Department of Energy & Climate Change

Costing Monitoring Equipment for a Longitudinal Energy Survey

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Executive summary

This report refines the estimate of costs put forward for a large-scale longitudinal energy survey. It recommends three packages of monitoring equipment, with estimated costs from £210 to £950 per dwelling to purchase and install the equipment.

This project follows on from UCL and NatCen's work on a feasibility study for the large-scale longitudinal survey, which they called 'LUKES'. Their work recommended carrying out a large-scale socio-technical survey of homes across the UK. Their tentative estimate for the total cost of this survey was £28 million over five years. Our work aims to refine the cost estimate for the monitoring equipment used in the survey.

We have carried out a literature review, and consulted widely with the home energy monitoring community, including running an Expert Panel workshop. We have also asked suppliers and manufacturers of monitoring equipment to give us prices for their equipment – in small numbers and at scale.

We found considerable uncertainty in the energy monitoring community about what are the most important research questions in relation to household energy use. There is also uncertainty about which variables a longitudinal energy survey should set out to monitor. As a result, it is not possible to propose a single solution to meet all needs and all aspirations for a national survey – it depends what you want to know.

What do we want to know?

Our contention is that the central question for the proposed survey is this: *What factors affect the total energy use and patterns of use for heating and major appliances in domestic homes?* A longitudinal survey should focus explicitly on determinants and patterns that are not easy to discern from shorter surveys. We argue that the most important variables to monitor are gas and electricity use (weekly), and internal temperature (hourly). These are the minimum requirement for improving understanding of energy use in the home and linking patterns of use to other characteristics, identified in parallel survey interviews (described elsewhere).

If resources are available to take more measurements, we advocate collecting higher resolution energy use data, and air quality data, and temperature data for the hot water flow pipes providing domestic hot water and space heating. Higher resolution electricity data would allow disaggregation of appliances energy use, while separate flow temperature data would help to disaggregate energy use for space and water heating.

Recommended packages

These priorities led us to recommend three packages of monitoring equipment:

Package 1 - 'Minimum monitoring', monitoring:

- weekly gas use
- weekly electricity use, and
- hourly temperature data for three rooms.

This will cost from £210 to £290 per dwelling to install and maintain monitoring equipment, depending whether internet access is already available.

Package 2 - 'Not relying on Smart Meters', monitoring:

- 30-minute gas use
- 10-second electricity use
- hourly temperature data for three rooms, and
- hourly humidity data for three rooms.

This will cost from £508-£803 per dwelling, depending whether internet access is already available.

Package 3 - 'Using Smart Meters', also monitoring:

- 30-minute gas use
- 10-second electricity use
- hourly temperature data for three rooms, and
- hourly humidity data for three rooms.

This package achieves cost savings from using Smart Meter infrastructure, at an estimated cost of £319 per dwelling, which should apply for homes with or without an internet connection. However, this package relies on using a Consumer Access Device (CAD) for the Smart Meter, which is not currently available.

These costs assume ordering devices for 1000 homes, monitored over two years, and include replacement costs for some failed devices. The installation costs would be similar for all three packages, with installation time varying from 1 hour per home to 1 hour 30 minutes (indicative cost of £70-£110 for installation, for an experienced installer, excluding briefing the householder and travel time). We recommend using Package 3 only when the Smart Meter roll-out is more advanced, and when CADs are available and have been tested in providing 10-second electricity data.

Our recommended packages are described in detail from page 26. In all cases, we restrict the choice of monitoring equipment to field-tested devices that are available off-the-shelf. Technical problems in this field are commonplace, and it would be a mistake to attempt to develop new, untested devices to install in up to 10,000 homes.

Cost calculator

We have described and costed 49 different monitoring devices, and developed a costing calculator that allows DECC and other researchers to choose appropriate equipment to meet different objectives, with different budgets. The cost calculator is available to download here:

www.tiny.cc/LongitudinalMonitoringCosts

Consensus for moving forward

There is some consensus in the community that total gas and electricity use are worth monitoring. About half of the 29 participants at a workshop believed we should monitor indoor temperature and occupancy, with significant minorities also wishing to monitor relative humidity, water use, and/or hot water supplied to radiators. Temperature and total electricity use are straightforward, and there is appropriate tried-and-tested equipment for monitoring at a cost of below £700 per home. However, there are currently no off-the-shelf devices for adequately monitoring ventilation or occupancy.

Reliability

Off-the-shelf monitoring equipment has proved more reliable than bespoke systems so far, but most systems have some teething problems, and it would be a mistake to assume that any monitoring equipment will be ‘fit and forget’. Ongoing operational costs, including periodic checks of equipment and to replace batteries, are likely to cost from £50 to £200 per home, depending on the exact configuration of monitoring equipment. Any large-scale monitoring project should check data collection regularly and if possible automatically, with prompt interventions where necessary.

Long-term reliability concerns are a compelling argument for piloting equipment before it is installed at scale. Some of the reliability issues are related to the skills and past experience of the installers, and we cannot be certain that monitoring equipment will record data as intended, in a form suitable for policy-related analysis, without testing the equipment, the installation team, and the delivery of information to analysis systems.

Future costs

Regarding future costs of monitoring equipment, it seems unlikely that monitoring hardware costs will fall – because microchips are a small proportion of the total cost. Similarly, installation costs are unlikely to change very much. However, monitoring reliability and particularly the reliability of home and wide networks are likely to improve over time. Device capability is also likely to improve, including potential to support disaggregation analysis (see below). This is a case for delaying or phasing the selection of monitoring systems until the technology is more established.

There is potential for the longitudinal survey to make use of Smart Meters now installed in more than one million UK homes, with roll-out continuing. This could be an economical way to collect total gas and electricity use data.

Introduction

We ran an expert panel meeting, reviewed the literature and asked monitoring equipment suppliers for information, including cost data

This project for the Government's Department of Energy and Climate Change set out to select appropriate monitoring devices for tracking energy use in homes as part of a large-scale longitudinal survey, comprising social and technical aspects of energy use. It also aimed to assess the cost of these devices, when purchased in large numbers, including the installation cost.

This project follows on from UCL and NatCen's work on a feasibility study for the large-scale longitudinal survey, which they called 'LUKES'. Their work recommended carrying out a large-scale socio-technical survey of homes across the UK. UCL's tentative cost estimate for this survey was £28 million over five years, which would be an unprecedented UK investment for a single project addressing household energy use.

UCL's full report[1] lays out in 270 pages how this survey would fill existing gaps in the evidence base relating to energy use in the home, and ultimately how it would lead to a step-change in the UK's collective understanding of how energy is used and the potential for achieving energy and carbon savings in the home.

The feasibility study said, quite accurately, that existing sources of data like NEED (the National Energy Efficiency Data framework), the English Housing Survey, and the Energy Follow-Up Survey, do not provide sufficient information to draw up and assess effective policy interventions.

DECC laid out three objectives for the present project:

- To determine what variables need to be included in the study to improve understanding, and which are priority variables.
- To explain what monitoring equipment is required to do this effectively.
- To put costs to purchasing this monitoring equipment, at scale, and to quantify the installation, maintenance and operational costs.

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[1] See http://www.ucl.ac.uk/steapp/research/projects/energy-lab

This report describes the methods we used to meet these aims, and what we learnt in the process. It lays out the main considerations to bear in mind when selecting monitoring equipment and working out how to install it. The report summarises an Expert Panel workshop we ran, involving 29 experts with first-hand experience of using monitoring equipment[2], and it lays out a set of possible candidate devices that could be used in energy monitoring.

The report outlines a Cost Calculator that we developed as part of the project, which allows DECC and other researchers to select monitoring devices appropriate for their needs. It also puts forward packages of devices that are suitable for different research questions and different variables.

The Cost Calculator is available to download here:

www.tiny.cc/LongitudinalMonitoringCosts

Methods

We used a combination of methods to put together the information needed to specify appropriate monitoring devices, and put costs to them. Information was collected via:

- Literature review
- Workshop
- Pro-formas
- Workshop discussions
- Feedback forms
- Telephone and email follow-ups in some cases
- Website searches and telephone calls to suppliers and manufacturers.

Studies included in the review

We list here studies that were represented by workshop participants and others where the monitoring equipment was described in sufficient detail to be useful.

Code	Status	Title and aims, references	Workshop rep.	Monitoring
Apatsche	Ended 2014	*Aging Population Attitudes to Sensor Controlled Energy* Aims to determine potential savings from turning appliances off based on occupancy Teddinet (2012) Apatsche (2013)	Stuart Galloway, Lina Stankovic	Uses AlertMe or Current Cost for overall electricity use, plus IAM plugs, custom motion sensors and temperature/humidity devices (Oregon Scientific). Uploads to custom logger based on Raspberry Pi every minute.

[2] Many of the delegates at the Expert Panel meeting were members of TEDDINet (Transforming Energy Demand through Digital Innovation), run jointly by Loughborough University and the University of Edinburgh, and funded by the EPSRC. See www.teddinet.org.

