Case for Support

Measuring and Evaluating Time- and Energy-use Relationships (METER)

Philipp Grünewald

The Candidate

Philipp aspires to becoming a new kind of leader in energy research, who uses his broad experience and skills to move between disciplines and create new connections between them. He has worked at the forefront of UK energy research and made important contributions to areas as diverse as electricity storage, demand response and community energy business models.

All of these, Philipp addresses with a pragmatic and problem focussed approach, which leads him to select his methods as required by the challenge. Often this has fostered the adoption of or collaboration with related disciplines and has equipped Philipp with a broad portfolio of tools, as well as a wide network of fellow energy researchers from a range of backgrounds.

This fellowship would allow Philipp to take his ambitions further and create stronger UK interactions on new research challenges that require interdisciplinary system thinkers. The proposed work is designed to take full advantage of Philipp's existing skills and strengths to deliver high impact research, while also providing great opportunities to develop new collaborations and research opportunities, which will position Philipp ideally to lead future research on complex and multi-disciplinary energy research challenges.

Philipp's in-depth knowledge of the strategic challenges in UK energy research allow him to address some of the most complex research challenges, reduce the problem to the key questions and analyse these with the necessary precision to deliver clear and policy relevant results.

He led and advised on research on the future role of electricity storage and established fundamental performance requirements, which have since become established facts underpinning UK policy and research priorities. Among them are the realisation that the cost of integrating renewables beyond 20GW capacity on the GB system could lead to positive net present values for storage even at present technology costs and that the efficiency of large scale storage in low carbon systems is commercially less significant than previously thought, due to the fact that storage operates on low short run marginal cost electricity [5,6] .

During his PhD, Philipp already delivered impact and influenced the policy and research landscape. He convened a high profile two day workshop at Imperial College London with senior stakeholders in storage from industry, policy and academia. This workshop led to the creation of funding for a ground-breaking study on the role of electricity storage in low carbon energy systems (Strbac, 2012), which has had significant traction in policy, industry and academia. Philipp advised on the scope of the call, formulated the tender documentation and oversaw the project delivery on behalf of the Carbon Trust.

Philipp also has significant industrial leadership experience, building on his first degree in Business-Engineering, and in senior management positions, which he will bring to this role, especially when seeking to develop engagement and collaboration with SMEs and other industrial partners. He was Senior Researcher and Technology Leader at a world leading SME in the development of advanced laser processing equipment for thin film photovoltaic manufacturing. Under Philipp's leadership, this business segment grew into an internationally recognised capacity, resulting in a multi-million dollar development contract with a major US semi-conductor supplier and a patent for laser scribing solar panels [40]. The business was acquired by the Swiss Oerlikon group and as their Product Line Manager for PV manufacturing equipment, Philipp managed international key accounts with leading PV manufacturers in Germany, China and the US, and oversaw the technology development from lab trials to sign-off for turn-key large scale production equipment.

Philipp works effectively as an individual and as a team member. His team of four became overall winner of the nPower graduate energy challenge, awarded by RWE board members at Wembley stadium in 2009, for an innovative energy service business model proposal [39]. With a team of ten he won a place at the Hydrogen and Fuel Cell conference in Washington DC for a residential hydrogen refuelling concept [18].

Philipp has a track record of funding for projects that deliver high impact on a wide range of subjects, starting with his research on laser optics as a Marie Curie Fellow and various DTI and EU funded projects on extreme ultra-violet lithography [8-10,21-23,25-27].

In 2008 he self-funded his MSc in Sustainable Energy Futures at Imperial College London and in 2009 received one of four UK Energy Research Centre (UKERC) Interdisciplinary Studentships for his PhD on the future role of electricity storage [38]. Since his viva on 15 March 2013 he has conducted post-doctoral work at the University of Reading [2,4,12,13,15], Imperial College London [28] and the University of

Oxford [1,3,11,14], with funding from the John Fell fund, the Technology Strategy Board, ESRC, EPSRC and the RCUK's Energy Programme. Philipp's commitment to publications and dissemination on all of his research interests has resulted in a rich publication record in technical and policy journals [1-10], as well as numerous public appearances at conferences, workshops and via webinar and radio [11-39].

