Futures 49 (2013) 35–48

Contents lists available at SciVerse ScienceDirect

Futures

journal homepage: www.elsevier.com/locate/futures

Single infrastructure utility provision to households: Technological feasibility study

Ferhat Karaca [a,g], Paul Graham Raven [b], John Machell [b], Liz Varga [c], Fatih Camci [a,h,*], Ruzanna Chitchyan [d], Joby Boxall [b], Bogumil Ulanicki [e], Piotr Skworcow [e], Anna Strzelecka [e], Leticia Ozawa-Meida [f], Tomasz Janus [e]

[a] IVHM Centre, Cranfield University, Bedford, UK
[b] Pennine Water Group, University of Sheffield, Sheffield, UK
[c] Complex Systems Research Centre, Cranfield University, Bedford, UK
[d] Department of Computer Science, University of Leicester, UK
[e] Water Software Systems Group, De Montfort University, Leicester, UK
[f] Institute of Energy and Sustainable Development, De Montfort University, Leicester, UK
[g] Department of Civil Engineering, Fatih University, Istanbul, Turkey
[h] Department of Industrial Engineering, Antalya International University, Antalya, Turkey

ARTICLE INFO

Article history:
Available online 1 April 2013

Keywords:
Utilities
Service provision
Future infrastructure
Household infrastructure
Emerging technologies

ABSTRACT

This paper contemplates the future of utility infrastructure, and considers whether an "All-in-One" approach could supply all necessary utility services to tomorrow's households.

The intention is not to propose infrastructure solutions that are currently technically feasible or justifiable, however; the objective is to present visions of future infrastructure that would only be possible with new advances in science and technology, or significant improvements and adaptations of existing knowledge and techniques.

The All-in-One vision is explored using several vignettes, each of which envisions a novel, multi-functional infrastructure for serving future communities. The vignettes were conceived using imaginative exercises and brain-storming activities; each was then rooted in technological and scientific feasibility, as informed by extensive literature searches and the input of domain leaders. The vignettes tell their own stories, and we identify the challenges that would need to be overcome to make these visions into reality.

The main aim of this work is to encourage radical approaches to thinking about future infrastructure provision, with a focus on rationalisation, efficiency, sustainability and resilience in preparation for the challenging times ahead. The All-in-One concept introduces the possibility of a unified and singular system for infrastructure service provision; this work seeks to explore the possibility space opened thereby.

1. Introduction

The provision of utility products and/or services is necessary to satisfy fundamental human needs [1], such as water to drink, environmental temperature control, lighting, personal hygiene, cooking and safety in the home. Utility provision also enables access to luxury services which fulfil those needs which exist above and beyond the fundamental necessities:

* Corresponding author at: IVHM Centre, Cranfield University, Bedford, UK. Tel.: +44 1234 750111; fax: +44 1234 758331x5766.
E-mail addresses: f.camci@cranfield.ac.uk, fatih.camci@antalya.edu.tr (F. Camci).

0016-3287/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.futures.2013.03.003

electricity, for example, allows the operation of a multitude of devices to heat water, cook food, enable communication and social interaction, and facilitate mobility (e.g. via battery-operated cars or wheelchairs). Hence these services – and the infrastructures that deliver them – are vital for supporting everyday household activities, and sustaining (or improving) quality of life.

There is a wealth of evidence for the poor state of national infrastructures; including those of developed and developing counties. For instance, Houlihan points out that most of the infrastructure across Europe built in the nineteenth century has now reached the stage where replacement rather than refurbishment is the only economically viable solution [2]. Improved and more reliable solutions [3] alongside forward-looking planning processes [4] are crucial to the success of future infrastructure systems. This is particularly factual in developing and emerging countries and regions where resources are scarce and infrastructure needs are huge.

Household utility provision has a particular importance for the comfort of individuals and family life. Current provision includes water, electricity, gas, information, and waste and sewage removal; each of these services, which are at the very heart of economic and social wellbeing, is provided via separate and antiquated infrastructures of great complexity. Management and maintenance of these disparate infrastructures requires huge capital and operational expenditure, often resulting in redundant investment, and causing mutual interference when elements of systems are in close proximity to one another [3]. Moreover, threats posed by climate change, land and soil erosion, deforestation, and water scarcity have forced actors in the built environment to progressively consider more sustainable solutions for infrastructure projects [5–7]. Advancements in science and technology suggest that some existing infrastructure systems may become redundant in the near future [8–10]; meanwhile, most utility companies are still considering reducing their infrastructural investments, and improving the efficiency of existing systems by merging provision. The majority of work in this area uses the word ''merge'' in terms of melding different utility companies, with their information systems and/or work groups, into a single division [11,12]; but the literal physical merging of infrastructural systems, however, remains an unexplored territory, the mapping of which demands visionary thinking.

This paper presents a radically novel perspective by considering the possibility of delivering all household utility services via a single utility product or infrastructure, hereafter referred to as the ''All-in-One''. We imagine singular and novel utility infrastructures for service provision 100 years in the future, any of which could replace the extant multiple systems. The aim of the work is to explore the possibility of such provision, and identify the science and technology challenges that would need to be addressed to realise the vision; these challenges will then become the focus of research and development towards facilitating a transition to a utility infrastructure designed with the resilience and efficiency the future demands.

2. Methodology

The true shape of the future is, of course, effectively unknowable; societal and ecological systems are extremely complex and high-order, and their myriad interactions and interdependencies nigh impossible to model with any degree of reliability. Scenario planning inspires strategic thinking, and is a common methodology used in the field of Futures Studies to transcend thinking limitations through the envisioning of predicted or preferred futures [13–15]. The usual approaches for creating scenarios are a blend of particular features of the qualitative, quantitative and participator methods [16]; are based on the opinions of experts or the objective data; and can be normative [17] or extrapolative [18].

In this paper we adapt the objective-focused technique to investigate a set of possible future infrastructures based on the All-in-One concept. Free-thinking and imagination were channelled to envision very different future infrastructure options, which were then expanded and described in ''vignettes'' [19]. The vignettes are fundamentally participatory, based on qualitative data, and follow normative narratives which aim to fix the desired future by identifying the necessary processes and mechanisms in emerging technological landscapes. They capture snapshots of different possibilities in our world as it may be in a hundred years hence, and illustrate the evolution from the existent multiple and disparate infrastructures to a single future ''All-in-One'' system, and the transformations and changes required in order to realise each vision.

2.1. The vignette building process

Our methodology adopts the framing, scanning, and visioning stages of a strategic foresight exercise as detailed in [20], combined with scenario building (Fig. 1).

To inform our vignettes, we first undertook a requirements analysis: a review of household environments intended to identify ''needs''.[1] We then considered various alternative ways of satisfying these needs. A comprehensive literature review and detailed science and technology search was carried out, and we engaged the input of external domain-specific experts using these sources. A list of current, emerging, and predicted technologies that could enable each vignette was generated. The collection of data pertaining to technologies of interest followed in two stages.

[1] Details are available on an online published document: http://allinone.uk.net/wp-content/uploads/2012/07/Definition_of_primary_and_secondary_needs_and_Requirement_Analysis.pdf.

