Heating systems through the lens of the boiler: detailed case studies to inform current and future heating system design

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Abstract

Boilers in hydronic heating systems are the norm in the UK. Through case study analysis, covering 4 houses with gas central heating systems for over 1 year and utilising novel monitoring of the on-board diagnostic data of the boilers, performance issues were identified in this mature technology which, if addressed, could deliver significant short term carbon savings.

ON/OFF cycling behaviour, plant size ratio and modulation range were found to be critical for the ability of the boiler to meet the space heating demand of the buildings effectively. Oversizing was prevalent with boilers consistently unable to modulate low enough to match the building space heating demand. Cycling behaviour resulted, known to be detrimental to efficiency, with the majority of boiler operations lasting less than 10minutes.

Selected case study analysis of incumbent technologies, such as boilers, utilising the latest in data collection techniques and connected appliances provides a cost effective insight necessary for the low carbon heat transition. Findings have implications for domestic energy demand range from incremental improvements in boiler system efficiency by addressing cycling to the updating of Building energy assessment models (e.g. SAP) to reflect and reward the efficiency benefits of good installation practices. An improved understanding of boiler operation may support improved product design and installation practices in the near term, and are beneficial to the next generation of domestic heat, such as heat pumps. Legacy infrastructure will persist in the stock, from the building envelope to radiators, tanks and controls.

Practical Application

Fundamental issues of oversizing and detrimental cycling behaviour are persisting in the industry. Practical steps can be taken to avoid oversizing for boilers immediately. Building an awareness of performance penalties associated with poorly planned heating installations will have added benefit for more dynamically sensitive technologies in the future, such as heat pumps.

Introduction

Gas boilers are the dominant technology in UK residential heating, and have been for over 30years (1). Over 20million are currently operating in UK residential heating systems with over 1 million installations taking place annually (2). Combination boilers (commonly referred to as ‘combi’ boilers), those providing heating and instantaneous hot water in the same appliance, are the most popular variant installed, with approx. 900,000 installed annually. This represents approximately 10,8000GWh of gas consumption capacity (based on median UK consumption (3)) persisting in the energy mix for the duration of the expected 15year lifetime of the boilers.

A significant efficiency improvement came to residential heating market in the early 2000s with the introduction of condensing boiler technology. Condensing boilers were effectively mandated by the minimum efficiency standards implemented in the UK in 2005 (4), leading to a steep increase in uptake which was instrumental in reducing energy demand (5). However, performance gap issues still persist (6, 7) indicating that the full potential of the gas boiler condensing efficiency has not yet been fully realised. As the UK’s dominant heating technology, further efficiency improvements and decreasing the performance gap for gas boilers has the potential to significantly decrease carbon emissions and energy use.

The UK Treasury (8) and recently the Committee for Climate Change (9) have called for eventual phasing out of natural gas combustion heating systems starting with a ban for new builds from 2025. Displacing the entrenched technology, the gas boiler, is a significant challenge for policy makers, industry and home owners. New build properties may be designed, in line with ever tightening building regulations, to take advantage of the full benefits of low carbon heating technologies such as Heat Pumps, or be designed to be intrinsically low or zero carbon utilising standards such as PassivHaus. Although new technologies are likely to still be installed in traditional hydronic central heating systems as today. With 20 million residential buildings currently heated by natural gas boilers, the retrofit/replacement market represents the bulk of the emissions that need to be tackled to achieve net zero carbon emissions by 2050 (9). Any strategy which aims to enable the transition at reasonable cost, will need to preserve much of the existing infrastructure. If pathways can be determined which allow for the integration of low carbon alternatives to gas boilers which can fit into the existing heating systems (taking on the same radiators, controls pipework etc.) then overall cost of the transition can be kept to a minimum, thereby increasing the likelihood of uptake.

In order to convert the majority of existing heating systems to lower carbon alternatives in a way that does not involve costly and disruptive wholesale replacement of complete heating systems and the adjoining infrastructure then a sound understanding of boiler heating systems and their operation is important. Studies have already shown (10, 11) that the potential for mistakes when installing low carbon system into existing homes and the misunderstandings surrounding operational capabilities in the minds of occupiers presents huge pitfalls for decarbonising heat.

