White Paper

Integrated Low and Zero Carbon (LZC) Heating Solutions

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The incorporation of zero carbon or renewable technologies in modern buildings is moving from the fringe into the mainstream. Many system designs now attempt to marry biomass or heat pumps or solar thermal with more conventional, low carbon technologies like gas fired condensing boilers as back-up. Unfortunately, a very high proportion of these designs fail to achieve the high operating efficiencies possible because the two technologies (low and zero carbon) have not been correctly integrated. It is just not sufficient to 'bolt-on' a zero carbon system to a condensing boiler system and expect improved efficiencies and reduced energy bills. Integration is much more than simple addition. It is a cohesive, co-ordinated and harmonious whole.

If LZC equipment and system design are not properly integrated there is the danger of…

- Increased first life cost
- Operational and maintenance problems
- Increased whole life cost
- Failure to deliver financial return on assets

…and all the associated economic and commercial risk factors these imply.

In order to successfully integrate LZC technologies, we must first understand how each of them operates in their optimum mode. This white paper will attempt to explain the key characteristics of each of the commonly used technologies and suggest ways in which these technologies can be successfully integrated to maximum effect.

In North America and the UK, low temperature hot water heating systems were traditionally designed with a supply temperature of 80°C (180°F) and a return of 70°C (160°F). Continental Europe took a slightly different approach and utilised a larger temperature difference. There, 80°C (180°F) supply and 60°C (140°F) was the norm. This doubling of the system Δt immediately halved the flow required. Let's take an example of a system with say a heat load of 240kW. With a Δt of 10°C the flow required would be:

$$\frac{\text{kW}}{\Delta t \times \text{sp.ht cap.}} \qquad \frac{240}{10 \times 4.2} = 5.7 \text{ L/s}$$

With a Δt of 20°C the flow required would be:

$$\frac{240}{20 \times 4.2} = 2.85 \text{ L/s}$$

This has a dramatic effect on pipe sizing, pump sizing, friction losses and ultimately electrical power consumption. Something as basic as the system Δt has a significant effect on the initial capital cost of a system but also, probably more importantly, on the whole life cost. Yes, the higher Δt does reduce the mean temperature difference from 75 to 70°C but, in an age of vastly improved building air tightness and thermal insulation, this has little impact on emitter size.

But why 80/70°C (180/160°F) or 80/60°C (180/140°F)? Well, these temperatures were selected for three reasons.

1. They were safely below the boiling point of water so there was little danger of over pressurising the system.
2. They were safely above the dew point of the flue gases so costly corrosion of the internal surfaces of the boiler was avoided.
3. They provided a fairly good LMTD (log mean temperature difference) for economic emitter sizing.

So, in a world where condensation of the flue gases was a real problem but a high surface temperature was not (and also where energy was relatively cheap) then the old order of 80/70°C (180/160°F) was fine.

What about today though?

Today, the majority of commercial heating systems in the UK incorporate gas fired condensing boilers. These are designed to be ultra efficient by extracting latent heat from the flue gases. This is done by dropping the temperature of the flue gases below the dew point, which for natural gas is around 54°C. When flue gases drop below the dew point, condensation forms. This condensate is acidic and quickly corrodes ferrous boiler and flue materials. So, unlike traditional boilers which were built from steel or cast iron, condensing boilers are built from aluminium or stainless steel.

But here's the rub, over 90% of the system designs we see which incorporate condensing boilers are still operating at 80/70°C. They will never condense - NEVER!

Yes they will be more efficient than an old cast iron atmospheric boiler but they will never reach the high efficiencies stated in the manufacturers' literature unless the system temperature is below dew point; ideally 50/30°C (122/86°F). The difference in efficiency can be as much as 10% depending upon boiler type and load. Figure 1 shows some typical efficiencies that can be achieved at various loads and system temperatures.

MBS Efficiencies vs Load and System Temperature				
Supply Temperature °C	% Load			
	100	75	50	25
80	87.0	86.8	86.6	86.3
75	87.9	87.9	87.9	87.9
70	88.8	89.0	89.2	89.4
65	89.7	90.1	90.6	91.0
60	90.5	91.0	91.9	92.6
55	91.4	92.0	93.2	94.1
50	92.3	93.3	94.5	95.7

Figure 1

These lower temperatures are ideal for underfloor heating and can work successfully with fan coils and air handling units. They also mean that standard radiators can be used in place of more expensive low surface temperature radiators in critical applications like hospitals, care homes and nurseries. The only thing they are not suitable for is domestic hot water generation. To prevent the formation of Legionella bacteria domestic hot water should be stored above 60°C. This would not be possible with a primary temperature of 50°C so domestic hot water systems should be designed as stand-alone constant temperature systems to avoid problems with Legionella.

Another area that's often misunderstood is the best control strategy for condensing boilers. Condensing boilers are at their most efficient at low load unlike traditional boilers where the opposite is true. Figure 2 graphically shows boiler efficiency at various loads.