CALEBRE	Ended 2013	*Consumer Appealing Low Energy technologies for Building Retrofitting* Evaluates retrofit strategies for solid wall housing from a user perspective. Investigated insulation, glazing and heating strategies including MVHR. Vadodaria et al (2010) Loveday and Vadodaria (2013) Vadodaria and Haines (2014)		Measures temperature and humidity (Comfort). Also monitored electricity and gas and deployed Ubisense presence sensors (UWB).
CHARM	Ended 2013	*CHARM* To evaluate the impact of feedback on energy usage and lifestyle (e.g. steps taken)) via phone apps Charm (2013)	Kevin Burchell	Monitored electricity consumption with real-time upload using mobile communications. Reported hourly.
CREST	Report 2010	*Centre for Renewable Energy Systems Technology* Richardson and Thompson (2010)		Measured whole house electricity at 1 minute intervals for 1 year, 22 dwellings. No details on loggers.
DANCER	Ongoing	*Digital Agent Networking for Customer Energy Reduction* The DANCER project will develop and test the extent to which a wireless sensor network augmented with Ultra Wideband (UWB) localisation technology and a decision-making agent can 'invisibly' reduce energy use in the home. *http://www.dancer-project.co.uk/*	Ricardo Russo, Kathryn Buchanan	Uses wireless sensors on appliances and UWB for localisation/presence. Aim is to control devices, not just monitor.
DEFACTO	ongoing	*Digital Energy Feedback And Control Technology Optimisation* Aims to understand the effectiveness of smart heating controls Mallaband et al (2014)	David Allinson	HOBO temperature loggers initially, then Z-wave gas (pulse counter) and electricity (current clamp) monitors, room temperature sensors and thermostats in 12 homes
EFUS	2011	*Energy follow-up survey* Follow-up to the English Housing Survey to collect data to update energy use modelling assumptions	Jack Hulme	Temperature in 800 properties for a year.

ENLITEN	Ongoing	*Energy literacy through an intelligent home energy advisor*	Sukumar Natarajan, David Coley	Monitors gas and electricity. Also using custom sensors for T, RH, light, PIR built on a raspberry Pi and CO_2 on another raspberry PI. Using mobile network for data transfer.
Evaloc	Ongoing	*Evaluating Low Carbon Communities* A survey of 90 households that took part in 6 communitties Gupta and Barnfield (2013)	Rajat Gupta	Monitors gas and electricity consumption, door opening and, occupancy. Some of these may be spot measurements or from household questionnaire. Monitors temperature, humidity and CO_2 as a measure of indoor air quality
e-Viz	Ongoing	*Energy Visualisation for Carbon Reduction*	Rory Jones	Using HOBO sensors for internal and external temperature, door/window opening and occupancy/light
HES	2010-2011	*Household Electricity Survey* https://www.gov.uk/government/publications/household-electricity-survey--2	Jason Palmer/ Nicola Terry	Monitored electricity circuits and individual appliances in 250 households, mostly 1 month but in 26 cases for a year.
IAHEM	2010-2014	*Intelligent Agents for Home Energy Management* Applies novel artificial intelligence approaches to the development of intelligent agents that will be transformational in empowering domestic consumers to visualise, understand and manage their energy use http://www.homeenergyagents.info/	Oliver Parson	Monitors gas and electricity, temperature and occupancy.
IDEAL	Ongoing	*Intelligent Domestic Advice Loop* Aims to implement behaviour inference from detailed sensing and hence give timely feedback. 576 houses Goddard et al (2012)	Nigel Goddard, DK Arvind	576 houses Sensors are wireless with 3 year battery life. Temperature +/- 0.5C, humidity +/- 2%, light level > 6 lux Electricity mesaured at 240Hz, Gas use with magnetic/optoelectric sensor. Temperature sensors on hot water pipes

LEEDR	Ended 2015	*Low Effort Energy Demand Reduction* Seeks to understand energy consumption in family life, use digital media, target energy reduction measures http://leedr-project.co.uk		Monitors gas, electricity, hot water, temperature, occupancy. Seems to use wireless networks,
Lynd-hurst	Report 2012	*Domestic energy use study: to understand why comparable households use different amounts of energy* Fell and King (2012)		Householders gave weekly meter readings. Used Thermochron iButtons to measure temperature in 3 rooms, hourly. Also took temperature data from local weather station
NSEMP	Report 2014	*The North East Scotland Energy Monitoring Project* Exploring relationships between household occupants and energy usage Craig et al (2014)		600+ homes with broadband Used Current Cost Envi to monitor whole house supply-records temperature, as well as electricity. 5 min intervals. Needs internet connection to upload data. Very good descriptions
OpenEM	Ongoing	*Open Energy Monitor*	Trystan Lea	This is an open source energy monitoring project with thousands of participants. There are two main types of sensors, one for electricity circuits and one environmental. The hub is based on a raspberry pi
REFIT	Ongoing	*Personalised Retrofit Decision Support Tools* Aims to support homes using Smart Home Technology	Lina Stankovic	20 houses, used Vera3 gateway/hub and various sensors/ Vera API used to transfer data to central database
SHA	ended	*Sovereign Housing Association* Post occupancy evaluation of energy use, environmental parameters and occupant behaviour on the new build low energy Beechfield View housing estate in Torquay.	Rory Jones	Measured electricity and gas, internal and external temperatures, door opening and present sensors

Smarter House-holds	2013-2018	*Smarter Households* Aims to develop an interdisciplinary intelligent digital system to help household members understand and directly manage their energy consumption and facilities bills including gas, electricity and water.	Shuli Liu, Elise Smithson	Monitors gas, electricity and water consumption, temperature, humidity and CO_2 in 20 houses
Swan	-	Various studies by Will Swan	Will Swan	Measures energy, temp, humidity, CO_2

Overview

There are lots of options for sensors, but none so far has been entirely unproblematic

How monitoring affects behaviour

Almost every past project monitoring energy use in the home has required repeat visits to homes to maintain equipment and/or resolve problems with recording data and/or transmitting it from sensors to hubs and hubs to a data centre outside the home. This means that the monitoring raises households' awareness of energy use, which very likely affects their behaviour, in ways that are not well understood - in line with the well-known Hawthorne Effect.

The very presence of sensors and data loggers may have an effect on how householders use energy. More discreet monitoring equipment may reduce this effect, but it is probably impossible to eliminate the effect completely. Rather, researchers need to recognise that monitoring affects behaviours and acknowledge this in analysis and reporting of their findings.

Architectures

Most projects use a central data logger/gateway system that collects data from multiple sensors using a wireless protocol and uploads data to a remote server using the internet or mobile communications, see figure below.

- Sensors may be powered or run on battery. The logger is always powered.
- In house communications use a variety of wireless protocols on different frequencies.
- Off the shelf systems typically upload to a proprietary server and data has to be pulled off this for analysis (e.g. RWE, AlertMe, Radio-tech). The REFIT project customised a Vera 3 server to upload data to a university server.
- The frequency of upload to the data server can be anything from a few minutes to a month. It needs to be often enough to detect failures in a timely fashion. If user feedback is needed then it needs to be much more frequent.

Sometimes projects use different architectures for different sensors – if they come from different systems and do not integrate well together. For example, the REFIT project used a 3rd party system for monitoring the gas meter, completely separate from the RWE system for the heating system and controls and a Current Cost system for monitoring electricity.

Apatsche developed an open source system integrating data from multiple sources and storing it securely, with suitable privacy safeguards. This is called ITL (acronym not explained anywhere). [3]

[3] https://github.com/itlenergy/itlenergy/

Homes with no internet or mobile

An important variant of this architecture is that if the home does not have a suitable internet or mobile network connection the data can be stored to an SD card and collected at the end of the study. This was implemented for the Apatsche monitoring system, custom built with a Raspberry Pi logger. There is the drawback that if there is any kind of failure it will not be picked up until the end of the study. Large amounts of data may be lost.

Many commercial data loggers can store data locally. For example the Eltek RX 250 RL will store up to 2 million readings. This would be almost year for 20 sensors at 5-minute intervals.

Standalone sensors

A few projects use standalone sensors that store data in on-board memory. This is more common with older projects such as the HES and Lyndhurst but some more recent ones too: DEFACTO, Calebre and eViz. Sensors of this sort include the HOBO product family and Thermochron iButtons. Systems like this are very easy to install. The eVis project installed an unusually high number of sensors (35, comprising temperature, light and door/window opening) in each home, taking half a day per home.

However it is not possible to detect equipment failures during the study. Data is retrieved from the sensors at the end. The EFUS project found that some of their temperature loggers were discarded by the householders during the study. They were supposed to be returned at the end, but about 15% did not come back.

In long term studies, independent sensors can suffer from drifting clocks. The e-Vis project found that their HOBO sensors reported time intervals between 3 and 7 minutes. This can make it very hard to analyse the data as it is necessary to deal with time intervals of different sizes.

Off the shelf versus custom build

Most projects monitoring household energy use have used off the shelf sensor systems, often from a product family – for example an Eltek gateway/logger and Eltek sensors. Other product families include Radio-tech, Current Cost, AlertMe.

Cost varies between product families (£30-£300 each). Scientific instruments such as Eltek and Radio-tech are generally more expensive, but they have specified accuracy and data loggers will store the data safely if there is a temporary problem with internet access. Consumer products such as Current Cost and AlertMe do not guarantee their accuracy and may drop data if there is no internet access for upload. Also there is no control over the frequency of readings.

There were three examples of custom built systems represented at our workshop, of which two use a Raspberry Pi for the data logger . They all have custom sensor modules, each comprising several sensors and a controller in a simple box. For example there might be sensors for temperature, humidity and light connected to a simple controller that handles the communications.

Developing a custom system for a large national study is a large task: ‘Going from a reserved prototype to a scalable deployable system is a lot of work!’ As well as skills in programming, design and prototyping it also helps to have experience in dealing sensor component suppliers and custom build services. It is important to consider ease of installation, especially when the installers are not technicians. The IDEAL project developed a phone app to help installers track wireless signalling problems.

Sensors

Off the shelf sensors usually belong to a product family. The cost varies widely depending on the intended market. Usually products aimed at householders (such as the RWE controllers and CurrentCost) are less expensive than specialist monitoring products such as Radio-tech or Eltek. However, the specialist monitoring products have a wide range of sensors available.

