Engineering Comes Home: Co-designing nexus infrastructure from the bottom-up

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Abstract

The 'nexus' between water, food and energy systems is well established. It is conventionally analysed as a supply-side problem of infrastructure interdependencies, overlooking demand-side interactions and opportunities. The home is one of the most significant sites of nexus interactions and opportunities for redesigning technologies and infrastructure. New developments in 'smart city' technologies have the potential to support a bottom-up approach to designing and managing nexus infrastructure. The Engineering Comes Home was a research project that turned infrastructure design on its head. The objectives of the project were to:

- Demonstrate a new paradigm for engineering design starting from the viewpoint of the home, looking out towards systems of provision to meet household demands.
- Integrate thinking about water, energy, food, waste and data at the domestic scale to support user-led innovation and co-design of technologies and infrastructure.
- Test new design methods that connect homes to communities, technologies and infrastructure, enhancing positive interactions between data, water, energy, food and waste systems.

- Develop a robust Lifecycle Assessment (LCA) Calculator tool to support environmental decision-making in co-design.

Working with residents of the Meakin Estate in South London, the project followed a co-design method to identify requirements, analyse options and develop and test a detailed design for a preferred option. The outputs were:

1) **Ethnographic study** of how residents use water, energy and food resources in their homes and key opportunities for engineering design to improve wellbeing and reduce resource consumption.

2) **Co-design** of decentralised infrastructural systems in three workshops in 2016-2017. The first workshop identified key priorities for development from the community using a novel token-based system design method, to enable participants to build up alternative designs for local provision of water, energy, food and waste services. The second workshop provided participants with factsheets and photographs of the candidate technologies, which were then analysed using a LCA Calculator tool. Rainwater harvesting was selected as the technology for further co-design in the third workshop, which focussed on scaling up a pilot installation.

3) **Pilot-scale smart rainwater system** was installed in partnership with the Over The Air Analytics (OTA). OTA's system enables remote control of the rainwater storage tanks to optimise their performance as stormwater attenuation as well as non-potable water supply.

4) **Lifecycle Assessment (LCA) Calculator** to enable quick estimation of the impacts of new systems and technology to deliver water, energy and food, and manage waste at the household and neighbourhood scale.

5) **Stakeholders,** including utilities, design consultancies and community based organisations, were engaged in three workshops to inform the wider relevance and development of the co-design methods and tools.

6) **Toolbox and method statements** to standardise and disseminate the methods used in the project for wider application and development.

Key Words

water-energy-food nexus, co-design, social housing, rainwater harvesting, community engagement

Introduction

The 'nexus' between water, food and energy systems is well established. In 2009 Sir John Beddington[1], then Chief Scientific Advisor to the UK Government, described the interconnections between food, water, energy and climate change as the 'perfect storm' brewing on the horizon of global events. The 'nexus' is typically discussed as an issue of supply-side infrastructure interdependencies, addressing issues such as the use of water in energy production, the energy intensity of water and wastewater treatment and pumping, and the need for energy to pump water to irrigate crops for food and bioenergy production. Demand-side interactions between nexus resources are discussed in terms of domestic water heating and the energy requirements for alternative water supplies such as rainwater harvesting and greywater reuse. This paper deepens the demand-side approach to resource interactions, focussing on the home as one of the most significant sites of nexus interactions. This leads to new opportunities for redesigning technologies and infrastructure to reduce demand and improve resource efficiency.

The 'Engineering Comes Home' research project approached the water-energy- food nexus from the bottom-up and exploited new opportunities for monitoring, feedback and control provided by 'smart' devices and the 'Internet of Things' (IoT). Through understanding people's everyday practices of consumption and engaging communities in co-design, Engineering Comes Home identified opportunities for engineers to design and configure smart, sustainable systems at household and neighbourhood scales, and to consider connections to urban and regional infrastructure systems. Whilst conventional supply-side design of infrastructure and technology addresses water, energy, food, waste and data as separate sectors, this project explored opportunities for designing across the nexus, starting with household demands and practices, and working outwards. It focussed on design of new technologies within the everyday cultures and needs of households and communities, rather than on individual behavioural change to reduce resource consumption.

