Imagining a Sewerless Society

B.D. Martin

P.H. Cruddas

P. Hutchings

Nexus Network Think Piece Series, Paper 005 (April 2015)

About the Nexus Network think piece series

Funded by the ESRC, the Nexus Network is a collaboration between the University of Sussex, the STEPs Centre, the University of East Anglia, and the Cambridge Institute for Sustainability Leadership. The Nexus Network brings together researchers, policy makers, business leaders and civil society to develop collaborative projects and improve decision making on food, energy, water and the environment. In July 2014, the Nexus Network commissioned 13 think pieces with the remit of scoping and defining nexus approaches, and stimulating debate across the linked domains of food, energy, water and the environment.

About the author(s)

Dr. Ben Martin (b.d.martin@cranfield.ac.uk)

Ben Martin is a Research Fellow at Cranfield University, and has been involved in developing a waterless toilet design with Gates Foundation funding. For his PhD he developed a novel nutrient recovery system from wastewaters, and holds an Environmental Science degree from Lancaster University. Ben is the corresponding author for the paper.

Dr. Peter Cruddas (p.h.cruddas@cranfield.ac.uk)

Peter Cruddas is a Research Fellow at Cranfield University looking at energy recovery from waste systems, including his PhD thesis on biogas generation from wastewater treatment and the use of thermal processing for faecal sludge management. He holds a BEng (hons) in Civil Engineering from the University of Bradford and an MSc in Water Management from Cranfield University.

Paul Hutchings (p.t.hutchings@cranfield.ac.uk)

Paul Hutchings is a Research Assistant at Cranfield University conducting PhD research into community management models for water supply in rural India. He holds BA (Hons.) and MA (Dist.) degrees in Geography from the University of Liverpool and has worked as a mix-methods researcher at the Chartered Management Institute.

Imagining a Sewerless Society

Introduction

Conventional sewer systems have a heavy impact across the nexus of water, energy, food and the environment. Large water demands can increase water scarcity and require significant energy for the conveyance of huge volumes of diluted sewage. Urban systems are frequently overloaded leading to discharge of raw sewerage directly to the environment whilst the vast potential for nutrient recovery is underdeveloped at a time when such outputs could have a role to play in global fertiliser markets[1]. Moreover, the challenge of expanding centralised sewers or, even more demanding, developing new sewer systems is hampered by a number of significant barriers, including the significant economic costs and planning challenges. In developing countries, this is felt most keenly, with the global disease burden from poor sanitation outweighing heart disease, tuberculosis, malaria, and HIV[2]. In the 20th Century, the World Health Organization[3] estimated that diarrhoeal disease alone killed 226 million people, the majority of which lived in low income countries, with poor sanitation and hygiene. Meeting this sanitation challenge has so far been beyond the conventional wastewater paradigm with no imminent solution from the prevailing model addressing the problem of sanitation access in poor, crowded cities.

As a consequence, significant efforts have been made to provide sewerless sanitation and alternatives to pit latrines in low income countries, which circumvent the requirement for massive infrastructure. From a nexus perspective, these technologies also have the potential to address many of the challenges created by conventional sewerage systems. In this sense, the developing world is introducing new technologies and service delivery models to not just 'leapfrog' existing technology, but actually redefine the future model for sanitation. This think piece reviews the current state-of-art of these technologies and considers how they intersect with the nexus of water, energy, food and the environment. It also imagines two future scenarios of sewerless options that could be developed to response to the global sanitation crisis and alleviate the impact of conventional sewers on the nexus. It ends by proposing a planning framework that outlines the environmental, technological, political-economy and socio-ideological considerations that are likely to impact the future development trajectories of sewerage infrastructure around the world.

The global need for a paradigm shift

Sewer systems can be evidenced in the Middle East and Indus valley as far back as 2,500 BCE and, where successful implemented, these systems have clearly increase welfare through the sanitation benefits they provide to populations. However the intensive infrastructure necessary and the resources required, provoke debate about whether a sewered network approach can be sustainable both for those countries with existing sewer infrastructure, and those that might be providing sanitation services for the first time. This argument will be explored in this section through case studies of two cities, London, to represent a developed world view, and Delhi, to represent the challenges of a developing nation.

The rapid urbanisation and associated sanitation crises of the industrial revolution were the drivers for extensive urban sewer networks in London. In response to the cholera outbreaks in the 19th Century, and triggered by the 'Great Stink' of 1858, Sir Joseph Bazalgette was tasked with designing London's modern sewerage system to remove human waste from the streets and the River Thames, diverting it instead downstream away from the city[4]. However, further urbanisation has placed a high stress on the sewer networks, and raises questions about whether a new approach to sanitation is required. The original London sewer network, completed in 1865, had a capacity for up to 4 million people, but today serves 8 million having expanded very little[5]. In addition, the original design allowed for 6mm/hour maximum rainfall capacity in the combined system, to drain surface stormwater away from the city, whilst the increased demands now mean that as little as 2mm/hour rainfall can trigger sewer discharge to the Thames[5]. In 2013, 55 million tonnes of untreated sewage were discharged to the Thames due to lack of sewer and treatment capacity[6]. To address this Thames Water is proposing £675m in sewage works upgrades, a £635m Lee Tunnel sewer project, and the controversial Thames Tideway 'super-sewer', estimated to cost £4.2bn[4].

Delhi is currently the 2nd most populous city on the planet with a population of 25 million residents which is estimated to rise to 36 million by 2030[7]. Its current sewerage infrastructure is woefully inadequate to serve today's population and based on current trajectories it will be tested to the point of collapse by the projected increase in population. The Delhi Jal Board (DJB), responsible for sewerage management, is under severe political pressure to improve its performance. In 2012, its 32 sewage treatment plants (STPs) treated 367 million gallons per day (MGD) out of the 680 MGD generated in the city with the remaining output being discharged untreated into local water ways, most notable the highly polluted Yamuna river that provides 70% of the water needs of the city[8]. These figures do not account for the many millions of residents who are not connected to the sewer network, with over half the children living in slums or unauthorized housing continuing to defecate in the open leading to a crippling rate of water-borne disease in the city[9]. This is despite investment of $270 million in the sewage sector in the period 2007-2012, which resulted in a mere 1 MGD additional capacity and 900 km of new pipes over five years[8]. Responding to this situation, in September 2014, the Delhi government published its $3.2 billion master plan for wastewater management. The plan intends to add 10,000 km of piped network and 75 new waste treatment plants in the next three years increasing treatment capacity to 3,800 megalitres a daily, or 836 MGD[10]. This is extremely ambitious given the current status, performance and trajectory of sewerage infrastructure in the city. It is proposed that the city stands to benefit from integrating decentralised options of wastewater treatment into its plans whilst also leveraging the business opportunities that arise from the huge nutrient recovery potential that exists within this volume of wastewater. The following section will outline the technologies that could play a role in this transition.