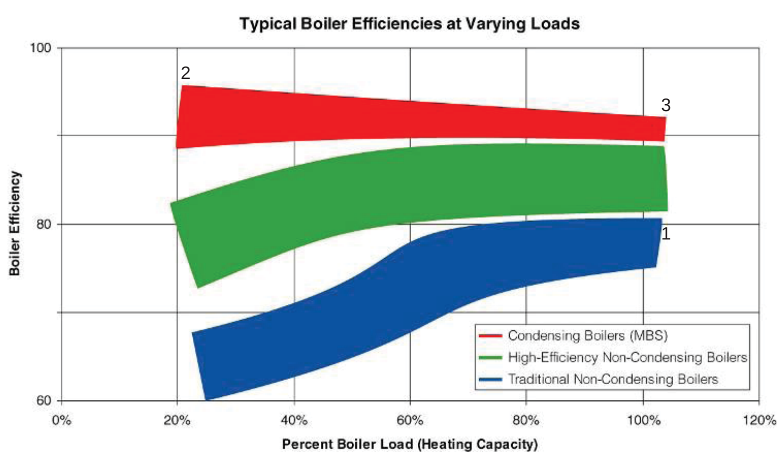

Figure 2

The accepted control strategy for multiple boiler installations is to stage each boiler up to full load and then sequentially bring in each of the other boilers until the load is satisfied. For traditional boilers that's perfect. We're switching them in and out at their peak efficiency point; full load (point 1). But, for condensing boilers it's far from perfect. Condensing boilers are at their most efficient at part load (point 2). This is because the heat exchanger surface remains constant but the fuel/air mixture is variable. So on low loads there is a greater surface area available to extract heat energy from the reduced gas/air mix.

If we then sequence condensing boilers at peak load we are actually switching them at their least efficient point (point 3). What we should do is run ALL multiple condensing boilers simultaneously at their lowest possible load to meet the building demand. This is called demand based control as opposed to the more widely used capacity based control.

Remember, space heating is a part load application. We size the plant for design day conditions but these conditions are rarely experienced in temperate climates. So it makes sense to try to match boiler load to the building demand rather than to the boilers' capacity.

As well as making sense from an efficiency viewpoint, demand based control gives us some other benefits. A boiler is like any other machine, it likes to run. Constant stop/starting of any machine accelerates wear and tear. It's a bit like driving a car flat out then braking when we see the lights change to red whilst still keeping our foot on the gas. Not fuel efficient or maintenance efficient. Also, when a boiler is restarted, it must go through a pre-purge sequence. This ensures that any unburnt fuel and products of combustion are purged from the system. To achieve this, the fan blows cold air through the heat exchanger and up out through the flue losing heat on the way. This wastes small amounts of energy but the costs mount up over the years.

So, if we're going to use condensing boilers, we should always try to ensure;

1. That they will at least operate in condensing mode by using system temperatures below dew point (preferably 50/30°C; 122/86°F).
2. We should try to adopt a demand based control philosophy instead of the old capacity based model.

Another area worth looking at is hydraulic system design. A typical LTHW system design is shown in figure 3.

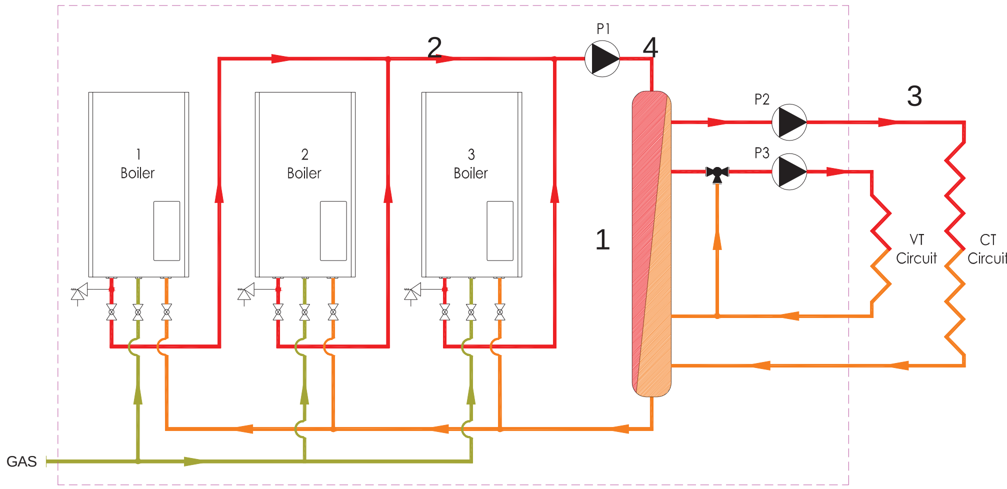

Figure 3

A low loss header (1) separates the primary and (2) secondary (3) circuits. The flow through the boilers is maintained by a constant speed pump (4) regardless of what happens downstream on the secondary side. Whilst this protects low water content boilers it is far from ideal for condensing boilers. As the demand on the secondary side reduces so the return temperature increases. The boilers are controlled on flow temperature and, as the flow rate is constant and the Δt is reducing, the boilers must modulate down to maintain the energy balance. For example, at a load of 100kW and a Δt of 20°C, the flow rate through the boiler would be:

$$\frac{100}{20 \times 4.2} = 1.19 \text{ L/s}$$

As the return temperature rises so the Δt reduces, let's say to 10°C. The load at the boiler would therefore reduce to:

$$1.19 \times 10 \times 4.2 = 50\text{kW}$$

All well and good you might think as long as the system design temperatures are low enough. If we're always controlling our system supply temperature below the dew point of the flue gases we're OK. However, if our system temperatures are designed at say 65/45°C, then reducing the Δt to 10°C would take the boiler out of condensing mode. Also, as boilers are staged off, the primary pump must still operate, sending hot system water through unfired boilers.

An alternative, improved design is shown in figure 4.

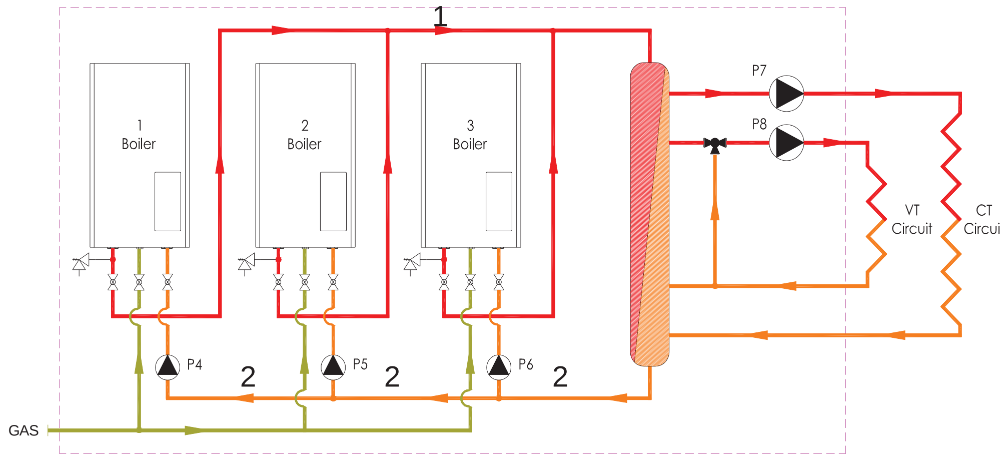

Figure 4

Here primary flow (1) is created by individual boiler shunt pumps (2). This eliminates the problem of flow through unfired boilers as the shunt pumps are interlocked with the boiler controls. However, the designs shown in figures 3 and 4 still utilise a capacity based control philosophy with constant speed pumps. It's all about the capacity of the boilers and not the demand on the system.

So what about systems that respond to the demand of the building rather than the capacity of the plant?

The MBS Single-Circuit shown in fig 5 incorporates an intelligent variable speed pump (P9) which modulates the flow rate to exactly match the load on the boiler. This pump acts as both a primary and secondary pump.

A traditional variable flow system would be controlled on pressure. As demand reduces so control valves start to close. The control system senses the increase in system pressure caused by the throttling effect of the valves and reduces the flow. However, in modern integrated designs like the MBS, the control point is demand not pressure. So as boiler loads falls, the system flow proportionally falls keeping control valves open as long as possible. Because of this, there is always some flow through the system. When demand is below the minimum firing rate of all boilers, individual boilers are sequenced off.