Philipp possesses excellent communication skills and gets repeatedly invited as a speaker, panellist and lecturer in voluntary and paid positions. He is innovative in his communications tools, using 3D printed graphs as engaging illustrations and animated interactive graphical representation of complex data and networks. He strives to continuously improve his communication skills and adopts new peer-to-peer learning approaches and participatory engagement techniques.

Interpersonally, Philipp has developed into an effective networker and he works with his connections to influence and shape the research agenda in a co-creative manner and through his enthusiasm for the subject. He set up LinkedIn groups for Sparks, the UK Energy Research Centre's network for early-career energy researchers, and the Oxford University Energy Alumni group. In total his groups have over 800 members.

Philipp is a proficient programmer and is experienced in building complex models with a variety of solvers. He has developed agent-based models and high resolution time series models and has on numerous occasions handled large and sensitive data. He has the necessary skills to develop the software and analytical tools required for this project and the ability to supervise the delegation of such tasks where appropriate.

Far sighted planning and strategic vision have positioned Philipp time and again at the forefront of research and in a position to shape and influence developments. This applies to his early work on advances laser processing, which led to the world's first commercial 13nm microstepper for Intel; his work on laser processing for solar cells, which pioneered new methods in emerging cell designs; or his early realisation of the need for and value of grid-scale storage, which pre-empted the recent uptake of interest in this subject. This proposal focusses on another emergent research area, which is still in its infancy and which Philipp seeks to advance through this fellowship.

Importance of the proposed work

This fellowship asks a fundamental and important question: "What is the temporal relationship between household activities and electricity consumption?". This is an emergent research area, which is still in its infancy and which would be significantly advanced through this Fellowship.

The UK's legally binding decarbonisation target calls for large-scale deployment of low-carbon electricity sources, which in many cases require greater system flexibility for their integration. This can either be achieved with conventional flexible generation or with new solutions, like improved networks, electricity storage and flexible demand. Estimates for the cost of integration range from £2bn-16bn annually (Strbac 2012a). Significant investments into the Grand Challenge on Energy Storage, the Supergen HubNet and the End-Use Energy Demand Centres position the UK at the forefront of international energy research in these areas. Despite these considerable research activities, the RCUK's energy strategy fellowship team, which performed a stakeholder review of the UK energy research landscape, identified data as a commonly raised concern. "The biggest data gaps were considered to be in the area of energy consumption" (Skea, 2013). These concerns are echoed by the IEA and many researchers and industry representatives across the UK, who require high quality and statistically reliable demand profiles for fundamental analytical and exploratory research into future system challenges.

Of particular relevance is peak demand, which constitutes the most critical period for security of supply. Its reliable provision has significant implications for system costs and decarbonisation options. The share of household electricity consumption during system peak demand has risen from 31% (Allera, 1990) to 45% (Lampaditou, 2005). Residential heat pumps and electric vehicles could further add to their peak load contribution (Strbac, 2010).

Demand-side flexibility has been suggested to mitigate this problem (Borenstein, 2005). Several small and large scale initiatives and studies focus on demand side flexibility and peak demand in a variety of ways, including economic models (Bradley, 2013; Roscoe, 2010), tariff response trials (CER, 2011; DECC, 2012), societal impact (Darby, 2012; Bulkeley, 2014), detailed case studies (Higginson, 2014) and appliance monitoring (EST, 2012; Zimmermann, 2012) or sophisticated mathematical methods (Haben, 2013). Between them, these studies collect behavioural as well as consumption data, but none has been able to collect both, concurrently and at statistically significant levels.

This proposal will overcome this gap by combining the research methods of time-use studies (TUS) with a new electricity profile collection approach. It goes well beyond the collection of mere consumption data. The innovative method proposed here combines electricity use profiles with the necessary social science intelligence, which creates new links between (supply side) energy research and other areas of strategic importance for the UK, such as demand response, fuel poverty, quality of life, health and well-being, and could also create links with food, entertainment and education, whose relationship with energy consumption so far lacked a statistically significant evidence base.

Stakeholders in academia and industry have expressed interest in these data and will benefit directly (see Letters of Support). METER data are expected to improve the quality of research in some of the UK's key priority areas, especially in end-use energy demand, storage and innovative network solutions, where demand profiles are crucial model inputs.

