Space heating operation of combination boilers in the UK: the case for addressing real world boiler performance

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Abstract

Residential space and water heating accounts for 23% of UK final energy demand and combination gas boilers are the dominant technology. Performance gap issues in gas boiler systems have been reported, with previous studies unable to isolate or quantify root causes for performance issues, hampered by indirect and coarse measurement methods. Utilising high frequency data, through state of the art boiler diagnostics from 221 UK combination boilers, assumptions in efficiency standards are challenged. Total heating energy consumption and number of hot water tappings are in line with national expectations but the observed cycling behaviour of boilers gives cause for concern due to links with lower performance and higher emissions. Most combi-boilers appear oversized for space heating and despite available modulation are unable to prevent rapid on-off cycling. Per day, half of combi boilers studied average more than 50 starts and 70% of starts average less than 10 minutes during space heating operation. Cycling contradicts assumptions in efficiency testing standards, which assume steady state operation, weighted by full and part power measurements. Addressing oversizing and excessive boiler cycling provides an opportunity to quickly and significantly reduce emissions associated with heating, at low cost through the ongoing replacement of millions of boilers.

Practical Application

Lessons learned from this research regarding the detrimental performance issues seen in gas combi boilers are directly applicable to the topics of boiler specification for building service engineers and installers, such as guidelines in CIBSE Guide A [1], CE54 Whole house boiler sizing method [2] and legislation set out in BoilerPlus from the Department of Business, Energy and Industrial Strategy. Plant Size Ratio, radiator hydraulic layout and controls can all contribute to the rapid cycling seen in the data and can all be influenced by building service professionals. Boiler modulation range is also crucial and manufacturers need to be aware of the benefits of extending modulation in new products.

Introduction

Ambitious targets for emissions reduction have been set in the UK under the Climate Change act of 2008, since residential energy demand accounts for 29% of UK final energy and 80% thereof is used for space and water heating [3]. This puts domestic heating emissions firmly in the spotlight. During the last twenty years, the use of gas fired combination boilers (commonly referred to as 'combis') for central heating has significantly increased in the United Kingdom, from around 12% in 1996 to over 60% in 2015 [4]. Such boilers provide domestic hot water (DHW) and central heating (CH) without a separate storage tank, as seen in Figure 1. Combination boilers offer a compact, low cost and low disruption solution for conventional central heating systems which, in the case of boiler replacement, often allow the homeowner to free up space by removing hot water storage cylinders, the prevalence of which has reduced from 63% to 38% between 1996 and 2014 [5]. This can also, be advantageous in terms of reduced storage tank losses due to 'on demand' or 'instantaneous' hot water production. The compact and simple nature of the appliances is clearly seen as an advantage in the market which can release valuable floor space, which ranges in value from the national UK average of £2,395 per square metre up to almost £20,000 in central London [6]. Since the introduction of new legislation in April 2005 in the form of Building Regulations Part L1, minimum efficiency requirements effectively made condensing boiler technology mandatory for new or replacement boiler installations [7]. This step change in the market towards higher efficiency boiler technology, led to an increase in the number of condensing boilers from 2% of the stock in 2001 to 59% of installed boilers in 2015 [4]. Condensing boilers can deliver efficiency gains of 10-15%, particularly when lower system water temperature enables scavenging latent heat from the combustion gases [8]. This simple improvement is highlighted by efficiency testing in steady state conditions for condensing and non-condensing operating regimes [9]. However, this is not mirrored by the operating regime, supported by compulsory building regulations where boilers can be upgraded to condensing versions without the corresponding change in emitter sizes to enable lower return temperatures. Epidemiological studies have shown that replacing boilers with condensing boilers has had a positive effect on energy demand [10, 11] but there remains room to investigate how much change was attributable to merely the act of replacement of old appliances, and how much potential improvement remains. Since the 1980s it has been known that although replacing conventional boilers with condensing will generate energy savings, further boiler efficiency improvements may be achievable. Optimising the hydraulic circuit, either in terms of emitter sizing or simply balancing radiator valves to ensure even distribution of heat and lower return temperatures can further improve the situation, in some cases from an initial 15% gain up to 30% with radiator tuning [12]. Although boiler sales have remained strong in recent years, radiators have not followed suit [13], implying that heating system upgrade is lagging behind boiler replacement improvements, which may be due, in part, to distress purchasing in the case of broken down boilers [14]. The issue of heating system installation is made more complex by the role of installers and plumbers in the heating system specification process where the influence of non-technical issues, such as installer communication with the user, can exacerbate matters [15]. It is suggested that many boilers are exchanged with no adaptation of the control or radiator system to ensure optimal operation possibly due to added disruption, cost and customer preference.

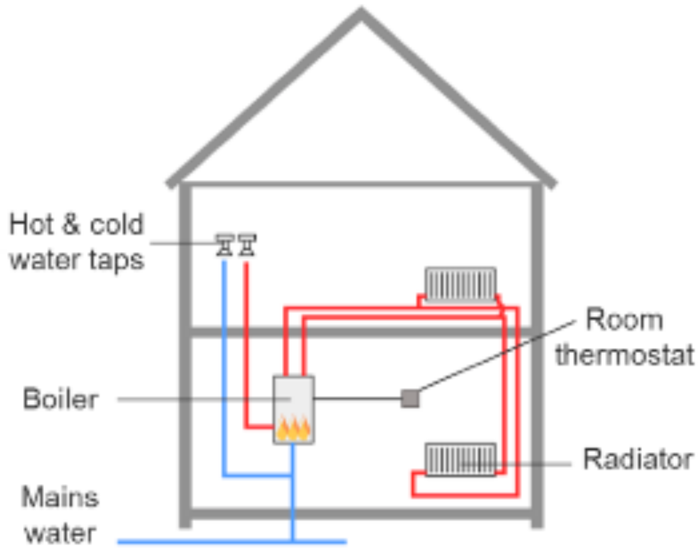

Figure 1: Schematic of typical combi boiler heating and hot water system.

Studies have reported discrepancies between boilers efficiencies in situ [16-18] and the efficiencies measured according to international standards [9] for both regular and combination boilers and across a range of manufacturers. Focussing on boilers only, as in these studies, belies the complexity of a modern heating system and the interaction of heat generation, distribution and control. Studies so far have focussed on boiler efficiency as a key performance indicator of the overall heating system, and have relied on building level gas consumption, heat meters, indirect temperature measurements, coarse measurement intervals (>5mins) which leads to limitations in the conclusions which can be reliably drawn from the data. Research in the field of heating system dynamics has been limited since boilers are seen as a mature and established technology, however performance influencing themes have emerged in the areas of cycling times, modulation level and in the case of condensing boilers, return temperature [19, 20] which shows the potential scope and direction of improvements in this area. While standardised heating appliance efficiency measurements [9, 21, 22] leading to appliance labelling [23] are useful for comparing one appliance directly to another, heating appliances are installed in complex heating systems, not as isolated appliances unlike other labelled whitegoods such as washing machines, dishwashers and fridge/freezers. Heating appliances are however more complex and the interplay between boiler, building and user makes energy labelling of heating appliances [24] and buildings [25, 26] more challenging.

