systems for commercial use with a rated capacity of 40 kW or more. (Product storage, display or dispensing in retail and food services to sell to end users.)	Above 150	From 2022	Primary refrigerant circuit of cascade systems with fluorinated greenhouse gases that have a Global Warming Potential (GWP) of less than 1,500.

Source: UK Government F-Gas Guidance)

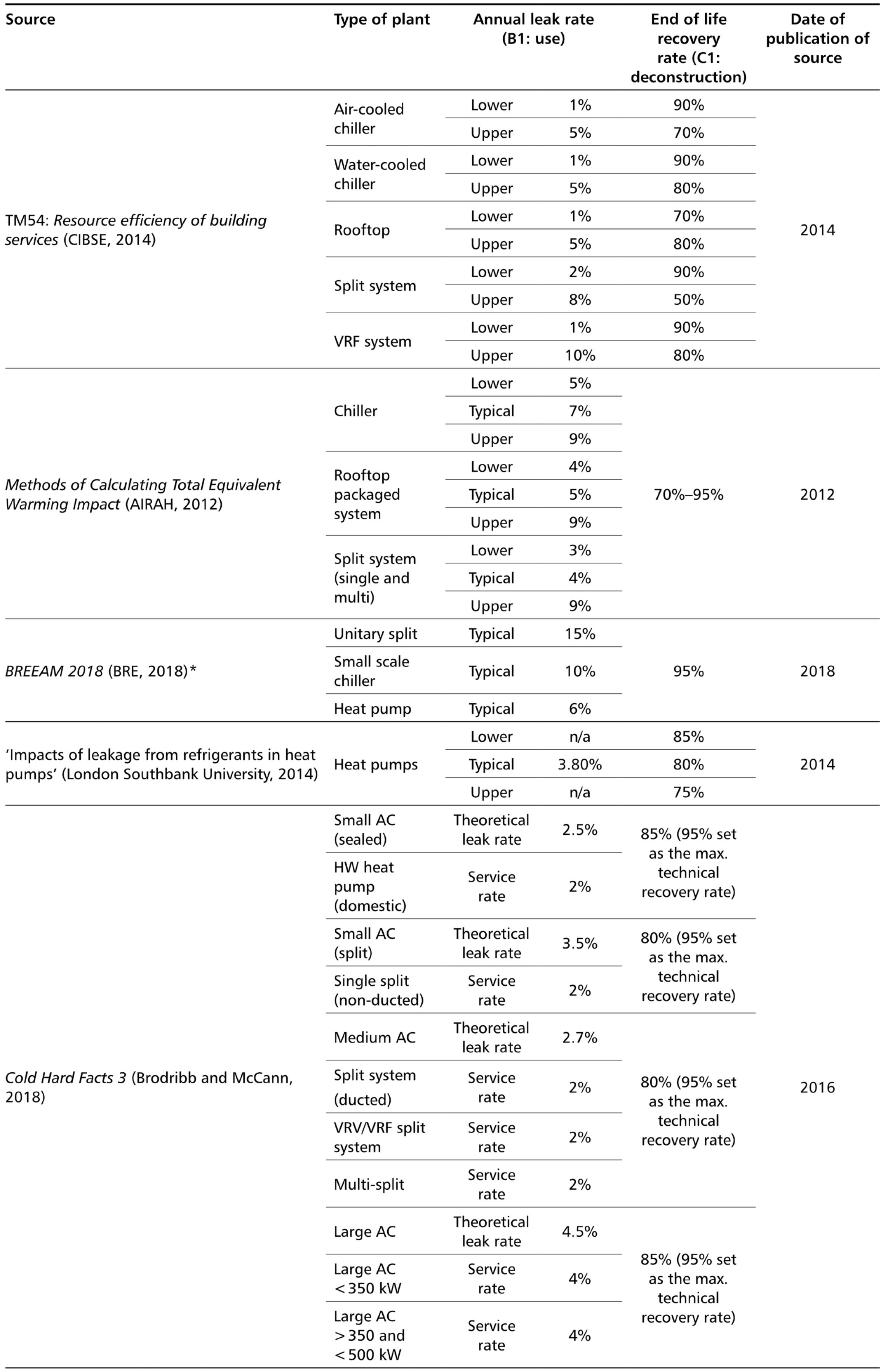


Air conditioning and heat pump systems: F gases banned in new products

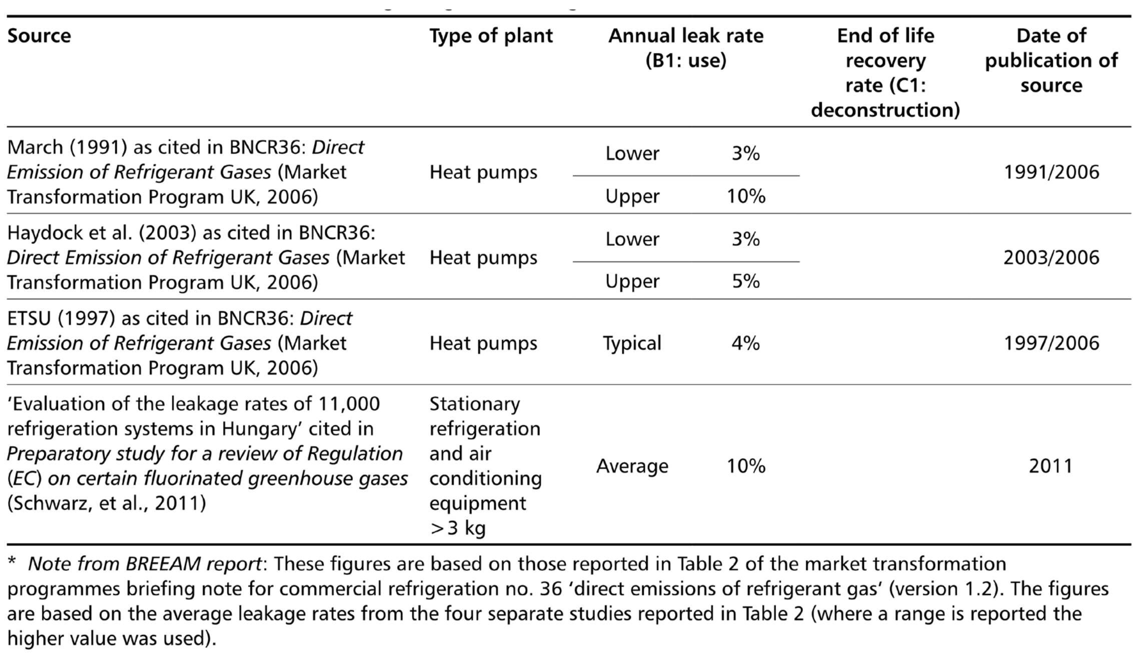
Type of F gas	Banned uses	Global warming potential	Date of ban	Exceptions from the ban
HFCs	All new cars	Above 150	Banned now	None
HFCs	Movable air conditioning equipment (user can move it between rooms)	Above 150	Banned now	None
All F gases	'Single split' systems that contain less than 3kg of refrigerant. (A system with one cooling coil connected to a remote condensing unit.)	Above 750	From 2025	Larger air-conditioning or heat pump systems, such as chillers or larger split systems

Source: UK Government F-Gas Guidance

REFRIGERANT EMISSIONS REFERENCE TABLES



Source	Type of plant	Annual leak rate (B1: use)		End of life recovery rate (C1: deconstruction)	Date of publication of source
TM54: *Resource efficiency of building services* (CIBSE, 2014)	Air-cooled chiller	Lower	1%	90%	2014
		Upper	5%	70%	
	Water-cooled chiller	Lower	1%	90%	
		Upper	5%	80%	
	Rooftop	Lower	1%	70%	
		Upper	5%	80%	
	Split system	Lower	2%	90%	
		Upper	8%	50%	
	VRF system	Lower	1%	90%	
		Upper	10%	80%	
Methods of Calculating Total Equivalent Warming Impact (AIRAH, 2012)	Chiller	Lower	5%	70%–95%	2012
		Typical	7%		
		Upper	9%		
	Rooftop packaged system	Lower	4%		
		Typical	5%		
		Upper	9%		
	Split system (single and multi)	Lower	3%		
		Typical	4%		
		Upper	9%		
BREEAM 2018 (BRE, 2018)*	Unitary split	Typical	15%	95%	2018
	Small scale chiller	Typical	10%		
	Heat pump	Typical	6%		
'Impacts of leakage from refrigerants in heat pumps' (London Southbank University, 2014)	Heat pumps	Lower	n/a	85%	2014
		Typical	3.80%	80%	
		Upper	n/a	75%	
