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Towards an Integrated Approach to Building Energy Efficiency: Drivers and Enablers

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Abstract — **While electricity, gas and water can be treated as natural resources individually, they are often heavily interdependent on each other; during the stages of generation, distribution and consumption. On this basis, the paper presents the case for an integrated approach to energy management in buildings, combining water, gas and electricity. The paper discusses the rationale and drivers for such an approach and describes a generic architecture for integrated energy management in buildings. Finally, it presents a state of the art review of present and recent EU research projects, aiming to identify ICT enablers that can realise this vision.**

Index Terms — **Green Buildings, Energy Management, Smart Homes.**

I. INTRODUCTION

EU is currently funding a wealth of research activity in the smart energy area. The European commission's FP7 funding framework identifies ICT as a major enabler of the low carbon society. ICT will allow domestic dwellings and commercial buildings to become key active nodes in the smart energy grid. The EC website [1] currently contains links and factsheets to at least 40 research projects in this area. Some of these tend to focus on software, middleware or hardware, whereas others analyse the socio-economic dimension to better understand user energy behaviour. However, all projects must deploy an energy management system with an underlying ICT architecture. A common feature of FP7 projects is to trial these solutions with the public in pilot schemes. In the interests of transparency, the authors are conducting this research for the one such pilot scheme in the '3ehouses' project.

This paper aims to distill the outputs of recent and current projects for a state of the art review of HEMS and BEMS. The first section examines the drivers for integration of energy supplies. Due to the intermittency of renewable energy sources, volatile energy prices and rapid technological advances it is useful to integrate electrical, gas and water metering, and where feasible, their usage. In temperate and cold climates, the most effective energy saving measures will be targeted at heating from gas or electricity. However, a spatial and temporal dependence on the energy cost of both services will dictate where energy saving measures are best concentrated, for any one building at any one time. An array of ICT solutions are available to calculate this on an ongoing basis.

In the second section of this paper, future architectures are identified that will bridge these services at the building level. Emphasis is given to

- Home Energy Management Systems (HEMS).
- Building Energy Management Systems (BEMS).
- Technologies to enable and promote end user interaction
- Standardisation related to HEMS technologies

II. SMART GRID

Currently, the term *smart grid* is defined differently by various stakeholders. For the purposes of this paper, the *smart grid* is considered at domestic and building level and includes interaction with the utility through communication pathways. This perspective is useful because the dwelling occupant is usually the asset owner, end user and energy customer, simplifying the human dimension of the analysis. In this paper, *smart grid* encompasses electricity, gas and water: and should therefore be thought of as a smart energy system rather than just an electrical power system. These supplies are selected as they are the most predominant in the UK. The integration may be extended to other energy sources where appropriate, such as oil, coal and biofuel. The reasons for this approach will be outlined in the next section.

Fig. 1 suggests a future domestic smart architecture that will involve the following key elements:

- An electrical AC grid, with metered export and import
- A metered gas supply
- A metered water supply
- Electronic appliances, possibly fed by a LVDC network
- Dry white goods (Fridge, freezer, dryer etc)
- Wet white goods (Dishwasher, washer, or washer/dryer etc)
- Individual appliance metering and switching
- A local communications network
- A communications gateway to the internet
- Sensor and actuators
- A heating system (electrical and gas)
- A domestic hot water system

