# An Exploration of Load-Shifting Potential in real in-situ Heat-pump/Gas-boiler Hybrid Systems

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## Abstract

Monitoring data from two hybrid air-source heat-pump/gas-boiler systems was used to explore the systems' potential for energy flexibility, i.e. the potential for shifting electrical load in response to grid requirements while maintaining acceptable performance in the overall hybrid system. In both cases a significant proportion of the heat pump load could potentially be shifted to the gas-boiler with only a modest increase in the overall energy consumption, provided certain operational conditions were met. Furthermore, under these operational conditions it is possible to estimate this additional energy consumption for a given system from simple heat output, and gas and electricity consumption data. This provides a potential basis for groups of similar systems equipped with smart technology to offer flexibility to the grid, while minimising the resulting energy penalty by choosing to use the most appropriate systems at any given time with respect to their operating conditions at that time. In addition, this type of flexibility means that the thermal comfort within the dwelling remains unaffected since overall heating requirement is met at all times by one of the two heating sub-systems.

**Keywords:** air-source heat pumps; demand-side management; electricity grid; energy flexibility

**Practical Application**

The ability to shift or shed electrical load in response to grid requirements is likely to become a significant, commercially-incentivised aspect of building energy systems in the future, to mitigate the stress on electrical grids at times of peak consumption. For domestic systems, aggregation will be a key factor, requiring 'smart' systems to provide real-time information to potential aggregators or grid operators. This paper explores what type of system information may be necessary in the case of hybrid heat-pump/gas-boiler systems, if loads are to be shifted from the heat-pump to the gas-boiler element, while minimising the resulting energy penalties.

**Introduction**

Energy efficiency and the reduction of energy consumption in buildings is a topic of the utmost importance at the present time, since in many countries, buildings account for a substantial fraction (generally around 40%) of the total energy consumed [1]. The urgent necessity for reducing fossil-fuel consumption has led to increasing focus on reducing energy use in buildings, and increased adoption of renewable technologies such as PV, solar thermal, biomass, micro-wind, and heat pumps, to provide buildings with space-heating, water-heating and power [2]. It may be anticipated that penetration of these technologies will increase even more in the future, especially if commitments under the climate change agreement signed in Paris in December 2015 are to be fulfilled.

However, increased penetration of renewable technologies can also give rise to other technical issues. Many countries are concerned about the future stability of the existing power grids [3], especially under scenarios which include a substantial increase in technologies which inject energy intermittently such as PV and micro-wind [4], or technologies which consume additional electrical energy such as heat pumps or electric vehicles [5]. The alternative to costly up-grading of grid infrastructure is improved matching of demand with supply by reducing peak demand or by shifting part of the peak demand in time, in response to grid signals. There is growing interest in the ability of buildings to contribute to either or both of these strategies, via exploitation of a property increasingly referred to as Energy Flexibility [6]. Energy Flexibility in buildings is a relatively new field of study and there is little clear understanding, as yet, of its potential for contributing to demand management initiatives, or of the technological or economic frameworks under which such a contribution might be made. The term itself may refer to any of a number of different possible strategies, for example temporary storage of heat in building fabric or in devices such as domestic hot water tanks [7,8,9], storage of electrical power in batteries [10] or the ability to postpone power usage via intelligent scheduling of appliances [11,12]. All of these approaches (among others) together with their consequences, are currently the subject of co-ordinated study in IEA EBC Annex 67: Energy Flexible Buildings [13].

Heat pumps are currently the preferred low-carbon space-heating option for the future among UK policy makers, but it is recognised that some of the difficulties associated with high penetration of heat pumps may be mitigated by the use of hybrid systems as bridging technologies [14]. Such hybrid technologies represent commercially available systems which are currently eligible for the UK government's Renewable Heat Incentive (RHI) scheme [15].

Delta Energy and Environment [16] performed a gap analysis on behalf of the Department for Energy and Climate Change (DECC) which, among other things, identifies the need for field testing of hybrid systems in the UK to better understand their flexibility potential.

In this paper, a preliminary exploration is made of the potential of hybrid heat pump/gas boiler systems to contribute to building energy flexibility, via analysis of real in-situ data from two hybrid air-source heat-pump/gas boiler systems. A methodology is proposed for estimating the energy penalty (i.e. the increase in total energy consumption) associated with shifting some proportion of the space-heating load from the heat pump to the gas boiler element in response to grid requirements. Estimation of the additional energy used may be an important factor if system owners or users are to be fairly compensated in the future for engaging in energy flexibility schemes, perhaps in a similar manner to the current renewable heat incentive (RHI) scheme operating in the UK.