Technologies for sewerless sanitation – the state of the art

The primary concern for decentralised sanitation systems is the containment, immobilisation, or destruction of pathogens in the solid portion of human waste. Whilst greywater is also a concern due to the detergent and nutrient load that can adversely affect the environment, it is the treatment of blackwater that poses the highest risks to human health and has the greatest implications for the nexus. Decentralised technologies for treating blackwater are therefore the main focus of this section. There are two main approaches to decentralised systems: short residence time toilets, like the Clean Team social enterprise in Kumasi, Ghana (Figure 1 and Table 1), where waste is collected frequently from the on-site system and taken to a larger plant for the majority of the treatment; and long residence time systems, such as composting toilets or septic tanks, where larger on-site facilities are required but perform a larger proportion of the treatment process in situ. The Ecological Sanitation[11] approach is an example of the long residence time approach (Table 1). However, both approaches produce residual products that require further treatment or disposal.

Figure 1: Clean Team Toilet demonstration by a customer

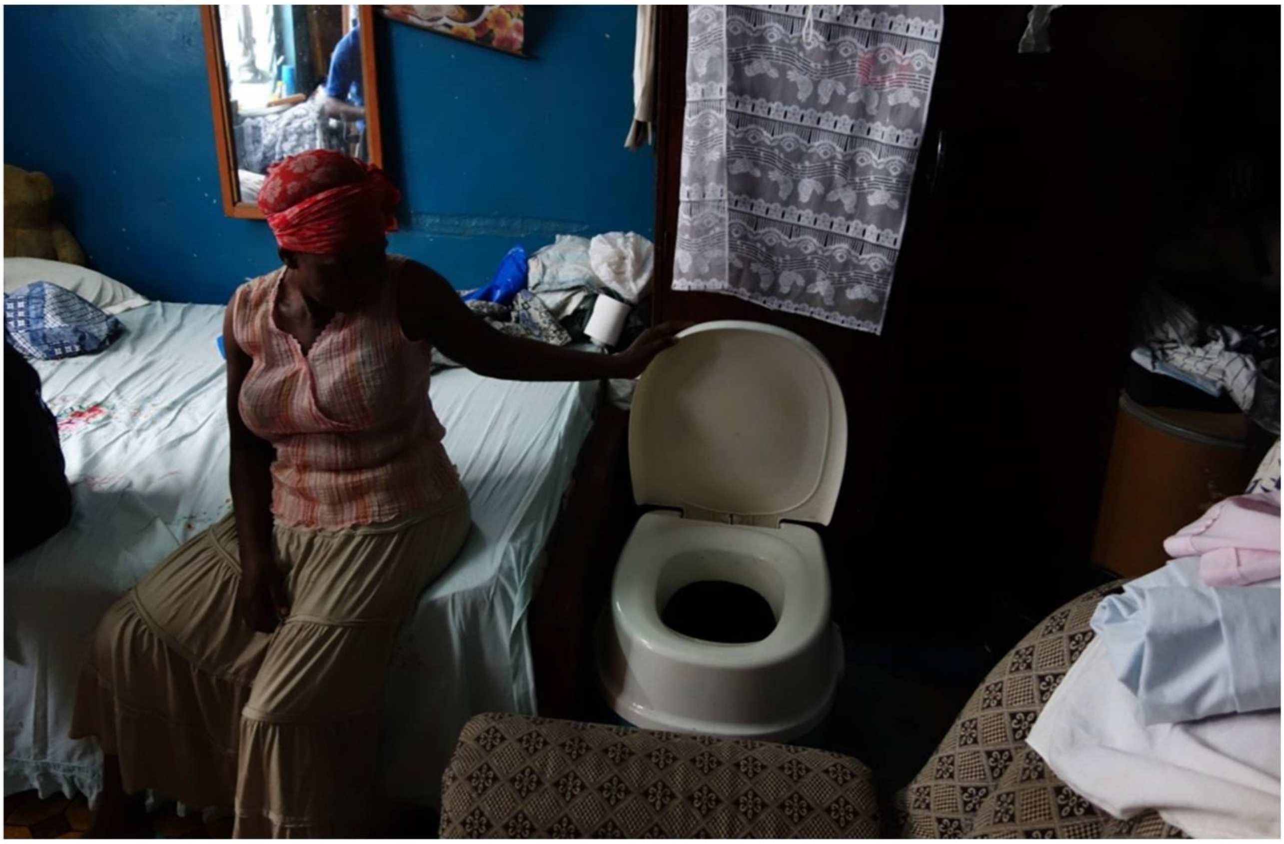


Table 1: A selection of current and future sewerless sanitation technologies, broadly in order of increasing complexity

System/ organisation	Method summary	Developmental status	Pathogen treatment	Water	Energy	Food	Environment	Reference*
Clean Team	Chemical container toilet with urine diversion – containers are collected twice a week and processed in a central facility	In operation, serving 500 households in Kumasi, Ghana Expanding to independently treat and recover resources in 2014/2015	Through use of biocide chemical	5 L required per cartridge to make up the chemical Net input	None recovered	No resource recovery	Prevents pathogens and faecal products contaminating water sources Increases local nutrient levels as urine is discharged directly	12
Biofil	Passive aerobic digestion using micro and macro organisms in a small footprint	In operation, installed in numerous schools, housing developments, office buildings in Ghana	Not measured	Water input required to flush the toilet	None consumed or output	Dry compost fertiliser and nutrient rich water outputs	Reduction or elimination of groundwater contamination	13
The Earth Auger	Urine diverting dry toilet	Field testing in Ecuador	Passive treatment through composing /dessication	No water required or produced	No energy required or produced	All resources captured are used for agricultural enrichment	No contamination, local reuse closes nutrient cycle loop	14
DEWATS	Decentralised treatment system comprising passive filtration, anaerobic reactors and wetland stages	Modular systems employed in low income country settings and	90 % reduction	None needed Nutrient enriched water output	None consumed Recovery through anaerobic digestion (biogas)	Effluent water has value as a fertiliser	Reduces groundwater contamination	15
ECOSAN	Various source separation techniques including composting/dehydrating toilets, anaerobic treatment, direct recovery of fertiliser products from urine using struvite crystallactors, and membrane technology	Modular, interchangeable systems in India, Syria and Germany	Elimination through prolonged storage, drying, or anaerobic digestion and incineration	None used, nutrient enriched water output	Little consumed (some technologies use vacuum), generation through biogas production	Effluent water used as fertiliser, organic matter from solids used as soil conditioners	Reduction or elimination of groundwater and environmental pollution, recycling to close nutrient loop	11

More advanced techniques that tackle the in-situ treatment of solids to prevent local exposure to pathogens use dehydration or combustion through gasification and pyrolysis, methods that also yield power, such as RTI International's system[19] (Table 1). Once the risk from pathogens is reduced, the remaining waste can be considered as a complex mixture of resources, containing water and nutrients. Direct water recovery from human waste can be achieved through source separation and purification of urine using passive filtration and aerobic digestion[15] (Table 1), pasteurisation using the heat from biogas combustion[17] (Table 1) or via pervaporation membranes linked to condensing media, such as Cranfield University's prototype Nano Membrane Toilet[16] (Figure 2 and Table 1).