The role of labelling alone is likely to be less important when selecting boilers compared to whitegoods, due to the power the installer has in its selection [15]. This is evidenced by the poor uptake of condensing boilers till the introduction of regulation, [11].

How heating system design, control and dynamic response impacts on boiler efficiency and the magnitude of their impact is not yet quantified from field data of sufficient quality to draw meaningful conclusions which could lead to improvements in standardised testing regimes to reflect the reality of real life heating systems.

When a heat demand is generated by the building thermostat or control, the boiler responds by heating and pumping hot water through the heating circuit, in an ideal system the response would enable the room temperature set point to be reached as quickly as possible without overshoot or delay. In practise even the most optimised heating system will be subject to delayed response of the room temperature due to thermal lag from building and heating circuit thermal mass; it is also possible that the heating system can fall short of its design potential and the user's expectation if the boiler is forced to operate with a series of short heating operations interspersed with periods of boiler idle. Such cycling behaviour may not only result in a delayed or irregular achievement of the required room temperature but also other undesired consequences related to efficiency and emissions [20, 27]. Understanding the manner in which this signal is generated and all steps in the feedback loop is crucial to optimising the overall system. Heating controls broadly fit into two categories, proportional control or thermostatic control, sending a modulated power request or ON signal respectively based on one or more inputs: internal temperature (as measured by the controller or its sensors), outdoor temperature, hysteresis, preheating or using a simple time program [28]. When proportional control is implemented then the boiler is expected to react by modulating the power output to the required level, which was not possible historically when boilers were limited to a fixed power or stepwise power delivery. Improvements in boiler technology have led to modern modulating boilers which can vary their thermal power gradually across a finite range and has allowed for combination boilers to produce hot water on demand using the same primary heat exchanger and a secondary plate heat exchanger to regulate the outlet temperature according to the tapping flow rate, although the advance of dual functionality may be leading to oversizing of the space heating output in order to accommodate the required hot water demand [29] which is consistently larger than central heating.

How a boiler reacts to timed thermostatic control is primarily down to heating system design and boiler internal algorithms. In the case of space heating operation, boilers normally include 'anti fastcycle' and pump overrun functions [30, 31] which limit the minimum time between burner starts. These functions mitigate undesirable control strategies from the heating system, which could lead to scalding hot water temperatures due to stored thermal energy in the boiler as well as reduced component lifetime by exceeding components cyclic or thermal limits. However, any delay in restarting space heating needs to be balanced against a possible occupant comfort penalty should the internal temperature drop noticeably. In the case of DHW mode in combi appliances the burner operation is concurrent with hot water demand, so no such functions are applicable. However, DHW always takes priority over space heating on the assumption that an interlude in space heating to satisfy a hot water demand will not be noticed, or at least not as much as a failure or delay in providing hot water. In the case of combination boilers, the distinction between CH and DHW operation is an important one. The means by which the demand can be affected differs: although both heating and hot water demand are complex, hot water is more directly related to user behaviour than heating. Hot water tappings are directly correlated to boiler operation in DHW mode but the central heating schedule from the room thermostat may not be representative of boiler operation. With short run times of the boiler the side effects of certain safety critical functions become more apparent. In the case of all gas boilers, regardless of manufacturer, a pre and post purge is necessary and mandatory [32] to clear the primary heat exchanger of combustion products which can inhibit ignition, the duration of these purge operations is fixed at approximately 30-45seconds depending on boiler type. Using the fan within the appliance, air is blown through the heat exchanger carrying heat out through the flue and out of the property, as well as costing electrical energy without contributing to space heating. In essence, during a heating demand, the shorter the period of operation when the boiler is producing heat (operational time) the more significant the flue loss due to fixed pre and post purge times of the boiler start/stop process becomes for the overall gross efficiency. The likely variation of flue losses with boiler operation time have been estimated in previous laboratory research (Table 1, [18]) and are strongly dependent on the length of cycle.

Table 1. Effect of Cycle times on boiler efficiency [18].

Operational time per cycle (seconds)	% change in gross efficiency
3600	0.0%
180	-1.5%
120	-2.3%
60	-4.1%
30	-6.8%
10	-11.8%

Short operational cycle times, of the order of 3 minutes or less, not only have a significant negative impact on the efficiency of the appliance leading to unnecessary CO_2 emissions, but they also influence the other emissions from the start up sequence itself, such as carbon monoxide (CO), nitrogen monoxide (NO) and total hydrocarbon (THC) including methane (CH_4). These emissions from imperfect combustion form a low fraction of the overall emissions if the boiler is running in a quasi-steady state, but a study of start and stop emissions [33] showed that these emissions increase significantly during boiler start and stop operation. With cycle operational times of the order of 150 seconds THC emissions are 0.8 mgC/kWh for the almost steady state and 95.6 mgC/kWh for the start/stop operation. This means the THC emissions are 120 times higher in start/stop operation compared to the steady state.

To try and extrapolate these laboratory measurements to a wider context is not supported by the research so far, since it was noted in the experiments that the emissions depend greatly on variables such as burner geometry and heating water temperature. The conclusion was limited to the statement that the magnitude of the emission bandwidth is expanded by the increased start/stop behaviour in a distinctly unfavourable direction [33].

Methane leakage from production and distribution infrastructure has already been identified in the research as an area of concern which can offset the CO_2 benefits of fuel switching from oil and coal to natural gas [34]. In the context of domestic boilers increase in emissions can potentially also offset greenhouse gas emission savings when considering that the THC consists mostly of methane, a strong greenhouse gas having a global warming potential (GWP) of $GWPCH_4 = 84$ for $t = 20$ year and $GWPCH_4 = 28$ for $t = 100$ year [35] compared to CO_2.