## Experimental Details

### *Monitoring System Details*

Two real in-situ systems were studied, one in the north of England, and the other in southern Scotland. Both were commercially available (Daikin Altherma) hybrid systems, capable of operating in either gas boiler mode, heat-pump mode or hybrid mode (both sub-systems together). The systems studied operated frequently in hybrid mode during the heating season, (unless there was no call for space-heating), with the gas-boiler element providing both domestic hot water (DHW) and additional space-heating not covered by the heat-pump element. The nominal output of the systems was 5kW (system 1) and 8kW (system 2) for the heat pump element, and 27kW (space-heating) and 33kW (hot water) for the two boiler elements.

The systems were installed by different installers, in different pre-existing dwellings with different thermal characteristics, occupancy patterns and load profiles. The influence of all of the above factors can give rise to significant variations in system performance which can often be difficult to understand and predict. This variability was illustrated for non-hybrid conventional heat pump systems in the UK by the Energy Saving Trust field trial results [17] where 83 different heat pump installations (ground source and air source) across the UK were initially monitored over a period of one year. Variability in performance was unexpectedly high and as a result, 38 of the systems were selected for interventions to improve performance and then (together with an additional 6 systems) monitored for a further year. Even after the interventions however, the variability between systems was still considerable. If the in-situ performance of heat pump systems operating alone is difficult to predict accurately, then clearly further work will be necessary to understand the characteristics of more complex systems such as hybrid systems operating in mixed mode (both sub-systems together). It is therefore expected that in any group of installed systems of this type, there will be a range of performance characteristics.

Heat pump/gas boiler hybrids are at present regarded as novel systems in the UK. Two such systems were monitored in accordance with Fig 1, in order to establish the performance of both the heat pump and gas boiler elements and to gain some insight into the conditions and settings which are likely to optimise overall performance. In addition to the parameters shown in Fig 1, internal and external temperatures were also measured. The installation of monitoring equipment was undertaken by Daikin Airconditioning UK, in consultation with their academic partners. Since the primary purpose of monitoring was to assess the sub-system performance characteristics, rather than to study the energy flexibility potential, the data disaggregation was not ideal for the purpose. In particular gas consumption was not disaggregated between space-heating and domestic hot water (DHW), giving rise to some degree of error in the overall energy efficiency calculations, which is discussed further in the Discussion section.

In these systems, the heat pump provides space-heating only, while the gas boiler provides instantaneous DHW (no storage tank) together with additional space-heating as required. Thus the system may operate in heat pump only mode, in gas boiler only mode, or in hybrid mode where both sub-systems are operational simultaneously. They are controlled by a proprietary smart logic system which attempts to select the most cost-effective heating mode at all times, taking into account external temperatures, internal space-heating and DHW demand and the relative cost of gas and electricity given the owners' input energy tariffs [18].

The monitoring scheme is illustrated in Fig 1, where EM refers to electrical consumption meters, HM refers to heat meters, GM to the gas meter and WM to the water volume consumption meter.

Each monitoring system consisted of two Siemens WFN21.E131 heat meters, of measurement accuracy class 3 to EN 1434 [19]. The heat meters measured total heat output to space-heating and heat pump heat output respectively. The boiler output to space heating was therefore calculated as the difference between these two heat meter readings. For one of the systems studied (system 1) the boiler heat output to DHW was also measured via a separate heat meter. However for the other system (system2) the output to DHW was estimated from the volume consumption, by assuming a temperature difference of 45°C corresponding to a set-point outlet temperature of 50°C and a mains inlet temperature of 5°C.

The electrical energy consumption of the heat-pump (including controls, displays etc.) and the gas boiler (including fan), were measured separately. The measured electrical consumption of the heat-pump included the distribution pump consumption, but the latter was also measured separately so that distribution pump consumption could subsequently be allocated between the heat-pump and the boiler according to the proportion of space-heating output, for the purposes of calculating the heat-pump performance and boiler efficiency values.

In addition, the gas and domestic hot water volume consumption were measured. A conversion factor of 11.221 kWh/$m^3$ (equivalent to around 40.4 MJ/$m^3$) was used for the energy density of gas supplied. This figure is close to the middle of the range quoted by the UK national grid of 37.5 – 43 MJ/$m^3$ [20]. However, the gas usage was not disaggregated between space-heating and DHW.  Finally, external and internal temperatures were recorded in order to ensure that thermal comfort was adequately maintained within the dwelling.

Data was recorded at approximately hourly intervals, but was then aggregated to daily and monthly performance figures in order to minimise any inaccuracies due to low output days or delays between registering electrical consumption and heat output.

From these measurements it was possible to calculate the performance of each sub-system on a daily or monthly basis, and also to calculate the overall energy consumption and energy efficiency defined as

(space-heating output + DHW output)/(gas energy input + electrical energy input)

all in kWh.