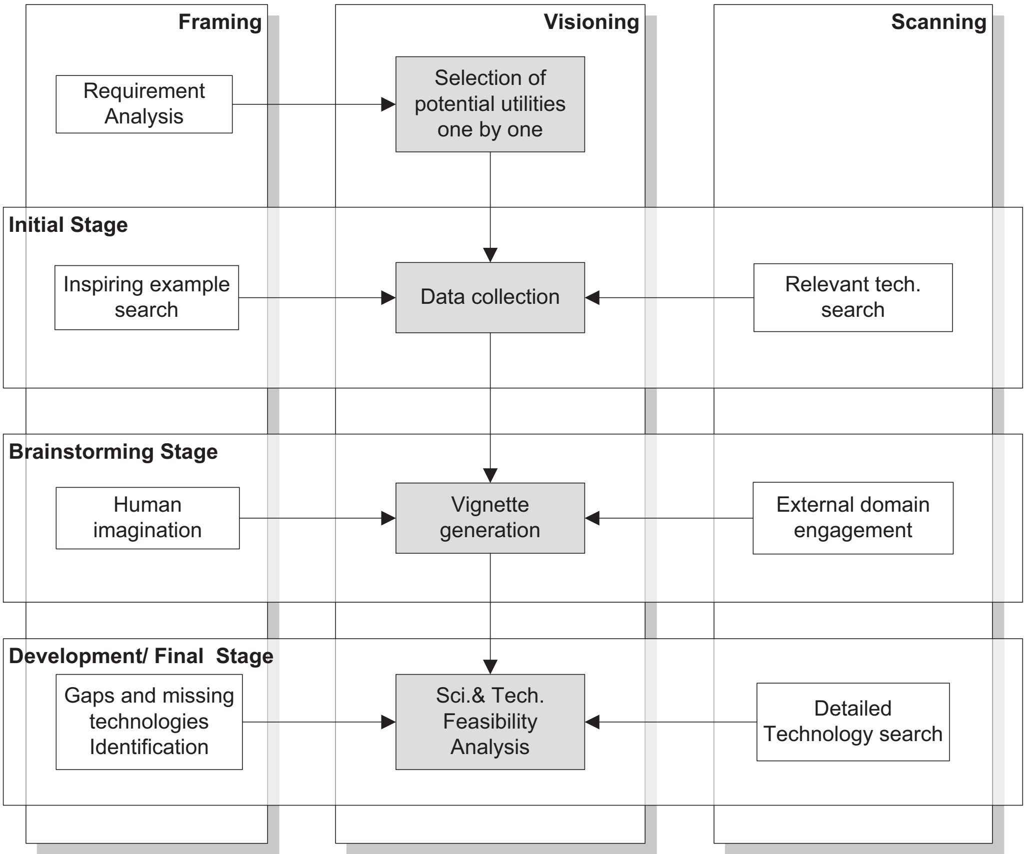

Fig. 1. All-in-One vignette construction methodology.

Firstly, identifiable emerging technologies with the potential for utility transformation were listed; more than 100 "generic technology titles" were stored in the project wiki[2] (http://allinone.uk.net/), and made freely accessible to any interested party. These technological details were used to root the vignettes in plausible and realisable science and technology. Secondly, potential alternative provision methods from the generic titles were investigated in greater detail.

The "inspiring example" was another important framing activity [21]; any technology or system that could, of itself, act as a lynch-pin for multiple utility provision was explored in detail. Using the generic technologies and inspiring examples as raw material, the vignettes were imagined into being.

Views were exchanged and insights developed at a scenario workshop, which was organised to engage the input of external domain-specific experts[3] and stakeholder representatives. Furthermore, the vignettes were presented in several venues (e.g. workshops, conferences, symposia and meetings), and further feedback solicited from within and without the project team. The resulting vignettes were highly creative, capturing the big picture; leaps of potentially holistic connectivity were made, which encouraged engagement; regrettably, however, these outputs were not easily comparable. In the final stage, we identified the gaps and missing, yet-to-be-invented technologies inherent to each vignette; the blank spots on the roadmaps, if you will.

3. The "All-in-One" vignettes

The necessary utility service inputs to a household can be reduced to water, energy, communication and transportation. All other requirements can be derived from these inputs by using devices or machines which transform or combine them. For instance, food can be grown using water and energy, while heating or cooling can be performed by energy supplied in solar, electric, or gas forms. The vignettes are discussed in the following sub-sections, wherein we (i) give a full account of our

[2] The wiki also allows anyone who applies for a user account to enter information about a technology and its capacity to produce or use utility products and services. Moreover, such contributions are strongly encouraged by the All-in-One project team.

[3] See the details about the "2111 Utility Service Provision Imagination Workshop" on http://allinone.uk.net/events/2111-utility-service-provision-imagination-workshop/.

assumptions about the nature of the knowledge being produced and the reasoning behind specific choices of technological or metaphorical approaches, (ii) describe the core visions, (iii) address the technological challenges, and (iv) identify the dominant challenges, and what must be done to resolve them.

The vignettes are intended to encourage people to question the need for multiple infrastructure systems, and to dare to think radically about the future of utility service provision. The radicalisation and reduction of infrastructure is a desirable outcome, but a variety of issues inhere in each possible future, even when only considering scientific and technological feasibility; as such, special attention was paid to the technological feasibility of the vignettes.

Each vignette was developed independently, and service delivery is discussed in non-quantified terms.[4] Provision systems which take water, beamed solar energy and transportation as their central resource or service were considered, as well as the possibility of fully decentralised infrastructure designed for subterranean or subaquatic habitations.

3.1. Vignette 1 – ''The Blood of the City''

Our first vignette takes its inspiration from the human body and other biological systems (e.g. trees and plants), and uses a water delivery infrastructure as ''the one''.

3.1.1. Assumptions and reasoning

The cell is the basic structural unit of biological entities, and its needs are supplied by capillaries and blood vessels; a house is the basic functional unit of the urban body, and its needs are supplied by infrastructure networks. Both cells and houses consume energy and water, and generate waste by-products which must be removed. This connection has etymological roots: the word 'cell' is derived from the Latin *cellula*, meaning ''a small room or house''. The human circulatory system can be seen as the irreplaceable natural infrastructure which provides the resources and services required by the cell. Similarly, a city has a number of different utility infrastructures which satisfy the requirements of the household. These similarities suggested the human circulatory system as an analogy for the utility infrastructure system of a future city.

This vignette proposes that water and energy could both be supplied to houses in a single pipeline, much as the human bloodstream delivers water and energy to cells, and that it should be possible to derive household energy from water much as plants do through photosynthesis. Confidence in this idea is based upon the ubiquity of the biological circulation system it resembles; a solution that has evolved over millions of years, and which perfectly performs multiple functions. Furthermore, existing water infrastructure could be modified to suit, negating the need to build from scratch, which is a principle barrier to all infrastructure projects for cost and logistical reasons.

3.1.2. Technological perspectives

Key infrastructure components in the city blood system can be categorised into (i) city level, (ii) community level, and (iii) household level plants, units and devices. Hydrogen enriched water can be pumped using similar technology to that currently in use.

Studies concerning the future of water supply solutions and technologies are plentiful [22,23] for existing supply models. However, this scenario requires that new processes be integrated, including hydrogen generation plants, hydrogen charge/recharge plants (to convert or sorb hydrogen into/onto a carrier material), and water/hydrogen enrichment and collection plants; these systems would be best folded into the existing plant facilities for water treatment and mains pumping. This would be similar to the set-up suggested by studies proposing a future hydrogen economy [24–26], with the only significant difference being the delivery of hydrogen carriers in water. The technological possibility of (and hurdles to) such a system are detailed in a parallel study [27].

Household level devices will separate the energy from the water. This separation process, much like that performed by the membranes of a cell, will extract the energy carrier from the water. New developments in biomimetic membrane technology [28] offer high throughputs with low energy consumption, but there are other mechanisms available, albeit more energy-hungry; these include reverse osmosis, forward osmosis, membrane distillation and electro-dialysis. Energy generation from hydrogen carriers is a very popular subject at time of writing, and there are dozens of technology alternatives which are highly efficient, environmentally friendly, resilient and safe [24–26].

3.1.3. Challenges/opportunities

The central challenge is the invention of a suitable energy carrier – perhaps some sort of hydrogen carrier in solution which is able to stay inert under water pipeline operational conditions while retaining its hydrogen content [27]. The energy carrier would be separated from the water in the home, and the extracted hydrogen would then be deployed in fuel cells, or stored in a way that allows it to be used by household devices, for example, for cooking, heating or lighting. A way to transport energy within the water without resorting to a secondary carrier has yet to be invented.

[4] An important part of future utilities provision is a benchmarking study for estimating future demand. To undertake this, we have begun collecting data on the storage and throughput capacity of all technologies/devices required for realisation of the vignettes. However, this is work in progress, and not detailed in this paper.

