Location and technology: An examination of cases and theories of invention, development and innovation of power generation and lighting technologies

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Abstract

This article examines invention, development and innovation of power generation, distribution and lighting technologies against theories of technological innovation. Contrary to the prevailing theories on energy innovation, technologies in the cases were not chosen and then transferred to niches for innovation, but rather were discovered, invented and/or developed in locations of application, often with quantifiable goals to improve or replace an incumbent technology in the niche. The implications of this novel finding are examined and new research issues are presented for further study.

Keywords

invention, technology development, power generation, technological innovation, locations of innovation

1. Introduction

The objective of this research was to examine invention, development and innovation in power generation, distribution and lighting against theories of technological innovation. Common to theories of technological change in management and socio-technical transition literatures are concepts of technology innovation within niches or contexts-of-application to exploit networks of actors, including customers, regulators, operators, users, suppliers, financiers, and others. Exploitation of niches opens up the opportunities for development with other social groups and, in successful cases, examples of technology and market diffusion "S" curves.

Specific to energy industries, technological innovation have been characterized by its complexity of product architecture and scale of production process.[1] One line of research has found that the greater the complexity of product architecture and lower the scale of production - the greater the importance of geographical proximity of users for innovators. The electrical grid is an example of a system with high complexity of product architecture and lower scale of production, versus solar PV which currently has a relative simple product architecture and high the scale of production.[2] With technical systems like power grids, this research has found that locational proximity is important for collaborative invention and development among industry consortia, private-public partnerships, including data collection and understanding of evolving standards in operational settings. This paper seeks to add to this research by examining in greater detail the roles of location in knowledge generation activities. Building on the observation of the importance of geographical proximity of users to innovators, I argue that locational forces are an important but understudied element of innovation processes in the aforementioned industries.

[1] Davies, Andrew. "The life cycle of a complex product system." *International Journal of Innovation Management* 1, no. 03 (1997): 229-256.

[2] Huenteler, "Technology life-cycles", 114.

2. Methods

Case studies of technological invention, development and innovation in power generation and lighting industries were examined. Archival research was undertaken for cases on electric lighting and the Francis Turbine. The subjects of the case studies were all well-known examples of energy technology invention, development and innovation, and chosen because of their extensive study by historians of technology and science & technology studies scholars. The cases offered detailed grounds for comparative analysis as well examination of the theories of technological innovation. Comparative methods were used to identify commonalities and differences within the case studies.

3. Theory

Theories of technological change in energy industries share with other industries concepts that the process is non-linear and subject to strong influence by social, cultural, political and technical forces.[3] Technological change is not, in contemporary models, driven primarily by supply side science to determine, for instance, the design of a mega-watt scale wind turbine. Even in scholarship that emphasizes the role of state investments in science and technology, state investments have been found to be accompanied by strong networks of public and private actors and non-linear development pathways.[4] This approach to technological change has been

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[3] Sovacool, Benjamin K. "What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda." *Energy Research & Social Science* 1 (2014): 1-29, 25.

[4] Mariana Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths.* New York: Anthem Press, 2013.

embodied in socio-technical transition theory.[5] It has also been applied to analysis of past and prospective energy transitions.[6]

Whereas scholars in the 1970s such as Lynwood Bryant could discuss the history of the diesel engine in light of concepts of invention, development and innovation, the trend now is to examine cases of energy innovation against not only these social actor and network approaches, but an emerging body of literature on sustainability transitions. No longer is energy technology invention, development and innovation told as the story of a great inventor, or a partnership between and inventor and business leader, or even a firm, but instead is situated within a framework of transformative change that acknowledges "an emergent, collaborative, multi-actor and multi-level process that will involve business, government, research and civil society."[7] Core tasks of successful innovation in this model involves development of shared visions and plans for diverse actors to work together toward common goals, overcome system failures or 'gaps' within and between niche markets.[8]

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5 Jochen Markarda, Rob Raven, and Bernhard Truffer, "Sustainability transitions: An emerging field of research and its prospects," *Research Policy* Volume 41, Issue 6, July 2012, Pages 955–967.

6 Robert C. Allen, "Backward into the future: The shift to coal and implications for the next energy transition," *Energy Policy* 50 (2012) 17–23. Roger Fouquet, "The demand for environmental quality in driving transitions to low-polluting energy sources," *Energy Policy* 50 (2012) 138-149. Roger Fouquet and Peter J.G. Pearson, "Past and prospective energy transitions: Insights from history," Energy Policy 50 (2012) 1-7. Arnulf Grubler , "Energy transitions research: Insights and cautionary tales," *Energy Policy* 50 (2012) 8–16. Nuno Luis Madureira, "The iron industry energy transition," *Energy Policy* 50 (2012) 24–34. Peter J.G. Pearson and Timothy J. Foxon, "A low carbon industrial revolution? Insights and challenges from past technological and economic transformations," Energy Policy 50 (2012) 117-127. Michael G. Pollitt, "The role of policy in energy transitions: Lessons from the energy liberalisation era," Energy Policy 50 (2012) 128-137. Christof Ruhl, et al, "Economic development and the demand for energy: A historical perspective on the next 20 years," *Energy Policy* 50 (2012) 109–116. Bruno Turnheim in, Frank W. Geels, "Regime destabilisation as the flipside of energy transitions: Lessons from the history of the British coal industry (1913–1997)," *Energy Policy* 50 (2012) 35-49. Chris Wilson, "Up-scaling, formative phases, and learning in the historical diffusion of energy technologies," *Energy Policy* 50 (2012) 81-94.

7 Twomey, Paul, and A. Idil Gaziulusoy. "Review of System Innovation and Transitions Theories." *Visions and Pathways project, Melbourne, Australia,* 2014.

8 Foxon, Timothy J., R. Gross, A. Chase, J. Howes, Alex Arnall, and D. Anderson. "UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures." *Energy Policy* 33, no. 16 (2005): 2123-2137, 2135.

This shared vision approach has become so influential that calls have emerged to understand entrepreneurship within cleantech as not merely units within a larger vision, and to assign entrepreneurs greater agency in the innovation and commercialization processes.[9] Similarly firms have been treated in contemporary literature as black boxes on which external factors impinge.[10] Niches, in this literature, enjoy a particular prominence as they provide the context for these social actors to shape emerging science and technology.