Residential heating systems, whether in new build or retrofit, inherit a legacy of procedures, protocols and experience that will shape the way they are implemented. From the plumbers who specify and install to the embedded heating behaviour of occupants, the history of central heating will inform its future. By re assessing the state of the incumbent technology, in terms of its strengths, weaknesses and resilience then we can work towards avoiding pitfalls inherent in the transition to a new technology. Case study analysis of boiler systems provides the foundation not only for potential improvement of the systems of today but a roadmap of pitfalls for the future.

The aim of this paper is to highlight lessons learned and the importance of thoroughly understanding the strengths, weaknesses and limitations of incumbent technology, in this case boilers, as a pre-requisite for a robust transition to the next generation of low carbon heat. Given that boilers, as part of hybrid systems supported by a hydrogen distribution network, look set to persist well into the 2040s, then the case for continuing research into boiler performance is strengthening. Through detailed case studies of incumbent mature systems in addition to field trials of novel technology, valuable insights can be gained which can better support frictionless progression to lower emissions. Additionally the research will investigate measures which can be implemented in the near term, within the boundaries of the existing boiler technology which can deliver immediate carbon savings. Although the savings maybe small when considered at the building scale, given the prevalence of boilers, the national benefits can be significant and cost effective. Large scale (n>200) remote logging of boiler controls (10second sampling) has revealed insights on the prevalence of cycling behaviour (12), linked to inefficient operation (13, 14). However, such studies reveal little about the context in which the boilers are operating either from the heating system or building perspective. In order to build a more complete picture of heating system performance characteristics, in particular dynamic effects overlooked by studies with half hourly sampling or less, then smaller scale case study analysis, together with high frequency heating system data monitoring can offer the insights that will inform short term measures to bridge the boiler performance gap but also deepen understanding of the heating systems that future heat sources will fully or partially inherit.

Four detailed case studies were undertaken. Three were located in the UK (2 combination boilers and 1 system boilers) and one case study in Germany (system boiler), monitoring of the boiler internal diagnostics was utilised to access high frequency internal sensor data. Access to the internal diagnostic data of the boiler itself is a distinguishing feature of this case study research and sets it apart in terms of the frequency and detail of data that was collected including: Power output level, operation mode, supply water temperature and circulation pump speed logged at 5second intervals. Boiler diagnostic data was supplemented with traditional temperature and gas/electric meter data a holistic view of boiler performance was acquired. Further detail on the monitoring methodology and data streams is described in the following section.

Boiler Diagnostic Data

Modern boilers have a relatively complex control system utilising microprocessor control and embedded software to optimise performance and ensure safe operation. The appliance control (distinct from the thermostat or room controller) requires continuous input data from sensors and actuators to calculate and implement the control strategy. With the advent of cost effective modern internet connectivity built into heating appliances, this detailed and high frequency internal data can be sent to a remote server to be stored and interrogated. Proprietary and open standards exist in the market defining the type of data and the communication protocol. In the case of the boilers in this study, which are all from the same manufacturer using a propriety system which can be translated to an open standard (15), although there are differences between models due to country and functionality differences (e.g. premium versus budget models), access to the boiler diagnostic data was made via a wired interface to the boiler control boards itself. The data was collected locally using a data logging device (16) which relayed the data to a remote server. The core parameters which can be monitored are listed in Table 1 and are common to all models included in this study.

Table 1: Boiler Parameters

Variable Name	Description	Unit
Actual Power	Current boiler burner power modulation 0 – 100 %	%
Nominal maximum Burner Power	Nominal burner power (maximum heat output, normally DHW)	kW
Date	Recorded date, Format: dd-mm-yyyy	-
Time	Recorded time, Format: HH:MM:SS	-
Heat Request Status CH Frost *Heat Request Status CH EMS* *Heat Request Status Switch*	ON/OFF Flags for CH heat request coming either from frost temperature alert, a connected EMS or the room thermostat switch	-
Heat Request Status DHW Frost *Heat Request Status DHW EMS*	ON/OFF Flags for DHW heat request coming either from frost temperature alert, a connected EMS or internal DHW flow detection	-