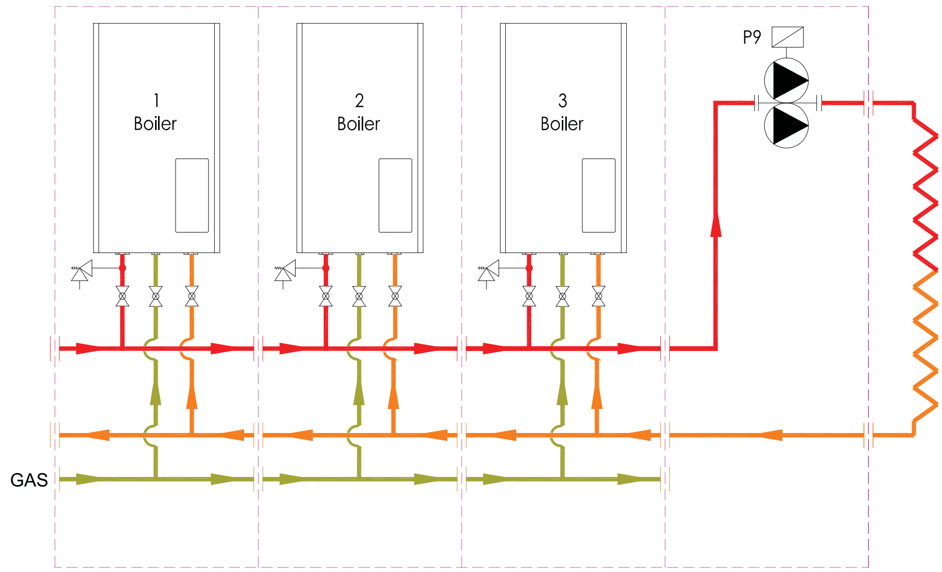

Figure 5

This type of integrated system is ideal for simple, single circuit systems. However, where multiple secondary circuits are required another approach is required.

The MBS Multi-Circuit adds variable speed control to the individual boiler shunt pumps and system secondary pumps as shown in figure 6.

By utilising the 0-10V modulating boiler control signal, we can vary the shunt pump speed so that the flow through the boiler matches the load. This maintains a constant Δt across the boiler and ensures that we never operate outside condensing mode. The variable speed system pumps, controlled on pressure, reduce flow as demand falls thereby preventing an increase in return temperature.

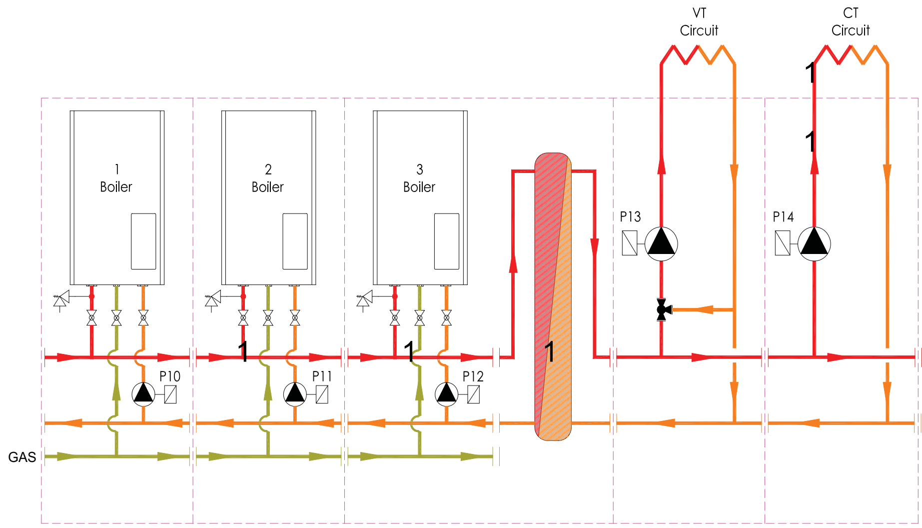

Figure 6

Finally, before we leave the subject of condensing boilers, let's look at how overall seasonal boiler efficiency (OSBE) is calculated in Part L of the UK Building Regulations. Section 2.4 of the 1st edition of the 'Non-Domestic Heating, Cooling and Ventilating Compliance Guide' (due to be updated in 2010) provides details of the method for calculating OSBE. However, it's important that the efficiencies entered in the worksheet relate to the actual design conditions. Some manufacturers only provide one set of efficiencies; often condensing mode only. If the system is designed as 80/70°C these efficiencies will not be appropriate.

A typical calculation for an MBS 240 operating at 50/30°C with a design load of 200kW and operating with demand based control is shown in figure 7.

Table 2: Worksheet for Calculating Overall Seasonal Boiler Efficiency of a Multiple Boiler System Using the Alternative Three-step Method

		Efficiency at Stated % of Boiler Output		Boiler Output at Stated % of System Output			Boiler Efficiency at Stated % of System Output		
Boiler no.	Rating kW	100%	30%	15%	30%	100%	15%	30%	100%
1	80	92.3	95.5	37.5%	25%	84%	95.1	95.7	92.3
2	80	92.3	95.5	0%	25%	84%	0	95.7	92.3
3	80	92.3	95.5	0%	25%	84%	0	95.7	92.3
						System Efficiency at Part Load	95.1	95.7	92.3
						Weighting Factor	0.36	0.45	0.19
							34.24	43.07	17.54
						Overall Seasonal Boiler Efficiency		94.85	

Figure 7

For the same application, but this time operating at say 80/70°C and with capacity based control, the calculation would be as in figure 8.

