On the edge of supply: designing renewable energy supply into everyday life

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***Abstract*—With peak oil behind us, nuclear generation capacity dwindling, and increasingly daunting looking carbon emissions targets, we are moving to a world where we must consider transitioning to renewable energy sources. Renewables are time varying and their inherent unpredictability must challenge our everyday assumptions around energy availability—leading, we believe, to an emphasis on 'supply' rather than 'demand'. Using a range of methods including action research, participatory design and technology mediated enquiry, we report on our work in partnership with the community of Tiree as an exemplar of this future. Tiree is the outermost of the Scottish Inner Hebrides—a remote island on the edge of the national electricity grid with a precarious grip on energy—here we uncover the role of renewables and the resilience of a community in moving away from traditional energy provision. We offer opportunities for designing ICT to support supply driven practices in this context, and a simple framework for exploiting under and over supply.**

I. Introduction

Since the industrial revolution we have enjoyed unprecedented access to fossil fuels. Our carbon rich diet of coal, oil and gas has fuelled industrial development and helped to establish a 'modernist framework' for comfort and convenience in the home predicated on energy use, 'on demand', whenever we want it.

The future of energy supply is looking rather less certain. To use the UK as a case study, and to borrow from M. King Hubbert's peak theory [1], peak gas in UK was reached in the year 2000 [2], and we now increasingly rely on overseas imports. Much of UK's nuclear capacity is reaching end of life over the next decade, requiring renewal [3]. Diminishing reserves of fossil fuels, and thus vulnerability to volatile costs, twinned with a need to make stringent targets to decarbonise the energy supply, will mean increasing reliance on renewables in the supply mix in the coming decades.

Energy from renewable sources (especially wind and solar power) is literally dependent on time-varying weather systems, and is thus inherently less predictable than traditional sources of power. This raises new questions for society about the use of electricity, and to what extent everyday practices and energy intensive infrastructures that support them need to adapt to embrace and work with fluctuating energy supply.

We set out to explore an envisionment of this future on a remote Scottish island of Tiree. In many respects the energy supply on Tiree is less secure, more intermittent and contains a greater mix of renewable sources. Importantly, the community on Tiree have established partial energy independence through building their own community wind turbine. But, as we find and report in this paper, renewables on the island are balanced against more carbon intensive sources of energy. We set out to explore this balance further. We are interested in the relationship the close community on the island may have with their renewables, and what we can learn from the initiative and resilience shown by the islanders in adapting to a more supply driven energy future.

In this paper we chart the experiences of living and working in this new energy context on the edge of supply. Through a series of technology mediated interactions, including interviews, field visits and workshops, we work with various stakeholders to explore the design of new technologies to promote awareness of variable and intermittent supply. We report on the discussion initiated and supported by the technologies we have developed, and contribute insights about new ways we might design to cope with fluctuations in energy supply. We finish with a simple framework that outlines a design space we might exploit more widely in future supply responsive design.

II. Related Work

One aspect we particularly need to communicate in our discussions on the island concerns the availability of energy supply (from renewables), and how this varies over time. Making energy 'more visible' is one of the goals of so called 'eco-feedback' design, since the invisible and intangible nature of electricity is often cited as a key driver for its profligate use and unsustainable levels of consumption in the home [4]. Provocative designs such as the erratic radio [5] raise awareness of collective grid load by detuning during high consumption periods. The power aware cord [6] glows brighter the more power consumed; whereas the 'flower lamp' blooms when household energy consumption reduces over time. It is unclear whether such designs are as effective (or perhaps ineffective) as conventional in home energy displays [7], as they are rarely deployed in practice—but it seems reasonable to assume so, given the critique that energy use is the result of supporting everyday practices (showering, laundering and keeping warm), which are mediated by social, cultural, technical and institutional dynamics, rather than as a series of rational informed choices [8].

Although we are focusing mostly on community scale renewables, we would note that prior work has explored attitudes to micro-generation (PV panels) using a technology probe involving several prototypical visualisations of energy availability, quantity, variability over time, and energy storage [9]. Researchers found that households with micro-generation did question their energy consumption, leading to shifting demand to times of peak generation. They also found differing levels of engagement with renewable supply, suggesting the need for specific designs for certain sub-groups of participants. Similar themes of future energy storage and 'saving' of energy have also been prototyped [10], suggesting that some practices (laundering) are 'shiftable', whereas others may be considered 'non-negotiable'. Interestingly, the authors also suggest more thoughtful consumption or 'slow energy' systems, such as windy day laundering or sunny-day bread making. It is interesting to note that on Eigg, which uses off-grid community owned renewables, households are subject to a 5kW cap, and are asked to voluntarily reduce their electricity demand when renewable sources are running low using a traffic light system displayed in community areas [11].