Heat Request Status Internal Detection		
Supply Temperature *DHW outlet Temperature*	CH supply temperature, measured by boiler Domestic Hot water temperature measured leaving the boiler	°C
Working Time total Burner *Working Time CH* *Working Time DHW*	Total working time of burner, Working time of boiler for CH or DHW heat supply, recorded by boiler control system	min
Number of Burner Starts *Number of Starts CH* *Number of Starts DHW*	Total number of burner starts / Number of burner starts for CH or DHW heat supply, recorded by boiler control system	-

The data streams originate from different sources within the boiler; sensors, actuators or internally derived parameters. The accuracy of the measurements can be subject to the tolerance of the components used in production, in the case of temperature sensors an accuracy of ±2°C is referenced by the manufacturer. However, these tolerances can only be used as guidelines since the detailed boiler component data is company confidential and only general figures are quoted here. . For *Actual power* the value recorded is the 0-100% modulation level calculated by the boiler control board which is then translated into a fan speed to regulate the gas/air volume, as is standard in modern condensing premix boiler systems. In order to reduce network traffic and processor load within the appliance, information is only transmitted when the value changes, intermediate values are added in post processing in a 'fill forward' manner consistent with the communication method. The effective sampling frequency of the boiler data, after post processing, is 15Hz.

Buildings and heating systems

The 4 case studies were undertaken in buildings with two different layouts of heating systems covering two combination boilers and two system boilers over a period of one year (see Table 2). Although it was not possible to take a representative sample of the UK housing or heating stock with four dwellings, it was decided to include 2 combination boilers, as the dominant boiler type in the UK but also 2 system boilers to provide insight into the alternative form of boiler heating systems but also as the preferred configuration for most boiler alternatives, where 'combi' operation (i.e. without heat storage) is not practical.

In all cases the heating systems had already been installed for a number of years prior to the commencement of the study and no interventions were made during the observation period. All boilers in the study are from the same manufacturer, in order to enable the high frequency boiler control diagnostic data logging. The homeowners were recruited from an existing network of contacts including two employees of the manufacturer of the installed boilers (System_W1 and System_W2).

Table 2: Case study details, building and occupants

Building	*Combi_RT1*	*Combi_RT2*	*System_W1*	*System_W2*
Location	Oxford, UK	Oxford, UK	Worcester, UK	Stuttgart, DE
Occupancy	2 adults, retired	2 adults, working 2 children	2 adults, working 1 child	2 adults, working
Building Type	Detached House	Detached House	Detached House	Semi-detached
Heated Floor Area	106 m^2	111 m^2	87 m^2	122 m^2

Heated Floors	Ground, First	Ground, First	Ground, First	Basement, Ground, First, Second, Attic
Age, approx.	1910 (2004 extension)	1980	1850	1960
Construction Type	Original Solid brick Extension cavity wall	Cavity wall	Solid brick	unknown
Insulation	Partial cavity	Partial cavity	none	80mm External
Window type	PVC double glazed	PVC double glazed	PVC double glazed	PVC double glazed
EPC Rating	E47	D63	unknown	unknown
EPC Energy Use	401	224	unknown	unknown

A summary of the heating systems, thermal outputs of the boilers and design building heat loads is given in Table 3. The range of the boilers refers to the minimum and maximum modulation of the thermal output. The modern boilers installed in the case study buildings were all premix fan condensing boilers with pneumatically controlled gas valves for regulating the gas/air mix. This type of boiler typically has a modulation range (max output:min output) of the order of 6:1. The SYSTEM_W2 boiler was a special case where a demonstration boiler had been installed with a modulation range of 1:10 enabling thermal output down to 2.5kW despite a maximum output similar to COMBI_RT2 and SYSTEM_W1.