3.1 Niches

The concept of a "niche" is widely used in the literature on technological innovation. Niches featured prominently in Geoffrey Moore's 2002 best seller, Crossing the Chasm.[11] It was based in part on Everett Rogers' 1962 *Diffusion of Innovations* and the segmentation of consumers into categories for innovators, early adopters, early majority, late majority and laggards.[12] Moore's catch-22 for the introduction of new high-tech products was that early majority customers wanted a reference from another member of the early majority, but none of this group would buy without first having consulted with several suitable references. To cross the chasm, Moore found companies must focus on one use case within a niche that is experiencing enough pain to motivate its users to use the new solution, and then for firms to move outwards once it had adoption in the niche. In the case of energy technologies these niches provide environments for learning, testing, improving, reducing risks and reducing costs for systems that are

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[9] Avdeitchikova, Sofia, and Lars Coenen. "Commercializing clean technology innovations–the emergence of new business in an agency-structure perspective." *Handbook of Entrepreneurship and Sustainable Development Research* 321 (2015), 20-21.

[10] Boons, Frank, and Florian Lüdeke-Freund. "Business models for sustainable innovation: state-of-the-art and steps towards a research agenda." *Journal of Cleaner Production* 45 (2013): 9-19, 16.

[11] Moore, Geoffrey A. *Crossing the Chasm: Marketing and Selling High-Tech Products to Mainstream Customers*. New York: Harper Business, 1991.

[12] Rogers, Everett M. *Diffusion of Innovations*. New York: Simon and Schuster, 2010.

often crude, imperfect, and expensive, but possess a potential competitive advantage of a more efficient or lower priced energy product or service.[13]

In the socio-technical transition literature, niches have been characterized as offering protected spaces in which new technologies can be developed and applied, and co-evolve in a process of learning, coercion and negotiation with users, policy makers and others.[14] One of big public policy observations has been that strategic niche management offers a better policy approach to technological change than a command-and-control approach. Kemp and coauthors explored the expediting of these transitions through strategic niche management:

> How does one create technological niches and manage them? First of all, it must be noted that niches are platforms for interaction; they emerge out of a process of interaction shaped by many actors. They cannot be controlled. Still, governments could try to contribute to these processes of niche formation by setting up a set of successive experiments with a number of new technologies; this is strategic niche management. Such a policy consists of five steps (elements): the choice of technology, the selection of an experiment, the set-up of the experiment, scaling up the experiment and the breakdown of protection by means of policy.[15]

This is particularly interesting for the snapshot it presents of a particular method of new knowledge generation. It begins with a choice of technology and then proceeds to design and execution of experiment. While I do not argue for a method of invention, develop and innovation that is common to all times, places and industries, I question whether technological innovation in the cases examined in this paper began with a choice of technology. I ask whether it instead began with selection of a site which led to an understanding of a problem.

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13 Wilson, Charlie. "Up-scaling, formative phases, and learning in the historical diffusion of energy technologies." *Energy Policy* 50 (2012): 81-94, 82.

14 Rip, Arie, and René Kemp (1998) “Technological Change”, in Steve Rayner and Liz Malone (eds.) *Human Choice and Climate Change, Vol 2 Resources and Technology*, Batelle Press, Washington D.C., 327-399.

15 Kemp, René, Johan Schot, and Remco Hoogma. "Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management." *Technology analysis & strategic management* 10, no. 2 (1998): 175-198, 186.

I am indebted to Johan Schot for his prior work on the topic. In a paper on technology innovation as an evolutionary process, he examined the concept of niches for radical new technologies with historical examples, including use of: wheels for ritual and ceremonial purposes; steam engines to pump water from mines; clocks in monasteries to mark the divisions in the timetable; assembly lines in the armoury of the American army for manufacture of muskets from standardized, interchangeable parts; and the telegraph for communication in railways.[16] From these niches, new branches developed for novel applications and locales for use of the technologies, such as the growth of gaslight from the niche of textile manufacturing to street lighting, theatres, cafes, and wealthy residences, and expansion from London to other cities in England, and to continental Europe. Scot also emphasized the crucial role that promises and expectations play in the creation and extension of niches. Given the uncertainty of technological development in niches, Schot argued that, contrary to the approach of many others, that the process must also involve parties to set expectations of new worlds, help birth new desires and visions, and promote and justify the new technology. Rather than there being a technology first or a market first, for Schot the two develop at the same time. By develop, he means discovery of the nature of the technology, pricing, impact on lives, and dangers. In this paper I am seeking to extend Schot's analysis and argue that for the technologies under examination, the niche or context of application preceded the technology. Location of application existed prior to the technology and profoundly shaped the fundamental understandings of the technology.

The concept of niches has been further explored and developed by scholars behind the concept of multi-level perspectives. Frank Geels has emerged as one of the leading researchers on the concept. He has published case studies on the transitions in water supply, cars, electrical systems, sewers and much else. The core concept is that these transitions are best studied

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[16] Schot, Johan. "The usefulness of evolutionary models for explaining innovation. The case of the Netherlands in the nineteenth century." *History and Technology, an International Journal* 14, no. 3 (1998): 173-200.

from a multi-level perspective to show not only the movement of disruptive technologies from niches into mainstream markets, but also the changes at the socio-technical regime level (markets, users preferences, science, culture, industry, policy and existing technology), and the top level of the socio-technical landscape. The landscape level puts pressure on the existing regime which creates windows of opportunity for novelties.[17] My approach to the study of technological innovation will hopefully not get lost in the micro-details of my case and appreciate the larger multi-level perspective that Geels has represented in his work. In studying the role of locations in technology creation I am seeking to integrate the landscape, regime and niche levels within the case study.

3.2 Mode 2

Although not a theory of technological innovation specific to energy innovation, the mode 2 theory of knowledge production has relevance for my examination of the energy invention, development and innovation case studies.[18] The mode 2 concept draws a sharp distinction between the old paradigm of scientific discovery, mode 1, and the new one of knowledge production, called mode 2. The old approach consists of experimental science, internally-driven by au-

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[17] The concept is already being applied by others in technology forecasting. See, for instance: Paula Kivimaa and Venla Virkamäki, "Policy Mixes, Policy Interplay and Low Carbon Transitions: The Case of Passenger Transport in Finland," *Environmental Policy and Governance* 24, 28–41 (2014). K. Söderholm and E. Wihlborg, "Policy for Sociotechnical Transition: Implications from Swedish Historical Case Studies," J*ournal of Environmental Policy & Planning*, 2014, 1-23. B. Van Bree, G.P.J. Verbong, and G.J. Kramer. "A multi-level perspective on the introduction of hydrogen and battery-electric vehicles" *Technological Forecasting and Social Change*, Technological 77 (2010) 529–540. Critical work on the concept includes the following studies. Audley Genus and Anne-Marie Coles, "Rethinking the multi-level perspective of technological transitions," *Research Policy* Volume 37, Issue 9, October 2008, Pages 1436–1445. Smith, A., Stirling, A., Berkhout, F., 2005. "The governance of sustainable socio-technical transitions." *Research Policy* 34, 1491–1510.

