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City blood: A visionary infrastructure solution for household energy provision through water distribution networks☆

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ABSTRACT

This paper aims to expand current thinking about the future of energy and water utility provision by presenting a radical idea: it proposes a combined delivery system for household energy and water utilities, which is inspired by an analogy with the human body. It envisions a multi-functional infrastructure for cities of the future, modelled on the human circulatory system.

Red blood cells play a crucial role as energy carriers in biological energy distribution; they are suspended in the blood, and distributed around the body to fuel the living cells. So why not use an analogous system – an urban circulatory system, or “city blood” – to deliver energy and water simultaneously via one dedicated pipeline system? This paper focuses on analysing the scientific, technological and economic feasibilities and hurdles which would need to be overcome in order to achieve this idea.

We present a rationale for the requirement of an improved household utility delivery infrastructure, and discuss the inspirational analogy; the technological components required to realise the vignette are also discussed. We identify the most significant advance requirement for the proposal to succeed: the utilisation of solid or liquid substrate materials, delivered through water pipelines; their benefits and risks are discussed.

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1. Introduction

Today, cities rely on multiple utility infrastructure systems of great complexity, which have high associated investment and management costs. There is a wealth of literature which provides evidence of the poor state of Europe’s infrastructure [1], highlighting a clear and urgent need for visionary approaches to revolutionising the current system.

In the years ahead, cities and other large communities will encounter resource distribution crises associated with dramatic population flux, with improper water and land resource utilization, with fossil fuel resource depletion, with increased investment overheads, and with spiralling maintenance and management costs; hence sustainable civic systems are necessary in order to minimise the impact of these emergent problems.

Furthermore, recent developments in climate research have also forced governments to select from the best available engineering practices in order to minimise environmental impacts [2,3]. In such circumstances, visionary thinking and radical new ideas can offer promising potential solutions. Had such social, environmental and political factors influenced us sooner, we would most probably have a very different urban infrastructure to that which we have today.

Tremendous effort has gone into the development of environmentally friendly infrastructure, ranging from one-shot local projects to regional and global schemes, such as carbon trading programs. There is, however, one obvious solution to the problems above: eco-friendly, sustainable, multi-functional and flexible infrastructure systems.

In this context, many innovative ideas have been proposed by corporations, scientists, engineers, artists and futurists in order to shape next-generation urban infrastructure systems for improved performance, as measured by increased efficiency, reduced costs, minimal redundant investment and research, and negligible environmental impacts. Examples include “smart grids” and “smart houses” [4], self-sufficient homes and cities [4–6], “smart cities” [7], new approaches to integrated infrastructure development [8], and even the provision of all utility services via one single infrastructure [9].

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This study highlights a key question in utility infrastructure foresight: “How different might our infrastructures look if, when we began to construct them, we’d known all that we know now?” Furthermore, it advances the radical concept of a combined household energy and water delivery infrastructure which might be made possible by emerging technological developments and advances.

The dominant technological challenge identified by this study is the distribution of a novel energy carrier or fuel via extant water distribution systems. Potential fuels and energy carriers include solid and liquid substrate hydrogen carriers, fossil fuels and biofuels. The ultimate aim of the study is not to advocate for the adoption of any particular solution, but to provoke discussion and thinking toward shaping a future infrastructure system which is environmentally friendly, sustainable, multi-functional, manageable and flexible; as such, we encourage the scientific community to consider this radical approach.

Section 2 presents the methodology used in the paper, while Section 3 discusses the results and findings; Section 4 presents the conclusions drawn from our evaluations and analyses.

2. Methodology

This study adapts an objective-focused technique [10] in order to evaluate a possible future infrastructure solution based on the All-in-One concept [9]. The methodology includes a series of five processes represented in a triangle, as shown in Fig. 1; it begins with the proposed vision, and each process then takes up the output of the one preceding it. The triangulation represents the filtering performed in each process.

The first step, key process identification, aims to define the engineering processes required to achieve the given vision. Next, the functional requirements of the selected key processes are analysed in the second step. The third step involves a search process to identify technologies which satisfy the requirements defined for the selected key processes; the selected technologies are then evaluated in the fourth process. The final step is the preliminary economic feasibility assessment of the suggested solutions.

The details of the original vision and the methodological processes are discussed in the following subsections.

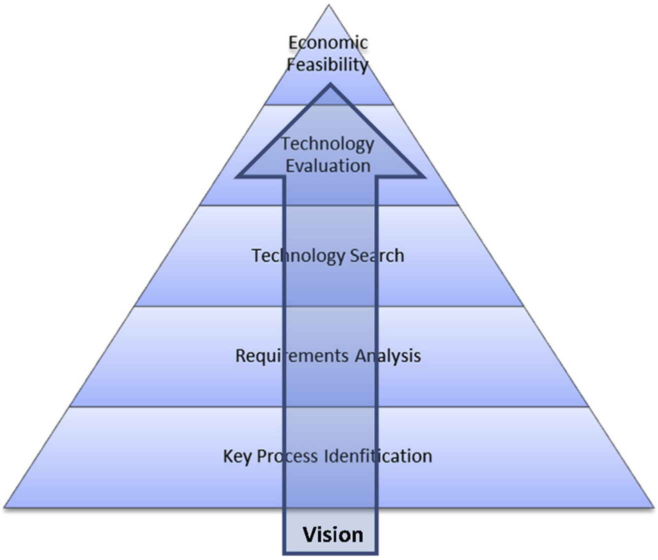

Fig. 1. Technological feasibility assessment and gap identification framework.