Figure 2: Cranfield University's prototype Nano Membrane Toilet

Nutrient recovery can be accomplished from urine using in-situ struvite crystallactors[18] (struvite is an ideal fertiliser product comprising magnesium, ammonium and phosphate), (Table 1) or through ammonia and phosphorus selective adsorbents. Even if the solid waste is combusted, nutrients can be recovered from the ash using sequential precipitation. There are a multitude of technologies currently available that are capable of treating human waste in decentralised systems, even at individual household scale (Table 1). The right technique to use depends on context, income level and country setting, power requirements, and the value of the outputs in relation to these criteria, i.e., pathogen kill only vs. complete resource recovery. Perhaps the most significant driver for change in this field in recent years has been the Bill & Melinda Gates Foundation, and their "Reinvent the toilet challenge," which seeks to develop a toilet that: neutralises pathogens in human waste and recovers energy, clean water, and nutrients; operates "off grid"; promotes environmental and economic sustainability, and is an aspirational product applicable to low income and high income countries alike[14]. The majority of the systems outlined here are a direct response to this call, and all address the stress nexus of water, energy, food and the environment (Table 1).

Whilst all of the techniques appearing in Table 1 are intended to operate independently of any sewage infrastructure, most will still be reliant on a centralised treatment plant to further treat the solids and to recover resources. An important consideration in these cases is how to transport and process the material in an energetically efficient and sustainable. However, if the sewerless toilets of the future can produce their resources in a small enough volume, i.e. without water or bulky, low value ingredients such as undigested fibre, then bulk volume of waste to be transported can be reduced by an order of magnitude from the volume of sewage currently created. This route would represent significant savings in comparison to the current sewage systems, in the amount of clean water required for flushing and transportation, the energy for pumping sewage, and the burden of treatment in removing the water again in the sewage treatment works[20]. Alternatively, a future solution could be a fully self-contained toilet that requires no special export or further treatment of the waste because the only outputs are energy and inert residue that can be included with domestic refuse.

Imagining a sewerless society: two scenarios

In light of the current and emerging technologies in ecological sanitation and resource recovery from human waste, this paper imagines two scenarios in which a sewerless society could function. Firstly, a self-contained toilet paradigm, representing complete off-grid sanitation, where household toilets become standalone, decentralised processing plants in their own right. In this paradigm, the households are wholly responsible for reuse and recycling technologies, which would include the useful byproducts generated from the self-contained toilet. Unusable waste is reduced to such an extent that it can be introduced to existing waste systems without significant impact. In the second paradigm a centralised processing approach is taken, whereby waste processing facilities become resource manufacturing sites, producing energy and fertilisers from the waste collected at household level. The efficiency of these plants will depend greatly on the design of the household toilet, as low efficiency methods are already available but requiring significant transport and post-processing capabilities. Advancing toilet designs in the same direction as the self-contained concept would reduce the amount of waste required to be collected, whilst also increasing the efficiency of the centralised plants.

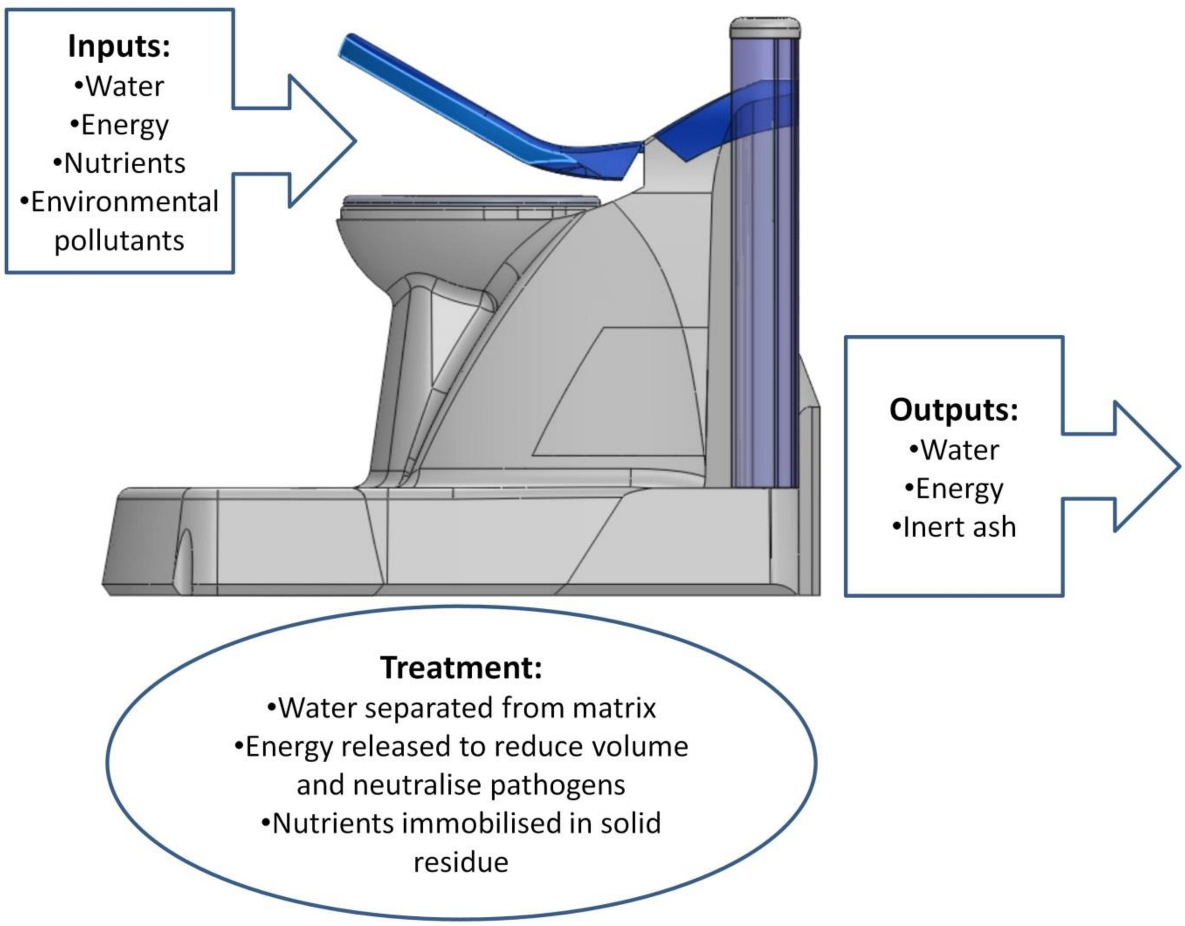
Two alternative paradigms are presented to both contrast two possible approaches towards sewerless societies, each with their own relative merits and weaknesses, but also to highlight a potential synergy between the approaches with respect to both technological and societal readiness. A centralised processing approach could develop as an intermediate step towards a self-contained toilet, continuing to utilise some centralised facilities particularly where new resource recovery technologies have been produced, or the two paradigms proposed could find synergy in different parts of the world, where technology availability and social acceptability may vary.