It is also possible to calculate an overall primary energy consumption and efficiency in a similar way, by multiplying all electrical input contributions (including the electrical consumption of the gas boiler) by a factor to take into account the energy cost of electricity generation. This could then be used instead of simple energy consumption in the methodology outlined below, without the need for any additional monitoring. For purposes of clarity, however, the argument developed here is based upon simple energy consumption.

Details of the dwelling characteristics were not collected, except to note that they were different in size, location, occupancy and calculated heat loss. In any proposed method for estimating energy costs of load shifting in groups of systems, it would be impractical to expect to have detailed knowledge of this information. Estimations should therefore take place using readily available system data only.

**Methodology for Estimating the Energy Penalty associated with Load Shifting from the Heat-Pump sub-system to the Gas-Boiler sub-system.**

If space-heating load is shifted at certain times from the heat pump element of the system to the gas boiler element, in response to grid requirements, it is clear that total heat pump heat output fraction for that day will decrease, and the total boiler heat output fraction will increase correspondingly, while the total overall heat output remains the same. Therefore internal thermal comfort is not affected, but the overall energy consumption over a period of time will increase, assuming that the heat pump element is operating with a performance factor greater than the boiler efficiency. Clearly if the heat pump is delivering all the required space-heating during the intervention period, then the energy penalty of shifting load to the gas boiler element will depend upon the coefficient of performance (CoP) of the heat pump at that time, which in turn depends upon variable external factors such as external temperature. However, if the system is operating in hybrid mode (as is likely when heat demand is high) the situation is more complex. If the energy penalty associated with load shifting under these circumstances is to be estimated in a way which may eventually prove amenable to automatic or intelligent control, it is necessary to relate overall system energy consumption (electricity and gas combined) as simply as possible to some readily measurable parameter or parameters such as (for example) the heat pump heat output fraction.

System energy consumption is expected to be dependent upon the heat output fraction of the heat pump, and also upon the actual values of both boiler efficiency and heat pump performance factor. However, heat-pump performance varies according to time of year (temperature lift) and other factors such as building characteristics and occupant behaviour. Similarly boiler efficiency can vary significantly depending upon factors such as domestic hot water usage and on-off cycling due to intermittent space-heating demand. When both systems are operating simultaneously, this makes estimation of overall energy consumption changes very complex, unless one factor can be shown to dominate the behaviour sufficiently to provide an acceptable estimate.

In order to demonstrate the dominance of heat-pump output fraction as a predictor of system energy consumption, the daily overall energy consumption (electricity and gas combined) was plotted against the daily heat-pump output fraction, for all the days for which complete data was available during the heating season. The heating season was taken as October 2014-March 2015 inclusive for system 1, but for system 2 very little space-heating was required during October 2014, so the heating 'season' in this case was taken as November 2014-March 2015 inclusive. This represented a total of 132 days (out of a possible 182) in the case of system 1 and 151 days (out of a possible 152) in the case of system 2. (Missing data was due to temporary equipment failures).

The plots thus obtained were sufficiently linear in nature over most of the range of heat-pump output fraction values, to provide a reasonable method of estimating whole system energy consumption as a function of heat pump output fraction, as shown in Fig 2. As might be expected, scatter tends to be greater at low heat pump output fraction values where the behaviour is dominated by the boiler sub-system, which may in turn be affected by DHW production as well as space-heating operation. Scatter is also greater for system 2 compared with system 1, possibly as a result of lower overall loads.

Nevertheless, the existence of this simple relationship can be used to estimate the energy penalties associated with shifting a percentage of the total heat output from heat-pump to gas boiler (thus reducing electrical consumption), by calculating changes in expected total energy consumption for (for example) a 5%, 10%, 15% and 20% output fraction shift in any given day.

**Results**

Figure 3 shows the estimated additional energy consumption, or energy penalty (kWh/day, gas and elecrticity) if 5% - 20% of the overall heat output is shifted from the heat pump to the gas boiler, plotted against the actual original (un-shifted) daily total system energy consumption (kWh/day, gas and electricity).

The plots can be fitted empirically to a polynomial, though in the case of system 2 most of the data-points fall in the approximately linear lower-energy consumption regime. Examples are given in Fig 4, for the case of a 20% shift in output from the heat pump to the gas boiler sub-system.

For system 1, if the original system energy consumption is around 125 kWh/day or more, up to 20% of the heat output may be shifted in any given day for an additional energy consumption penalty of less than 5 kWh. Similarly, for system 2, when the original system energy consumption is around 80 kWh/day or more, up to 20% of the heat output maybe shifted for an additional energy consumption penalty of 6 kWh or less. Broadly speaking, therefore, if both systems are in their own higher energy consumption regimes, system 1 offers slightly greater flexibility potential than system 2.

