ICE

IT Communications Energy network convergence: Opportunity for decentralised local-owned data centers

Laura Watts

ICE
IT Communications Energy network convergence:
Opportunity for decentralised local-owned data centers

WHITE PAPER

Draft version 8/2017

Laura Watts

Associate Professor
IT University of Copenhagen

& Sand14
www.sand14.com

ice@sand14.com

This draft white paper is a work-in-progress,
intended to elicit discussion and participation.
Corrections and comments welcome.

Overview_

The data industry is now an energy industry. Data centres are benchmarked and marketed by their Power Usage Efficiency (PUE) and Data Center infrastructure Efficiency (DCIE), metrics promoted by the Green Grid consortium, although the measure is imprecise and contentious.[1] One report suggests that the entire ICT industry uses 7.5% of the total global electricity supply, with data centers about 20% of that, led by increasing shift from device to cloud based services, such as video streaming[2]. The industry association, Data Centre Alliance, has one of its main goals 'improvement in environmental sustainability'.[3] The carbon footprint of 'The Cloud'–the server side data processing that supports almost all online use, from search to email to streaming to apps–is estimated to be similar to the aviation industry–about 2% of global emissions.

Intel test of immersion cooled servers using Green Revolution's Carnotjet solution https://youtu.be/6IX9U2zal_I

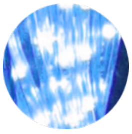
Reducing energy costs whilst reducing carbon is paramount to the data industry. The largest single energy and financial cost in data centre processing is cooling IT equipment, so access to cold water and/or a natural cool climate for heat-exchange is a basic requirement.[4]

Major players in the data industry, from Amazon to Apple, from Facebook to Google, are committed to reducing their fossil-fuel energy use by relocating their data centers to cold geographies (such as Scandinavia) and coastal locations, and generating or buying local green renewable energy on a massive scale. Some examples:

- Facebook data center in Luleå, north Sweden, is co-located with a hydroelectric dam.
- Apple has built a 20 MW photovoltaic array covering 500,000 square feet in North Carolina to power its data center over the road; and it is building a new data center in Denmark, a country that can generate more than 100% of its energy needs from wind.[5]

[1] PUE is rejected by some since it measures the energy use of the data centre, not its efficiency. It includes the efficiency of the power delivery network, but provides only a broad comparison between the IT load and energy consumption, without including the efficiency of the equipment used.
[2] See Greenpeace, 2015.
[3] See Data Center Alliance, 2014.
[4] See Hogan, 2015.
[5] http://www.datacenterknowledge.com/the-apple-data-center-faq/

- Google has a data center in coastal Hamina, north Finland, and has invested in a bespoke seawater cooling system;[6] the data center in The Dalles, Oregon, is located on the shore of the Columbia River, and benefits from the region's cheap electricity generated from the many dams along its length.
- Iceland's Verne Global is a multi-tenanted data center powered by the country's excess and cheap geothermal energy.



There is a growing convergence of the IT, Communications, and Energy industries

–or what this author calls, ICE.

Aside from the above trends, another indicator of this convergence is the move in computing towards 'grey utility'[7] (the cloud as pay-per-use, and infrastructure-as-a-service, for example). This follows a similar shift in the telecoms industry, which is struggling as a bit-pipe commodity industry. Energy has been a grey utility industry for some time. ICE is all 'grey'. This white paper and its attention on the environment, social, as well as technical issues offers an approach that counters that trend.

The implications due to ICE are based on the disjuncture between centralised network topology versus peripheral low-carbon renewable energy resource. The environmental resource cannot be moved, and data centres are moving to co-locate with wind, solar, hydro, geothermal and other renewable supply.[8] Data processing is where the energy is, not where the data terminals or cables are. ICE transmission networks were built for centralised fossil fuel power stations and cities, and are the wrong topology to support low-carbon data processing at the geographic edge.

The risk is intransigence in policy governance and markets that fail to invest in updating ICE infrastructure–a freezing situation–where data, telecoms, and energy networks remain fixed in their current centralised shape. There is also a risk that computational models that are blind to the physical network architecture challenges create impractical solutions. Software solutions alone miss both the physical and socio-political challenges.