Attempting to shift 'peaky' everyday practices to smooth 'hot spots' of demand into 'cold spots', known as demand levelling, is an everyday concern of electricity distributors [12]. Scottish Hydro's *Total Heating Total Control* (THTC), uses remote controlled electric storage heaters to synchronise use with available off peak electricity [13]. Pricing strategies are often used to implicate householders in such strategies. As early as 1979, a controlled experiment using time-of-use pricing showed that dynamic pricing did not induce conservation, but did significantly contribute to shifting electricity use from peak to off-peak periods [14]. Dynamic peak pricing (DPP) combines punitively priced electricity at times of very high predicted load, together with a range of notifications (SMS, Phone, in-home-display, email) to temporarily reduce the use of electricity (mainly due to air conditioning) on particularly hot days [15]. While DPP is effective at triggering short term load reductions, emergent rebound effects such as pre-cooling ahead of such events may in fact lead to more energy consumption—and such interventions do nothing to fundamentally question the presumed 'need' for the energy committed to cooling in the first place.

Shifting practices has also been a recent focus for ICT interventions: 10 households were asked to book time-slots of a shared renewable powered washing machine whose pricing depends on national grid load [16]. The system was naturally disruptive of routine and at times proved difficult to align with the uncertainties of everyday life, but did deliver organisational and economic benefits—raising the tension between convenience and sustainability.

In our work, we do not focus on demand levelling, but rather consider how communities might exploit the peaks and troughs of energy supply found in contexts where renewable sources form a substantial proportion of the energy mix—energy systems that incorporate a high degree of variation and intermittence. As a vehicle to explore this energy future, we are seeking to understand the relationship islanders of Tiree have with their energy system, which we believe stands as an exemplar for this kind of emerging situation in the UK and many other parts of the world.

III. Approach: A Technology Mediated Enquiry

In order to engage and work in a research partnership with the islanders of Tiree, a community very much 'on the edge' of the UK's infrastructure, and with complex needs, requires that we establish mutual trust, specialist skills and care. We follow an innovation management framework called *Speedplay* [17]. Speedplay is a participatory, agile and transformative digital-innovation management approach that has emerged from working in research partnerships with hard-to-reach communities with multiple complex needs [18].

Speedplay is a theoretical framework for a management style that 1) works in partnership with all stakeholders including end-users; 2) supports team building by engaging team members in cross-cutting tasks; 3) promotes individual self-direction by matching primary responsibilities to individual skills; 4) applies a variety of research methods and design techniques; and, 5) systematically uses design and problem solving to promote both critical and lateral thinking.

A. Speedplay as a Mind-Set

Speedplay is a reflective process characterised by four distinct and iteratively overlapping steps: prepare, (co)design, build, and sustain. The first step focuses on trust-building through up-skilling and a clear disclosure of the values underpinning the research partnership; the second, on understanding what and whose needs the technology is responsive to including individuals' dreams and aspirations; the third, on gaining a grounded and experience-based knowledge of the economic and environmental research-context; the fourth, on sustaining longevity of action through knowledge sharing and pro-active participation of all the parties involved in the partnership. From a theoretical perspective, Speedplay paces this process by applying a streamlined version of plan-driven methodologies such as PRINCE2 to a vision for a socially transformative research founded on principles of Action Research (AR) [19], Participatory Design (PD) [20] and Agile Iterative Development (A-ID) [21].

In contrast to developing *top-down* models of energy or GhG externality, our goal is to understand the relationship the people of Tiree have with energy. Speedplay is largely driven through situated engagement with users, so much emphasis is placed on researching with the community and developing understandings and technologies collectively *bottom-up*. Central to our enquiry is the design and build of technology prototypes that, by becoming part of the enquiry, embed and support the partnership needs, values and aspirations.

B. ICT Mediated Dialogue

This design approach requires, an interdisciplinary skill-set and, on an epistemological level, a shared view of technology prototypes as means-to-an-end rather than as end-products. In other words: to responsibly introduce technology innovation in complex contexts requires technical expertise as well as a mindful attitude and experience-based knowledge [22], [23].

For this we have used a series of technology prototypes, each designed as a vehicle for sharing skills, building trust, addressing the needs, and supporting the aspirations of the partnership. In other words, our prototypes are *talking points*, *provocations* [24], and *digital artefacts* designed to play different roles to suit the various stages of the innovation and transformation process: from up-skilling, to trust-building, awareness-raising, creativity-unlocking and requirement-capturing.

In this case, our series of technology prototypes, shown in Figure 1, are part of an ongoing dialogue with the islanders, in which the designs probe and trigger the elicitation of responses and ideas, to which we respond in later designs—building our understanding.

Our initial artefacts (1) and (2) focused on communicating the time varying nature of the community owned wind turbine on the island: an LED-augmented 'physical' Christmas cards ('Tilley Twinkle') whose lights changed colour depending on Tilley's energy output data, and a 'virtual Christmas tree' whose lights replayed the last 24 hours of wind turbine output to web visitors. These were sent at Christmas time to contacts made during our initial fieldwork visits in October 2013. We then used these as a talking point during interviews throughout late December, early January. Based on our interviews, we developed further prototypes (3) and (4): radio-controlled smart plugs ('SQRL') that can switch appliances on and off depending on renewable energy availability, and 'WindyBrew', a kettle that only boils when sufficient renewable energy is available, and latterly, Ping Pong Power (5) and Energy Detectors (6) used and described in workshops on the island this February, see Section V). The energy detectors are part of a longer running engagement (7) which will be continuing from the end of March 2014.