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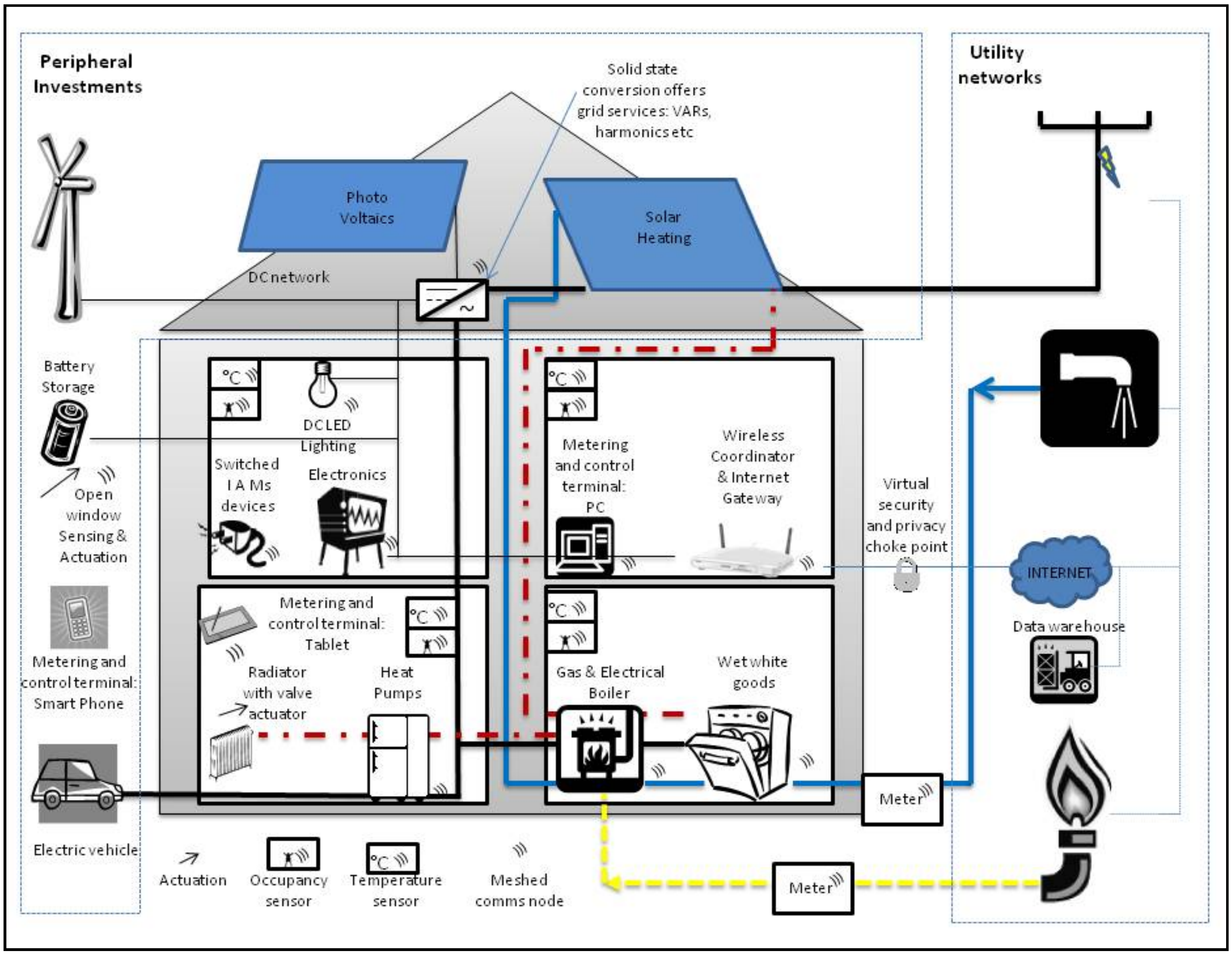

Fig. 1. A future domestic smart architecture

- Peripherals:
  Electric vehicles
  PV Cells
  Wind turbines
  Solar hot water heating
  Power Conversion

III. DRIVERS FOR AN INTEGRATED APPROACH

The interconnection of power systems allows greater security of supply through redundancy. In recent years, this philosophy is behind the interconnection of asynchronous grids with HVDC links. This is also true of gas transmission networks with a growing network of high pressure pipelines crisscrossing Europe. In the UK, National Grid benefits from the joint operation and tight integration of the gas and electricity transmission systems, because the majority the UK's centralised plant such as CCGT relies on natural gas. Might there also be a case at the building level? How might this kind of 'energy hedging' benefit the smart grid?

Although users may not always be conscious of the fact, providing buildings with water, gas and electricity all involves energy expenditure. Clearly, electrical power must be generated in some way, and gas is used as an energy source, mainly for on-site heating and cooking. The shipment, transmission and distribution of gas involves a complex supply chain with shipping, a network of high pressure pipes, storage, and a lower pressure distribution network. Water must be purified and pumped, where necessary, to overcome natural pressure gradients. Waste water must be processed so it can be released into rivers and seas with minimal environmental impact.

The geographical location of a building has considerable bearing on the best energy solution. In temperate climates, such as much of Europe, this is likely to vary considerably from day to day as well as season to season. This is in part due to the intermittency of renewable generation and partly because outside temperature dictates the use of heating or air conditioning. Usually, the overall energy efficiency from onsite gas use is far better than the equivalent electrical energy due to generation losses and resistive losses in transmission and distribution. If gas and other fossil fuels are predominant in the generation mix, the emissions are therefore also reduced by onsite use of gas. But at times when the level of low carbon generation is above a threshold, emissions are better from using electricity. The calculation of such a threshold is not trivial. The relative price of each energy source is another matter, as renewables and nuclear plant are often more expensive to build and maintain.