In both scenarios, it is not anticipated that existing sewer networks would be rendered redundant. In the UK and other developed countries, the sewer systems carry a combination of urban runoff (i.e. drainage of rainfall from buildings and streets), greywater (of low biological risk, derived from sinks and baths), and blackwater (untreated human waste). In storm events, wastewater treatment plants have extra capacity to store and treat the water at a later time, when the storm has passed. However, in times of prolonged, heavy rainfall, the water industry is permitted to discharge directly to natural systems. These discharges are particularly problematic because the combined nature of the sewage system means that they also contain blackwater[21.] Whilst some drainage systems would need to remain in place to deal with urban runoff, the health of the receiving ecosystem would be much improved if blackwater was never allowed to enter it. Similarly, the carriage and treatment of greywater in the current sewered society is particularly inefficient given the low risk of pathogenic contamination. Greywater does contain ammonia, phosphorus and nitrogen, nutrients that are problematic for the environment, but at levels of around 10 % of those found in blackwater[22]. A number of different technologies have been applied to treat and recycle urban runoff and greywater in decentralised settings, including small constructed reed bed wetlands, membrane bioreactors and "green roof" recycling systems[23]. It has already been shown that decentralised systems for treating greywater are much more sustainable in terms of water quality, energy consumption, and CO_2 emissions than a centralised reuse system that also treats blackwater, only demanding between 11.8 and 37.5 % of the energy consumed in a centralised treatment plant[24]. Whilst the technology and the will already exists in many cases for the decentralised treatment of greywater and urban runoff[25], it is the treatment of blackwater that poses both the highest risks and greatest opportunities for human health and the stress nexus of water, energy, food and the environment, and is consequently the main focus of this think piece.

A fully self-contained toilet

In this scenario, the widespread uptake of a fully self-contained toilet is explored. Users will replace their current sanitation system with a portable or fixed unit that is compact enough to be accommodated within existing facilities. Like most appliances, financial options could be offered, ranging from owning the unit outright and self-maintaining it (internal parts are likely to need regular servicing), or renting it from a managing company with service schedules included in the payment schedule. Both models can be applied to low income and high income countries alike. The overall vision for the unit is that the only inputs are derived from human waste (and possibly toilet paper or wash water depending on the cultural setting), and the net outputs are water, energy and inert waste for inclusion in household refuse (Figure 3).

Figure 3: A vision of a fully self-contained toilet



With current state of the art toilet designs in mind (Table 1), the treatment of human waste in a fully self-contained system is likely to begin with the separation of urine and faeces. Whilst diverting toilets with separate channels in the bowl have not been reliable to date (mostly because of user behaviour), there are other methods that can achieve urine/solid separation within the unit, requiring no change to user behaviour. An internal holding chamber can be employed with an overflow weir that separates out gross solids. Whilst this does mean that the urine is potentially contaminated with pathogens, it also means that one internal reservoir contains >99% water, and the other ~70% (the average amount of water in human stool). The liquid treatment can now commence, using micro or nanofiltration processes, for example. Modern filtration membrane materials made from silicon tubing are now available that are cheap to buy in comparison to more complicated polymers, and can reject all solids and pathogens from passing through. The idea here is to selectively remove water from the urine as a vapour, which can then be condensed downstream and recovered. The water will be pathogen and nutrient free, and safe to dispose of directly into the environment. In the meantime, the solid waste is prepared for a combustion process, being dried by the heat generated from the combustion of previously processed faecal matter. The combustion of dried solid residues generates enough power to run the filtration process, likely to be accomplished using a small vacuum pump. The interception of CO2, NOx and SOx from the burning solids can be achieved using a suite of adsorbents such as zeolites, activated carbons, chemisorbents such as calcium and magnesium oxides and silica/amine hybrids[26]. Ash from the process will be microbiologically inert and therefore safe for disposal alongside household waste. These technologies are all existent and can be accommodated within a unit barely larger than a conventional toilet with cistern.

The average amount of water used per person per day in the United Kingdom is 150 litres, of which 50 litres are used to flush the toilet[27]. Since no water is used in the fully self-contained toilet, the use of such a system represents a saving of approximately 415 million litres of water per day in London (based on the current population of 8.3 million), and would make proper sanitation far easier to achieve in a low income country setting that has no water supply infrastructure. Furthermore, the water recovered from the system could be in the region of 1 – 1.7 litres per person per day. This water, like the ash residue, will have no pathogens in it, and could be disposed of directly to the environment or used in combination with greywater recycling systems to water plants around the home or to clean floors or even clothes in particularly water stressed environments.

The energy balance of the self-contained toilet is likely to vary depending on the number of users, diet, and intestinal microbial diversity[28]. Broadly speaking, intestinal energy absorption is approximately 90%[29], so that of each daily intake of 2000 kilocalories, only 200 kcal are available post digestion. Not everyone produces stools every single day, and this means that the potential faecal energy per person per day could range from 0 to 2.5 MJ/d[30], or 0 to 0.69 kWh. To put this into perspective, and assuming complete combustion of the solids within the toilet, this upper energy yield could run a 60 watt incandescent lightbulb for 11.5 hours. This energy is not inconsiderable, and if more than one person is using the toilet every day, there's a good chance a dependable fuel will be supplied from it. The bulk of the energy produced will be used to run the toilet, but it may also be possible to output a small amount that could be reintegrated into the national grid or used to charge batteries in the absence of an electrical network. Even if the toilet is neither a producer nor a user of energy, the carbon footprint of dealing with the problem of human waste will be dramatically reduced if the system does not rely on sewers and pumping stations to transport the waste to the treatment works.