The opportunity is a social plus technical one. It would combine technical solutions with sociocultural solutions–include people and politics with their smarts and silicon. For example, Software Defined Networking (SDN) coupled with environmental feedback and energy network management could support new Distributed System Operators (DSOs). These would be local community groups, established through collaboration, which would allow communities who already have knowledge and expertise in their data and energy

[6] https://www.google.com/about/datacenters/inside/locations/hamina/

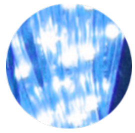
[7] Most famously discussed in Carr, 2004.

[8] This tendency is most pronounced with single-tenant server farms. Data center customers can be resistant to their 'cloud' location in remote locations.

networks to manage their local ICE networks. They would manage their own data and energy system.

The solution weaves together existing research and knowledge in domains that are not connected at present: DSOs have been proposed in a move towards Smart Grids and a smarter power network;[9] there are proposals for SDN and OpenFlow architecture to be made energy-aware in order to create green cloud computing;[10] the importance of 'invisible work' by local experts in the maintenance of infrastructure has been well-discussed in the research field, Infrastructure Studies.[11]

Overall, the opportunity is for decentralised, small-scale and local-owned data processing at the geographic periphery, which can be implemented through *ad hoc* localised infrastructure improvements.



The data and energy network problems are devolved to the local level, where the particular environmental, social, and technical resources can be mobilised and transformed in unique, local solutions. Infrastructure update and innovation now moves to the edge.

ICE _ Challenges_

The following outlines the challenges due to ICE convergence in more detail.
As a high-energy consumer with a massive carbon footprint, the data industry must now either become a renewable energy producer or negotiate supply and favourable green tariffing. This makes data companies important players in national and international energy markets, as both producers and consumers.

Data centres are being built in regions where there is environmental resource: cold water, high renewable energy potential (wind, solar, hydro, with the potential for wave, tide, biomass). These weather-rich regions are often distant from traditional centres and cities. These regions are at the edge of the network: distant from transport hubs, from telecommunications backbone, from grid capacity, from towns and cities.

Facebook Luleå Data Center exhibit in Teknikens Hus @LuleåDataCenter facebook page.

---

[9] National Infrastructure Commission, 2014.
[10] Moghaddam, Lago, and Grosso, 2015.
[11] Star S.L, 1999; Harvey, Jensen, and Morita, 2016.

The environmental resource is immovable. No policy instruments or creative tariffing can move planetary geology and geography that makes rich renewable energy: the tidal resource is limited, solar is effective in some places and not others, the potential for wind is not isotropic. This is in contrast with high-carbon fossil-fuels, which can be transported as raw fuel to where they are consumed.

Transmission infrastructure is the crucial issue. There are two options: either data must be transmitted between distant data processors and centralised end users (such as undersea transmission); or electricity must be transmitted between distant generators and centralised data processors (such as interconnector cables). Either data or energy has to move–and data transmission is far more cost effective and less lossy.

Electricity pole in Orkney, Scotland, where national grid capacity is limited, but environmental resource is extensive.

However, both telecoms and electricity transmission networks have a topology designed for urban centralisation. Fossil fuel power stations (wth the notable exception of nuclear power) are proximate to consumers; telecoms network build-out, both fixed and wireless, begins at the centre and is limited at the edge. Remote rural regions with high renewable energy generation can have low bandwidth, and often fall outside the so-called Universal Service Obligation–with 'not spots' where data is squeezed. In short, neither electricity grid nor telecoms network topologies are designed to support a low-carbon data industry that requires high-capacity transmission between remote edges and centre.

Thus, a green data industry requires the long term, high-cost repurposing of both electricity grid and telecoms networks. Governance at the national level–in many North American and European countries–has entrenched resistance to, and political bias against, investing in national infrastructure or creating policy instruments that demand market action.[12] The failure of Universal Service Obligation is one such example–'decent' broadband access for the whole UK population is still being debated.[13] There is even more resistance to investment in geo-remote locations and their infrastructure. Lobbying by the data industry in collaboration with renewable energy rich local governments and communities is one option. This white paper presents another.

[12] Wide ranging, and well-cited, discussions of different regions sociocultural approaches to energy infrastructure are gathered together in Szeman and Boyer, 2017.
[13] See report from the UK Regulator, Ofcom 2016.