[18] Gibbons, Michael, Camille Limoges, Helga Nowotny, Simon Schwartzman, Peter Scott, and Martin Trow. *The new production of knowledge: The dynamics of science and research in contemporary societies.* Sage, 1994, Gibbons, Michael. "Science's new social contract with society." *Nature* 402 (1999): C81-C84. Nowotny, Helga, Peter Scott, and Michael Gibbons. "Introduction: Mode 2 Revisited: The New Production of Knowledge." *Minerva* 41, no. 3 (2003): 179-194.

tonomous, university and discipline-based researchers. Its ideal is Newtonian empirical and mathematical physics. In contrast, the new knowledge is carried out in the context of application, produced through socially distributed, application-oriented, trans-disciplinary projects, subject to multiple accountabilities, and intended to be useful. Examples include chemical engineering, aeronautical engineering and computer science. It is different than applied science in that it does not apply science in contexts-of-application, but rather makes science and produces new knowledge in contexts of application.[19] The authors distinguish between 'weak contextualization' such as situating research within national research and development programmes and 'middle range' or 'strong contextualization'. The middle range contains the majority of mode 2 science in which transaction spaces help local contingencies shape new knowledge. Strong contextualization involves the use of powerful reflexive articulations between science and society, such as social movements, e.g. feminism or environmentalism.[20] I argue that the idea of contexts-of-application is relevant for this study given the strong role that locations have in the case studies for the design of new technical systems. Although not necessarily a part of a context-of-application (or niche), locations-of-application extend the mode 2 concept to explain the forces exerted by material environments in shaping new knowledge creation inside and especially outside of research institutions.

3.4 Research Question

The research question I examine is whether locational forces profoundly shaped the fundamental understanding of technology in the cases. Did choice of technology come first, followed by design and conduct of experiment, and subsequently scale-up? Or did the study of

[19] *New Production of Knowledge*, 203.

[20] Mode 2 Revisited, 191.

locations comes first, whether as part of a niche or context-of-application, setting the context for the design of technologies or technical systems in early energy transitions?

4. Case Studies

In this section I review the five case studies, with a focus on the roles of location in the invention, development and innovation of new technologies or technical systems.

4.1 Smeaton, de Parcieux and Euler Overshot Water Wheels

The American engineer and historian Terry Reynolds wrote that "Between 1752 and 1754 John Smeaton, an English engineer; Antoine de Parcieux, a practically oriented French mathematician; and Johann Albrecht Euler, a Swiss-German physicist and mathematician, independently established that the overshot-gravity waterwheel was significantly more efficient than the traditional undershot-impulse water wheel."[21] Simply put, the overshot waterwheel turned as a result of water flowing over the top of the wheel, versus the undershot wheel in which water flowed underneath and turned the wheel clockwise with the current. Smeaton and de Parcieux's discovery arose from practical problems while Euler's was made through the direct application of mathematical analysis and scientific theory to technical problems. Prior to these co-discoveries, the prevailing theory of water power was from the French mathematician Antoine Parent of the Academie des Sciences. Parent had used the undershot water wheel as his model and neglected to factor gravity into his calculations of the maximum efficiency of waterwheels. The neglect of the gravity was most likely influenced by the location of the Royal Society of London and the Academie des Sciences in Paris. Undershot waterwheels were common in these cities given their topographies, with low falls and relatively high water volumes. Hence, the overshot water

[21] Reynolds, Terry S. "Scientific influences on technology: The case of the overshot waterwheel, 1752-1754." *Technology and Culture* 20, no. 2 (1979): 270-295, 270.

wheel was more likely to be familiar to academicians and afforded them the best opportunity for direct study.[22]

Location was also important to the discoveries by Smeaton and de Parcieux. For Smeaton the performance of experiments on operating conditions for water wheels "was probably the result of one of his early commissions to design a watermill."[23] Smeaton was not alone in his interest; British mill builders and designers also wanted reliable data to understand how to extract the maximum available power from existing facilities, given shortages of adequate waterpower sites.[24] According to Reynolds, "Smeaton's decision to undertake model experiments to establish the optimum operating conditions for water wheels was probably the result of one of his early commissions to design a watermill."[25] This led to a total of nine experiments as reported in his paper of 1776. So concerned was Smeaton with location that he only reported in 1759 on experiments conducted in 1752 and 1753, after he had applied his deductions in real practice so he was assured that he had found the right answer.[26]

In the case of de Parcieux's discovery it was Louis XV's mistress, Mme de Pompadour, who provided the practical problem and geography that led to his discovery that gravity was the force that drove the greater efficiency of the overshot waterwheel. She wanted a water supply for her chateau. De Parcieux was asked to investigate the problem by a colleague of the Acad-

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22 Reynolds, "Scientific influences on technology", 274-5.

23 Reynolds, Terry S. *Stronger than a hundred men: a history of the vertical water wheel*. No. 7. Johns Hopkins Univesity Press, 2002, 223.

24 Smeaton, John. "An Experimental Examination of the Quantity and Proportion of Mechanic Power Necessary to be Employed in Giving Different Degrees of Velocity to Heavy Bodies from a State of Rest. By Mr. John Smeaton, FRS." *Philosophical Transactions of the Royal Society of London* 66 (1776): 450-475, .

25 Reynolds, *Stronger than a Hundred Men*, 223.

26 Smeaton, John. "An Experimental Enquiry concerning the Natural Powers of Water and Wind to Turn Mills, and Other Machines, Depending on a Circular Motion." By Mr. J. Smeaton, FRS." *Philosophical Transactions* 51 (1759): 100-174, 100-101.

emie des Sciences. Assuming the best approach was to make use of the power from a small river nearby and calculating that an overshot waterwheel would be impractical, De Parcieux saw that he could get more power from the descending weight of the water in an overshot alternative. His experiments with pulleys and weights confirmed his insight.[27]

As to the role of science in the discovery of the overshot waterwheel's greater efficiency, there are differing views. The older view had been that De Parcieux and Smeaton were "scientific engineers".[28] Smeaton had been judged to have had a brilliant capacity for experimentation, as demonstrated in his "Experimental Enquiry" paper.[29] Reynolds came to a different conclusion: "If waterpower is a representative area, the impact of science on the development of technology during the 18th century was indirect and largely secondary to traditional technological methods. It was the work of the practically oriented engineers (Smeaton and de Parcieu using traditional technological methods (mechanical intuition, physical analogy, and model experimentation), and only indirectly influenced by science, who had an effect on the waterpower technology of the era. Johann and Leonhard Euler, who attempted to apply science directly to technology, had little impact. Had they never worked on waterpower, the course of technological development would have been unchanged."[30] Likewise, a recent paper on this topic has concluded that "theoretical work written on the subject had a very limited impact on the technological development of the wheels, mainly because they were not read by engineers, in particular, they were not read

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27 "Scientific influences on technology", 278-9.