2.1. Vision

We propose the joint provision of energy and water through a single pipeline network. This approach has the potential to eradicate the redundant investments attendant on multiple discrete infrastructures, and to reduce negative environmental impacts. This system resembles a city circulatory system, and was originally proposed as a potential “All-in-One” infrastructure solution [10].

The cell is the basic structural unit of the biological body; its needs are supplied by the capillaries and blood vessels. A house is the basic functional unit of the urban body; its needs are supplied by networks of infrastructure. Blood is the carrier liquid which delivers and collects water, energy, and waste products throughout the body via the arteries and veins of the circulatory system.

Of course, an analogy can only stretch so far, and comes complete with its own pros and cons – so while a biomimetic approach might provide a workable solution to urban infrastructure improvement, such a solution must be assumed to come with inherent challenges alongside its advantages, and we endeavour to explore both in the sections to follow.

2.2. Key process identification

The main aim of this visionary study is to encourage people to question the assumed need for multiple discrete infrastructure systems, and to dare to think radically about the future of utility service provision. Four key processes required for a viable system have been defined, as follows: energy generation and water supply (process 1); unified energy and water delivery (process 2); household energy and water utilisation (process 3); and wastewater management, onsite treatment and waste to energy technologies (process 4).

Process 1, the “generation” phase, involves combining energy carriers with water prior to distribution: in the “blood of the city” analogy, this represents the lungs, where oxygen is combined with haemoglobin in the blood; in the proposed distribution system, this is the power generation unit where the energy is stored in the energy carriers and fed into the city blood.

Process 2 is the distribution of the energy carriers within the water, process 3 is the separation of the energy carrier from the water at the final consumption point. This paper focuses only on the innovative part of the proposed system, namely the unification of energy and water delivery (process 2); readers are directed to the extant literature for evaluations of suitable alternatives for future energy and water provision, household utilisation, and waste management technologies and components (processes 1, 3 and 4).

A graphical illustration of the “blood of the city” vignette and its key processes is presented in Fig. 2.

2.3. Requirements analysis

The technological feasibility of an infrastructure project depends on its capacity to fulfil certain physical requirements, such as the volume of water which must be delivered per household by a pipeline system. Here we discuss the requirements we assume of our proposed system.

Firstly, required levels of household energy, water, and waste disposal provision were calculated with reference to statistical data for current consumption levels in the UK; then some baseline assumptions were made in order to extrapolate a projection of future household utility requirements. Secondly, the infrastructure’s throughput requirements – such as the volume of water to be distributed, and the energy-carrier mass percentages in the joint delivery system – were calculated.

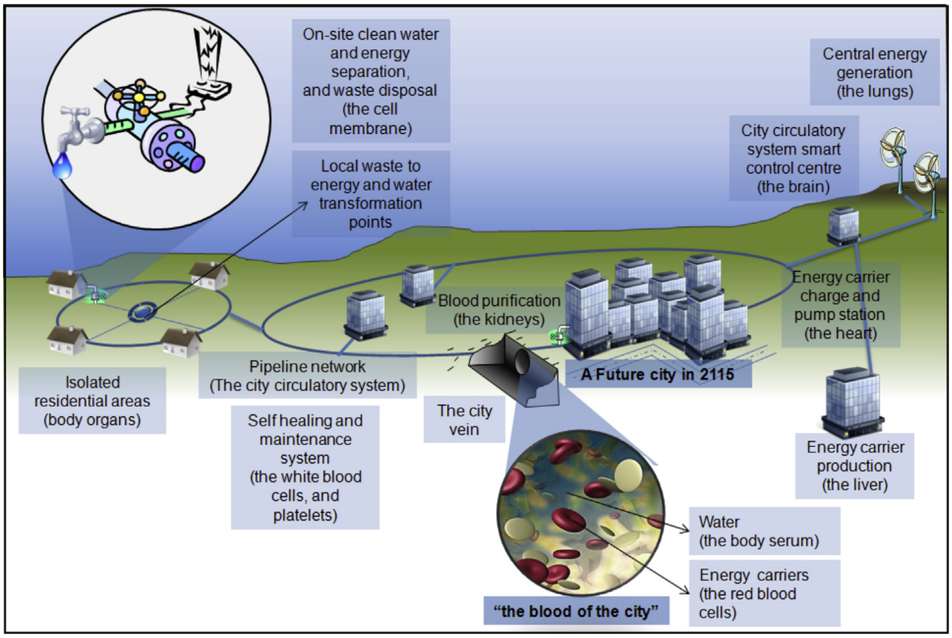

Fig. 2. Graphical illustration of the blood of the city vignette and key process.

2.4. *Technology search and evaluation*

In this particular work, special attention was paid to the technological feasibility of the proposed solution. Accordingly, we followed the scientific and technological feasibility assessment and gap identification method suggested by Karaca et al. [10], using a strategic foresight exercise combined with scenario building. This included a comprehensive literature review, and a detailed science and technology search supported by the input of external domain-specific experts. The technological details thus obtained were used to root the "blood of the city" vision in plausible and realisable science and technology. As a last step in this process, potential alternative provision methods from among the generic technologies uncovered by the search were investigated in detail, and technological and scientific gaps to realisation were identified.