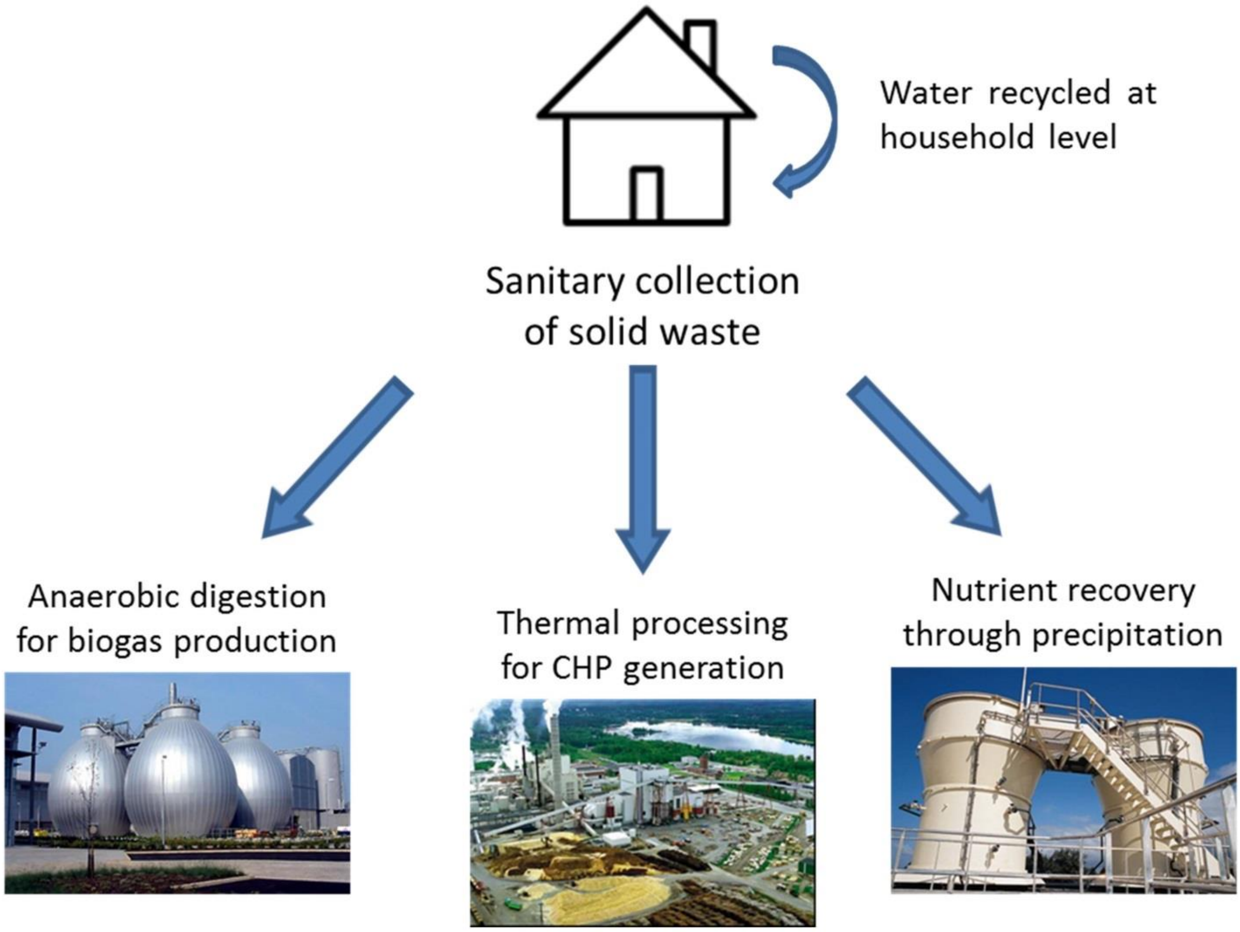
Whilst the ash is likely to be high in nutrients, containing up to 11% phosphorus by mass[31], residual heavy metals and the possibility of the presence of persistent organic compounds[32] make it potentially unsound for fertilising crops that will re-enter the human food chain. The technology currently doesn't exist that can separate the nutrients, metals, and pollutants from the ash in a small enough footprint to be viable at the household scale, but it would be the ideal option. With current technology, it is envisaged that the material could be included in household recycling schemes, where centralised processing plants could be employed to separate out the components. Where this is not possible, landfill is the alternative. The key point is that the ash represents a much lower risk to human health than untreated faecal material.

The main environmental benefit of the widespread adoption of self-contained toilets is their water saving ability. The reduced carbon footprint in comparison to sewage networks, achieved through the self-sustaining energy balance, is also of great significance. Additionally, performing carbon capture on the combustion line within the self-contained toilet will minimise or eliminate greenhouse gas emissions. This compares favourably with the current state of the water industry, which emitted over 5 million tonnes of greenhouse gases during 2010–2011[33], of which 2.8 million tonnes can be attributed to wastewater treatment[34]. For low income countries that are currently without proper sanitation, the total elimination of pathogens in the environment would be of immediate benefit, instantly improving human health and reducing child mortality.

A centralised processing approach

An alternative scenario would involve maintaining in-house water treatment through a new generation of toilet design, but with centralised processing of by-products in order to achieve economies of scale in resource recovery. The toilet would process human waste into re-usable water, which could be connected to greywater reuse initiatives, and solid products that could be collected alongside municipal solid waste schemes already in operation in many parts of the world. These solid products would provide an ongoing income stream, increasing private sector interest in the sanitation sector or enabling government led schemes to be financially sustainable (Figure 4).

Figure 4: Resource recovery options for centralised processing plants. *Photo credits: John Kaufield, ClimateTechWiki, NHM.ac.uk*



The toilet design required for the centralised processing concept does not require such technical challenges as a fully self-contained system. The level of technology, however, will reflect the extent of resource recovery possible. For instance, already in the developing world emerging technologies are being utilised for biogas recovery from faecal sludge, such as the

LooWatt program in Madagascar which operates on a community level shared-toilet scale[35]. In Ghana, the Clean Team project provides household toilets with urine diversion, whilst the solids are collected with the potential for biogas production or thermal processing[12]. Whilst urine diversion would reduce the liquid content and overall volume of waste collected for processing, it also reduces the possibility for nutrient recovery, as the high phosphorus and nitrogen content of the urine is not utilised. More advanced toilet designs, akin to the self-sustained concept described in section 3.1, could precipitate or adsorb nutrients out of the liquid stream during treatment, either for collection or for household use, whilst also providing a level of dewatering within the toilet, further reducing the liquid and bulk volume of solids to be collected. An important design aspect of a toilet for centralised design is likely to be the collection vessel, to ensure the waste is contained safely and the extraction from the toilet by household users is easy and clean. The Clean Team system uses replaceable hard plastic bins, whilst LooWatt uses biodegradable bags for ease of digestion at the processing stage. Whilst technologically easier to implement than the self-contained concept, it would require a higher level of household interaction with their own processed waste, which could provide a social barrier to implementation and uptake, particularly in the developed world where the 'flush and forget' paradigm has become standard, and the majority of the public are removed from the concept of interaction with their own waste.

The collection system is envisaged to operate on a household level, a model which already operates successfully in many developed countries. Indeed, the recent focus on recycling of municipal waste means that both the public and the service delivery sector in many countries are already familiar with the concept of separation of wastes, with different collection dates, and different delivery terminals for the separate waste streams in order for resource recovery in increasingly complex solid waste management systems[36]. In the developing world, solid waste management continues to improve as part of city development[37], whilst the increasing spread of advanced on-site sanitation systems requiring pit latrine desludging or septic tank waste removal mean the collection market is developing in these regions[38]. There would be a number of different options for the resource recovery that could be explored and decisions could be based on technological advances and availability as well as local conditions.

Similar to the self-contained toilet, the in-house toilet for the centralised processing model would also aim to achieve waterless or near-waterless operation, in order to reduce the water requirement for flushing and to limit the amount of liquid waste that needs to be processed. The water savings reduce the treated drinking water demand to households, whilst the clean water produced by the toilet could be a valuable commodity itself for use in a greywater system or for cleaning, watering plants and feeding livestock.

There are a number of options in the operation of a centralised processing model that could change the energy profile of the system. Currently, two primary options are being explored for energy recovery from faecal waste. Anaerobic digestion has now become a widespread technology in conventional wastewater treatment, where sludge produced from wastewater treatment works is digested, typically at 35°C in heated digesters, to reduce the bulk volume of solids and to produce a biogas rich in methane. This gas also contains levels of hydrogen sulphide that require treatment, but once the gas has been 'upgraded' by removing this and other compounds, it can be combusted for CHP generation[39], used to power cars[40], or even sold back into a national gas grid where one exists[41]. In 2011 there were 146 anaerobic digesters already in use in the UK wastewater treatment industry[42], and many of the larger digesters at larger centralised works already import solids from smaller works[43], meaning they are a market-ready technology that would require only little adaptation to receive waste from a household basis. In developing countries, anaerobic digestion is also being used on faecal wastes, with sludge from pit latrines and septic tanks used to generate biogas for cooking[44], and for electricity generation[35]. The advantages of utilising AD, particularly for developing country contexts, is that the required infrastructure is much cheaper and easier to operate than thermal destruction, and there are also options for utilising the gas, both for cooking and power generation, without the need for high-tech gas upgrading[44,35]. Whilst this can cause erosion to infrastructure and prohibits the gas from a national grid, it provides a simple and easy use of the gas without high costs. The digestate remaining after digestion does require post-handling, but can be processed for use as a fertiliser[35].