This research is therefore not only important in supporting ongoing investments in energy research, but it could provide a platform for the development of new research themes for the UK's future societal and economic challenges. The development of these new themes forms part of this proposal.

Background on Energy and Time-use data collection

Two fundamentally different approaches are used by social scientists seeking to understand time-use of a population on the one hand, and energy researchers wishing to explore a population's consumption of energy on the other. Time-use research is based on diary information collected from a large sample of individuals. The full scale 2000/01 UK Time-use survey (TUS) collected 21,000 diary days, while the smaller follow up study in 2005 still collected 5,000 (Lader, 2006). Participants provide diary information about their activities with 10 minute resolution in hand written diaries. These diaries are subsequently coded by categories set out by the Harmonised European Time-Use Surveys (HETUS) to allow comparisons between EU member states, as well as to explore longitudinal trends (Eurostat, 2014). Importantly, participants are only asked to provide one or two days of diary information. This ensures that participation is not too onerous. The statistical significance stems from the large number of participants, such that these studies provide evidence that is suitable to support policy development.

First attempts to combine time-use and energy-use information from secondary data are undertaken by DEMAND (2014), who use the Trajectory Global Foresight time and location data of 500 people to explore activity sequences and mobility patterns. In energy research, consumption data collection generally follows a different approach. The Irish Commission for Energy Regulation study is one of the largest of its kind. It sampled total household electricity consumption for around 1000 households in 4 different time of use tariff groups and one control group of similar size for over one year (CER, 2011). The Ofgem funded Consumer Led Network Revolution (CLNR) also collected time resolved electricity use profiles, comprising a sizable control group of over 8000. The qualitative research captures 131 domestic participants and appliance data are collected for fewer than 100 households (CLNR, 2014). The Household Electricity Survey (HES) equipped 251 homes with appliance level meters and monitored these for between one month and a year. Information about behaviour and practices is collected via questionnaires for a small subset of participants (EST, 2012).

As Figure 1 illustrates, sample sizes for activities underpinning energy consumption tend to be orders of magnitude smaller than the energy data samples by CER (2011) and CLNR (2014). This is in large part due to the complexity and cost of instrumentation, but means that many recent studies have to attempt to extrapolate from as little as 72 households (Firth, 2009) or 30 sample days (CER, 2014) to elicit national consumption patterns.

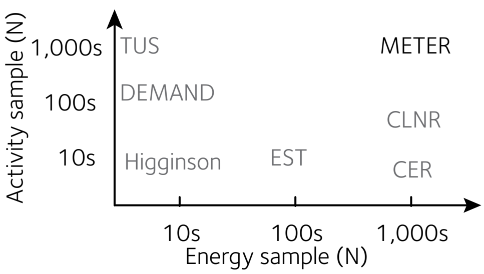

Figure 1: Orders of magnitude of sample sizes in selected studies

Sample size requirements for statistically relevant research

How large would a statistically significant sample need to be? For energy consumption based research to deliver policy relevant evidence, it must be scalable to the national level and have sufficient resolution, such that the effect of interventions can be separated from the noise.

An order of magnitude approximation can be made with some simplifying assumptions. As a minimum requirement the confidence in the mean values collected should have an accuracy (ε) of five percent or better (less accuracy could miss potentially important demand contributions, while greater accuracy could be undermined by instrumentation error). The confidence interval for these data should at least meet the scientific standard of 95% (two standard deviations). The mean (μ) of UK household electricity consumption is on the order of 4000kWh per annum (DECC, 2014), with a standard deviation (σ) above 3000kWh, resulting in a Coefficient of Variance (CoV) of around 0.8. The Wald method for binomial distribution thus suggest a minimum sample size of around 1000.[1] This is very much an 'order of magnitude' estimation of the lower bound, due to the simplifying assumptions above. In practice, demand is not normally distributed and individual end uses may follow more complex distributions. During peak demand—a period of particular interest for this research—the aggregated CoV for households has been found to be around 0.5 (Bulkeley, 2014). Yet the distribution of sub-loads is higher than the aggregated total. As the peak-demand snap-shot of 42 homes in Figure 2 and research by Morley (2011) suggests, the variation of appliance uses is higher and thus requires larger sample sizes. A sample size of 2000 would be sufficient for a CoV of up to 1.14.