Table 2: Worksheet for Calculating Overall Seasonal Boiler Efficiency of a Multiple Boiler System Using the Alternative Three-step Method

		Efficiency at Stated % of Boiler Output		Boiler Output at Stated % of System Output			Boiler Efficiency at Stated % of System Output		
Boiler no.	Rating kW	100%	30%	15%	30%	100%	15%	30%	100%
1	80	87.0	86.3	37.5	75	100	86.3	86.8	87.0
2	80	87.0	86.3	0	0	100	0	0	87.0
3	80	87.0	86.3	0	0	50	0	0	86.6
						System Efficiency at Part Load	86.3	86.8	86.9
						Weighting Factor	0.36	0.45	0.19
							31.07	39.06	16.38
						Overall Seasonal Boiler Efficiency		86.51	

Figure 8

As you can see, there's a difference of over 8% in efficiency with a 20 ΔT and demand based control. The minimum OSBE for new buildings is 84% (Part L2A 2006) so theoretically everything's OK. But Part L stipulates the minimum standards required. If all elements only just meet or barely exceed these minimum standards, it is unlikely that the building will gain approval.

One final word on condensing boilers – nitrous oxide (NOx). NOx is a greater contributor to greenhouse gases than CO^2. Although NOx is not covered in Part L, it is covered in the Pollution section of BREEAM. Any boiler that has NOx emissions of less than 40mg/kWh at 0% oxygen can gain 3 BREEAM credits. The MBS system meets this test and has a NOx level of only 20mg/kWh.

Now we're set up to get the best out of our Low Carbon systems let's see how we can successfully integrate some Zero Carbon solutions.

Modern day building design requires a holistic approach. Architects can no longer design a marvellous glass edifice and ask the engineer to design systems to satisfy its heating and cooling needs. The architect and engineer must now work together and collaborate to produce a building that not only looks good aesthetically but also performs well from an energy perspective. The usual approach is to adopt the Design Hierarchy shown in figure 9.

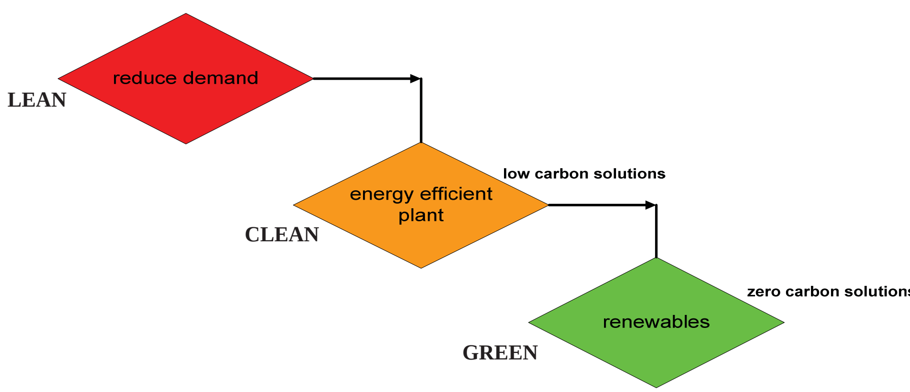

Figure 9

The design team ensure that the building design is as lean as possible by carefully selecting the ideal orientation to provide natural lighting and appropriate solar gain. They also ensure that the building is as air tight as possible to reduce infiltration losses whilst maintaining healthy indoor conditions. The key here is to reduce demand, the most important step in any system design.

Next the engineer selects appropriate low carbon or clean technologies to meet this reduced demand. This is where the optimised condensing boiler design utilising low system temperatures with demand based control and variable speed Sensorless pumping technology play a major role.

Last but by no means least the engineer introduces the Zero Carbon or Renewable technologies. These are often relatively expensive in relation to the energy they provide so current thinking often limits these solutions to 10 or 20% of the building load. Some sources, like solar thermal, are also not always available. As technology advances, production volumes increase and manufacturing costs fall together with the desire for net zero carbon buildings, this contribution will inevitably increase.

The three zero carbon technologies most commonly used in building services are solar thermal, biomass boilers and heat pumps.

There are three main types of solar thermal collector; flat plate, evacuated tube and unglazed plastic. Flat plate and evacuated tube collectors are most commonly used in the commercial environment. Unglazed plastic are low efficiency units and used mainly for domestic swimming pool applications so we'll ignore them at this stage.

Glazed flat plate collectors typically give 350 – 500kWh/m^2. They have...
• Good price to performance ratio
• Cheaper than evacuated tube
• Simple well-developed technology
but...
• Require more roof space than evacuated tube
• Must be installed at an optimum angle
• Lower efficiency than evacuated tube
• Achieve lower water temperatures than evacuated tube

There are two types of evacuated tube collector available – heat pipe and direct flow and these typically give 550-800kWh/m^2. They provide...
• Higher operating temperatures
• Higher energy yield from same collector area
• Lower weight than flat plate
• High temperature differences possible between fluid and outside air possible
• Can be installed at any angle between horizontal and vertical
but...
• More expensive than flat plate
• Cannot be integrated in roof structure

The main benefits of solar thermal are;
It is clean and virtually maintenance free, it has a good price to performance ratio and it is a simple, well-developed technology.