An alternative option is thermal destruction, either by combustion or gasification/pyrolysis. This would involve feeding the solid waste into a unit similar to that incorporated in the self-contained toilet, but at larger scale which is already in commercial manufacture. These systems reduce solid inputs to an inert ash, whilst excess heat can be used for electricity generation. This electricity could be sold back to a national grid in more advanced economies, or could be used to charge battery units to supply more advanced toilet designs that might require electricity – these could be exchanged at the household level during solid waste collection. Large centralised combustion and gasification technologies are already in use both for municipal solid waste[45] and industrial solid wastes[46], and a new generation of power stations are incorporating biofuel burners, in which household solid wastes could also be deposited[47]. A key element to the successful use of thermal destruction technology to human waste will be the reduction of water content that can be achievable – a maximum solids content of around 25% could be expected from human waste[48], whilst 40% is required to make thermal destruction feasible. This extent of dewatering could be achieved inside the toilet at household level, using similar technology to the self-contained toilet. Centralised facilities could be utilised for further dewatering, particularly in the presence of excess heat at CHP plants, but achieving dewatering at household level is highly preferential, both for reducing the weight and volume of waste that would need to be collected and to recycle as much water in-house as possible.

Whilst the centralised model can benefit from economies of scale in these recovery technologies, as well as providing an extra level of safety through processing waste at regulated facilities with trained personnel on hand, the energy balance will be affected requirements for the collection system. The use of electricity or biogas for fuelling collection vehicles could be explored as these alternative fuel sources develop in the automotive market, whilst incorporation with existing solid waste systems could be explored.

The recovery of nutrients could be possible from within the toilet, either by adsorption or less common methods as struvite preciptation for phosphorus recovery and air stripping for nitrogen recovery[49], producing concentrated by-products. These could potentially be utilised at household scale, but it is expected that collection alongside the solid wastes would be more practical, as the collection system would already be in place, and wholesale collection and sale of fertilisers would improve the economic incentives for system operators as well as help support volatile fertiliser markets in the food production sector. Additional nutrients that remain in the solid phase could potentially be extracted at a centralised facility, prior to energy recovery processes such as anaerobic digestion or thermal processing such as pyrolysis or combustion, and there are currently a number of pilot and full scale technologies available[50]. In addition, where anaerobic digestion is used for energy recovery, the remaining digestate can also be processed for use as a fertiliser product as discussed in the previous section, and may be a more viable option in developing countries to avoid the higher level technologies for full-flow nutrient recovery.

The environmental benefits in avoiding mixing blackwater with stormwater, and the environmental contamination that can follow both in developed and developing countries (see section 2.1), are the same as with the self-contained toilet. In addition to the saving on treatment works emissions discussed in section 4.5, these also include a significant reduction in pumping requirements to transport the water to the treatment works. However, the carbon emissions from a centralised model are more complicated, as the transportation of the collection system must be taken into account. Where possible, gas or electric powered vehicles could reduce these emissions, and could be fuelled from the central processing facilities. Excess power and/or gas generated at these facilities can be sold, either back into a national grid or on smaller scale to local consumers, such as cooking gas, and phone charging, to offset carbon emissions.

Towards a sewerless society – evaluation and planning framework

The technologies described in the above paradigms exist, either at commercial, pilot or conceptual level. This section now proposes a planning framework for assessing the trajectories towards the use of such technologies in a sewerless society. It addresses technological development but also provides a broader framework for incorporating social, economic and political factors that would be essential for a transition to this paradigm. The ultimate aim is to develop a framework that can be applied to different settings in order to develop an empirically grounded Theory of Change (ToC) for moving toward a sewerless society in any specified situation, such as the two technological scenarios presented above. For this purpose, this section brings together thinking from socio-technical systems[20,51,52] and sector-level Political Economy Analysis[53,54], to propose an approach for assessing and delineating the social and material factors that shape or have the potential to shape the wastewater sector. The framework recognises that material infrastructure cannot be considered through a wholly technical paradigm as it is part of a broader socio-technical system that has co-evolved with social practices and values. For example, such a perspective recognises that, whilst the washing machine led to significant shifts in laundry practices, social norms regarding washing machine use have also lead to significant changes in the design of the technology[55]. Similarly, the planning framework for a sewerless society must therefore recognise the relational aspect of social and technological change which is path-dependent but driven by the complex relations between technical innovation and broader societal pressures.

Table 2: Planning Framework for Sanitation Sector

Environmental	***Technological***	***Political-economy***	***Socio-ideological***
More material ←-- → More socially constructed			
Structures Geographical – location, availability and type of land, hydrogeological conditions, water-source conditions, local agricultural conditions, climatic conditions; Human settlements – population density, household size; Biological - prevalence of infectious diseases, including rates of diarrhoea.	**Structures** Infrastructure – existing sewerage infrastructure, transport infrastructure, supply chain infrastructure ; Technical – technologies in the innovation piped-line, human resources.	**Structures** Economic – sector composition, systems of production and maintenance of infrastructure/technology, division of labour, human resources; Energy and resource markets – supply & demand for energy, supply and demand for agricultural products; Political – regime type, sovereignty, legislative process, initiating regulatory change, EU regulation.	**Structures** Social - Class, caste, ethnicity, nationality, gender, age, (dis)ability; Ideological - Sanitary hygiene practices, assumptions about sanitation, health and the environment, social norms.
Institutional "rules-of-the-game" Land tenure; Environmental regulation; Planning regulation; Official status of areas (forestry, SEZs, heritage, farming).	**Institutional "rules-of-the-game"** Asset ownership; Wastewater output standards and regulation; Intellectual property regime.	**Institutional "rules-of-the-game"** Property rights; Economic regulation; Tax system; Legal system; Political regime (executive, legislature, electoral system, judiciary); Local government bureaucracy Patronage, chieftainship, corruption.	**Institutional "rules-of-the-game"** Social norms; Sanitary habits and practices; Consumer demand; Laws & rules on rights, such as disability legislation; Customary governance structures (e.g. caste councils); Education system.
Key Actors Shaping Institutional Dynamics Government (National, State, Local); Supranational governance organisations.	**Key Actors Shaping Institutional Dynamics** Utility operators (public or private); Government (National, State, Local); Supply chain companies; Researchers & Technologists.	**Key Actors Shaping Institutional Dynamics** Utility operators (public or private); Government (National, State, Local); Civil society.	**Key Actors Shaping Institutional Dynamics** The Public; Educators; Marketers; Civil society; Government (National, State, Local).