There are further challenges faced by the data centre industry in its current approach. So far, the industry seems to be replicating the old order: centralisation. New data centers are either located in existing population centres or are massive in scale. Their topology is 'star' like. This leads to three challenges:

- The landing onto rural land and forests of the data center buildings, industrial equipment, roads, and sprawling renewable energy farms that power them, are not unequivocally welcomed by those who live there–both humans and nonhuman wildlife. There is a history of NIMBY-ism (Not In My Back Yard) for wind turbine farms,[14] with people celebrating them in principle but resistant to what they become in practice: often 'extraction' sites, more equivalent to mining, which take energy out of the local environment and make money for absent owners.

- Local communities can gain very little from these massive installations next door. Job creation is unremarkable, perhaps fifty or so technicians might be needed. These sites are under high-security, cutting them off from visitors and participation in the local community. Although the data industry often does its best, through substantial donations to local schools and nonprofits, for example, these sites remain physically isolated.

- Large-scale data centres risk being myopic in their renewable energy supply: selecting one, such as wind or solar. But, as has been well-discussed, renewable energy is unpredictable and uncontrolled: the wind blows on the wrong days; cloud cover reduces PV production at the wrong time. Having a dirty baseload, such as oil and gas power, is considered the solution but this increases the carbon footprint and must be purchased from the energy market.

- 'Star' network topology is inherently risky due to having a single point of failure. The centre has to be replicated in order to have some redundancy. Distributed 'mesh' networks are topologically more robust.[15] The myth of the internet has long promoted the idea that, due to its packet-switched origins in Cold War ARPANET, the data network design has an inherent resilience.[16] But as research on trace routes for surveillance, as well any map of the undersea transmission network, shows, this is no longer the case.[17] Data networks are nodal and therefore more precarious in practice.

---

[14] Cass and Walker, 2009; Cass N, Walker G and Devine-Wright P, 2010.

[15] For a cultural theory discussion of mesh and star network topology see Mackenzie 2010.

[16] Nicola Starosielski, 2015, discusses the imagined resilient internet versus the limited undersea network.

[17] For work that physically traces packets see the Big Data Surveillance project (http://www.sscqueens.org/projects/big-data-surveillance) and Canadian case study: Obar and Clement 2013.

These challenges could all be addressed through a decentralised approach to data centers.

Orkney's Electric Future, a local government and an Urban Foresight project, brings together electric cars and local-owned wind turbines.

Research has shown that local ownership and participation in renewable energy infrastructure projects can negate NIMBY-ism.[18] Community collaboration, rather than financial compensation, is a slow process that requires expertise to manage, but such collaboration can expedite local planning and create goodwill that will overcome obstacles throughout the data center lifetime.[19]

Geographic dispersion would mean a diverse 'energy mix' available for data processing. Rather than one environmental resource, you disperse your data processing over several environments (solar, hydro, wind, tide, geothermal etc.). This 'energy mix' approach, along with energy storage options, could negate the need for dirty baseload.

Geographic dispersion also places less demand on single large bit and energy pipes in ICE networks, and promotes flexible topologies. For example, smaller scale means you could have a mix of Fixed Wireless, Fibre to the Premise (FTTP), and other solutions, tailored for each individual site. Innovation and upgrade can be *ad hoc* and bespoke. Distributed, small-scale data centers with a 'mesh' network topology, would also restore some physical redundancy to the data network.

With decentralisation and wide-area distributed processing, data security moves to the fore. Encryption must be bundled in with the software solution, especially over IP. Rather than the physical building requiring high-security, the packets and data stream is the site of security; and there is huge research in this area.[20] This would open up the possibility for visitors to the infrastructure, and the data center becoming a civic space or, at least, having areas that can participate in civic life.

---

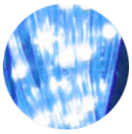
[18] See Moss, Becker and Naumann, 2015.

[19] For an extended discussion of different business models and collaborations in local community energy business see Entwistle, Roberts, and Xu, 2014.

[20] Sezer, Scott-Hayward, Chouhan et al., 2013.

ICE _ Solutions_

This section outlines, in brief, some potential building blocks for the sociotechnical solution It is written for a general audience with references to the research details.