The main limitations of solar thermal are;
- Low energy to area ratio,
- Potential for summer overheating
- Aesthetics (some regard panels as unsightly).

Biomass is defined as any plant derived organic material that renews itself over a short period. The most common form of biomass encountered in commercial building services applications is the direct combustion of wood in the form of chips or pellets.

Wood pellets are denser than wood chip (typically 600-700 kg/m^3) and therefore require a much smaller storage area. They can also be blown or gravity fed and have an energy density of around 5 kWh/kg. However, they are more expensive than wood chip and are generally less readily available. Typical boiler sizes range from 15 kW to 150 kW.

Wood chips are less expensive and less dense than pellets (typically175-350 kg/m^3) and so require larger storage areas. The fuel feed system normally requires a walking floor and/or auger feed. The energy density is around 2-4 kWh/kg. However, wood chips are generally more readily available than pellets. Typical boiler sizes range from 25 to 1000 kW.

The main benefits of biomass systems is that they provide continuous energy production… unlike wind or solar and they are an economic alternative to fossil fuel like oil, coal or gas. They are flexible and scalable from a single domestic boiler to a power plant and they are an established, well-proven technology; there are thousands of successful installations across Europe.

There are three main limitations of biomass.

1. Biomass has a far lower energy density than fossil fuels so storage requirements are greater.
2. Availability can fluctuate so the ability to operate with alternative fuels is desirable.
3. Control is not as easy as gas so load levelling via thermal stores is essential.

A heat pump is a device which takes up heat at a certain temperature and releases it at a higher temperature, just like a refrigerator. There are 3 generic types of heat pumps; ground source, air source and water source.
Ground source heat pumps are classified as either water/water or water/air and these are the typical CoPs we can expect assuming a heat source of 5°C

Under Floor Heating	typical temperature range 30/35°C	CoP 4.0
LT Radiators	typical temperature range 35/45°C	CoP 3.5
Radiators	typical temperature range 50/60°C	CoP 2.5

The heat source for ground source heat pumps is usually a closed ground loops or an open loop. Closed ground loops are installed as either vertical bores, which are generally 100mm to 150mm dia and 15 to 180 metres deep and give around 1kW for every 30 metres, or horizontal 'Slinkys' which are installed 1.5 to 2 metres deep. Open loop systems utilise the heat available in ground water or ponds and lakes.

Air source heat pumps are also available. These usually have lower CoPs than ground source but do not require extensive civil work.

The main benefits of heat pumps are that there are few moving parts, they are reversible and can be used for cooling in summer and it's a well-proven technology. The main limitations of heat pumps are the relatively low output temperatures for best CoPs and, for ground source, ground conditions may not be suitable and the cost of ground works can be high.

So, now that we've briefly looked at the different Low and Zero Carbon solutions, how can we successfully integrate them? We've already said that we can't just 'bolt' these together and expect a happy outcome and figure 10 shows us why.

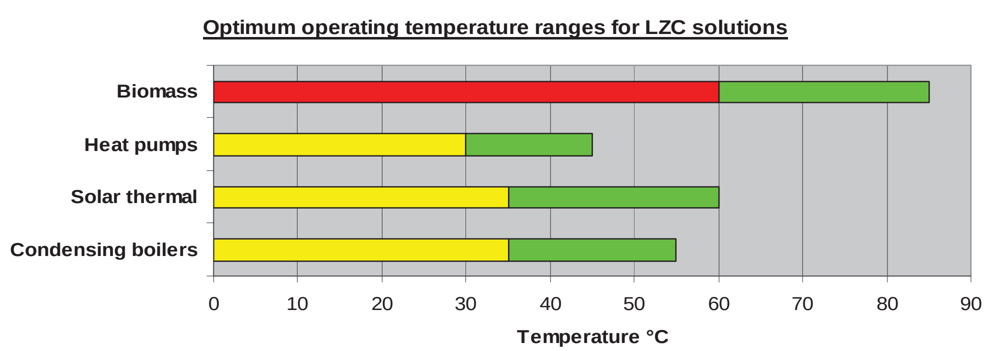

Figure 10

Each of our commonly used Low and Zero Carbon solutions operate at differing optimum temperatures shown in green. Heat pumps, solar thermal and condensing boilers can all certainly still operate at even lower temperatures, shown in yellow, but the heat that they will produce can't be effectively utilised for many space heating applications. Biomass must definitely not be allowed to operate in the red zone because this will cause serious maintenance and operational problems such as back-end corrosion and incomplete combustion resulting in clogging of the fire grate.

So, if we design a system with a biomass boiler to take the base load with gas condensing boilers taking peak loads and providing standby back-up, then the biomass boiler wants to run at 80/60°C whilst the condensing boiler wants to run at 50/30°C. In the vast majority of designs we see, the biomass camp takes priority because of the serious operational problems that would be the result of operating below 60°C. Thus the system is designed at best for 80/60°C or at worst for 80/70°C even though there are usually variable or low temperature circuits which require far less. Figure 11 shows a typical biomass/gas condensing boiler design.

