Review of LCT systems performance monitoring options

(Report on Work Package 3)

Guidelight

(Ofgem Round 2: Discovery- Supporting a just energy transition)

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Executive Summary

This report (covering Work Package 3) presents a systematic review of different options for technical performance monitoring of selected Low Carbon Technologies (LCTs - heat pump, PV and PV-battery) which are commonly deployed by local authorities through different retrofit schemes in low income and vulnerable households. For this purpose, a methodological framework was developed (Figure ES1) which broadly includes review of- (a) standard monitoring schemes for the selected LCTs, (b) sensors and kits used for performance monitoring of selected LCTs, and (c) performance monitoring of LCTs used by local authorities and related challenges, and (d) selection of innovative monitoring approach based on robustness and applicability to be deployed in SIF Alpha and Beta phase projects.

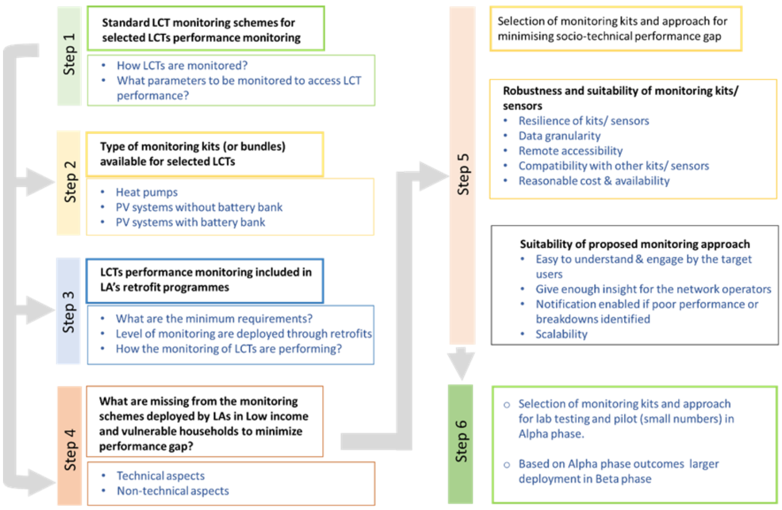

Figure ES1 Framework for the systematic review of LCT monitoring

The report identifies that as expected the real life performance and hence the impact of different LCTs may be lower than the expected levels articulated by the manufacturers and installers, and thus pose risk of creating socio-technical performance gap in low income and vulnerable households (Section 3 & 4). Furthermore, the common issues associated with the standard performance monitoring of LCTs which have been presented in Section 5.1 can be addressed by providing innovative solutions as listed below.

1. Simple and easy to understand visualisation of LCT performance monitoring.
2. Provision of simplified warnings in the case of sub-optimal performance or technology failure.
3. Adding additional sensors for studying household energy consumption and indoor environment.
4. Smart interactive advice protocols to achieve maximum financial benefit of the installed LCTs.
5. Backup provision for missing data due to sensor issues leading to total failure of monitoring system.

To deliver the aforementioned key aspects of performance monitoring the report suggests that a combination of physical monitoring and a soft sensor monitoring approach will be needed that can leverage data-driven models and algorithms to predict key performance parameters of the installed technologies (Figure ES 2).

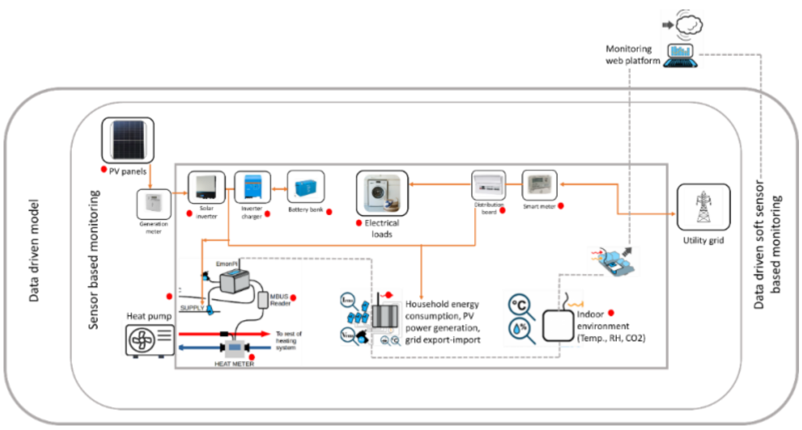

Figure ES2 Proposed outline of the hybrid monitoring approach for data collection of low carbon technologies Red dots indicate key data collection points using different sensors (Source: authors' own illustration).

1 Introduction

The United Kingdom is one of the major global economies to legislate targets to achieving net zero carbon emissions by 2050. Household energy uses in the UK contributes more than a quarter of national greenhouse gas emissions (Palmer and Cooper 2013), and almost three quarters of household energy is used for space and water heating (Gillich 2019). The Committee on Climate Change (CCC) indicated that achieving the 2050 emissions reduction target would not be possible without decarbonising the residential heating sector (CCC, 2015 and CCC 2017). Similarly, the government's Clean Growth Strategy emphasized this as the UK's greatest policy and technical challenge in meeting the carbon targets (BEIS, 2017).

While the net zero 2050 target cannot be delivered without decarbonising the residential sector, an estimated investment of £250 billion will be required by this date (BEIS 2022) for prioritising the integration of Low Carbon Technologies (LCTs), such as heat pumps for domestic heating, micro generation through solar photovoltaic (PV) and energy storage by using battery banks alongside improving insulation (fabric first approach) of existing building stocks. However, domestic heating (space heating and hot water) remains the key focus of decarbonising residential sector as this accounts for around 14% of total UK emissions (Institute for Government 2021). Willingness to switch to low carbon heating is still relatively low (14%) in the UK across the whole residential customer spectrum, and the main barriers to adopt low carbon heating are high perceived costs, scepticism about saving money through reduced energy bills and perceived disruption during the installation (Ofgem 2021). Nevertheless, there appears to be no separate (or published) research available regarding the willingness of low-income and vulnerable households to shift towards low carbon heating. However, there is a significant mismatch between what consumers think they need to do to reduce the impacts of climate change and the actual behavioural changes needed (BESI 2021).

The following section of this report will assess the involvement and practice of local authorities (LA) in deploying LCTs at the low income and vulnerable households. This will be followed by a review of the options for monitoring the performance of LCTs and recommendations for innovative monitoring to minimize potential socio-technical performance gaps for intervention in the next phase(s) of the project.

2 Local authorities and residential LCT retrofit

According to a current estimate, around 13% of households in England are fuel poor compared to 25% in Scotland, 14% in Wales, and 24% in Northern Ireland. A significant proportion (over 15%) of the fuel poor households in England live in social housing (Hinson and Bolton 2023). A similar picture prevails in Scotland, Wales and Ireland.

Local authorities (LA) in the UK have been playing a vital role in driving local climate actions alongside the government (DLUHC 2022). Most (78%) of the local authorities have declared a climate emergency, and many of these have already made their own strategic commitments on reaching net zero by 2050 (LGA 2021a). The UK government is committed to supporting LAs to deliver their climate commitments.

Local authorities across the UK are in unique position to play a crucial role in supporting strategic net zero targets, while delivering many other benefits due partly to their role as social landlords. For example, in 2021 the local government association (LGA 2021b) proposed an outline plan for delivering local net zero, which includes multiple benefits, such as (i) retrofitting 3.49 million homes with energy efficiency measures by 2030, that translates into 1,017 homes retrofitted each day to save £698 million energy bills each year, (ii) create warmer and comfortable homes and buildings with health benefits that would reduce costs to the NHS by £1.9 billion every year, and (iii) create almost 31,000 new, skilled jobs in the construction and retrofit industries. To date, there are several government backed funding schemes helping local authorities in providing energy efficiency and clean heating upgrades through deploying low carbon technologies (LCTs), especially in low income and vulnerable households. Some of key schemes are summarised below.

a) **Green Homes Grant**[1]: Energy efficiency improvements for properties with EPC ratings of D and below targeting low income households with incomes below the £30,000 threshold. Also covered homeowner and residential landlord towards the cost of installing energy efficient improvements. Supports typically covered up to two-thirds of the cost of chosen improvements, with a maximum government contribution of £5,000. If someone in the household, received certain benefits, voucher covered up to 100% of the cost of the chosen improvements. The maximum overall government contribution is £10,000. Delivery of this scheme was not in particular through the local authorities.

b) **Home Upgrade Hub**[2] (HUG): HUG schemes (HUG 1 and HUG 2) offer government funding for the LAs to deliver on energy efficiency and clean heating systems in low income households to tackle fuel poverty as well as achieving UK's 2050 Net Zero commitment. This is a £2.5bn manifesto commitment delivered through HUG phase 1 (£150m investment for low-income households with homes off-gas grid) and HUG 2 (£218m investment for 200 selected LAs).

c) **Local Authority Delivery (LAD)[3]:** The LAD schemes funded a total £500m (phase 1 and phase 2) for LAs through five local Net Zero Hubs (North East, North West, Midlands, South East and South West). LADs delivered economic stimulus to build a green recovery in response to the economic impacts of Covid-19 and successfully upgraded around 50,000 homes with energy efficiency and low carbon heating measures.

d) **Social Housing Decarbonisation Fund (SHDF)**[4] **:** The Social Housing Decarbonisation Fund (SHDF) was launched in 2019, with a proposed £3.8bn available over a 10-year period to help decarbonise a significant proportion of social housing stock. The fund subsidises measures such as ground source heat pump installations to tackle fuel poverty, reduce emissions and increase the energy efficiency of homes. A total of £778 million was offered to 107 projects through Wave 2.1 of the Social Housing Decarbonisation Fund.

e) **Energy Company Obligation scheme (ECO)**[5]: The Energy Company Obligation (ECO) is a government energy efficiency scheme in the UK designed to tackle fuel poverty and help reduce carbon emissions. ECO schemes also emphasize on Home Heating Cost Reduction Obligation (HHCRO) on medium and large energy suppliers. The scheme already had four iterations ECO, ECO 1, ECO 2 and ECO 3. The current scheme is ECO4 which will run until March 2026.