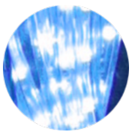


Green Data Centers

Software Defined Networking and its OpenFlow protocol have become an industry standard architecture, allowing network virtualization. There are proposals for SDN to be made energy-aware.[21] Distribution is then based on the energy data, such as renewable energy capacity. The green SDN creates an energy efficient data route. This could be expanded to create inter-data-center processing, allowing for decentralised green cloud computing.

Major vendors already use SDN to create inter-data-center routing. For example, Google B4 is their globally-deployed software defined WAN, which splits application processing to balance capacity with demand.[22]

There are now a multitude of different approaches to Green Data Centers, which attempt to address increasing energy efficiency through distributed networking. For example, energy-aware resource allocation for data centers is a research topic in itself.[23]



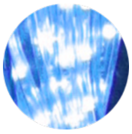
Off-Grid Data Centers

Data centers that are off-grid have also been proposed and now built, which would use different renewable energy source. Morgan Stanley, the US bank, proposed a $400m Scottish off-grid data centre powered by tidal energy, using Atlantis Resources tide energy turbines[24] (now being commercially deployed in north Scotland)[25].

Microsoft opened their zero-carbon, off-grid waste-to-energy-powered data center in Cheyenne, Wyoming, in collaboration with Siemens Energy Management and FuelCell Energy–which is powered by anaerobic digestion from biogas methane produced at the nearby Dry Creek wastewater facility.[26]

---

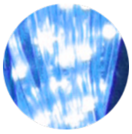
[21] Lin and Yu, 2017; Liu, Wang, Liu et al., 2009; Chen, Grosso, Veldt et al., 2011.
[22] Jain, Kumar, Mandal, et al., 2013.
[23] Bahari and Shariff, 2016.
[24] https://www.off-grid.net/huge-off-grid-data-center-for-bank/
[25] See the Meygen Project at https://www.atlantisresourcesltd.com/projects/meygen/
[26] https://www.energymanagertoday.com/microsoft-opens-grid-data-center-0106475/



Distributed Smart Grids

Solutions to decentralise national grid management have been well-developed. Registered Power Zones were enacted on the grid in 2006 in the UK. Active Network Management systems have since been installed around the world to manage capacity in localised areas and balance load. ANMs shut down generators when grid capacity has been reached to prevent over-capacity issues, which is often a problem where renewable energy is a major load.[27]

The UK National Infrastructure Commission outlined 3 steps towards a smarter and decentralised national grid in its 2016 report.[28] These were: energy storage, active network management, and undersea interconnectors between energy markets (e.g. the North Sea interconnector between Norway and UK). The report also proposed active distribution system operators, or Distributed Systems Operators (DSOs), who would have local knowledge of their network needs and could load balance appropriately. They note the that this could be an opportunity for new profitable local business–DSOs could establish local energy markets, for example–as well as resolve the problem of national grid load balancing.



Infrastructure invisible work

Within the field of Infrastructure Studies (an interdisciplinary field within Science & Technology Studies and Anthropology), it has long been understood that infrastructures are social and technical, they hold together through both technical and social labour–and the work of those who design, build, and maintain infrastructures are often invisible and remarked, even by those in the industry.[29] Those who tend the sewers, the administrators who manage the legal papertrail, the cleaners and technicians who keep the server room dust free, and those who labour in standards organisations and their auditing to establish protocols and measures that mean an infrastructure can hold over space and time. The technique for studying such work is called 'infrastructure inversion' which is akin to turning the infrastructure upside down to look at its roots and relations that make it operate.[30]

There are key qualities to infrastructures, which include both its embeddedness in communities of practice, and its reach over diverse landscapes.[31] In short, infrastructure is only able to have 'universal' qualities through extraordinary and often contingent work in many local places.[32]

---

[27] Anaya and Pollitt, 2014.
[28] National Infrastructure Commission, 2014.
[29] Harvey, Jensen and Morita, 2016.
[30] Star and Ruhleder, 1996; Bowker and Star, 2000.
[31] Star, 1999.
[32] Bowker, 1993.

Much research has also shown how communities and individuals, rather than users, adapt technologies to their local cultures and environments–designers who live elsewhere cannot anticipate the lived experience of technologies in use.[33] Designers 'script' their expectation for how a technology is used within an infrastructure. People with their environments 'de-script' technologies to make them work in practice.[34] Technologies do not get 'rolled out' unchanged into the social world, but often do not work without being adapted (and adaptable) by people in local practice.