Fig. 2 shows that the instantaneous optimal energy solution for an individual building will depend on on-site generation,

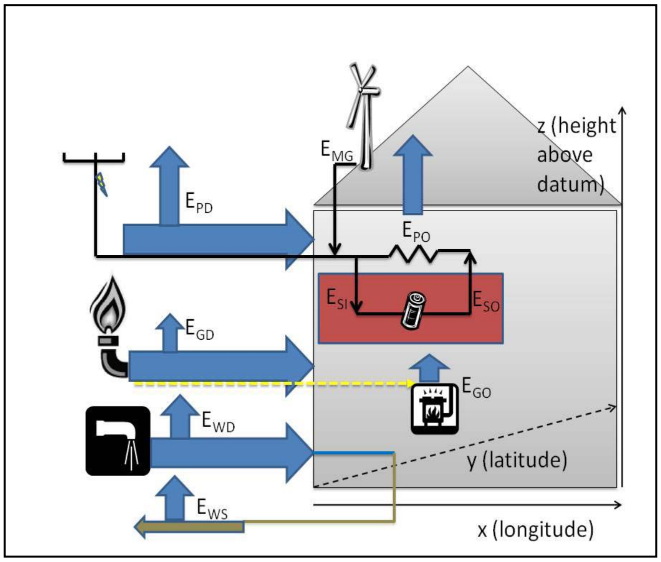

Fig. 2. A future domestic smart architecture

storage, and the power system's generation mix. It will also depend on the efficiency of the electricity and gas supply chains, the entire energy usage in water delivery and waste processing. Since this is location specific, the geographical coordinates (x,y,z) of the building are important. In pure energy terms, it can be simply quantified as a linear sum of energy inputs and outputs (1).

$$\begin{aligned} E_T(t_0) = \; & E_{WD}(x,y,z,t) + E_{WS}(x,y,z,t) \\ & + E_{PD}(x,y,z,t) + E_{GD}(x,y,z,t) + E_{PO} \\ & + E_{GO} + E_{SI} - E_{SO} - E_{MG}(x,y,z,t) \end{aligned} \tag{1}$$

Where in (1),

E_T is total instantaneous building energy expenditure, at time t_0

E_{WD} is the energy used in water delivery, a function of location, time and dependent on occupant demand

E_{WS} is energy due to sewerage, a function of location, time and dependant on occupant demand

E_{PD} is energy due to gas delivery, a function of location, time and dependent on occupant demand

E_{GD} is energy due to gas delivery, a function of location, time and dependent on occupant demand

E_{PO} is onsite use of electrical energy, dependant on occupant demand

E_{GO} is onsite use of gas energy, dependant on occupant demand

E_{SI} is input to onsite energy storage

E_{SO} is output from onsite energy storage

E_{MG} is onsite micro-generation, a function of location and time

The challenge then becomes to minimise E_T, subject to the constraints of occupant demand. However, the dimensions of monetary cost and emissions cost of energy complicate the optimisation because the two are not necessarily correlated. Assuming the goal is to minimise environmental impact, ultimately this requires fundamental market redesign so that low carbon energy is artificially subsidised. Until this occurs the optimisation must either be multidimensional or the emissions cost and monetary cost be appropriately weighted and incorporated in a single proxy variable. To complicate matters further, future and history values, at times ($t_0+\Delta T$) and ($t_0-\Delta T$) respectively, will affect the current optimal solution. The justification for this is that cheap clean energy may be stored and used in leaner times, and occupant demand is a key determinant of most of these terms. Better weather prediction and onsite sensing and measurement unlocks the realistic possibility of estimating how the past and future values dictate the present using statistical models.

Each term in (1) and moreover, the appropriate ΔT in each case, is a complex question, that must be answered in detail, and are indeed the subject of much ongoing research and debate. The answer, as in most real engineering problems, are likely to be 'it depends on…'. In other words, a building's objective function for cost and emissions has many terms whose coefficients fluctuate on various timescales. A single paper cannot begin to quantify these terms - an entire research career could be devoted to each. It is obvious however that the ability to opportunistically select energy sources will result in a lower E_T, as it is clear that a great deal of real time or near real time measurement and control is required, and this must be delivered by the ICT infrastructure.