For custom built sensor modules there is a very wide choice of sensors supporting serial protocols such as I2C (inter-integrated circuit) or SPI (system peripheral interface). The I2C is a higher level protocol than the SPI and requires less custom programming. The controller can be an SoC (system on a chip) such as the NRF51422 (Apatsche), or possibly an Arduino (like Open Energy Monitor's system).

For battery powered sensors, the frequency of data readings and the strength and reliability of the wireless communications are important factors for battery life. Weak signals with frequent dropouts mean the sensor must keep resending the data and this uses up the battery quickly. Thus battery life can be much shorter than expected. Also, doubling the frequency of readings will halve the battery life – but at least that is predictable.

Wireless protocols in the home

There are a range of wireless protocols in use: WiFi, ZigBee, Zwave, ANT and others. These generally operate on one of several radio bands shown in the table below.

2.4 GHz	Wifi, Zigbee	Has to coexist with many other devices using WiFi channels. This band is notoriously bad at going through solid walls.
868 MHz	Z-Wave, ANT	This band is better for going through walls but the long aerial is fragile. This band is intended for low power remote controls operating over very short distances.
433 MHz	Current Cost	Similar to 868 MHz

Wireless signals are weakened by obstructions that can be permanent (such as walls) or temporary (such as people being in the way). This problem can cause data loss as well as shortened battery life.

Weak wireless signals can be mitigated using repeaters. For example, WiFi range extenders are widely available for about £20 and there are variants for other protocols. Z-Wave repeaters cost £30-40. Extenders may use power line carrier functionality to carry network signals through the home's electricity network. However, this is non-trivial and CAR's experience suggests that powerline repeaters can be problematic. Inserting a repeater alone does not immediately fix the problem as the network has to reconfigure itself. Using ZigBee it may be sufficient to power down the hub for a few minutes but with Z-Wave each sensor needs to be reset.[4]

Uploading data to a server outside the home

Data can be uploaded using either the internet or mobile communications, depending on facilities in the home. If the home already has internet this is usually easier. However, some householders are in the habit of turning broadband on and off. (This can be addressed by using local storage.)

Mobile communications may require extra equipment such as a dongle or modem and a package from a mobile network to supply bandwidth or quota. Radio-tech data concentrators (RT Wi5) comes with GPRS as standard. Mobile networks can be patchy even within homes, and this puts physical constraints on where the gateway can be installed. The signal usually works better on an upper storey of the home. This will in turn affect communications with the sensors.

Many system providers include a proprietary cloud data storage service. The data then needs to be pulled from that service.

Scalable data handling solutions

A large survey may involve hundreds if not thousands of households, and thousands of readings from many sensors in each home. As well as installing the monitoring equipment, resources must be allocated to planning and running a system for managing the data. This will require a database recording metadata about the recording devices as well as the data readings. Handling processes should support appropriate detection and management of missing and outlier readings, allowing for filling in or correcting data when appropriate, with tracking of these changes. Where data is collected over the internet, processes should allow this data to be loaded automatically and checked for inconsistencies, with problems reported to an administrator.

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[4] http://blog.smartthings.com/iot101/a-guide-to-wireless-range-repeaters/

Capitalising on Smart Meter data

The Smart Meter Roll-Out should be an opportunity to collect household energy data with minimal equipment costs, although this is not possible at the moment because the infrastructure is not yet available

Smart Meters may provide an ideal opportunity to gather consumption data as a part of a household energy monitoring campaign. The 2015 DECC publication ‘Smart Meters, Smart Data, Smart Growth’ outlines the options for accessing Smart Meter data[5]. Survey organisations and data collection contractors will be able to take advantage of Smart Meters installed as part of the national roll-out, to assist them in collecting detailed medium-resolution (half-hourly) energy use data from homes.

Around one million homes had been equipped with Smart Meters by the end of 2014[6]. The main installation phase begins in 2016, and all homes are expected to have a Smart Meter installed by 2020. Data collection will be possible in 2016, when the communications infrastructure becomes live.

The benefits for a survey organisation are:

- There is no need to install monitoring equipment to measure whole-house gas and electricity consumption
- The Smart Meters are installed as part of the Smart Meter Roll-Out at no cost to the survey organisation
- The householder would simply need to provide their consent to enable the survey organisation to collect the Smart Meter data
- Gas and electricity use data will be available for the last 13 months at a half-hourly resolution and for the last 24 months at a daily resolution (which could be before the survey begins and provide a baseline monitoring period)
- Electricity export data will be available for the last 3 months at a half-hourly resolution (which allows onsite generation technologies such as Solar Photovoltaic Systems to be studied)
- Current tariff information will be available (which allows cost of energy bills to be calculated)

The main challenge for a survey organisation will be in accessing the Smart Meter data once the householder has given their consent. There are two options:

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[5] http://www.smartdcc.co.uk/media/19720/2903086_decc_cad_leaflet_6th__1_.pdf

[6] DECC (2015) Smart Metering Implementation Programme - DECC’s Policy Conclusions: Early Learning Project and Small-scale Behaviour Trials. London: DECC. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/407539/1_Early_Learning_Project_and_Behaviour_Change_Trials_Policy_Conclusions_FINAL.pdf

- Access through the Data Communications Company (DCC), a centralised body that manages all communications between smart meters and energy suppliers, network operators and other authorised DCC users. In this case the survey organisation would either need to become a registered DCC user in their own right (which involved several contractual and security steps as well as an annual fee) or to contract the data collection to another company who is already a registered DCC user.
- Access through a device placed in the home which can communicate directly with the Smart Meters (known as a Consumer Access Device, or CAD). In this case the survey organisation would need to purchase and install the CADs, as well as to either collect the data from the CAD themselves (through the internet or a mobile network) or to pay a third-party company to do this for them. The advantages of the CAD option is that 10-second electricity use data can be collected (which provides opportunities for disaggregation) and the consumption data can be collected in near real-time if needed. The drawback, at present, is that no suitable CADs are yet available.

Sensors

Different issues affect different sensors that could be used. The location of sensors, and monitoring micro-generation, can both pose particular problems.

Installing the sensors in the home

The best position for sensors depends on their type. For example, temperature or air quality sensors need to in the middle of a wall, about 1-1.5m up. This makes them very visible so they need to be discrete. However, presence sensors need to be much higher up.

If sensors are not fixed in place they can be moved. However, fixings can cause damage that needs to be fixed when they are removed. For light-weight sensors 3M removable poster strips and similar products can be used to stick them to walls etc. However these are not suitable for all surfaces.

Some sensors need power (CO_2 sensors, for example). If they block sockets householders are likely to unplug them so it is essential to provide suitable adapters so that householders are not inconvenienced. Also it can be hard to find a nearby socket so extension leads may be necessary.

Monitoring electricity

Electricity can be monitored at three levels:

- at the mains
- at the circuits
- individual appliances

For homes that have any generation systems such as Solar PV panels, the mains is not a reliable measure of appliance use, because the generator will supply some of the power. Also, power at the mains can flow in two directions. In these cases, it is necessary to measure either:

- Mains power (directional) and generated power (usage is power from the grid + generated power), or
- Individual circuits and add them together.

Mains electricity can be measured either:

- using a current clamp on the mains input (any meter, but this is less accurate than a pulse counter unless voltage is measured as well as current)
- counting pulses from a pulse meter (not smart meters)

- taking input from a smart meter (not commonly available yet but may be within the timeframe of the study).

Individual appliances use can either be measured directly using individual appliance monitors (IAMs) or be inferred by disaggregation of the total power use. Disaggregation is not a mature technology and the consensus is that this requires high resolution data (more than 10-second) for reasonable accuracy.

Most researchers agree that there is no need to measure all appliances – only the main energy users, perhaps those that use more than 5% of overall electricity. By this rule, appliances to monitor would include fridges and freezers, ovens and cookers, kettles, washing machines, tumble dryers and dishwashers, TVs, lights, showers and set top boxes, see table next page[7].

Measuring at the circuit level is good for separating out lighting and some very high consuming devices that are on separate circuits – like cookers and shower. These appliances cannot be measured with IAMs as they do not have plug sockets. It also makes disaggregation of the other devices (see next section) easier as there are fewer of them on each circuit.

We used data from the HES to identify the large consuming appliances. The table below lists appliances consuming 5% or more of household electricity in at least 10% of homes. This suggests that large kitchen appliances, followed by lighting, should be priority items for appliance-level monitoring, along with electric showers where an electric shower is used.

Appliance type	Proportion of appliances of this type using 5% or more of electricity (%)
Fridge freezer	92
Freezer	71
Dishwasher	67
Cooker	62
Oven	57
Tumble dryer	47
Lighting	46
Shower	45
Kettle	40
Fridge	33
Washing machine	33
TV	33
Set top box	19

For measuring at the circuit level there is normally a current clamp for each circuit and a separate measure of mains current and voltage. This requires an electrician to fit and is time-consuming because it means manipulating many items in a small space. It normally involves turning off the power. Circuit level monitoring was used for the HES using Multivoies. The Open

[7] Based on CAR's analysis of the Household Electricity Survey data, the most detailed survey of electricity use in the home undertaken in the UK.

Energy Monitor system also monitors at this level and has been used in projects such as monitoring work by the Carbon Co-op in Manchester[8].

Where homes have micro-generators such as PV panels, these must be monitored as well if electricity usage is needed. Most generation meters have a pulse light which can be monitored easily with a pulse counter.