The human circulatory system also removes waste materials from the cells. At this stage it was decided to deal with waste within the household by composting, using small-scale waste water or bio-plants; mixing waste material into the ‘‘blood’’ would present sanitation, maintenance and separation challenges. However, the human body manages this extremely well. The greater challenge, then, is to create a similar multifunctional utility infrastructure, perhaps using multiple membranes or other technologies, which would be capable of delivering water and energy, whilst simultaneously removing and sequestering waste materials.

3.2. Vignette 2 – ‘‘The Intertubes’’

Our second vignette takes a less literal approach to the ‘‘All-in-One’’ question in that, rather than attempting to meet all needs by derivation from a single utility product, it simply draws together current provision methods into a unified, resilient, easily maintained and easily expanded meta-system.

3.2.1. Assumptions and reasoning

This vignette turns one of the biggest hurdles to infrastructure rationalisation – the irreducible requirement for physical transportation, be it of food and goods, utility products and services, waste and recyclables or even people – on its head, making it the central focus of the question. It starts from the assumption that an efficient and ubiquitous goods transportation network is a prerequisite for a modern developed economy, and that the construction of such might permit a large-scale improvement, expansion or rationalisation of other utility network infrastructures to occur in parallel.

‘‘The Intertubes’’ draws heavily for initial inspiration upon the ‘‘Foodtubes’’ proposal [29] for a lightweight, underground, rapid pipeline-capsule food and freight transport system, with large loops of underground tunnels carrying a variety of specialist capsule types. The network would be constructed using ‘‘trenchless’’ tunnelling methods,[5] and would have terminals at ‘‘supermarkets, shopping malls and markets, colleges, schools, large offices & institutions and at waste recycling depots’’; the rhetorical thrust of the proposal is a sizeable reduction of goods vehicle traffic on UK roads, especially in urban areas, with a concomitant reduction in pollutant and GHG emissions, and energy consumption.

3.2.2. Technological perspectives

This vignette develops the Foodtubes idea in two novel ways. Firstly, it exchanges the ring-network topology of Foodtubes for a rhizomatic, non-hierarchical network topology, with traffic management handled by computer in a similar manner to the ‘‘packet-switching’’ protocols that underpin the Internet. Such protocols respond effectively to short-term fluctuations in traffic load, making most efficient use of the system capacity available. They also allow for swift re-routing around damaged connections in the network, making for resilience through effective (re)deployment of redundant capacity.

Secondly, this vignette adopts a ‘‘single-duct’’ approach to infrastructural development and capacity expansion. During the construction of the tunnel system, auxiliary pipes and ducts could be run alongside the main Intertubes ducts, far more cheaply than running new ducts in separate projects. This means the routing of high capacity electricity and telecommunications cables (e.g. HVDC cabling for the former, and high-cap optical fibre for the latter) would spread across the areas served by the transportation network, increasing the resilience of provision of these services as well as ensuring said networks can be easily maintained (e.g. by robots or drones that travel the Intertubes tunnels).

3.2.3. Challenges/opportunities

There is no reason that the system could not incorporate two different sorts of tunnel – small-gauge high-speed for goods, larger-gauge lower-speed for human transit – on major interurban trunk routes, with network growth and capacity expansion being driven by demand in an organic fashion; this would expand the human mass transit capabilities of the system in such a way that it could gradually replace less efficient intra- and interurban human transit. However, significant work would be required in order to refactor the system for human comfort; cargo may break, but it does not write letters to the management.

In this vignette, the dominant hurdles to realisation are socio-political and economic in nature; for a start, the lobbying power of not only the fossil fuel sector but the haulage industry – which already has a powerful if underestimated position in UK domestic politics – would be a significant barrier to getting such a system past the proposal phase. The comparative invisibility of an underground system should minimise NIMBY objections, and indeed the concomitant reduction in urban traffic may provide a counter-lever of opinion against the aforementioned vested interests, but the difficulty of overcoming the ingrained sense of entitlement around personal vehicle ownership in the West cannot be overstated, no matter how appealing the benefits of a sea-change may be. Nonetheless, the core technologies required to make the Intertubes a reality are already existent and in use; all that remains is to scrape together the political will, and combine them.

[5] Trenchless tunnelling methods – such as Horizontal Directional Drilling (HDD), Pipe Ramming, Moling and Horizontal Auger Boring – are a growing sector of the contemporary construction industry; their appeal lies in the facility to lay pipes, ducts and tunnels with minimal disruption to the surface above.

3.3. Vignette 3 – "The Solar Globe"

Our third vignette turns its attention to the most abundant energy source available on the planet: sunlight. With sufficient affordable and non-polluting energy available, the provision of other products and services can be decentralised to whichever level at which they scale best.

3.3.1. Assumptions and reasoning

Of the available energy resources, solar is the most abundant by far. The sun generates 23,000 TWyr yr^{-1}; over 200 times more than all our other resources combined [30]. It is also freely available and, although non-renewable, will last for around 5 billion years! Solar radiation can be used to generate electricity, heat, and water and to enable communications, through the deployment of a variety of currently available technologies at personal, local, industrial, community, regional and potentially even national level; thus it is very flexible, scalable and universally available. Less than 1 h solar radiation at Earth's surface could satisfy global energy demand for more than a year – if it could all be harnessed. To circumvent availability issues due to planetary weather conditions, terrestrial solar radiation could be supplemented with solar radiation collected on the moon and distributed to the Earth's surface via coherent beaming technologies.

3.3.2. Technological perspectives

In "The Solar Globe", individual homes, industries, agriculture and entire cities are powered by cheap, efficient, non-polluting solar power. Solar-powered technologies will produce drinking water, enable global communications and transportation, and power numerous personal, household and community-level devices.

In locations that enjoy abundant sunshine, terrestrial solar radiation will be captured and converted into electricity at local, community and national level, so as to minimise demand on extant national infrastructure. Existing power stations will be complemented by solar power stations to reduce the need for fossil and nuclear fuels. Where solar radiation is not so abundant (and to overcome atmospheric pollution problems such as volcanic ash, or to circumvent the remoteness of a consumer location), blue-sky research advocates building a ring of photovoltaic panels around the equator of the moon in order to capture lunar solar radiation [31]. Terrestrial buildings of all types will be constructed from (or retrofitted with) suitable collector materials [32,33], thereby gathering terrestrial and lunar-beamed solar radiation. Lunar-generated energy will be transferred to terrestrial collectors using microwave and laser technologies, and/or satellites [31,34,35]. Microwaves and laser beams can travel through rain clouds, dust and smoke, and can be beamed at targets as diverse as mini-receivers on individual homes, larger collectors for communities, and especially giant collectors at dedicated solar power stations.

Where it is required to distribute the collected energy, existing electricity infrastructure will be employed. Eventually, however, existing infrastructures will evolve into smart, high-temperature superconducting DC grids [36,37], supported by smart, large-scale superconducting magnetic storage [38] to mitigate peak demands and smooth provision. The scale of these grids, however, will be minimised due to increased local, community and national-level generation, and the possibility of varying power transmission from the moon. A myriad of solar devices – from phone chargers to hot water systems – will further reduce energy demand from the extant main infrastructure.

3.3.3. Challenges/opportunities

Criswell [40] presented a comprehensive case for a lunar solar power system [39] while highlighting many of the significant challenges. This work was built upon when Criswell undertook a review of the technology base for an operational lunar-based system [40]. The Shimizu Corporation suggests that much of such a base could be manufactured in situ using robots [31]. The majority of raw materials required are present in the lunar regolith; this would negate the need to transport huge quantities of equipment and materials from earth to the moon. An abundant, easily extracted source of ^3He on the surface of the moon which could be used in D-^3He fusion reactors [41] (terrestrial or lunar-based), thus generating potential extra benefit. It seems most of the challenges for lunar-based solar power can be overcome, and the potential benefits to humanity would be immeasurable. Those challenges are still significant, however, requiring significant advances in robotics, manufacturing, aerospace, laser/microwave, remote control, and energy collection storage and transmission technologies – to name but a few.