The potential complexity of the load-shifting problem can however be appreciated by noting from Fig 3 that, under circumstances where both systems were operating at (for example) a daily energy consumption of 50kWh/day, the energy penalty associated with shifting 10% of the heat output would be slightly greater in the case of system 1, compared with system 2. This is likely to be a result of variations in the sub-system efficiencies/CoPs. In fact, for the periods covered by the data the heat pump sub-system CoPs were 3.66 and 3.88 for systems 1 and 2 respectively, while the boiler efficiencies were 0.82 and 0.75 respectively. The heat pump subsystems both fall well within the range expected from the Daikin literature (CoP between 3 and 4). The boiler subsystems show efficiencies somewhat lower than the SAP 2012 (Standard Assessment Procedure) winter value 0f 0.84 for condensing combi-type boilers, which is likely to be because this value is for boiler systems which are not part of a hybrid system, and are therefore operating at higher load factor. System 1 had the slightly lower overall heat pump CoP, but the higher overall boiler efficiency, indicating the possibility of a degree of trade-off in the performance of the two sub-systems.

It is interesting to consider what percentage of daily heat output would need to be shifted from the heat pump element to the boiler element in a simple practical scenario, for example, if any call for heat pump use was re-directed to the boiler element between the hours of approximately 5pm and 6pm, in order to assist in alleviating part of the UK early evening electrical consumption peak [21]. This information has been extracted from the monitoring data for a few randomly-chosen days in January 2015 for both systems, and the results are shown in Table 1.

In some cases the heat pump sub-system was not operating anyway at the specified time, and therefore there was no output-shifting capability. Although the results shown in Table 1 are indicative only, they suggest that in cases where the heat pump was operating during this time, then redirecting the call for heat to the boiler would tend to result in overall daily output shifts of around 5-7.5% in the case of system 1, and 3-5% in the case of system 2, during January. If the systems are operating at total daily consumption values around 50kWh/day, these small shifts represent energy consumption penalties of around 3-7 kWh/day for system 1 and around 2-6 kWh/day for system 2. Energy penalties are of course lower if the systems are operating at higher values of total energy consumption.

## Discussion

### *Sources of error and uncertainty*

The data for these systems was collected for the purpose of assessing system performance characteristics, and therefore was not ideally suited to the analysis discussed in this paper. In particular, the gas consumption was not disaggregated between space-heating and domestic hot water, and therefore the total system energy consumption calculations include both space-heating and DHW. If it had been possible to disaggregate space-heating from DHW, and consider the former in isolation, it is likely that the plots shown in Fig 2 would show less scatter, particularly in the case of system 2 where overall heat output was lower and DHW represented a greater fraction of the boiler sub-system output. It should be remembered also that DHW consumption for system 2 was estimated from the volume consumption, rather than measured directly.

The monitoring system geometry may have resulted in the existence of a time lag for heat being registered on each of the two heat meters (total heat output to space-heating, and heat-pump heat output to space-heating). Since the boiler output to space heating is calculated as the difference, this may lead to errors, especially when the boiler space-heating output is low. However, the data used is aggregated into periods of 24 hours, which should reduce the effect of these types of errors.

The method described is applicable only to the heating season, and the results are best defined for days when there is significant heat output from both heat-pump and boiler elements. Although this may be regarded as a constraint on the energy flexibility potential, it is also true that the shifting of load from electrical energy to gas is more likely to be required under such conditions.

*Economic Considerations*

The cost to the user of shifting from heat pump to gas boiler operation is mitigated to some extent by the fact that gas is cheaper than electricity. However, heat pump operation is, in simple terms, more cost effective than the boiler provided the ratio of heat pump CoP to gas boiler efficiency is greater than the cost ratio (neglecting the small electrical consumption element of the gas boiler, and assuming that the CoP and boiler efficiencies remain constant). Therefore if we assume the seasonal average values given for CoP and boiler efficiency for the two systems studied, then there will be an economic cost associated with the shift for system 1 if the electricity to gas cost ratio is less than 4.36 (3.66/0.84) and for system 2 if the electricity to gas cost ratio is less than 5.17 (3.88/0.75). At any given moment, however, the heat pump CoP and boiler efficiency values may vary from this average figure.

*Discussion of results*

The two systems studied show slightly different characteristics with respect to flexibility potential as shown in the difference between the underlying relationship between heat-pump output fraction and overall energy consumption. This is attributed to differences in the dwelling locations and characteristics, and in the operation of the systems themselves, and results in system 1 showing generally somewhat more flexibility potential than system 2, as it typically operates at higher daily energy consumption. This may be due to greater heat loss, greater demand by the occupants, different local climate, or any combination of these factors. However, if both systems were operating at (for example) 50 kWh/day consumption, the results show that the energy penalty associated with shifting 5-20% of this load is less for system 2. Therefore, under these conditions, system 2 would be the better choice for load shifting.