Boiler manufacturers will often implement custom algorithms with regards to the start up sequence to support smooth establishment of a stable flame, this can require starting at a relatively high power level (independent of current heat demand) and then modulating to the required level. Because these algorithms can vary widely between manufacturers and are not captured in either emissions or efficiency testing it is not yet possible to assess the impact on the wider boiler population. On the basis that short cycling operation of gas boilers generally negatively impacts expected efficiency and gaseous emissions and in order for condensing combi boilers to build upon their proven track record of energy savings and achieve their full potential, the causes of short cycles should be identified, quantified and considered in standards and legislation. To understand to what extent such conditions occur in real buildings it is necessary to identify and quantify cycling operation of boilers through boiler measurements at a suitable temporal granularity. Indirect methods, such as temperature measurements on the heating circuit or radiators, have been sufficient for drawing conclusions about daily heat demand [36] but do not offer the precision required to analyse boiler response: measured heating circuit temperatures will lag behind boiler firing and may not respond quickly enough to see short cycles. New measurement techniques are needed to provide the quality of data needed for a deep analysis of the fine temporal cycling behaviour of boilers. Access to boiler diagnostic data in modern heating appliances allows for recording of high frequency data for a fraction of the cost and effort compared to traditional methods. Remote logging has also allowed low cost recording of data from many locations simultaneously, thus allowing higher levels of detail than previous studies and greater insight. With modern data acquisition tools and an appreciation for heating system dynamic operation and control, insights can be gained which can contribute to further improving gas-boiler-based heating system performance.

This paper sets out to utilise these latest measurement methods to perform a detailed analysis of boiler performance, thereby opening new possibilities for in-situ heating system research and contributing to the understanding of boiler performance knowledge.

Methods

Boiler diagnostic data

Due to the compact multifunctional nature of combination boiler construction (see Figure 2), the operational characteristics of all CH and DHW demands are captured in the internal sensor and diagnostic data of the boiler itself. In contrast to more traditional central heating systems with tank storage, the combination boiler appliance control is taking care of regulating hot water supply to the building directly without external supplementary controls, sensors or storage. Concentrating thermal, hydraulic and control aspects into one appliance is advantageous to the user in terms of space saving but also for researchers this presents the opportunity to access one source of data for heating and hot water supply and demand. Modern boilers have a relatively complex control system utilising microprocessor control and software to optimise performance and ensure safe operation. The software algorithms require input data from sensors and actuators to calculate and implement the control strategy, some aspects of which are mandated by legislation, common to all manufacturers and models, but many are uniquely developed by the manufacturer to meet customer requirements and expectations. This sensor data is usually only utilised for the control of the boiler operation in concert with thermostats and controls, but modern internet connectivity has been implemented, by manufacturers [37], to send the data to a remote server where the data can be stored and interrogated.

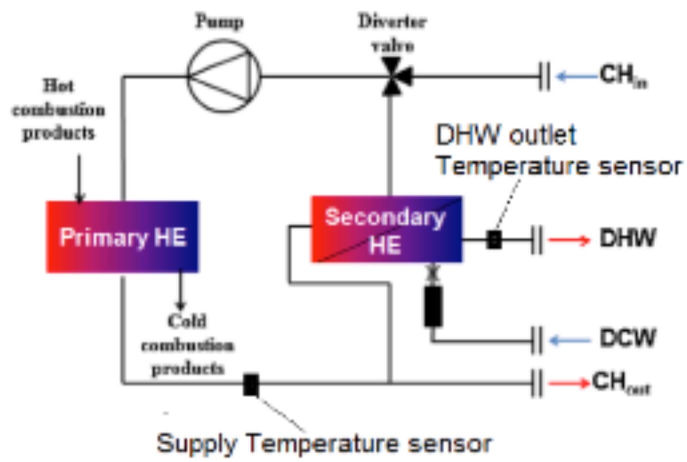

Figure 2. Combination boiler schematic. (CH: Central Heating, DHW:Domestic Hot Water, DCW: Domestic Cold Water, HE: Heat Exchanger)

Many boilers models introduced to the market in the last decade have the facility to transmit the internal diagnostic data via the internet to a central server. The data is available via the proprietary Energy Management System (EMS) bus. A download of 338 boiler data files, logged from February 2014 to August 2015 was made available to the researchers as common '.csv' files, which is one per boiler. Boiler installations were not randomised and no contextual variables were collected to stratify the sample, although there is some evidence presented later in this section to suggest that the installations analysed were not atypical of UK combi boiler systems. Each boiler records a total of 109 variables, the most pertinent of which are listed in Table 2.

Table 2. 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* *Heat Request Status Internal Detection*	ON/OFF Flags for DHW heat request coming either from frost temperature alert, a connected EMS or internal DHW flow detection	-
Supply Temperature	CH supply temperature, measured by boiler	°C

DHW outlet Temperature	Domestic Hot water temperature measured leaving the boiler	
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 datastreams come from various sources within the boiler; sensors, actuators or calculated internally by the boiler control board. As such the accuracy of the measurements can be subject to the tolerance of the components used in production, as is the case of temperature sensors, where the manufacturer states an accuracy of ±2°C . 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. 100% boiler modulation refers to the maximum boiler output but, in many combi models, this is only used for DHW preparation and maximum CH would be less than this value. The control of the fan is normally achieved by means of a feedback loop between the boiler control and on-board fan electronics, the current speed of the fan is measured using a hall sensor and the interpreted signal sent back to the boiler control with an estimated accuracy of ±200rpm across a range of approx. 5000rpm. 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.

The data collected is not recorded at a fixed time step but only sent from the boiler when a parameter changes, this method has been implemented by the manufacturer in the boiler software to reduce the total data volume transmitted and therefore the load on the homeowners internet connection.

The csv files were imported into Matlab for analysis and visualization. Conversion from csv into the native Matlab '.mat' files was necessary to reduce the file size and respective load times to a practical level so analysis could be carried out on a desktop PC. Initial visualisation of individual boiler logfiles and prototyping of the analysis algorithms was carried out on an individual desktop PC, enabling fast debugging iterations, before utilising greater processing power to analyse all boiler logfiles from the dataset and collate the results.

Only boiler datasets of at least 12 months were included in the CH analysis. On average 404 days were recorded per boiler. Also, as is common with remote datalogging activities, data loss and corruption is possible and was addressed prior to analysis. A number of pre-processing filter steps were carried out to ensure that unreliable data was excluded from analysis, this included the following pre-processing filters for all data files:

- Is the channel data within expected limits? E.g.
    - Is 'Actual Power' in the range 0-100%

- Is there corroboration of the Heat Request Status? Internal Detection has to identify the DHW demand (i.e. Flow turbine measurement & DHW outlet temperature)

An advantage of multiple channels of data from the boilers is that logic checks could be carried out to verify data quality and events, for example, a central heating demand flag is sent as a Boolean, but at the same time, the burner must fire, the pump and fan must run and finally the central heating water temperature must rise. Operation is similar for domestic hot water, but with the addition of the flow turbine sensor and hot water outlet temperature signals. Together these signals were used in the analysis to corroborate the existence or false logging of heating and hot water demands. Similar corroboration of signals is used by the boiler internal software for error detection.