IV. Tiree Context

From our one to one stakeholder interviews and periodic all hands stakeholder meetings, we have developed a detailed picture of how energy is supplied, and experienced on the island of Tiree. We now describe a little about life on the island, its situation and how energy is experienced there.

Tiree is the outermost of the Inner Hebrides off the West coast of Scotland. When compared with mainland UK, Tiree is a small island of approximately 10 miles by 5 miles; and has a population of around 650, dotted around the island in farm crofts and small clustered communities. It is a wild and beautiful island, constantly exposed to the elements and weather from the sea. Strong winds and in many ways the weather are an ever present feature of island life. With an abundance of wind, strong tides, and an enviable record of sunshine dating back to the middle-ages, the island is in many ways ideally placed to exploit renewable energy sources.

Physically and metaphorically, the islanders are 'on the edge' of UK's service infrastructure: the island's energy supply is connected to the mainland via an undersea cable to neighbouring islands and then the national grid, but this cable is ageing and gets considerable abuse from the rocks and the tides. Islanders often experience short intermittent power-cuts that disrupt electronics and electrical appliances, shortening their operating life. Larger power-cuts, mainly due to storm damage are not uncommon, as the strong and blustery winds take their toll on the electricity distribution on the island. But periodically, when the link to the mainland breaks, the island power is cut and then isolated to its own power source: a 3MW diesel power station. Diesel is then shipped to the island every few days to maintain service until the cable link to the mainland can be restored (which is an extremely difficult and weather sensitive operation). Around 7,500–10,000 litres (about 150 car fuel tanks every day) of fuel are used every 24 hours to meet the 1–1.5MW of nominal demand needed to power the homes, public services and businesses on the island.

The islanders are by necessity frequently called upon to be resilient in all their walks of life—this includes energy supply. The community took the considerable initiative to bid for funding to support a community owned wind turbine. After a lengthy and complex process, a 920kW turbine (known as 'Tilley'[1]) was installed and has been generating since March 2010. Due to the exposed situation of Tiree, Tilley often operates at high efficiency: this electricity is sold to the grid and provides a revenue stream to fund community development 'windfall' projects. Micro-generation with wind and solar power, especially on crofts is increasingly common on the island; but larger micro-generation projects are sometimes compromised at the planning stage by fears of impacts on the precious and well preserved natural environment and wildlife.

Although Tilley's peak output is theoretically capable of meeting around ⅔ of the electricity demand on the island, the situation that emerges is rather more complex. Wind power typifies 'on supply', energy is available when the wind blows but varies literally and metaphorically 'with the wind'. The diesel generators, on the other hand, output a steady supply that is adjusted upwards or downwards to meet changes in demand by skilled operators who monitor and match the phase of the energy on the island to the rest of the UK. As is common with wind turbines, a 'power sink' is needed to cope with conditions where energy is too abundant, at other times, alternative sources of electricity are needed to 'shore up' the gap between supply and demand.

On Tiree, the undersea cable (and hence a mix of energy sources including mainly non-renewables) is currently essen-

[1] After the well known miner's lamp http://en.wikipedia.org/wiki/Tilley_lamp.

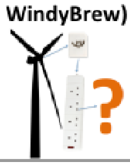
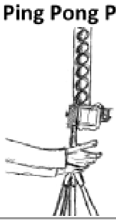
PROTOTYPES	REACH			
	OnSupply Partnership	**Wider Stakeholder Group**	**Tiree Community**	**External Stakeholders**
1) Tilley Twinkle (TT) 	Show & Tell for London-based onSupply partner, London.	Show & Tell, first wider-stakeholder meeting, Tiree. (10 participants)	Postage of 2 x TT Christmas Cards to Tiree community members Show & Tell during field-work , Tiree. (9 participants)	Show & Tell, CleanwebUK meet up, London. (30+ participants)
2) Turbine Tree 	Turbine-Tree Digital Christmas Greetings emailed to partnership			Co-designed with Lancaster University (LU) Energy Manager – The first prototype used data from LU Wind Turbine. Emailed to LU mailing lists
3) WindyBrew 	Small scale technical trial with the members of the core research-team, Lancaster.	Show & Tell, second wider-stakeholder meeting , Tiree. (12 participants)	Show & Tell during house visit of micro-turbine owners, Tiree.	Show and Tell with LU Energy Manager and LU students, Lancaster.
4) SQRL (increment of WindyBrew) 		Show & Tell, second wider-stakeholder meeting , Tiree. (12 participants)	Show & Tell during house visit of micro-turbine owners, Tiree.	
5) Ping Pong Power 		Show & Tell, second wider-stakeholder meeting , Tiree. (12 participants)	Used during HackIT workshops activities, Tiree (20+ participants)	
6) Energy detectors 		Show & Tell, second wider-stakeholder meeting , Tiree (12 participants)	Built and Used during HackIT workshops, Tiree (20+ participants)	
7) Energy Island (EI) 	Co-design of EI on-line platform and day-trips activities with Tiree Youth Officer, Tiree	Show & Tell, second wider-stakeholder meeting , Tiree (12 participants)	4 x EI Day-trips around Tiree 'Energy Points' with children (8-13 y.o.) Newsletters with EI Day-trips findings sent to families	EI widely accessible on-line