*Practical Energy Flexibility Potential*

While a shift of the order of 5 kWh/day of heat output for an individual hybrid system only represents a small amount of electrical energy peak demand reduction, (of the order of 1.5 kWh, depending upon the CoP of the heat pump), increased penetration of similar hybrid systems in the future means that groups of systems could be aggregated to offer significant peak load reduction to the grid, provided appropriate control technology was available. Aggregation of systems into groups would make it possible to predict on a statistical basis how many systems were operating under suitable conditions (i.e. heat pump in operation and significant daily output from both heat-pump and boiler) at any given moment. Furthermore, the underlying relationship between heat-pump output fraction and daily overall energy consumption is fairly readily determined via longer term measurements of heat output and gas and electrical consumption. This relationship varies to some extent from system to system, depending upon factors such as dwelling characteristics, system operational characteristics and user behaviour, but an initial programme of detailed monitoring may be sufficient to provide some understanding of the range of variability and the factors likely to determine an individual system's place within the range. With a knowledge of all these factors, including the current state of the systems, an aggregator would be able to provide a required amount of load shifting from the available pool of systems while minimising the energy penalty to each individual system, and ensuring that the thermal comfort of users is not affected.

## Conclusions

Hybrid heat pump/gas boiler systems could contribute to the Energy Flexibility of a building by offering the potential to shift a percentage of the load from the heat pump sub-system to the gas-boiler sub-system in response to grid necessity.

The precise energy penalties (additional energy consumption) associated with doing so in real, in-situ systems are dependent upon a large number of variables, but can be estimated with reasonable confidence from output and consumption data for individual cases within certain operational constraints.

Results from detailed monitoring of two systems in the UK show that significant fractions of heat output (corresponding to scenarios such as not allowing heat pump use for around 1 hour at a time of peak consumption) can be shifted, for a reasonably modest additional energy consumption and that this additional energy consumption may be readily estimated from a knowledge of typical daily heat output and energy consumption values over the heating season, together with current daily energy consumption at the time of the intervention.

This suggests the possibility of automated or intelligent control of load shifting based upon minimising energy penalties, in scenarios where there is significant penetration of these types of systems. It also suggests a possible method of estimating energy penalties in the case of individual systems in order to form a basis for compensating users who are willing to allow remote control of their systems.

This type of load shifting requires no energy storage within the building, and carries no risk of compromising the thermal comfort of occupants, since the normal heat demand is met at all times, and only the heat-pump to gas boiler load balance is changed. However, in practical terms it seems likely that any energy flexibility service potential arising from this strategy would be best offered by aggregated groups of systems, in order to increase the predictability of the amount of electrical energy reduction available at any given time.

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## Data

Data is the property of Daikin Airconditioning UK Ltd

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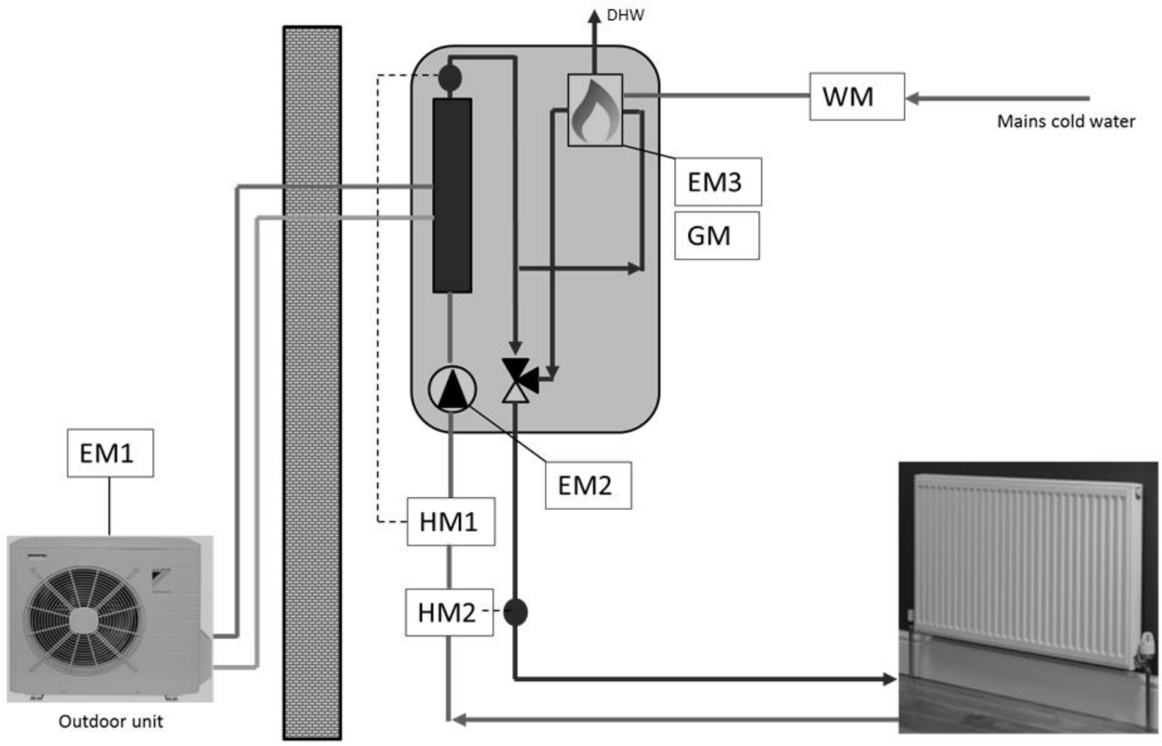
*Fig 1: Hybrid system monitoring scheme.*