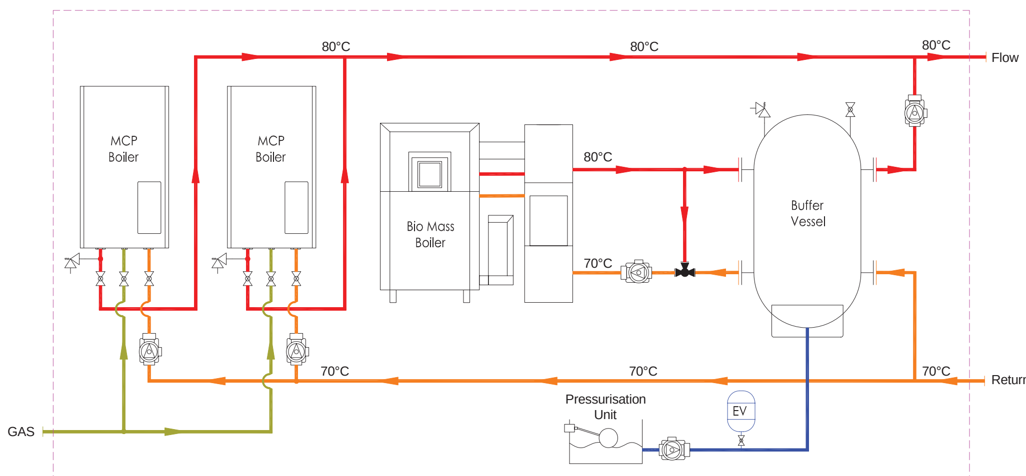

Figure 11

This system will work. But it will cost more to install and it won't work at optimum efficiency. A 400kW system, designed at 80/70°C would cost around 19% more to install because of larger pipe and pump sizes and around 13% more in running costs than a truly integrated low and zero carbon system which operates each subsystem at its optimum operating temperatures.

An example of an integrated design is shown in figure 12.

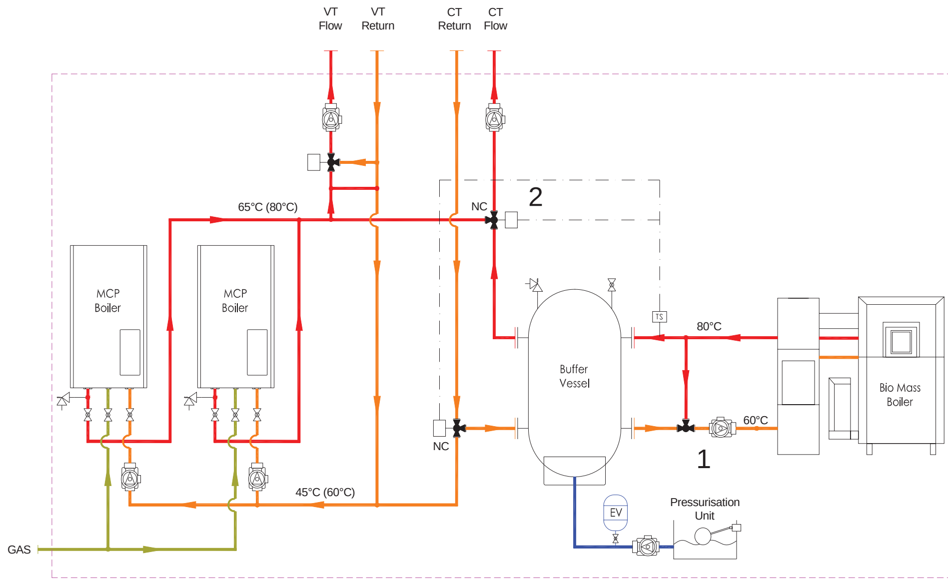

Figure 12

In the solution shown here, the biomass boiler feeds a buffer vessel. On start-up the hot supply water is diverted via the 3-port valve (1) into the biomass boiler return. Once the return water reaches 60°C, the 3-port valve starts to close to the by-pass and allows water through to the buffer vessel and eventually heats it to 80°C. The pump on the CT circuit draws water from the buffer vessel through the 3-port valve which is normally closed to the by-pass port.

The gas fired condensing boilers serve the VT circuit(s) with LTHW at 65/45°C. A 3-port mixing valve and pump on each VT circuit reduces the system temperatures further as required.

Normally, the biomass and condensing boiler systems are separated by the 3-port diverting valve (2) on the common flow header. However, in the event of a failure of either the condensing boilers or the biomass boiler, the 3-port valve will open to allow flow from one to the other.

And it's not just with biomass and gas condensing boiler designs that these problems occur. It happens with all low and zero carbon systems like solar thermal and heat pumps as well. Figure 13 shows a system that combines ground source heat pumps with gas condensing boilers to provide LTHW for HWS generation and for space heating via air handling units and underfloor heating.