However, as with all such technical investments there is a risk that the precise building context, the installation process and the way in which the new energy infrastructures are understood and used may lead to lower than anticipated efficiencies and energy demand reduction. This is known as the performance gap and it may also lead to unanticipated consequences for local supply networks if unexpected additional new power demand for 'clean heating' coincides with existing peak demand periods.

2.1 Risk of socio-technical performance gap

The performance gap of LCTs (heat pump, PV, battery storage) is the difference between the predicted (modelled) and observed (operational) energy performance (Borgstein et al., 2016; Gram-Hanssen 2013; Gram-

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[1] This scheme is now closed. For more information please check Green Homes Grant: make energy improvements to your home (closed) - GOV.UK (www.gov.uk)

[2] HUG 1 scheme has been ended and HUG 2 scheme will end in March 2025. For more information please check https://homeupgradehub.org.uk/

[3] The latest round of LAD scheme 3 (LAD3) had the completion deadline on March 2023. For more information on LAD schemes please see https://www.gov.uk/government/publications/green-homes-grant-local-authority-delivery-scheme-phase-2-funding-allocated-to-local-net-zero-hubs

[4] SHDF 1 and SHDF 2 are now closed. For more information on SHDF1 & 2 see https://www.gov.uk/government/publications/social-housing-decarbonisation-fund and https://www.gov.uk/government/publications/social-housing-decarbonisation-fund-wave-2

[5] Ofgem has been appointed as the administrator for ECO schemes on behalf of the Department for Energy Security and Net Zero. For more information please see Energy Company Obligation (ECO) | Ofgem

Hanssen and Georg 2018). Performance gaps of LCTs can be due to either purely technical reasons, or because of non-technical reasons such as user behaviour, lack of technical knowledge and poor environmental factors. LCTs performance gap which are the resultant of combination of technical and non-technical (social aspects) reasons can be termed as socio-technical performance gap. Research indicates that integration of low carbon technologies (i.e., heat pump, PV) through retrofit programmes may not deliver positive outcomes equally across all consumer segments. For instance, for some energy users in the UK, such as those in fuel poverty, low carbon systems may not necessarily improve their affordability (Gillard et al., 2017) as they may not have access or opportunity to join the most suitable electricity tariff (i.e., hindered by pre-payment meters). Furthermore, poor technology literacy in combination with digital exclusions may subside the expected benefits of LCTs leading to slow uptakes (Sareen 2021). Risk of poor social inclusion resulting from low carbon retrofits in social housing in southern Europe has been reported by Desvallées (2022). A study in Australia indicated concern about potential inequitable outcomes in energy inequalities from low carbon retrofit subsidies used to increase energy improvement activities in the low income customer segment (Willand 2020). Therefore, such decarbonisation through technological and infrastructural shifts must account for required changes in behaviour, awareness and lifestyle supported by appropriate knowledge development and engagement interventions (Sovacool 2019). Therefore, the LCT retrofit approach, especially for the low income and vulnerable households should be more than just achieving the net zero target and it must deliver related socio-economic benefits.

Based on related studies (Darby 2013; Bouzarovski S. and Petrova 2015; Day et al., 2015; Snell and Brown 2018; Torotta 2018; Ahlrichs et al., 2020; Watson and Munday 2016; Sovacool 2019; Desvallées 2022; Willand 2020) potential reasons related to LCTs retrofit and the risk of socio-cultural performance gap in low income and vulnerable households are listed below.

a) ***Building fabric issues****:* Older housing stocks, particularly those occupied by low-income and vulnerable people, may have inherent structural and fabric issues that limit the effectiveness of retrofit measures. Poor insulation and air leakage can affect the performance of retrofitted technologies and reduce the expected energy savings.

b) ***Poor quality installations of LCTs****:* In some cases, retrofits may be carried out by inexperienced or unqualified contractors, resulting in poor-quality installations. Inadequate insulation, improper sealing, and substandard equipment can significantly diminish the performance and energy efficiency of the retrofitted systems.

c) ***Lack of user engagement and education****:* Engaging and educating occupants about the purpose and operation of low carbon technologies is essential for maximizing their benefits. Without proper user engagement and sufficient system understanding, residents may not fully utilize or maintain the retrofitted systems, leading to underperformance and lower energy savings.

d) ***Occupant behaviour****:* The behaviour of occupants plays a significant role in achieving energy savings and carbon reduction. If residents do not adopt energy-efficient practices, such as controlling heating and ventilation appropriately or minimizing wasteful energy uses, the overall benefits of the retrofits may be diminished.

e) ***Inadequate maintenance and monitoring***: Regular maintenance and monitoring of retrofit systems are essential for ensuring their optimal performance over time. If maintenance is neglected or monitoring systems are not in place, issues such as equipment malfunctions or declining efficiency may go unnoticed, leading to reduced performance and energy savings.

f) ***Rebound effects:*** Rebound effects occur when energy efficiency gains are offset by increased energy consumption or behavioural changes. For example, if occupants increase their energy usage or extend their comfort settings in response to lower energy bills, the expected energy (and emissions) savings from retrofits may not be fully realized.

Recent work has suggested that a number of these issues can only be addressed by extending the "*current emphasis on technical-material changes to include an equally strong focus on researching and potentially changing the energy-related expectations, aspirations and actual activities of those who inhabit and use these buildings*." Rau et al (2020). Further this paper goes on to note that an "*integrated approach to energy retrofitting that combines technology-aided changes in material conditions with a parallel re-shaping of householders' views and practices to achieve real and lasting reductions in energy use*" is needed. The purpose of this report is to understand what monitoring options would be required for assessing the potential scale of the performance gap and then testing the efficacy of social/knowledge interventions that are intended to result in these kinds of re-shapings. A secondary objective is to understand the potential for such monitoring to support innovative data-driven intervention.

3 LCT performance monitoring

As discussed earlier in this report, it is often recognised that the real life performance and impact of different LCTs are lower than the expected levels articulated by the manufacturers and installers based on energy service modelling, which can be more associated with low income and vulnerable households creating an unequally distributed socio-technical performance gap. Therefore, it is crucial to monitor and evaluate the performance of LCT retrofits to ensure that more vulnerable groups are not further disadvantaged. For this purpose, quantitative technical performance gaps assessment must be accompanied by identification of qualitative factors.

Based on the aforementioned six inter-related potential reasons of risk of creating socio-cultural performance gap in low income and vulnerable households (see Section 2.1), the importance of innovative and comprehensive monitoring for all LCT retrofits has been illustrated in Figure 1. It is clear from Figure 1 that Innovative performance monitoring should be the combination of technical performance monitoring supported by non-technical interventions.

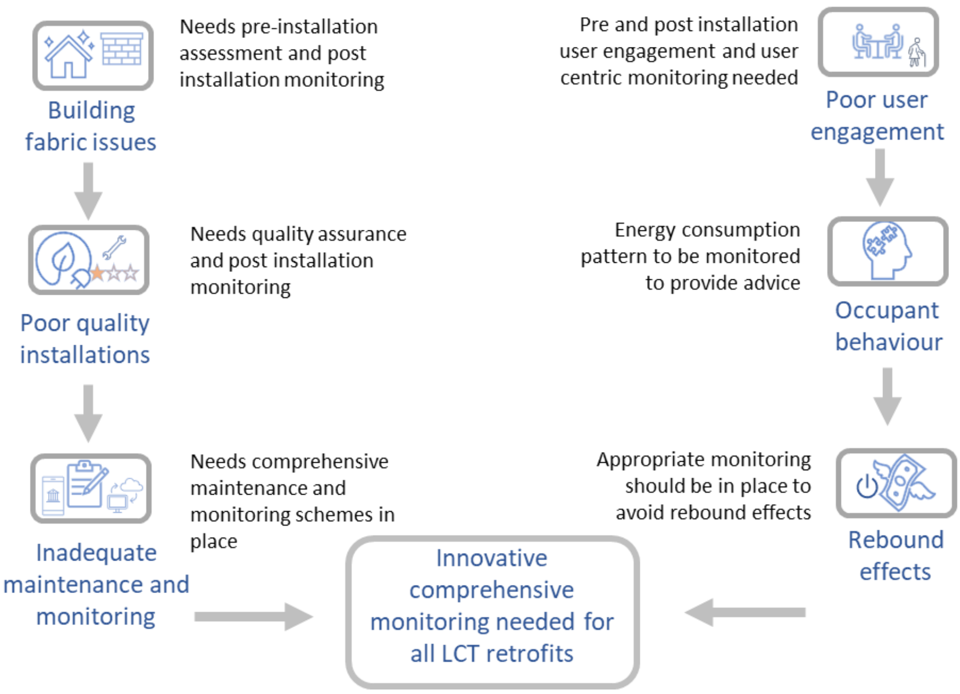


Figure 1 Illustration of importance of innovative and comprehensive monitoring of low carbon technologies to avoid the risk of socio-technical performance gap. Technical factors are presented on the left and non-technical factors on the right (Source: authors own illustration).

4 Review of technical performance monitoring of LCT retrofits

This section of the report (covering Work Package 3) presents a systematic review of different options for technical performance monitoring of selected LCTs (heat pump, PV and PV-battery) which are or will be commonly deployed by the local authorities through different retrofit schemes in low income and vulnerable households. For this purpose, a methodological framework as presented in Figure 2 has been developed. This framework broadly includes a review of- (a) standard monitoring schemes for the selected LCTs, (b) sensors and kits used for performance monitoring of selected LCTs, and (c) performance monitoring of LCTs used by local authorities followed by selection of innovative monitoring approaches based on robustness and applicability in the Alpha (lab testing and a small number piloting) and Beta phase of the project (large number deployment).