[8] http://carbon.coop/about-us

Disaggregating electricity use

Disaggregating electricity use allows researchers to identify specific appliances from their energy signatures, and this usually relies on high resolution data

Providing fine-grained electricity consumption information down to the level of individual appliances can be achieved either by monitoring each device separately or by *disaggregating* measurements on a circuit that feeds all of the appliances. Disaggregation has the potential to greatly increase the attribution of energy use to specific devices without the need for more physical components to be installed. Determining how energy is used is an important step in determining why energy is used.

Disaggregation requires the analysis of time-series measurements, using inference to attribute portions of use to specific appliances.

For example, many refrigerators exhibit a very high power spike when starting up, lasting at most a few seconds. After this, they enter a long stable cooling period and then eventually turn off as the required temperature is reached. When their internal temperature rises above the threshold set in the refrigerator, they once again start up with a high power spike. This pattern will be conspicuous in measured data even when the data includes the consumption of other devices. Knowing the general consumption characteristics of the refrigerator provides a means to perform this disaggregation.

This approach is particularly suited to a domestic setting, where a small number of appliances account for the bulk of electricity use. One can *fingerprint* the pattern(s) of use of common energy-intensive devices and store these as profiles in a database. A disaggregation system can be told what appliances are present, or automatic recognition of devices may become possible. Fingerprinting and monitoring may also be used together to determine that an appliance is becoming less efficient over time.

There are two distinct but related issues in disaggregation. One is temporal granularity, the other is *where* disaggregation is performed.

Readings at ten-second time intervals provide information related to phase changes in appliance operation, for example switching to a spin cycle in a washing machine. High frequency readings (several thousand times per second) can characterize certain devices, even if they do not exhibit large changes in consumption when on. Lower frequency readings can be processed locally, or be transferred to a remote server for disaggregation analysis. But high frequency readings require at least some local processing, simply due to the volume of data.

This is an area that is likely to develop during the time frame of the proposed monitoring exercise: there is a considerable recent literature regarding disaggregation; it is the subject of current research in a number of universities; and there is at least one new venture in the UK whose business is to provide disaggregation analysis services (Informetis).

Developers of disaggregation technologies include ONZO[9] and Informetis[10], the former a smart

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[9] http://www.onzo.com/2014/02/onzo-demonstrates-smart-metering-2-0-at-european-utility-week/

meter manufacturer, the latter a spin out from Sony located in the UK. However, there are also considerable open source efforts currently underway with a community of researchers who, for example, use and contribute to a Reference Energy Disaggregation Dataset (REDD)[11].

The dynamics of proprietary versus open solutions is difficult to predict.

It may be desirable to install different configurations of equipment in early phases of the survey either to transmit, e.g. ten-second data in a highly compressed form for remote analysis, or to carry out analysis locally. Both of these approaches will require the ability to reprogram the monitoring equipment, but neither requires a great deal of local processing power. A comparison between information gleaned from households with and without disaggregating monitors (and the additional costs) could inform further deployment.

We contacted three companies that have disaggregation products at present. Navetas were too busy with other commercial partnerships but ONZO and Informetis were willing to support a project of this nature. ONZO offer an analysis-only service. They can generally identify major power users in the home, up to about half of all energy consumption, based on consumption data at 1-second resolution (ideally active and reactive power). At 10-second resolution, potentially supplied by smart meters, they would recognise the same appliances but miss some usage events. They recommend uploading data to their service daily or weekly, to ensure data continuity. This could be through the internet or mobile network. ONZO can also disaggregate gas use based on 1 hour resolution data, distinguishing heating from cooking only (not distinguishing space and water heating). ONZO declined to give a quote for publication but we considered their estimate reasonable.

The Informetis product is very different, offering real time disaggregation (after an initial 14-day learning period). They supply their own current-clamp and gateway box, which functions mainly as a data compressor and feed. This uploads to their servers continuously using WiFi and broadband internet or mobile network. Installation often requires an electrician as the gateway device needs power and also needs to be near the meter. They also expect to reliably identify at least 4-5 main appliances. Their product is doing well in Japan and is on trial in the UK now. Their service is expected to cost approximately £150 for the hardware and then £8/month/home initially. They expect these costs to fall significantly within two years or so.

All disaggregation services need accurate consumption data. For households with microgeneration it is possible to measure generation as well as meter consumption, so that actual consumption can be calculated.

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[10] http://www.informetis.com/static/Informetis%20%20Overview%20for%20website%20-%20October%202014.pdf

[11] http://www.cs.cmu.edu/~zkolter/pubs/kolter-kddsust11.pdf

Monitoring gas consumption and heating

Heating presents particular challenges when it comes to monitoring, but it constitutes by far the largest use of energy in the home, often with more opportunities for savings

Gas consumption can only be monitored at the meter. Most systems involve attaching a device to the meter to count pulses from an LED light that reports gas use. However, there are a number of difficulties:

- There are many different types of meter, needing different attachments
- Not all meters have light pulse output.
- All equipment installed needs ATEX approval to show it is safe to use in an explosive atmosphere.

When smart meters are installed they will not have a pulse output so it will be necessary to rely on the data generated by the meter. This is in 30-minute intervals.

Third party monitoring systems are available. For example REFIT used Smart Monitoring Systems for their homes. This company swapped in their own meters. Unfortunately the swap was handled poorly by the utility companies, resulting in incorrect bills for many householders.

It may be useful to disaggregate gas use into space heating, hot water and cooking. However, this is difficult, and we are unaware of any work disaggregating gas use from a single monitored feed.

Strathclyde/Herriot Watt/Glasgow School of Art's Apatsche project tried fitting heat meters into some homes to monitor output from the boiler. However, the meters had to be plumbed into the heating circuit. This was expensive, requiring specialist installers, and leaving a permanent impact on the home. This strategy was used in only a very few homes.

Two other studies (IDEAL and DANCER) used temperature sensors on water pipes to infer use of heating. The sensors clipped on so were easy to install. IDEAL also used sensors on individual radiators. These sensors can be used to indicate the times when heat is supplied but not how much gas is used or how much heat is delivered. In principle they could help to disaggregate gas use.

It should be possible to measure heat flow through a hot water pipe in a non-invasive way by a combination of temperature and flow rate. Flow can be measured using ultrasonic devices that clamp onto the pipe. However, this is specialist equipment and none of the projects we studied used this technique. Further, we suspect calibration would be needed in different installations.

For homes that have warm air heating, it is theoretically possible to monitor heat flow through the ducts by measuring temperature and air flow rate. None of the studies we reviewed attempted this. Similar systems would be needed for air conditioning or MVHR systems.

Monitoring other heating fuels

None of the studies in our review monitored any heating fuel other than gas. There was no experience in monitoring the use of oil fired boilers or solid fuel systems.

Environmental sensors – internal

Most studies measured room temperature in at least one room. In many cases humidity was measured at the same time: sensors often measure the two together. Examples include Radio-tech Ecosense, Eltek GD10, EmonTH, Hygrotrac, and several custom sensor packages. Humidity is an important factor for health and air quality. CO_2 is also relevant to health and air quality, but is less often monitored. One study that did so (Gupta and Barnfield, 2013) found CO_2 was much more variable than humidity and frequently exceeded 2000 ppm in bedrooms overnight when windows were kept closed.

Some researchers consider that humidity and CO_2 are not important for air quality because they are affected by occupancy. Measurement of CO, NOx and VOCs is recommended instead. However, none of the studies we reviewed included these measurements.

Three studies (IDEAL, REFIT and ENLITEN) included light sensors. These were variously used to infer behaviour such as sleeping and turning lights on and off (when there was a sudden change in light levels).

Other aspects of thermal comfort such as air flow (draughts) or radiative temperature were not measured in any of the studies we reviewed.

Environmental sensors – external

Some projects monitored external temperature as well as internal: SHA, eViz, Apatsche and DANCER. Two of these measured temperature and humidity, while Apatsche installed a multi-function weather station also monitoring noise. Noise is relevant because it affects window opening behaviour.

However, some researchers felt that it was better to obtain data from local weather stations than to monitor it directly. This is because there is rarely a good location to measure even temperature, since close to buildings the immediate environment is affected by shading and shelter from wind. Weather stations are less local but they are better sited, more reliable and easier to obtain measurements from.

Also many felt it unnecessarily to continuously measure noise. It would be sufficient to use a noise map or take some spot readings.

Occupancy sensing

PIR motion sensors were widely used to detect occupancy, but they can give false negatives, especially when the occupiers have not moved for a while.

The Apatsche project is working on an intelligent occupancy sensor incorporating three different types of sensing device, including an ultrasonic proximity detector as well as PIR. It is hoped this will prove more accurate than any one sensor alone.

The CALEBRE project included a study mapping occupancy and energy use, for which they used a very accurate real time tracking system based on ultra wideband radio frequencies called Ubisense. The occupants were required to wear tags (Gillort and Spataru, 2013).

There is another technology under development called device free localisation (DfL). This utilises the fact that our bodies block radio signals (Naghiyev et al, 2014). The authors believe this is unlikely to be deployable in the timeframe of the study.

Window and Door opening

Several projects (REFIT, SHA and eViz) used door and window sensors to report when they were open or closed. A variety of sensors were used. However these sensors only report if the window or door is open, not how wide it is open. Some researchers felt that data collected by questionnaire was at least as useful.

Recommended Monitoring Packages

Choosing untested monitoring equipment would be very risky. It is better to learn from the experience of past projects, and focus the choice of equipment around clear research questions.