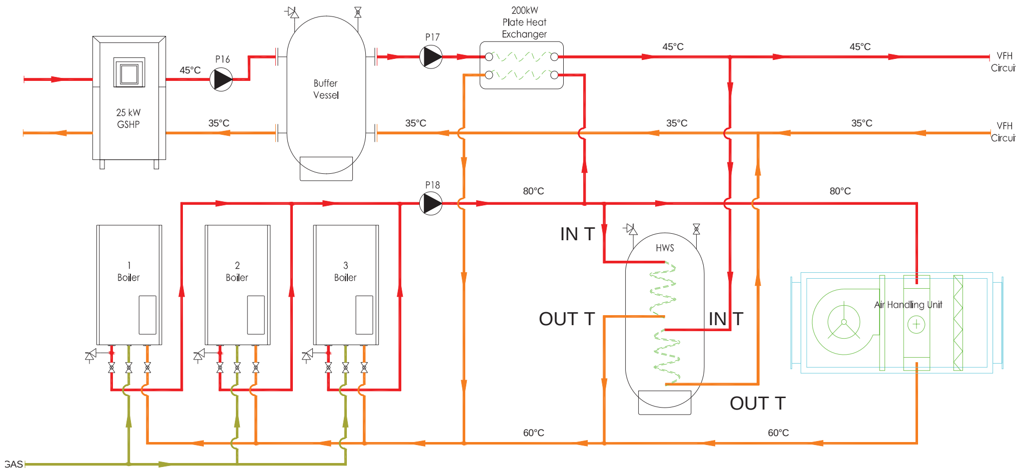

Figure 13

The design is generally good. The GSHP contributes to the underfloor heating load in the winter and pre-heats the HWS in summer and winter. The gas condensing boilers serve the upper coil of the HWS calorifiers, the AHU and make-up any shortfall between the GSHP and the UFH via a plate heat exchanger. However, once again the higher operating efficiencies are sacrificed in order to provide a high primary HWS temperature. And, although a 20°C Δt is used from the condensing boilers a 10°C Δt is used all the way from the GSHP to the UFH circuits.

An alternative integrated solution is shown in figure 14.

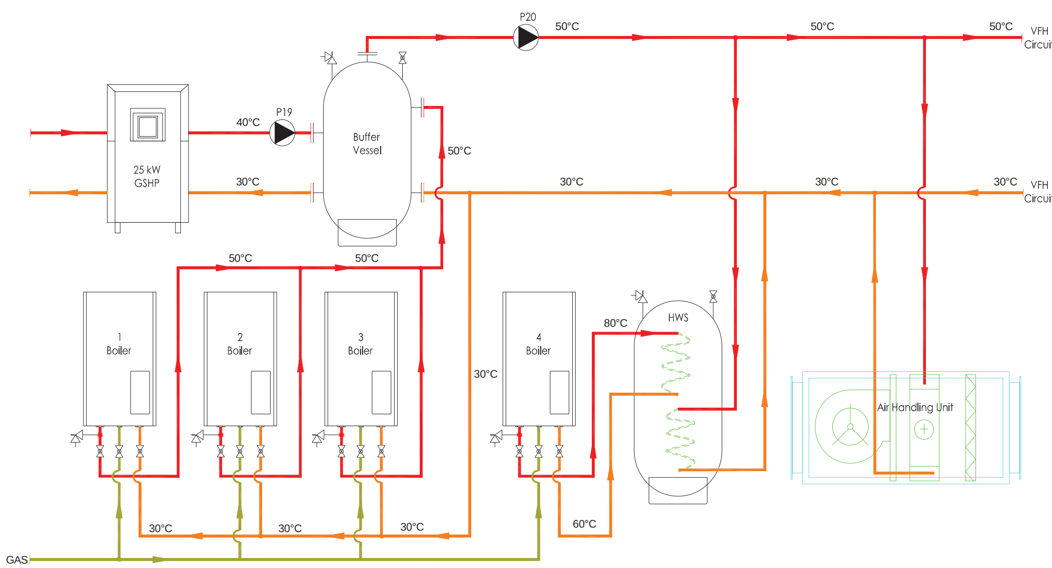

Figure 14

By revisiting the system temperatures we've been able to omit the plate heat exchanger and a set of pumps, reduce the pipe sizes and increase the efficiencies of the condensing boilers and the heat pump. This means a significant reduction in installation costs and ongoing operating costs.

Armstrong has developed a series of integrated LZC heating solutions showing how condensing boilers can be successfully combined with solar thermal, biomass, heat pump and CHP technologies. Hopefully, these solution sheets together with this white paper will help highlight the problems created by 'bolt-on' LZC solutions and aid the reader in designing systems which help lower the carbon footprint as well as reducing first and whole life costs. ■