Low carbon technology (heat pump, PV system) manufacturers and installers use different types of monitoring kits delivering various levels monitoring. The review of sensors and kits used for the performance monitoring of selected LCTs is presented under two categories. These are review of (a) individual sensors for monitoring, and (b) complete monitoring kits (package). For the qualifying sensors and complete monitoring kits the following criteria were applied.

i) Wireless connectivity and remote accessibility
ii) Hardware interoperability
iii) Robustness and resilience
iv) Data accuracy and granularity
v) Low power optimised (long battery life)

However, while selecting smart devices and sensors (internet of things- IoT) for LCT monitoring their data processing and transmission protocols should be carefully considered (see Figure 3) so that interoperability is not compromised.

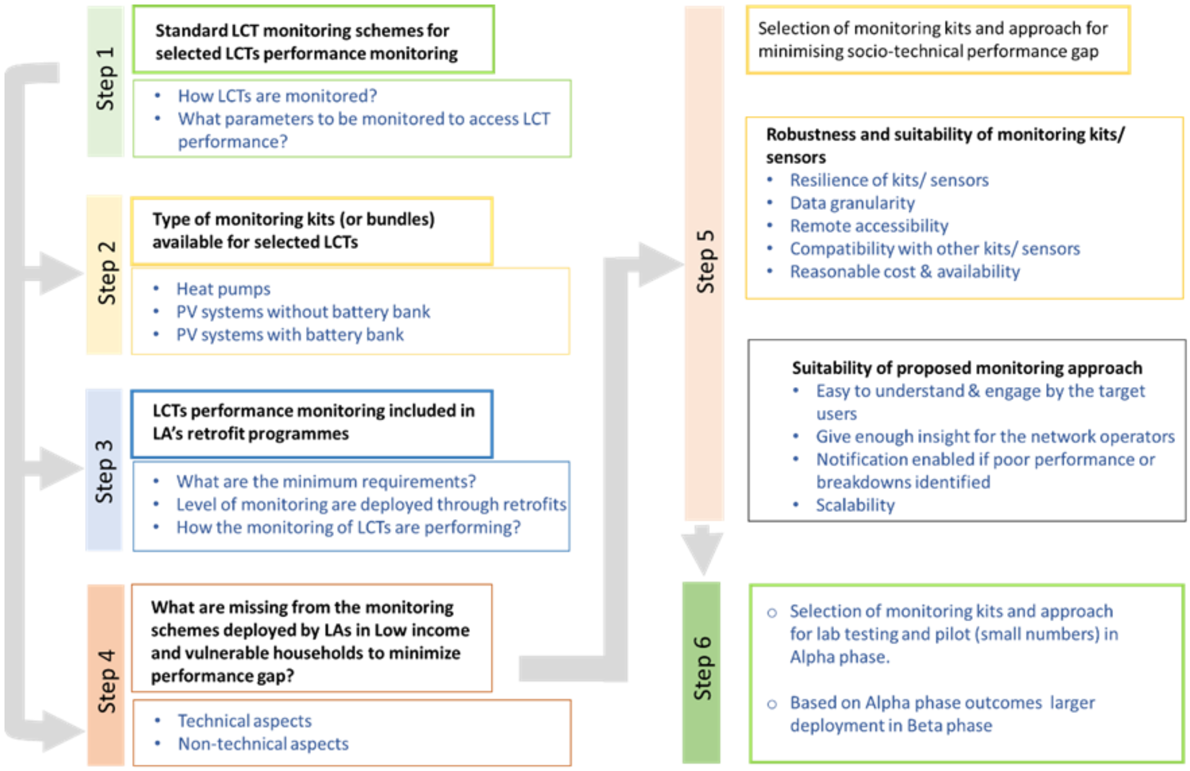


Figure 2 Steps of systematic review of LCT monitoring

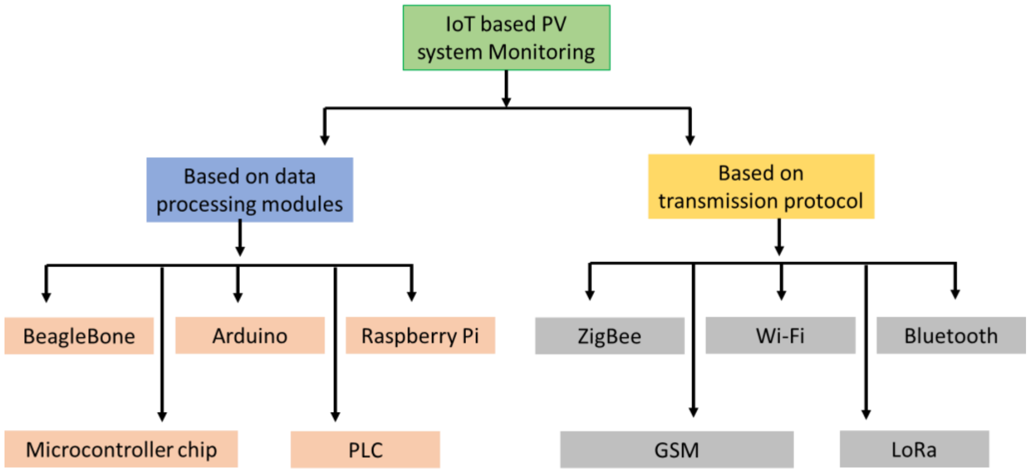


Figure 3 Different data processing technology and data transmission protocols for low carbon technology monitoring (Modified from Ansari et al., 2021)

4.1 Heat pump performance monitoring

There are mainly two types of heat pumps used in the residential sector in the UK. These are- air source heat pump and ground source heat pump. According to the Energy Saving Trust (https://energysavingtrust.org.uk/) air source heat pump is the most commonly used type in the UK. Although the technology fundamentals of these two heat pump types are similar, this review of performance monitoring mainly focuses on the air source heat pump system (Figure 4) due to its frequency of installation compared to ground source heat pumps.

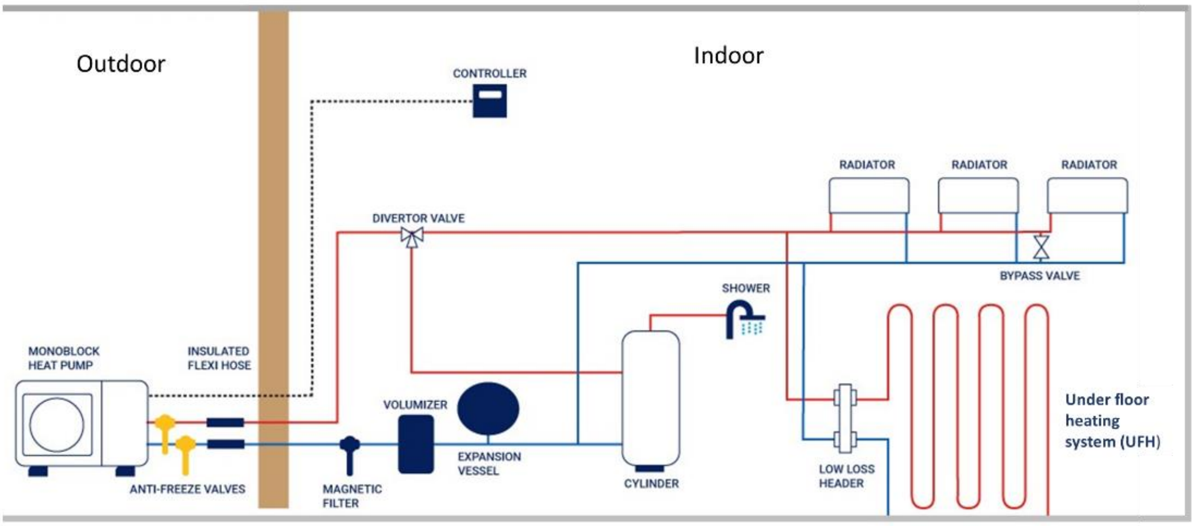


Figure 4 Outline of a standard monobloc air source heat pump (Modified from James Hargreaves. https://www.jameshargreaves.com)

Efficiency of a heat pump is defined as the Coefficient of Performance (COP), which is the ratio of heat energy produced per unit of electricity used by the unit. As electricity consumption by a heat pump is related to seasonal fluctuation of outside temperature, its performance is also rated with a Seasonal Performance Factor (SFP) that indicates the average COP of the heat pump over a whole heating season.

Typically, heat pumps utilize a variety of sensors to monitor and control various aspects of their operation. The type and number of specific sensors used in a heat pump system can vary depending on the make, model and type of heat pump and its application. Some commonly used sensors and their functionalities in heat pump systems are listed below. These sensors in conjunction with appropriate control algorithms, enable the heat pump to operate efficiently, maintain desired temperature levels, and optimize energy usage.

a) ***Temperature Sensors:*** Temperature sensors are integral to heat pump operation for measuring the temperature at various points in the system, such as the ambient air, evaporator, condenser, suction line, discharge line, and supply/return lines. These sensors help to monitor the heat exchange process, optimize system performance, and maintain desired temperature levels.
b) ***Pressure Sensors:*** Pressure sensors are employed to measure the refrigerant pressure at different stages of the heat pump cycle. They provide valuable information for system control, including compressor performance, refrigerant flow, and system efficiency. Commonly used pressure sensors include low-pressure and high-pressure sensors.
c) ***Flow Sensors:*** Flow sensors are used to measure the flow rate of the heat transfer medium, such as water or refrigerant, in the heat pump system. They ensure proper flow through the evaporator, condenser, and heat exchangers, enabling efficient heat transfer and system operation. Flow sensors are especially important in geothermal and water-source heat pump system.
d) ***Humidity Sensors:*** Humidity sensors are employed in heat pump systems with dehumidification capabilities, such as those used for air conditioning or humidity control. These sensors measure the relative humidity of the indoor air, enabling the heat pump system to adjust its operation accordingly.
e) ***Level Sensors:*** Level sensors are utilized in heat pump systems that require liquid level monitoring, such as for condensate collection or refrigerant storage. These sensors help to maintain optimal liquid levels and prevent overflow or inadequate refrigerant supply.
f) ***Air Quality Sensors:*** Some heat pump systems may incorporate air quality sensors to monitor the indoor air quality parameters, such as carbon dioxide (CO_2) levels and particulate matter. These sensors can trigger ventilation or filtration actions to maintain a healthy indoor environment.
g) ***Power Sensors:*** Power sensors are used to measure the electrical power consumption of the heat pump system. They provide data on energy usage, allowing for energy monitoring, analysis, and optimization.
h) ***Defrost Sensors:*** Heat pump systems operating in cold climates often have defrost sensors that detect frost build up on the outdoor unit. These sensors trigger defrost cycles to remove ice or frost, ensuring efficient heat transfer and preventing system damage.