IV. ENERGY AND WATER

According to the World Health Organisation [2] clean water and sewerage systems are some of the most important factors that determine a nation's average life expectancy. As of 2010, about 84% of the world's population have access to an improved water source. In economically developed countries, almost every building therefore has clean running water and adequate sewerage. As with the other major utilities, the ubiquity of this resource in such places renders it almost invisible, but the organisational feat in delivery is nonetheless substantial. Moreover, energy is expended in every stage in the water supply chain, from purification to pumping to sewerage. Quantification of this cumulative energy on a per building basis is non-trivial however, and varies considerably, for a number of reasons. The energy required in delivery is deeply dependent on the location of the building, simply due to head loss: pumping water uphill in a small pipe is harder than pumping along a level in a wide pipe. The wider region in which it is located is also important due to rainfall and demand. For example, in California [3] it is estimated that 19% of the *total* energy usage is due to water supply. The somewhat reductionist explanation given here is that 'two thirds of the population live in the south, but two thirds of the precipitation falls in the north'. Clearly energy expenditure related to water supply is substantial anywhere water demand outstrips precipitation, necessitating the natural water cycle to be artificially diverted. Small islands that rely on shipped fresh water are an extreme example. Where seawater is plentiful, desalination may be powered on renewable sources, with the added benefit that unlike electrical energy, fresh water is relatively easy to store.

Conversely, large quantities of water are essential in many forms of power production. This interdependency of water and energy is referred to as the 'water-energy nexus' [4]. This complex interplay of parameters leads to a large temporal and spatial variability in water related energy use. The only certainty is that in future, water will be increasingly scarce as the rising population and climate change events (such as flooding and droughts) cause increasing stress on the supply. Economic growth in large developing countries will cause particular pressure points. Water companies may therefore be required to produce real time information on how the energy expenditure due to water supply varies. At the building level, water usage will become an important metric of overall energy consumption and so high frame rate metering will be necessary. In the first instance, improved metering and displays will help users reduce their water usage, allowing them to compare with a baseline and make adjustments. In future, appliances for washing, dishwashing and cleaning will be schedulable, with a 'water economy button' alongside the 'power economy button' becoming commonplace. Actuators could reduce mains water pressure during critical shortages, switch in loops to recycle domestic 'grey water' for toilet flushing. Needless to say, an underlying ICT sensing and control infrastructure is essential to do this.

V. ENERGY AND GAS

If a building's hot water and interior is heated onsite by natural gas or propane, this resource will usually account for the largest proportion of a building's energy expenditure. Barring unusually large electric loads, this is always true in northern Europe where the air conditioning load in summer is dwarfed by the energy used for space heating in winter. Apart from domestic hot water, gas is mostly used elsewhere for cooking, representing a significant short term load. Where present, the gas supply is therefore an extremely important resource to consider, and arguably more important than electricity in many cases.

Due to a simpler and more direct distribution process, energy from gas is currently less expensive than energy from electricity. In the UK, it costs at present, around 3 times less per kWh. However, comparison of *emission* costs depend on the generation mix at any given moment. If the portfolio of generation is dominated by fossil fuels, it is far less polluting to use gas onsite rather than burn it for generation and suffer system losses. However, at times when the generation mix, both local and remote, reaches a threshold of low carbon sources, emissions will be favourable for electricity. A 2008 report from the UK government body DEFRA, [5] estimates electrical emission costs at 0.537 $kgCO_2$/kWh whereas natural gas, at point of use, is only 0.206 $kgCO_2$/kWh. Here, electrical transmission losses are estimated at 7.5% but there is also a smaller but significant energy cost involved in gas delivery from shipping, transmission and distribution. However, in the UK onsite use of gas is likely to remain favourable for some time, unless there is substantial onsite renewable energy available. Conversely, in France, with a portfolio of over 90% nuclear and hydrogeneration, the emissions from electrical heating are more favourable [6]. However, in the context of nuclear's poor response time and the wider European power market, using electricity to meet peak winter heating loads may only give modest emissions savings, as ultimately this must be supplied by peaking fossil fuel plant. The output of local renewables is highly weather dependent. At one time, domestic hot water may be better produced by direct solar heating and supplemented by gas. At another, local and large-scale wind may be sufficient to supplement solar panels. Hybridising a boiler to use both a resistive, electrical immersion heater and gas heating is straightforward, but calculating when best to switch to electrical heating is not trivial. It is clear the solution will require a real time, distributed, computational effort and input of both local and remote data. The greater the granularity and accuracy of the information, the better the energy efficiency will be. For example, zonal thermostats, and individual radiator actuators will offer far better sensing and control than a single thermostat per-dwelling. Put simply, if 40% of the rooms are occupied, there is no justification for all rooms to be heated to 20°C. The ramp up times for heating mean that manually turning the radiators off until heating is required means that occupant's must sacrifice comfort and convenience, especially if they only visit the room for a short time. The added constraint of comfort implies an extra term in the optimisation, but is highly subjective to the user.