Fig. 1: Series of technology prototypes used to engage stakeholders (in chronological order).

tial in maintaining sustainable energy supply: energy flows to the grid (generating electrons but also revenue); the grid also acts as the 'buffer', soaking up oversupply, or providing energy when there isn't enough from the turbine. When the cable breaks, Tilley could be generating nearly 1MW of energy, more than enough to damage the power station's generators. The infrastructure is simply not set up to cope with a time varying load of such magnitude, irrespective of whether it physically could cope with fluctuations. So, when the cable is broken (in some cases for months awaiting repair), when the energy from Tilley is arguably at its most needed, the turbine is throttled back to its lowest maintenance setting (50kW).

What emerges for our project, is a complex energy environment, with a mixture of sources with time-varying characteristics, and an equally complex set of everyday practices around energy use.

V. Workshop Description

To help facilitate a dialogue around time-varying and intermittent energy sources, and help us understand potential roles for future technologies in exploiting its use, we held two technology mediated workshops on the island in February 2014.

A. Workshop Overview

The workshop sessions were designed to build and explore themes that emerged from fieldwork conducted on the island in December 2013–January 2014. The first workshop was intended to engage with adults and teenagers on the island to draw out the perception of both renewable and non-renewable energy, and encourage ideation around the use and sharing of energy from intermittent and non-continuous energy sources.

This workshop was divided into three primary sections:

- *Warm-up task*. The warm-up task (Inter-dimensional Energy) was designed to introduce participants to each other, break down possible barriers and to prepare participants.
- *Ping Pong Power (PPP) game*. A game intended to help the participants of the workshop visualise different patterns of energy supply.
- *Generative task*. The purpose of this session was to *hack* the PPP game, with the intention of eliciting processes and mechanisms that might help be more effective at the game—an analogue for real-world processes and devices, allowing us to tease out design ideas from the community.

The second workshop was organised for younger participants aged from 6–13 years. As this age group are normally relatively isolated from much of the energy context (i.e. energy bills etc.), this workshop was mainly intended as a community engagement activity, but also as a way to inspire participation and interest from the participants' guardians.

This workshop was divided into two primary sections:

- *Simplified Ping Pong Power (SPPP) game*. A simplified form of the PPP game focusing on energy from renewable sources. The purpose of this game was two fold: to act as a warm-up activity, and to help the participants visualise the dissemination of renewable energy.
- *Make-it task*. The purpose of this session was to build *energy detectors*, which were bespoke devices that measure the approximate wind speed and sunlight.

B. Warm-up Task

Earlier interviews suggested a diverse array of perceptions, awareness and knowledge about energy on the island. So to normalise this, we designed our warm-up task to focus on the concept of highly intermittent energy supply.

The warm-up task was both to prepare participants for the group workshop tasks, but also an attempt to break down barriers as the participants were drawn from a number of different age groups and backgrounds. We also wanted to remove any perceived barriers due to any apparent mismatch in expertise. To achieve this we used a '*Neutral-Zone Metaphor*' [25] to temporally place all the participants in a space where no-one could claim expert knowledge as a means to diminish hierarchies and place equal value among the group [26].

This was realised through '*Inter-dimensional Energy*': a fictional and limitless energy source but with intermittent properties. This metaphor was designed and tailored to represent aspects of our project [27] and link to the other workshop activities. Inter-dimensional Energy was presented to the workshop participants in the form of a small hand held prop (see Figure 2), and they were asked to imagine ways that they may harness and use this fictitious energy source.

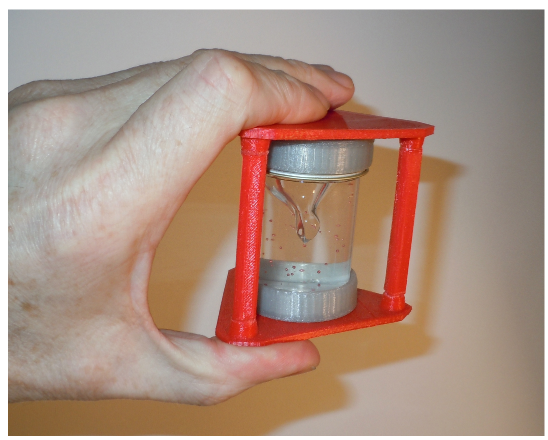


Fig. 2: Fictional energy artefact *Inter-dimensional Energy*.

C. Ping Pong Power Game

As supply driven energy use is not the currently established model of energy consumption, a way was needed to present it in a way that was both understandable and interesting to all members of the community. The Ping Pong Power (PPP) game was developed to help the participants visualise and physicalise the proposed energy ecosystem. Once the participants had engaged with the game, it was expected that they might be able to better understand the new energy scenario, and thus participate in a dialogue regarding the utilisation of renewable energy when it was abundantly available.

At the start of the game, participants were grouped into teams of two, and each team member was given one of two roles: *collector*, or *householder*. The *collector* was tasked with collecting the ping pong balls (*energy*) as they were dispensed and to deliver them to the *householder* team member; the *householder* then had to allocate the energy to one of the boxes placed in front of them. Each box represented a different household appliance, each with a different energy (ping pong ball) requirement.