In this paper we outline a co-design project that ran in 2016-2017 in a housing estate in south east London. The project resulted in an IoT-enabled rainwater harvesting tank and hose being installed on an estate downpipe for residents to use. The paper starts with a review of the relationship between infrastructure provision and everyday resource using practices, then provides details of the co-design process and outcomes, and concludes with reflections on how this approach might be used more widely in infrastructure design and management.

Infrastructure scale, resource consumption and innovation

Infrastructural systems are central to structuring modern patterns of consumption of natural resources. In contrast to other forms of consumption, consumption of resources through infrastructure services is inconspicuous, largely unnoticed but deeply entangled with everyday habits, routines and practices[2].

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[1] Beddington J. Food, energy, water and the climate: a perfect storm of global events? London: Government Office for Science. (2009).

[2] Shove E. Comfort, Cleanliness and Convenience: The Social Organisation of Normality. (Berg, 2003).

Infrastructure, and its services and resources form part of the background of everyday life, typically only entering the users' consciousness when something breaks down, when resources are scarce or when absent altogether[3].

The conventional scale of infrastructure provision is in sharp contrast with the everyday experiences of users as they consume water, energy or other services. Water, energy and food are central to some of our most private and intimate activities – using the toilet, preparing and sharing a meal, showering, bathing children or tending a garden. By contrast, urban infrastructures are typically managed and designed as large technical systems, operating over urban and regional scales, with little reference to the detailed experiences of resource consumption. This disconnection between the scale of everyday resource using practices and the scale of provision of infrastructure services limits the adaptive capacity and resilience of cities in the face of resource constraints and environmental change.

Demand-side response activities have opened up a field of research about how parts of infrastructure can be designed to bring users more reliably into the frame of resource management. End users, even residents in their homes are increasingly being seen as key to achieving system aims and are described as 'co-managers' of national infrastructure systems by van Vliet et al[4]. However the residents' role is typically restricted to using the equipment on their side of the meter appropriately. From shower timers, to thermostats, smart meters to time of use tariffs, information and equipment are being designed to bring user interaction in line with networked utilities' distribution priorities. In studies by Sofoulis and others, citizens have shown tremendous willingness to change their behaviours to conserve resources, but the technologies and infrastructure of resource provision are often insufficient to support their efforts[5][6][7].

New applications of information and computer technologies (ICT) in infrastructure networks and services are changing how they are operated and managed, and consumer experiences. Sensor networks provide data about the operation of infrastructure systems, including demand, and developments in control systems allow for improved system management and operation. Smart meters and home systems provide consumers with more information about their resource use and enable remote control of household devices and systems. Data about consumer use of infrastructure services provides new opportunities to analyse demand to identify opportunities to reduce it and to plan future infrastructure services to meet demand more efficiently and to improve services standards. ICT and smart city technologies also provide opportunities for centralised control of decentralised systems,

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[3] Edwards P. Infrastructure and Modernity: Force, Time and Social Organization in the History of Sociotechnical Systems, Chapter 7 in Misa T., Brey P. and Feenberg A. (eds) Modernity and Technology (MIT Press, 2011).
[4] van Vliet B., Chapells H. and Shove E. Infrastructures of Consumption: Environmental Innovation in the Utility Industries (Earthscan, 2005).
[5] Allon F. and Sofoulis Z. Everyday water: cultures in transition. Australian Geographer 37 (2006).
[6] Doron U., Teh T. H., Haklay M. and Bell S. Public engagement with water conservation in the Lower Lea Valley, UK. Water and Environment Journal 25 (2011).
[7] Sofoulis Z. Big Water, Everyday Water: A Sociotechnical Perspective Continuum: Journal of Media and Cultural Studies 19 (2005).

allowing operational efficiency and reliability without the distribution inefficiencies associated with centralised infrastructure networks.