The unit of enquiry, and therefore the primary focus of accuracy for METER is on the temporal relationship between electricity consumption and activities. Loads can be measured with 5% accuracy, while the precision is in the 1s temporal resolution of the profile data.

To keep the required sample size to a minimum, careful participant selection will be used. End uses that are less common (e.g. hedge trimming), may result in lower accuracy. So long as their contribution to overall demand is small, this may be acceptable. An exception should be made for emerging applications like electric heating, electric vehicles and micro-generation, which could become more significant over time. This fellowship will bias the sample selection in favour of these groups, such that the impact of future trends can be more accurately understood. Sampling will also consider demographic changes, including shifts towards larger proportions of single occupier households. Furthermore, a focus on winter weekdays, which are most likely to coincide with peak demand at the residential, local and national level, allows to gain maximum scientific insight from samples in the region of 2000 households. The sample selection will be informed through stakeholder inputs during the workshops and by the advisory panel.

Cost of data collection

The Household Electricity Study (HES) instrumented a total of 251 households at appliance level and measured minute-resolution electricity consumption for between one month and a year. The project budget was £850,000, which equates to over £3,000 per household. Even with added learning the 'high-instrumentation' approach is likely to remain costly. Reduction in equipment cost not withstanding, the labour cost of installing (and removing) meters by qualified personnel and the collection of surveys is likely to keep the cost well above £800 per household. While HES has provided many insights into appliance usage patterns, the sample size is relatively small and its findings are not representative at the national level. A statistically significant sample with this approach is likely to cost in excess of £1.6 million for data collection alone.

The proposed research

Combining time-use and energy-use research yields a number of mutual and wider benefits. This section sets out how this will be achieved while at the same time significantly reducing the cost of data collection.

Significant intelligence can be gained from the parallel recording of activities and electricity use. For instance, potentially under-reported activities in diaries, such as hours of TV time, can be calibrated based on the consumption profiles, thereby improving the accuracy of time-use studies.

The main advance over conventional energy monitoring approaches is that the electricity use profile can be attributed directly to energy uses. This can be more valuable than appliance level consumption (which can also be disaggregated to some extent as discussed below). It is commonly accepted that consumers do not use energy, or even appliances for their own sake, but for the energy services they provide. Practice theory goes further and suggests that the agency lies with practices themselves - culturally established norms that are 'enacted' by consumers (Shove, 2012). The latest UK research applies practice theory to understand energy use and its flexibility in response to requests to shift demand (DEMAND, 2014).

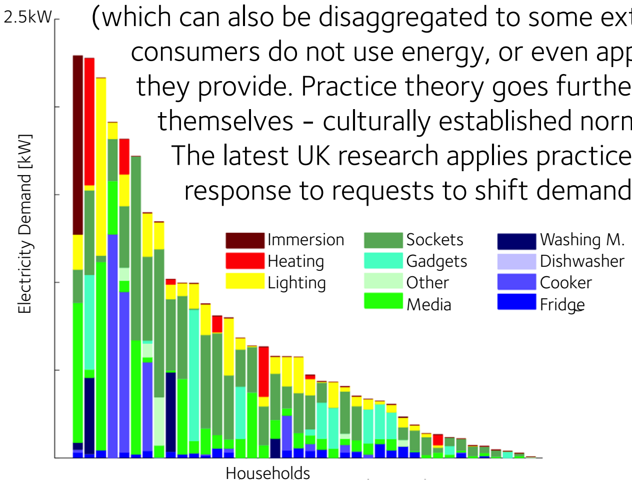

Figure 2: Diversity of load over 30 min. at peak demand

By understanding the temporal links between practices (for instance 'washing': the sequences of preparing laundry, washing, drying, ironing and handling), secondary activities (for instance preparing a meal) and the surrounding triggers and constraints (clean clothes for sports event, meal times, appointments), a new perspective for our understanding of the scope and effect of changes to energy use profiles can be gained.