A number of conditions were attached to the delivery of the balls, namely, they could not be thrown to their team member, and once a ball was out of the hands of the participants, the ball was no longer in play (the energy was lost). Uncollected balls were dropped directly into a plastic container, representing wasted energy. The balls were dispensed from two bespoke devices (*ping pong ball dispensers*), which released balls at different rates: one released a ball consistently every 4 seconds, and represented the energy pattern typically generated by non-renewable sources, whilst the other released energy at an intermittent rate, mirroring the time dependent and variable nature of renewable energy.

The game was separated into three rounds. The first round was used to familiarise the participants with the game rules, and as an opportunity to explore their energy usage habits. The second round was introduced with the addition of a rule, which stated that *if an appliance is only partially powered by the end of the round, points would be deducted from that team*. This additional rule was added to encourage the teams to strategically power their appliances, rather than to power all simultaneously—a strategy that in the real world may result in a *brown-out*. For the final round, the rules of the game remained mostly unchanged; however, instead of each team having an individual score, the teams would contribute to an aggregate score. Furthermore, a random selection of appliances from each team were marked as important, and the powering of these appliances would result in bonus points for the entire group. To aid in the powering of the priority appliances, the *collector* from each team were now able to deliver ping pong balls to any other *householder*. This strategic and collaborative round was intended to explore the participants attitudes to the sharing of available energy as a common, communal resource.

D. Generative Task

The aim of the generative task was to give the participants of the workshop a chance to reflect on the previously played PPP game, and to start the elicitation of design ideas, requirements, and constraints—ultimately, this would lead us to further explore the mechanisms and processes that may form part of a digital intervention aimed at better exploiting the renewable energy more effectively. The task resulted in the participants filling in a number of worksheets with design ideas in the form of written concepts and sketches (Table I). This data was later analysed after the workshop, which we discuss later (see Section VI). Additionally this process helped offer some visual confirmation that participants understood the dynamics of energy supply that we were hoping to communicate.

E. Underlying Technology

1) Ping Pong Ball Dispenser: The ping pong dispenser is an Arduino powered device that releases ping pong balls at a pre-determined rate. Ping pong balls are loaded into the dispenser via an acrylic tube, which in turn feeds a tumbler mechanism. All parts of the tumbler mechanism were produced using rapid prototyping techniques (i.e. 3D printing). Movement of the tumbler mechanism was driven by a standard servo motor that allowed up-to 180°of rotation. Once a ball has been loaded into the tumbler, it will be released when the tumbler next rotates.

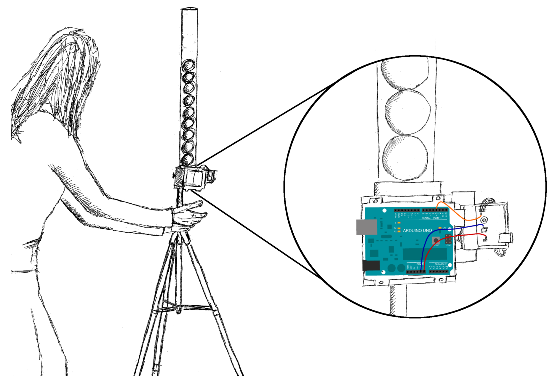


Fig. 3: The Ping Pong Ball Dispenser in operation.

Figure 3 illustrates the ping pong ball dispenser in use by a workshop participant. Because the game would be played by participants with varying heights, an important consideration was how to mount the dispenser mechanism. In order to satisfy this, the dispenser was mounted on an off-the-shelf camera tripod, allowing its height to be customised for each workshop session. Another consideration was the placement of the dispensers within the venue, and whether there was any plug sockets available to power them. As this was unknown until the day of the workshop, the ping pong ball dispensers were designed to be powered by either a 12 volt DC adaptor or a 9 volt battery.

2) Energy Detector: The energy detector was developed as a key element for the make-it task in the second workshop. The detector, which follows the form of a magnifying glass, integrates a propeller and small solar panel, and allows it user to sample an approximate measure of energy from the sun and the wind. The energy detector was designed to be constructed from a set of kit parts (see Figure 4); its discrete components were manufactured before the start of the workshop. These components were subsequently assembled by the workshop participants with help and guidance as required.

It is important to note that the intention of the energy detector is to provide an *indication* of wind or light, rather than an accurate measurement of it. Furthermore, the values indicated on the energy display do not represent formal electrical measurements because the intended age range of the user was 6–13, and as such were unlikely to relate with the terms *voltage* and *current*.