A. *Real time optimisation example*

It may be helpful at this point to focus on a specific example. As mentioned earlier, space heating in many cases is responsible for the highest expenditure of a dwelling's energy. A simplified model of a building's thermal heat flow found in [7] uses implicit first order differential equations (2) and (3)

$$C_a \, {}^{dT_a}\!/_{dt} = Q_i - K_i(T_a - T_w) - K_f(T_a - T_o) \qquad (2)$$

Where in (1)
- C_a is the thermal capacity of the air in the zone (and the fast response elements with little thermal capacitance, such as windows) (in $kJ.K^{-1}$)
- T_a is the temperature of the air node (i.e. room), (in K)
- Q_i is heat power input to the air node (i.e power from radiator) (in W)
- K_i is the conductance between the air and structure nodes (in $W.K^{-1}$)
- T_w is the average wall temperature (in K)
- K_f is the conduction of the fast response elements (in $W.K^{-1}$)
- T_o is the outside air temperature (in K)

The wall temperature is also time dependant

$$C_w \, {}^{dT_w}\!/_{dt} = K_i(T_a - T_w) - K_o(T_w - T_o) \qquad (3)$$

In (3), the extra variables introduced are

- C_w is the lumped thermal capacitance of the structure in ($kJ.K^{-1}$)
- K_o is the conductance between structure nodes and the outside air

If the 'air zone' is the air in a room, and the appropriate sensors and actuators are installed, the input energy, E_h, (4) may be minimised, subject to the (occupant subjective) constraint of comfort temperature, T_a, and the time required to achieve this temperature, $(t_2 - t_1)$.

$$E_h = \int_{t1}^{t2} Q_i dt \quad (4)$$

Conduction constants are fixed and depend on building materials, but their correct calibration requires a qualified installer or an architect's detailed records. However, depending on their sensitivity, they may be estimated and then remotely updated using ICT. All variables may be measured with temperature probes. Wall temperature may be measurable with infrared thermal imaging, or in new build, a temperature probe placed in a wall cavity. The complexity of the problem must be hidden from the user, representing a research opportunity for a machine learning thermostat based on user preference and predictive occupancy. A UK government research consortium 'retrofit for the future' has patented the 'Wattbox' that achieves this challenge on a per dwelling granularity [8].

VI. ENERGY AND ELECTRICITY

For a number of years, storage generally has been described as the magic bullet in power system problems. Electric vehicle batteries and stand alone installations may provide this at building level, but their market penetration is uncertain and cannot be relied upon. However, integration of supply systems in buildings could at least provide pseudo-storage through the thermal inertia of refrigerators and buildings. From a power system perspective, there is huge potential benefit from demand side management [9]. In under frequency emergencies, electrical heating loads could be shifted to gas to shave peaks and fill troughs thus offsetting a critical variability in renewables. This reduces spinning reserve requirements and the need to fire up expensive and dirty marginal plant. 'Wet' white goods, that require hot water, may be integrated into the domestic hot water loop so they benefit from direct solar heating, and thus reduce electrical heating load. An example of this application is the BeyWatch architecture, that integrates solar PV, solar heating and wet white goods in the so-called 'combined photovoltaic and solar system' 'CPS' [10]. Such a facility is a key feature of fig. 2.

VII. A GENERIC DOMESTIC ICT ARCHITECTURE

If energy services are integrated at the building level, their intelligent use relies on an ICT infrastructure. This allows the highly temporally and spatially dependent problem to be continually optimised on an ongoing basis.

With reference to fig. 1, the salient features of such an infrastructure are discussed in the following subsections.

A. Ubiquitous communication

Virtually every device in fig. 1 is a node on the communication network. These are most conveniently designated local communication, nodes residing inside the dwelling, and global communication, those outside the dwelling. Local requirements are very different from the global network.

1) Local network

For the local network, simple packets with small payloads mean simplicity, robustness, scalability and cost are the main considerations. The main debate regarding the local network is about whether it is best to achieve this with wired protocols or wirelessly, with radio signals. Wired protocols such as KNX, BACnet, LonWorks and Modbus may require a dedicated physical layer or some may be specifically designed to use the local electrical wiring, such as X10 and HomePlug. Most wired protocols are developed with industrial control in mind. For example, Modbus has become a de-facto standard for industrial SCADA systems, but its simplicity and open source availability also make it a promising contender for local communication in energy efficient buildings.

The key advantage of power line carrier (PLC) methods is using existing electrical wiring to also convey information. However they may be susceptible to noise from an increasing penetration of non linear loads and an open circuit failure mode results in both a loss of power and communication. X10 is one such PLC standard that uses a burst of data at the current zero crossing. It was originally developed for home automation, but is beginning to show its age with very low data rates and no means of encryption. The HomePlug family of standards are geared towards domestic computer LANs and are therefore somewhat over-specified, making them high cost per node.