2.5. *Preliminary assessment of economic feasibility*

Our aim is not to provide a comprehensive economic feasibility assessment of a realisable infrastructure system, but rather to advance reasonable arguments by addressing some realistic criteria related to our revolutionary infrastructure concept. This fits the nature of a visionary study, as almost no measured or experimental data is yet available to quantify the phenomena under consideration [41]; as such, we have compared some "city blood" circulatory system alternatives with conventional disparate electricity grids and water pipeline networks (EW) as currently in use. As identified in the extant literature, the most significant economic criteria of a pipeline network infrastructure are installation investment and operational overheads [12]; hence, we have focused on arguments related to these cost criteria in order to provide a preliminary assessment of the proposed system's economic feasibility.

At this point, an installation cost estimation methodology for an existing technology (e.g. fuel, water, H_2, or CO_2 pipeline networks) was followed, in order to compare the possible "blood of the city" systems with conventional energy and water distribution systems. There exist multiple pipeline investment cost models, including linear cost models, pipeline weight based models, quadratic equations, and flow rate models [43]. A linear cost relation model suggested by Van der Zwaan et al. [11] was selected; this model deploys a linear cost relationship in order to calculate investment costs based on a constant cost factor, accounting for the diameter and length of the selected pipeline stock, and applying correction factors for different terrains, for (not) following traditional pipeline corridors, and for different regions. Details are available in Ref. [11].

3. Results and discussions

This section discusses the results obtained during the four steps of the methodology.

3.1. *Key processes considered*

In any infrastructure feasibility analysis, a definition of the system boundaries and infrastructure components under consideration is essential [12]. A vignette of this scale, by necessity, includes not only the unified distribution system under consideration, but also an assortment of related developments in the fields of infrastructural sustainability and future energy markets; however, exploring them in detail is beyond the scope of this paper.

3.1.1. *Water delivery*

One of the cost- and investment-related advantages of the proposed system is that it makes (re)use of an existing infrastructure – namely urban water distribution networks – with some modifications. This redeployment of legacy infrastructure may confer a significant economic advantage on the proposed system [13]; it would reduce multiple disparate utility delivery infrastructures – e.g. gas, electricity and water – into one united circulatory network. In such a system, the carrier liquid would be water, which can be pumped using well-studied and established methods and systems.

3.1.2. *Energy delivery*

The key scientific hurdle in this vignette is the distribution of energy using water as a medium. Technologies and applications with the potential to realise a combined water and energy delivery system already exist: examples include pneumatic freight-capsule pipeline transport [14,15], the production of H_2 from water using solar light [16,17], and hot water piped from district-heating cogeneration plants. District heating, when considered as a way of using water to "carry" energy, may be the most technologically feasible system for unified energy and water distribution at the present time. However, almost all district heating applications focus on centralised hot water generation and distribution for use in residential or commercial space-heating applications; the "blood of the city" proposal takes this approach one step further by also allowing clean, potable water to be extracted from the system.

In addition to these known practices, this study suggests an alternative energy delivery option: solid/liquid-substrate hydrogen carriers and/or bio/fossil fuels, dissolved or suspended in water, their extraction at point of use made feasible by future advances in materials science and technology. The fuel or the energy carriers, mixed into city water and distributed through water pipeline, would be separated from the city blood and collected at receptor sites (e.g. houses, buildings); there, they will be utilised to generate useful energy (e.g. in hydrogen fuel cells). One possible delivery process involves (re)charging energy carriers or introducing fuel to the water at a central location (much as lungs do with oxygen in our bodies), pumping the resulting mixture around the community through pipelines (much as the heart does), and then processing the carriers or fuel on-site in order to extract energy for household energy use (much as the cells of the body extract oxygen from oxygenated blood cells).

3.1.3. *Energy and water separation*

The other important feature of the concept is that in every receptor site (e.g. houses, dwellings), potable water will be separated from the "city blood" (a mixture of water and energy carriers) by means of an on-site filtration/separation system, acting in a manner analogous to the interface between capillaries and cell membranes. This process is made possible by recent advances in biomimetic membrane technologies, which have opened up new possibilities for water purification whose advantages include high throughput and reduced energy consumption [18]. The technology alternatives are not limited to biomimetic membranes, however; there are other promising (albeit more energy-intensive) processes, such as reverse osmosis, forward osmosis, membrane distillation, and electrodialysis.

3.1.4. *Limitations*

In the human circulatory system, blood also removes waste materials from cells and tissues. In a city circulatory system, however, it might be a better solution to treat black and grey wastewater locally in each building, or at small-scale local wastewater treatment plants [19,20], thereby avoiding the need to transport clean water and wastewater together in the same pipeline system, which would lead to complex sanitation, pollution and maintenance challenges. Thus this study assumes the inclusion of domestic conversion of grey water into potable water as part of the community's technological landscape.