28 Cardwell, Donald Stephen Lowell. "Power technologies and the advance of science, 1700-1825." *Technology and Culture* 6, no. 2 (1965): 188-207.

29 Musson, A. E., & Robinson, E. *Science and technology in the industrial revolution.* Manchester: University Press of Manchester, 1969.

30 Reynolds, *Scientific influences on technology*, 295.

by Smeaton and were soon forgotten."[31] Smeaton, it turned out, was not sure how to account for the unexpected twofold superiority of gravity wheels to impulse wheels.

4.2 Gas Lighting

According to Johan Schot in an article on the use of evolutionary models for technological innovation, gas lighting emerged from a limited and local niche based on an alliance between developers and English textile barons.[32] To explore the origins and development of gas lighting in British cotton mills and the City of London, we fortunately we have the scholarship of the historian Leslie Tomory.[33] Tomory distinguished between the first wave of classic technologies of the Industrial Revolution and a second wave of nineteenth century technologies. The first-wave technologies were invented and deployed by individuals and small partnerships, required relatively little capital, and were dependent on artisanal skills for their invention and development, owed little to contemporary science. In contrast second wave technologies were dependent on contemporary science and formal organized research, required more capital, and therefore were usually built and run by larger companies or institutions.[34] Tomory's book on the origins of the gaslight industry argued that gas lighting was the first technology to have all the attributes of the second wave. Presumably, then, as a second wave technology gas lighting generation and distribution would be subject to much less influence from local factors, and much

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[31] Capecchi, Danilo. "Over and undershot waterwheels in the 18th century. Science-technology controversy." *Advances in Historical Studies* 2, no. 03 (2013): 131-139, 138.

[32] Schot, Johan. "The usefulness of evolutionary models for explaining innovation. The case of the Netherlands in the nineteenth century." *History and Technology, an International Journal* 14, no. 3 (1998): 173-200.

[33] Tomory, Leslie. "Competition and regulation in the early history of the London gas industry, 1800–1830." *The London Journal* 39, no. 2 (2014): 120-141. Tomory, Leslie. "The environmental history of the early British gas industry, 1812–1830." *Environmental history* 17, no. 1 (2012): 29-54.

[34] Tomory, Leslie. Progressive Enlightenment: The Origins of the Gaslight Industry, 1780-1820. MIT Press, 2012, 1-2.

greater influence from the pneumatic chemistry of Joseph Black, Jason Priestly and Antoine-Laurent Lavoisier.[35]

But what instead occurred instead was development of technology, social and business practices in the context of a complex, integrated and tightly coupled system. Although invention of technological components preceded reduction to practice in cotton mills, the development of a technical system only occurred within those mills.[36] Specifically, pneumatic chemistry provided the concepts (inflammable air, hydrogen and carbon) as well as instruments and processes, including the retort (closed furnace), pneumatic trough, lime purification of carbon dioxide and hydrogen sulphide (discovered by Joseph Black), and the gasometer, used to storage gas and measure its volume (made famous by Lavoisier).[37] This integration of these components and development of a system of gas lighting system was based on the application of knowledge, instruments and techniques in the cotton mills.

There is an even a stronger case for location-based-invention and development in the origins of the London gas network. The separate co-invention and demonstration of gas production, purification and storage for lighting in London occurred over a decade or more. There were four separate acts of invention: in 1785 at Louvain, Belgium by Jan-Pieter Minckelers, between 1792 and 1794 in Redruth, England by William Murdoch, in 1796 by Philippe Lebon in Paris, and in 1802 Zachaus Winzler in Vienna. Murdoch's version was the only one for the four that was led to development of a commercial technical system. Murdoch had originally been inspired from experiments with combustible gases in Matthew Boulton's laboratory in his nearby Corn-

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[35] Tomory, Leslie. "Gaslight, Distillation, and the Industrial Revolution." *History of Science* 49, no. 4 (2011): 395-424, 415.

[36] Tomory, Leslie. "Let it burn: Distinguishing inflammable airs 1766–1790." *Ambix* 56, no. 3 (2009): 253-272.

[37] Tomory, Leslie. "The origins of gaslight technology in eighteenth-century pneumatic chemistry." *Annals of science* 66, no. 4 (2009): 473-496, 474.

wall residence. Murdoch designed and built a system to store and deliver the gas to light his living room.

By 1798 Murdoch was working for Boulton and Watt at the Soho foundry and manufactory in Birmingham and conducting minor experiments. But work in earnest on the invention occurred only later following Gregory Watt's visit to Lebon's new thermolamp in Paris in 1801, and the realization that Boulton and Watt might be beaten to gaslight by a Frenchman. This invigorated experiments with the goal of producing a viable technology, and "a good deal more work was needed to scale up the apparatus."[38] By 1803 a scaled version of the gasometer has been designed and constructed. In addition, through extensive experimental work by Murdoch and others at Boulton and Watt "identified many and solved some of the problems associated with building industrial-scale gas plants, including how best to charge the retorts, extending the lifespan of apparatus and improving its robustness, dealing with gas purification and supply, flame efficiency, assessment of economics, and so on."[39] According to one account, "Murdock's experiments in the last years of the eighteenth century illustrated how gas lighting progressed from an experimental to an industrial stage" and by 1805 the "gas technology, in its basic outlines, was … fully developed"[40]

The niche that Boulton and Watt focused on were industrial mill owners, the same customers for their steam engines. Boulton & Watt's success in commercializing gaslight owed much to the firms to its skills and experience in ironworking and to making scientific instruments, and second to its many resources, including access to capital, existing network of industrial customers, and marketing and advertising abilities. As with the promotion of the steam engine, Boulton and Watt prepared detailed calculations from demonstration projects to show that cost

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[38] Tomroy, Origins of Gaslight Technology in Eighteenth-Century Pneumatic Chemistry, 493.

[39] Tomroy, *Fostering a New Industry*, 6.