Table 3: Case study heating system information

	COMBI_RT1	*COMBI_RT2*	*SYSTEM_W1*	*SYSTEM_W2*
Boiler Range (min-max CH)	8 - 31kW	7 - 24kW	7 - 27kW	2.5 - 25kW
Boiler type	Combination	Combination	System	System
Radiator size	22kW	11.5kW	12.5kW	unknown
Building Heat Loss (26C ΔT)	8.9kW	8.8kW	7kW	5.1kW
Controller	Room Thermostat	Room Thermostat	Weather Compensation	Weather Compensation

In all cases boiler diagnostic data was accessed and recorded, allowing high frequency (5 second interval) recording of the internal sensor measurements and control parameters from the boiler (summarised in Table 1). This enables identification of fast acting dynamic behaviour of the heating system such as short operating cycles and hot water demands (in the case of the 2 combination boilers, including flowrates and temperature). In addition, temperature measurements (min 5 internal, 1 external) and gas/electric meter data were collected. The types and number of sensors and measurements in the 4 case study dwellings are presented in the following table:

Table 4: Summary of case study sensors and measurements

Building designation ->	**COMBI_RT1**	**COMBI_RT2**	**SYSTEM_W1**	**SYSTEM_W2**
Boiler diagnostic data	X	X	X	X
Outdoor temperature	X	X	X	X
No. of indoor temperatures	9	9	5	5
Building level gas & electric consumption	X	X		
Solar Radiation (Horizontal)	X			

It is worth noting that it was not practical to install heat meters in the dwellings as part of the measurement campaign so robust estimation of efficiency was not possible within the scope of this case study campaign. By combining the disaggregated thermal energy delivered by the boiler, corroborated by the gas meter, with the internal and external temperatures a Power Temperature Gradient (17) could be plotted to determine the in situ total building heat loss as presented in Table 3.

Role of Plant Size Ratio in efficiency

The Plant Size Ratio is the ratio of the heating plant thermal output to the building design heat demand (for a given temperature difference). Previous studies, current design guidelines (18) and recent simulations (19) tend to agree that a certain amount of oversizing, PSR > 1, is necessary when intermittent heating operation is utilised in order to ensure acceptable warm up duration, but that excessive oversizing could represent unnecessary capital investment and may be detrimental to the system efficiency. The dynamic simulations conducted in previous research (19) enabled analysis of various heating system configurations in a virtual house showing how oversizing can manifest itself as reduced efficiency and increased cycling. The modulation range, the ratio of maximum to minimum thermal output, of modern pneumatic premix boilers (such as those included in this study) is normally fixed and governed by the capabilities and tolerances of the gas and air mixing componentry. When oversizing of the main heating plant occurs then this inevitably raises the minimum thermal output of the appliance and therefore lowers (or totally negates) its ability to modulate and match the building special heat demand. Therefore it is important to highlight that high PSR alone is not enough to induce detrimental cycling, but combined with limited modulation problems can occur.

Observations from the heating system

The insight from this case study analysis is primarily derived from the level of detail afforded by the boiler diagnostic data. In Figure 1 an example is shown to demonstrate the granularity of the data and the features of the boiler behaviour that become visible with this type of data. In contrast to measuring half hourly gas consumption or heat meter data, accessing the boiler power level and internal supply temperature data sheds light on the underlying operation of the boiler, which in turn allows identification of behaviours detrimental to system performance.

Literature and recent simulations have shown that cycling behaviour of boilers reduces system efficiency, due to the increased impact of standby losses, decreased control of flow temperature (and therefore return temperature and condensing). Boiler operation such as that in Figure 1 is far from ideal, where the power level of the boiler is not constant and the cycling behaviour exhibited after 0715 is characterised by short periods of boiler activity followed by zero power modulation and pump overrun. The resultant central heating water temperature leaving the boiler (Supply Temp) is characterised by rapid rises when the boiler fires followed by rapid cooling to what is probably a more representative temperature of the bulk heating system water temperature.

This mode of operation is understandable when considering the boiler control system in this dwelling. The boiler is connected to a simple programmable room thermostat which indicates a call for heat by switching a relay connected to the boiler. From the perspective of the boiler this signal is a simple ‘call for heat’, a required room temperature increase of 1°C is indistinguishable from 10°C. As a result the boiler internal control defaults to delivering the setpoint it can control, supply temperature/central heating water temperature. This is shown in the figure as the horizontal line and it can be seen that for the initial period of boiler operation, the boiler can control the heating system in this manner until the modulation level of the boiler approaches its minimum value, after which the cycling behaviour begins. Since the call for heat persists, the boiler is forced to restart, at which point the internal control (in the absence of more sophisticated signal from the room/system controller) aims to deliver the supply setpoint temperature. When the power ramps up to reduce the supply temperature deficit, there comes a point where the rise in supply temperature is deemed too fast and possibly indicative of a blocked or thermally saturated heating circuit. At which point the boiler stops firing, the pumps continues to run for a period and the boiler waits until the ‘anti-cycle’ time has elapsed before restarting, assuming the call for heat is still in force. The ‘anti-cycle’ time is a parameter in the boiler which operates similarly to a hysteresis band on a room thermostat, it defines the minimum period of time between boiler firings, thereby avoiding rapid firings which could damage the boiler and the system.