Enabling "The Solar Globe" would spawn new technologies, industries and employment opportunities. Global pollution would decrease, and standards of living will improve as the ubiquity of clean power "anywhere" overcomes geographically imposed restrictions which currently cause industrial limitations and public health problems. Transport would be rationalised; non-perishable and heavy goods would be moved round the globe by solar-powered shipping and trains, while lighter perishable goods will be moved using solar aircraft. Most perishables will be produced closer to points of consumption to reduce transport requirements and cost. More local haulage will take place via enhanced river and canal systems using solar barges and electric vehicles will transfer goods to consumer outlets and enable people to travel. Drinking water production will be augmented using solar dehumidification, distillation and desalination processes, and rainwater harvesting will support water provision for other uses. Communication, information and entertainment provision will continue to evolve, and be distributed through a growing selection of universally rechargeable consumer devices.

3.4. Vignette 4 – "Subterrania"

This vignette is set in 2111 after the worst-case global warming scenario has come to pass; average global temperatures have risen by 13 °C and sea levels have risen by 11 m [41], and the equatorial regions of the globe are uninhabitable. The more temperate regions, reduced in area due to sea-level rise, are much hotter than at present, and suffer highly unpredictable swings in weather patterns; populations have hence migrated towards the remaining habitable land. The only option for the majority is to live underground, underwater or upon the surface of the water in enclosed capsules – although some communities could cling on to the surface in currently uninhabited areas such as Greenland, Siberia and Antarctica. The main technological issue for these underground and underwater communities will be lack of solar energy and natural light.

3.4.1. Assumptions and reasoning

Heating, ventilation and air conditioning (HVAC) systems have developed since the industrial revolution into a worldwide industry providing thermal comfort and indoor air quality for small to large enclosed areas. HVAC systems are integrated with the environment for the input of fresh air and the expulsion of waste. HVAC systems for modular under water or under-ground dwellings would need further integration, creating a network of resilient inter-connected systems; it is further proposed that these systems become the carriers of power and water (in uncondensed form). Electricity would be transmitted continuously over these systems, and then picked up 'wirelessly' and consumed by devices which transform the electricity into lighting or power. Water would be condensed for drinking and essential uses only; substitutes for other uses of water such as laundry and personal hygiene would be required. Reservoirs of rain water or desalinated sea water could be created for community use. The benefit of the proposal would be the transformation of indoor HVAC systems into sustainable multi-purpose life-sustaining systems.

3.4.2. Technological perspectives

"Subterrania" is not such a fanciful idea as it may initially appear; there are already examples of underground communities and plans for underwater installations, such as the tunnels of London, the Cheyenne Mountain Complex [42], Coober Pedy in South Africa [43], the 'Earthscraper' in Mexico City [44] and the underwater hotel in Dubai [45]. An example of modular housing upon the water is the green float complex [46].

In this vignette, communities would be nearly self-sufficient. They would need to import some raw materials (metals and wood), some specialised manufactured goods, and tools where local manufacture is not practical or economic. Provision of electricity would be supported by wind farms or photovoltaic cells on exposed surfaces. Communities could join together into cities and nations, and into global networks for trade and communication. The underground and underwater pathways will be used by battery electric vehicles for the transfer of goods and services wherever practicable, so as to minimise the need for surface transport.

Within each community, HVAC would be provided centrally. Natural sunlight would be 'piped' throughout the community to ensure human health, supplemented as necessary by wireless-powered broad-spectrum florescent lighting. A centrally managed environment of air, power and water would limit the need for supplying utilities to individual households. Each household or 'cell' would be connected to grey water and organic waste disposal systems; organic waste will be macerated in each household and piped to a central duct network in which waste falls by gravity to the base of the community, where it is collected for re-use or recycling.

3.4.3. Challenges/opportunities

One key success factor for the "Subterrania" vignette is the design of the multi-functional utility pathways. Transportation of breathable air from which power and potable water can be extracted is a major challenge, and resilience and maintenance would become critical issues. Pathways between cells and between communities would require the design of modular integration protocols for inputs and outputs of resources. These pathways would need to be robust against accidental damage, earth tremors, weather effects (including high temperatures) and other hazards, perhaps due to the use of technologies such as ultra-high performance concrete (UHPC) [47]. These pathways would need to be carefully mapped during the design phase of each community, and the risks assessed to minimise maintenance; for instance, the sizing of pathways would need to be future-proof, and a strong premium placed on modularity and interoperability.

A second key issue is the sizing of communities, cities and nations, and the distribution of activities between these various scalar levels. This is a question of resource availability, technology and economics. The movement of citizens would be severely constrained, with little movement beyond their home community, so the need for virtual communication will become paramount – as will the indoor cultivation of food supplies, building upon technologies such as underground rice production [48].

4. Discussion and reflection

All four vignettes created in the process of this study highlight two important arenas of change and modification. It was to be expected that changes, modifications or outright replacements of existing infrastructural systems would be dominant motifs, given that was the initial direction of the research question, and we will discuss the technological and operational implications of these shifts in Section 4.2, followed by the implications for resource consumption in Section 4.3 and the behavioural changes required of the user base in Section 4.4. But first we draw attention to the concomitant changes in the social and political fabric of communities undergoing these radical upheavals of infrastructure, which open the vignettes out into sociological spheres of enquiry.

4.1. Whose infrastructure? Communities, collectives and choice

We consider it notable and important that all four vignettes have converged onto the community perspective, albeit in different ways and from different directions; infrastructure is inherently the product of (and the domain of) collective action, and while the possibility of individual mitigation actions – such as the retrofitting of water conservation and collection technologies to an individual household, for example – inheres in three of the four vignettes, the time-scale, massive cost and technological realisation hurdles of all the proposed systems demand that they be undertaken by a community with sufficient coherence and consensus to ensure the project is seen through to completion.

So, what is the optimal size for a community, in infrastructural terms? The literature awaits detailed research and analysis of such questions, but in the interim we may assume it likely that the answer will vary considerably as a function of numerous variables. These would include the service or resource in question, the geography and environment of the region, the technologies and infrastructures already in place, the degree of penetration of local individual mitigation strategies, and many more. We here discuss water as an example.

There are plentiful existing technologies which would allow the average household to supply its own drinking water without recourse to the mains infrastructure; in most environments, for instance, a dehumidifier would be capable of meeting the potable water demands of a family home with a minimal energy footprint. For non-dietary uses – bathing, laundry, toilet flushing, etc. – rainwater harvesting systems with filtering and storage components could fill the gap; if sufficient space is available, such systems could harvest and store from a few hundred to thousands of litres for instant availability. Smaller systems would run the risk of shortfall in periods of little precipitation, however, as well as the problem of ironic plenitude wherein there is more rain than the system has capacity to cope with; issues of this sort can open the door to community-scaled solutions. Such a community might look at minimising impervious surfaces to maximise soak-away to groundwater, for instance, and setting up communal tanks to collect and store excess run-off. Due to the ‘‘low-tech’’ nature of the systems in question, water is arguably the most ideal candidate for this sort of communal decentralisation of infrastructure, with community-scale solutions being deployed in such circumstances that households are unable to ‘‘off-grid’’ themselves reliably – a row of terraced houses with minimal loft space for storage tanks, for instance. A similar roll-out of community-scale potable provision, and of grey- and black-water recycling solutions, is also well within the technological reach of most communities currently served by mains water infrastructures, though the changes of consumer behaviour and attitude required to make such a shift possible are very much non-trivial. Such changes might be easy to enact in a small rural community with strong social cohesion, but the logistics of, say, a whole small city deciding to off-grid itself with such solutions are far more daunting. But the small city would have, in theory at least, more money, more resources, more labour – all of which might bring a different scale of solution into economic viability; they might build their own sewage treatment works, for example, or drill deep wells to tap and pump groundwater. If there is some ageing infrastructure already in place, it might be incorporated into the new solution.