[40] Schivelbusch, Wolfgang. *Disenchanted night: The industrialization of light in the nineteenth century*. Los Angeles: University of California Press, 1995, 18-19.

effectiveness of their technology, in this case that it was a lower cost solution than candles. They also published these calculations in an 1808 Royal Society paper in *Philosophical Transactions* to promote Murdoch as the original inventor of this breakthrough technology.[41]

Although Boulton and Watt emerged as leaders in commercialization of gaslight, the firm quickly lost interest in the manufactured-gas business. Evidence from drawings and plans from 1810 to 1812 show that development had effectively ended, with retort design unchanged since 1808. The last recorded sales were in 1815. This was a conscious decision by the firm given plans to focus resources on the steam engine business due to its greater projections for profit. This turned out to be of great benefit of the other firms that would follow Boulton & Watt into the gas lighting business. It was agreed in Boulton and Watt that the manufacture of gas lighting should be farmed out to other manufacturing firms to the extent possible, recognizing that this would effectively transfer knowledge and skills to these other firms who would be their competitors. This was especially significant for opening up of gas lighting markets in London by the Gas Light and Coke Company (GLCC).

GLCC arose form the work of German "visionary and charlatan" Frederick Albert Winsor.[42] Seized by the idea in 1804 to launch a gaslight company in London, he began efforts that year to develop the venture and raise financing. Following an 1807 demonstration, a battle emerged between Winsor and Murdoch over Winsor's proposed act of Parliament to deploy a gaslight system.[43] Murdock wanted to instead establish gas lighting in industrial applications and then subsequently build a gas network in London and other residential sectors. It was not until 1812 that GLCC was established, and during the remainder of the decade the firm reduced to

[41] Tomroy, *Fostering a New Industry*, 24

[42] Falkus, Malcolm E. "The Early Development of the British Gas Industry, 1790–18151." *The economic history review* 35, no. 2 (1982): 217-234, 225.

[43] Melaina, Marc W. "Market transformation lessons for hydrogen from the early history of the manufactured gas industry." In *Hydrogen Energy and Vehicle Systems*, pp. 123-158. CRC Press, 2012, 139.

practice the first gas network. According to a 1985 article by the historian Malcom Falkus, factory owners and potential customers were the most instrumental factors in the introduction of commercial gas lighting.[44] He characterized it as a demand-induced case in which the distinction between an original invention and subsequent innovation was to some extent were reversed.[45] Original invention occurred while designing and building the London gas network. Tomroy agreed with Falkus that GLCC's creation of the London gas network model involved significant and difficult inventive work, while also - consistent with his thesis about second wave technologies - found crucial contributions from Boulton and Watt, including training workers who would work in the London residential business, as well as within parts suppliers in Birmingham and Manchester.[46] Consistent with contemporary theories of technological innovation, it was not just inventors and managers who shaped the technologies, but also users, managers, government and mediators.[47]

4.3 Francis and Pelton Water Turbines

The Francis water turbine, developed in 1847 at Lowell, Massachusetts, and the Pelton water turbine, developed in the 1879 at Camptonville, California (north of Sacremento), were triumphs of empirical research and experimental testing in operating environments. Their work followed after but was largely uninformed by the invention of Benoit Fourneyron's reaction water turbine in 1832. These American turbines were not only significant as prime movers of industry before steam engines began to dominate American power generation for industry in the second

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[44] Falcus, 233.

[45] Falcus, 234.

[46] Tomory, Leslie. "Building the First Gas Network, 1812-1820." *Technology and Culture* 52, no. 1 (2011): 75-102, 102.

[47] Tomory, "Building the First Gas Network", 77.

half of the nineteenth century, but by the end of the nineteenth century helped to launch modern water-powered electricity generation.[48]

James Francis' development of the turbine that would bear his name was based on a design from the civil and hydraulic engineer Uriah Boyden.[49] Boyden's construction of turbines dated back to 1844. It was similar to Fourneyron's design, except for an addition to reduce instability and increase efficiency. Like Fourneyron, Boyden had used a Ponybrake to measure efficiencies, which showed he was achieving efficiencies of 78 to 88%. Francis, with cooperation from Boyden, built in 1851 a large-scale test facility in a Lowell canal to test and improve Boyden's design. As with testing of the Fourneyron design, nearly all material variables were carefully controlled and measured, including use of a large Ponybrake dynamometer to measure power output.

The debate among historians about the invention of the Francis turbine has focused on the role of science, not questions about location. There is general agreement on the invention during testing of design in the canals at Lowell, Massachusetts. Louis Hunter in his history of industrial power in America wrote that the successful first demonstration of a large scale water turbine at Lowell was "almost wholly pragmatic and empirical, largely ignorant of and indifferent to theoretical considerations" and was distinguished by "the emphasis at the outset on the thorough testing of the results in the operation of the wheels."[50] Testing of turbine designs was performed under water at the Lowell canals. Edwin Layton had a similar view of the development of the Francis turbine: that it was not a case of a science-based development.[51] Layton instead

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[48] Smil, Vaclav. "Energy in world history" *Encyclopedia of Energy*, Volume 6. 2004 Elsevier Inc., 555.

[49] Worthen, W. E. "James Bicheno Francis." In *Proceedings of the American Academy of Arts and Sciences*, 333-340. John Wilson and Son, 1892.

[50] Hunter, Louis C. A History of Industrial Power in the United States 1780-1930: Volume One: Waterpower in the Century of the Steam Engine. Eleutherian Mills-Hagley Fondation, 1979, 292.

[51] Layton, Edwin T. "Scientific technology, 1845-1900: The hydraulic turbine and the origins of American industrial research." *Technology and Culture* 20, no. 1 (1979): 64-89, 65-66.

saw a process of turbine development that evolved from the experimental testing in Lowell and then subsequently the development and application of science as the industry matured.[52] Edward Constant had a different view. He argued that the specific testing technologies used in development of the Francis turbine incorporated scientific principle and measurement techniques in the invention process.[53] Constant examined the history of the dynamometer (or Prony brake) to measure the torque produced by an engine or turbine. What was important for Constant was that the Prony brake physically embodied scientific information and thus provided a medium for science-technology interaction in testing under the canal water in Lowell.[54]

The invention and development of the Pelton water wheel was also profoundly shaped by locale. The American millwright and carpenter, Lester Pelton, invented the Pelton water wheel in the late 1870s from his studies of mining equipment and operations in California's gold rush territories. In contrast to Lowell, with its relatively flat geography, the terrain of California's gold rush was characterized by high-head, high-pressure, but relatively low-volume water power resources.[55]. The Pelton design improved upon the earlier Knight wheel, developed at the nearby Knight Foundry, in Sutter Creek, California (just south of Sacramento). Peyton's invention was based on the observation that water wheels moved faster when the jets of water hit the edges of the cups and reflected in a half circle, instead of hitting the middle of the cup with a splash that made less use of the water energy.[56]

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[52] Layton Jr, Edwin T. "Millwrights and engineers, science, social roles, and the evolution of the turbine in America." In *The Dynamics of Science and Technology*, pp. 61-87. Springer Netherlands, 1978, 87.