In total control data from 338 boilers was collected, however due to the above mentioned pre-processing criteria, 221 could be used for the analysis of central heating data. 117 boiler data files were discarded due to one or more of the following reasons:

- Measurement period less than one year
- Missing data periods (>20days total)
- Missing parameters

Using these criteria allowed the data to be used for yearlong energy and cycle analysis of CH and DHW operation without significant data gaps. All boiler data under consideration in this research is from boilers produced by Bosch Thermotechnology and all are gas fired combination boilers. The models found in this dataset draw attention to the common practise of oversizing of boilers, which is prevalent in the combi boiler market. Due to the dual function of hot water and heating required from a combination boiler the function with the higher thermal demand takes precedence when specifying an appliance for a given building installation. Figure 3 shows the breakdown of the maximum thermal power output (DHW) and maximum central heating output of the reported boilers. Note that the maximum thermal output can differ between central heating and domestic hot water, with the latter being the higher. The boilers were a mixture of models with different ratios of maximum power to maximum CH output, hence the different distributions in the charts, but all boilers were either 25 or 31kW CH output.

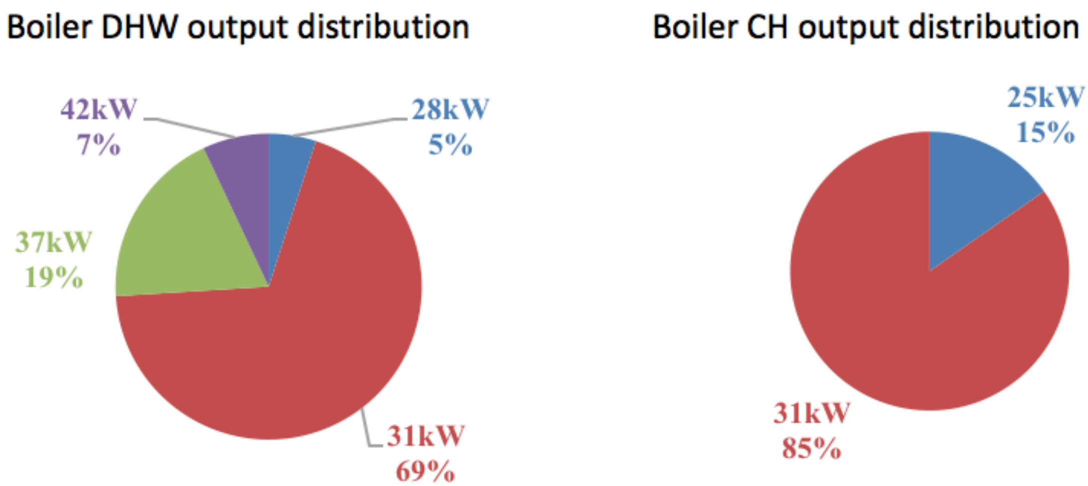

Figure 3: Nominal maximum Burner Power of the appliances

Boiler energy consumption was derived by multiplying the average actual power level, expressed in 0-100% modulation, by the known nominal maximum Burner Power, then summing over the time period where the respective CH or DHW flag was active, thereby distinguishing between heating and hot water energy consumption. This is an approximation for the gas consumption of the boiler and not a direct measurement. Although the boiler modulation level follows closely the fan speed, the exact volume flow rate of gas which is fed to the burner as a result of the fan controlled pneumatic gas valve depends on the inlet gas pressure at the valve, this pressure is not measured by the boiler and therefore remains unknown, although it should not be outside the range 19 - 23 mbar at the gas meter and 16.5 - 20.5 mbar at the boiler gas valve, taking into consideration gas pipe losses within the building [38, 39].

Boiler UK context

Although the details of the buildings in which these boilers are installed is not known, and therefore a direct assessment of the suitability of the boiler thermal output to building thermal load cannot be made, a qualitative comparison with the estimated space heating load of the UK housing stock shows that even the smallest recorded boilers (28kW DHW 25kW CH) is larger than would be normally necessary when considering a simple steady state heat requirement for the buildings. Figure 4 shows the distribution of design building heat loss [40](-2°C outdoor, 21°C indoor, steady state) derived from the building stock data in the Cambridge Housing Model, CHM, [41]. Included in the CHM model is the fabric heat loss and ventilation loss as derived according to the UK Standard Assessment Procedure [42]. Estimating the steady state design day heat loss in this manner shows that almost all buildings would require a boiler of less than 36kW output and 95% below 20kW with a median value of approx. 6kW. However, combination boilers are generally sized according to instantaneous hot water demand, which exceeds the space heating demand, therefore leading installers to size boilers on hot water only with little regard for boiler size relative to space heating demand, known as the plant size ratio (PSR) [43] . Whilst the boilers analysed here were not selected by a stratified sample across the built stock, given this context it is likely that a significant number of boilers in the analysis dataset are oversized with respect to space heating.

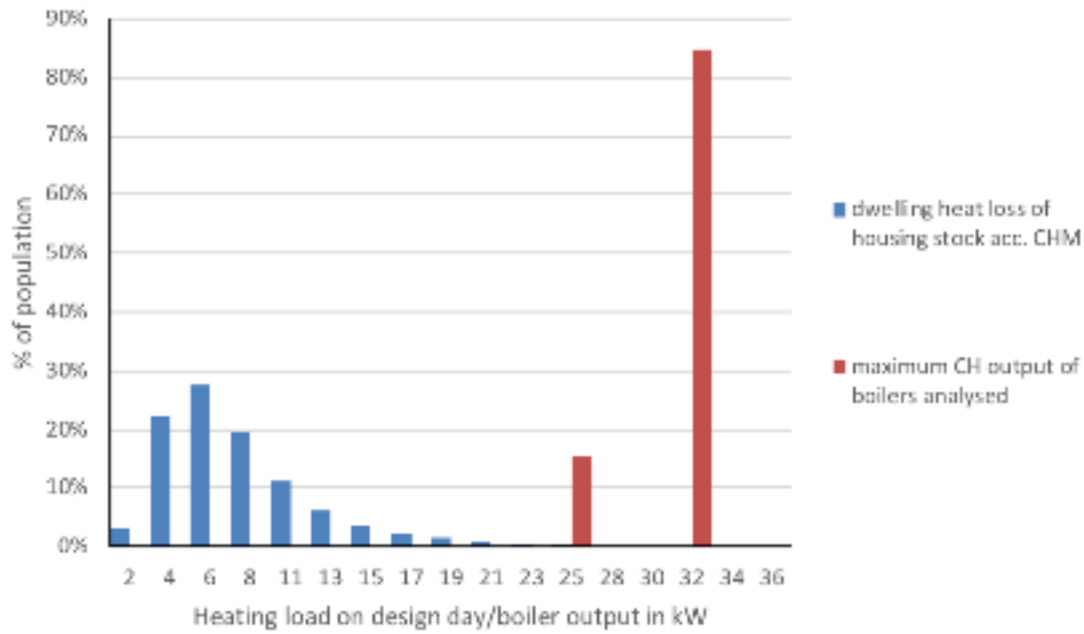

Figure 4: Distribution of English housing stock building heat loss on design day as predicted by the Cambridge Housing Model [41] compared to the maximum CH output of the boilers analysed in this paper.

