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A comparative analysis framework for assessing the sustainability of a combined water and energy infrastructure

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ABSTRACT

The evolution of infrastructure is a long journey that requires the concomitant advancement of associated sciences and technologies. Today's disparate utility infrastructures could be the starting point for such a journey, from where future infrastructure may develop to a degree of perfection that will enable multifunctional use; thereby removing duplication, capital and operational cost and risk, improving sustainability. This paper presents a framework for a sustainability analysis of a futuristic idea, "City-Blood", that proposes to distribute energy and water through a single infrastructure. Analytic Hierarchy Process (AHP) has been used to analyse qualitative and quantitative data to determine the relative sustainability of several City-Blood implementations by comparing them against existing disparate electricity and water delivery systems. Each solution considers extreme economic, social, and environmental contexts that affect the need for the infrastructure and resource use.

1. Introduction

There are few, if any, historical precedents for the directed development of an infrastructure. Each individual system has, perforce, developed piecemeal in an iterative and haphazard fashion in response to the changing needs of the society or civilisation that built it, with new developments and improvements enabled by new scientific or technological discoveries, and by the increasing synthesis of initially separate systems as their functions enable one another's improvement or enhancement. As ecological awareness and economic priorities have developed over time, the efficiency, safety and equity of resource distribution have become increasingly important in our evaluations of said systems. However, path-dependency leaves us wrestling with legacy infrastructure — aging systems whose inefficiencies are increasingly unacceptable, but upon which we are so utterly reliant that simply swapping them out for something newer and better is impossible. Newer infrastructures – telecommunications, for example – are installed alongside and crosswise to older ones, and rapidly become functionally entangled with one another: modern water distribution and sewerage systems could not function without the electricity grid; the electricity grid relies upon telecommunications for its real-time management; telecommunications rely upon electricity; the list goes on. The metasystem – the "system of systems" formed by infrastructural interdependency – grows ever more complex, especially in our cities, which are now home to half the world's population, with that proportion set to increase considerably over the next few decades [1].

The challenge is compounded by the moving benchmarks of public expectations of infrastructure, influenced by factors such as environmental concerns, population expansion, resource scarcity, resource distribution inequity, sanitation standards, maintenance and operational costs, and other (often more subtle and hard to discern) sociological changes. Societies gradually ascend through Maslow's hierarchy of needs as they develop, but the new quickly becomes normal,

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which then quickly becomes necessary; witness, for instance, the status of access to the internet, a system which barely existed thirty years ago, but which is already listed as a basic human right according to the United Nations. The more infrastructure a society has supporting it, the more reliant upon them it becomes; rural societies in developing nations, accustomed to precarious and unreliable access (if any) to basic infrastructure, are able to muddle through blackouts and downtime with the resilience of adaptability, but to imagine a major city such as London, New York, Berlin or Dubai suddenly bereft of electricity for more than an hour is to imagine utter chaos.

In the latter half of the 20th Century and these first fractious years of the 21st, there have emerged new environmental and social pressures on global human society as a result of the unchecked growth of our anthropogenic "footprint", and its impacts on the planet we call home. Such pressures include, but are by no means limited to: air pollution; acid rain; ozone layer depletion; climate change and "global weirding" due to GHG emissions; deforestation; biodiversity losses; drug-resistant epidemics; surface water sedimentation; groundwater depletion, pollution and contamination; land erosion due to incautious construction and large-scale industrial agricultural processes; flooding; and population displacement as a result of either any of the above, or efforts to mitigate or compensate for any of the above, or conflicts resulting from any of the above. These factors have placed yet greater burdens on existing infrastructures, and – regrettably, but perhaps inevitably – show no sign of abating, thus making an irrefutable case for the development of more sustainable and reliable infrastructural solutions for the cities of tomorrow.

Had such social, political and environmental concerns influenced us sooner, we would perhaps have a very different sort of urban infrastructure to that which we have today. It is not hard to see what such a system's basic requirements would be for the cities of our near future: a minimal ecological footprint, sustainable deployment and equitable distribution of resources, flexible functionality, affordable maintenance and operational overheads, and sufficient excess capacity to cope with on-going expansion of demand.

Much effort has already gone into the development of sustainable infrastructure systems, ranging from small and/or local single-project efforts to regional and global schemes such as carbon-trading markets, but such attempts are inevitably as piecemeal as all the infrastructural development attempted heretofore. Furthermore, many radical and innovative solutions have been proposed by scientists, engineers, artists, writers, futurists and corporations, with the intention of shaping next-generation urban infrastructure systems for optimal service, as measured by increased efficiency, reduced operational costs, minimal redundant investment and research, and negligible environmental impacts. However, assessing the suitability-for-purpose of such systems remains a largely unexplored problem.

In this study, we present an experimental comparative analysis framework (CAF) with which to evaluate the sustainability of radical urban infrastructure solutions, and demonstrate its application to "the Blood of the City", a visionary proposal for the unified provision of energy and water through a single pipeline system [2]. The Blood of the City (BotC) proposal has the potential to eradicate the redundant investments attendant on building multiple discrete infrastructures (i.e. separate systems for the distribution of water and energy), and to reduce environmental impacts; furthermore, it presents a new paradigm for domestic energy supply. The biomimetic question is: "would it be possible to distribute a combination of potable water and energy-carrying materials to homes via a single pipeline network, much as our blood vessels carry energy and water to the cells of our bodies?" By reconceiving the city as equivalent to a complex organism or "body" comprising many different cells, one can imagine urban infrastructure evolving into a form of advanced circulatory system that sustains the life and health of the body, enabled by advances in materials science and other technological domains.

The future is, of course, inherently unknowable — but by proposing a preferable future, it may be possible to direct researchers, investigators and policy-makers toward more sustainable and desirable iterative solutions to the problems of urban infrastructure. In the process, it should be possible to identify the most critical technological advances required to actualise such systems, and to assess the desirability of a solution against a variety of different circumstances or contexts. As such, we propose that the contextual desirability of a solution and the criticality of its required technologies are key factors in its overall feasibility.

The CAF demonstrated in this study has two components. First, we perform a sustainability analysis informed by a set of reasonable technical, environmental and social criteria considered pertinent to urban domestic infrastructure solutions; this is primarily a qualitative assessment, based on a comparison of the BotC proposal with conventional electricity and water distribution systems as in use currently. Secondly, we perform a series of "wind-tunnel tests" by situating the proposed system in a series of scenarios intended to represent a variety of possible contexts – environmental, economic and social – in order to assess its sustainability as a function of the circumstances in which it might be deployed; after all, one city's ideal solution might be another's economic nightmare.

In addition to the analysis outlined above, this study aspires to encourage further visionary thinking and foresight around the issues attendant on our existing infrastructural systems, and to open up further discussion around ways in which our civilizational needs might be met by more sustainable solutions in the cities – if not the world – of tomorrow.

2. Methods and Methodology

2.1. Comparative Analysis Framework

This framework (Fig. 1) was developed from a scenario-based strategic planning activity suggested by [3]. It starts with the selection of a scientifically and techno-economically feasible case study, a vignette of a visionary "preferred future" infrastructure system and/or design. The framework also requires the selection of a contemporary/conventional solution as well, in order to act as a realistic known-quantity benchmark for comparison. Once these selections are made, the framework follows a series of analytical steps.

Firstly, a set of reasonable criteria and indicators with which to assess the system's sustainability must be identified. The main criteria and indicators which are considered in this assessment are rooted in technical, environmental and social

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