To monitor the operational performance of a heat pump manufacturers and installers often follow the standard equipment monitoring protocols. Below is the list of monitoring equipment used in heat pump installations.

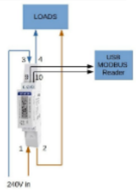
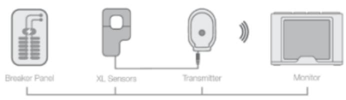
a) ***Energy Meters:*** Energy meters or submeters (kWh meter) are devices that measure the electricity consumption of the heat pump system. They provide data on energy usage, allowing to monitor and track the heat pump's electricity consumption over time.
b) ***Temperature and Pressure Sensors:*** Temperature and pressure sensors are used to monitor the operating conditions of the heat pump. They provide real-time data on the temperatures and pressures at different points in the system, allowing to assess the performance and efficiency of the heat pump.
c) ***Heat Meters:*** Heat meters measure the amount of heat generated or extracted by the heat pump system. They can be used to monitor the heat output or heat absorbed by the heat pump, providing valuable data for performance evaluation.
d) ***Data Loggers:*** Data loggers are devices used to record and store data from various sensors and meters over time. They can collect and log data such as temperature, pressure, flow, and energy consumption at regular intervals, allowing for comprehensive monitoring and analysis.
e) ***Remote Monitoring Systems:*** Remote monitoring systems utilize internet connectivity and data transmission to provide real-time monitoring and control of heat pump performance. These systems collect data from various sensors and meters and present it through user-friendly interfaces accessible via computers or mobile devices.

It is crucial to select monitoring equipment which are compatible with the specific heat pump model and system configuration. Additionally, the accuracy, reliability, and compatibility of the equipment with the chosen monitoring and analysis software or platform are also important. Specific monitoring equipment needed may vary depending on the type and complexity of the heat pump system.

4.1.1 *Individual sensors for heat pump monitoring*

Table 1 below presents a short list of some suitable sensors with key characteristics which have been deemed suitable for heat pump monitoring based on the criteria mentioned above in Section 4.

Table 1 Some selected sensors with their characteristics used for heat pump monitoring

Electricity consumption monitoring	
SDM120 electricity meter 	• 1-DIN Module (17.5mm) • Single Phase (1P2W) 45A AC (Direct connected) • Voltage: 230V AC • RS485 Modbus RTU for accessibility • Dual pulsed outputs • Digital Backlit Display • Multi-functional parameters
RI-D35-100C energy meter 	• Two module width DIN rain mounted • Single phase 100A (Direct connected) • Voltage: 230V AC • RS485 Modbus or M-bus for accessibility • Dual pulsed outputs • Digital Backlit Display
Efergy Elite-4.0 power meter 	• Clip on mini CT sensor 50mA – 90A • Voltage range 110 -600V • Accuracy 95% • Accessibility: Wifi, M-bus • Power: Mains supply and battery ○ Two different tariff settings available ○ Alert enabled (for maximum consumption target).
ALTA wirless current sensors 	• Clip on CT sensor up to 150A • Power supply: Battery and external DC 3.0 - 3.6 V • Accuracy 96% • Accessibility: Wifi, Mbus ○ Alert enabled (for maximum consumption target).
Aeotec Energy Meter Gen5 	• Clip on CT sensor up to 60A • Power supply: Battery and external DC 3.0 - 3.6 V • Power supply: 230V AC • Accuracy 98% • Accessibility: Wifi
Heat metering	
Sharky 775 heat meter 	• Compact energy meter used for measuring the energy consumption in heating / cooling application. • Communication Outputs: M-Bus, MODBus, Pulsed, Radio • Compliance: MID Class 2, RHI Compliant • Power Supply: 230V AC mains powered/ battery powered

Sontex superstatic 440 heat meter 	• Compact energy meter used for measuring the energy consumption in heating / cooling application • Compliance: MID Class 2, RHI Compliant • Power Supply: 230V AC mains, 24V AC, 24V DC, battery • Communication interface: M-Bus, MODBus, Pulsed, Radio
Kamstrup 403 heat meter 	• Compact energy meter used for measuring the energy consumption in heating / cooling application • Compliance: MID Class 2, RHI Compliant • Power Supply: 230V AC, 24V AC, battery • Communication interface: M-Bus, MODBus, Pulsed, Radio
SensoStar U Heat Meter 	• Class 2 MID approved to EN1434, RHI Compliant. • Maximum Temperature 130 Deg. C. • Power supply: 230VAC or 24VAC, battery • Supplied with Unions / Tails. • Communication interface: Wired M-Bus, M-Bus, Modbus, Pulse Inputs, LoRaWAN.
Qalcosonic E3 heat meter 	• Heat energy meter with integrated ultrasonic flow sensor • Compliance: MID Class 2, EN1434, RHI compliant. • Power supply: 230V AC, 24V AC, battery • Communication interface: M-Bus, wireless M-Bus (868 MHz), Pulsed, BACnet and Modbus RTU.
Danfoss SonoMeter 30 	• Ultrasonic energy meter with integrated flow sensor. • Compliance: MID class 2, RHI compliant. • Power supply: 230VAC or 24VAC, battery • Power supply: M-Bus, radio OMS 868 MHz, RS-485 Modbus RTU, pulse output or optical interface
Temperature sensors	
Sensata 4000 	• Highly accurate PT1000 RTD (Class AA) • -40 to 85d C range • 100nF capacitor for electric noise reduction • Outer polyolefin heatshrink • RoHS complaint
Bosh Givare PT 1000 	• Highly accurate PT1000 RTD (Class AA) • -40 to 90d C range • Outer polyolefin heatshrink • RoHS complaint
Air quality sensors	
Titan TPVRCO2 (Combines temp., humidity & CO2) 	• Sensor: NDIR technology • Outputs: CO2: 0-10V for 0-2000ppm Temp: 0-10V for 0-50˚C (10K3A1 thermistor) Humidity: 0-10V for 0-100% • Power Supply: 24V AC/DC (+/- 15%) • Power Consumption: 100mA
Emon TH (Combined temp. & hunmidity)	• Power supply 1.9V - 3.6V • Operating range: humidity 0-80% RH; temperature -40~125 deg C

<table>
<tr><td>
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Accuracy humidity +-3% RH
Accuracy Temperature: +-0.4 degC
Active current: 150uA
Sleep current 0.06uA
Measurement time: 2.6ms = 10ms
</td></tr>
<tr><td>TPZRCO2HT (wirless)
(Combines temp., humidity & CO2)
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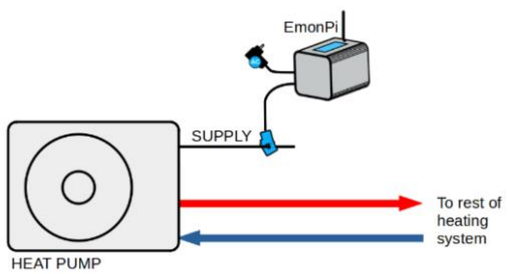
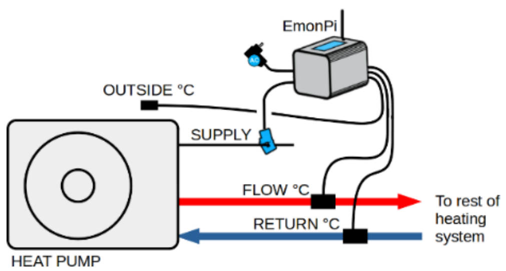
Power: 3.6V 2600mAh lithium battery Battery
Network technology: Zigbee
Frequency: 2.4GHz
Transmission range: ~ 30-60m indoor
200m outdoor (line of sight)
Measurement Accuracy: +/- 0.5˚C @ 25˚C (temp)
+/- 3% (humidity)
+/- 50ppm + 2% of reading (CO2)
</td></tr>
</table>

4.1.2 *Complete kits for heat pump monitoring*

Heat pump manufacturers and installers often include complete monitoring kits for the users for performance monitoring. Table 2 presents example of four different levels of complete monitoring solutions[6] that can be provided by the OpenEnergyMonitor (https://openenergymonitor.org/).