1 Based on the these values as per $N = \left(\frac{1.96 \times \sigma}{\epsilon \times \mu}\right)^2$

Phase 1: Parallel energy and diary collection

This fellowship will deploy smart-phones, which have been reconfigured to act as high resolution electricity meters (Figures 3 and 4). The microphone port is connected via simple electronics to a current clamp. The system can capture electricity consumption with high temporal resolution (1 second) and sufficient accuracy to detect changes in consumption (<5%). This technology has been adapted and tested by the applicant as part of a Technology Strategy Board funded project in Watchfield (CEGADS, 2014) and an ESRC study Collecting New Time Use Resources (CNTUR, 2014) in collaboration with the Centre for Time Use Research.

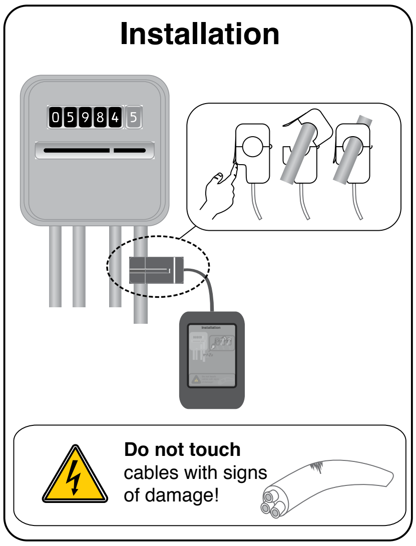

Figure 3: Visual installation instructions on the device

Key to its application is the ease of installation and use of the meter. It can be sent to participants in the post, alongside the diary, with visual instructions for installation, as illustrated in Figure 3. Once 'clipped' to the mains, the meter will switch itself on at midnight of the pre-specified diary date and begin recording and storing data on battery power, while participants document activities on the day in their diary (Figure 4a). Afterwards, diary and meter are returned by courier. Data are transferred to a dedicated computer (no network connections for ensure data security) and the battery is recharged for redeployment in the next household.

Phones and current clamps are CE certified consumer products and thus safe to use without the need for trained installers. Participants have minimal engagement with the meter. The unit shown in Figure 3 is packaged as a black box with no settings, connections (other than the clip) or buttons. This minimises the sense of 'being monitored', which could affect behaviour. All procedures undergo university ethical clearance procedures and participants receive consent forms explaining the nature and options for the usage of data prior to the trial. They receive their annotated use profile for review and can give consent for its publication.

Phase 2: Energy triggered diary collection

The use of smart phone technology opens up exciting avenues for innovation. Hand written diaries are onerous to fill in and may lead to errors and loss of information when filled in *post-hoc*. Phase two of this fellowship will collect diaries with smart phone technology (Figure 4b). Each household participant over the age of eight can use a device which is paired via a direct peer-to-peer network to the electricity meter (no set-up or router required). This allows additional, targeted and event driven collection of information. Location and movements can be recorded based on GPS and relative WiFi strength signals.

Participants who are in or near the home will receive prompts to select from a tailored short-list of activities (i.e. suggests activities that are typical for that time of day or consumption pattern). The participant can touch the relevant activities to confirm them, swipe through other activities and sub-activities or input their own description via text or audio recording.

Such requests can be triggered randomly within the 'active' time of participants (as assessed through the device's motion sensor). A bias will be applied to collect at times of greatest interest. Furthermore, requests can be event triggered, including national and/or local peak demand periods and patterns picked up by the METER sensor, such as a sudden rise or prolonged use of electricity. This approach is a new and powerful method to collect the most relevant data with minimal interference with participants.

One shortcoming of the single meter approach over the instrumentation of the entire household (as in the HES example) is that individual appliances cannot be measured directly. This fellowship will explore three routes to gain appliance level information. 1) The temporal resolution of the electricity consumption data is sufficient to disaggregate certain loads with characteristic profiles. Fridges, for instance, are easy to identify at night due to their periodic on-off pattern and can be extracted from the aggregate profile. Some disaggregation approaches are publicly available, for others, collaborations may be sought. 2) The time-use information can provide valuable insights to improve on the disaggregation approach. In many cases the activities performed allow for direct conclusions of the type of load in use at the time. The event triggered collection method discussed above can be used to gain specific knowledge about times of uncertain appliance use. 3) Additional instrumentation for the most difficult to aggregate loads will be explored during the project. The additional cost and complexity can be weighed up against the additional intelligence gained, once sufficient data has been collected. Additional sensing that will be considered in particular are gas boilers and cookers. Temperature, humidity and light sensors or longer collection periods (>1 day) could further enhance the explanatory power of the data. These will be deployed in trials and rolled out in larger numbers if deemed sufficient value for money. Other additional parameters and priorities for collection may emerge from early stakeholder engagement workshops.