Wireless is attractive for being less intrusive and requiring no wiring installation. Wi-Fi and Bluetooth are well established but are also over specified in terms of data and range, increasing cost per node and power consumption. For a device to be completely wireless, a battery is required and low power consumption becomes a critical design constraint. ZigBee, based on IEEE 802.15.4, offers a self organising, hierarchical, pseudo-mesh network. The low duty cycle of end nodes aim to keep battery lifetimes in excess of two years, whereas routing nodes normally require an external power supply to handle more traffic. The power source problem is addressed by EnOcean, a similar specification to ZigBee albeit with nodes that harvest energy form their environment. Although it is not yet clear if this technology will remain prohibitively expensive for some time, and nodes requiring significant mechanical actuation still require batteries.

2) Global network

For global communication, a dedicated, radial network may be achieved on a point to point basis with a number of technologies, including GSM cellular networks, fiber optic links, satellite services or some form of power line carrier (PLC). However, if the data servers are physically dispersed, connection to the internet at some stage is mandatory. The access point to IPv4 may be in the home via a broadband enabled landline or a neighbourhood area network (NAN) with a Wi-Fi mesh or WiMAX coverage. Global communication demands high data rates, especially if it must share the dwelling's other data traffic, such as downloads, video streaming, voice over IP or femtocell backhaul. Existing infrastructure may need augmenting to allow a continual trickle of upstream data, which quickly accumulates to a significant volume. When remote, real time control is involved, latency and robustness become safety critical. The broadband link may therefore require a redundant network, and the very highest form of authentication and encryption. It is worth remembering, however, that the internet was designed from the outset to be tolerant of failure and now underpins many modern feats of organisation.

B. Advanced metering infrastructure

It is essential to measure how much each supply is being used on a near real time basis. Of the three services described, the metering of gas is complicated because the calorific value depends on the gas composition as well as the temperature and pressure. The volume of gas delivered to the dwelling is the measured quantity, but the price must be calculated taking the other parameters into account. Fitting a new gas meter is expensive, intrusive and time consuming. Retrofitting to legacy gas meters is thus more feasible in many situations. Many meters feature a built in switch that briefly closes with every unit consumed. A voltage applied across terminals will result in a pulse of current every time the contacts close. A number of market-ready ‘pulse counters’ are available to perform this simple function. For meters without this facility, optical character recognition (OCR) units may be deployed. These devices sit on the face of the meter, and use robust edge detection character recognition to give an absolute meter value. Either retrofit solution is the entry point into the ICT infrastructure, which may be wired or connected via radio signal to a collector. At time of writing, such solutions are expensive considering their simplicity, but when the demand for products increase, large manufactures will ramp up production, driving prices down an order of magnitude. Water metering is simpler than gas because the fluid is incompressible and the volume measured directly relates to gas. However, electronic water meters must be ruggedized for a damp environment.

Legacy electricity meters present a similar retrofitting issue. Many emit an LED pulse per unit of consumption, a photodiode or a phototransistor-based module will count these pulses and remotely transmit them. However, another non-intrusive solution is a simple CT collar that clamps around the mains infeed of the dwelling and measures the magnitude of the current. The RMS power is calculated, assuming a nominal mains voltage and unity power factor. In terms of electricity, this basic principle may be extended to the individual appliance level with a passive device placed at the through socket. These devices are known as Individual Appliance Monitors (IAMS) and can also act as a remote, radio controlled switch for the appliance. A simple feature often built in is to detect appliance standby mode and switch off such ‘vampire loads’. A number of solutions are available on the consumer market, offering a plug in through socket for a standard 13 amp 3-pin wall socket. The modules can also be built into the appliance, or placed in a wall mounted enclosure. Some higher end devices, more geared towards research, give instantaneous voltage, current and phase angle. Another, ultimately cheaper possibility is non-intrusive load monitoring (NILM). This is based on high sample rate current *and* voltage measurements at a single dwelling in-feed. Changes in real and reactive power draw are fed into clustering methods to determine which appliances are being used at any time and thus their individual load contribution [11]. The main technical challenge is then the knowledge base that the machine learning element uses to recognise a multitude of possible appliance signatures. Even if this can be overcome robustly and practically, the existence of such data raises tough questions on privacy and security [12]. Such information may be useful to cyber criminals, and perhaps more realistically, unlocks the possibility of a deluge of targeted advertising.

C. Dispersed computation

The optimal energy solution clearly requires a large amount of real time, or near real time data and some computational effort. This information must then be acted on, either by the end user after it is presented to them, or through adjustments that could eventually be automated in a closed loop.