The steady state heat loss requirement of a building is only part of the picture, and would be sufficient for heating system design in buildings where the operative internal temperature was required to be constant. However, variable heat schedules mean that the heating demand periods change in an intermittent manner and additional thermal power is needed to raise the internal temperature quickly in order to deliver the comfort that occupants expect, the response time will depend on the building and the heating system. Parameters such as the heat loss coefficient, thermal mass, heater thermal output, emitter size and temperature will all combine to determine the responsiveness of the internal temperature. Compensating for the intermittent heating schedule and taking into account the thermal response of the building from slow (masonry walls, internal partitions) to fast (lightweight external cladding, suspended floors and ceilings), first approximations of the increase in heating plant size can be seen in Table 3. The number of heating hours of a residential house is standardised as 9hrs (2hrs mornings, 7hrs evenings) on weekdays and 16hrs (as one block) at weekends in the SAP national calculation model for Energy Performance Certificates, and also measured as between 6-14hrs in field research [44] and therefore the estimated requirement for plant oversizing (compared to steady state) would be a maximum of 2. This would increase the median expected plant size from 6 to 12 kW in the case of light construction fast reacting buildings; slower, more thermally massive buildings would not require such over dimensioning since the internal temperature will drop slower in between heating periods.

Table 3: Plant size multiplication factors according to building thermal response [1]

Daily hours of heating operation	Multiplication factor acc. building thermal response	
	Slow	Fast
12	1.0	1.0
6	1.1	2.0
4	1.2	2.8

Using the logged power level data, CH/DHW mode flags and the recorded thermal output of the boilers it is possible to integrate the delivered annual (Feb 2014 to Feb 2015) thermal energy to DHW separately from the space heating circuit during the heating season (October to May). Further comparison with the estimated annual space heating from the CHM is therefore possible and presented in Figure 5. First assessment shows that despite the significantly larger boiler size than the UK building stock would require, which has been linked to increased energy consumption [19] and lowered efficiency [20], heating energy demand is of the same order of magnitude with a median of 12,400kWh/year compared with 17,000 kWh/year from the CHM for the building heat demand. The CHM predicts more buildings with heating demand of more than 50,000kWh and a generally larger number of buildings with higher heating demand compared to the analysed data. This may relate to the lower likelihood of finding combi boilers in larger buildings with multiple bathrooms, and therefore high peak DHW demand, despite sufficient boiler heating capacity. However, as noted above, the analysed data does not come from a representative sample of UK dwellings and must therefore be interpreted with care. Despite this issue, the measurements and the CHM data are broadly similar, and consistent with where most combi-boilers are installed i.e. in smaller properties.

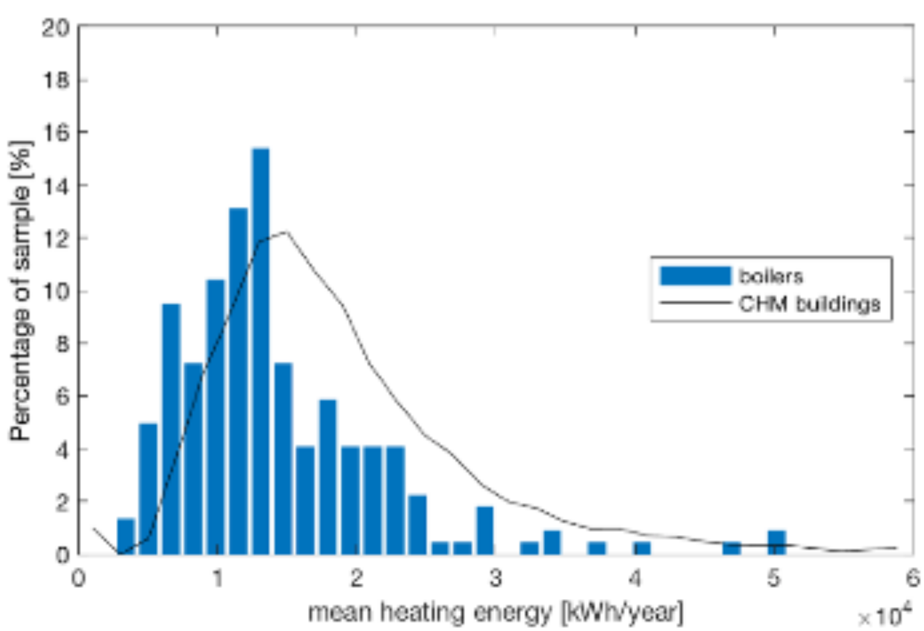

Figure 5: Annual building space heating energy demand derived from boiler data compared to modelled space heating demand of the English housing stock (Field data & CHM [41])

Results and discussion

Boiler cycling and start/stop behaviour

In the following analysis, a distinction is made between a heating demand (Domestic Hot Water, DHW or Central Heating, CH) and a boiler start. In the case of a combination boiler a heat demand will occur either when a hot water outlet (tap, shower etc.) is opened and the flowrate is above a predetermined threshold, or when the room thermostat makes a call for heat to raise the internal temperature to the required set point at that time. However, heat demand needs to be differentiated from boiler start. In the case of DHW the relationship is direct since the demands are equivalent to the boiler starts, the boiler directly recognises the flow of water to the hot water outlet via a turbine and initiates the burner start sequence. Combination boilers will always give priority to DHW demands on the basis that a short interruption in space heating will not be noticeable when compared to delayed hot water. In the case of room controllers, a wide range of controllers are available on the market which vary from simple timers with no thermal measurement of room temperature, to weather compensating and so called 'smart' controllers. How these controls decide when and how to send a demand signal to the boiler is not always transparent. In the case of thermostatic relay control a switch is closed when the temperature rises above a certain threshold (room temperature setpoint, with consideration of hysteresis) sending a demand to the boiler and conversely opening the switch when the temperature is reached and the demand has been satisfied. The magnitude of the temperature rise required is not communicated to the boiler and its viewpoint of an on/off thermostat as described is indistinguishable from a simple timer. Additionally, multiple control systems may be present in the dwelling, such as a room thermostat, linked to the boiler directly, and thermostatic radiator valves which limit the flow rate based on the setpoint at the radiator. If these two systems are not aligned then demand can be requested by the controller but be unable to be delivered because of the closed radiator valves the mechanism of which is discussed further in the next paragraph. To a lesser degree the same phenomena could be experienced through the undersizing of radiators, either pushing a condensing boiler into a non condensing regime or forcing the boiler to cycle. A number of installation specific features can lead to a disparity between the heat demand and the number of starts the heater makes to fulfil the demand. No one component of the heating system will determine the magnitude of the mismatch.