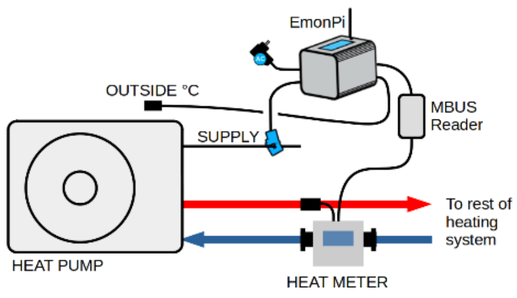
Table 2 Different levels of heat pump monitoring solutions (Source: *https://openenergymonitor.org/)*

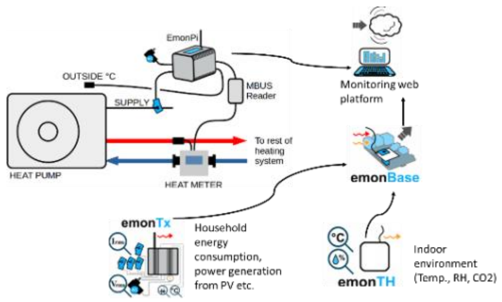
<table>
<tr><th>Monitoring solution type</th><th>Characteristics</th></tr>
<tr><td colspan="2">Monitoring level 1: Basic monitoring no CoP</td></tr>
<tr><td>
</td><td>

Monitors only the electricity consumption by the heat pump using either the EmonTx or the EmonPi.
A CT sensor needs to be clipped around either the insulated line or neutral cable for the heat pump.
This provides detailed 10s resolution power consumption graphs as well as cumulative energy consumption in kWh on a daily/monthly/annual basis.
It's possible is to use the power graphs for a basic insight into potential issues such as excessive cycling.
</td></tr>
<tr><td colspan="2">Note: It is also possible to measure the electricity consumption with higher accuracy using a pulse output from an electricity meter or modbus output from an SDM120 DIN rail mounted meter.</td></tr>
<tr><td colspan="2">Monitoring level 2: Basic monitoring no CoP</td></tr>
<tr><td>
</td><td>

Monitoring electricity consumption by the heat pump and system temperatures using EmonTx and EmonPi.
This can be done by using one-wire DS18B20 (See Table 1) temperature sensors along with a CT sensor clipped around either the insulated line or neutral cable for the heat pump.
</td></tr>
</table>

[6] OpenEnergyMonitor system can be used to monitor the performance of heat pumps. For more information please see https://docs.openenergymonitor.org/applications/heatpump.html

Monitoring level 3: Monitoring COP- Flow rate and Heat	
	• COP of heat pump is measured by measuring the heat output in addition to the electrical input. • This can be done by either interfacing with a heat meter or a pulse counter, or a flow meter with an analog voltage output (Grundfos or Sika Vortex Flow Meter. See Table 1). • Suitable heat meters are: Sharky 775, Sontex superstatic 440, Kamstrup 403 or Qalcosonic E3 (See Table 1). • Suitable flow meters are: Grundfos or Sika Vortex flow meter (See Table 1).

Monitoring level 4: Monitoring COP: Flow rate, Heat metering and other environmental parameters	
	• This includes similar level of heat pump monitoring scheme as in Level 3 above. • It also includes household energy consumption monitoring using EmonTX and EmonTH. • Based on the size and structure of the house a separate EmonBase is recommended. • Level 4 monitoring can provide a comprehensive data collection on heat pump and overall household energy performance.

4.2 PV-battery system (grid connected) monitoring

Solar photovoltaic micro generation can help to reduce the carbon footprint of the residential sector by replacing non-renewable grid electricity with self-generated 'clean' electricity. Self-consumption can also substantially reduce energy bills, especially when retail prices are high. In addition, an increasing number of local authorities in the UK have been installing grid connected PV and PV-battery systems in social housing sector, especially in the low income and vulnerable households as indicated earlier in Section 2 to deliver on local net zero strategic targets. If installed PV and battery systems are maintained and monitored appropriately to get optimum performance, these can deliver maximum financial benefits for the users and technological advantage for the network operators by helping to reduce peak demands on the local supply network(Figure 5).

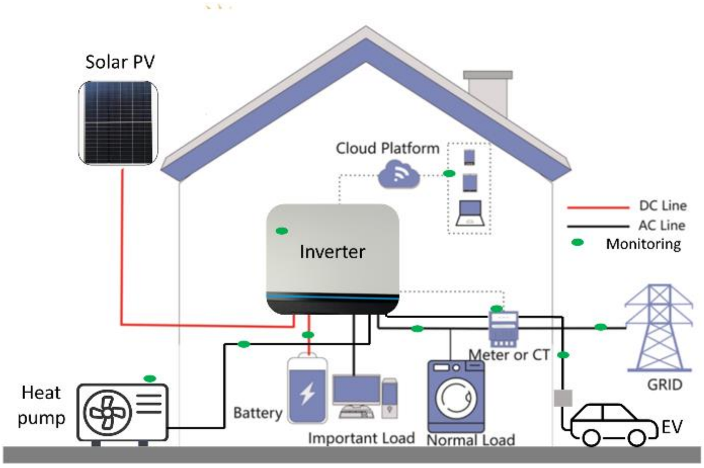
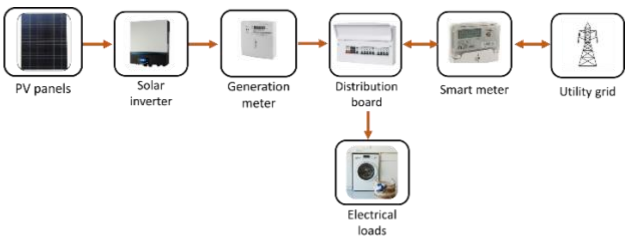
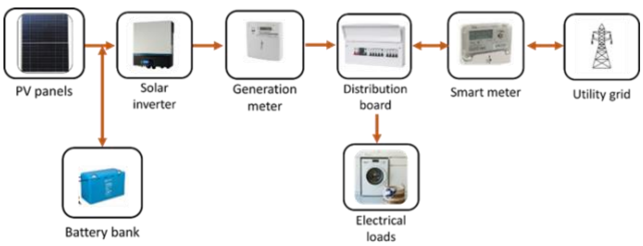
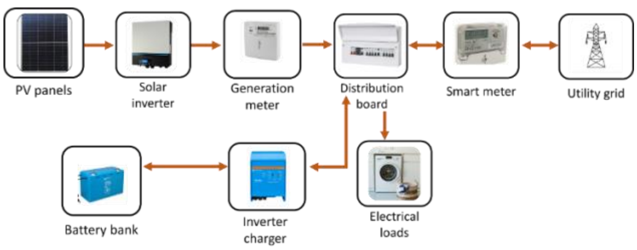
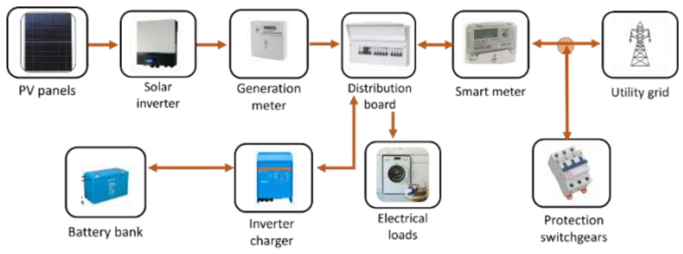


Figure 5 An illustrative presentation of a grid connected PV-battery system installed residential building with different monitoring points for optimising technical outputs and maximising financial benefits (Source: Modified from https://www.newstrail.com/).

Although such low carbon technology installations funded by different government retrofit schemes may have range of system combinations as presented in Table 3, the fundamentals of performance monitoring remain almost similar.

Table 3 Different architecture of residential PV systems

PV system architecture	Characteristics
PV system with no energy storage	
	This type of PV system is commonly used in residential installations. Unused energy generated in the day time is exported to the grid.
DC Coupled PV system with energy storage	
	In this configuration a battery bank is connected on the PV side (DC) of the solar inverter. Usually a high voltage battery bank is used to match PV voltage. Battery bank cannot be charged from the grid. System usually do not operate in the event of a power cut.
AC Coupled PV system with energy storage	
	In this configuration the battery is connected on the AC side of the solar inverter. An additional battery inverter charger is used to convert battery power to 230 V AC and vice versa. Battery can be charged from the grid with the additional switchgear installation.
AC Coupled PV system with energy storage and back-up	



This is the optimum setup for grid interconnection of the domestic PV systems., which required an additional inverter charger. It allows operation of the PV system in the event of a power cut. Extra protection relays are required to enable AC loads to be run either from grid or from the battery and to provide a new neutral earth connection.

Regardless of system type and architecture, monitoring a PV system can deliver the benefits listed below.

a) ***Performance optimization:*** Monitoring allows for real-time assessment of the system's performance, enabling proactive maintenance and optimization. It helps identify issues like underperforming components, shading, or system inefficiencies, allowing for prompt corrective actions.

b) ***Energy management:*** Monitoring provides insights into energy generation, consumption, and storage patterns. This information helps optimize energy usage, prioritize self-consumption or grid export, and effectively manage battery charging and discharging cycles for improved energy efficiency and economic benefits.

c) ***Fault detection and diagnostics:*** Monitoring enables the detection of faults or anomalies in the system, such as module failures, battery malfunctions, or grid connection issues. Early detection and diagnostics help minimize downtime, prevent further damage, and facilitate timely repairs or replacements.

d) ***System security and reliability:*** Monitoring ensures system stability and grid compliance by monitoring parameters such as voltage, frequency, and power quality. It helps detect abnormal grid conditions, voltage fluctuations, or islanding events, ensuring the safety and reliability of the grid-connected PV-battery system. Furthermore, optimally operated PV systems can help the utility network stability.

e) ***Financial management***: Monitoring allows for accurate measurement and verification of energy generation and consumption. It facilitates performance tracking, billing reconciliation, and financial analysis, supporting effective energy management and maximizing return on investment (ROI).

f) ***Data-driven decision making:*** Monitoring generates valuable data on system performance, energy flows, and environmental factors. This data can be analysed to gain insights, identify trends, and make informed decisions regarding system upgrades, maintenance schedules, energy purchasing, or grid interaction strategies.