Both tasks of feedback and automation require a microprocessor. For scalability, these must be dispersed and embedded within the infrastructure. Such a statement may be a truism, but it is important to explicitly state that it is not desirable, to have a remote, centralised server directly controlling heating valves or appliances. Each device on the local network should be capable of operating properly and safely without connectivity, albeit at a less than optimum efficiency. Remote services must be confined to an advisory role rather than a supervisory one. As such remote ‘price or operational’ signals must always be subservient to local commands.

The gateway, as the point of common coupling between the global and local network, perhaps has the most important and demanding task:

1. It pulls and aggregates sensor data from the local network. Sensor data is stored locally, and subject to security and privacy checks, is relayed to remote clients, such as utilities, for diagnostic purposes.

2. It serves data to a web service, which consumers may log into at home or remotely. Such a web service may also provide annonymised, aggregated consumption averages for subscribers to compare with.

3. It pulls data from various virtual warehouses and real time feeds on the global communications network. These are then relayed to wherever relevant for actuation or display.

Currently, most home gateways have an onboard CPU of modest computational ability and even more modest onboard memory. Given the aforementioned demands, there may be an emerging market for gateways with better hardware specification, equivalent to a small-form PC. These platforms act like a server: always on and available. Such tasks cannot be easily assigned to any existing domestic hardware such as a PC, laptop or tablet. However for some applications, the gateway is only required to reliably store and forward data when it is needed. If the user is present via a terminal, (i.e. for manual remote control or feedback) the computational task may be migrated to the user’s terminal.

Computation in the global network is dispersed in the sense that remote websites provide a specific service. For example, this may be meteorological data or forecasts, consumer market signals or the real time generation mix. Such an architecture is a multi-agent system (MAS). In this case a global monolithic, hierarchical structure is not feasible, let alone desirable.

The gateway will then have the computational task of real time optimisation of energy usage, and send requests (not commands) to embedded micro-controllers for certain actuation tasks. These might be adjusting a valve of a radiator, delaying a dishwasher cycle or turning off a fridge compressor for a few minutes. As is the case today, read-only firmware will remain on the microcontroller to achieve operation with or without connectivity, and this will override requests that compromise safe operation of the device. Consensus on the protocol for accepting such requests will be a huge challenge in the world of embedded systems. One FP-7 project focusing on this problem is eDIANA [13].

D. *Advanced display & user interface*

The display and user interface is a crucial element. For early implementations that rely on human behaviour change, the user interface is critical to success or failure. Commercial GUI design is perhaps not a task that should be assigned solely to engineers. Technical people with numerate backgrounds may prefer straight forward tachometers and odometers, but others may connect better with a more pictorial representation [14]. This gives some opportunity for software-based user customisation, such as one might choose a ‘skin’ on an open source music player or social networking page. Whilst there may not be a general consensus on the best user interface, the only criterion must be a meaningful and accurate quantification of real time and cumulative usage against user and regional baselines.

The collation of this information in one place gives the end user a more quantitative understanding of their overall energy usage. Gas, water and electricity may be presented on one or several dedicated GUI displays, or may be viewed through a multipurpose device such as a smart phone, laptop, computer, TV, or web enabled tablet. The growing popularity of touch screen tablet computers presents opportunities for the consumer electronics market. In the home these devices may serve a dual function: their docking/charging station may also be a mount on which the energy display interface resides. A user who regularly consults their tablet for web based video, email and games is more likely to glance at the display if it is set as a default desktop.

It is hoped that the proper target information and feedback will influence the user’s behavior such that cost and environmental impact is minimised. Greater awareness may also foster investment in peripherals that yield increased savings in a positive feedback loop. This is not guaranteed however, and is moreover, difficult to measure through social science. The respondents to an energy survey or pilot may be self selecting, in that those with environmental concerns are more likely to participate. Also, over time, behaviour may default to the pre-smart metering ‘business as usual’ after user interest begins to wane. It is not the remit of the engineer to speculate on the level of user participation, merely to provide options if this should prove to be unexpectedly low. Regardless of what social studies suggest, the only guaranteed solution removes the user by automating efficiency actions. Enthusiasts can still have the option to customise but a benefit to the casual user is they do not have to rely on their own economic motivation or levels of ‘eco guilt’, which may fluctuate, but are instead free to get on with their short and busy lives. In an automated scenario the GUI does not become redundant, but continues to report good news on emissions and money savings and encourage further investment in smart peripherals.