Water is a forgiving utility, in that it is highly amenable to decentralisation interventions at almost every scale: communities of any size could successfully take steps to decentralise or otherwise modify their current circumstances with respect to water provision and sewerage disposal, were they of a mind to do so. Indeed, with water, the environmental factors are probably dominant over the community size factor; by way of example, communities in regions with scarce rainfall, such as sub-Saharan Africa, would find their spectrum of viable solutions narrowed by the need to optimise for efficiency of extraction, distribution and storage. Environment and geography – especially local levels of natural resources, renewable or otherwise – will play a far larger part in the question of scale for energy provision solutions, and this offers a potentially valuable path for further (and much more quantitative) research. But we feel that the importance of community size as an influence on solution choice (and indeed on transition/realisation pathways) is implicit in all four vignettes, and that this insight merits further exploration.

The ghost at the banquet here is choice, or perhaps consent. Researchers and policymakers alike, when considering paradigmatic changes to the infrastructures that underpin the lives of entire populations, should bear in mind many of the admonitions of Rittel [49], but most especially his pithy dictum ‘‘no one likes to be planned at’’ – by which he means to caution those who would impose huge structural changes on a population unaware (or uncaring) of the necessity for such changes. Community size also plays an important role, here, as does location: it seeks likely, for instance, that small rural communities, less dependent on centralised systems and less under the thumb of bureaucratic hierarchies of governance, would be better positioned to make autonomous collective decisions about (re)investing in their infrastructural systems. Such autonomous opportunity becomes more scarce as community size increases, but – as suggested previously – larger projects become economically viable to a larger community. But that same increase in economic footprint brings with it greater leeway for dissent, NIMBYism (Not In My Back Yard), the erosion of consensus and the petty machinations of local power-politics. Thus it becomes apparent that, no matter what sort of infrastructural refactoring one might be considering, deep sociological analysis and stakeholder engagement will be crucial components of any successful roll-out. ‘‘The Solar Globe’’, by way of example, would require political and popular willpower and commitment (not to mention money) on a literally global scale ... but the results would be many orders of magnitude more impressive than that of any project conceived and executed by a smaller community.

4.2. Which infrastructure? Adaptation, improvement, replacement

All four of our vignettes envision a reduction and rationalisation of infrastructure systems, but their strategies and routes towards that goal vary considerably, relying on a mixture of completely new systems, modifications of existent systems, and the decentralisation and reintegration of systems at the local level. Here, we examine the knock-on effects and implications of these changes, and identify gaps in the roadmaps: the technologies required to make the systems not just possible but viable.

The circulatory system proposed in "The Blood of the City" uses a suite of existing technologies augmented by multifunctional artificial materials which do not yet exist. It is dependent upon modifications and improvements to extant water supply infrastructure in order to deliver energy carriers and water in the same pipelines. Distribution, measurement and control would be managed by smart, high-capacity coding and signal transformation systems. Biomimetic membranes for pressure-driven water purification would be deployed in plants scaled to the community and conglomerate-community levels in order to exploit economies of scale with what are sure to be expensive cutting-edge materials; indeed, it would make sense for the hydrogen enrichment and separation systems to be folded into such plant as already exists for the treatment and pumping of mains water. Meanwhile, self-cleaning reservoirs, disinfection and water conservation technologies will be deployed at the household level. Recent improvements in high-density solid hydrogen carriers and bio-carriers [50,51], and fuel cells [52] are the forerunning technologies emerging to address the challenge of actually getting the hydrogen into the water. Vacuum or gravity separators (e.g. micro-hydro cyclones) will enable the separation of water and energy carriers, while smart control devices provide continuous data to the distribution infrastructure and calculate the volume of energy particles needed. "The Blood of the City" does not initially envisage using the unified infrastructure to deal with waste material. However, further technological development – perhaps using multiple membranes and other yet-to-be-invented technologies – will ultimately lead to the system dealing with both the delivery of water and energy and the removal of waste materials – just as in the human body.

"The Intertubes" has no obvious gaps in its technological requirements; the techniques, materials and systems involved are all currently available at various degrees of maturity. As proposed, "The Intertubes" could provide the majority of current utility services to households in its deployment zone: the "multiducting" approach ensures ample capacity for energy and communications provision via HVDC cabling and optical fibre, though it is assumed that a suitable (and affordable) source of energy is available to supply the power required. The Intertubes system itself might be able to supply the bulk of its own power needs via solar installations on its surface depots, or through extensive networks of geothermal taps going still deeper beneath the tunnels. It would be possible, at least in theory, to use water pressure to propel the capsules along the network tubes – rather like the way air was used to propel the capsules in old internal postal systems in large buildings – but the multiple contamination vectors (not to mention the possibility of water ingress to the electricity ducting) rule this out as a viable way for the system to carry water for household use. As such, a shift to bottled water delivery for drinking purposes is assumed, alongside a reconfiguration of the urban and suburban landscape to facilitate some degree of rainwater harvesting; these interventions would reduce the strain on extant water mains systems considerably. However, the system as proposed is not suited to including in sewerage capture and treatment, primarily because it is not a "door to door" network that connects individual households. Nonetheless, load mitigation in parallel with changes in water provision could reduce systemic load to a point where existing sewerage capacity becomes plentiful; furthermore, waste could be dealt with locally or at the community level by composting, bio-solids production, waste-to-land applications, and bio-energy production schemes.

"The Solar Globe" suggests a radical and all-new energy generation and delivery solution, but the use of existing power infrastructures would continue in the early phases of the project. Solar technologies would be implemented as widely as possible at local level to reduce energy demand; small-scale applications to include solar-thermal systems and dehumidifiers for hot water and drinking water production respectively, while photo-voltaic panels would produce electricity for heat, light and communication, and to support air and ground source pumps to offset heating needs. Surplus power would be stored in batteries, or in yet-to-be-implemented or invented technologies aimed at smoothing the availability curve. Entire buildings would be used as solar collectors to produce electricity, and made with specialist construction materials so as to create large stores of slow-release heat in colder climates. Large solar collectors would be built to run in parallel with existing fossil fuel and nuclear power stations to reduce dependency on them. Up to this point, "The Solar Globe" is largely within the realms of the presently possible; the technologies required are already available, though considerable improvements in efficiency and cost would increase viability and accelerate roll-out. However, the proposal includes a radical extension of the infrastructure, which would see a ring of photovoltaic panels constructed around the equator of the moon, and this takes us deep into the realm of the speculative. The greatest barrier to any operation in space is the logistical challenge of getting the materials to where they are required. The current paradigm of mass-to-orbit haulage is still liquid-fuel rocketry, which is not only dangerous and prone to spectacular failure, but also so expensive that it is out of the reach of all but the biggest nation-states (or federations thereof). In situ materials sourcing and construction of the lunar collector ring by autonomous robotic builders is a possible solution to this problem, but it still requires some amount of material to be sent aloft, as well as demanding a degree of either (a) highly flexible and responsive remote control over the builders or (b) autonomous machine intelligences which can be trusted not to do anything untoward while unattended – up to and including doing nothing at all! Thus a global push towards completing such a project would provoke innovation in fields that at first glance seem unrelated, namely autonomous machines and remote operations, and alternative space-launch paradigms.

"Subterrania" is unique among the four vignettes in that its infrastructure and the community which the infrastructure serves are contiguous, interdependent and indivisible; neither can exist nor function without the other. This places a strong premium on interconnectivity and modularity in the design of the HVAC systems at the core of the project, as they must not only pass clean, breathable air of a suitable temperature and humidity to each habitation unit, but also act as efficient ducts for potable water and electrical energy. Such a modular approach might well be amenable to the use of rhizomatic routing protocols like those that underpin the internet (and which play an important role in "The Intertubes"); the system would need to be not only resistant to damage, but able to route efficiently around physical disruptions in such circumstances as damage is unavoidable – a state of "graceful failure", to use the parlance of network specialists. As in the other vignettes, there is a clear need for a slew of household-level devices to convert the master utility into other necessities: air to drinking water, air to energy, and so forth. Suitable technologies are already in existence, if only in a nascent form, and many have been mentioned in discussion above, requiring only a slight reconceptualization in order to accommodate the hyperfrugality and systems criticality attendant on the subterranean lifestyle. For the sake of health and well-being, however, "Subterrania" would require considerable emphasis to be placed on issues less pressing for surface-dwellers: the distribution (or simulation?) of "natural" light; ventilation throughput in complex tunnel network topologies; integration and modularity protocols for the infrastructural hardware; and resilience through vigilant risk management. The latter would likely become a significant component of the workaday culture of the community, much as in a submarine or space-station, where the behavioural protocols are rigid and ritualised in order to prevent accidents which might endanger the entire community.