[53] Constant, Edward W. "Scientific theory and technological testability: Science, dynamometers, and water turbines in the 19th century." *Technology and Culture* 24, no. 2 (1983): 183-198.

[54] Constant, "Scientific Theory and Technological Testability", 193.

[55] Constant, Edward W. "On the diversity and co-evolution of technological multiples: Steam turbines and Pelton water wheels." *Social Studies of Science* 8, no. 2 (1978): 183-210, 184.

[56] Constant, "On the diversity and co-evolution of technological multiples:, 202.

Underlining the importance of location for the inventive process, contemporary theory still does not understand the flow processes in Pelton turbines, at least to the extent of other fluid machines like pumps and Francis turbines. Moreover, even the optimum bucket number of a Pelton wheel has only been determined by experience and model tests, and has frustrated hydromechanical theory due to the complex flow conditions in high-speed jets and the unsteady interaction between the high-speed jets and the rotating buckets.[57]

4.4 Edison's Electric Lighting System

Edison's initial electric lighting system was one of the cases that others have cited in studies of sociotechnical transitions and niche management. In particular, Johan Schot referred to incandescent lamp use in shopping windows, building ornaments, and festivals as an example of a technological niche.[58]

Previously an inventor of components of a technological system, it was with the establishment of his research laboratory in Menlo Park in 1876 that Edison decided to develop a system of electric lighting. Edison's approached problem solving systematically, and his inventive method synthesized the technological, economic, and scientific.[59] Tomas Baker Hughes described Edison's gift for invention this way: "Edison focused on one level of the process of technological change - invention - but in order to relate everything to single, central vision, he had to reach out behind his special competence to research, develop, finance, and manage his inventions…Edison's genius lay in this ability to direct a process involving problem identification, solution as idea, research and development, and introduction into use…In problem identification, an

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[57] Zhang, Zh, *Pelton Turbines*, Springer-Verlag Berlin Heidelberg 2017, 3.

[58] Schot, Johan. "The usefulness of evolutionary models for explaining innovation. The case of the Netherlands in the nineteenth century." *History and Technology, an International Journal* 14, no. 3 (1998): 173-200.

[59] Hughes, Thomas Parker. "The electrification of America: the system builders." *Technology and Culture* 20, no. 1 (1979): 124-161, 125-6.

inventor perceives a situation that can be defined as a problem."[60] For Edison's electric lighting system, identification of problems was grounded in perception of a particular situation. Within the situation Edison employed a reserve salient-critical problems method that involved the identification of critical issues that stood in the way of advancing the overall system, such as the non-durability of experimental lamp filaments.

Work on the invention of the incandescent lamp began on August 27, 1878. On September 20, 1878 Edison was noting calculations of the amounts of copper needed for the system wiring. By October 1878, a year before he built a practical incandescent lamp and released a basic generator design, Edison had prepared a basic design for his lighting system. In December 1879 development had moved from experimentation with components to laboratory-scale system models and then to a small, pilot-scale system for lighting Menlo Park. This permitted Edison to estimate in 1880 the cost for a ten thousand lamp central station. The result was that a gas lighting system of ten thousand lamps cost $136,875, much higher than the estimated cost of an electric lighting system of $45,989. Edison noted the difference would pay for patent rights and interest.

The work at Menlo Park involved problem solving by electricians, mechanics, and scientists with various components of the system. A review of the first 200 of the laboratory notebooks from November 1878 to 1880 showed that the physicist and mathematician Francis Upton as the most frequent author of notes on experiments and calculations.[61] Edison knew he had to draw upon science in developing his system and Upton served this purpose, although Edison's larger systematic approach ignored disciplinary scientific boundaries. What was instead ordered were the priorities that defined the problem. The primary need was for electric

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[60] Hughes, Thomas P., *Networks of Power: Electrification in Western Society, 1880-1930*. Baltimore: The Johns Hopkins University Press, 1983, 18-19.

[61] Friedel, Robert Douglas, Paul Israel, Bernard S. Finn. *Edison's Electric Light: Biography of an Invention* New Brunswick, New Jersey: Rutgers University Press, 1987, 4.

light that was less costly than gaslight. Within this understanding the problem, the solution that emerged was the realization that Ohm's and Joule's laws defined the terms for a solution. By September 1882 the system was in commercial operation at the Pearl Street generation station in New York City.

Of Edison's approach to understanding the context for the invention of incandescent light technology, he read extensively and deeply about gas-lighting from central stations, especially the economics of gas lighting.[62] He also surveyed the potential market for lighting at his initial planned central station in the Wall Street district in New York. Further, he analyzed the operating cost of arc light generators that he had acquired for test purposes. This, in turn, provided the basis for choosing a high-resistance lamp filament and cost of copper wiring for his system, so as to be competitive with gas lighting.[63]

While others have said there is no evidence of any extensive investigation of the gas industry until the spring of 1879, it is clear from Edison's notebooks that he ordered books on the gas industry in November 1878, about three months after beginning the electric lighting research.[64] There is also evidence of calculations in Edison's notebook from November 1878 of gas consumption for lighting. He calculated gaslight burner consumption of 5 cubic feet of gas per hour at 10 hours per day.[65] On this basis a 10,000 gas lamp system was found to consume 500,000 cubic feet of gas per day, or 182,500 cubic feet per year. Using a cost of gas ranging from $1.00 to $1.50 (from Menlo Park newspaper clippings during the fall of 1878) this translat-

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[62] Hughes, "The electrification of America", 132.

[63] Hughes, "The electrification of America", 135.

[64] Friedel, Robert Douglas, Paul Israel, Bernard S. Finn. *Edison's Electric Light: Biography of an Invention* (New Brunswick, New Jersey: Rutgers University Press, 1987), xii.