E. *Sensing Measurements and Actuation*

Sensing technology is essential in order to derive real time information about the dwelling at high granularity. Cost and durability are more important than high precision. Measurements and technologies may be grouped into function and summarised in table 1.1, the most suitable technologies for each function are highlighted in bold font.

Measurement	Sensor	Description
Temperature	-Thermocouple	Junction of two metals gives temperature dependant change in potential. Cheap, robust, but not sensitive
	-Resistance temperature sensor	Platinum based component, high accuracy but slow response time
	-Thermistor	**Simple, resistance dependant resistor suitable for -90 to 130°C. Cheap and durable.**
Occupancy	-Infra-red sensor	Low cost passive infra red device only detects motion
	-Infra-red barrier/shower	Middle cost, but reliable sensors for building choke points
	-360 degree IR sensor	**Sensitive, middle cost solution for domestic interiors**
	-Ultrasonic sensor	High cost, high accuracy sonar based device
	-Camera	High cost requires advanced signal processing, privacy sensitive
	-Infrared Camera	Very high cost, requires signal processing, privacy sensitive
Light Intensity	**-Photodiode**	**Semiconductor that responds to light using photoelectric effect**
	-Phototransistor	Operates on similar principle. Slower but more accurate.
Humidity	-Resistive Hygrometer	Faster response but exhibits temperature dependence and hysteresis, accuracy 5%
	-Capacitive Hygrometer	**Slow response but more accurate (3%) and better temperature operating range**
Open point (to detect ventilation from open windows & doors)	-Contact switch	Simple mechanical switch but relies on moving parts
	-Reed sensor	**Switch that operates in presence of magnetic field, may be coupled to a coil**
	-Pressure sensor	Detect room ventilation by change of pressure

Due to their widespread and long term use in industrial applications, most of these solutions individually are well understood, low cost and durable. There is therefore a business case for providing an array of measurements at every local communication node. The primary function of each device should be supplemented by at least a temperature and light intensity measurement. However, where batteries are required, careful consideration is necessary over the tradeoff between regularity of measurements and sensor power consumption.

Occupancy is possibly one of the highest cost sensing requirements, but it is also vital for many automation applications. In some cases an occupancy measurement may be achieved by sufficiently high granularity of proxy measurements. For example, an IAMS device detecting appliance operation, a change in light level, coupled with a change in temperature and door opening will reliably indicate that a person has occupied or left a room. Moreover, intelligent use of such sensor data can predict duration and nature of occupancy such that superfluous heating is avoided. If an occupant has briefly entered a utility room to switch on a washing machine, there is no need to heat this room for maximum comfort.

Actuators are necessary to act on sensing measurements. Where possible, switching and control should be achieved electronically, using solid state devices without moving parts. This can be achieved relatively simply for most tasks, for example, lighting levels and electrical heating. One very important task that must be achieved mechanically is the actuation of radiators in a gas central heating dwelling. In most gas heating systems an adjustable valve controls the flow of hot water to a room radiator. The water temperature is controlled by the centralised thermostat in the boiler. The manual radiator dial may be replaced by a motorised device, coupled to a room thermostat and the local communication hub for room by room heating. The inherent lack of mains power means that current devices on the market must rely on batteries, presenting a research opportunity for advanced energy harvesting to trickle charge these nodes.

F. Domestic smart grid peripherals

Peripheral investments may be defined as those involving considerable expenditure over and above the basic ICT infrastructure. It is feasible for most energy users to make a lump investment in local communications, metering and lighting, such that it will interact with legacy meters and appliances. However, peripherals do not come under this umbrella as they represent almost equivalent expenditure. With reference to fig. 1, these investments may include: micro generation, electric vehicle(s), solid state power conversion (bi-directional rectifiers/inverter) and battery storage. It is not within the scope of this paper to deal with these devices in technical detail. However, the wisdom of micro generation is greatly affected by the resource at the specific building location. A PV panel may not be sensible on a south facing roof if it lies in the shadow of a high rise building or tree, a good wind resource regionally is useless if the wind turbulence at building altitude is prohibitive. The underlying ICT architecture must therefore allow and foster modular, flexible investment in peripherals. The UI should display the future and current benefits, whilst hiding the technical complexity from the user.

VIII. CONCLUSION

This paper discusses the case for integration of energy services at a building level. The spatial and temporal dependency of the instantaneous energy solution highlights the need for a dense local network of sensors and actuators connected to a global communication network of remote and distributed data sources. The underlying ICT infrastructure must be modular, interoperable, flexible and extensible. Further research opportunities are cited, such as the room by room heating example. The need to investigate holistic market models and technical architectures that optimise a dynamic, multi-utility environment is discussed throughout.

IX. BIOGRAPHIES

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