*Fig 2: Underlying relationship between daily whole system energy consumption (gas and electricity) and daily heat pump heat output fraction for both systems.*

*Fig 3: Energy penalties associated with shifting 5%-20% of daily heat output from heat pump to gas boiler sub-system, vs original total system energy consumption (gas and electricity).*

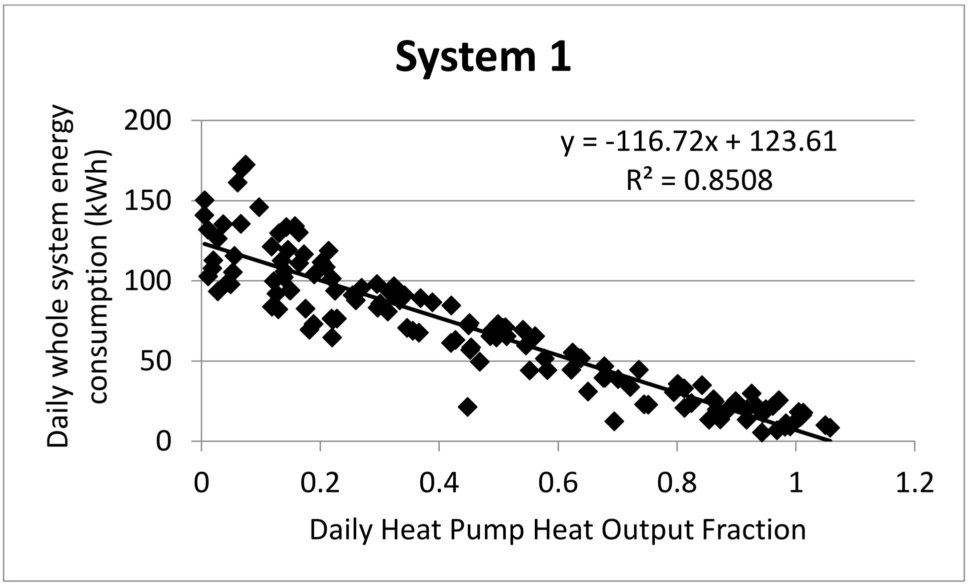
*Fig 4: Examples of curve-fitting for a 20% shift of daily heat output from heat pump to gas boiler (as given in Fig 3).*

*Table 1: %age heat output shift required if heat pump not operating between 5pm and 6pm.*



DHW
WM
Mains cold water
EM3
GM
EM1
EM2
HM1
HM2
Outdoor unit


*Fig 1*



System 1
y = -116.72x + 123.61
R² = 0.8508
Daily whole system energy consumption (kWh)
Daily Heat Pump Heat Output Fraction
0
50
100
150
200
0
0.2
0.4
0.6
0.8
1
1.2