ICE _ Case Studies_

Two case studies that highlight how solutions have already been integrated into Living Laboratory-style prototype projects in the field.

1_ Island Community Hydrogen Network

Orkney islands, off the northeast coast of Scotland, has become a test site for multiple energy systems: it is the site for the European Marine Energy Centre (EMEC), an on-grid test site for wave and tide energy generators; it has had both a Registered Power Zone and then Active Network Management system since 2005, and the UK's first grid battery was tested there in 2017. At a community level, a new affordable housing scheme has installed Tesla Powerwall home batteries as standard, the islands have more electric cars and micro wind turbines per person than anywhere in the country, and there is a growing hydrogen fuel network. In essence, the islands are emblematic of a smart grid.[35]

Of particular interest is the Orkney Surf n Turf project,[36] a community renewable energy project to transform both tide energy from EMEC and wind energy from a large-scale community owned wind turbine into hydrogen fuel cells. This stored hydrogen is then used to power boats at the local harbour. The project has a number of funders, from EU H2020 to Local Energy Scotland, and is part of a wider European hydrogen fuel


Deployment of HS1000 tidal turbine at European Marine Energy Centre (EMEC) test site (Image: Andritz Hydro Hammerfest)

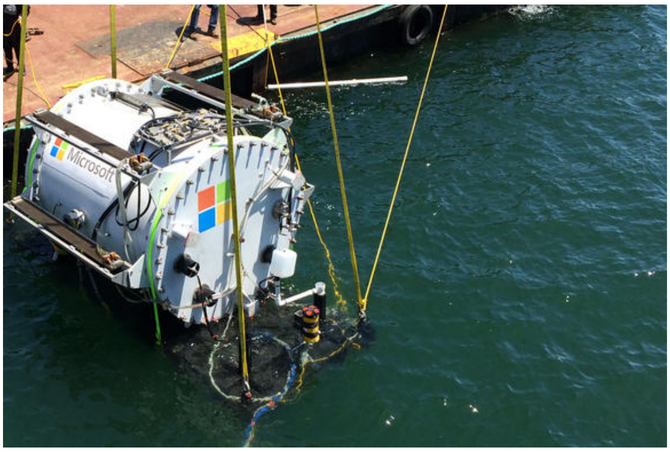
[33] Leach and Wilson, 2014.
[34] Akrich, 1992.
[35] See local government energy strategy (http://www.orkney.gov.uk/Council/C/soes-2017-2025.htm) which aims to "Positioning Orkney as the globally recognised innovation region to develop solutions for the world's energy systems challenges."
[36] http://www.surfnturf.org.uk/

initiative; Orkney is now the site of a European project to establish a full hydrogen fuel supply chain.[37]

The project is not led by a commercial vendor or energy operator. Instead, it was initiated and led by the Eday island community (200 people), and demonstrates how a small community group with rich environmental resource and big ideas can make technical innovation happen, which is transformative of the energy network.

2_ Wave Powered Data Center

Microsoft has been developing an underwater data center. Based on the premise that water is a requirement for cooling equipment, and complete immersion would make heat-exchange more efficient. Microsoft also promotes the potential for reduction in latency if it is deployed offshore from large coastal populations, and the potential for rapid deployment (although this may not reflect the realities of marine spatial planning). Project Natick involved the design and installation of a prototype subsea data center. The prototype was powered by the grid during deployment in 2015, but Microsoft states, "we envision that future subsea datacenters will be powered by renewable marine energy sources such as offshore wind, wave, tide, or current."[38]



'Leona Philpot' undersea data center being deployed (image: Project Natick, Microsoft)

A similar idea has already been proposed by Google who have a 2007 patent for a floating, container-based data center, which incorporates the Pelamis wave energy converter. The diagrams in the patent shows a wave energy farm with around forty Pelamis devices creating 40MW to power the ocean-based data center boxes.[39]

[37] https://www.bighit.eu/
[38] http://natick.research.microsoft.com/
[39] http://www.datacenterknowledge.com/archives/2008/09/06/google-planning-offshore-data-barges/

ICE _ Vision_

In order to imagine what such a low-carbon, community-owned data center looks like practice, the author has written a short story, *Liveable Data: a Low Carbon Science Fiction* (due to be published by Routledge, 2018). This extends work on Social Futures and the concept of the green Liveable City[40], and proposes thinking through the implications for a world with Liveable Data.