[65] Edison, Thomas Alva, Menlo Park Notebooks: Notebook #1 N-78-11-28 (1878-1879), [N001001; TAEM 29:19],

ed to an annual cost of natural gas of $182,500 to $273,750.[66] These figures are lower than Edison's estimate from 1880, in which he estimated income from 10,000 installed lamps to be $136,875. Although Edison used the same assumptions for gas consumption per light burner and gas cost ($1.50 per thousand cubic feet), by 1880 he had dropped his assumed daily usage of lighting from 10 hours to 5 hours.[67]

A second area of invention, development and innovation that was critical to the successful deployment of the electric power grid was in business model innovation. Edison's early licensed franchise owners struggled or were unable to make profits given the proliferation of small scale power generation plants, few customers in niche markets for luxury goods, and low capacity factor of plants, running only 5% of the time in some cases.[68] The Chicago Edison franchise was, for instance, losing money as one of more than twenty small electric-light utilities. The turn-around for Chicago Edison and electric utilities in general arose from the innovations of Samuel Insull, the former personal secretary of Thomas Edison and head of the Edison utility for Chicago beginning in 1892. Insull pioneered the aggregated load, large scale, monopoly business model as the best way to manage electric power generation, transmission and distribution. The goal was to lower rates by increasing the scale of operation and expanding markets. He achieved this by buying up utilities, shutting down the small scale generating facilities, and using large prime movers to serve the increasingly diversified customer base to increase his load capacity, e.g. streetcars at dusk and dawn, residential customers during the evening, businesses

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[66] An article dated 09/28/1878 titled "Gas in London and New York" in the *New York Sun* quoted a cost of $1.50 per 1,000 cubic feet for gas delivered in New York. See Miscellaneous Scrapbook Series: Cat. 1032 (1878) [SB032134a; TAEM 27:923]. A subsequent article dated 10/18/1878 titled "Electric and Gas Light" in the *New York Sun* referenced a price of $1.00 per 1,000 cubic feet of furnished gas below 34th Street. See [MBSB2] Special Collections Series -- Charles Batchelor Collection -- Scrapbooks: Cat. 1241 (1878-1881) [MBSB20956X; TAEM 94:378]. Courtesy of Thomas Edison National Historical Park.

[67] Hughes, "The electrification of America", 134.

[68] Bakke, Gretchen. *The Grid: The Fraying Wires Between Americans and Our Energy Future*. (Bloomsbury Publishing USA, 2016), 66.

in late afternoon and early evenings, industry for late day, and streetlights at night. Eventually, he connected the Chicago system with suburban companies and neighbouring municipalities, inventing the regional utility.

Insull was, according to Hughes, “a systems conceptualizer comparable to Edison, but on a high level of abstraction…His conceptual syntheses involved social and market needs, financial trends, political (especially regulatory) policies, economic principles, technological innovations, engineering design, and managerial techniques.”[69] He also embraced regulation by government in exchange for monopoly protection from other electric power generation, transmission and distribution companies. The system concepts were developed in the context in which they were applied. As such, Insul’s invention of the regulated power utility benefited in an event more direct way from field-based development.

4.5 Mega-Watt (MW) Scale Wind Turbines, 1970s and 1980s

Case studies on the development of MW scale wind turbines in the 1970s and 1980s have been written by scholars from the social sciences, public policy and science and technology studies fields. The 1998 paper, “Signs of Hubris: The Shaping of Wind Technology Styles in Germany, Denmark, and the United States, 1940-1990”, was one of the first to inquire into the reasons for Danish success in developing MW scale wind turbines.[70] Financing was not the critical factor between 1975 and 1988 the United States government spent twenty times more than the Danes, and Germany spent five times more than the Danes on wind power research and development, according to the author. The article found that reliable and successful wind turbine designs were mostly developed by non-academic technicians, engineers, and artisans using a

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[69] Hughes, “The electrification of America”, 148-9.

[70] Heymann, Matthias. "Signs of hubris: the shaping of wind technology styles in Germany, Denmark, and the United States, 1940-1990." *Technology and Culture* 39, no. 4 (1998): 641-670.

craft approach and small scale-up tests, versus designs proposed by academic engineers under government-sponsored, engineering science research programs. This bottom-up approach of the Danes has been contrasted with an American top-down methodology that sought to develop wind turbines through computer simulations borrowed from the aircraft industry.[71] The aim was to generate fast technological advances and radical innovations for building large wind turbines. However, once the support from the American government stopped, the data and information from the failed projects was found to be almost worthless. In contrast the Danish case featured the now often cited factors of guaranteed prices for wind power, scale up of small and medium-sized wind turbines by engineers and skilled artisans, knowledge sharing and learning along the establishment of branch organizations and a strong industry association, a test station, active grass root movements and public support.

This widely cited 2003 paper, “Bricolage versus breakthrough: distributed and embedded agency in technology entrepreneurship” also addressed the topic of how it was possible for one group of actors in Denmark to prevail over another in America deploying far superior resources.[72] The authors labeled the two contrasting approaches to technology entrepreneurship as *bricolage* (Danes) and *breakthrough* (Americans). By *bricolage* the authors meant resourcefulness and improvisation, characterized by modest yet steady gains made through the embedding of developers in accumulating artifacts, tools, practices, rules and knowledge and communication among distributed users and producers, such as design of the double brake system and flexible fibreglass wind turbine blades. This included a steady scale-up of designs all the while incorporating the inputs of diverse actors. Users offered continual feedback while

[71] Vestergaard, Jens, Lotte Brandstrup, and Robert D. Goddard III. "Industry formation and state intervention: the case of the wind turbine industry in Denmark and the United States." In Online version of a paper published in the Academy of International Business (Southeast USA Chapter) Conference Proceedings (November 2004), pp. 329-340. 2004.

[72] Garud, Raghu, and Peter Karnøe. "Bricolage versus breakthrough: distributed and embedded agency in technology entrepreneurship." *Research Policy* 32, no. 2 (2003): 277-300.

those in test centres - the crucial location of application - developed evaluation routines that co-evolved with experiences in the field. In contrast, the Americans aimed to harness science to generate dramatic outcomes. All the while, Danish policy makers "modulated" the emergence of the market to keep the technological path alive. This included the creation in 1979 of a substantial 30% investment subsidy for buyers of certified wind turbines. As the efficiency of wind turbines increased, direct investment subsidies were reduced gradually to 25% in 1983, 20% in 1985, 15% in 1987, 10% in 1988 with no subsidy in 1989. In contrast, policies in the US first amplified and then abruptly terminated the wind gold rush, thereby generating considerable problems for US wind turbine firms. A recently published paper on this topic has also found that government policies, specifically Danish feed-in-tariff and replacement certificate programs significantly impacted the timing of shutdown and upgrade decisions made by turbine owners and accelerated the development of the wind industry in Denmark.[73]

These findings were consistent with those in a paper published in 2004 which found manufacturing, scale-up and implementation successes in Denmark were aided by prominent learning-by interacting among turbine producers, turbine owners and researchers, versus relatively poor progress in the Netherlands due to reliance on a typical 'science-push' approach.[74] This was also consistent with a 2012 paper "Winds of change: communication and wind power technology development in Denmark and Germany from 1973 to ca. 1985", which argued that effective communication by engineers and technicians was a crucial component for the rapid success of Danish wind power technology (but not the only one, e.g. political support and mar-

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[73] Cook, Jonathan A., and C-YC Lin Lawell. "Wind turbine shutdowns and upgrades in Denmark: Timing decisions and the impact of government policy." In *2015 AAEA & WAEA Joint Annual Meeting, July 26-28, San Francisco, California*, no. 204960. Agricultural and Applied Economics Association & Western Agricultural Economics Association, 2015.