4.3. Why infrastructure? On future resource husbandry

All four vignettes highlight the criticality of access to energy and water for community survival, and the need for careful husbandry and conservation of the raw resources from which they are taken, renewable or otherwise, is implicit. Here we discuss strategies and tactics for achieving such conservation while meeting the basic needs of the vignette communities.

4.3.1. Energy

The ready availability of energy, and of devices to convert it into consumable services, supports the quality of life enjoyed by the developed world today, and there is a clear relationship between humankind's technological evolution and easy access to power. The consumption of energy satisfies fundamental human needs, and is therefore an essential resource if we wish to evolve into a yet more advanced technological society.

Although there are arguably 200 years' worth of coal and gas resources remaining, the extraction and continued use of fossil fuels is becoming ever more expensive and environmentally damaging. However, existing renewable energy technologies can be inefficient, expensive, and prone to intermittency due to the fluctuating natural phenomena on which they depend; it is inevitable, then, that an existing or as yet undiscovered clean energy resource will have to be exploited more fully to meet our future power needs.

Nuclear is currently an unpopular energy source, for many reasons; however, thorium and deuterium/tritium reactor designs may help to put a shine back on its tarnished image. Thorium is set to drive a new wave of industrial revolution in Asia, promising to provide power to an extra two billion people as they shift to Western lifestyles. Thorium is cheaper and much cleaner than previous nuclear fuels, and current reactor designs promise almost zero CO_2 emissions, far less toxic waste, and no weapons-grade by-products; the process can also be used to clean up the mess left from nuclear weapons and uranium reactors [53]. The thorium reaction takes place at regular atmospheric pressures, so it does not require the vast and costly containment architecture of conventional reactors. It will be possible to build very small underground nuclear power plants to supply energy to small communities and average sized cities; this move to distributed and decentralised generation will reduce the need for an extensive transmission infrastructure. Deuterium/tritium reactors are also much more clean and controllable then current trans-uranide technologies, and there is an inexhaustible supply of tritium in the lunar regolith – though this is the only immediate bulk source of this otherwise rare fuel [54].

All our vignettes either focus on clean power provision, or assume the availability of such. In "The Solar Globe" and "The Intertubes", solar and/or geothermal energy are proposed to address future household energy needs, while "The Blood of the City" uses hydrogen as a carrier technology for energy created from an unspecified resource, which might be solar, geothermal, nuclear or even legacy-fossil in origin. "Subterrania", by contrast, requires wind and solar energy to be collected on the planetary surface; these renewable sources are assumed to be abundant in this climate-changed scenario. Without any doubt, however, the most sustainable clean energy source is the sun, which could supply the current energy needs of all humankind many times over if it could all be harnessed efficiently; it seems logical, therefore, that solar should be the first choice of primary energy resource when planning for the future.

4.3.2. Water

Water is the most fundamental of all needs, and will remain so in perpetuity. Without it, organic life as we know it simply cannot exist; where it is scarce, industry and agriculture falter, with dramatic concomitant effects on quality of life. In today's developed countries the oversupply (and thoughtless waste) of clean drinking water is the norm; for example, the average per capita water consumption in England and Wales is 150 L per day. In less developed countries, however, it may just be a few litres per day, and many still have no access to safe drinking water at all. This situation will be exacerbated for all by continued climate weirding, predicted population growth and migration patterns, and the compound cumulative effects of environmental pollution.

Extant drinking water infrastructures are inefficient because they leak. Add to leakage the excess losses for hygiene (flushing toilets), industry, agriculture and consumer wastage, and we find as little as 3% of the total volume of drinking water produced is actually used for its stipulated purpose. A future option is to treat only sufficient drinking water to meet the requirements of a healthy diet, and to use less rigorously treated and/or recycled waters for industrial and agricultural purposes.

All the vignettes emphasise the vital importance of clean water availability for future communities, just as for today's. It will be necessary to protect existing clean water resources, and to investigate ways of producing potable water from both existing sources and potential new ones, such as seawater, grey-water (e.g. ''used'' household wastewater, such as bath water) and atmospheric humidity.

''The Intertubes'' foresees a reduced provision of drinking-grade water as inevitable, and proposes its distribution using easily transportable custom-designed receptacles. The communities of ''Subterrania'', on the other hand, are provided only the utterly essential volume of drinking water, and thus require substitutes for other services currently based on potable water, such as laundry and personal hygiene; the closed loop environmental systems required for such provision would focus strongly on efficiency and discourage profligate consumption. ''The Solar Globe'', meanwhile, would make water production methods such as desalination and distillation more economically viable due to the availability of cheap clean power that could be ''beamed'' to almost anywhere on the planet; alternatively, solar power could enable decentralised water production at the household level. ''The Blood of the City'' assumes a stable supply of water to be piped through its modified mains systems, but the possibility of reducing overheads by decentralising potable-grade water treatment to the household level (possibly by including the necessary filters in the same mechanism used to extract the hydrogen carriers) is implicit.

Independent of the vignettes under consideration, future structural engineering and construction must directly address the need for conserving water. Green buildings that use rainwater capture to supply all in-building usage are already being proposed and built, with the filtered water being used for everything from toilet flushing to drinking water [55]. A proposed biomimetic mango-leaf LED street lighting unit captures rainwater to create power to recharge its batteries the ''stalk'' conveys the water to local storage for recycling/reuse [56]. In the United States, the power and agricultural industries account for 49% and 31% of annual pumped water demand respectively [55]. If lunar-based solar power generation became the norm, and if excessive food consumption and waste could be tackled, water resource conservation would not be such a pressing issue – especially if conservational attitudes and behaviours were ingrained into all aspects of modern life.

Local decentralised strategies produce the greatest water consumption savings when compared to fully or partly centralised solutions. Although water autonomy requires a substantial increase in per capita energy consumption due to the increased energy footprint associated with point-of-use water treatment, waste-to-energy systems may produce a higher energy return when they are associated with such a system. The cost could also be offset by the negation of the need for treating and pumping huge volumes of water, and by the use of local solar power solutions.

4.4. How infrastructure? Behavioural shifts and social engineering

Fundamental human needs, as reflected in the lower levels of Maslow's hierarchy [1], are not subject to significant change over time; however, as time passes, the way these needs are serviced may change radically. People do not demand specific products such as electricity or gas; nor are they interested in where their drinking water originates, or how it is produced. They simply require utilities that they can use – either directly, or through various technologies or appliances – to satisfy those fundamental needs. In today's households, the standard suite of utilities comprises water, energy, communication, and transport. Water is unique in that it directly serves a fundamental need simply through consumption. A multitude of devices are employed to fulfil other needs; kettles, central heating boilers, cookers, telephones or vehicles. Combinations of many device types are used to satisfy different levels and combinations of need.