Political Economy Analysis (PEA) helps anchor the framework by providing a more structured approach to anticipating how this co-evolution of social and technical factors is both shaped by and shaping the behaviour of actors in the sector. Based on the new institutional economics of North[56], PEA is an influential model for anticipating sector-level change in development projects[53,54]. It is particularly valuable as it helps identify important political-economy questions, such as who stands to benefit from change and who may lose out, which are fundamental to proposing a realistic ToC. From this perspective, the socio-technical sanitation systems in London, Delhi and elsewhere consist of the existing infrastructure and physical environment as well as a varied coalition of actors who are governed by institutional structures and norms that shape their behaviour. These institutions can be formalised, such as water quality regulation, or informal, such as anal hygiene practices, but together these institutions represent the "rules of the game" that dictate how actors act within the sector[56]. Certain actors, such as governments, have a much greater potential to change the system whilst particular structural conditions, such as groundwater depletion, can radically shift the balance of incentives for actors. In terms of realising planned change, creating a convergence of interests between powerful actors is more likely to lead to a sustainable transition, whilst a single actor promoting change is likely to hit resistance from the other actors, who may be better served by the status quo. Such principles are important to consider when anticipating sector-level change and so provide guiding principle in the application of this planning framework.

Applying this thinking to the sanitation sector, a planning framework has been developed centred on four meta-categories – environmental, technological, political-economy, socio-ideological – that helps group relevant structures, institutions and key actors (Table 2). Broadly speaking, the environmental category refers to the overall geographical setting and biophysical conditions; the technological typology includes existing infrastructure and the availability of technology; the political-economy domain includes the sector composition and regulation, as well as the political governance model; finally, the socio-ideological category concerns how class, gender, age and disability intersect with sanitation and the norms and beliefs around sanitation infrastructure. Whilst, the relevant actors initially identify include government agencies (e.g. municipalities, local, national and supranational bodies), private water companies and their supply chain, small-scale private sector agents, the general population (both, sewerage users and those without sanitation facilities), civil society groups and many more individuals and groups. The categories are not mutually exclusive with actors and institutions spanning different areas, nor do they follow an inherent flow or hierarchy of causality, with changes in any domain having the potential to lead to changes in any other.

However, it is envisioned that any transition to the sewerless society would involve fundamental shifts in these areas.

In anticipating the application of this basic framework to case studies, such as London and Delhi, the structural conditions, institutional structures and key actors in each area would be identified. This would involve making uses of the available secondary data, such as environmental and demographic databases, to provide information on the structural conditions listed in the table. Detailed qualitative descriptions of the current institutional structures would also be collected, ideally from interviews with relevant stakeholders, as well as a detailed inventory of actors in each domain. This assessment could be used proactively, in conjunction with a conventional ToC approach[57], in which the end goal of a sewerless society is imagined and then planners work back from this point to identify the changes that need to occur to reach this goal. An emphasis here will be identifying the short, intermediate and long term decisions that planners can take to shape the co-evolution of the socio-technical system. It could also be used reactively, to capture how structural conditions are changing in order to anticipate future developments in the sewerage sector, whether that is towards the radical sewerless option or a more reformist future. This could involve assessing historic and current trends to make informed predictions on future developments. Whilst the application of this framework is beyond the scope of this think piece, this section provides a solid conceptual foundation for identifying and assessing the logical pathways of change that would need to occur to reach a sewerless society.

Conclusions

This paper argues that sewerless sanitation technology has the potential to transform the way wastewater treatment intersects with and shapes the nexus of water, energy, environment and food. Technically speaking, compared to conventional sewerage systems, such technologies could deliver a saving of 50 litres of water per person per day in the UK, reduce the energy demand of waste water systems, provide a means for resource recovery of phosphorus and nitrogen products that can be used to fertilise agricultural land, and reduce the chemical and pathogenic contamination of natural ecosystems. In an age where many developed cities are facing significant costs in rehabilitating and expanding existing sewerage systems and many cities in the developing world continue to have completely inadequate sewerage facilities for their growing populations, it becomes prudent to seriously consider alternatives to the conventional model of centralised sewers. To some extent this is already happening in the developing world as organisations such as the Clean Team social enterprise in Kumasi, Ghana, experiment with a new generation of sewerless toilets. However, sewerless technologies continue to remain niche and widespread uptake has not occurred. Moving beyond the technical literature, the paper ends by considering what factors are shaping the current developmental trajectories of socio-technical sewerage systems. Drawing on PEA, it proposes a planning framework that brings together environmental, technological, political-economy, socio-ideological factors and which represents a useful starting point for further empirical investigation into these matters.

Bibliography

1. Cordell, D., Drangert, J.-O., White, S. The story of phosphorus: Global food security and food for thought. Global Environmental Change 2009, 19 (2): 292-305.

2. Murray, C.J.L., Lopez, A.D. Global mortality, disability, and the contribution of risk factors: Global Burden of Disease Study. The Lancet 1997, 349 (9063): 1436-1442

3. World Health Organization. Global health risks: mortality and burden of disease attributable to selected major risks. World Health Organization Publication, Geneva, Switzerland, 2009, 70.

4. http://www.thameswater.co.uk/about-us/10092.htm (accessed 17th October 2014)

5. http://www.expressdrainagesolutions.co.uk/news/infographic-victorian-sewers-london-thames-tideway/ (accessed 17th October 2014)

6. http://www.thamestidewaytunnel.co.uk/news/media-centre/london%E2%80%99s-river-treated-like-a-loo (accessed 17th October 2014)

7. United Nations. World Urbanization Prospective: 2014 Revision, New York, 2014, 168.

8. CAG-India, (2013), Report No. 2 of 2013 Government of Delhi - Report of the Comptroller and Auditor General of India on Social Sector (Non PSUs). New Delhi: Comptroller and Auditor General of India.

9. Delhi Mission Convergence (Samajik Suvidha Sangam), (2012), Water and Sanitation Baseline Survey 2012, New Delhi: Government of NCT of Delhi (GNCTD).

10. Delhi Jal Board, (2014), Draft Sewerage Master Plan 2031. New Delhi: Delhi Jal Board.

11. Werner, C., Panesar, A., Rud, S.B., Olt, C.U. Ecological sanitation: Principles, technologies and project examples for sustainable wastewater and excreta management. Desalination 2009, 248: 392 – 401.

12. http://www.cleanteamtoilets.com/our-model/ (accessed 04/09/14)

13. http://www.biofilcom.org/static/pdf/how-biofil-toilet-system-works.pdf (accessed 04/09/14)

14. http://www.gatesfoundation.org/What-We-Do/Global-Development/Reinvent-the-Toilet-Challenge (accessed 04/09/14)

15. http://www.borda-sea.org/basic-needs-services/dewats-decentralized-wastewater-treatment.html (accessed 08/09/14)

16. http://www.nanomembranetoilet.org/ (accessed 09/09/14)

17.http://info.ncsafewater.org/Shared%20Documents/Web%20Site%20Documents/Annual%20Conference/AC13_ TechnicalProgram/Wastewater/WW_Mon_PM_01.20_Forbis-Stokes_PAPER.pdf (accessed 09/09/14)

18. http://www.bluediversiontoilet.com/ (accessed 09/09/14)

19. http://abettertoilet.org/toilet-technologies/ (accessed 09/09/14)

20. Teh, T.-H. (2013). Bypassing the flush, creating new resources: analysing alternative sanitation futures in London. Local Environment 2014, 1–15. doi:10.1080/13549839.2013.847409

21. Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., Morgan II, R.P. The urban stream syndrome: Current knowledge and the search for a cure. Journal of the North American Benthological Society 2005, 24 (3): 706-723

22. Gray, S.R., Becker, N.S.C. Contaminant flows in urban residential water systems. Urban Water 2002, 4 (4): 331-346.

23. Memon, F.A., Zheng, Z., Butler, D., Shirley-Smith, C., Lui, S., Makropoulos, C., Avery, L. Life cycle impact assessment of greywater recycling technologies for new developments. Environmental Monitoring and assessment 2007, 129 (1-3): 27-35.