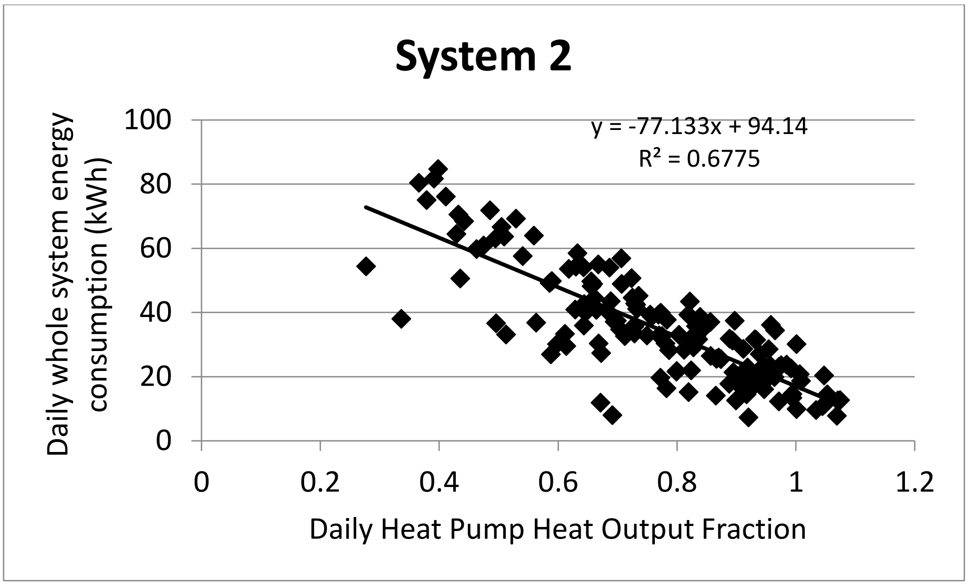
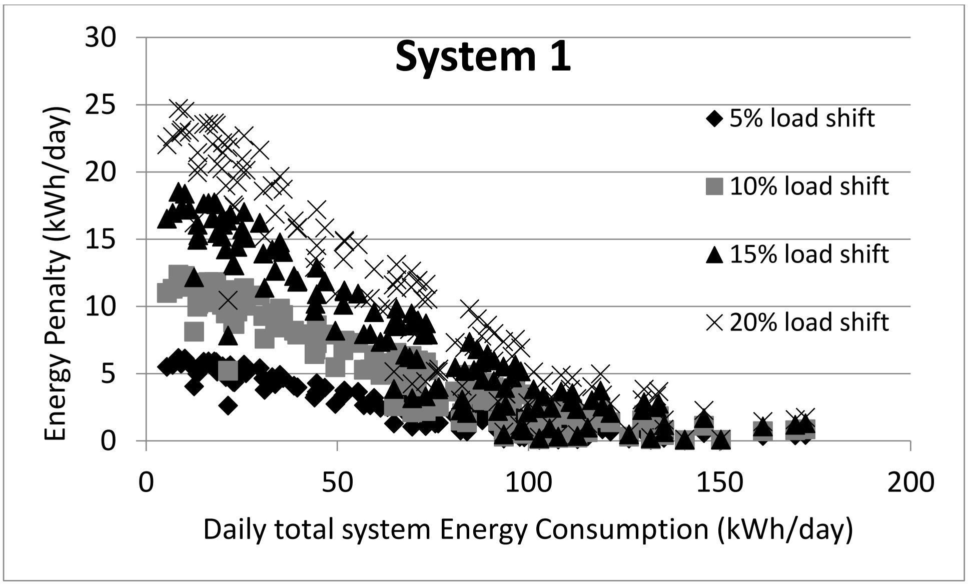



*Fig 2: Underlying relationship between daily whole system energy consumption (gas and electricity) and daily heat pump heat output fraction for both systems.*



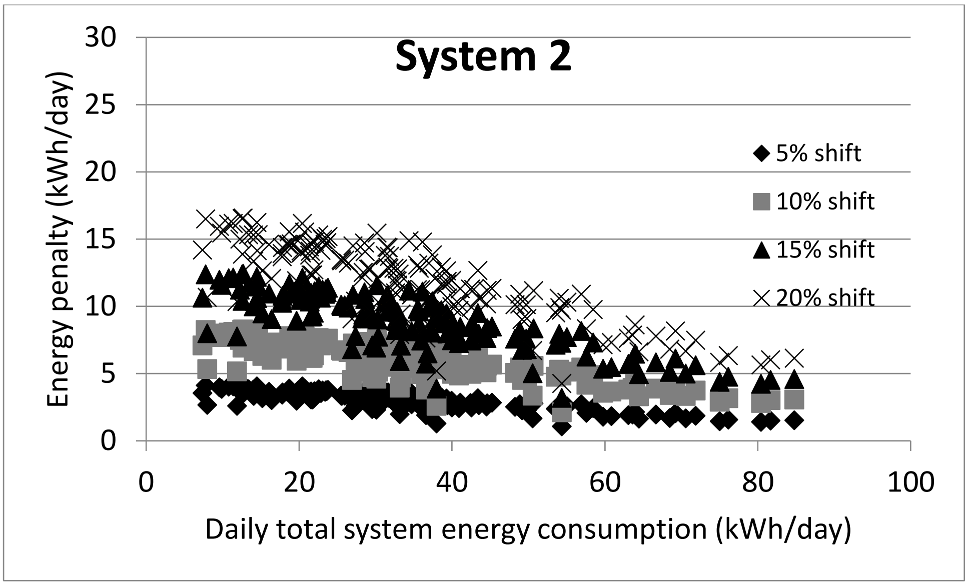
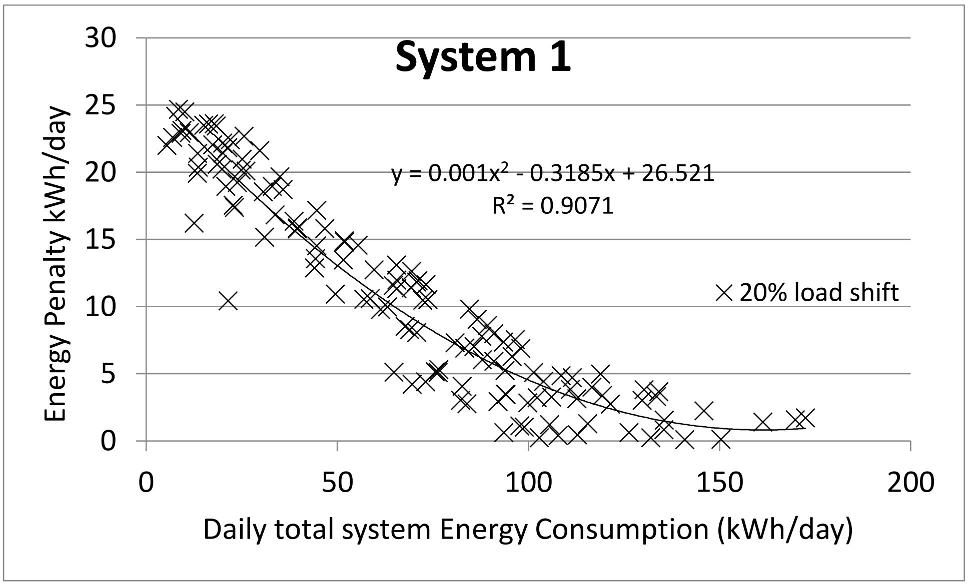