People also have secondary, luxury needs. These *should* be less important than fundamental needs – but, once a community becomes accustomed to a luxury, it is often subsequently perceived as essential, as a necessity; this misconception is supported and reinforced by consumerist economies. Behavioural change is polarised; it is easy to assimilate luxury into lifestyle, but very difficult to take it out again. Water is, again, an illustrative example. All household water in the UK is delivered at potable levels of treatment, and per capita consumption is approximately 150 L per day; the fundamental need, however, is just a few litres per person per day for drinking, cooking and hygiene. The huge disparity between these figures can be attributed to luxury use. The UK has been historically fortunate in having sufficient water resources to disregard efficiency and waste. Consequently, economical arguments make it acceptable to lose 30% of all drinking water to leakage, and unnecessarily high household consumption is tolerated. Such ''luxury waste'' is also apparent in energy accounting; unnecessary profligate uses of heating and lighting are a prime example. Communication suffers similarly, albeit in the abstract; large quantities of rare elements are currently consumed to manufacture mobile communication devices which are often discarded while still perfectly functional, so as to upgrade to the latest model – another function of the consumerist economic principle. It is imperative that this paradigm is overturned as resources become more difficult, environmentally damaging and expensive to obtain.

The availability of an unlimited cheap energy source may challenge such thinking, however. The infrastructure of "The Solar Globe" would provide effectively limitless energy, but this should not be taken to mean that energy waste should become acceptable. A solar infrastructure, like any other power infrastructure, still has to be suitably sized, operated and maintained, and wastage increases cost independent of resource availability. Hence the underlying necessity of an attitudinal shift in the population – a shift towards frugality and mindful consumption patterns – in the scenarios behind all four vignettes; the technologies alone will not solve the fundamental problem, which is that of unexamined greed and profligacy in resource usage. It should be noted that it is the developed nations of the West in which this problem is most severe; the citizens of developing nations, heretofore unaccustomed to cheap safe provision of power and water, have been obliged to take a more frugal outlook. However, as economic changes bring more and more of the population out of poverty, those citizens will turn their eyes to Western lifestyles, and wonder why they might not live the same way. It remains to the West to lead the way in sacrificing convenience for the chance of a sustainable future; without such a sacrifice, it will be impossible to argue for the same attitudes in those newly upwardly mobile populations.

It is difficult to predict how people will react to new approaches to service delivery. Generally, people do not like change; stability is key to most people's comfort and security. Water provision, for example, is a surprisingly emotive issue. People might refuse to use recycled grey-water or water extracted from air, for ethical, religious or personal reasons, and the thought of treating waste water in the household or locally will be repulsive to some. Clearly, there is an important role here for education and stakeholder engagement, and for accommodating (wherever possible and practicable) those who take issue with particular practices, on whatever grounds. It will be important to teach the realities, possibilities and benefits of new technologies or approaches from an early age, and to ensure ecological perspectives are maintained. Education, choice and financial incentives will be important considerations in manufacturing acceptance for community-wide solutions to future utility service provision. The spectre of popular political resistance to such changes – and the inevitable accusations of tyranny, indoctrination and forced submission that will accompany such – will haunt any such project, just as it haunts the utility projects of the present day.

The vignettes described in this paper are purposely futuristic and challenging. This does not mean they are impossible or unacceptable, but in addition to those attitudinal shifts already described, long-term planning and investment will be required; this flies in the face of contemporary short-term/quick-gain policymaking, wherein lip service is paid to foresight and sustainability in order that business might carry on largely as usual. Targeted R&D and industrial funding must be provided, red tape must be removed, and new thinking and skills must be fostered and supported by educational reform. Governments, scientist, and engineers will have to collaborate and all citizens must understand not only the need for change, but how it will be realised, and why their wholehearted participation is central to achieving the goal. This is a big ask, as any politician would freely admit – but if the perceived benefits are sufficient, nothing is impossible.

The recent promotion and uptake of renewable energy options and technologically developed household infrastructure and devices, reflects a positive – though far from universal – attitude and response from politicians, leaders, policymakers, managers, and end users. This is especially true of affordable and reliable multi-function devices that provide higher quality service, and technologies which minimise health impacts and environmental damage are growing in popularity. Future infrastructure and devices providing combined water and waste services, energy, and communication have the potential to be just as well received as solar panels or condensing boilers have been in the past.

It has been shown that change can be suggested through education and encouraged through reward. This study suggests shifting people's knowledge and perception to a new paradigm aimed at radically merged singular infrastructures for household utility provision; if technology and population can be encouraged to work in harmony, profound structural changes become possible.

5. Conclusions

"The Blood of the City", "The Solar Globe" and "Subterrania" all demonstrate the theoretical possibility of providing all basic household requirements using a single infrastructural system, under very different contextual circumstances. Some challenges are unique to each vignette, but commonalities emerge around matters such as resource husbandry, behavioural change, and the requirement for new or improved devices to handle the transformation or conversion of the single utility into the services required.

"The Intertubes" is the only vignette which explicitly integrates a transport service. Transportation is an oddity among infrastructures due to its inherent interstitiality, and its interdependence upon the other basic utilities; "The Solar Globe" implicitly offers the possibility of clean solar-powered transit and haulage, while "The Blood of the City" leaves the question open. The citizens of "Subterrania", by comparison, will likely have far more immediate concerns than transportation.

All four vignettes are scientifically and technologically feasible, to a lesser or greater degree. However, all of them require some advances or improvements to existing technologies in order to be fully realised as engineering solutions; implementing them in the messy real world of human socio-politics will require many more changes in attitude and behaviour, some of which may be easier to achieve than others. Interestingly enough, conformity of thought and resistance to change are implicitly reflected even in these deliberately visionary "blue-sky" vignettes. Whether by design or subconscious influence, they remain largely within the realms of current possibility, and constrained by contemporary notions of what a society needs (as well as how it should act to achieve those needs). They have been influenced by a narrowness of thinking, by the ingrained belief in technological and social limitations, by current industry models and perceived socio-political pressures. It remains clear that, when it comes to macro-engineering solutions and problems at the scale of infrastructure, the engineering is only half of the challenge; the hardest task may be convincing the population not just of the need for change, but also of the necessity that they play their part in it.

Acknowledgments

This project entitled ''All-in-One: Feasibility Analysis of Supplying All Services through One Utility Product'' was supported by the Engineering and Physical Sciences Research Council (EPSRC) under the reference number EP/J005592/1.