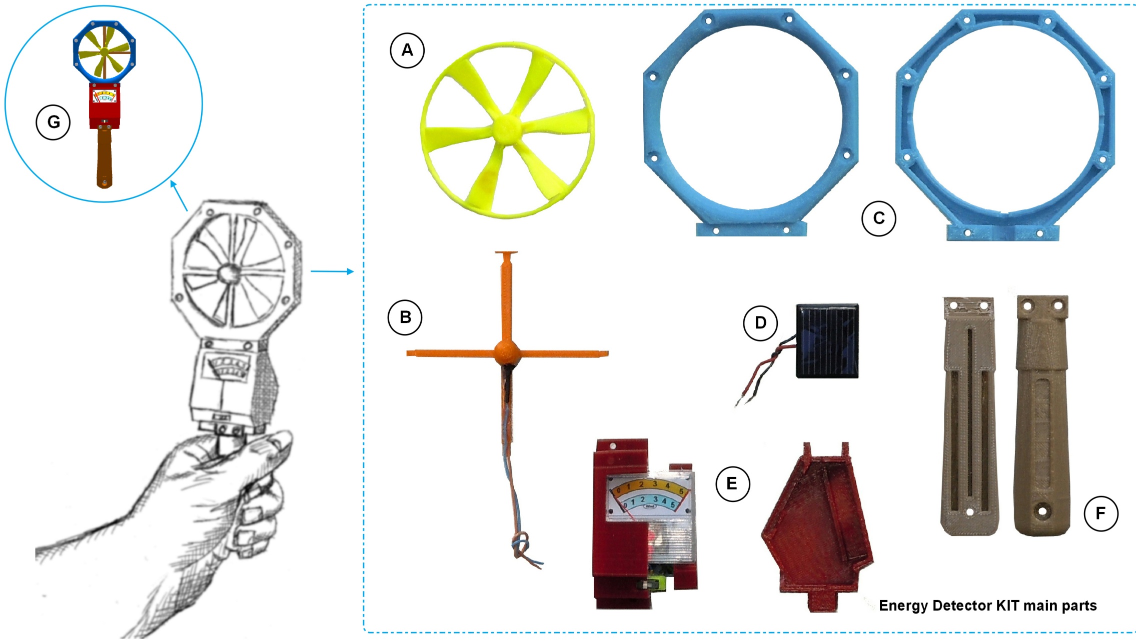


Fig. 4: Solar and wind detector constructed with the children during the second workshop.

Figure 4 shows a breakdown of the kit of parts provided to construct the energy detectors. As the energy detector was intended for outdoor use, an important consideration was the construction material, and whether those materials could withstand the wind and potentially wet weather found on Tiree. As such, the body of the energy detector was made from printable ABS plastic, and was also created using 3D printing techniques to facilitate its rapid development. In addition to the durability afforded by the plastic, it also provided an aesthetic that was hoped would appeal to younger age groups.

To measure sunlight, a small solar panel (Figure 4: item D) was fitted to the back of the device, which when exposed to light, generated a small voltage. This electric charge was used to move the needle on a simple low voltage meter (4: item E) taken from an off-the-shelf 1.5 volt battery tester—this meter was also enclosed in the plastic housing. For the measurement of wind, a type of propeller (4: item A) was attached to a small electric motor (4: item B), which when driven, acted as a dynamo and generated a very low voltage; the resulting voltage is displayed on the meter. To choose between the measurement of wind or solar energy, a small slide switch was placed under the display to select between each mode. Both the motor and solar panel were sourced from an off-the-shelf toy.

Since their deployment, the energy detectors have been used as part of activities arranged with the local school to map potential locations of power generation on the island. This sustained engagement with the young of Tiree has been important in continued participation from the community.

VI. Emerging Themes

Learning by example and through physical activities plays an important role in the learning cycle [28]. The warm-up task and PPP game were thus important in helping the participants cultivate an understanding of the problem domain, and to exercise them in thinking about different energy scenarios. The participants were encouraged to discuss their thoughts regarding the utilisation of varying energy supply, and sketch and annotate their ideas on a number of supplied worksheets, sticky notes, and other stationary. In addition, fieldnotes and photographs were collected to provide further material for post-workshop analysis. From this data, it was hoped that ideas for better utilising and adjusting to available renewable energy in the Tiree context might be suggested by the participants, as well as revealing the underlying themes that drive them.

Table I depicts a subset of the ideas and sketches produced by the participants during the generative task in the adult workshop. A number of themes have emerged from the data that suggest that the participants were interested in mechanisms and processes related to the storage, forecasting, and prediction of energy. Furthermore, an undertone of *community* was apparent, with worksheets containing some reference to *community*, and *big*; this was often the case when describing storage and synchronisation with the community and the energy supply.

It is perhaps worth stating, that our picture of the island and our insight into their perception of energy isn't formed purely from the workshop sessions, but is rather a function of all the engagement opportunities we have pursued with the community, including interviews and informal ethnographic observations. It is the intention of the authors to use these themes and ideas, as well as our understanding of the island context, to further develop the dialogue, participation and collaboration with all our participants in our future work.