Our starting point for specifying monitoring equipment for a large survey involving up to 10,000 homes is that the equipment should be tried-and-tested in the field. There are at least 20 research projects around the UK that have attempted to use custom-built monitoring equipment, and without exception they have encountered reliability problems in the field. It is also time-consuming to develop custom devices, and the necessity to field-trial them and iron out problems means that attempting to develop new custom devices would risk delaying the start of any longitudinal survey.

This means that we restrict our list of recommended devices quite consciously to field-tested devices that are available off-the-shelf.

There was little consensus at our Expert Panel workshop on what the research questions should be in the proposed longitudinal energy survey (see next section). We recommend focusing on questions that are better answered in a longitudinal study, rather than shorter durations. Since the majority of energy use in the home is for heating rather than appliances, the questions and monitoring must include heating. We suggest the following as the central question relating to household energy use:

What factors affect the total energy use and patterns of use for heating and major appliances in domestic homes?

Based on this research question, we would prioritise variables as follows

Top priority:

- Gas consumption (weekly)
- Electricity consumption (weekly)
- Temperature in three rooms: living room, bedroom, room where the thermostat is located (hourly)

Medium priority:

- Gas consumption (hourly)
- Electricity consumption (10 seconds)
- Temperature and humidity or CO_2 in three rooms, as a proxy for air quality (hourly)
- Hot water pipe temperatures, to help disaggregate gas use for water/space heating (5 minutes)

Low priority:

- Individual appliances (using Individual Appliance Monitors, IAMs)
- Lighting levels
- Motion or presence sensors
- Door or window opening sensors

The top-priority variables give only overall patterns of total gas and electricity use. They allow gas use, likely to be mainly heating in most cases, to be correlated with room temperature. External temperature can be obtained from weather station records. This is not necessarily accurate for the precise location of the home, but it is often difficult to find a location near the home that is unaffected by shading or wind shadow to install an external temperature sensor. Such devices are also error-prone and introduce unnecessary uncertainty (are unusual readings caused by local weather effects, or errors with the sensor or recording?) Weather station records are good enough to show trends between heating, and external temperatures for individual homes.

The medium-priority variables include more detailed information about gas and electricity use, sufficient to support simple disaggregation. Humidity or CO_2 is added to the mix to give an indication about whether there is sufficient ventilation in the home. This is of particular concern where homes have energy efficiency measures installed that improve air tightness. High levels of moisture or CO_2 may also have adverse health effects on occupants - particularly if moisture leads to mould growth. (Humidity and CO_2 levels may be affected by door and window opening, but this too is of interest and such monitoring may provide limited clues about actual patterns of ventilation.)

The low priority variables are not necessarily less important, but current sensor technology is not good enough to give useful data. Individual appliances are normally monitored through plug-in devices that are unsatisfactory in several ways. They are often awkward to install – even after getting behind the fridge there may not be room for an IAM – and in more accessible places, appliances may be moved around and plugged in in different places. It is also much harder to measure appliances without plugs, such as showers and cookers, where IAMs are not suitable. However, major appliances use can be identified post-hoc from detailed electricity data. If this service is not available at the start of the study, we recommend capturing and retaining the data so that it can be analysed later on.

Motion or presence sensors are notoriously inaccurate and door or window opening sensors are too limited to be useful as they only give a binary indication whether a window or door is open or shut, not how much the opening is open.

The LUKES study proposal recommends three levels of monitoring, with more detail applied to fewer homes at each level. However our brief was not to tie ourselves to these levels, but to make more general recommendations. With this in mind, we recommend the following three packages, based on the high- and medium-priority variables. Costs are based on 1000 homes for two years each, and include some replacements due to equipment failure. We have not included time for briefing the households about the study or equipment, and this should be costed elsewhere (most likely together with a household interview). Hardware costs would be a little higher for smaller numbers, where economies of scale in purchasing sensors do not apply.

The table gives an overview, and a more detailed description of each package follows the table.

Package summary: hardware costs per home for at least 1000 homes, over two years

Package	Variables	With broadband	Without broadband	Maintenance
Package 1: Minimum monitoring	Weekly gas, electricity plus hourly temperatures	£207	£294 (standalone)	Standalone package needs regular maintenance checks
Package 2: Not relying on smart meters	Hourly gas, 10 seconds electricity, hourly temperature and humidity	£508	£803 (using 3G mobile)	Needs battery checks
Package 3: Using Smart Meters	Gas and electricity plus temperature and humidity	£319 (estimated)	Possibly the same	***Not available with current technology***

Package 1: Minimum monitoring

This package uses smart meters for gas and electricity if they are already installed, but otherwise the householder must read their meters weekly and log them. (This makes data less reliable, but keeps cost to a minimum.) Where no broadband is available, HOBO sensors can record temperature for several years at hourly intervals. However, where broadband is available, Current Cost temperature sensors are cheaper and have the advantage that data can be uploaded automatically so it is not necessary to visit the homes regularly just to check the equipment is working. The Current Cost temperature sensors need a Current Cost gateway, which comes with a current clamp to work and once it is installed it may as well be used.

We have assumed that monitoring equipment will be left behind. The residual value after several years of use will be less than any cost of removal. Ideally, leaving equipment in place would be a very low-cost way to continue collecting useful data. However, for householders who prefer to withdraw, we propose sending them simple instructions for unplugging the equipment they do not want any more by email. This would have very small cost implications for the research team.

On the other hand, if the study allows for the equipment to be re-used, then savings are possible, as long as the cost of decommissioning and collection is less than the replacement cost of the equipment used. Decommissioning is always quicker than installation.

Homes with broadband internet

Variable	Equipment	Year 1 cost per home (equipment+ installation)*	Ongoing annual cost per home (maintenance+ replacement)	Total cost per home (whole study)	Notes
Gas use (weekly)	Data from an existing smart meter OR Householder reads meter and enters over the internet or by phone	none	none	none	Unless the household has a smart meter, will need to remind householder to send in readings. Compliance will not always be good.
Electricity use (weekly)	Current Cost Electricity (clamp)	£78	£8	£85	
Temperature hourly (3 rooms)	Current Cost Temperature sensor	£81	£8	£89	Download data from the Current Cost server regularly to check functioning
	Current Cost Data-logger	£33	£0	£33	Data may be sent directly to DECC or analyst organisation

Total hardware cost £207/home, including installation, replacing 10% of failed devices each year, and maintenance (replacing batteries), but excluding travel costs.

*Installation costs assume installer costs of £500 a day

Homes without broadband internet

Variable	Equipment	Year 1 cost per home (equipment+ installation)*	Ongoing annual cost per home (maintenance+ replacement)	Total cost per home (whole study)	Notes
Gas use (weekly)	As internet homes	none	none	none	Unless the household has a smart meter, will need to remind householder to send in readings. Compliance will not always be good.
Electricity use (weekly)	As above	As above	As above	As above	As above
Tempera-ture hourly (3 rooms)	HOBO UX100-001	£241	£53	£294	Maintenance visits needed every six months to replace batteries, included in costs

Total hardware cost £294 per home, including installation, replacing 10% of failed devices each year, and maintenance (replacing batteries), but excluding travel costs.

Package 2: Medium-priority variables, not relying on smart meter technology

These packages include electricity monitoring at a frequency sufficient to support disaggregation of major appliances. The monitoring and disaggregation company ONZO told us that hourly gas use is enough to distinguish heating from cooking, though not space heating from water heating. We cannot give a cost for the disaggregation service, as ONZO regard this as commercially sensitive.. The Zwave product family is cheaper than Eltek's system, but it requires internet broadband, whereas Eltek supports 3G as well and can be used in more homes.

These packages do not include monitoring of hot water pipes because we were unable to find any off-the-shelf sensors fulfilling the requirements. Room temperature sensors do not have the temperature range needed (up to 80C) and are also the wrong shape. The Thermochron DS1922T has the range and small size, but it has insufficient memory to last more than a few weeks. It could store only three weeks of data at five-minute intervals. If this is considered useful, the devices could be posted back by the householder after three weeks. They cost £28 each in quantities of 100 or more, so two for each home would cost an extra £56, plus postage. However, they could be reused many times.

Homes with broadband internet

Variable	Equipment	Year 1 cost per home (equipment+ installation)*	Ongoing annual cost per home (maintenance+ replacement)	Total cost per home (whole study)	Notes
Gas use (30 minute)	AMR from Smart Systems	£40	£40	£80	Installation and maintenance costs are included in AMR's fees
Electricity use (10 second)	Aeon Labs Clamp Power meter one (100A)	£88	£8	£95	Needs mains power near to meter
Tempera-ture and humidity, light and motion (3 rooms)	Aeon Multisensor (AEOEZW074)	£134	£31	£166	1-year battery life
	Vera Edge Zwave Plus 500 data-logger	£147	£15	£162	Program to upload data daily
Disaggregation	Using ONZO disaggrega-tion system	Price on application	Price on application	Price on application	No additional maintenance/ installation costs
Extension cable		£6	-	£6	

Total hardware cost £508 per home (including 2 years AMR), including installation and maintenance for battery replacement, excluding travel and disaggregation.

Researchers may need to put in extension leads for power to the mains clamp sensor. However, these have modest cost - say £6 each for bulk purchases.

Our costing assumes that equipment will be left behind at the end of monitoring, as with Package 1. Smart Monitoring Systems will be responsible for decommissioning their equipment if appropriate.