3.2. *Requirements analysis*

3.2.1. *Household utility demand and provision*

Today, the average consumption of gas and electricity by UK consumers (i.e. assuming a three-bedroom property) are estimated at about 25,000 kWh and 5500 kWh per year, respectively [21]; the average daily energy requirement for households is hence calculated to be approximately 84 kWh. The mass of household solid waste generated per capita in England in 2012 was 449 kg per person [22].

Our vignette assumes that one might generate a significant part of the energy required to heat and power one's home by way of on-site energy harvesting processes; this is one of the most environmentally friendly options for future housing needs [23]. The technological transition from inefficient traditional fuels (e.g. natural gas, coal) to more efficient modern fuels (e.g. hydrogen), and from existing electricity grids to decentralised energy generation systems (e.g. solar panels, fuel cells) connected to smart grids, will not completely negate dependency upon existing energy delivery infrastructure, but may reduce it significantly. Rooftop solar panels deployed for both energy and hot water generation have the potential to replace up to 75% and 24% of household electricity and gas consumption respectively. As a result, the delivery capacity required of the proposed system corresponds to 76% of current average household gas provision, while it only corresponds to 25% of average electricity provision.

In addition, we assume that advanced waste treatment technologies would be readily available to tomorrow's houses and residential blocks. These technologies and devices will make significant contributions to household consumption levels by reducing dependency on extant water and waste-water infrastructures; the requirement for solid waste collection service will also be minimised. Furthermore, with the help of new and emerging technologies such as bio-filtration or bio-fuel cells [24,25], the use of waste as an energy source in the houses of the future is no longer the fantasy it was once assumed to be. In a recent study, the internal chemical energy of wastewater was measured at 7.6 kJ/L, which offers significant energy generation potential [26]. Thus the bio-energetic potential of domestic waste and wastewater is calculated to be equivalent to 4.4% of total household gas consumption; in these calculations, grey and black water treatment efficiencies are assumed to be 90%, and we further assume that remaining wastewater will be removed using a future de-watering technology. After these assumptions, the amount of energy required by each house from the proposed energy delivery system is calculated to decrease from 84 kWh/day to between 50 and 60 kWh/day.

It should be noted that these estimates assume no significant reduction of energy consumption in the household, e.g. through the use of more efficient appliances, or installation of advanced insulation materials. It is to be hoped, however, that the on-going improvement of technologies will lead to a dramatic reduction in domestic energy consumption; this would create a yet more ideal setting for the proposed system, given that the capacity demanded of it could be significantly lower.

The average daily household water consumption per capita is around 150 L in the UK [27]; we have assumed a decrease to 100 lt/day/person would be possible in the future, and that individuals will consume less water and produce less waste per capita, even though the total volumes will be higher due to the inevitable increases in population (Indeed, this is less a wish than a necessity, given the increasing prevalence of water and resource scarcities, and increased demand due to concomitant population growth.).

3.2.2. *Calculated capacity requirements*

Based on the above estimates, the average energy carrier/fuel delivery requirements and mass loads in the pipeline system were calculated. For potential energy carriers or fuels, we considered: solid hydrogen carriers; liquid organic hydrogen carriers (LOHC); liquid phase chemical carriers (e.g. aqueous sodium borohydride, ammonia borane, and hydrazine borane); and both soluble and insoluble liquid fuels (e.g. ethanol, methanol, biodiesel, diesel, and gasoline). The mass contributions of the carriers and/or fuels were also calculated, and are reported in Table 1. These mass calculations are very straightforward, and the ratios computed might be

Table 1
Summary of the hydrogen storage materials and their technological and scientific feasibility for the water pipeline delivery.