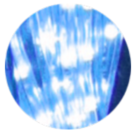

Sunrise over Stromness, Orkney

Download draft Liveable Data at_
goo.gl/BGygyp

ICE _ Goals_

This white paper presents a concept, and an opportunity, due to IT Communications and Energy (ICE) network convergence.

The goal is to build a prototype sociotechnical system in a Living Laboratory, in collaboration with a suitable local community.



This would be a trial 'ICE Systems Operator' (ISO). This prototype would be a sociotechnical testbed that brings together both social and technical solutions. This would require partners and expertise that would include the following:

- Green cloud computing research
- Data center industry partner
- Telecoms operator (either fixed or wireless)
- Community partner (with expertise in their local energy and telecoms)
- Renewable energy producer (either small-scale device or energy operator)
- Infrastructure studies researcher (to create and maintain the sociotechnical collaboration between partners)

Interested? Join the collaboration. Contact ice@sand14.com

1. ***Update this white paper with your ideas and expertise***. Send updates, corrections, comments and edits to this white paper. This will lead to the next draft having collaborative authorship with experts across relevant disciplines. The

[40] See John Urry's work on Social Futurs (2016).

writing can be used as the basis for discussion and application to funding partners.

2. ***Join the Mailing List.*** Participate in the ICE mailing list to share ideas. Interested participants, and those with related interests and expertise, should contact the author to be added to the mailing list.
3. ***Propose Potential Partners and Solutions***. Identify and propose potential partners, and specific social and technical solutions, that could make the prototype project happen.

ICE _ Summary_

ICE convergence is an opportunity to both resolve a triple IT, Communications and Energy infrastructure upgrade challenge, and to support local communities in places where environmental resources are rich but economic resources can be scarce.

European Marine Energy Centre (EMEC) hydrogen electrolyser, 500kW, which transforms both tide energy and community wind energy (image: http://www.surfnturf.org.uk/page/hydrogen)

This approach to ICE convergence shatters the fixed entanglement of infrastructures that are the wrong shape, into smart fractured pieces that can be resolved ('melted down' so to speak) at the local level. For example, ICE convergence might include hydrogen fuel cells in one place, tide energy in another, smart metering in another; WiMAX here, 5G over there, undersea fibre to there. It creates the opportunity for local decision-making about ICE that is appropriate to the local environment and local culture. It transforms Universal Service Obligation from a top-down regulatory problem into a bottom-up commercial opportunity for the margins to support the centre. Big companies can still focus on the big places and integration. Small bespoke companies are allowed to focus on the small bespoke places–innovating as and when needed.
In ICE, innovation moves to the edge.

References_

Akrich, M. (1992) The De-Scription of Technical Objects. In Bijker, W. and Law, J. (eds.) *Shaping Technology/building Society: Studies in Sociotechnical Change*. Cambridge MA: MIT Press.

Anaya, K.L. and Pollitt, M.G. (2014) Experience with smarter commercial arrangements for distributed wind generation. *Energy Policy* 71: 52–62.

Bahari, H.I. and Shariff, S.S.M. (2016) Review on data center issues and challenges: Towards the Green Data Center. In: *2016 6th IEEE International Conference on Control System, Computing and Engineering (ICCSCE)*, 129–134.

Bowker, G. (1993) How to be universal: some cybernetic strategies. *Social Studies of Science* 23: 107–127.

Bowker, G. and Star, S.L. (2000) *Sorting things out: classification and its consequences*. Cambridge MA: MIT Press.

Carr, N.G. (2004) *Does It Matter?: Information Technology and the Corrosion of Competitive Advantage*. Boston: Harvard Business School Press.

Cass, N. and Walker, G. (2009) Emotion and rationality: The characterisation and evaluation of opposition to renewable energy projects. *Emotion, Space and Society* 2(1): 62–69.