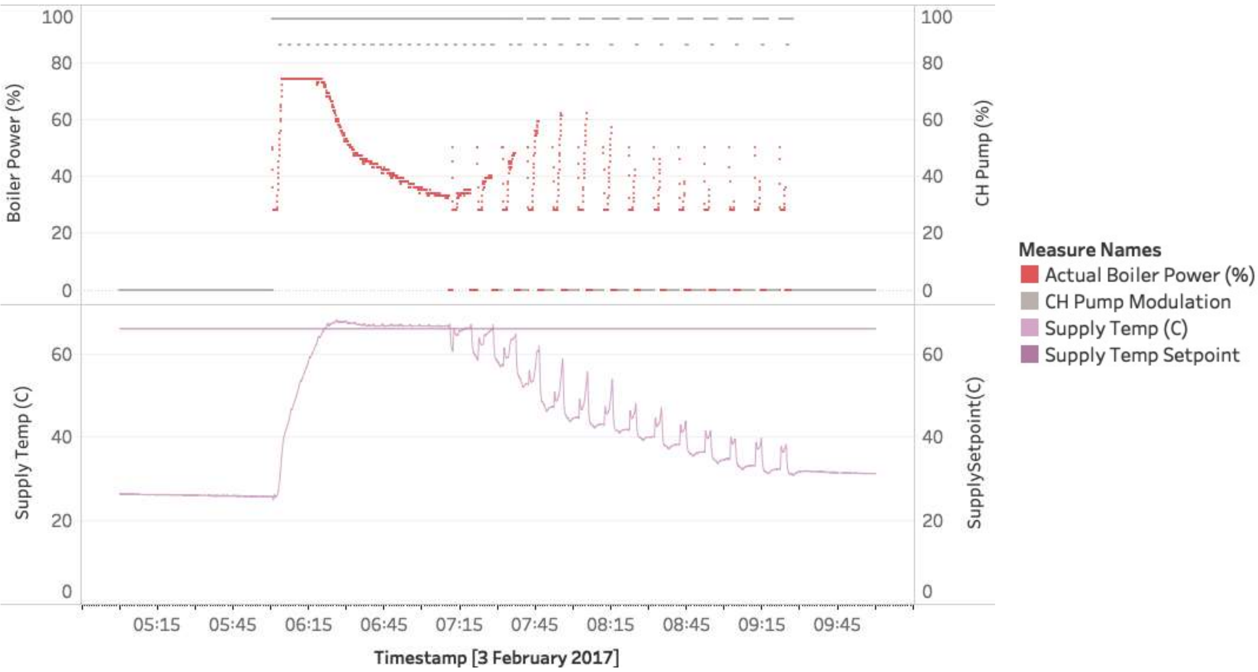

Figure 1: Example of recorded boiler diagnostic data from COMBI_RT1

Building on the detail of the data collected, the cycling of the case studies can be quantified by measuring the duration the boiler is active in heating mode between firings (diagnostic data allows disaggregation of heating and hot water, for both combination and system boilers). The distribution of which is shown in Figure 2. The x axis scale of cycle duration has been chosen to highlight the short nature of the majority of heating cycles, especially in the case of the combination boilers and to a lesser extent SYSTEM_W1, all of which have more than 50% of space heating operating cycles less than 6minutes. However SYSTEM_W2 has most cycles longer than 15minutes, implying higher efficiency due to lower proportion of standby losses.