The phones can further be used to collect socio-demographic information from participants and for them to take pictures of key appliances.

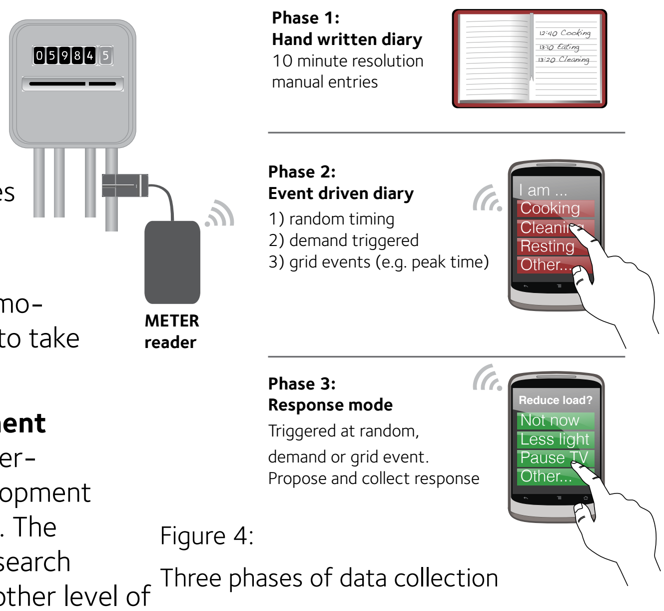

Figure 4:

Three phases of data collection

Phase 3: Feedback mode and response assessment

A strong motivation for this research is a better understanding of demand response options and the development of models to assess load shifting scope and impacts. The METER approach is ideally suited to inform these research interests with evidence. The third phase deploys another level of innovation, which opens up vast opportunities for expansion and the development of collaborative initiatives and to test theories on participant response.

Participants receive messages to influence their activities at relevant times. Messages could suggest high electricity prices for the next hour, offer a reward for reduced load, or use socially motivated triggers and nudges routed in behavioural economics. More innovatively, messages could suggest a change to current activities from a selection, based on the intelligence gathered about the energy uses gained in Phase 2, as shown in Figure 4c. Their actual response can be observed both through the consumption profile and via follow up messages interrogating the subsequent activities, as per Phase 2.

This phase, especially in conjunction with the previously established baseline data on consumption profiles, could be used to test theories on the most effective means to effect load shifts and provide valuable insights into the dynamics, scope and barriers to demand response and changes in energy use patterns. Which theories to test will be decided in consultation with the advisory panel. The scale at which the new approach allows this research to be carried out, can deliver statistically robust results and detailed background information about 'how' demand responses are delivered and how this impacts on other practices, including potential 'bounce-back' effects, whereby suspended demand could lead to a higher peak load after the request period.

Cost of large scale data collection

To perform this research at the required scale of 'thousands of households', the costs of the conventional approach need to be reduced significantly. This proposal minimises both material and labour costs. Each device, including current clamp, costs less than £70 and can be reused in excess of 10 times (as long as devices are returned). The equipment cost per household is therefore less than £10 in phase 1. Multi-device households in phase 2 with 5 devices would incur instrumentation costs of around £45 including signed postage and collection via courier.

For sample sizes of 2000, as set out above, the data collection cost would be in the region of £90,000 as opposed to more than £1.6 million for the instrumentation/survey approach. Future investigations could realise further savings due to the intelligence gathered with this approach. Conventional smart meter data–even if only collected with 30 minute resolution–can be more meaningfully interpreted with potentially minimal additional instrumentation. The exact requirements for additional instrumentation will be assessed based on the high resolution data of this study. Smart meter data could become readily and cheaply available to researchers over the next decade. The correct interpretation of such 'big data' requires a detailed understanding of its meaning, which this research would contribute towards.

Resources and Management

Philipp is an experienced project manager and will draw on these skills to ensure successful completion of the stated deliverables to time and within the proposed budget.