Cass, N., Walker, G. and Devine-Wright, P. (2010) Good Neighbours, Public Relations and Bribes: The Politics and Perceptions of Community Benefit Provision in Renewable Energy Development in the UK. *Journal of Environmental Policy & Planning* 12(3): 255–275.

Chen, Q., Grosso, P., Veldt, K., et al. (2011) Profiling Energy Consumption of VMs for Green Cloud Computing. In: *2011 IEEE Ninth International Conference on Dependable, Autonomic and Secure Computing*, pp. 768–775.

Data Center Alliance (2014) DCA Mission Statement. Available at http://www.data-central.org/?page=MissionStatement

Entwistle G, Roberts D and Xu Y (2014) *Measuring the Local Economic Impact of Community-Owned Energy Projects*. James Hutton Institute and Gilmorton Rural Development. Report for Community Energy Scotland. Available at http://www.communityenergyscotland.org.uk/

Greenpeace (2015) Clicking Green: A Guide to Building the Green Internet, May 2015. Available at http://www.greenpeace.org/usa/wp-content/uploads/legacy/Global/usa/planet3/PDFs/2015ClickingClean.pdf

Harvey P., Jensen C.B. and Morita A. (eds) (2016) *Infrastructures and Social Complexity: A Companion*. Abingdon/New York: Routledge.

Hogan, M. (2015) Data flows and water woes: The Utah Data Center. *Big Data & Society* 2(2).

Jain, S., Kumar, A., Mandal, S. et al. (2013) B4: Experience with a Globally-deployed Software Defined WAN. In: *Proceedings of the ACM SIGCOMM 2013 Conference on SIGCOMM*, SIGCOMM '13, New York, NY, USA: ACM, pp. 3–14.

Leach, J. and Wilson, L. (2014) *Subversion, Conversion, Development: Cross-Cultural Knowledge Exchange and the Politics of Design*. Cambridge MA: MIT Press.

Liu, L, Wang, H., Liu, X., et al. (2009) GreenCloud: A New Architecture for Green Data Center. In: *Proceedings of the 6th International Conference Industry Session on Autonomic Computing and Communications Industry Session*, ICAC-INDST '09, New York, NY, USA: ACM, pp. 29–38.

Lin, L. and Yu, S.Z. (2017) A Distributed Green Networking Approach for Data Center Networks. *IEEE Communications Letters* 21(4): 797–800.

Mackenzie, A. (2010) *Wirelessness*. Cambridge MA: MIT Press.

Moghaddam F.A., Lago P. and Grosso P. (2015) Energy-Efficient Networking Solutions in Cloud-Based Environments: A Systematic Literature Review. *ACM Comput. Surv.* 47(4): 64:1–64:32.

Moss, T., Becker, S. and Naumann, M. (2015) Whose energy transition is it, anyway? Organisation and ownership of the Energiewende in villages, cities and regions. *Local Environment* 20(12): 1547–1563.

National Infrastructure Commission (2014) *Smart Power*. Available from: https://www.gov.uk/government/publications/smart-power-a-national-infrastructure-commission-report.

Obar, J.A. and Clement, A. (2013) *Internet Surveillance and Boomerang Routing: A Call for Canadian Network Sovereignty*. SSRN Scholarly Paper, Rochester, NY: Social Science Research Network.

Ofcom, UK Government (2016) *Achieving decent broadband connectivity for everyone: Technical advice to UK Government on broadband universal service*. Available from: https://www.ofcom.org.uk/__data/assets/pdf_file/0028/95581/final-report.pdf

Sezer, S., Scott-Hayward, S., Chouhan, P.K., et al. (2013) Are we ready for SDN? Implementation challenges for software-defined networks. *IEEE Communications Magazine* 51(7): 36–43.

Star S.L. (1999) The Ethnography of Infrastructure. *American Behavioral Scientist* 43(3): 377–391.

Star, S.L. and Ruhleder, K. (1996) Steps toward an ecology of infrastructure: Design and access for large information spaces. *Information systems research* 7(1): 111–134.

Starosielski, N. (2015) *The Undersea Network*. Durham NC: Duke University Press.

Szeman I and Boyer D (eds) (2017) *Energy Humanities: An Anthology*. Baltimore: Johns Hopkins University Press.

Urry, J. (2016) *What is the Future?* Cambridge: Polity Press.