Design for sustainability

Infrastructure is typically designed by expert engineers and planners, with citizen involvement restricted to consultation in formal decision-making processes or specific community outreach to minimise conflict with local communities. It is rarely subject to co-design, in which users and providers work together to design technologies and systems. The Engineering Comes Home project aimed to test co-design methods for infrastructure provision, starting with everyday needs for water, energy and food and designing systems to meet those needs in partnership with householders. The objectives of the project were to:

- Demonstrate a new paradigm for engineering design starting from the viewpoint of the home, looking out towards systems of provision to meet household demands.
- Integrate thinking about water, energy, food, waste and data at the domestic scale to support user-led innovation and co-design of technologies and infrastructure.
- Test new design methods that connect homes to communities, technologies and infrastructure, enhancing positive interactions between data, water, energy, food and waste systems.
- Develop a robust Lifecycle Assessment (LCA) Calculator tool to support environmental decision-making in co-design.

The project drew on two strands of design thinking to inform the co-design methodology. The first looked to the participatory design tradition developed within the field of information technologies to find ways to engage residents in the design process. The second looked to the tradition of product design within the sustainability design field, in order to look at how interventions can disrupt the status quo of WEF resource use in the home.

Participatory design has been a field of research and practice in Information Technologies since the 1970s[8]. This field has led to more open design practices moving first to user-centred design which observed people's practices to improve design, then to user-led design which put users in charge of identifying the design problem, to co-design which embraced both suppliers and users to work together in defining problem spaces and design solutions[9]. At its core, participatory design is about improving the systems that serve people and emancipating the users through engaging them in the design process.

Design for sustainability is focused primarily on the environmental impact of designed goods and services. Its origins lie in product design and improving product performance to provide consumers with the same service levels while reducing the volume of resources used. Challenges such as the 'rebound effect' led design theorists to consider not only a product's performance, but also its use by people.

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[8] Simonsen J. and Robertson T. Routledge International Handbook of Participatory Design (Routledge, 2012).

[9] McDougall S. Co-Production, Co-Design and Co-Creation: What Is the Difference? Stakeholder Design. http://www.stakeholderdesign.com/co-production-versus-co-design-what-is-the-difference/. (2012).

This has led to fields such as 'persuasive technology design' which encourage more sustainable consumption behaviours through product design. Recent approaches to sustainability and design draw on Social Practice Theory to engage with resource using practices[10], and Actor Network theory to move beyond the individual as the source of agency[11]. These methods study social practices around resource use and then use design methods to disrupt or innovate and project possible alternative socio-material configurations and co-evolutions.

Life Cycle Assessment (LCA) has evolved into a major decision support tool for design for sustainability and related fields. The quality of the design and decision support LCA provides is determined in terms of its relevance to the type of questions to be answered. Originally, the starting point in LCA was with its application to relatively simple choices, for instance, in making technical changes to a product or choosing a material over another in relation to packaging. LCA tools are increasingly used to support decision makers with quantitative evaluations of the decisions they make throughout the lifecycle of their products or systems. However, the current generation of tools is mainly targeted at experts or users with a significant background in industrial and environmental processes. There is considerable interest from the LCA community in pushing the boundaries beyond expert users and being able to develop the next generation of LCA tools that can help a wider range of participants in the design process, bringing LCA into participatory design and co-design processes.

Testing nexus co-design

The project put these design principles into practice in order to test whether the co-design infrastructure was possible. In this section we discuss the co-design process employed in our project on the Meakin Estate in Southwark . This social housing estate has 123 flats, ranging from one to four bedrooms arranged in three low rise blocks with shared gardens and courtyards.

The core co-design process was carried out in three half day workshops, preceded by an ethnographic study of water-energy-food related practices (Figure 1). The workshops were held in the estate's community hall and involved 19 residents (15% of the total number of households). The process was run by the research team, supported by an external facilitator, videographer[12] and the local Tenants and Residents Association. The research team undertook analysis, design and evaluation of the processes in between the workshops, building on participants' ideas and preferences expressed through the workshops and ethnography.