Material type (S: Solid, L: liquid)	Specific energy (kWh/kg)	Energy mass requirements (kg of mass per 100 L of water)	Technological and scientific feasibility
Clathrate hydrates (the encapsulation of hydrogen in water) (S)	1.67 [47]	35.9	Pure hydrogen hydrate might also be a suitable solution for the water pipeline scenario: the storage material is water, and the hydrogen is stored in a molecular form that requires no chemical reaction for its release. However, methane hydrate storage requires −20 °C at atmospheric pressure [48], while hydrogen hydrate requires high pressure for formation (200 MPa at 273 K) [47]. This is a clear feasibility problem for distribution or storage in water pipelines, given the normal operating pressure range of water pipelines (350–550 kpa); further investigations and developments are required in order to find ways to keep the hydrates resistant after their formation
Metal hydrides (S)	2.53 [49]	23.7	Water might damage the bare metals used in hydrogen storage, which are highly reactive with water; on the other hand, recent studies show that this problem can be solved or controlled by encapsulating the metals with hydrophobic ceramic shells [50], by employing hydrided powders with ceramic overlayers derived from alcoxides [51], or by coating with PS (polystyrene) [52]. The use of solid form hydrogen storage materials in a city blood system can only be scientifically feasible if we assume that water-resistant hydrogen storage materials will become available in the future
Adsorbent carbonaceous materials (e.g. activated carbon (AC)) (S)	1.67 [53]	35.9	The technological limiting factor of AC is that, typically, high pressure and low temperature cryogenic tank conditions (e.g. 77 K and up to 4 MPa for [53]) are required to increase its storage capacity; furthermore, the behaviour of hydrogen-adsorbed AC in aqueous solution is not well-known. Activated carbon incorporates a platinum catalyst which allows the hydrogen atoms to bond directly to the surface of carbon particles, and to be released when needed; it also allows hydrogen to be stored at atmospheric pressure and room temperature [54]. Studies intended to research new materials or technologies which enable the storage and release of the energy carrier (e.g. hydrogen) at room temperature and pressure have particular importance given their relevance to the operational conditions of a water pipeline system; such studies exist [54–57], but they are largely focussed on finding a safer storage method, rather than on the delivery of materials in solution or slurry via pipeline
Nanostructured materials (e.g. CNTs (carbon nanotubes)) (S)	1.82 [57]	33.0	CNT pore sizes range between 0.7 nm and 1.2 nm, and they show great potential to overcome the stated problems of precipitation, falling out of solution, and other issues attendant on a pipeline system for slurry distribution; however, CNT behaviour in aqueous solution is not well-known. With suitable advances in materials engineering, their storage capacity and resistance in water may be further enhanced. Previous literature has reported a disadvantage of CNTs, namely that hydrogen stored in oxide nanomaterials can only be partially released at room temperature due to strong chemical adsorption [57]; however, their resistance may be an advantage when distributed with water in a pipeline system
COFs (Covalent organic frameworks) (S)	3.33 [58]	18.18	COF synthesis is quite recent [58]. COFs possess material advantages including high porosity, thermal stability and large surface areas, and they usually possess even lower mass density – a significant factor for any material in pipeline slurry distribution. Both the covalent and metal organic frameworks only operate as effective hydrogen storage materials at very low temperatures, rendering them technologically infeasible for the “city blood” system
MOFs materials (Metal organic framework) (S)	2.5 [59]	24.0	Some MOFs are very sensitive to water, but it might be possible to transport them in water by the use of coating applications or other modifications on material level. Water might spoil the reproducibility of MOF samples, and hence of the hydrogen storage capacity; their life time and hydrogen saturation characteristics should be tested/improved in water distribution. MOFs exhibit much lower gravimetric capacity for H_2 at ambient temperature and pressure, but the capacity pertains
perhydro-N-ethylcarbazole (L)	1.93 [13,60]	31.1	Among the best understood LOHC (liquid phase organic hydrogen carriers), its potential as a hydrogen storage material is due to its reversible reaction and the recyclability of reactants and products [61]. The dehydrogenation reaction can be achieved by heating, which is a simple process. It is insoluble in water, making it a perfect candidate to mix and deliver in water pipeline systems. Its short and long term behaviours in water should be investigated further. The most significant feasibility problem is its toxic and ecotoxic profile, but that could be mitigated through advancements in separation and pipeline distribution technologies (e.g. better insulation to minimise pipeline leakages), or through the invention of new environment friendly nontoxic LOHC materials
Sodium borohydride (L)	3.6 [34]	16.7	One of the most studied LCHC (liquid phase chemical hydrogen carriers) in the literature. Undergoes self-hydrolysis at room temperature, liberating its hydrogen content. It is highly reactive with water, however, so likely not a feasible candidate for city blood delivery

Table 1 (*continued*)

Material type (S: Solid, L: liquid)	Specific energy (kWh/kg)	Energy mass requirements (kg of mass per 100 L of water)	Technological and scientific feasibility
Ammonia borane (L) (AB) and Hydrazine borane (L)	6.53, 5.13 [34]	9.2, 11.7	AB and HB are other LCHC system alternatives; they are quite stable in air at room temperature, and soluble in water. The AB and HB Hydrogen release processes can be accomplished by thermolysis and metal-catalysed reactions. HB's theoretical hydrogen storage capacity is not as high as that of AB, but its aqueous solution is more stable for longer periods against unplanned hydrolysis. Both materials are good city blood candidates, due to their stability and reaction control methodologies in water
Ethanol (L)	7.85	3.8	Ethanol has minimal health and environmental impacts. Recently introduced techniques and methods provide very attractive low energy separation solutions, since they can – in theory – separate a diluted ethanol–water mixture with total efficiency [40]. Among all the energy carriers and fuels discussed in this paper, ethanol is the most feasible city blood energy carrier
Biodiesel (L)	2.37–3.25	18.5	The use of the liquid biofuels – e.g. bioalcohols, vegetable oils, biodiesels, biocrude and synthetic oils – in a city blood system might be a slightly more viable option than the use of liquid fossil fuels
Diesel (L)	3.76	16.0	The behaviour of liquid fossil fuels in water is well known and studied [35–38]. Diesel and gasoline are considered insoluble in water, even though some minute amounts can be dissolved. The main hurdles to distributing diesel and gasoline mixed in water are related to the difficulty of providing a high performance on-site separation system, as well as maintenance and energy requirement overheads, and the potential impacts on human health and ecosystemic stability
Gasoline (L)	12.20	4.9	

decreased significantly by future advances in material sciences, by the invention of high-capacity hydrogen carrier materials, and/or due to changes in energy consuming technologies and behaviours; any decrease in the mass-contribution ratio offers improved operational overheads.

The following sections focus on alternative and emerging materials and methodologies for energy storage and distribution, which comprise the most significant scientific and technological challenges to the realisation of the proposed system. Their characteristics – and the infrastructural characteristics required in order to use them successfully in the suggested distribution system – are also discussed in detail.