Certain aspects of mandatory safety and operational functions of all boilers, coupled with heating system design can lead either to a delay or to the premature termination of the boiler operation before the heating demand has been satisfied. The nature of combination boiler functional priority is again pertinent here due to the need to fulfil DHW demands at the expense of an interruption in space heating operation. Causes related to heating system design include, but are not limited to, hydraulic blockage and insufficient heat transfer to the building. These could result in a maximum allowable temperature being reached at the supply temperature (CH water leaving the boiler as per Figure 1) sensor in the boiler leading to termination of heat delivery. A maximum limit is set in order to prevent boiling in the appliance and damage to the heat exchanger. Hydraulic blockage in the CH circuit could be caused by debris or a mismatch of room controller and Thermostatic Radiator Valve (TRV) setpoint causing the TRVs to be closed and therefore insufficient heat transfer to the building, with a bypass installed a complete blockage can be avoided by allowing a short circuit back to the boiler. Similarly, the boiler/room control system also plays a significant role. When the room controller is only capable of sending a binary heat demand signal, the boiler has no mechanism to modulate down when approaching the setpoint temperature of the room, therefore overshoot is to be expected [19]. We believe this type of simple room controller was installed to control all the boilers monitored as part of this study, this conclusion was reached due to the lack of a modulating signal input in the EMS data, not because of any filtering criteria. Simple room controllers would seem to represent the general state of installed heating controls in the UK as seen in other studies of boiler performance [29]. Improvement can be made with proportional controls capable of estimating the required power demand based on the temperature difference between current and setpoint room temperature. At low demand levels (i.e. less than 20% of the boiler capacity), the minimum modulation level of the boiler, typically 20/30% of the maximum output [45], can result in a higher level of energy delivered to the heating system than required[19] and therefore a higher return temperature, eventually resulting in maximum supply temperature being reached.

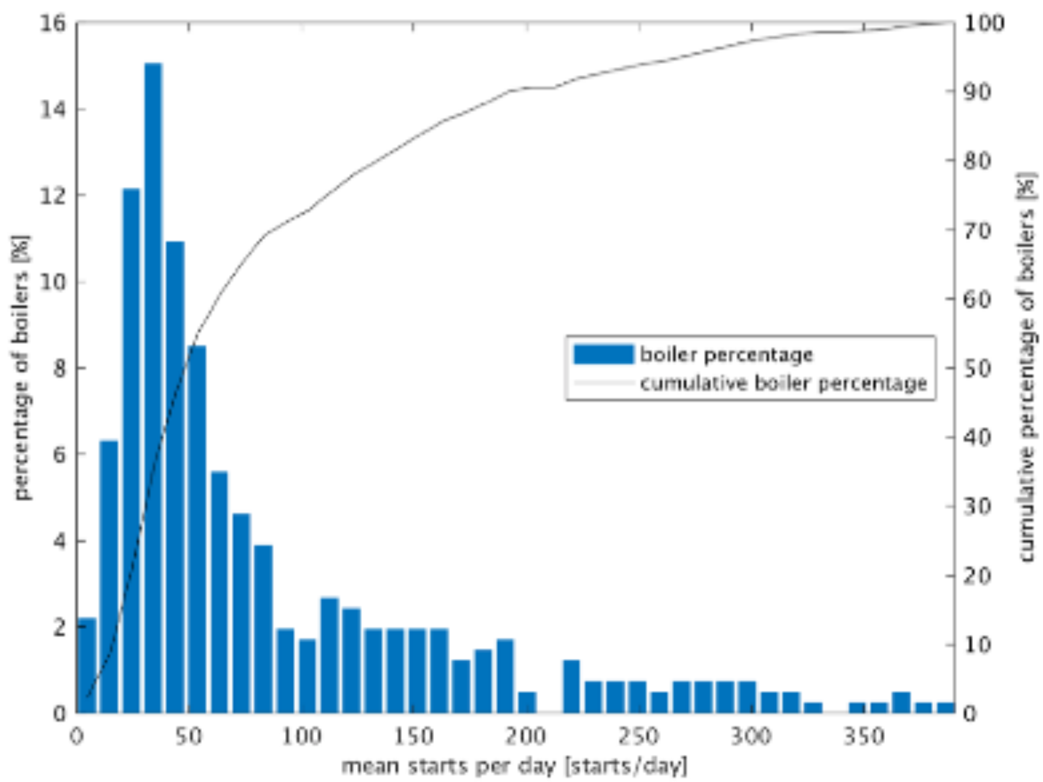

Figure 6: Histogram of total annual boiler starts, all boilers Feb 2014-Feb 2015

Figure 6 shows a wide range of number of daily boiler starts, 70% of boilers have less than 100 starts per day. On average this would be 4 starts per hour. The median of 53 boiler starts per day, contrasts starkly with the mean of 93, reflecting the extended tail of boilers with high daily boiler starts**.**

This was further investigated using the CH/DHW flags, which allow the differentiation of the starts according to the associated heat demand type. Due to the direct correlation of DHW demand and DHW start, the histogram shown in Figure 7 can be directly compared with EN13203-2 [22], the European standard used for heating appliance performance testing for hot water production. EN13203-2 describes standardised DHW profiles in terms of total hot water demand but also in the form of daily tapping profiles corresponding to different household demand groups from small (S, 11 tappings) through to extra extra large (XXL, 30 tappings).

Simple comparison of the average boiler starts recorded (see Figure 7) shows there are a small number of boilers making high numbers of DHW starts but the median of 18 tappings and mean of 36 tappings per day. From the L and XL size tapping profiles of EN13203-2 (DHW production efficiency testing standard), between 19 and 24 tappings per day are stipulated, which broadly agrees with the average values see from the data in Figure 7. But with a quarter of households in this sample making more than 40 tappings per day then consideration should be given as to how this impacts the national demand hot water, in the European standard context, and the representative distribution of light and heavy users of hot water.