[10] Kuijer L. Implications of Social Practice Theory for Sustainable Design. Delft University of Technology. (2014).
[11] Teh, T.H. Hydro-Urbanism: Reconfiguring the Urban Water-Cycle in the Lower Lea River Basin, Doctoral Thesis, University College London. (2011).
[12] Videos of the three workshops are available to watch at http://www.engineering.ucl.ac.uk/engineering-exchange/video-articles/

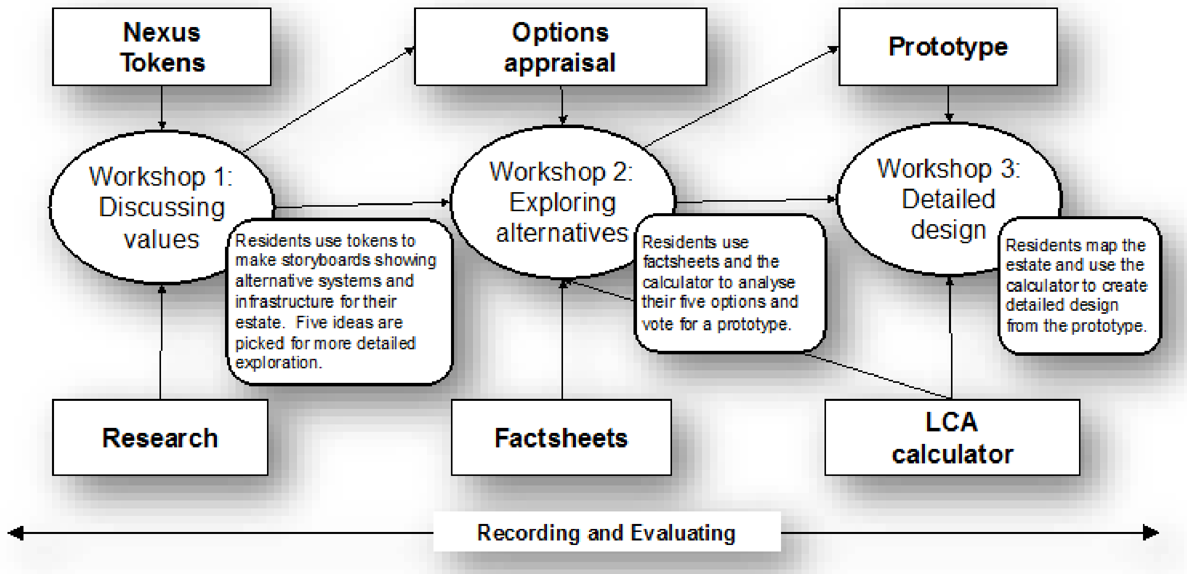

Figure 1: Nexus co-design process

Capturing requirements

The project commenced with ethnographic research into how residents use water, energy and food resources in their homes and key opportunities for engineering design to improve wellbeing and reduce resource consumption. The ethnography showed that residents had high motivation to conserve resources, even though their energy and water use are not metered. Residents had diverse interests in food growing, waste reduction, energy and water conservation, with a strong general interest in alternative sources of water and energy. The project developed and documented methods for recording water, energy and food practices in homes, including room audits, diaries, appliance logging and interviews. These tools and the data collected enabled householders' experiences and preferences to be used as the starting point for the co-design process.

The first co-design workshop identified community priorities using a novel token-based system design method, to enable participants to build up alternative designs for local provision of water, energy, food and waste services (Figure 2). Participants' values were elicited in the first workshop using the 2-4-8 method. The project developed methods for field observation and analysis of data from workshops to inform design choices. Video and audio recordings of the workshops were analysed to confirm the values and needs of the participants to produce a long list of possible design interventions. The long list was analysed using an options appraisal method based on desirability and feasibility, to produce a short-list of five candidate systems for further design and analysis at the second workshop - food growing, wormery, composting, rainwater harvesting, waste compaction and food sharing.

Figure 2: Using Co-design Tokens to discuss infrastructure options

Evaluating options

The second workshop provided participants with factsheets and photographs of the candidate technologies, which were then analysed using a bespoke LCA Calculator developed specifically for the project (Figure 3). Participants explored scenarios based on the five shortlisted technologies and at the end of the workshop voted to develop rainwater harvesting as the preferred option.