3.3. Technology search and evaluation

The key question posed in this study is: “could it be possible to distribute both water and energy through a single pipeline network, much as our bloodstreams do for our cells?”, and our answer envisions that the existing urban utility infrastructures might evolve into an advanced form of circulatory system for the urban body, by way of advances in materials science and other technologies. Many contemporary multi-functional artificial materials and well-designed solutions to engineering and architectural problems have been inspired by biological phenomena [28,29], and a great deal of work has been done on making multi-scale structures for functional integration using this “biomimetic” or bio-inspired approach [30]. Artificial intelligence and genetic algorithms are the best-known examples of bio-inspired methodologies; further studies of biological systems are expected to deliver promising new solutions and engineering applications, and bio-inspired engineering research is expected to be an important and expanding field in the coming years.

Would it be possible to deliver and collect energy carrying materials in a liquid medium (or “city blood”)? Might emerging technologies enable such an infrastructure? Discussions of the technological requirements and feasibilities attendant on this idea follow.

The search process focuses on two types of energy carriers: hydrogen carriers and fuels (e.g. biofuels and fossil fuels); different subtypes of these energy carriers are identified for evaluation.

Various combinations of liquid/water and solid/water mixtures might act as solutions to the problem of energy delivery in water. The potential liquid/water mixtures include biofuels (e.g. ethanol, methanol, and biodiesel), conventional fuels (e.g. gasoline and diesel), and liquid-phase chemical and organic hydrogen storage materials (e.g. N-Ethylcarbazole, sodium borohydride, ammonia borane (AB), hydrazine, and hydrazine borane), while the solid/water mixtures – also known as ‘slurries’ – are limited to solid substrate hydrogen carriers (e.g. clathrate hydrates, metal hydrides, carbonaceous materials, nanostructured materials, covalent organic frameworks (COFs), metal organic framework materials) suspended in water. Though both slurries (solid and liquid mixtures) and solutions (liquid and liquid mixtures) may be transported by pipeline, the possibility of the carrier material precipitating (or “falling out of solution”) is a problem attendant on slurry distribution [31].

Each of the potential mixtures is discussed in the following sections, wherein we explore their flaws and feasibilities, as well as the developmental hurdles which must be overcome in order to deploy them in such a system. The viable storage materials and their specifications are summarised in Table 1.

3.3.1. Solid substrate hydrogen carriers

The emerging potential of hydrogen as an energy carrier has attracted considerable worldwide interest. Most of the literature dealing with hydrogen delivery and transportation focuses on different delivery pathways. The most suitable form of hydrogen delivery for household use was previously assumed to be the low-pressure gas pipeline, but recent studies related to the utilisation of hydrogen in a sustainable energy economy have questioned the feasibility of constructing of a new distribution network for carrying compressed hydrogen, not to mention the required plant for pressurization, safety regulation and storage

[32]. It is hence a significant challenge to identify forms of hydrogen that can be stored and transported without substantial risk and/or expense, while still retaining the high energy capacity of hydrogen gas [33].

The use of ultra-high-capacity nanoparticle-sized materials may be a realistic and economic solution to the given problem. However, adding and removing hydrogen to and from such carrier materials requires complex processes which add cost and complexity to the overall delivery system. Precipitation; poisoning; reactions with water; falling out of solution; operational conditions; safety and health requirements in the pipeline system – these problems must be solved by materials science before any such system could be operationalized. An example of the infrastructural components required – and the future technologies they demand – for solid substrate hydrogen carrier delivery in water is illustrated in Fig. 3.

3.3.2. *Liquid substrate hydrogen carriers*

The solid-phase hydrogen carriers discussed above have yet to meet the requirements the proposed system would make of them: they would contribute significant mass to the liquid, because their gravimetric hydrogen capacities are low; they are highly reactive with water; and their optimal handling pressures and temperatures differ significantly from those in a standard water mains network. As such, liquid-phase hydrogen carriers may offer a more viable alternative. From an operational perspective, it is always easier, safer, and more pragmatic to distribute a liquid mixture in a pipeline network than a slurry. While the search for a safe and efficient liquid-phase hydrogen storage material has yet to make significant progress, some advantageous chemical and organic aqueous and liquid compounds have been invented, such as N-ethylcarbazole, cyclohexane, methylcyclohexane, decalin, aqueous sodium borohydride, ammonia borane, hydrazine, and hydrazine borane [13,34].

3.3.3. *Liquid substrate fossil fuels/bio-fuels*

Since the dawn of the Industrial Age, fossil fuels have been used, directly or otherwise, to satisfy the majority of household energy demands; their behaviours in water are well known and closely studied [35–38]. Diesel and gasoline are effectively insoluble in water, though some minute amounts can be dissolved. Aromatic hydrocarbons, for instance, are more soluble than alkanes [38], but their toxicity and negative impacts on human health and ecosystems would be serious concerns were they to be mixed into water systems.

Recent advancements offer high quality separation processes [37], but they mostly focus on the expulsion of water droplets in order to improve the fuel. The main hurdles to delivering diesel or gasoline mixed in water are related to the current lack of a high performance on-site separation system, as well as significant maintenance and energy overheads, and the ecological and biological impacts of the use of (and exposure to) such hydrocarbons.