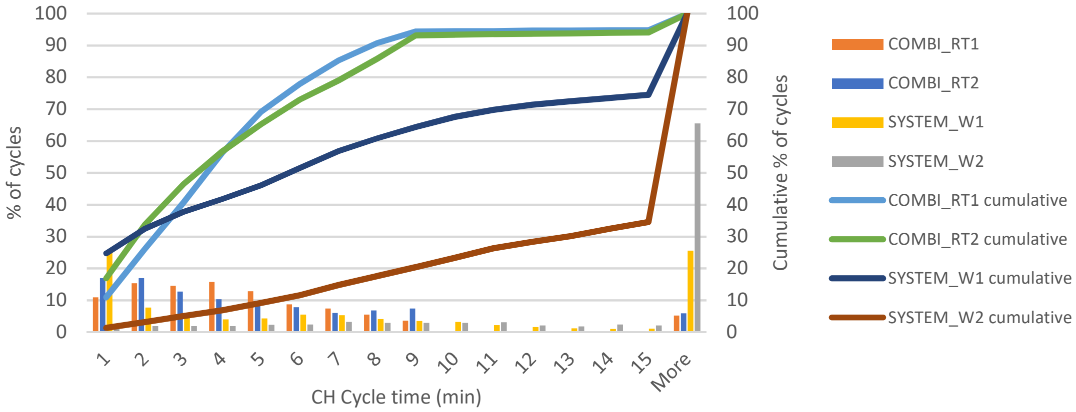

Figure 2: Distribution of boiler heating cycle duration length (1-15min duration 1minute bins)

Short cycle times, as seen in Figure 2, will tend to reduce the overall efficiency of the boiler by increasing the impact of the fixed electrical overheads of start-up and shutdown electrical losses from fan and pump operation in addition to the flue losses which are incurred through the same fan overrun . Whether these differences in boiler cycle times also reflect a tendency for the longer operating boilers (SYSTEM_W1 and W2) to operate in the more efficient supply temperature regime can be determined from the data presented in Figure 3. Although the return temperature is a truer determinant of boiler condensing ability at any given time, and therefore efficiency, a return temperature sensor is not fitted to the boilers in these case studies and was therefore not recorded. However, a lower supply temperature will inevitably lead to a lower return temperature and therefore an indirect appraisal of the probability of efficiency operation.