Philipp will report every six months to the members of his advisory panel, composed of project partners, independent experts, and other key stakeholders. The panel includes at least one representative from

National Grid, two SMEs, one utility and senior UK and international academics. A bi-annual two page report will summarise the progress of the fellowship, key findings, next steps and decisions for consultation.

METER will run for five years and be organised into three work streams as illustrated in the Work-Plan:

Work stream 1) Design of experiment. During this phase stakeholders will be engaged to ensure the data collection and survey design capture the relevant information and that results can be distributed and shared via the appropriate channels. Three workshops will be convened in this work stream. The first is an 'expert workshop' for fellow researchers, policy makers and representatives from industry directly involved with demand response activities. This will ensure that the research is performed at the leading edge internationally and build effectively on existing knowledge in the field. The second workshop engages a wider group of indirectly related research disciplines to raise awareness of the study and explore opportunities to build new interdisciplinary collaborations and maximise impact of the findings. This workshop will identify priorities for participant selection and sampling parameters. The third workshop is targeted at pre-trial participants and will seek to collect feedback on their experience to ensure that the procedures are clear, any concerns and uncertainties can be addressed and to refine the communication with future trial participants. In work stream 1 the recruitment procedures for the trial participants are developed, the equipment is tested and refined and the data collection infrastructure is created.

Work stream 2) Data collection. Data collection is focused on winter periods. During the first winter (2015/16) initial data collection will use conventional written diaries (phase 1, N=200), while the procedures for event triggered surveys is being developed. Building on the experience of these early samples, phase 2 in winter 2016/17 will collect data for 1800 households using event driven diaries, as well as a first samples from 200 households using response mode (phase 3). The third winter will complete the collection with 200 more phase 2 and the remaining 1800 phase 3 collections, such that 2000 households have been sampled for each.

Work stream 3) Analysis and dissemination. The data analysis will include correlation, clustering and sequence analysis methods to identify relationships and dependencies between different parameters and explore synchronicity of activities and entropy indices. This will include forward looking scoping exercises to ensure future studies can be performed with minimal cost and take full advantage of new insights. By applying the intelligence emerging from METER data, smart meter consumption data can be interpreted more effectively. This work stream will also develop novel interactive data dissemination and visualisation tools, as proposed by Ellegård (2011) to ensure the data is communicated and disseminated effectively.

A wealth of information needs to be analysed as part of this fellowship and new methods and tools are expected to be developed during this process. This part of the fellowship offers opportunities for researchers to join the team and contribute insights from practice theory, statistical analysis of large data, and novel data interrogation and visualisation tools. A series of workshops to explore the relevance of the data will be conducted with experts and stakeholders to build new collaborations leading to its meaningful applications in new business models for energy service providers, system planners and wider policy implications. All of these are well aligned with European Horizon 2020 priorities and suitable consortia are expected to be developed as part of this fellowship.

METER has clearly defined deliverables. The three sets of data will be published in suitably anonymised and aggregated format within six months of each collection phase. Six key publications including methodology, results and new analytical tools are identified in the work plan. Further deliverables include six scheduled workshops and a public online portal for dissemination and engagement, including an animation explaining the relevance of this research to the wider public.

Team development

To ensure the effective delivery of the fellowship's aims, the following support, staff and collaborators will be sought: Device development will be carried out in collaboration with Pilio Ltd, who will contribute a 15% position throughout the project. A 30% position will support software development, and a further 20% position will assist with administrative and communication efforts. One post-doctoral research associate will assist the fellowship with data analysis and will be working with colleagues at the Oxford Engineering department to explore the development of new and lower cost sensing and data collection options, including gas/heat and environmental parameters, such as light level and temperature.

Additional funding will be sought separately to support two DPhil students, whose contribution could further enhance the analytical depth of METER. The first would be co-supervised in Oxford's Mathematical Institute and the new Big Data institute to specialise in the analysis of the collected data, beginning one year into the project. A second position, starting in year 2, will be co-supervised in the Oxford Centre for Time-use Research and will work on the analysis of insights that can be gained from the additional information contained in the METER data. Both DPhils would benefit from Oxford's breadth in energy research and be trained to work interdisciplinary and to collaborate with other related activities and support Philipp's vision for an interdisciplinary research group with excellence both in technical areas and social sciences.