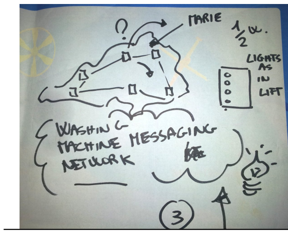
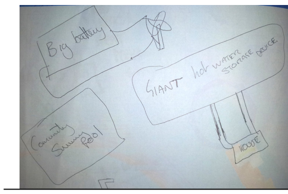
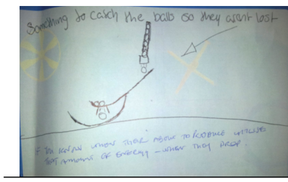
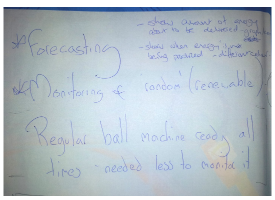
Workshop Artefact	Notes
	A common theme observed in the sketches is that of *community*, or *synchronisation*, and the sharing energy as a community resource. Furthermore, there is evidence to suggest that a visual indicator (i.e. lights) might be a method to communicate energy availability.
	Storage was presented as a possible means to better utilise abundant available energy; this is certainly hinted at with the illustration of *big* and *community* battery/storage mechanisms. The theme of *community* emerged repeatedly throughout the generated materials.
	Different mechanisms to mitigate the waste of balls (energy) by slowing their decent were often sketched. These bear a strong similarity to storage, as it infers that energy use is being deferred until a later date. This is indicated with the term *catch* used in the description.
	Forecasting and monitoring the release of energy/balls was evident within the workshop, which demonstrated a desire to understand the potential amount of energy available. Moreover, ways to signal and communicate the availability of energy through *light* and *sound* were hinted at.

TABLE I: Example themes extracted from adult workshop session.

VII. Reflections and Implications

Reflecting on the themes and insights emerging from our dialogues with the islanders, reinforced by concepts emerging during the workshops and in follow up discussions, we see the following areas, which may to at least some extent benefit from new ICT designs. As is common with sustainable ICT, many of the proposals and directions we might explore take us also toward wider reshaping of infrastructures and practices [8]:

A. Communicating energy availability

Not surprisingly, there is considerable ‘buy in’ to renewables on the island. Pragmatically, as long as feed in tariffs exist, wind and solar power is extremely cost effective, not only can it pay for itself and reduce energy costs (recall many households are entirely powered by electricity, including domestic heating), but it can also lead to revenue streams for the islanders. Despite this, the complex energy situation on the island is not easy to appreciate, and it is fair to say that most do not have a solid grasp of how Tilley’s energy is used, nor when she is producing energy (and thus revenue) for the islanders. There is a clear role for technology mediated communication in presenting and representing the flow of energy on the island to help build further connections with Tilley.

B. Synchronising with supply

Emerging from our interviews, as supported in the literature [9], is some evidence that already some within the community may already subscribe to the notion of *on supply*, as an interview respondent noted:

> She “*looked outside at her turbine before deciding whether to put on the bathroom heater*”, and would “*choose to put the washing on when it was windy*”.

Our challenge is to help develop technology to help foster the same connection to community generation as we can already find at this micro-scale.

However, as an aside we would also note that renewables are not straightforward here. Whereas on the mainland neighbourhood concerns and attitudes to renewables are often a barrier to planning, on the island it is rather the sites of special scientific interest and concerns over preserving the wild areas and migration patterns of wildlife, that constrain. It is also clear that for many the capital cost of the equipment is a major barrier in itself, rendering renewables very much as a preserve of those with means (e.g. downsizing to the island, or with businesses). The strong and gusty winds on the island are also a challenge—small turbines that would be fine on the mainland, are often simply ripped apart by the gusts of wind—so larger and consequently more expensive (e.g. 15kW+ turbines) are needed.

C. Managing time-varying load

It is also interesting to note how the need to be self-sufficient has led to a dependency on fossil fuels to underpin sustainable generation, both at a micro and a macro level. Despite the best sustainable intentions, an otherwise sustainable croft has small diesel backup generators to prop up supply—it’s a rugged island and at the end of the day, one needs to keep warm. The community turbine (Tilley) itself, cannot function without the ballast of the national Grid—suggesting that new ways of managing the time-varying load of renewables must be found at varying infrastructural scales. There is a clear need for innovative solutions to help manage load and smooth supply, to encourage independence and reduce the fragility of energy supply on the island.

D. Supporting community resilience

From the workshops especially, some powerful expressions of community and metaphors for community sharing of energy were expressed. The community worked together as a team, ensuring that surplus energy they captured was distributed around to those with the need. It was interesting to note that less energy got wasted (less ‘balls in the bucket’, so to speak) as a result of the community minded actions of the group. Partly, of course, we are witnessing gameplay and optimisation of strategy to match the outcomes of the game, but also we suspect there is something deeper. As one interviewee told us:

> “*it is pretty common for the electricity to go off on the island[. . .]We just light the candles*”

This is a community that is already close, has already worked together to create energy generation (Tilley) for the benefit of the community. We believe that designing to further support and encourage community resilience and adaptability is an interesting design space.

VIII. Design Framework

Resulting from our dialogue and findings so far, are new opportunities for the design of energy systems (represented graphically in Figure 5), both at a household appliance level, and in the broader energy eco-system and community infrastructure of the island. Rather than consuming energy on demand, we might try to think of alternative energy strategies 'reconstruct[ed] around principles of interrupted rather than continuous supply' [29, p. 142], actively exploiting the time-varying nature of renewable energy in new ways for community gain. Whereas variation is normally expressed as a consideration of demand, and something to be levelled and met with more energy supply, we might attempt the converse: to synchronise everyday life with supply.