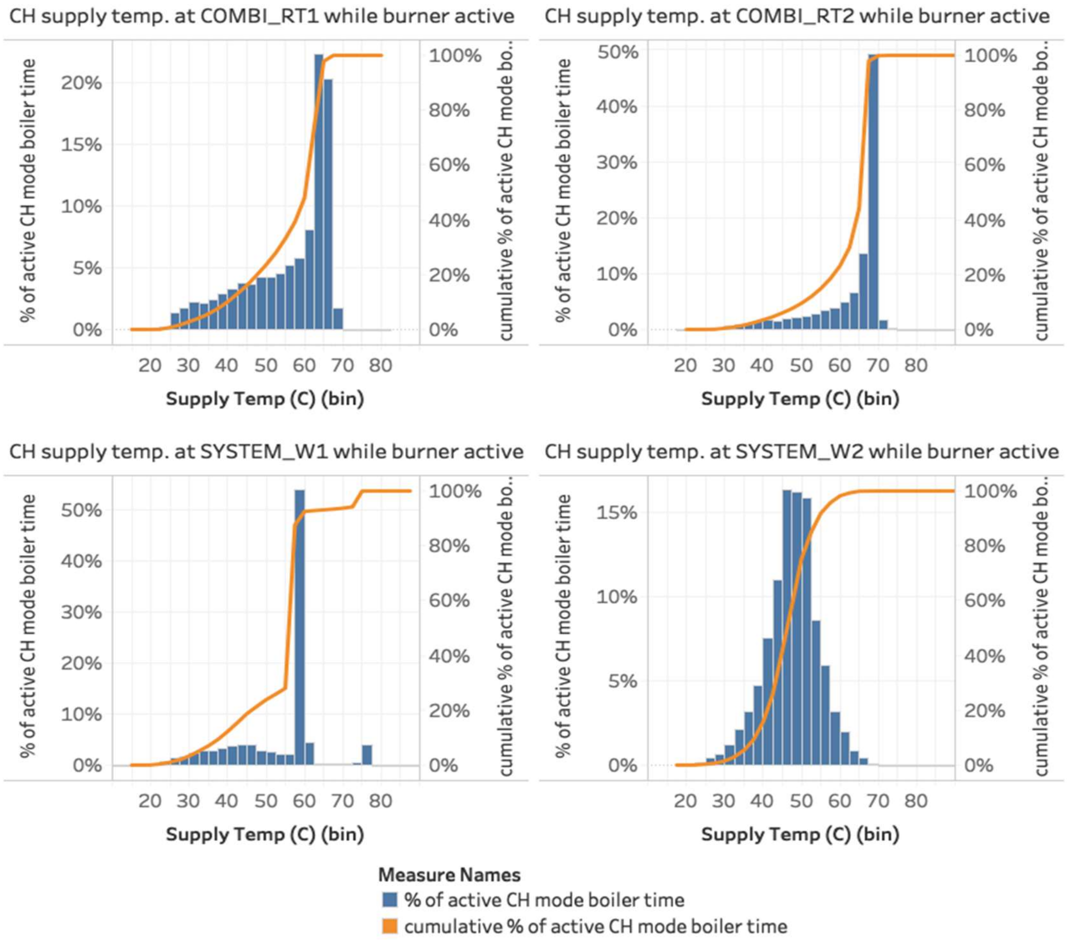

Figure 3: Distribution of boiler supply water temperature

SYSTEM_W2, as well as having the longest operating times, also has the lowest supply temperatures, with over 90% of the operating time spent below 60°C (the approximate threshold of latent heat gain through condensation (20)), indicating predominantly condensing behaviour and higher efficiency. The other case study boilers tend to cluster around an upper bound which corresponds closely with the user determined supply setpoint temperature. In addition to being linked with boiler cycle length, these differences can also be connected to the different room control types with the Room Thermostats connected to the combination boilers unable to offer proportional feedback to the boiler thereby the boiler defaults to simple supply temperature control. It would seem that SYSTEM_W1 also tends to this mode of control.

Without the ability of the boiler to match building heat load it will inevitably be forced to switch off to avoid overheating itself and the internal space. The comparison of the weekly building heat load and the lower bound of the boiler power modulation range is shown in Figure 4. In this context the cycling behaviour of the boilers can be more readily understood. Only in the case of SYSTEM_W2 is the boiler able to match accurately the building heat load due to the lower minimum modulation.