Figure 3: Using LCA Calculator on tablet computer to evaluate impacts of infrastructure options

The Calculator was used with community participants in the workshop. It was found to be helpful to provide further information on the technology options and to anchor the use of the Calculator in practical, community-relevant questions. The Calculator provided a solid base on which sustainable design discussions could happen. It gave participants insight into the scale of material flow given different design choices - such as the amount of waste generated over a month or the irrigation requirements of a raised bed - and environmental impacts of these options. Participants used the graphical interface to adapt and scale the systems to their community and their area. For example, some participants used their experience of community engagement to restrict the amount of food waste flowing in to the system, judging that a maximum of 50% of residents would get involved with a local composting initiative. Other participants concentrated on the physical layout of the estate, adjusting the volume and number of wormeries or rainwater tanks to fit with what they felt would suit the topography. The outputs were used to evaluate different options. Some participants were interested in the emissions figures and adjusted system sizes to maximise reductions, others focused on volume of useful resources (e.g. tomatoes) that their estate could produce. Overall, participants showed good engagement with the numbers provided by the Calculator, particularly when specific questions were raised about details of nexus design implementation. Consequently, the Calculator facilitated realistic decision-making in participants with little practical engineering experience.

Demonstrating smart systems

Rainwater harvesting was selected at the end of the second workshop as the technology for further co-design. It was important to provide a physical prototype of rainwater harvesting in order for community members to understand how it operated, the physical dimensions and constraints of the technology. In order to provide a physical demonstration of the principles and technology of rainwater harvesting, a rainwater harvesting unit was installed in partnership with the firm Over The Air Analytics (OTA). The OTA system uses Internet of Things capability to enable remote control of the rainwater storage tanks to optimise their performance as stormwater attenuation as well as non-potable water supply. Whilst the residents had chosen rainwater harvesting as a source of non-potable water, the OTA system provides the additional benefit of stormwater management, demonstrating the connections between local systems and urban scale infrastructure. The OTA system also demonstrates the value of IoT data and control systems in managing decentralised infrastructure.

Typically, rainwater management systems (RMS) and other sustainable drainage measures are implemented without monitoring systems, making it difficult to assess true system performance. Historically the lack of data collection has been associated with the high cost of SCADA (Supervisory Control and Data Acquisition) systems. Smart, real-time control systems for rainwater management have yet to be deployed throughout the water management infrastructure and consequently the application of IoT in the water sector represents a highly disruptive innovation. The development of digitally connected IoT technology poses an opportunity for big data to be included in the future design and operation of RMS[13]. Building on the need for RMS to; 1) provide demonstrable water savings; 2) achieve stormwater control criteria and; 3) for IoT to be integrated and demonstrated as a viable low-cost alternative to SCADA, a pilot installation of a smart RMS was completed in conjunction with the Future Cities Catapult.

OTA Analytics installed a household-scale RMS, on the Meakin Estate in February 2017, in conjunction with the Future Cities Catapult. The RMS was designed such that the residents could use rainwater from an 800 litre above ground tank for garden watering using a hose. The control system was programmed to enable access to a range of rainwater reuse philosophies e.g. automatic stormwater release prior to

[13] Wong B. P. and Kerkez B. Real-time environmental sensor data: An application to water quality using web services, Environmental Modelling Software 84 (2016).

storms; or maximising rainwater storage for summer months. The system was configured to enable the users to maximise rainwater reuse in the summer, whilst reducing to a lower storage level during winter months.

Data collection and remote control were achieved through installation of OTA's active control hardware and a communications module. The project initially planned to access the LoRaWAN network associated with the Digital Catapult's "Things Connected" team. Unlike traditional offline data logging technologies (which are limited in terms of the frequency of data collection), the SYMBiotIC platform was configured to capture and interrogate data at 1-minute time intervals. The platform was launched, building on intellectual property derived from the University of Exeter's Centre for Water Systems, and on a five-year collaboration with one of the UK's leading water company's innovation department.