Homes without broadband internet

Variable	Equipment	Year 1 cost per home (equipment+ installation)*	Ongoing annual cost per home (maintenance+ replacement)	Total cost per home (whole study)	Notes
Gas use (30 minute)	AMR from Smart Systems	£40	£40	£80	Installation and maintenance costs are included in AMR’s fees
Electricity use (10 seconds)	ZigBee HA Single Phase Power Clamp	£142	£12	£154	Battery will probably need changing at this recording frequency
Occupan-cy, tempera-ture, light	ZigBee multisensor ZHOT101	£225	£19	£245	
Data logger/ gateway	Greenbox zigbee data logger ZC-GB-EM-UK	£276	£49	£325	Needs SIM card
Disaggrega tion	Using ONZO disaggrega -tion system	Price on application	Price on application	Price on application	No additional maintenance/ installation costs

Total hardware cost £803, including installation and maintenance, excluding disaggregation.

Visits will be needed to change batteries on the electricity sensor. In addition, not all gas and electricity meters can be monitored with a pulse counter, so it may be necessary to swap meters or use a pulse meter for the electricity instead, though this is likely to be less accurate.

Package 3: Medium-priority variables, using Smart Meter technology

This package relies on Smart Meters to read gas and electricity data. There should be a Smart Meter in every home by 2020, but there are currently almost 1.5 million in place (less than 6% of the 27 million UK homes)[12]. Further, since at least 10-second electricity data is needed for conventional methods of disaggregation, it also requires a Consumer Access Device (CAD) to capture the data and upload it to a server. Products of this type are not yet available. When they arrive they will probably have their own networking, so it may be most economical to install standalone temperature and humidity sensors, avoiding the expense of another data logger/gateway.

Costing for this package has been prepared by using the Calculator, but readers should note that the costs of accessing smart meter data are not yet fixed. We have assumed that gas meter data can be obtained at no cost from the Data Communications Company and that a Consumer Access Device for the electricity smart meter will cost only £25 installation and no cost thereafter.

Homes with broadband internet

Variable	Equipment	Year 1 cost per home (equipment+ installation)*	Ongoing annual cost per home (maintenance+ replacement)	Total cost per home (whole study)	Notes
Gas use (30 minutes)	From Smart Meter	£0	£0	£0	
Electricity use (10 secs)	CAD device to fetch data at 10 second frequency	£25	£0	£25	Estimated cost
Tempera-ture and humidity (30 minutes)	HOBO UX100-003	£241	£53	£294	1 year battery life
Disaggrega tion	Using ONZO disaggrega-tion system	Price on application	Price on application	Price on application	No additional maintenance/ installation costs

Total hardware cost £319 per home [estimated], including installation and maintenance but excluding travel and disaggregation.

This package could support homes without internet as well, if the CAD device can use mobile networks for data upload. However, we recommend delaying the use of Smart Meters in

[12] http://www.energysavingtrust.org.uk/domestic/cy/content/smart-meters

monitoring until appropriate CAD devices are available, and ideally until Smart Meters are more widely available. In the interim, it would be possible to install a Smart Meter preferentially in homes that agree to participate in a survey, but this would probably increase the costs of the survey.

Expert Panel Workshop report

Some 29 experts on household energy monitoring came to a workshop to share their experiences of installing and using monitoring equipment, and how much it costs

This part of the report is based on what was said during the workshop and on the forms we asked people to fill in during the workshop. In some cases, information collected in post workshop conversations is also included. The forms completed during the workshop are tabulated at the end of this section. We invited all members of the TEDDINet network[13] to attend, plus others known to CAR who are active in this field. The main consideration in deciding who to invite was having hands-on experience of using energy monitoring equipment in homes. In total, there were 29 participants at the workshop, listed below.

Chris Hole	The Technology Partnership
David Allinson	Loughborough University
David Coley	Bath University
David Shipworth	UCL
DK Arvind	Edinburgh University
Elise Smithson	Coventry University
Gary Raw	UCL
Ian Cooper	CAR
Ian Leslie	Cambridge University
Jack Hulme	BRE
Jack Williams	DECC
Jason Palmer	CAR
Jez Wingfield	Independent (NEF)
Kathryn Buchanan	Essex University
Kristy Revell	DECC
Lina Stankovic	Strathclyde University
Nicola Terry	CAR
Nigel Goddard	Edinburgh University
Oliver Parson	Southampton University
Rajat Gupta	Oxford Brookes University
Ricardo Russo	Essex University
Rory Jones	Plymouth University
Shuli Liu	Coventry University
Steven Firth	Loughborough University

[13] See http://teddinet.org/

Stuart Galloway	Strathclyde University
Sukumar Natarajan	Bath University
Tom Kane	Loughborough University
Trystan Lea	Open Energy Monitor
Will Swann	Salford University

The workshop was divided into four sessions, structured around four questions:

Q1. What are the most important research questions relating to energy use in homes?

Q2. What are the most important variables to monitor?

Q3. What are the most important lessons from your monitoring experience?

Q4. How do you expect monitoring costs to change in the future?

Session 1: Research questions

A wide range of different research questions was proposed by participants, and there is no clear consensus on exactly what we could learn from a longitudinal survey. However, there were four clusters of interests mentioned by several participants. First, to understand where energy is used in homes, and as a subset of this where energy is 'wasted' (which could in principle be saved). Second, to understand how patterns of energy use are changing over time (including breaking down changes by social or demographic groups). Third, to understand more about the relationship between perceived thermal comfort and temperature (alongside other parameters). And fourth, to understand more about electricity use by different appliances.

Several participants also referred to the need to understand more about the gap between model estimates and actual energy use in homes.

Session 2: Monitoring variables

There was more consistency in responses to this question. Most delegates said that monitoring gas consumption is a priority. Most of them also felt that it is important to monitor total (real) electricity use. About half of the participants thought it is important to monitor room temperatures, and about half felt that monitoring occupancy of rooms was important.

Rather fewer people (around a third) wanted to monitor water use, with another third wishing to include hot water supplied to radiators. A similar number argued for monitoring CO2 and/or relative humidity, often as a proxy for ventilation.

There were strong differences of opinion when it came to monitoring appliances, with some arguing that this is unimportant because most energy is used for space and water heating, while others said we need to know more about electricity use – and which appliances use most energy.

There were also differences of opinion when it came to monitoring occupancy, with some saying poor occupancy data is worse than none at all. There were also forceful detractors about the value of internal and external temperature, saying that temperature alone cannot answer questions about thermal comfort or health.

Only one person thought it is a priority to monitor air quality (VOCs).

Session 3: Past monitoring work

IDEAL

The IDEAL project (ongoing) is using custom sensors and a custom hub based on the Raspberry Pi. There is a wireless sensor box monitoring temperature and other parameters in each room. It is normally attached to a wall. This runs on very low power, so battery life is 2-3 years. It achieves this by reporting only significant changes rather than at regular intervals. There is also a temperature sensor for clipping to a pipe and other sensors for meters.

This design is on its 3rd or 4th iteration and they expect it to be ready in 4- 6months.

A whole house can be installed in three hours for £450. They have an iPhone app showing wireless signal strength to aid installation. It is not necessary to find the best geometry – just a workable one. The wireless band they are using is 2.4 GHz - the same as WiFi. The system needs to be simple enough to install by non-technical installers – this is a challenge!

Open Energy Monitor

The Open Energy Monitor system is an open source design. The sensor nodes are based on Arduinos and the hub is a Raspberry Pi. They supply a cloud data storage service – the hub can store locally or upload to this. Their system is used by hobbyists and some universities. The Carbon Co-op in Manchester uses it (http://carbon.coop/). There are 11,500 active feeds – currently on one server. If necessary, extra servers could be added.

Their power sensor for circuits measures real power only. They do not have a design for measuring gas.

The Open Energy Monitor system is available for purchase, and very economical. The base system is £120 and each circuit costs an additional £10/circuit. This does not include installation. It is aimed mainly at hobbyists, and it may not be reliable enough for use in a national survey.

REFIT

The REFIT project monitored 20 households with mains electricity and nine appliances for two years. There were very few errors. They used the ZWave wireless protocol with a Current Cost meter connected to a Vera 3 hub. This then sent data over the internet to the university server. All sensors were powered so there were no battery issues. They did lose data when the householder turned the broadband off and the data did not upload.

Putting plug monitors onto e.g. washing machines was problematic because of the need to get in behind the machine. However, in some homes there were so few problems installers could be in and out in half an hour. Others cases took up to two hours.

Off the shelf kit is recommended for reliability. Open source energy monitors are also very cheap but their reliability is questionable. In any case it is essential to collect data centrally and check it regularly and automatically, to enable prompt interventions in case of failure.

EFUS

There was no wireless capability at the time so the Energy Follow-Up Survey of the English Housing Survey used standalone temperature loggers. They were only £10 each but proved reliable. They monitored 800 properties for 1 year each. However, at the end of the project the householders were supposed to post them back – about 15% did not come back.

ENLITEN

They monitored 70 homes with a hybrid system with:

- bespoke sensors for the environment and a Raspberry Pi data logger (temperature, humidity, light and PIR)
- commercial pulse counter sensor for the electricity and gas (Cloogy)

Neither was more reliable than the other. Gas was monitored at 15-minute intervals but the rest at 5-minute intervals.

For meters that did not have a pulse they used an adapter that converted from reading the rotations of a dial to a pulse, so as to use the same hardware and communications system.

All sensors needed power. Since the hardware was from the EU they needed plug converters.

The data from the PIR was not good enough to use as occupancy data.

They had varying levels of success, some homes had quite a lot of gaps.

Replacement rates need to be factored into costs, especially with low cost systems.

Custom systems

Developing custom systems is a lengthy task. This monitoring project should not be regarded as a hardware development opportunity. One workshop participant said: 'Going from a reserved prototype to a scalable deployable system is a lot of work!'