[74] Kamp, Linda M., Ruud EHM Smits, and Cornelis D. Andriesse. "Notions on learning applied to wind turbine development in the Netherlands and Denmark." *Energy Policy* 32, no. 14 (2004): 1625-1637.

ket subsidies).[75] The paper claimed that this communication grew from a social movement in Denmark that developed a common language through meetings, venues, markets, journals, and hubs of technical communication like the Test Station for Small Windmills.[76]

The case of MW scale wind turbine development has also been studied from a multi-level analysis paper perspective, specially the Dutch failures of wind in the late-1970s and PV in the mid-1990s. It found the lack of innovation in these niches was due to a technology-push character of the research and development, little attention for the societal embedding of new technologies, and government policy that was fickle and did not provide for long-term guarantees and stability.[77]

5. Discussion

In the case studies the location of projects in specific testing locations or detailed examination of locations-of-application preceded discoveries, inventions or development. These locational forces shaped technology and technical systems. This included: a chateau and mill for discovery of the greater efficiency of overshot water wheels; the City of London for development of the world's first gas lighting network; Lowell canals for development of the Francis water turbine; Northern California foundry for development of the Pelton water wheel; the gas lighting system for invention of Edison's electric lighting network; and Danish test sites for mega-watt scale wind turbines.

[75] Nielsen, Kristian H., and Matthias Heymann. "Winds of change: communication and wind power technology development in Denmark and Germany from 1973 to ca. 1985." *Engineering Studies* 4, no. 1 (2012): 11-31.

[76] Heymann, Matthias, and Kristian H. Nielsen. "Hybridization of Electric Utility Regimes: The Case of Wind Power in Denmark, 1973–1990." *Energy Transitions in History* (2013): 69.

[77] Verbong, Geert, and Frank Geels. "The ongoing energy transition: lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004)." *Energy Policy* 35, no. 2 (2007): 1025-1037.

Like the mode 2 context-of-application concepts, these locational forces may be characterized as strong, middle ground or weak. Strong locational forces shaped the emergence of new knowledge in projects that were physically undertaken in operational environments and directly influenced by site features or actors. This includes the design of a water-turbines in a canal or at a foundry, or the discovery of the overshot waterwheel's greater efficiency (than the undershot waterwheel) at a mill. Middle range locational forces include the use of techno-economic models prepared from data collected from locations-of-application, and the use of models to shape technology development plans. This included the preparation of cost models for candle illumination that were used to set goals for the design and performance of new gas lighting systems, and likewise for gas lighting costs used to inform the development of electric lighting. Weak locational forces, by contrast, were seen in research undertaken in laboratories without consideration of embodied use, such as U.S. federal government labs that sought to develop in the 1970s MW scale wind turbines, employing wind models prepared for aircraft design, versus Danish development efforts that were design in light of testing of prototype devices at wind test sites.

A second feature of the cases is a preoccupation among scholars, especially historians, of the role of scientific theories, measurement instruments and methods in new knowledge generation. In many of the cases there was at least some discussion of the science-technology relationship. For water wheels scientific theory acted as a foil. Of the energy technologies surveyed after Tomroy's second wave of innovation, only wind turbines seem not to been informed directly by either fundamental scientific information or instruments that arose form such research. Gas furnaces, the Francis and Pelton water turbines and Edison's electric power grid, all derive and have been improved in one way or another from scientific research. The Francis and Pelton turbines were particularly interesting in the way that scientific methodologies made their way into the cases through measurement instruments constructed within the build environment.

A third feature of the cases is that incumbent technologies in contexts of location provided critical information for invention, development and innovation. In each of the cases there was an incumbent technology that was used as a basis to measure improvement of the new technology. In the case of the overshot water wheel, it was the water wheel itself. Gas lighting used candles to define its value. Water turbines were compared to water wheels. Edison set his sights on the gas lighting system when designing his electric power grid. Wind turbines in the 1980s were measured against fossil fuel and nuclear generation plants.

Fourth, techno-economic models and revenue models provided important tools to understand the niche problem or incumbent technology challenge. The model was provided by James Watt and his creation of the unit of horsepower to set a quantitative standard for the measurement of power, and Boulton and Watt's introduction of gauges to measure the pressure and power of their steam engines to show customers the greater efficiency than other engines and horses. Likewise for gas lighting, Boulton & Watt prepared calculations to show the mill owners the cost advantage over candles. Both the Francis and Pelton turbines were developed using the Pony Brake to measure the efficiency of their design activities. Edison measured his system's value on a cost basis versus gas lighting, which would eventually be translated into a dollar per kilowatt indicator and used also for wind turbines.

6. Conclusion

In conclusion, locational forces profoundly shaped the fundamental understanding of the technology. The locations of applications surveyed in the cases provided spaces for learning, shaping and adapting of new technologies, as well as preparation of techno-economic models used in making design decisions. Technologies were invented and developed in or with reference to specific locations-of-application, often with quantifiable goals to improve or replace an incumbent technology within the niche. Ironically, in energy industries the improvement of technologies in these locations of application provided the foundation for breakthroughs.

7. Further Research

This preliminary survey of theories and case studies is intended to lay the foundation for further research as well as open up new avenues of research. The follow-on research includes expanding the surveys of theoretical literature and case studies, as well as adding other historical cases, e.g. gasoline and diesel engines, as well as studies of contemporary systems. In addition to surveys, further primary research may be undertaken.

There are policy and practice implications from this research. If the initial indications of this research can be validated in further studies, public and private funds and funding programs in energy industries will want to better understand and situate their capital in projects that account for locations-of-application. The implications of this study for government laboratory and university research managers are especially profound given that their research is often laboratory based and connections to locations-of-application can be quite weak. This preliminary research has focused on two primary means in which locational influences are exercised in technology development, i.e. locating projects in operational environments and conducting detailed studies of locations before beginning technical system development. More study of these means should be undertaken before consideration is given to formulation of new methods of research and development practice. Other methods of understanding locations may also be studied and developed.

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