Biofuels, however, are a newly introduced fuel class, and possess great potential as alternative fuels to supplement or replace petrodiesel. They have several advantages over fossil fuels, including renewability, sustainability, biodegradability, and lower ecotoxicology and GHG emissions profiles [39]. The use of liquid biofuels –

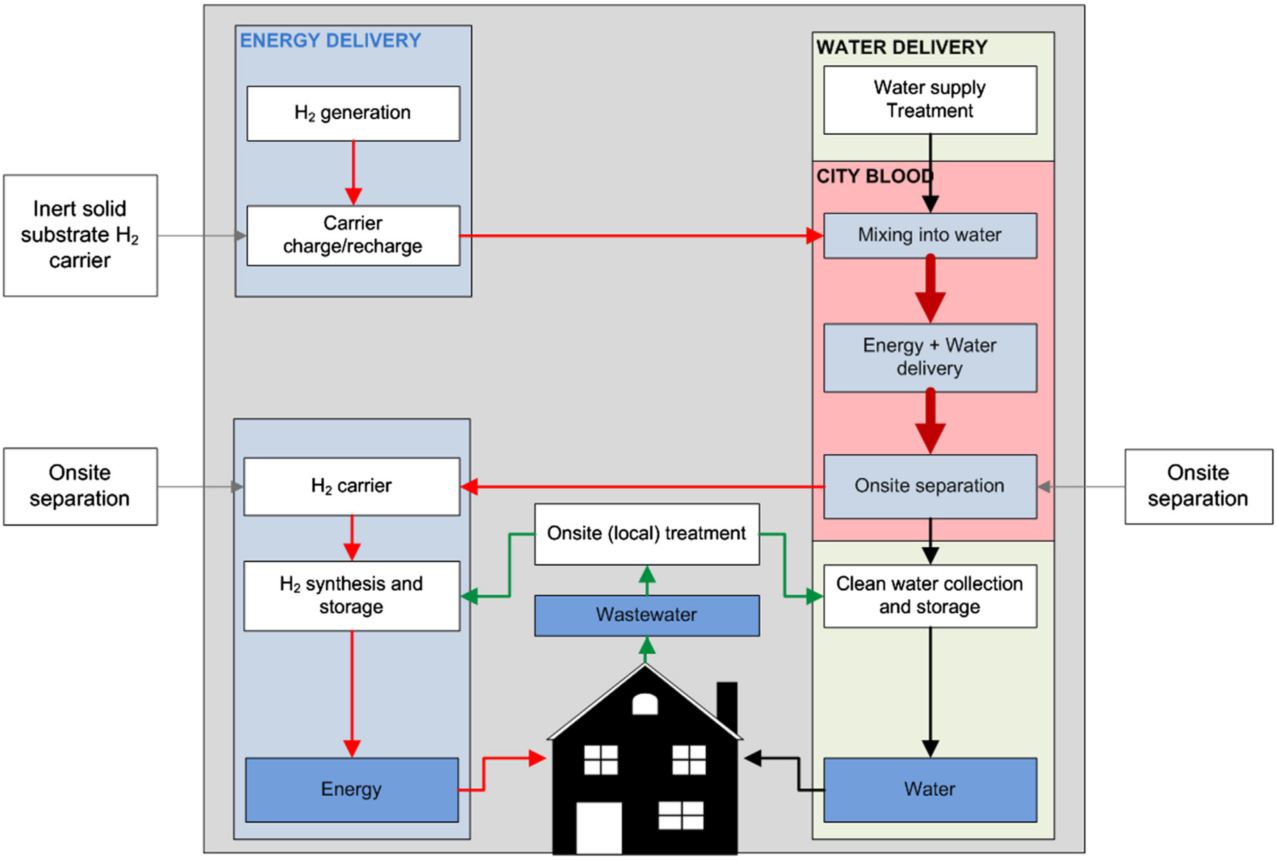

Fig. 3. Main components of the infrastructure provision and required future/emerging technologies in the city circulatory system vignette: the case of solid substrate hydrogen carrier delivery in water.

e.g. bioalcohols, vegetable oils, biodiesels, biocrude and synthetic oils – in a circulatory system might be more viable than liquid fossil fuels; ethanol, for example – a by-product of the fermentation of renewable resources such as plant biomass – not only dissolves in water easily, but is also a very clean fuel with minimal health and environmental impacts.

The ethanol fermentation process produces a mixture of water and ethanol, which are subsequently separated using either the conventional distillation method or the more modern adsorption method [40]. As such, tried and tested separation methods are already available for ethanol, and these might be suited to the proposed system. The most recent techniques and methods provide very attractive low-energy separation processes, as they can theoretically separate an ethanol–water mixture with total efficiency [40]. In the realisation of the "city blood" vision, the water–ethanol separation process might be relocated to the receptor sites (i.e. the household level of the infrastructure) as an alternative to its conventional centralised position in the ethanol purification/distillation process. Among all the energy carriers and fuels discussed herein, ethanol is the most feasible "city blood" energy carrier.