However, some found that there were not commercial systems available to do what was needed, so custom development was necessary. Those who have developed custom sensor packages now have experience in working with sensor component suppliers and custom build services. This is valuable.

A team at Heriot Watt is developing a sensor for occupancy that packages three different devices including PIR and an ultrasonic proximity detector. Data from these will be scored by an artificial intelligence learning algorithm. This sensor should be ready soon.

As well as custom hardware, several projects developed custom software to collate and manage the data. The Apatsche project has resulted in an open source platform called ITL[14]. (It has an MIT licence). This combines data from different sources such as AlertMe, Netatmo and their custom equipment and maintains the data securely, and with privacy safeguards.

[14] See https://github.com/itlenergy/itlenergy/

Need to optimise performance with proprietary systems

Standard network protocols do not scale well. They are fine for just a few devices. It is necessary to use proprietary protocols for good performance and scalability.

Many protocols do not scale well for high resolution data, since it demands too much power from the battery. This is an area where optimisation is needed.

Several projects have used compressed reporting – only reporting changes. For example IDEAL is one, COGENT (Coventry University) is another (http://www.coventry.ac.uk/ research-bank/research-archive/engineering/cogent-computing/). But this can generate bias because there has to be a threshold for a significant change.

For compatibility, it is easiest to stick with one product family.

For large scale projects or data it is important to consider the scalability of data management systems as well as data collection.

Electrical circuits

Some measuring devices need an electrician to install, for example, circuit level current clamps. Enthusiastic amateurs using Open Energy Monitor might do this themselves but a survey of this type needs to follow strict safety protocols. Also, one should allow one day to install circuit level monitoring whereas for simpler installations it might be possible to manage three per day.

The HES monitored at the circuit level and also monitored most appliances, but did not record which appliances were on which circuit. There is a project for specifying metering metadata: NILM Metadata, maintained by Jack Kelly.[15]

One should record changes in metadata over time, e.g. meters monitoring different appliances.

Gas meters

Gas metering is particularly difficult. There are two options:

- Install a smart meter and collect the data (currently restricted to 30-minute intervals)
- Attach a device to count pulses or disk rotations. However, it is necessary to have permission from the meter asset manager to do this. All equipment must have ATEX approval (for 'explosive atmosphere' appliances). There are many different types of meter and you need corresponding types of attaching device. There are some cheap solutions for this e.g. from Navetas. This measures every 15 minutes for a two-year battery life.

Pre-payment meters are particularly difficult to attach things to.

When gas meters are replaced with smart meters then there will not be a pulse or dial to watch, so we will be restricted to what the smart meter itself can tell us.

[15] See https://github.com/nilmtk/nilm_metadata

The REFIT solution for gas meters involved a third-party monitoring company (Smart Monitoring Systems) who swapped in their own gas meters. Unfortunately, the swap was not handled correctly by the householder's gas suppliers and in many cases there were incorrect bills following the swap.

Other fuels

None of the projects represented had experience of measuring other fuels such as oil or solid fuel. Not including these households could be a serious omission, even though they are a small percentage of the whole stock (9% for Great Britain[16]).

Environmental sensors

The positioning of e.g. temperature sensors is critical – out of sunlight etc. Sensors that are not fixed to the wall can get moved – but if you fix them to the wall then you have to pay redecoration costs at the end. Or can use 3M strips to attach things to the wall and in theory remove them easily.

Wireless in the home

The 868 MHz band is better for going through walls but the aerial is long and fragile. Also, components for working in this band are more expensive than for the 2.4 GHz band, which is much more widely used.

Wireless networks are prone to temporary glitches because people and other obstacles get in the way.

Some projects used power line networking instead of, or in combination with, wireless – for example to improve transmission between floors. The socket units can act as a wireless hub. It does require using sockets but they are pass-through for power.

There was disagreement as to whether ZWave is easy to set up or not.

Communications from home to server

For home to server communications, Apatsche is considering walk-by or even drive-by data capture using wireless from the home hub to equipment carried by a researcher. Since their homes were very close together they could also have considered a White Space Network solution. This technology supplies internet connectivity over a range of about 10 km.

Some projects used GSM for data upload. However mobile signals are often patchy.

Householder interference

Reliability is a challenge, and a lot of this is due not to the equipment, but the household environment. Some householders are more 'reliable' than others (less likely to turn things off or move things, less likely to turn off the broadband etc.) In general it is best not to rely on the

[16] Baker W. (2011) Off-gas consumers: Information on households without mains gas heating. London: Consumer Focus. Available from: www.consumerfocus.org.uk/files/2011/10/Off-gas-consumers.pdf

households' own broadband if possible. Also, never block sockets (use extension leads and adapters) or your devices will be unplugged.

Devices installed must be discrete. People do not want their home to look like a laboratory. Some householders threw out equipment they did not like.

Installations need to be done consistently. Also, installers must take time to explain to the householders what they are doing. Householders will be interested to know and the more they understand the less likely they are to interfere with the devices afterwards (e.g. by moving or unplugging them). (Recognising that this increases the chances of a Hawthorne effect, where householders change behaviour because they know they are being monitored.) Therefore installers need more than just technical skills and must not be rushed. It is useful to develop materials for the householders to refer to.

However, in some cases too much understanding is also a problem - the Apatsche project found that some householders, who had access to their own telemetry, moved devices around to improve reception

Other reliability issues

Experience shows that return visits to fix things are the norm rather than the exception. *'You will need to visit each house many times.'*

Some researchers were concerned about the reliability of Raspberry Pi computers.

'Also be prepared to accept incomplete data from any one house and spend money on larger number of houses rather than perfect data from fewer houses.'

'Timestamp issues [are a problem] (e.g. Eltek system time stamp for individual sensors is pseudo random to avoid transmission clashes).'

Short/long projects, frequency of visits

For short projects or where frequent visits are needed for other reasons (e.g. every two months) standalone sensors like the HOBO are adequate. They can be just as reliable as remote monitoring. The EVALOC project ran 50 homes with standalone systems and 49 with remote monitoring, and there was little between them in reliability.

For very long projects data will rot if there are no visits. For example, meters may be replaced. Appliances plugged into IAMs will move. Some people recommend visits every three months anyway.

For long projects, there was some concern that sensors may drift and need recalibration but this has not been checked.

People on panels get 'conditioned' to the point where they are not representative. The more frequent contact the quicker this happens.

It is hard to arrange visits to homes.

Other general comments

You should run a pilot study first.

Do not expect a one-size fits all solution. There is variation between homes that require different solutions.

Be prepared to deal with outliers.

It is a mistake to over monitor or over-evaluate. The more you monitor the more there is to go wrong. You only need to monitor the large energy items.

Session 4: How will costs change in the future?

Gas and electricity

The smart meter rollout will have a big impact. For gas, smart meters installed in homes will make bespoke solutions impossible and will limit studies to what the smart meter will provide – 30-minute intervals. This means monitoring gas needs to have at least two metrology solutions – with and without smart meters. Alternatively, the study could be limited to sample only homes with smart meters, or get them fitted.

Smart meters for electricity do not preclude use of a current clamp as well so the same solution can be used with and without. The smart meter can supply 10-second data to an in-home network and this could, on paper, support some disaggregation. However, in-house-displays supporting this may not be available in time for the start of this survey.

At some point in the future it may be that consumer distribution boards come with monitoring capabilities (or simply current transformers) built in. But at the moment that would be a significant extra cost and will likely be adopted, and assessed, in non-domestic situations first.

Oliver Parson is working on disaggregation algorithms using the HES data which is based on two-minute intervals. The algorithms will be published. There is also an open source toolkit for disaggregation.

Other components and costs

If prices are dropping, it may be better not to buy in bulk up front, rather buy in equipment as and when it is needed. However, prices are not likely to drop, because microchips are a small proportion of the cost.

A stable software architecture (with standards) would help to drive down costs.

Prices for sensors are unlikely to fall significantly. They are already inexpensive and manufacturing costs are unlikely to change.

Hardware prices may not change but resilience and reliability will probably improve. ‘Price will not come down but capability will go up. ‘However, if competition lowers prices, that could come at the cost of reliability and calibration drift.’

Battery technology improvements could reduce the number of maintenance visits needed.

However, unless the return visits are reduced, it could be that installer costs dominate overall.

Tables of Responses

What are the most important research questions? Any other comments?

Response
80% Energy Use is for Space heating: 1. How much energy is required to achieve What Indoor Air Temperature? 2. How do Energy and Air Temperature Change with changes to the Household, Fabric, heating system, weather, etc?
How do people use energy and why? What will the impact of smart metering initiatives be? • Reduced energy consumption? • Increased awareness and knowledge? • Load shifting? How easy/hard is to shift demand? Can we profile households in terms of their energy use?
This project is all about how to cut energy use. Therefore there is only one question: where and how much energy is wasted in the home?
What are people doing with energy? (fact) Why are they doing those things? (motivation) How do both of these evolve over time and correlate with: • Policy interventions • Technology changes • Social attitude changes
How do people interact with doors and windows in terms of indoor temperatures?
1. When/Why do people heat home? 2. When/Why [do they] use the amount of hot water they do? 3. Where are the heat leaks in the house? 4. Also [energy use] for heat pumps, cooking and window opening 5. If costs are tight most [unknown] can be ignored from climate change questions
How representative are the assumptions related to occupant presence and actions, i.e. occupancy, set points, underpinning heating periods, building simulation models (BBEM, dynamic etc.)
How do households react to intervention (price, new technology)? Do energy consumption patterns segment into distinct groups?