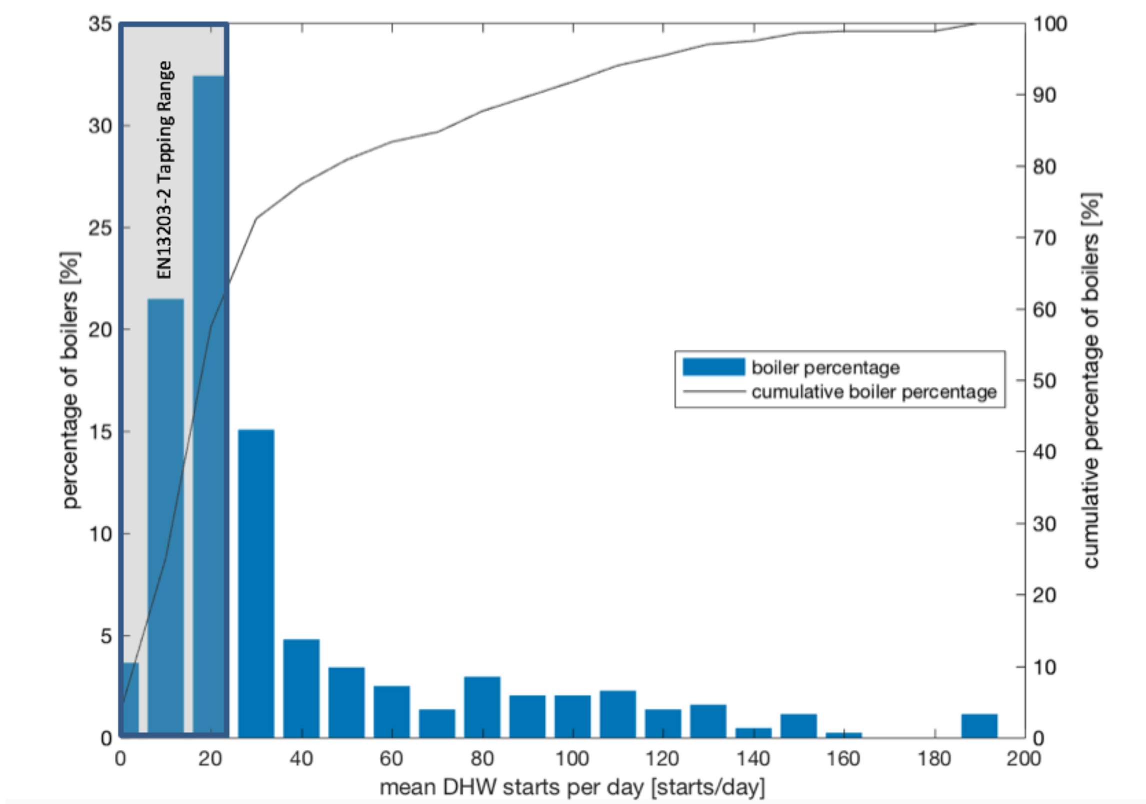

Figure 7: Histogram of average DHW starts per day (EN13203-2 Tapping range shaded in grey)

Removing the DHW starts and focussing on the genuine CH starts leaves a distribution of average starts per day during the heating season (October to May). If a theoretical heating system (infinitely and ideally modulating with instantaneous heat delivery) is considered operating on a heating degree-day then according to the bi-modal heating schedule specified in SAP [42, 46] and observed in practice [44] then one could ideally expect only 2 central heating starts per day, one in the early morning and one in the late afternoon. Considering that combination boilers will inevitably experience priority DHW demands during space heating operation then this idealistic situation is clearly unrealistic. In addition, transitional periods at the beginning and end of the heating season will result in heating demand that is not consistent during the daily heating schedule. In transition periods solar gains increase and heat loss to the environment decreases, further increasing the likelihood of premature satisfaction of the heating demand, although outdoor temperature compensation and variable schedule controls could be used to offset this effect. However, around half of the boilers under investigation had an average daily number of CH starts above 50, as shown in Figure 8. Even considering DHW demand interruptions and transitional heating days where partial heating is required and the boiler will cycle as a result, it is clear that some other phenomena are involved which lead to the high number of starts. The exact cause, or whether this high number of CH starts is leading to either a drop in efficiency or an impact on occupant comfort cannot be directly determined from the dataset available.

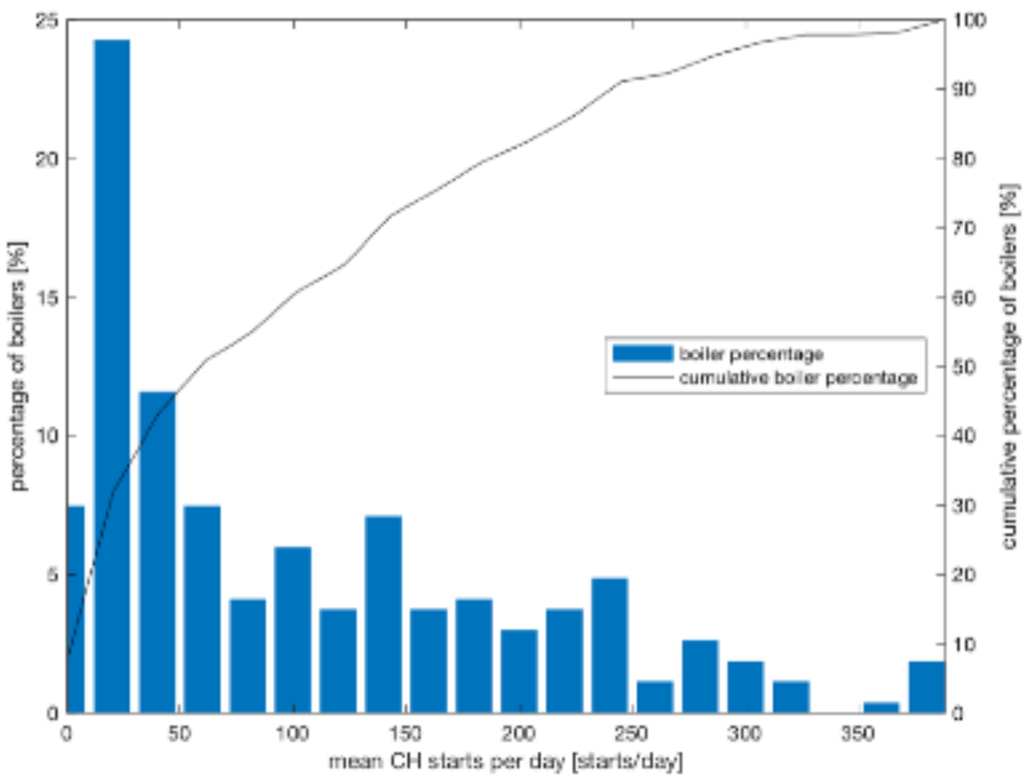

Figure 8: Histogram of average CH starts per day

Similarly, Figure 9 shows that the duration of each CH boiler operation also deviates significantly from what would be expected in a heating system where the operating time is concurrent with the heating demand schedule and modulating to meet the minute by minute heat loss. SAP describes a standard UK heating schedule to be 0700 to 0900 and from 1600 to 2300 on weekdays and weekend heating times are from 0700 to 2300, which implies boiler continuous operating times of the order of hours, potentially 2-7hours. However, the boilers observed show average runtimes per start in CH mode in the range of 1-30 minutes with 70% of boilers averaging under 10 minutes before interruption.