4.2.1 *Sensors used for PV system's performance monitoring*

Several sensors are commonly used to monitor the performance of grid-connected residential PV-battery systems. These sensors provide real-time data on various parameters of the system, allowing for effective monitoring and analysis. Here are some key sensors used in this context.

a) ***Solar Irradiance Sensor***: This sensor measures the intensity of sunlight or solar irradiance that reaches the solar panels. It helps assess the solar panel's performance and determine the available solar energy for electricity generation.

b) ***Current Sensors***: Current sensors are used to measure the current flowing through different components of the PV battery system, such as solar panels, batteries, and inverters. They provide insights into energy flows, battery charging and discharging rates, and overall system efficiency.

c) ***Voltage Sensors***: Voltage sensors monitor the electrical potential or voltage at various points in the system, including solar panels, batteries, and grid connection point. They help to ensure that the voltage levels are within the desired range for safe and efficient operation.

d) ***Temperature Sensors***: Temperature sensors are employed to monitor the temperature of critical components such as solar panels, batteries, and inverters. Monitoring temperature helps assess system performance, identify overheating issues, and optimize the system's thermal management.

e) ***Power Meters***: Power meters measure the real-time power generation, consumption, and export or import of electricity to and from the grid. They provide accurate data on energy flows, helping assess the system's overall performance and grid interaction.

f) ***Energy Meters***: Energy meters measure the cumulative energy production and consumption over a specific period. They provide information on the total energy generated by the PV system, energy consumed by the household, and excess energy exported to the grid. This data is crucial for billing, financial calculations, and analysing energy usage patterns.

g) ***Battery monitor or state of Charge (SoC) Sensors***: SoC sensors are used to monitor the charge level of the battery bank. They provide information on the remaining capacity of the battery, allowing users to optimize battery usage and avoid overcharging or deep discharging, which can affect battery lifespan.

h) ***Other environmental Sensors***: Environmental sensors, such as temperature and humidity sensors, are used to monitor the ambient conditions around the PV system. They help assess the system's performance in different environmental conditions and identify any adverse effects on energy generation or system efficiency.

These sensors, when integrated into a comprehensive monitoring system, provide valuable data for analysing and optimizing the performance of grid-connected residential PV battery systems. By monitoring key parameters, homeowners, system operators, and maintenance teams can identify issues, make informed decisions, and ensure the efficient and reliable operation of the system. Table 4 presents the specific parameters for detailed monitoring of grid connected PV-battery system and 5 includes some key sensors used for these monitoring purpose. Some of the required sensors (energy meter, indoor environment monitoring sensors) listed in Table 1 can also be used for PV-battery system monitoring.

Table 4 List of parameters used for PV system monitoring (Source Aghaei et al., 2020)

Parameters	Specific parameters
Meteorology	Irradiance Air speed Ambient temperature
PV array	Module temperature Output power Output current Output voltage
Storage system	Current from storage Current to storage Operating voltage Power from storage Power to storage
Load	Load power Load current Load voltage
Electrical grid	Power from the utility grid Power to the utility grid Current from the utility grid Current to the utility grid Utility voltage

Table 5 Some selected sensors with their characteristics used for PV system monitoring

	Solar irradiance sensor
SSR2AD Solar Radiation Sensor 	• Working temperature: -40 to 60°C • Output signal: 0-5V & SDI-12, RS485 • Supply voltage: 3.3-15Vdc (allowed ripple voltage 100mV) • Sensing element: Fotodiode • Radiation intensity: 0 – 1595W/m2 • Accuracy: +/-3% • Temperature influence: <+/-0.15%/°C
SX2596 Solar Radiation Sensor 	• Spectral range: 300 ~ 1100nm • Supply: 5V,12-24VDC • Range: 0-1500W/m2 • Output: 0-5V,4-20mA,RS485 • Temperature effect: ±0.08%/°C • Operating temperature: -40°C – +80°C • Ingress Protection: IP65 • Weight (unpacked): 420g
High precision solar sensor 	• Power supply range: 10V~30V DC • Output mode: RS485/analog signal • Working humidity: 0%~100%RH • Working temperature: -40°C~60°C • Measuring object: sunlight • Measuring range: 0~1800W/m2 • Resolution: 1W/m2 • Power consumption: 0.08W • Non-linearity: <±2%
	Solar generation meter
Emlite generation meter 	• Nominal voltage: 220-240V AC • Nominal frequency: 50Hz (variation ±5%) • Current (Iref): 5, 10, 15, 20A • Maximum current (Imax): 100A • Temperature range: -40 to 70degC
PJW 100A meter 	• Type : Single phase • Nominal voltage: 220-240V AC • Nominal frequency: 50Hz (variation ±5%) • Maximum current (Imax): 100A • Temperature range: -40 to 70degC
	Battery monitor
Victron BMV 700 	• Battery voltage, current, power and state of charge • Remaining time at the current rate of discharge • Programmable visual and audible alarm • Programmable relay • Shunt selection capability up to 10.000 Amps • VE.Direct communication port • Stores range of historical events • Wide input voltage range: 6,5 – 95V DC • High current measurement resolution: 10 mA (0,01A)
RENOGY battery monitor	• Battery voltage, current, and state of charge

	• Voltage range: 10-120V • Working dissipation: 10-15mA • Current accuracy: ±1% • Voltage accuracy: ±1% • Programmable relay
Weather data monitor	
Fronius weather station  	Fronius Sensor Card / Box can accommodate up to six sensors for measuring insolation, ambient temperature, module temperature, wind speed, etc. Data be integrated into the Fronius DATCOM system along with inverter data.

Monitoring the performance of residential PV-battery system often can be coupled with monitoring of household energy consumption and other environmental parameters to develop most suitable and smart decision making tools for reducing any potential socio-technical performance gap.

5 LCT performance monitoring used in LA's retrofit schemes

Under current guidance and eligibility criteria, LCT retrofit intervention decisions by the LAs are mainly made based on the EPC ratings of the housing stock. Once LCT retrofits are delivered, a new energy rating of a specific home is then generally carried out based on energy modelling. Actual performance monitoring of the installed technologies are not accounted for in this regard and thus any potential performance gap cannot be identified. Reviewing of the related documents it is clear that there is no standard requirement of monitoring the operating performance of low carbon technologies funded under any of the current government schemes (i.e., Green Homes Grant , Home Upgrade Hub , Local Authority Delivery (LAD), Social Housing Decarbonisation Fund (SHDF), Energy Company Obligation scheme (ECO)) used by the local authorities in the UK. This is further evident from the Local Authority Domestic Retrofit Handbook[7] that performance monitoring of LCTs is not included in the business case.

However, almost all manufacturers and installers include some basic level of monitoring (i.e., for heat pump: electricity consumption, heat energy generation, flow temperatures; for PV-battery systems: power generation by the PV panels, consumption by the household, export to the grid, battery state of charge) so that any post installation operational issues can be identified and resolved. In many cases installations will send monitoring data to a data store managed by the installer or housing provider. In this case it would be possible to use this data to assess performance without the need to install extensive further monitoring equipment.

5.1 Issues with LCT monitoring and potential solutions

Common issues with the residential LCT performance monitoring can be the technology itself, the installation process or can be related to the user (Aghaei, 2021). With the commonly used LCT performance monitoring platforms, many households without significant technical knowledge (low income and vulnerable or otherwise) would find it difficult to understand the graphical presentations. Furthermore, the issues could be related to the monitoring kits and online dashboard. Some examples of common issues and potential solutions are presented below and in general they illustrate Strengers' suggestion that such interfaces are designed for *resource man – "an efficient micro-resource manager—or a "Mini-Me" version of his utility provider (who) responds rationally to*

[7] Local Partnerships commissioned by the Department of Business, Energy and Industrial Strategy (BEIS) via the five Regional Energy Hubs produced the Local Authority Housing Retrofit Handbook to provide practical advice to local authorities. https://localpartnerships.org.uk/wp-content/uploads/2021/07/Local-Partnerships-LA-Domestic-Retrofit-Handbook-July2021.pdf

price signals and makes informed decisions based on up-to-date and detailed data provided about the costs, resource units (kilowatt hours). For these tasks he needs information, dynamic prices, and enabling technologies, such as automated smart appliances and micro-generation systems, which allow him to transform his home into a resource control station." Strengers (2014).

Unfortunately, as Strengers noted, there is plentiful evidence that most energy users are not 'resource men' (or women) and that the provision of ever more detailed information will not inevitably enable 'smart choices' to be made or 'smart management' to be enacted.

Example 1: A heat pump's operational data visualisation presented in Figure 6 below shows the outside temperature of a house, flow and return temperatures, electricity consumptions by the heat pump and the heat energy delivered by the system. From this graphical presentation the user may not understand whether the heat pump is working optimally.

> **Potential solution:** A simple colour coded visualisation (i.e., *Green for optimum performance (very good), amber for just below optimum (good) but can be improved, and red for very poor performance which needs immediate attention*) based on data driven *in situ* background performance analysis of COP.

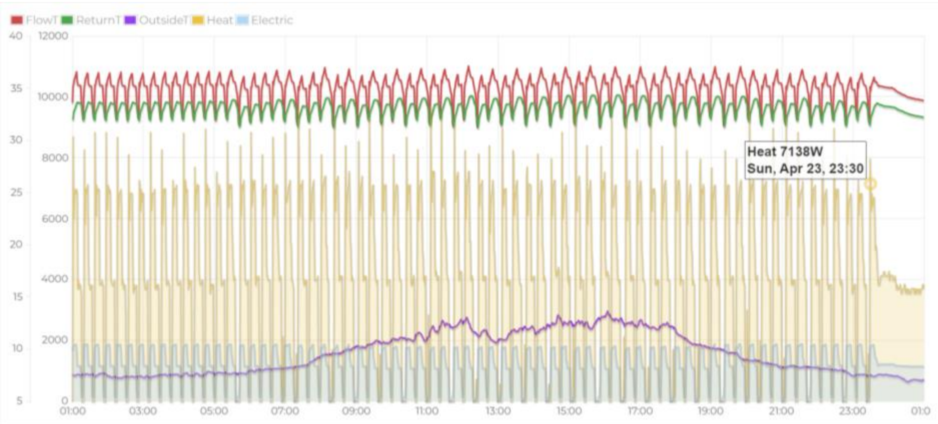


Figure 6 A heat pump monitoring platform with relevant data visualisation (Source: https://heatpumpmonitor.org/)

Example 2: In Figure 7, power generation by a PV system and the solar electricity consumed by the household along with the battery state of charge (SoC) are presented by the monitoring dashboard. In this case without the daily total and daytime only electricity consumption data the user may not have a clear understanding of how to better utilise the PV and battery power to achieve maximum economic benefits.