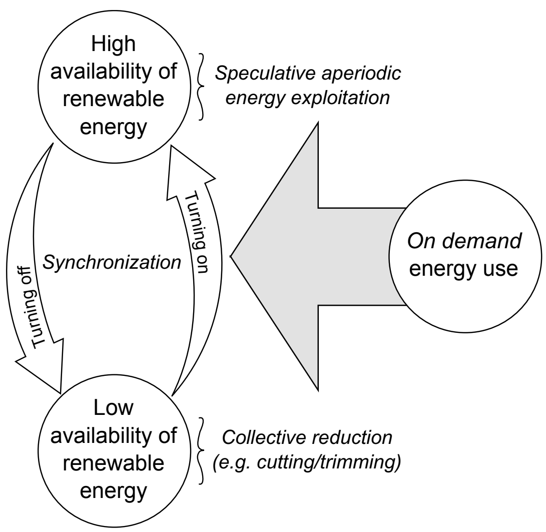


Fig. 5: OnSupply framework—exploiting and reacting to changes in energy supply.

A. Opportunistic Exploitation

As with one of our participants' own wind energy, and Pierce and Paulos suggest [10], during times of high levels of renewable energy and low demand we might consider *opportunistic* and perhaps *optional* uses of the energy that is available at low cost (or even zero cost, depending on whether the energy can be consumed directly). Ideas resulting from the workshop naturally include the prosaic (such as storing the energy in a battery for later use—a strategy often employed with renewables, as on Eigg [11]); but also, delightfully, include ideas that would benefit the community *at a community scale*, such as:

1) Heating volumes of water (such as a swimming pool)—water has a high specific heat capacity, and akin to a storage heater, can be used to store excess heat. A nice side effect of this is that it reduces the cost of running a community swimming pool (or may indeed be the only heat source). Such systems have already been employed to exploit waste heat from data centre cooling[2];
2) Providing heat to a small spa or medical complex, particularly for the elderly—there is considerable experience with storage heaters on the island already (recall, that heating is provided by electricity in many premises). Storage and underfloor electric heating could provide warm facilities for elder care (such as a care home), or be used to heat therapeutic and spa facilities;
3) Heating greenhouses to stimulate the growth of local produce (and hence a new island industry). Geothermal energy is used in Iceland to enable the growth of fresh vegetables in heated greenhouses; a similar principle could be employed on Tiree to boost crop growth. Note that Tiree should be very well suited to agriculture of this kind, since it was considered something of a breadbasket for nearby monasteries in the middle ages due to an impressive sun record: it was said to yield two crops per year.

B. Collaborative Load Management

However, our findings also suggest a further set of design options when renewable supply is low to reduce demand, *mediated by ICT*. Naturally, we might exploit the existing infrastructure to help smooth supply and demand. Well insulated appliances can potentially survive for considerable periods without energy, especially if already at operating temperatures—to use Pierce et al.'s terminology [30], *cutting* or *shifting* energy use to another time. So differentially powering home infrastructure or 'supply aware' appliances could be designed explicitly to exploit time-varying rather than continuous energy supplies.

But such strategies, while however compelling, do nothing to challenge our assumptions and reliance on continuous supply. We need to recognise that, as Trentmann puts it, we're all 'hostages to electricity' [31, p. 13] and consider how to instigate broader, less energy intensive reconfigurations of everyday life. As is already true on Tiree, the electricity infrastructure is more fragile than it might appear, and bringing the infrastructure's fragility into focus can be 'a vital source of variation, improvisation and innovation' [32, p. 6].

The citizens of Tiree are adaptable and innovative, and already highly sensitised to the weather in prosecuting their daily lives. It's possible that by developing technologies that help them reflect, predict and plan for the future availability of energy, that lower demand practices can be developed, or even old ones revived (c.f. [33]).

IX. Conclusions and Future Work

We believe that in the near future, irrespective of whether the driver is cost, carbon or climate change, the energy mix will incorporate more renewable sources—bringing a new focus on variability in the supply of energy. In this paper,

[2]For example, a data centre in Uitikon, Switzerland warms a community pool using a heat exchanger from 2,800MWh of waste heat.

we have reported on the experiences of living and working in an approximation of this new energy context on the edge of supply, with the islanders of Tiree. Using a series of technology mediated interactions to build trust, and explicate ideas, we have developed an understanding of the energy context and barriers to sustainability of supply. We have also highlighted new community scale design opportunities, and offer a simple design framework around this that focuses on i) speculative (community) uses of bonus low cost renewable energy, and ii) collective reduction (community load shedding/ time shifting/ encouraging the development of or restoring low impact practices).

In our future work we plan to continue the dialogue based on our most recent prototypes (including our 'energy detectors', Figure 4) to start communicating the potential for future renewables and continue to develop prototypes to explore the link to Tilley and her predicted output, to help islanders plan their lives around her energy availability. We are encouraged by the engagement from the community so far and are doing what we can to help model the feasibility of some of the proposed ideas and infrastructural changes that have emerged, to help identify whether any are practically and financially viable.

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