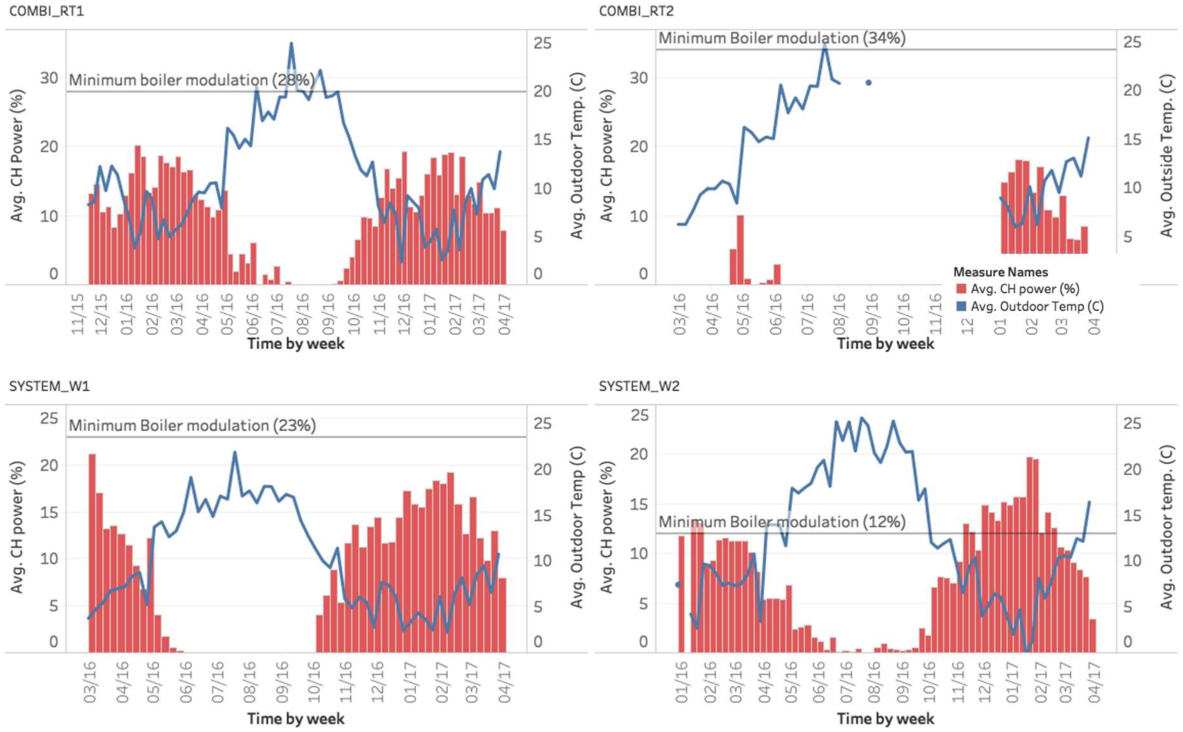

Figure 4: Mean weekly heating power and outdoor temperature compared with minimum power output of boiler

The mean CH power over each week is always below the lower modulation limit of the installed boiler for 3 of the 4 systems. This shows that even including heat up periods where maximum boiler power is called upon (see Fig.2) the mean building heat load is less than what the boiler can provide without entering cycling operation.

Conclusions

Gas boilers are the dominant technology in the UK residential heating landscape representing a long co-evolution of technology, skills, habits and practices. Despite this history, analysis of the case studies shows that installations which are oversized and operating sub-optimally still persist.

Mixed temperature and boiler diagnostic data collected as part of a case study framework show boiler cycling behaviour across all the observed dwellings; the extent of cycling seems closely linked to the plant size ratio and the modulation range of the boiler itself. The oversizing observed in the case studies is excessive according to industry norms recommended to balance rapid warm up times and costly investment in large plant.

Avoiding excessive oversizing and considering the minimum output of the installed heating plant is an important aspect of design and installation which is especially pertinent in the case of heat pumps. In the case of current day boilers, the ‘Combi’ operation was expected to be a crucial factor in oversizing, where sizing would be driven by hot water demand rather than space heating, and this was true for the combi boilers observed. However, the system boilers were also oversized implying that act of oversizing is not purely predicated on instantaneous hot water demand issues. Other factors must be playing a role such as a perception of acceptable level of safety factor when sizing and under heating being a larger risk to installers than under performance (caused by cycling) in terms of potential call back, although further research would be needed in this area.

The observation of widespread cycling was possible due to the case study measurement campaign and the inclusion of high frequency boiler data. Whether the cycling led to decreased efficiency in these cases was not measured (notably due to not recording delivered heat) however, the observations made during this relatively short and cost effective case study campaign do highlight areas of concern this should be readdressed for the current technology (boilers) and held in mind in the ongoing technology transition in building heat. Learnings from these case studies can be used to inform assessment tools such as the Standard Assessment Procedure (SAP) and Energy Performance Certificates (EPCs) which overlook the effect of oversizing of the heating system assuming that efficiency is constant and independent of boiler sizing. SAP makes some standard downward adjustments to boiler efficiency (21) based on field observations (6), as well as upward adjustments for certain control types. These case studies together with simulation (19) and wider observations (12) point to PSR as a metric for formally adjusting efficiency of boiler-based heating systems in a more robust and transparent manner. The current lack of integration of PSR into assessment tools is one aspect of a system which ignores this important aspect of system design thereby offering no method of making visible or penalising poorly designed systems.

Learning the lessons of incumbent mature heating technologies is a valuable exercise in highlighting issues that can deliver immediate benefits (reducing oversizing of boiler installations) and understanding the landscape into which the next generation of heating technologies will be installed. Where new technologies are less resilient to dynamic operational conditions, such as heat pumps with cycling, then continuation of the same practices could prove especially costly. Case study analysis of the incumbent technology together with the latest connected appliance data can provide a cost effective and broader picture of the issues to be addressed in a technology transition than demonstrator projects of the new technology itself. The wide range of existing homes, heating systems, occupants that can be chosen from to monitor without the uncertainty or cost of a technology intervention can shed valuable light on what challenges the new technology will face.

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