> **Potential solution:** The monitoring system can be combined with monitoring of other parameters (i.e., total electricity consumption, day and night electricity import from the grid, battery power usages, electricity export to grid) which can be done through integrating different monitoring sensors with the inverters (Figure 8 & 9)[8]. Such comprehensive monitoring can be presented with easy to understand visualisations indicating when to use more PV power to reduce the electricity bill (i.e., pre heating home when solar power is available, using dishwasher or washing machine and deferring non-critical loads to cheaper PV power). This responds to Strengers' call for meaningful 'energy practice' related feedback, not just kWhs. Furthermore, a warning/ advice protocol (text message, alarm) can also be used to draw the attention of the users in the case the system is underperforming or has developed any fault or if there is an opportunity to have financial benefits through using power from the battery bank or exporting power to the grid. A data driven model can be developed for this

[8] Such comprehensive monitoring solutions have been used by the Sustainable Energy Research Group, University of Southampton in different research project in Africa and Middle East. https://energy.soton.ac.uk and Kitonyoni mini-grid operational data - University of Southampton Blogs (soton.ac.uk)

purpose by combining additional monitoring (i.e., indoor parameters such as room temperatures, humidity, CO2) and soft sensor approach[9].

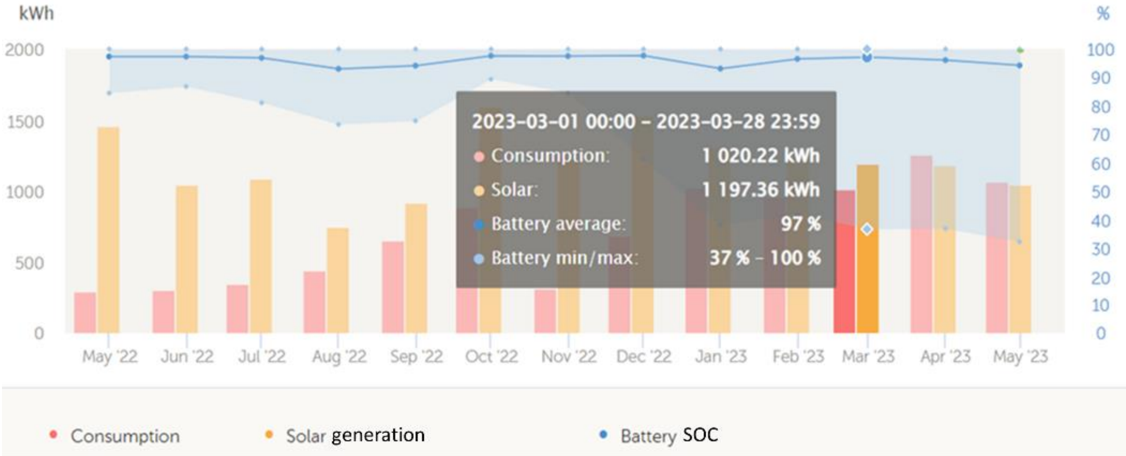


Figure 7 A typical PV-battery system monitoring dashboard (Source: victronenergy.com)

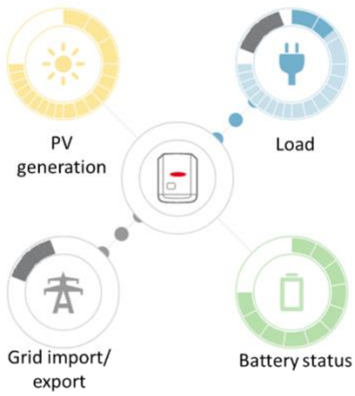


Figure 8 A PV-battery system monitoring dashboard using grid tie inverter

Figure 9 A PV-battery system monitoring dashboard using inverter-charger

Example 3: A better presentation of heat pump performance monitoring visualisation (compared to example 1 above) with the COP value presented in Figure 10, still may not present the 'right' information as there is no indication of *in situ* optimum value of COP at that specific time.

Potential solution: A data driven expected *in situ* performance benchmarking analysis of COP values can be used to compare with the actual COP value. This will indicate if the heat pump is performing optimally. A warning protocol (text message, alarm) can also be used to draw the attention of the users in the case the system is underperforming or has developed any malfunction. Continuous data driven benchmarking can be developed by using additional monitoring (i.e., indoor parameters such as room temperatures, humidity, CO2). This may be more suited to use by a housing provider's energy manager than the householders themselves unless they have additional understandings of what to do in the case of under-performance.

[9] Soft sensors have been reported to supplement online instrument measurements for process monitoring and control. For more information please see https://www.sciencedirect.com/science/article/pii/S0098135406001293

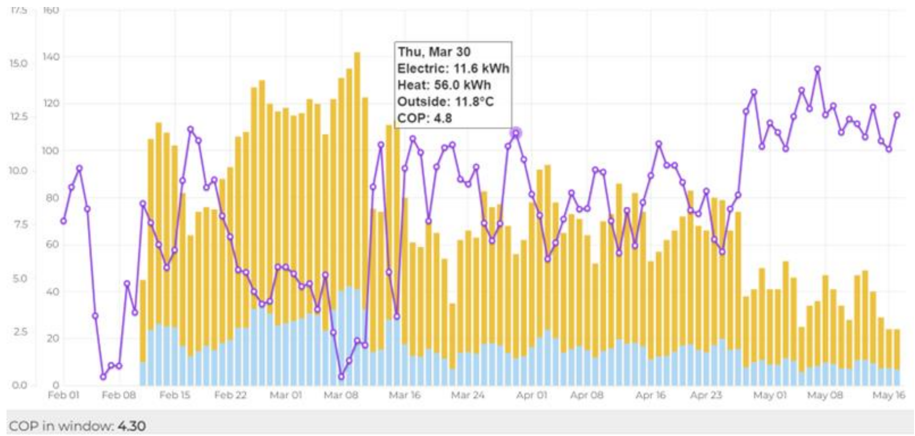


Figure 10 A heat pump monitoring platform with its coefficient of performance (COP) value (Source: https://heatpumpmonitor.org/)

Example 4: A very common phenomenon of remote performance monitoring is data missing due to either technology malfunction or sensor communication error as presented in Figure 11 and 12. The user may not be aware if the heating system is underperforming in such situations.

Potential solution: Backup soft sensor based monitoring approach can be applied to supplement missing data from installed sensors. A warning protocol (text message, alarm) can also be used to draw the attention of the users in the case that any of the sensors is not working, the system is underperforming or has developed a fault.

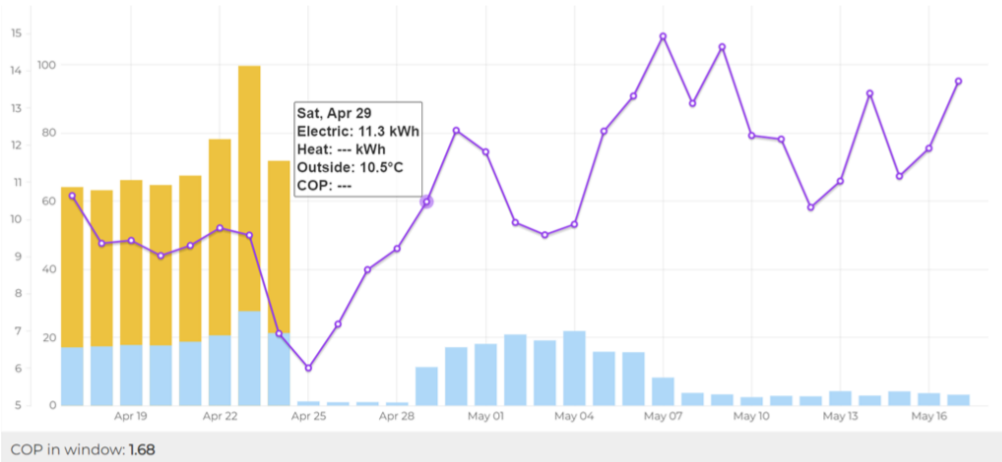


Figure 11 A heat pump monitoring visualisation with missing performance data (Source: https://heatpumpmonitor.org/)

HeatpumpMonitor.org *An open source initiative to share and compare heat pump performance data*

Property							Heating system				Annual Performance			
# Location	Type	Built	Floor Area	Heat Demand	Insulation		Make / Model	Output	Source	Emitters	Electric	Heat	SCOP	Charts
Machynlleth, Wales	Office building	Pre-1900	50 m²	7500 kWh	Fully insulated ...		Mitsubishi Ecodan	6 kW	Air	Underfloor heating	922 kWh	4265 kWh	4.6	Link »
Gloucestershire	Detached	Pre-1900	180 m²	7200 kWh	Fully insulated ...		Mitsubishi Ecodan	5 kW	Air	Existing radiators	812 kWh	3558 kWh	4.4	Link »
Stratford-upon-Avon	Detached	2012 or newer	210 m²	7300 kWh	Fully insulated ...		Vaillant Arotherm+	7 kW	Air	Underfloor heating	1768 kWh	7566 kWh	4.3	Link »
Banbury	Semi-detached	1983-2011	100 m²	-	Some insulation ...		Vaillant Arotherm+	7 kW	Air	New radiators	1768 kWh	7566 kWh	4.3	Link »
Telford	Detached	Pre-1900	140 m²	11236 kWh	Fully insulated ...		Vaillant Arotherm+	5 kW	Air	Underfloor heating	1368 kWh	5829 kWh	4.3	Link »
Llanberis, Gwynedd	Semi-detached	Pre-1900	70 m²	8000 kWh	Solid walls		Samsung Gen 6	5 kW	Air	New radiators	1875 kWh	7976 kWh	4.3	Link »
Banbury	Semi-detached	1940-1982	100 m²	-	Some insulation ...		Vaillant Arotherm+	8.2 kW	Air	New radiators, ...	1095 kWh	4590 kWh	4.2	Link »
Oxford	Semi-detached	1900-1939	72 m²	7500 kWh	Some insulation ...		Vaillant Arotherm+	3.5 kW	Air	New radiators	1770 kWh	7299 kWh	4.1	Link »
Heat Geek Towers, Camberley	Office building	1940-1982	80 m²	6000 kWh	Non insulated ...		Vaillant Arotherm+	5 kW	Air	New radiators	2698 kWh	11066 kWh	4.1	Link »
North Yorkshire	Detached	1983-2011	165 m²	15500 kWh	Fully insulated ...		Grant Aerona3	6 kW	Air	New radiators, ...	1996 kWh	8158 kWh	4.1	Link »