Cold Hard Facts 3 (Brodribb and McCann, 2018)	Small AC (sealed)	Theoretical leak rate	2.5%	85% (95% set as the max. technical recovery rate)	2016
	HW heat pump (domestic)	Service rate	2%		
	Small AC (split)	Theoretical leak rate	3.5%	80% (95% set as the max. technical recovery rate)	
	Single split (non-ducted)	Service rate	2%		
	Medium AC	Theoretical leak rate	2.7%	80% (95% set as the max. technical recovery rate)	
	Split system (ducted)	Service rate	2%		
	VRV/VRF split system	Service rate	2%		
	Multi-split	Service rate	2%		
	Large AC	Theoretical leak rate	4.5%	85% (95% set as the max. technical recovery rate)	
	Large AC <350 kW	Service rate	4%		
	Large AC >350 and <500 kW	Service rate	4%		



Source	Type of plant	Annual leak rate (B1: use)		End of life recovery rate (C1: deconstruction)	Date of publication of source
March (1991) as cited in BNCR36: *Direct Emission of Refrigerant Gases* (Market Transformation Program UK, 2006)	Heat pumps	Lower	3%		1991/2006
		Upper	10%		
Haydock et al. (2003) as cited in BNCR36: *Direct Emission of Refrigerant Gases* (Market Transformation Program UK, 2006)	Heat pumps	Lower	3%		2003/2006
		Upper	5%		
ETSU (1997) as cited in BNCR36: *Direct Emission of Refrigerant Gases* (Market Transformation Program UK, 2006)	Heat pumps	Typical	4%		1997/2006
'Evaluation of the leakage rates of 11,000 refrigeration systems in Hungary' cited in *Preparatory study for a review of Regulation (EC) on certain fluorinated greenhouse gases* (Schwarz, et al., 2011)	Stationary refrigeration and air conditioning equipment >3 kg	Average	10%		2011

* *Note from BREEAM report*: These figures are based on those reported in Table 2 of the market transformation programmes briefing note for commercial refrigeration no. 36 'direct emissions of refrigerant gas' (version 1.2). The figures are based on the average leakage rates from the four separate studies reported in Table 2 (where a range is reported the higher value was used).

Collated refrigerant leakage rates for different system types, Source: CIBSE TM65