Detailed system design
The third co-design workshop enabled participants to design an estate-scale rainwater harvesting system. The workshop involved an estate walk-around to map existing drainage infrastructure and opportunities for rainwater harvesting (Figure 4). Participants were informed about the relationship between urban runoff and environmental pollution from combined sewer overflows, and the benefits of rainwater harvesting as a sustainable drainage measure. A rainwater harvesting calculator based on the same principles as the LCA Calculator was used by residents to explore options and inform decisions about tank sizing and location. The outputs of the workshop were options for system design of rainwater harvesting on the estate.

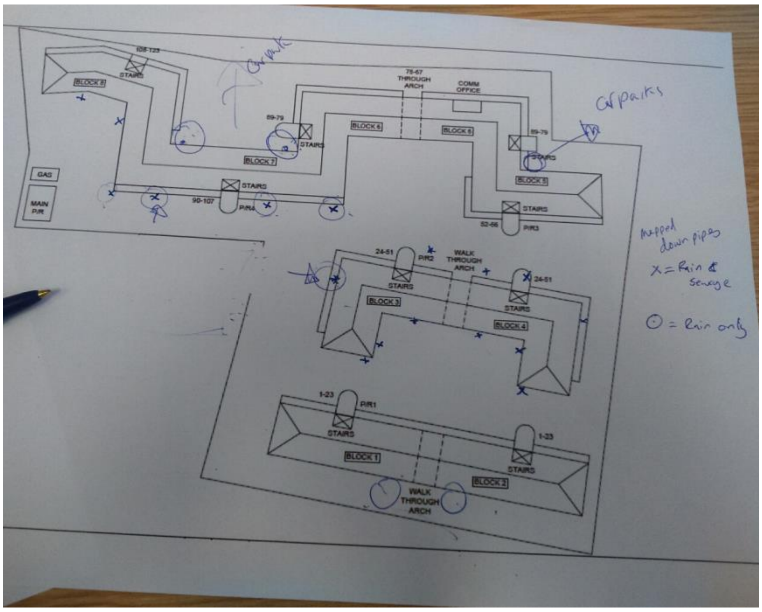

Figure 4: Mapping rainwater harvesting sites and drainage infrastructure

Conclusions

The water-energy-food nexus is a significant challenge for infrastructure designers and managers. Sustainable solutions to reduce consumption and improve resource efficiency and resilience require both demand and supply-side approaches. It is also important to address the relationships between supply and demand, recognising that systems of supply shape the possibilities for everyday practices that demand resources. Engaging users of resources in the design of systems to meet their needs holds promise as a means for overcoming the conceptual and practical barriers between big systems of provision and small, intimate everyday practices of consumption.

The Engineering Comes Home project demonstrated that local communities are capable of engaging in discussion and design of technical systems to meet resource needs that are typically supplied by large, centralised systems. Discussing options for alternative supply systems provided a unique context for engaging with the larger systems of provision and their environmental impacts. For instance, participants in the project increased their knowledge of urban drainage and combined sewer overflows through their interest in rainwater harvesting for water supply. The pilot rainwater harvesting also provided a demonstration of the capability of IoT technologies to improve management of smaller-scale technologies, linking data infrastructure to everyday experience of rainwater, car washing and gardening. Through participating in a design process that attended to the specific needs and values of the community, residents not only developed ideas for improving their neighbourhood but they also increased their infrastructural literacy, improving understanding of how centralised systems of provision operate.

Supporting co-design of infrastructure required the development of novel ICT based design tools. The LCA and Rainwater Calculators were integrated into the design process and brought powerful analytical and design tools into the hands of non-expert users. The design process and tools are adaptable for other contexts but emerge from the specific context of the Engineering Comes Home project. Aligning the choice and development of the design tools with the specific needs of the co-design process enabled an integrated, systems-based approach to co-design.

New technologies provide opportunities for innovation in infrastructure design and delivery. Engineering Comes Home demonstrates the value of integrating these new technical developments within a novel bottom-up approach to design. Starting from the everyday needs and values of householders and communities provides a unique position from which to develop sustainable and resilient infrastructures for the water-energy-food nexus.

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