Figure 12 An opensource heat pump monitoring platform. The Gray texts indicate missing data and hence no corresponding COP values (Source: https://heatpumpmonitor.org/)

6 Minimum requirements for identification of performance gaps

In summary, the minimum requirements for monitoring are:

- **Heat pumps:** Electricity consumption by the heat pump, heat energy produced by the heat pump, total energy consumption and usages pattern by the household, indoor (different rooms) and outdoor temperatures.
- **Solar PV-battery systems**: Electricity generated by the PV system, PV electricity consumed by the user, PV electricity exported to the grid, electricity imported from the grid, battery charge and discharge cycles including SoC, electricity usages pattern by the household and tariff.

These would be required to establish the scale of the performance gap in specific households and could be used to test social/knowledge interventions (ref WP2 and WP4).

In addition, these monitoring infrastructures could also be used as the basis for additional innovative monitoring-based solutions. These are discussed in detail in the next section.

7 Innovative monitoring-based solutions

As indicated earlier in this report (Section 3 & 4) that the real life performance and hence the impact of different LCTs may be lower than the expected levels articulated by the manufacturers and installers, and thus pose a risk of creating socio-technical performance gap in low income and vulnerable households. Furthermore, the common issues associated with the standard performance monitoring of LCTs presented in Section 5.1 could be addressed by providing innovative solutions to support low income and vulnerable households as listed below.

1. Provision of simplified warnings in the case of sub-optimal performance or technology failure (together with options for action) – especially useful for housing service managers or for households with sufficient knowledge of which actions to take, potentially provided by social/knowledge interventions;
2. Adding additional sensors to gain clear understanding of household energy consumption and indoor environment – again potentially of more value to housing service managers and coupled with social/knowledge interventions to improve performance;
3. Intuitive and easy to understand visualisations of LCT performance monitoring that relate to everyday energy using practices or 'sufficiently correct' mental models of system dynamics to enable 'more

efficient use' and/or 'self-correction'. Again this would need to be supported by social/knowledge interventions;

4. Smart interactive advice protocols that respond to real time data flows to enable users to achieve maximum financial benefit of the installed LCTs. Ideally these would guide householders or energy managers ('expert mode') through a set of responses to 'improve' system settings and their own practices;
5. Backup provision for missing data due to sensor issues leading to total failure of monitoring system.

These key aspects of monitoring solutions could potentially be delivered by deploying a combination of physical monitoring and soft sensor monitoring approach to assess LCTs performance by leveraging data-driven models and algorithms that can estimate or predict key performance parameters of the installed technologies. This approach can combine the use of basic and essential physical sensors and virtual sensors to create a hybrid soft monitoring approach. A step-by-step process for the proposed soft sensor development is presented below.

Step 1: *Define the LCT Performance Parameters*: Identify the key performance parameters of the heat pump and PV-battery system that need to be monitored. For a heat pump, these parameters might include the coefficient of performance (COP), heating or cooling capacity, energy consumption, or efficiency. For PV-battery system these can include optimum PV generation, grid export-import related to financial aspects, battery state of charge, total energy consumption, indoor environment data.

Step 2: *Gather data:* Collect relevant data from the heat pump and PV systems, including sensor measurements, operating conditions, environmental factors, and historical performance data. Ensure that the data is representative of various operating conditions and covers a wide range of scenarios. A long period of monitoring (over 12months) at multiple premises will be required to data robustness and model validation.

Step 3: *Build a data-Driven model:* Develop a data-driven model that relates the available sensor measurements to the desired performance parameters (based on long period of data from multiple premises). This model can be built using various techniques such as regression analysis, machine learning algorithms (e.g., neural networks), or physics-based modelling combined with data-driven approaches.

Step 4: *Train the model*: Use the collected data to train the data-driven model. Split the data into training and validation sets, and use the training set to optimize the model's parameters or coefficients. The validation set can be used to evaluate the model's performance and make any necessary adjustments.

Step 5: *Validate the model:* Validate the trained model using unseen data or data from separate test sets. Assess the model's accuracy and reliability in estimating the desired performance parameters. Make adjustments or fine-tune of the model if needed.

Step 6: *Deploy the Soft Sensor*: Implement the trained soft sensor model within the LCTs system or monitoring infrastructures. Connect the soft sensor to the available sensor data inputs and let it continuously estimate or predict the performance parameters of interest.

Step 7: *Periodic hybrid model updating:* Periodically retrain or update the soft sensor model using new data to account for any changes in the heat pump system's behaviour, such as component degradation, system modifications, or changes in operating conditions.

Step 8: Scale up the hybrid monitoring model: Once developed and validated, the hybrid monitoring model can be scaled up to mass deployment for reducing risk of socio-technical performance gap.

An outline of the proposed hybrid monitoring model is presented in Figure 11 below.

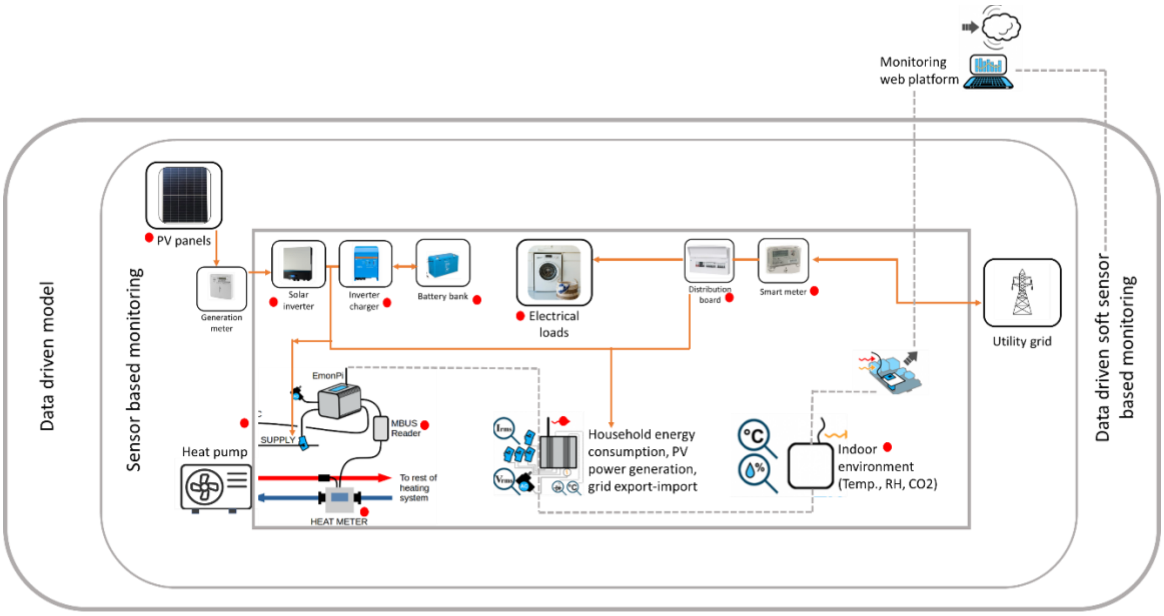


Figure 11 Proposed outline of the monitoring approach for data collection of low carbon technologies for their performance analysis to reduce socio-technical performance gap. Red dots indicate key data collection points using different sensors (Source: authors' own illustration).

8 Conclusion

It is crucial to monitor and evaluate the performance of LCT retrofits delivered by the local authorities in order to understand and potentially 'correct' detected performance gaps. For this purpose, quantitative technical performance assessment must be accompanied by the identification and development of solutions to associated qualitative factors such as user awareness and energy consumption behaviour to reduce socio-technical performance gaps. Furthermore, integration of residential low-carbon technologies (e.g. heat pumps, solar photovoltaic systems) at scale may influence the stability of the low-voltage electrical grid, which therefore will require reinforcement to deal with potential cable and transformer overload, voltage unbalance and harmonic dissertations (Espinosa and Mancarella, 2014; Meunier et al., 2021; Ruf 2018). Therefore, it is crucial that the installed LCTs are working at their optimum level with respect to intended energy efficiency not only to deliver net-zero objectives but also to minimise the need for network operators to invest in costly future grid reinforcement.

This review report presents the performance monitoring trends of the LCT retrofits by the local authorities, risk and socio-technical performance gaps, available monitoring technologies and approaches, and potential issues and challenges of standard performance monitoring. Based on the findings we suggest:

1. An innovative hybrid monitoring approach to establish the scale of the socio-technical performance gap;
2. The use of the approach to assess the effect of a range of social/knowledge interventions (ref W2P)
3. Potentially the use of the approach to pilot and then prototype innovative monitoring based solutions

This would require the approach to be piloted and tested at a small scale in the alpha phase of the project and larger trial deployment over a longer period in the beta phase. The learning and outcome of this innovative LCT monitoring approach could then be scaled by local authorities and DNOS in partnership as part of future LCT retrofit programmes to assess performance outcomes and also power network demand implications.

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