In addition to the networks and client contacts available to the fellowship through community groups, project partners and other databases, participant numbers can be boosted through social media engagement as explained in the Pathways to Impact. Other risks and contingencies are listed in the table below.

Risk	L	I	Contingency key: **L**ikelihood, **I**mpact, **L**ow, **M**edium, **H**igh
Recruitment of participants	M	H	Partner Pilio and other networks give access to several thousand households. If sign up rates are not sufficient, recruitment and data collection will be extended into year 3&4.
Devices not returned	L	M	Participant may keep devices in the hope to use them as smart phones. Phones are low cost units, branded as university property, password protected and participant will enter an agreement to return them. Additional courier collection can be arranged.
Handling large data	L	H	The applicant is highly competent at handling and curating large data sets securely. Sensitive data will be stored on a non-networked computer.
Ethical concerns	L	H	All procedures will undergo ethics clearance. Participants will be fully informed and asked for their consent prior to participating and after reviewing their data.
Low response rate	L	M	Hand written diary response rates are around 60%. The ease of participating in event triggered collection should lead to higher rates. If particular groups show low response rates, targeted additional rounds will be undertaken.
Technology failure	M	H	The devices are mass market products and the software is operating robustly. Technical issues can be addressed by the fellowship team.
Lack of interdisciplinary engagement	M	M	The applicant has a strong track record of engaging with a broad range of disciplines. The experience to date has shown a keen interest by a wide community of researchers. Workshops will be facilitated to foster their involvement.
Management	M	H	The applicant has extensive experience in delivering complex projects to time and budget. The resources requested are adequate for the success of the project and with additional funding impact could be increased further.
Quality of applicants for the team	H	M	As a novel area of research the skills required for this project are specific and demanding. Suitable applicants may be difficult to find. Some potential candidates are already known to the applicant. Others may be identified through his extensive networks. If the required skills are not available, otherwise talented individuals can the trained into the roles.
Impact of results	L	H	The findings of this study can be disseminated directly to relevant researchers and policy makers in the UK, to which contacts already exist. Further dissemination routes will be developed throughout the project via workshops and other engagement activities.

Choice of host organisation

The University of Oxford is uniquely suited to host this innovative and interdisciplinary fellowship. The Oxford Energy Network comprises over 180 senior researchers addressing issues in energy more broadly than any other UK university. Oxford brings together a highly stimulating mix of social scientists, economists, technical and policy experts, who between them can approach problem focused research challenges in innovative and effective ways.

The Environmental Change Institute in the School of Geography and the Environment has established itself as the hub of interdisciplinary energy research at Oxford. It hosts the Oxford Energy Network and has a long standing track record of contributing with high impact on energy policy and economic matters. The Lower Carbon Futures group, led by Dr Nick Eyre, has extensive expertise on energy demand research and consumer interaction with energy feedback. It leads the theme on Decision Making for UK Energy Research Centre (UKERC), the largest UK Research Council centre in the field of 'whole energy systems'. Within this theme the 'Energy Practices and Energy Services' and 'Demand Response decisions' projects align well with Philipp's proposed research. Dr Eyre also leads the energy demand team working in the UK Infrastructure Transitions Research Consortium, a £4.7million EPSRC Programme Grant, which is developing new system models to enable long term planning of national infrastructure systems.

Oxford is also home to the world renown Centre for Time Use Research (CTUR), led by Professor Jonathan Gershuny, whom the applicant is already collaborating with on early trials of concurrent collection of time-use and electricity consumption information. The links to these and other parts of the University, such as Mathematics, Engineering and Computer Science, will be fully exploited and further strengthened during this fellowship, making Oxford an ideal location for this research.

The considerable interest expressed by fellow academics, industry representatives and other groups in the proposed work suggests that this fellowship could also be conducted as a collaborative research project. However, that route would have two serious drawbacks. Firstly, the exploratory and fundamental nature of the research question would have to give way to more pragmatic and pre-defined research goals. The options this fellowship offers for development of novel collaborative themes, especially in Phase 3, would be restricted, if formal collaboration agreements at the outset had to be agreed. Secondly, a collaborative project would not allow Philipp the same degree of freedom to creatively develop his ideas and vision for his research. The fellowship approach allows him to establish a career in this field and maximise his long term impact on the research agenda on end-use energy demand.

References (see also List of Publications)

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