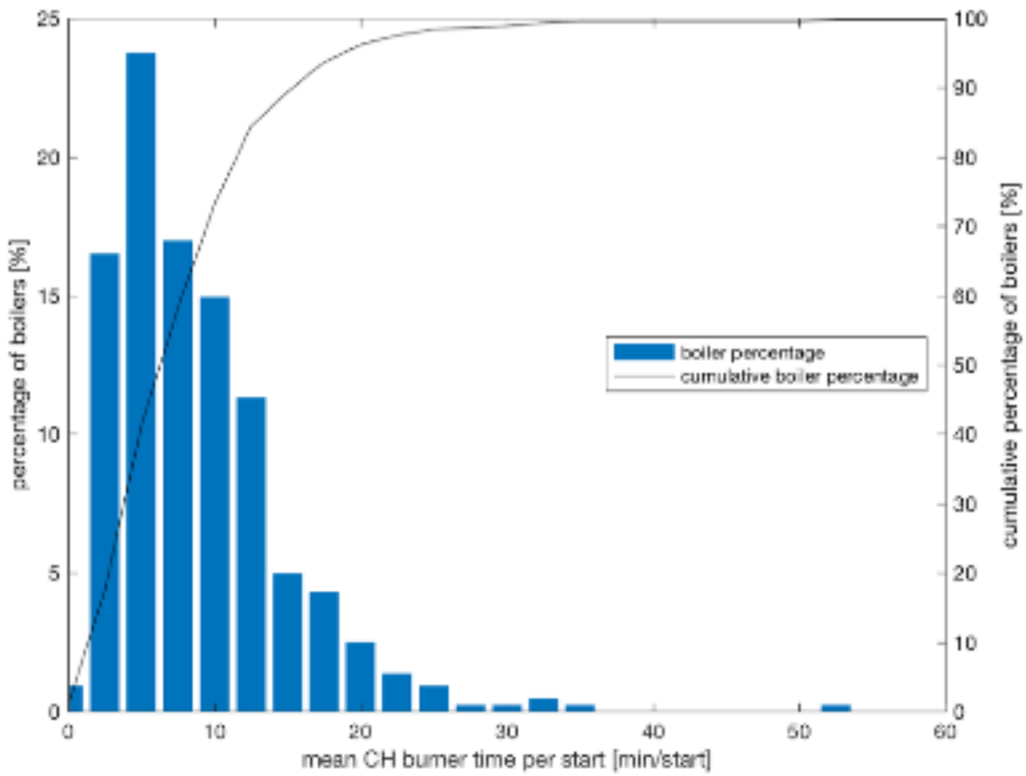

Figure 9: Histogram of mean CH runtime per start

Conclusions

Utilising boiler diagnostic data to investigate heating system behaviour in a level of detail and accuracy not normally possible has highlighted performance issues previously undetected in research studies.

Previous studies of boiler performance across manufacturers has shown that a performance gap is present between expected and real efficiency; correction factors have been implemented on this basis in SAP, but with no reference to their cause or mitigating parameters. The high start-up emissions and efficiency penalty of cycling gas boilers suggests that avoidance of cycling behaviour should be a priority for the heating system. The high number of boiler starts observed in this study in CH mode is of relevance not only because of the implied increase in methane emissions with their higher greenhouse warming potential, but also because of an associated drop in efficiency due to the short running times. Due to a tradition of steady state testing based on the assumption of optimal sizing of boiler and heating system, legislation is mostly oblivious to these hidden emissions. Tendency of installers to oversize boilers in installations due to a focus on hot water demand [29], compulsory boiler safety features and mandatory legislation combine to make this a national issue. Although the data presented here cannot identify the specific causes for high cycling in installed boilers in UK housing stock, they are suggestive of an endemic problem, oversizing of boilers and additional compounding factors such as emitter sizing, control setup and hydraulic balancing are likely to contribute. Further research is required to identify the causes of high boiler cycling and the potential mitigation measures that may be taken.

It is clear that current legislation such as EN15502 and SEDBUK for boiler efficiency or SAP for building performance does not take account of the issue of oversizing and cycling. Some boiler manufacturers are moving to address oversizing issues in combi boilers, such as Bosch Thermotechnology [47], by moving to a wider modulation range compared to the current state of the art of 1:6 (e.g. 2.4 to 24kW compared to 4 to 24kW). Benefits of a higher modulation range should be the ability of the boiler to reduce its heat output in line with the building heat loss in mild winter and season transition days where previously boilers may have reached their lowest output and were forced to cycle. Currently the trend for installers to fit combination boilers based on maximum DHW output with additional safety margin will continue to determine the upper power output of boilers and therefore the move to larger modulation ranges is in keeping with market drivers. However, the benefits will not be visible to consumers, prior to purchase, unless the current performance testing regimes change. Industry or academic led innovation in the area of gas boilers is not encouraged by the regulatory framework. Therefore, it can be assumed that the situation is unlikely to change until legislators make efficiency testing procedures reflect the realities of heating installations. The topic of cycling cannot be solved solely by modulation range, a holistic view of the heating system within the building envelope, and the factors influencing its installation must be considered to improve efficiencies.

Investigating the performance of one major component of the heating system, the boiler, identified a wide range of observable behaviour. Further consideration of the heating system in a more holistic manner could reduce operational phenomena that are associated with higher environmental impact, considering the choices made when sizing emitters/boilers, fitting TRVs, setup up bypasses, balancing radiators, and selecting control strategies. Legislative tools such as performance and emissions testing and scrappage schemes could be improved by looking more broadly at the heating system rather than only one component of it. However, economic consequences should also be considered, mandatory measures which benefit efficiency may result in increased installation costs, which would discourage or delay much needed upgrades to heating systems. Further research will benefit from looking at the heating system as a whole and at its operational context; this is needed to quantify the benefits available from reducing cycling. Such research can support legislation and the industry going forward to close the performance gap with respect to boiler based heating systems. The complexity of heating system operation and control strategies are highlighted by this analysis and further research may address the interfaces of boiler, controller, heating circuit and ultimately occupant in order to better understand the root causes for phenomena such as cycling and to minimise emissions associated with their operation.

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