How can we classify energy use as waste (i.e. no utility)
[Unknown word] people wrong about energy consumption? What can they do?
How much energy do dwellings use? How does this change over time? What do these changes tell us about why the energy is being used?
How do internal temperatures change over time? How can we better model energy use, i.e. how can we improve our models used (i.e. SAP, BRISNSM, etc)
How much energy do different appliances use? How stable is it over time? Effect of changes in: • Weather • Appliance stock • Occupancy • Prices
Energy used over time: Itemised - Electricity – Gadgets - Gas – Heating –Hot water Monitor changes in energy use over time. As a function of external variables (e.g. cost of fuel, energy policies) As a function of human factors (eg. Levels of comfort, over time)
Why do models (statistical) based on behavioural variables explain so little of the observed variance in home energy consumption? a) missing variable bias or; b) instrument imprecision ? What do we use to ensure to avoid threats to internal validity from confronting bias and under-determination? What social factors does energy use in the home serve?
What is the link between members of the household and energy consumption related to heating and cooling and humidity rates in weather? What is relationship between health and comfort of householders and their patterns of energy use (for all occupants of the household)?
Integrating qualitative and quantitative data for more meaningful feedback. Understanding energy consumption in home. Associating domestic practices (e.g. cooking, washing, etc.) to energy consumption to understand where energy is consumed. Understanding appliance signatures (large enough sample of appliances) to

improve their energy efficiency, helping in disaggregation. How does consumption and use of appliances vary over time, introducing of smart home kit, smart meters, utility energy services.
Depends what we are wanting to know? What are typical interval temperature ranges for different types of household (occupancy, ages, household income, occupancy pattern, etc.) As above but for gas /electric energy (and other energy types off gas grid). Types of heating patterns for different households and effect on energy use and energy efficiency. How do households respond to different government initiatives (eg. Green deal, low energy bulbs, efficient appliances)? Energy use for different archetypes.
What is the set of monitors required to run for 5 years with minimal intervention (such as battery charge) to monitor parameters and context to better understand behaviour related to energy consumption.

What are the most important variables? Any other comments?

Relates to heat as above: In order: Gas meter (Whole house) Electricity meter (whole house) Room air temperature (every room) Heat meter on [unknown words] Blown Door Test RdSAP Assessment Does electricity matter (below whole house)? Given that majority of energy use is for heating? Better to know nothing about occupancy than flaky data.
Gas meter Electricity meter Water meter If research question is to do with reducing energy then should focus on monitoring consumption across the board and focusing on main high consumption areas (i.e. space heating, lighting, hot water).
Forget anything that isn't about items that use more than 5% of demand. So kill: meters on individual electrical appliances, and boiler settings (this can be set [unknown words] then you changed the slide!

Whole gas – energy /01m3 Whole electricity – every second, real and apparent Boiler – heating supply temperature Water – heating supply temperature Thermostat operation monitoring These 5 will allow many behaviours to be inferred.
Gas Electricity Temperature – Bedroom, living room Relative humidity CO_2 level
Top 5 Gas meter (high sample rates) Bottom 5 Noise Electric meter on output of PV system Meter on fridge (efficiency and replacement cycle known from other data) PWG in lamps External temperature
Gas Electricity Occupancy Heating set points, periods, space Boiler control
Electricity per circuit with disaggregation /identification Gas Internal temperature Motion in room Air quality Internal energy sources
CO_2 and Humidity monitoring, as the valve increase the ventilation will take the most people to reduce the energy consumption. Gas meter, elect meter, water meter, heat meter on boiler supply to rads, water meter on gas supply to rads.

1. Air Temperature 5. R.H. 2. CO2 - vent rate, vent behaviour, other VOC, also quite cheap now 3. Electricity meter 1. Gas meter 6. Radiator temperature as proxy for boiler operation External: Solar Radiation, Wind speed/DIR
Gas and Electricity Internal temp Wall temp
Most useful: Whole home gas, electricity and water. Circuit level electricity data Gas or electricity for heating Individual appliance electricity data would also be useful, but not be possible for £500/house Least useful: Uncommon equipment, eg. PV/ Solar thermal systems Air quality and windows opening sensors.
Gas use for heating/hot water/cooking Electricity - harder to select. Use some [unknown words] Human factors – levels of [unknown word] Comfort as a function of use and change of use of energy consumption items.
Top Water meter on boiler supply to rads Electricity meter Gas meter Heat meter on boiler supply to rads Boiler monitoring (off/on) Room occupancy Room CO2 Bottom Internal temp External temp
Essential Gas, Adaptive thermal comfort, Electricity, Water, CO2, Air speed, Whole house disaggregation of heat and power Not Essential Individual appliance, humidity, Surface temperature and TRVs (was removed from screen) Other Sources Noise maps, Local authorities air pollution Met office data Missing – what were the reasons for these data? Energy use driven by behaviour needs. Less detailed energy consumption and more on occupant satisfaction?
1. Aggregate gas metering 2. Power load (electricity) metering

3. Sub metering of a range of appliances (not the same per house) to capture as many appliances as possible (sample of 20 of each appliance) 4. Aggregate water metering 5. Quantitative data (how often is the appliance or water fixture used, what for, how long per use) 6. Temperature in rooms used most often.
Internal temperature/humidity: - average for household - Variations across households Improved Energy Use. Efficiency of conversion of Energy to Heat. Set Points of Heating/Hot water controls. Internal air quality - CO_2 Proxy? Sub-metering of electricity use. Q – if we don't know the details of the baseline performance of fabric/systems it will be difficult to truly understand impact of households (e.g. What are "real" values, what is air permeability, what is background ventilation rate, etc ?)
Temperature, RH, hot water pipes' temperature, electricity, gas, CO_2, VOC, IR for movement meters

What are the most important lessons from your monitoring experience? Any other comments?

1. Gas and electricity monitoring is very difficult. Households can always got a new smart meter fitters (so you lose your asset). Just fit smart meters. 2. Temperature sensors are most B+ Put in the right place and must stay there. Develop materials that train the households. 3. People turn broadband routers off. 4. Don't use this as a hardware development exercise! 5. Measuring solid fuel (coal, wood) district heating. 6. It's hard to arrange access to houses
N/A Product is still in development (Gas monitoring as challenging)
You will need to visit each house many times
Going from a reserved prototype to a scalable deployable system is a lot of work! The more low-frequency cases (dwelling situations) [unknown words].
Don't over monitor/over evaluate How to deal with [unknown word]
Monitor the large energy items only. But monitor well. Ignore mobile phone charger use, etc. Focus on heating, hot water, drafts, air quality, etc. Also be prepared to accept incomplete data from any 1 house and spend money on larger number of houses rather than perfect data from fewer houses. Some sensors (as opposed to whole systems) e.g. CO2 should fall in cost.
Data loss. Reliability of sensors Do commercial sensors exist that do everything we want?
Communication reliability Storage "Interference" by occupancy Ease of insulation Does one size fit all
Data missing from the automatic [unknown] equipment
Need to factor in failure/replacement rate in overall most with "low cost" systems
Piloting is essential [unknown words]

Household energy use survey (from a user prospective): - Should have monitored whole – home usage - Should have recorded metering hierarchy, e.g. which appliances are also monitored at circuit level. There is a project for specifying metering metadata search – NILM Metadata, maintained by Jack Kelly (jack.kelly@imperial.ac.uk) - Should record changes in metadata over time, e.g. meters monitoring different appliances.
Gas monitoring must be challenging, e. g. energy use and monitoring
N/A
Off the shelf kit, robustly tested, and becoming very cheap. Automation UK, e.g. sells cheap clamps and non-intrusive Z-wave sub-meters and environmental sensors. Alternatively, open-source energy monitors are very cheap and can be integrated via a Pi to server. Reliability is questionable. Highlight the need for remote data checking (automatically) to enable real-time intervention (in cloud data management).
Problems with householders interfering with monitoring equipment (e.g. unplugging or moving sensors). Getting permissions to access primary utility meters and other issues such as Atex approval or prepayment meters. Timestamp issues (e.g. Eltek system time stamp for individual sensors Pseudo random to avoid transmission clashes). Calibration drift of sensors.
[unknown words]
Reliable ways of displaying the network using non-technical installers

How do you expect monitoring costs to change?

2017 – More houses have smart meters Get gas and electricity from smart meter. Possible to attach temperature sensors to smart meter? Share comms. and database?
The cost is only for the kit, the numbers of visits to keep it working. So this might not improve.
Gas/electricity scene will change with rollout of smart meters, but it is hard to predict how. Price won't come down but capability will go up. If there is [unknown word] platform (e.g. from Pest or BG), then economies of sale might come in to play.
Smart metering may bring [unknown word] Perhaps attach Temp/RN/CO2 sensors to smart meters communication systems.
Hard to answer, no longer driven by technology change. Market related developments (companies such us NEST et. Al, creating a supply chain) will matter more. Also gives [unknown words]
Stay the same
Disaggregation Smart meters as information sources Gas sensors
Cheaper with gas , electricity and water meters. Charges on the data communications, plus the meters and software supply companies.
Some aspects of monitoring will be cheaper, e. g. microprocessors, sensors themselves are quite cheap now and manufacturing/ internal costs unlikely to change in a big way.
Small fall in costs.
As home area networking reliability and service improve, the number of visits required will reduce, but not disappear. Aggregate gas and electricity sensors will become redundant as smart meters are deployed, being replied by Consumer Access Devices. This limits data resolution to 10 sec electricity and 30 min gas, but the financial benefit is significant.

No change in cost. House features out of sensors but price unchanged.
SMEs on IT consulting companies [unknown words].
Will go down.
Use of light-based wireless comms. Battery technology improvements

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