24. Matos, C., Pereira, S., Amorim, E.V., Bentes, I., Briga-Sa, A. Wastewater and greywater reuse on irrigation in centralized and decentralized systems – An integrated approach on water quality, energy consumption and CO_2 emissions. Science of the Total Environment 2014, 493: 463-471.

25. Pidou, M., Mamon, F.A., Stephenson, T., Jefferson, B., Jeffrey, P. Greywater recycling: Treatment options and applications. Proceedings of the Institution of Civil Engineers: Engineering Sustainability 2007, 160 (3): 119-131.

26. Choi, S., Drese, Jeffrey H. and Jones, Christopher W. Adsorbent Materials for Carbon Dioxide Capture from Large Anthropogenic Point Sources. ChemSusChem 2009, 2: 796–854.

27. http://www.waterwise.org.uk/data/resources/25/Water_factsheet_2012.pdf (accessed 25/09/14)

28. Jumpertz, R., Le, D.S., Turnbaugh, P.J, Trinidad, C., Bogardus, C., Gordon, J.I., Krakoff, J. Energy-balance studies reveal associations between gut microbes, caloric load, and nutrient absorption in humans. American Journal of Clinical Nutrition 2011, 94 (1): 58-65

29. Wierdsma, N.J., Peters, J.H.C., van Bokhorst-de van der Schueren, M.A.E., Mulder, C.J.J., Metgod, I., van Bodegraven, A.A. Bomb calorimetry, the gold standard for assessment of intestinal absorption capacity: Normative values in healthy ambulant adults. Journal of Human Nutrition and Dietetics 2014, 27 (SUPPL2): 57-64.

30. Murphy, J.L., Wootton, S.A., Jackson, A. Variability of fecal energy content measured in healthy women. American Journal of Clinical Nutrition 1993, 58 (2): 137-140.

31. Donatello, S., Tong, D, Cheeseman, C.R. Production of technical grade phosphoric acid from incinerator sewage sludge ash (ISSA). Waste Management Journal 2010, 30: 1634-1642

32. Weigand, H., Bertau, M., Hubner, W., Bohndick, F., Bruckert, A. RecoPhos: full scale fertilizer production from sewage sludge ash. Waste Management 2013, 33 (3): 540-544.

33. http://www.water.org.uk/home/news/press-releases/indicators2010–11 (accessed 25/09/14)

34.https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69346/pb13562-future-water-080204.pdf (accessed 16/10/14)

35. http://www.loowatt.com/system/ (accessed October 17 2014)

36. Pires A., Martinho G., Chang N-B. Solid waste management in European countries: A review of systems analysis techniques

37. Hoornweg D., Bhada-Tata P. What a waste: A global review of solid waste management, World Bank, Washington DC, 2012

38. Ingallinella A.M., Sanguinetti G., Koottatep, T., Montanegro, A., Strauss, M. The challenge of faecal sludge management in urban areas – strategies, regulations and treatment options. Water Science and Technology 2002, 46 (10): 285-294. doi:

39. Poschl M., Ward S., Owende P. Evaluation of energy efficiency of various biogas production and utilization pathways. Applied Energy 2010, 87 (11): 3305-3321. doi: 10.1016/j.apenergy.2010.05.011

40. http://www.wessexwater.co.uk/news/threecol.aspx?id=6044 (accessed October 17 2014)

41. http://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/agriforenergy_2_international_biogas_and_methane_report_en.pdf (accessed October 17 2014)

42. http://www.biogas-info.co.uk/index.php/ad-map.html (accessed October 17 2014)

43. Cruddas P.H., Wang K., Best D., Jefferson B., Cartmell E., Parker A., McAdam E. Diagnosis of an anaerobic pond treating temperature domestic wastewater: An alternative sludge management strategy for small works. Ecological Engineering 2014, 63: 64-71 doi: 10.1016/j.ecoleng.2013.12.011

44. http://www.newstimeafrica.com/archives/35876 (accessed October 17 2014)

45. http://www.vir.com.vn/green-power-in-hanoi.html (accessed October 17 2014)

46. http://www.waste-management-world.com/articles/print/volume-13/issue-6/special-waste-energy-focus/waste-gasification-final-coming-age.html (accessed October 17 2014)

47.http://www.biomassenergycentre.org.uk/pls/portal/docs (accessed 17 October 2014)

48. ‘Characterisation of urine, faeces, and blackwater’ presentation available from webpage http://ocw.unesco-ihe.org/course/view.php?id=8 (accessed 17 October 2014)

49. Antonini S., Paris S., Eichert T., Clemens J. Nitrogen and phosphorus recovery from human urine by struvite precipitation and air stripping in Vietnam. Clean – Soil, Water, Air 2011, 39 (12): 1099-1104 doi: 10.1002/clen.2011.00.036

50. http://www.sswm.info/content/advanced-nutrient-recovery (accessed 17 October 2014)

51. Geels, F. W. From sectoral systems of innovation to socio-technical systems. Research Policy 2004, 33(6-7), 897–920. doi:10.1016/j.respol.2004.01.015

52. Geels, F. W., & Kemp, R. Dynamics in socio-technical systems: Typology of change processes and contrasting case studies. Technology in Society 2007, 29(4), 441–455. doi:10.1016/j.techsoc.2007.08.009

53. Edelmann, D. (2009). Analysing and managing the political dynamics of sector reforms : a sourcebook on sector-level political economy approaches. London. (to replace with: http://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/5232.pdf (accessed 17/10/14))

54. Hudson, D. Leftwich, A. (2014). From Political Economy to Political Analysis. University of Birmingham. To replace with: http://www.dlprog.org/publications/executive-summary-from-political-economy-to-political-analysis.php accessed 17/10/14

55. Shove, E. Comfort, Cleanliness and Convenience: The Social Organization of Normality. Bloomsbury Academic 2003, 221.

56. North, D. C. Institutions, Institutional Change and Economic Performance. Cambridge University Press 1990, 152.

57. http://r4d.dfid.gov.uk/pdf/outputs/JSRP/ToC_Lit_Review.pdf (accessed 17/10

The Nexus Network

www.thenexusnetwork.org

@uk_nexus

For general enquiries
E info@thenexusnetwork.org
T 01273 678350

The Nexus Network
SPRU
University of Sussex
Jubilee Building
Brighton BN1 9SL
UK

To receive updates about
Nexus Network events and
funding opportunities sign up

www.thenexusnetwork.org/join

Funded by the ESRC, the Nexus Network brings together researchers, policy makers, business leaders and civil society to develop collaborative projects and improve decision making on food, energy, water and the environment. Nexus Network Project partner

University of Sussex

STEPS centre

UNIVERSITY OF CAMBRIDGE
INSTITUTE FOR SUSTAINABILITY LEADERSHIP

University of East Anglia