References

[1] A.H. Maslow, A theory of human motivation, Psychological Review 50 (1943) 370–396.
[2] B. Houlihan, Europe's ageing infrastructure, Politics, Finance and the Environment 4 (1995) 243–252.
[3] F. Camci, B. Ulanicki, J. Boxall, R. Chitchyan, L. Varga, F. Karaca, Rethinking future of utilities: supplying all services through one sustainable utility infrastructure, Environmental Science & Technology 46 (2012) 5271–5272.
[4] S.W. Schuckmann, T. Gnatzy, I.-L. Darkow, H. a. von der Gracht, Analysis of factors influencing the development of transport infrastructure until the year 2030—a Delphi based scenario study, Technological Forecasting and Social Change 79 (2012) 1373–1387.
[5] W.W. Clark, H. Lund, Integrated technologies for sustainable stationary and mobile energy infrastructures, Utilities Policy 16 (2008) 130–140.
[6] J. Nill, R. Kemp, Evolutionary approaches for sustainable innovation policies: from niche to paradigm? Research Policy 38 (2009) 668–680.
[7] J. Morrissey, U. Iyer-Raniga, P. McLaughlin, A. Mills, A strategic project appraisal framework for ecologically sustainable urban infrastructure, Environmental Impact Assessment Review 33 (2012) 55–65.
[8] E.S. Heidrich, T.P. Curtis, J. Dolfing, Determination of the internal chemical energy of wastewater, Environmental Science & Technology 45 (2011) 827–832.
[9] S. Judd, C. Judd, The MBR Book, Butterworth-Heinemann, London, 2006.
[10] S. Cheng, B.E. Logan, Sustainable and efficient biohydrogen production via electrohydrogenesis.pdf, PNAS 104 (2007) 18871–18873.
[11] W. Shaw, 3 in 1 merged information systems maximize efficiency, Transmission & Distribution World (2004) 20–29.
[12] M. Isbell, A. Lee, Charlotte–Mecklenburg successfully integrates field operations by managing individual and organizational strengths, American Water Works Association Journal 98 (2006) 85–90.
[13] P. Bishop, A. Hines, T. Collins, The current state of scenario development: an overview of techniques, Foresight 9 (2007) 5–25.
[14] T. Kuosa, Evolution of futures studies, Futures 43 (2011) 327–336.
[15] M. Amer, T.U. Daim, A. Jetter, A review of scenario planning, Futures (2012).
[16] K. Haegeman, E. Marinelli, F. Scapolo, A. Ricci, A. Sokolov, Quantitative and qualitative approaches in Future-oriented Technology Analysis (FTA): From Haegeman, K., Marinelli, E., Scapolo, F., Ricci, A., & Sokolov, A. (2012). Quantitative and qualitative approaches in Future-oriented Technology Analysis (FTA): Fro, Technological Forecasting and Social Change (2012).
[17] L. Andreescu, R. Gheorghiu, M. Zulean, A. Curaj, Understanding normative foresight outcomes: Scenario development and the ''veil of ignorance'' effect, Technological Forecasting and Social Change (2012) 1–12.
[18] R. Fildes, The evaluation of extrapolative forecasting methods, International Journal of Forecasting 8 (1992) 81–98.
[19] O. Saritas, Y. Nugroho, Mapping issues and envisaging futures: an evolutionary scenario approach, Technological Forecasting and Social Change 79 (2012) 509–529.
[20] A. Hines, P. Bishop, Thinking about the future, guidelines for strategic foresight, Social Technologies LLC, Washington, DC, 2007.
[21] M. Marien, Futures studies in the 21st Century: a reality-based view, Futures 34 (2002) 261–281.
[22] F. Macedonio, E. Drioli, a. a. Gusev, a. Bardow, R. Semiat, M. Kurihara, Efficient technologies for worldwide clean water supply, Chemical Engineering and Processing: Process Intensification 51 (2012) 2–17.
[23] S.-L. Loo, A.G. Fane, W.B. Krantz, T.-T. Lim, Emergency water supply: a review of potential technologies and selection criteria, Water Research 46 (2012) 3125–3151.
[24] W. McDowall, M. Eames, Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: a review of the hydrogen futures literature, Energy Policy 34 (2006) 1236–1250.
[25] W. Mcdowall, M. Eames, Towards a sustainable hydrogen economy: a multi-criteria sustainability appraisal of competing hydrogen futures, International Journal of Hydrogen Energy 32 (2007) 4611–4626.
[26] J. Andrews, B. Shabani, Re-envisioning the role of hydrogen in a sustainable energy economy, International Journal of Hydrogen Energy 37 (2012) 1184–1203.
[27] F. Karaca, F. Camci, P.G. Raven, City blood: household energy provision through water distribution infrastructure, Energy, under review.
[28] P.S. Zhong, T.-S. Chung, K. Jeyaseelan, A. Armugam, Aquaporin-embedded biomimetic membranes for nanofiltration, Journal of Membrane Science 407–408 (2012) 27–33.
[29] J. Carter, S. Hadland, N. Hodson, D.W.F. Fcilt, Foodtubes, URL: www.noelhodson.com/index_files/foodtubes-project-team.htm, 2011 (last accessed 07 August 2012).
[30] A. Jeanne, A. McDonald, N. Nakicenovic, No Titleenergy in a Finite Word, Ballinger Publishing Company, Massachusetts, 1981.
[31] Shimizu_Corporation, Shimizu's Dream, Lunar Solar Power Generation-LUNA RING-, URL: http://www.shimz.co.jp/english/theme/dream/lunaring.html, 2012 (last accessed: 20 January 2013).
[32] R.V. Ralegaonkar, R. Gupta, Review of intelligent building construction: a passive solar architecture approach, Renewable and Sustainable Energy Reviews 14 (2010) 2238–2242.
[33] H.-Y. Chan, S.B. Riffat, J. Zhu, Review of passive solar heating and cooling technologies, Renewable and Sustainable Energy Reviews 14 (2010) 781–789.
[34] T.N. Anderson, M. Duke, G.L. Morrison, J.K. Carson, Performance of a building integrated photovoltaic/thermal (BIPVT) solar collector, Solar Energy 83 (2009) 445–455.
[35] D.R. Criswell, Solar power via the moon, The Industrial Physicist 8 (2002) 12–15.
[36] A.P. Malozemoff, S. Fleshler, M. Rupich, C. Thieme, X. Li, W. Zhang, et al., Progress in high temperature superconductor coated conductors and their applications, Superconductor Science and Technology 21 (2008) 1–7.
[37] R.M. Scanlan, A.P. Malozemoff, S. Member, D.C. Larbalestier, Superconducting materials for large scale applications, Proceedings of the IEEE 92 (2004) 1639–1654.
[38] W. Buckles, W.V. Hassenzahl, Superconducting magnetic energy storage, Power Engineering Review, IEEE 20 (2000) 16–20.
[39] D.R. Criswell, Energy markets: the challenges of the new millennium, in: Lunar Solar Power System: Industrial Research, Development, and Demonstration, World Energy Council 18th, Buenos Aires, 2001, 1–17.
[40] D.R. Criswell, Lunar solar power system: review of the technology base of an operational LSP system, Acta Astronautica 46 (2000) 531–540.
[41] F. Pearce, Worst case global warming scenario revealed, New Scientist 2539 (2006) 10–11.

[42] Cheyenne Mountain Complex, URL: http://www.norad.mil/about/cmoc.html, 2012 (last accessed 07 August 2012).
[43] Living Underground?, URL: http://www.interestingfacts.org/fact/living-underground#.TzVMKJghZSU, 2012 (last accessed 07 August 2012).
[44] A. Furuto, The Earthscraper/BNKR Arquitectura, URL: http://www.archdaily.com/156357/the-earthscraper-bnkr-arquitectura/, 2011 (last accessed 07 August 2012).
[45] Hydropolis Underwater – The Largest Underwater 10 Stars Hotel, URL: http://www.house-arch.com/hydropolis-underwater-the-largest-underwater-10-stars-hotel.html, 2012 (last accessed 07 August 2012).
[46] D. Quick, Green Float concept: a carbon negative city on the ocean, ECOGIZMO (2010) 1–3.
[47] Bunker-busting Smart concrete, The Economist. March 3rd (2012).
[48] Trends in Japan, Underground Urban Farm, Fruit and Vegetables Grown Under Office Building, URL: http://web-japan.org/trends/lifestyle/lif050317.html, 2005 (last accessed 20 January 2013).
[49] H. Rittel, On the planning crisis: systems analysis of the 'First an d Second Generations', Bedriftsokonomen (1972) 390–396.
[50] Y.S. Nechaev, On the solid hydrogen carrier intercalation in graphane-like regions in carbon-based nanostructures, International Journal of Hydrogen Energy 36 (2011) 9023–9031.
[51] G.-J. Xie, B.-F. Liu, J. Ding, H.-Y. Ren, D.-F. Xing, N.-Q. Ren, Hydrogen production by photo-fermentative bacteria immobilized on fluidized bio-carrier, International Journal of Hydrogen Energy 36 (2011) 13991–13996.
[52] Y. Wang, K.S. Chen, J. Mishler, S.C. Cho, X.C. Adroher, A review of polymer electrolyte membrane fuel cells: technology, applications, and needs on fundamental research, Applied Energy 88 (2011) 981–1007.
[53] M. Kazimi, Thorium fuel for nuclear energy an unconventional tactic might one day ease concerns that spent fuel could be used to make a bomb, American Scientist 91 (2003) 408.
[54] H.J. Smith, A.A. Gurshtein, W. Mendell, International manned lunar base: beginning the 21st century in space, Science & Global Security: The Technical Basis for Arms Control, Disarmament, and Nonproliferation Initiatives 2 (1991) 209–233.
[55] R. Campbell, K.S. Porter, Green buildings: a response to water shortages in the United States? Journal of Water Law 21 (2010) 178–188.
[56] A. Miklosi, Mango, URL: http://www.adammiklosi.hu/index.php?p=146, 2013 (last accessed 20 January 2013).