3.4. Preliminarily assessment of economic feasibility

3.4.1. Investment cost

The investment cost of a new pipeline system is one of the forerunning factors governing the success or failure of attempts to transform an extant system into something more sustainable [42]. In this section, the investment cost of the "city blood" circulatory system is evaluated according to the criteria given in the linear cost relation model suggested by Ref. [11]. Some major assumptions have been made in the comparison of the installation costs of the blood of the city and conventional water pipeline systems:

1. Existing water and energy systems will eventually have to be replaced due to asset decline, as discussed in the introduction.
2. An existing technology for distribution pipelines can be used as a baseline for a cost calculation of the "city blood" system.
3. Cost of pipeline materials is proportionally representative of the installation cost of the distribution pipeline system, and we further assume that both system types can utilise the same pipeline materials.
4. A "city blood" pipeline network would follow similar routes and pass through similar terrains to those of a conventional water network.

These assumptions are a necessity, since the real installation cost of utility infrastructure is commercially sensitive information [44], and it is thus almost impossible to make any useful estimation of cost parameters for the future (e.g. 100 years hence). The proposed system is based on water pipeline systems, with additional materials distributed in solution; according to Van den Broek et al.'s linear model [11]and the assumptions specified above, the cost of the proposed network will be proportionally higher than a conventional water pipeline network installation of similar scale. The minimum mass contribution per 100 L of water is 3.8% (e.g. for ethanol delivery) while the maximum is 35.9% (e.g. for solid substrate hydrogen carriers). The total length of the pipeline networks are assumed to be the same; therefore the selection of the appropriate pipeline diameter, which is related to the square root of total mass delivered, is the only parameter that makes significant differences to the costs in either system, with a variation ranging between 1.9% (min) and 16.6% (max).

In order to obtain some tangible figures, we estimate the cost of the like-for-like replacement of existing water and energy distribution as follows.

Estimated pipeline construction cost per mile is around 1.3 M$ (assuming carbon-steel pipes) [45], whereas the construction cost of new underground power distribution lines is around 0.5 M$ per mile [46]. This gives a combined cost of 1.8 M$ per mile for installing both water and energy distribution systems. A "city blood" system may require different pipeline gauges, depending on the average energy carrier/fuel delivery requirements and the mass loads in the pipeline system, as discussed above. The cost is calculated by adding the extra cost of using larger gauged pipes to the previously calculated baseline cost of a carbon-steel water distribution system, i.e. 1.3 M$ per mile.

The investment costs for a "city blood" system were thus calculated out as between a minimum of 1.32 M$ and a maximum of 1.52 M$ per mile. As these results demonstrate, the installation cost of a "city blood" system would be no more expensive than the sum of the installation costs of separate water and energy distribution systems.

3.4.2. Operational cost and benefits

The proposed system is based on water pipeline systems, with additional materials distributed in solution. As such, the operational costs are mainly related to pumping and maintenance, but such costs are an important component of any economic feasibility assessment.

The mass load to be distributed through the pipeline is used as the most crucial parameter for defining the pumping cost. The energy capacity per kilogram of each carrier or fuel is used to define the quantity of materials which must be distributed to satisfy demand. The pumping cost for water is taken as the baseline, and the cost is assumed to increase in a linear relationship with the increase in the mass due to the necessity of adding materials to the water; as such, the extra operational costs of the system are expected to be between 3.8% and 35.9% relative to the baseline cost. This result is only for pipeline distribution, and the operational cost of the conventional energy delivery is not included in the base assumption; further note that this analysis is based on the current absorption capacity of the materials discussed, and that the invention of materials with a higher absorption capacity would alter these results significantly.

Maintenance costs are another crucial factor in assessing economic feasibility, but it is not currently possible to fully consider the operational conditions and risk factors for the proposed system; thus, for simplicity, it is assumed that they are the same as those attendant on the current system. This indicator focuses on the effects of the materials in solution upon maintenance requirements, e.g. increased rates of pipeline corrosion. As with pumping costs, maintenance costs increase in proportion to the corrosiveness of the material to be distributed. The materials with the highest risk are identified as liquid soluble fuel delivery, liquid substrate hydrogen carrier delivery, and solid substrate hydrogen delivery, and conventional energy and water, respectively.

4. Conclusion

This study addresses a visionary idea for water and energy delivery, the "blood of the city". The dominant technological hurdle to be overcome is identified as the development of a water-resistant, high-capacity energy carrier that should stay inert under standard water pipeline operational conditions while retaining its energy content, and which should be easily separated from and recombined with water. The potentials and limitations of well-known solid and liquid substrate hydrogen carriers, fossil fuels and biofuels in this context are studied and compared, and the technological and scientific feasibility issues for their deployment via existing water distribution networks are analysed; ethanol is shown to offer the greatest potential at this time. While there exist a range of new advances and technologies with which to potentially realise this vision, this study also explores the economic feasibility of using existent technologies, finding clear evidence that this idea demands significant investment in innovation, research and development.

The “city blood” system is an analogy to the human circulatory system, meaning that the underlying principle is an established and reliable natural phenomenon; as such, while it may be a radical departure from contemporary infrastructural engineering conventions, it is not as far-fetched as it may initially appear. So we conclude our paper by asking again, “why should a single-network “city blood” circulatory system not be implemented as the main utility distribution infrastructure for cities of the future?” We invite the research community and industry experts to further explore the possibilities we present herein.

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