*Fig 3: Energy penalties associated with shifting 5%-20% of daily heat output from heat pump to gas boiler sub-system, vs original total system energy consumption (gas and electricity).*



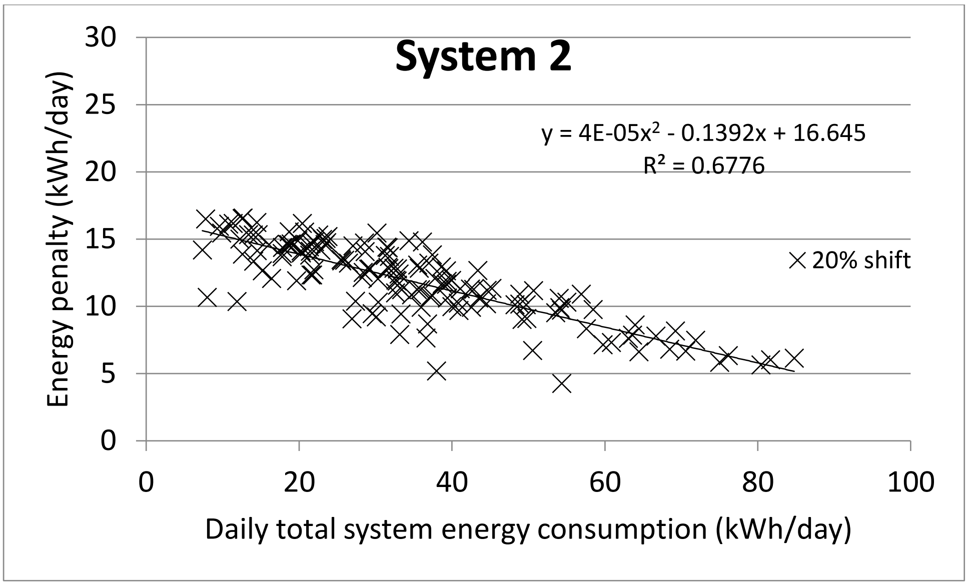



*Fig 4: Examples of curve-fitting for a 20% shift of daily heat output from heat pump to gas boiler (as given in Fig 3).*

| Date | **System 1** | | | **System 2** | | |
|---|---|---|---|---|---|---|
| | Total heat output (kWh) | HP heat output Between 5pm and 6pm (kWh) | %age heat output shift if heat pump not used between 5pm and 6pm (%) | Total heat output (kWh) | HP heat output Between 5pm and 6pm (kWh) | %age heat output shift if heat pump not used between 5pm and 6pm (%) |
| 1/1/15 | 62.8 | 4.3 | 6.8 | 39.1 | 0 | N/A |
| 7/1/15 | 68 | 4.9 | 7.2 | 63.4 | 2.9 | 4.6 |
| 14/1/15 | 92 | 4.7 | 5.1 | 88.8 | 3.15* | 3.5 |
| 19/1/15 | 120.5 | 0 | N/A | 87.1 | 3.15* | 3.6 |
| 28/1/15 | 109.7 | 0 | N/A | 83.3 | 3.75* | 4.5 |

* Values estimated by interpolation since time stamp of hourly data was between 5pm and 6pm.

*Table 1: %age heat output shift required if heat pump not operating between 5pm and 6pm.*